CHARCOAL, FOOD, AND WATER PRODUCTION IN THE TROPICS: APPLYING NEXUS THINKING TO IMPROVE RESEARCH AND POLICY APPROACHES IN COMPLEX LANDSCAPES

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Urbanization, food, and water consumption trends in many tropical countries show that demand for charcoal (as a source of cooking energy), meat, grain and water will rise to proportions that surpass the ability of existing ecosystems to supply these services simultaneously and at desired qualities. Consequently, drastic changes to policy and practice are needed to improve ecosystem potential and/or alter demand trends.

Traditional charcoal production in sub-Saharan Africa, South East Asia and Latin America often competes or co-exists with livestock keeping and agriculture and has a tendency to occur in water-limited woodlands. The co-occurrence of charcoal and food production results in complex landscapes characterized by strong interactions between subsystems, managed by multiple sets of actors, with potentially competing objectives. These social-ecological systems provide goods and services that are essential to millions of people throughout the global south. Nevertheless, there have been very few detailed studies of such systems, particularly on the individual and combined effects of charcoal, crop, and livestock production on the hydrological system that maintains them and vice versa. As a result, these multi-use landscapes are typically managed by short-sighted, highly generalized, mono-sectorial policies that ignore important tradeoffs and undercapitalize on synergies. A system-level approach could provide important insights that improve and expand current understanding of this energy-food-water nexus.

Tackling urgent and complex problems composed of multiple and interrelated factors lies at the heart of nexus thinking - an approach that “examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments” (UNU-FLORES 2015) and relies on interdisciplinary research and multi-sector policy teams. It has attracted significant interest from international organizations, the private sector and governments as a way to develop integrated equitable solutions that involve inputs from multiple stakeholders. However, this approach is notably absent in the research arena.

Identifying appropriate interventions for achieving sustainable charcoal and food production and maintaining the underlying hydrological system on which they depend requires that the systems are considered simultaneously and that their biophysical, social, and political inter-relations are well understood. Taking charcoal as the nexus entry-point, this Research Topic aims to generate new understanding of charcoal production systems by incorporating agriculture and hydrology into the matrix. We were interested in empirical articles, reviews, meta-analytical articles and perspective papers that address at least two of the three nexus components and which offer provocative and insightful perspectives into the nexus as a whole.

We hope that this Research Topic will 1) facilitate identification of research gaps, policy opportunities and priorities for the nexus, 2) kick-start the development of a community of researchers and practitioners working on the nexus, and 3) permit the development of a research agenda that explores the nexus globally across multiple study sites.

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Co-exploring the Water-Energy-Food Nexus: Facilitating Dialogue through Participatory Scenario Building

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The "water-energy-food nexus" has become an increasingly popular way to frame the challenges associated with reconciling human development objectives with responsible management of natural resources and ecosystems. Yet the nexus is complex, requiring effective engagement between expert and Non-expert stakeholders in order to understand biophysical inter-linkages between resources and resource flows and social interactions between different actors in the socio-ecological system and landscape. This can be a substantial challenge due to varying levels of knowledge and understanding amongst actors with divergent, and often entrenched, interests. This paper presents insights on how participatory scenario-building processes can create space for dialogue amongst stakeholders with differing knowledge, experience, priorities, and political perspectives. Drawing on completed and on-going research applying a "nexus toolkit" in Ethiopia and Rwanda respectively, we contribute to a generalized conceptual framework for addressing, communicating, and assessing the water-energy-food nexus, with a particular focus on how to utilize the nexus concept in practice. This framework has significant potential to help better understand interactions at landscape level, for example, between charcoal production, food production, and environmental systems. We find that participatory scenario-building processes that facilitate engagement beyond technical aspects to include social, economic and political concerns provide a valuable space for discussing and negotiating development pathways that are sustainable both biophysically and socio-economically. In addition, the involvement of stakeholders throughout the project process greatly enhances the quality and legitimacy of results. Furthermore, we suggest that by building capacity amongst stakeholders to maintain a quantitative "nexus toolkit," it has a better chance of informing decision-making and for supporting the development of more technically refined analyses of alternative decisions and management strategies.

Keywords: water-energy-food nexus, scenario planning, stakeholder dialogue, co-exploration, Ethiopia, Rwanda

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INTRODUCTION

In recent years, the "water-energy-food security nexus" has become an increasingly popular way to frame the challenges associated with reconciling human development objectives with responsible management of natural resources and ecosystems (Bazilian et al., 2011; Hoff, 2011; Howells et al., 2013). The value of the "nexus" concept lies is its ability to clarify inter-linkages and competition for resources between different sectors of the economy and highlight the implications on development of (un)coordinated decision-making and management in these sectors. Therefore, a nexus approach is useful when there is a need to plan and govern interdependent resource-related matters, for instance, when different sectors depend on the same resources or the direct inputs from each other. In low-income countries, this pertains to hydropower generation, irrigation, fodder production, manure management, and the charcoal sector. In the latter case, a nexus analysis is of specific relevance given the complex interactions between the charcoal sector and deforestation, ecosystems, energy use, and income generation (see Chidumayo and Gumbo, 2013; Mwampamba et al., 2013; Zulu and Richardson, 2013).

The intrinsic complexity of the "nexus," particular in relation to the charcoal sector, underlines the need for effective engagement between expert and non-expert stakeholders in order to understand biophysical inter-linkages between resources and resource flows and social interactions between different actors in the socio-ecological system and landscape. Stakeholder engagement is also essential for building dialog and negotiating solutions around how to better coordinate decision-making and management across sectors for the purpose of sustainable and equitable development. However, achieving effective engagement between expert and non-expert stakeholders can be a substantial challenge due to varying levels of knowledge and understanding amongst actors with divergent and often entrenched, interests, and power to influence decision-making.

This paper presents insights on how participatory scenario-building processes can create space for dialog amongst stakeholders with differing knowledge, experience, priorities, power, and political perspectives. In doing so, we contribute to a generalized conceptual framework for addressing, communicating, and assessing the water-energy-food nexus, with a particular focus on how to utilize the nexus concept in practice to better understand challenges faced in the charcoal sector. To illustrate insights on how participatory scenario-building processes can help to illuminate particular nexus contexts in reality and create space for dialog on solutions to more integrated development pathways, we draw on completed and on-going action research projects in Ethiopia and Rwanda respectively. In these projects, we utilized a quantitative "nexus" toolkit, based upon the dynamic linking of a water and biomass modeling software tool—Water Evaluation and Planning (WEAP)—with an energy and climate modeling software tool—Long-range Energy Alternatives Planning (LEAP).

THE FOOD-ENERGY-WATER NEXUS CHALLENGE IN SUB-SAHARAN AFRICA

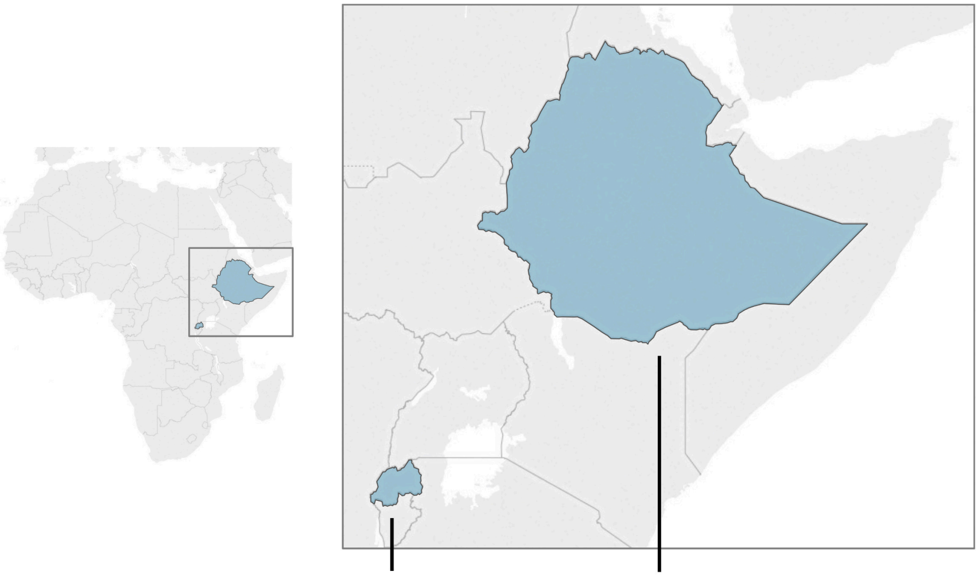
Many countries across Sub-Saharan Africa are witnessing rapid growth and development, largely driven by the processes of energy transition and agricultural transformation (Africa Progress Panel, 2015; AfDB, 2016). Sustainable energy transitions involve moving away from traditional biomass use to more modern energy services, ensuring universal access to reliable electricity supply, all whilst meeting climate change mitigation goals. Options may include modern bioenergy and hydropower, both of which require access to water and land resources. Meanwhile, agricultural transformation typically refers to improved productivity through intensification and commercialization, as well as integration into world markets. Such transformation is likely to require significantly higher energy and water inputs to improve productivity. At the same time, withdrawal of water upstream for irrigation purposes may reduce the water available for hydropower generation and ecosystems. A changing climate places further emphasis on the need to effectively manage water resources to adapt to and minimize the impacts of more frequent droughts. These changes, in addition to population increases and shifting patterns of consumption, lead to greater demand for natural resources and ecosystem services (Hallding et al., 2012; Jäger and Patel, 2012; Bierbaum et al., 2014). These pressures are exacerbated by the impacts of climate change, potentially leading to degradation of resources and leaving many millions of people food, energy, and water insecure (Matthew et al., 2010; Lee et al., 2012).

The future of charcoal production, trade and use is closely connected to processes of energy transition and agricultural transformation. Increased use of charcoal in urban centers in sub-Saharan Africa complicates attempts to facilitate an energy transition to cleaner low-carbon energy services: over 80% of urban households in the region rely on charcoal as their main source of cooking, and demand is set to increase as population grows and urbanization continues (Zulu and Richardson, 2013). At the same time, the clearing of forest to make way for agricultural land often provides opportunities for charcoal production using cleared forest resources (Mwampamba et al., 2013). The environmental and ecosystem impacts of charcoal production—whether from forest resources cleared for agricultural production or otherwise—can be severe (Chidumayo and Gumbo, 2013).

Within Sub-Saharan Africa, Ethiopia, and Rwanda stand out as two countries with ambitious development plans based around transforming agriculture and energy transition. Although, vastly different in terms of geographical size and population, both countries show similarities in their GDP per capita, percentage of the population employed in agriculture and energy access rates (see **Figure 1**).

Ethiopia has ambitions to become a middle-income country by 2025. A variety of targets have been set to help it reach this goal, including a number related to the agriculture and energy sectors. In 2010, the Government of Ethiopia established the Growth and Transformation Plan (GTP) followed by the Climate-Resilient Green Economy (CRGE) strategy in 2012 (Ministry of Finance and Economic Development, 2010; Federal Democratic Republic of Ethiopia, 2012). Both policy documents describe a pathway toward developing and modernizing the national economy in a sustainable, climate-compatible manner.

Ethiopia's GTP and GTP II targets build on long-standing agriculture growth and set targets associated with agricultural inputs (such as improved seeds, fertilizer, mechanization, land), energy generation (hydropower), irrigation, conservation, and land use. For example, by converting grazing and/or forest



	Rwanda	Ethiopia
Size (total area)	1,104,300 sq km	26,338 sq km
Population	102,374,044 (19.5% urban, 80.5% rural)	12,988,423 (28.8% urban, 71.2% rural)
GDP (PPP)	$161.6 billion	$20.42 billion
GDP per capita (PPP)	$1800	$1800
Employment in agriculture	Almost 80%	Around 90%
Energy access	85% urban, 10% rural	67% urban, 5% rural
Development strategy	Growth and Transformation Plans (GTP)	Economic Development & Poverty Reduction Strategies (EDPRS) Vision 2020
Green growth strategy	Climate Resilient Green Economy (CRGE)	Green Growth and Climate Resilience Strategy (GGCRS)

FIGURE 1 | Country comparison. CIA World Facebook (CIA, 2016).

land into cropland, the government aims to achieve a 13 per cent increase in cultivatable land. Meanwhile, irrigated land is expected to increase by more than 400 per cent during the same time period. Lastly, fertilizer use is projected to increase by roughly 100 per cent, leading to dramatic increases in productivity and agricultural output: e.g., increasing crop productivity by 30 per cent, power generation by 300 per cent, and sugar production by 600 per cent (Ministry of Finance and Economic Development, 2010).

As well as these conventional economic growth objectives, GTP also sets out a National Resource Conservation Plan that aims to rehabilitate land and increase forest cover. The CRGE strategy—which aims to ensure ambitious national development plans are not adversely affected by climate change—further describes these conservation targets (Federal Democratic Republic of Ethiopia, 2012). While the targets set out in the CRGE strategy—shown in **Table 1**—are admirable, it is unclear whether all direct impacts or potential conflicts between targets have been adequately explored. For example, there is little to suggest that conflict between water use for irrigation and hydropower development has been studied. Similarly, continued and increasing exploitation of forest resources for charcoal production and construction purposes may make it increasingly difficult to meet forest cover targets. By 2014, over three million tonnes of charcoal were being consumed each year in Ethiopia's urban centers; as in many countries in sub-Saharan Africa, attempts to regulate charcoal production and trade to make it more sustainable have been ineffective (Bekele and Girmay, 2014). Considering and pre-empting such conflicts is particularly important when analyzing potential welfare impacts, preparing coping mechanisms, and managing environmental feedback effects at the local level.

Furthermore, the rapid expansion of hydropower and irrigation infrastructure has heightened tensions with neighboring countries that depend extensively on water resources originating from the Ethiopian highlands for household, agricultural, and industrial consumption. Yet it also signals a changing geopolitical climate in which Ethiopia is becoming an important force in the Horn of Africa region (Rahmato, 2011; Verhoeven, 2011). Given these related concerns, it is unlikely that all the goals of the GTP and the CRGE can be met simultaneously, particularly when following a conventional sectoral approach (Karlberg et al., 2015a).

Meanwhile, Rwanda has committed itself to becoming a middle-income country by 2020. The countries Vision 2020 and Economic Development and Poverty Reduction Strategies

TABLE 1 | Green growth strategies in Ethiopia and Rwanda.

Issue areas	Ethiopia's CRGE	Rwanda's GGCRS
Land and agricultural transformation	Improving crop and livestock production practices for higher food security and farmer income while reducing emissions Safeguarding forests and reforestation in order to maintain their economic and ecosystem services, including as carbon stocks	Ensuring sustainable land-use and natural resources management resulting in food security and the preservation of biodiversity and ecosystem services
Energy transition	Increasing electricity supply from renewable sources for domestic and regional markets Leapfrogging to clean, efficient and modern and technologies in transport, industrial sectors, and buildings	Achieving energy security and low carbon energy supply, while avoiding deforestation
Societal impacts		Societal protection, including reduced vulnerability to climate change

Federal Democratic Republic of Ethiopia (2012); Republic of Rwanda (2011).

(EDPRS I and II) both set out clear intentions to intensify agriculture and increase national energy output (Republic of Rwanda, 2013, 2007). For example, agriculture is expected to grow by 8.5% annually and energy generation is expected to grow from 45 MW in 2006 to 563 MW in 2018, mainly through development of hydropower. These ambitions are also present at a sub-national level, with District Development Plans including provisions to modernize agriculture, invest in energy production and expand many water-intensive activities, such as mining, industrial development, and ecotourism.

These development goals place increasing pressure on limited water and biomass resources. Competition over water resources demanded by hydropower, irrigation, and water supply to major towns and various industries has the potential to create serious conflict. Meanwhile, biomass scarcity causes the country to import biomass from neighboring countries as well as having to allocate croplands to wood plantations, such as eucalyptus; in 2009, 21% of the biomass consumption was ascribed to unsustainable use of biomass and "the constant flow of charcoal into Kigali, exerts a considerable pressure on the wood resources of the country" (Drigo et al., 2013, p. vii). In addition, an intensified agricultural sector will demand more energy and water per hectare, although a modernized energy sector less dependent on traditional biomass is likely to be less land-intensive.

In order to better understand the linkages between different sectors in future scenarios, Rwanda developed its Green Growth and Climate Resilience Strategy (GGCRS) in 2011 (Republic of Rwanda, 2011). The GGCRS was developed to guide decisions around natural resource management, investments and policy as well establish demonstration initiatives to support climate resilience activities and community livelihoods. The GGCRS centers around three cornerstones, shown in **Table 1**.

Whilst green growth and development plans in Ethiopia and Rwanda appear impressive—and have garnered significant support from international development partners (The Economist, 2010)—these ambitious national plans raise a number of concerns. In both countries, the political reality is complex. Despite exhibiting the formal institutions of democracy, civil society remains "stunted" (Matfess, 2015). Political opposition in Ethiopia is weak (Kefale, 2011) and the failure to meaningfully engage stakeholders at all levels of society, particularly at the local level, raises key issues of equity, representation, and recognition. This is likely to further exclude those who are already politically and socially marginalized (Jones and Carabine, 2013). There have been impressive efforts in Rwanda to reconstruct and modernize the country after genocide (Uvin, 2001; Ansoms, 2008), including huge steps to achieve better gender equality in political representation, with women taking 64 per cent of parliamentary seats in 2013 (United Nations, 2013). However, citizen participation is low in areas such as policy making, formulation of laws, decision-making and development, and evaluation of local government programmes (Interayamahanga, 2011). Decentralization has not increased the voice of local people, but has merely allowed the central level to extend its influence to the local level (Ansoms, 2008). This "developmental authoritarianism" (Matfess, 2015) reduces the prospects for democratic deliberation over green growth strategies and plans and the potential for developing alternative pathways and understandings of "sustainability."

Taken together, these issues point to the need for approaches that can "open up" space for dialog in order to deal with complex nexus issues. Such approaches need to be based on quantitative assessments of resources availabilities, as well as qualitative analysis of the impacts on whole socio-economic systems. Our goal is to develop, test and apply such an approach through a process of collaborative stakeholder dialog.

PARTICIPATORY SCENARIO BUILDING APPROACH FOR CO-EXPLORING THE NEXUS

The inherent complexity of the water-energy-food nexus approach makes stakeholder participation essential, particularly if space is to be opened up for actors with different perceptions to be heard, particularly those who are often marginalized. One way to open up space for co-exploration and dialog around nexus issues is through a participatory scenario-building approach, combining qualitative, and quantitative methods.

Scenario Building for the Water-Energy-Food Nexus

Scenario building is becoming widely appreciated as an effective way in which to explore interactions between complex social and environment systems over the medium-to-long term (Swart et al., 2004; Kok et al., 2007; Volkery et al., 2008). Essentially, scenario building is a way to posit ideas about the future, with scenarios describing how the future may develop based on a certain set of assumptions about potential drivers of change and uncertainties (Bradfield et al., 2005; Millennium Ecosystem Assessment, 2005). Exploratory scenarios are particularly relevant for investigating the water-energy-food nexus, as it allows us to explore development pathways arising from the interactions between different sectoral strategies.

Exploratory scenarios can be qualitative, quantitative or—more often than not—a mix of the two. Often a "story and simulation approach" (Alcamo, 2008) is pursued whereby qualitative scenarios—storylines or narratives—describing the broader picture of future development are quantified for use in computer-based modeling tools. Typically, each scenario represents a possible future state of the social and environmental system under consideration (Spielmann et al., 2005).

Exploratory scenarios can also be used at different levels. For example, at the global level, scenarios were used in the IPCC Special Report on Emissions Scenarios (SRES; Nakicenovic et al., 2000) and in Shared Socioeconomic Pathways (SSPs; O'Neill et al., 2015), the new scenario process replacing the SRES scenarios. On the local level there are numerous studies employing scenario planning, e.g., climate adaptation planning (Baard et al., 2011; Carlsen et al., 2013), integrated water resource management (Voinov and Gaddis, 2008) and governance of sustainable development (Bohunovsky et al., 2011).

Participation and Engagement

Building scenarios can be done in many ways. Typically scenarios are constructed by developing a storyline or narrative (as in the story and simulation approach), based around first prioritizing the most uncertain and most important driving forces. These driving forces might encompass trends associated with population growth, economic growth and urbanization, potential changes in climate and planned policies, and interventions. Given the unlimited range of scenarios that can be developed, it often makes sense to narrow down to a small number of particularly relevant scenarios based upon broad plausible storylines/narratives. A typical starting narrative is the "business-as-usual" scenario, whereby the key drivers affecting future development are on-going demographic trends, such as population growth, economic growth, and increasing urbanization. Other scenarios may be based upon the implementation of planned national polices and interventions, or on certain climate change projections.

This leads to key questions around who defines the storyline, and whose voice is represented in this version of the future? Who decides which driving forces are most important? The water-energy-food nexus presents a particular challenge given the complex inter-linkages between sectors and the different future pathways identified with by actors in different sectors. Furthermore, quantifying a given future pathway for use in an analytical scenario building may place a bias on the views of technical experts over those of non-experts (e.g., practitioners, policy makers, and the public).

How might participation improve planning and decision-making processes? Fiorino (1990) identifies three main rationales for increasing participation. The first is *substantive*: the public's judgments about risk are equally sound, and sometimes better, than those of experts; hence, increasing participation can improve the outcomes of planning. From this perspective, participatory nexus scenario planning can help to increase knowledge and understanding of the water-energy-food security nexus in a particular context, particularly nuanced framing with multiple perspectives. Combining factual information and analytical techniques with "local knowledge and subjective perceptions" (Pahl-Wostl, 2002) "imagination and expertise" (Volkery et al., 2008) from different stakeholder groups can help to build consensus on the current conditions and key driving forces (Andersson et al., 2008) and lead to more accurate scenarios reflecting local realities (Patel et al., 2007; Reed et al., 2013).

The second rationale for participation is *instrumental*: decisions that involve citizens are seen as more legitimate; hence, increasing participation ensures better buy-in, which leads to better results. Increasing participation in nexus scenario building may help to ensure "that all stakeholder groups involved have a high degree of confidence" (Andersson et al., 2008). It is vital to ensure future scenario storylines are credible, legitimate and salient, particularly "with respect to personal beliefs, the equifinality of alternative development pathways, the validation and uncertainty of assumptions, stakeholder engagement in visions development, and participatory methods" (Rounsevell and Metzger, 2010). Making sure scenarios are relevant to stakeholder needs and priorities (Reed et al., 2013) may significantly increase the chances of buy-in to subsequent policy proposals based upon the nexus analysis (Robinson et al., 2011).

The third rationale is *normative*: the best judge of citizens' interests are citizens themselves, hence, increasing participation is the right thing to do. This normative drive for participation is derived from the need for dialog to clarify problems, identify unavoidable trade-offs and negotiate viable solutions to complex and uncertain environmental and societal problems (Patel et al., 2007; Voinov and Bousquet, 2010; Ravera et al., 2011). Participatory processes can help trigger conversations on future developments between stakeholders who might never typically engage with each other (Volkery et al., 2008). If managed effectively, such engagement can "increase the level of understanding between the various groups and therefore ameliorates the potential for future conflicts" (Andersson et al., 2008).

Challenges to Effective Participation

Despite the allure of participatory scenario building approaches to co-explore and address water-energy-food nexus issues, there are significant challenges to ensuring participation is effective. There are many rungs on the ladder of participation; from token participation (consultation and informing) to full citizen power (partnership and control; Arnstein, 1969). Not all mechanisms that are considered "participatory" actually provide opportunities for full engagement. In some cases, stakeholder engagement is merely symbolic (Voinov and Bousquet, 2010).

Participation in nexus scenario building is made difficult by the complex issues involved, typically crossing multiple sectors beyond the knowledge of any one person. This difficulty may be amplified if the quantitative technical models used to build scenarios are inaccessible. Indeed, there is often a risk of overwhelming stakeholders (Robinson et al., 2011). Avoiding this risk requires considerable investment in time and resources to ensure that complex information and decisions are presented to non-technical stakeholders in an accessible way (Kok et al., 2007; van Vliet et al., 2010; Robinson et al., 2011).

Despite best efforts, there remains the risk of participatory processes being framed such that the range of options considered reflects the preferences of incumbent interests. In this sense, participation is used as a "technology of legitimation" (Harrison and Mort, 1998 in Stirling, 2007, p. 264). As Stirling (2007) argues, participatory processes do not inherently solve the problem associated with expert-led planning: the sensitivity to framing by powerful interests. In order to make a difference, participatory processes need to open up the decision space beyond the options preferred by those with the most power and influence. They need to better inform and determine the technical analyses, and uncover alternatives that might not otherwise be considered.

Participatory Nexus Scenario Building in Ethiopia and Rwanda

Given the potential benefits and pitfalls of participatory processes to understand and seek solutions to the water-energy-food nexus, it is important to design a structured—but flexible—process or method to effectively and sincerely engage with stakeholders as one moves between "story" and "simulation." In our research in Ethiopia and Rwanda, we sought to co-produce different plausible development scenarios with stakeholders. In Ethiopia, the geographical scope of our study was the Lake Tana sub-basin[1], while the Akagera river basin formed the geographical scope of our study in Rwanda[2]. The scenario co-production process in each case study was used to create space for dialog amongst stakeholders with differing knowledge, experience, priorities and political perspectives on how to address challenges and opportunities pertaining to the nexus.

The process, shown in **Figure 2**, was based on a set of iterative steps consisting of engagement with technical and non-technical stakeholders to identify the current state of affairs and posit scenarios about how the future might unfold, followed by quantitative modeling of these scenarios. In a workshop setting, stakeholders and the project team jointly developed the assumptions, populated the model with their own data and critiqued the results of the tool in an iterative approach until the model is deemed credible. Moreover, stakeholders analyzed the socioeconomic and environmental impacts of the results and compare them with the goals in national strategies and policies. Lastly, stakeholders participated in the formulation of new policies and technical innovations to be tested in the toolkit, thereby supporting the development of new interventions. Application of the "nexus tool-kit" in Ethiopia, including quantitative scenario modeling results on the water-energy-food nexus in the Lake Tana region, are available (see Karlberg et al., 2015a). Scenario modeling in Rwanda is still on-going and thus results are not yet published.

Initial Stakeholder Engagement and Model Development

The first step of the process consisted of initial engagement with stakeholders to understand the current context and setting, and discuss initial narratives or storylines about the future. In both case studies, local project partner(s) invited stakeholders for broader stakeholder engagement, as well as to be part of a smaller technical team who were part of developing the quantitative tools. In Ethiopia, the local project partner was the Bahir Dar University, a prominent university in the case study region. In Rwanda, and our local partner was the Albertine Rift Conservation Society (ARCOS), a conservation NGO headquartered in Kigali.

A first workshop was held with the broader stakeholder group to introduce the water-energy-food nexus concept, map out actors and institutions, define current issues pertaining to the nexus, and finally to create initial scenario narratives. In Ethiopia, 40 stakeholders attended the this first workshop, with participation from, for instance, the Bureau of Water Resource Development, the Bureau of Agriculture, the Bureau of Energy and Mines, the Fisheries Association, Environment Protection, Land Administration and Use Bureau, the Abbay Basin Authority, and Bahir Dar University. In Rwanda, around 25 stakeholders attended, representing the Ministry of Natural Resources, the Rwanda Natural Resources Authority, the Ministry of Agriculture, the Ministry of Local Government and the three districts specifically targeted in the study. In both countries, it proved challenging to attract stakeholders from the government authorities and state-owned utilities in the energy sector.

In the first workshop in both Ethiopia and Rwanda, stakeholders were initially asked to describe the current situation in terms of water and land-use for energy and food production and related socio-ecological impacts. This information was used to develop the initial reference scenario, also called "business-as-usual" (BAU). In this scenario for both cases, all existing resource

[1] https://www.sei-international.org/mediamanager/documents/Publications/SEI-DB-2013-Nexus-Blue-Nile-Ethiopia.pdf.

[2] https://www.sei-international.org/mediamanager/documents/Projects/FONERWA_Project_Flyer[2].pdf.

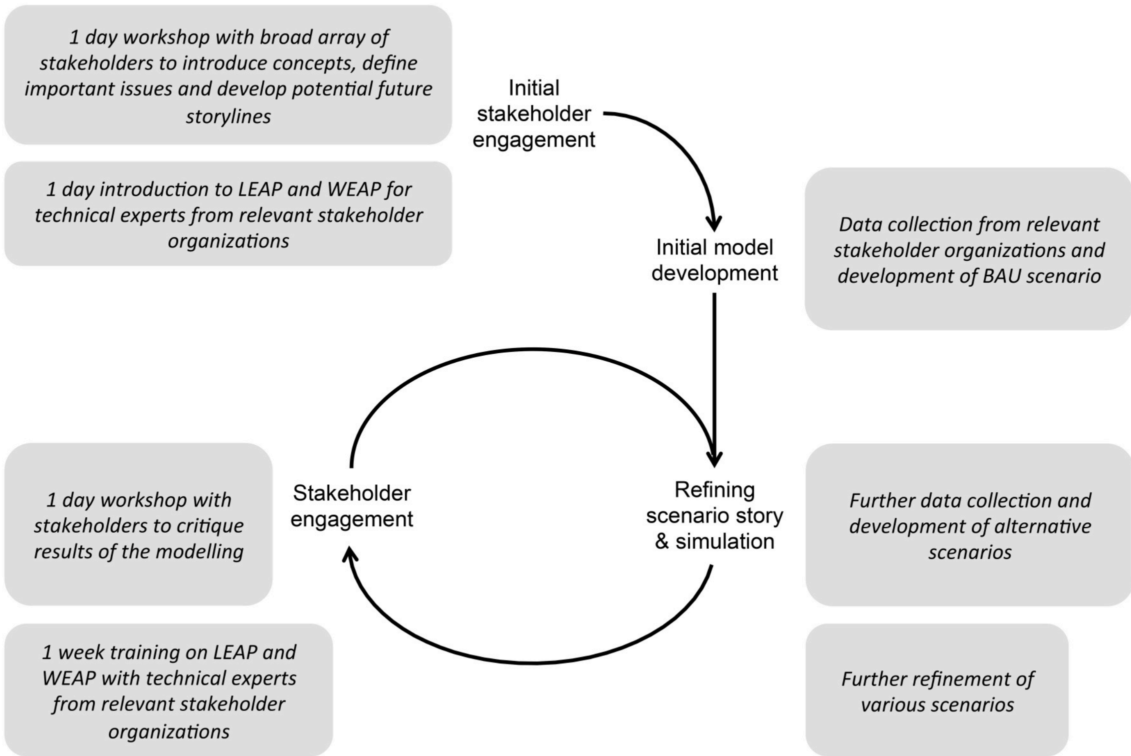


FIGURE 2 | Iterative participatory scenario planning in Ethiopia and Rwanda.

management practices were assumed to remain the same, or change according to historical trends, but distributed amongst a growing population as per expected growth patterns. In order to compare this BAU development pathway, the stakeholders were then asked to generate a second scenario based on the national policy framework. For example, population growth in Ethiopia and Rwanda were expected to continue at 3.1 and 2.5 per cent per year (the figure for Ethiopia is adopted in the specific case study area). Meanwhile, agricultural transformation in both countries would continue to unfold slowly and energy transition would remain hampered by continued dependence on traditional or marginally more efficient biomass energy.

Back-to-back with the first workshop, an initial training on the quantitative tools used in the projects (the "nexus tool-kit") was provided to the local technical team in each country. The intention was to engage experts early on to acquire knowledge on the tool-kit so that they could co-develop the application and be proficient users at the termination of the projects. Typically participants in this team were technically proficient junior/mid-level employees from stakeholder organizations, who may or may not already have prior knowledge of the modeling tools. In Ethiopia, the technical team for LEAP consisted of representatives of the Ethiopian Electric Power Company (EEPCo), the Environmental Protection, Land Administration and Use Bureau and the Mines and Energy Resources Development and Promotion Agency and Bahir Dar University. The technical team for WEAP included representatives from for instance the Bureau of Water Resource Development, the Bureau of Agriculture, the Abbay Basin Authority, the Amhara Regional Agricultural Research Institute (ARARI), and Bahir Dar University. In Rwanda, the technical team members came from for instance the Energy Utility Corporation, the Ministry of Infrastructure, the Ministry of Natural Resources, the Rwanda Natural Resources Authority, the Water and Sanitation Corporation, and a number of representatives from three districts specifically targeted in the study. In Ethiopia, it was particularly challenging to find energy experts. In Rwanda, energy experts were easier to access, but agricultural experts were difficult to access.

Based on the information gathered during the workshop, semi-structured interviews, local data-repositories made available by the stakeholders, and information found in the literature, a first model application was built using quantitative tools ("nexus tool-kit"). In our particular "nexus toolkit," we used the Water Evaluation and Planning (WEAP) tool[3] and LEAP[4]. These software tools are two of the most common water and energy planning tools used globally today, particularly in data scarce environments. In dialog with stakeholders, the tool can be applied to test classical "what if" questions (e.g., what if we increase the energy tariff, subsidize fertilizer, build more irrigation dams etc.). SEI's WEAP and LEAP "nexus toolkit" are

[3]http://sei-us.org/software/weap.
[4]http://sei-us.org/software/leap.

modeling tools that use a broad set of data collected in the field and from other sources. The toolkit can then analyse several development pathways, conduct stakeholder analysis of outputs and finally evaluate different development pathways.

Refining Scenario Story and Simulation

After the initial model application was completed by the modeling experts, a full-week training with the technical team was held in Ethiopia and Rwanda. During this week, the local application of the model was used as the training material. For instance, in Ethiopia the WEAP and LEAP model for the Lake Tana region was used. In Rwanda, a national level LEAP model was used and a WEAP model covering the Akagera basin was used. In this way, the technical team were given the opportunity to critique and refine the model assumptions and results—given their local knowledge—and were able to direct the modeling team to better or more appropriate data as necessary. In both cases, the technical training led to the emergence of invaluable and previously inaccessible reports and associated data on energy, water, and agriculture in the respective countries.

After a period of time, during which the model continued to be refined, a second workshop with the broader stakeholder group was then conducted (yet to be done in Rwanda). In Ethiopia, this workshop employed the use of the SWOT analysis approach (Strengths-Weaknesses-Opportunities-Threats). The SWOT analyses were complemented with questions about potential winners and losers under each scenario. The insights generated by these exercises thus highlighted the implications of each development trajectory for a variety of different stakeholder groups. Based on these implications, a set of unresolved dilemmas, also under the national framework scenario, were identified. As a response to this, the stakeholders defined a third scenario, hereafter called the "Nexus" scenario. As a result, the interaction between stakeholders and scientists in Ethiopia generated a revised set of narratives as well as a clearer understanding among the scientists on which data to include in the LEAP and WEAP models for the Lake Tana region.

Co-exploring Scenario Impacts

In consecutive workshops in Ethiopia, modeling work was analyzed and critiqued by the technical team, which led to a refinement of data and assumptions in an iterative process, until the results were deemed credible. In Rwanda, these workshops will take place in 2017 and 2018. The broader stakeholder group in the Lake Tana region participated in refining the scenarios and assessing impacts, again using SWOT analysis. The outcome of participatory scenario modeling work in Ethiopia was identification of clear, yet unresolved, conflicts and trade-offs over national plans for water resource use in agriculture and energy and over current patterns of biomass resource use, as well as development of a "nexus" scenario that sought to address these conflicts and trade-offs (Karlberg et al., 2015a).

Overall, each step in the process can be iterated as necessary to further refine the models/scenarios, build competence within the technical team and increase dialog between stakeholders. When discussions move toward seeking solutions that address trade-offs, etc., then the process can be viewed as coming to a close. For instance, the dialog might lead to plans for several promising technical innovations that may have positive impacts for both transforming the agricultural and the energy sectors, such as micro-hydro schemes, bio-digesters, improved cook-stoves, water harvesting dams, conservation agriculture, etc. If the both the direct and indirect impacts of upscaling these technologies are unclear, the "nexus tool-kit" can in these cases help to quantify the resources allocations to different sectors and potential environmental impacts, as well as the production of both food and energy for different development trajectories.

DISCUSSION AND LESSONS LEARNED

In order to further explore the conceptual approach demonstrated in this paper, we relate the process and methodology applied in the two case-studies in Ethiopia and Rwanda respectively with the rationales for participation (substantive, instrumental, and normative; Fiorino, 1990), and are thus able to confirm the relevance of all three in our proposed approach to scenario building in nexus studies. Furthermore, we provide a few concrete examples from each case-study as a way to illustrate how the water-energy-food nexus may play out in resources constrained, low-income countries in the tropics, with specific focus on charcoal.

Local Knowledge

The substantive argument for participatory nexus scenario planning emphasizes the importance of local knowledge and perceptions in fully understanding the water-energy-food security nexus in a particular context. During the initial interactions with the stakeholders a number of nexus issues that were of importance in the specific local setting were identified. In Ethiopia, our initial discussion revolved around water use for irrigation, hydropower generation, and maintaining environmental flow requirements in rivers and lakes. However, in subsequent workshops it became increasingly clear that biomass use for food, fodder, and fuel was just as important. Moreover, the use of water and biomass for energy and food production were strongly linked; current over-use of biomass for fodder and fuel was causing severe land-degradation and could only be partially offset by higher reliance on alternative energy sources such as electricity (e.g., hydropower). The analysis showed that if the management of biomass was to continue unchanged, demand would exceed supply by a factor of three by 2030 (Karlberg et al., 2015b), which has potentially severe implications for all sectors depending on biomass use, such as the charcoal industry and livestock rearing. Specifically, the demand for fuelwood, partly consisting of demand for charcoal, is predicted to exceed supply of woody biomass by a factor of five by 2030, thus highlighting the urgent need to address the energy supply situation and specifically the cooking fuel component.

In Rwanda, the current overuse of biomass for charcoal production, and the governance implications thereof, was one of the entry points for discussion. Being severely constrained by productive land area, the country will need to make well-informed decisions and come to agreement on how to best make use of this land and the associated biomass. As the charcoal sector currently employs a significant proportion of the population, such decisions need to be followed by a strategy for providing alternative sources of income for those that currently derive their livelihoods from this sector, should the decision be to reduce the dependence of charcoal in the energy sector in future. Such alternatives are currently being co-explored with the stakeholders and the research team in the on-going project in Rwanda.

As discussions developed, it became clear that the interactions between the processes of agricultural transformations and energy transitions was strong and complex and that there was a need for quantitative assessments to provide illustrations of different plausible development trajectories to support the planning of natural resources management which hitherto had been based on educated guesses on the developments of the other sectors, at best. Participatory scenario building can significantly contribute to a critical review of data on issues pertaining to the water-energy-food nexus.

Legitimacy

The instrumental rationale for participatory scenario building revolves around the notion that decisions involving citizens are likely to be more legitimate. We found that the iterative process of model development and scenario refinement in Ethiopia and Rwanda helped to make the narratives significantly more relevant and appropriate from the perspective of the stakeholder groups. Moreover, by co-developing the local model application with a team of technical experts scrutinizing and contributing to data, assumptions and results, improved the quality of the application.

Also, past project experience shows that if local stakeholders can maintain a quantitative model, it has a better chance of informing decision-making. In this context a note of caution is warranted. Nexus analysis quickly becomes complex and is therefore resource consuming. Thus, before embarking on a full-scale nexus analysis, it is critical to hold an initial workshop and perform some initial sector specific quantifications of resource demand and supply to reveal if any nexus issues actually exist. It is important to remember that not everything is a nexus issue, and some issues can be managed more easily within a specific sector.

Trade-Offs and Governance

The normative drive for participation highlights the importance of stakeholder dialogue to clarify problems, identify unavoidable trade-offs and negotiate viable solutions to complex and uncertain environmental and societal problems associated with the nexus. The process highlights constraining and reinforcing interlinkages between different sectors and thus stimulates vital discussion between stakeholder groups who may not have discussed their separate future pathways with each other before. The projects brought together stakeholders from the food, water, energy, and environment sectors to discuss the implications of different development trajectories and to jointly develop new strategies that would address outstanding dilemmas. To support this dialogue, the co-creation of the scenarios and the joint analysis of the impacts resulted in a better understanding of the dilemmas facing each sector and hence a more common ownership of the development of the region by all stakeholders. Moreover, since the analysis was based on the data and assumptions made by the local experts, and provided a quantitative illustration of different development trajectories, the focus on the discussions was on impacts and options for resolving dilemmas, rather than arguing and guessing over resources availabilities. Even though there was often disagreement amongst the stakeholders on what constituted more or less desirable uses of resources, there was a shared understanding of that whatever each sector does will impact on the others. As a consequence, in Ethiopia all stakeholders expressed a need for continued dialogue to ensure cross-sector coherence. The outcome therefore was the forming of a cross sector platform for dialogue, and an improved understanding of joint issues pertaining to resource scarcity (in this case specifically water and biomass) and the needs of other sectors. The project also revealed gaps in the current policy framework that would need to be addressed to ensure a desirable future for all.

During the workshops in both Ethiopia and Rwanda, a lot of time was spent discussing which actors and/or institutions that have the mandate to govern nexus issues. This experience was also shared in a nexus rapid appraisal conducted in Zambia (Zur Heide et al., 2015). It appears that water management agencies have a central role to play, since they commonly have a mandate to plan water resources allocation amongst several stakeholders. Yet, they lack the land-use aspects and can also be said to have vested interests. On the other hand, most stakeholders did not suggest a new institution to take on the role of overseeing nexus issues. In this context, the issue of level is also important, i.e., should the nexus be managed a local, national or regional levels. It appears that most actors are present at the national level which is also where policies are being developed, so the national level will be, if not possibly the only level for nexus governance, so at least a critical one. In summary, we note that the ownership of the process is a challenge which has to be addressed in each specific local context.

Challenges

A number of outstanding challenges were also identified in both projects. Firstly, we note that actors sit at different levels at different sectors. For instance, in Ethiopia we conducted social network analyses on the agriculture, energy, water, and environment sectors (Stein, 2013). It was found that whilst agriculture, water and environment consisted of large actor networks ranging from the local to the national level, the energy network was smaller and most actors were concentrated at the national level. As a consequence, it was sometimes difficult to get participation by energy actors in workshops held at the local level. Moreover, despite the energy sector in Rwanda and Ethiopia being more than 80% biomass based (World Bank, 2009) the energy sector actors were predominantly focused on electricity. Since biomass scarcity is a major challenge and impacts greatly on land management, the lack of focus on bioenergy becomes problematic from a nexus perspective.

On a related note, it became clear during the stakeholder workshops that different stakeholders had different abilities to impact the decision on the ultimate use of resources. In Ethiopia for instance, stakeholders expressed that hydropower generation, followed by irrigation, took priority over meeting environmental flow requirements. We therefore identified a challenge to manage different power relations amongst actors in a nexus context.

Lastly, we note that implementing a cross-sector process inevitably takes time. Changing policy and planning processes normally takes longer than the duration of a research project. On the other hand, the uptake of quantitative tools to support the planning and decision-making process is faster. Overall, we conclude that the impacts of a nexus project are most likely experienced beyond the closing of the project, and therefore a strong local partner with a clear mandate to continue to support the process is critical to achieve long-term impacts.

CONCLUSIONS

The water-energy-food nexus concept takes an integrated approach to understanding ways in which human development can be pursued without adversely affecting natural resources and ecosystems. In this regard, the nexus approach has significant potential for exploring the barriers to and opportunities for sustainable production, trade and consumption of charcoal—an important and growing source of energy and income in sub-Saharan Africa. However, the complexities of the nexus require careful engagement with stakeholders to manage conflict and tensions around potential winners and losers of any future change or intervention.

In this conceptually-oriented paper, we proposed a participatory scenario-building process that facilitated engagement beyond technical aspects to include social, economic, and political concerns. Applying this participatory scenario-building process in empirical studies of the water-energy-food nexus in Ethiopia and Rwanda, we found that such a process provides a valuable space for dialogues around development pathways that are sustainable both biophysically and socio-economically. Co-production and co-exploration of quantitative scenarios stimulates vital discussion between stakeholder groups who may not have discussed their separate future pathways with each other before, and contributes to a shared understanding of how the sectors depend on each other, and therefore illustrates the need for joint solutions to outstanding dilemmas. We found that even though there was often disagreement amongst the stakeholders on what constituted more or less desirable development outcomes, there was a shared understanding of the interlinkages between the sectors and how those could be addressed. Our proposed methodology to participatory scenario building addressing the water-energy-food nexus highlights the relevance of substantive, instrumental, and normative rationales for stakeholder involvement.

Furthermore, we found that equipped with technical expertise and knowledge of how their sector fits into the broader socio-ecological landscape and system, stakeholders may be able to achieve more sustainable and equitable options to address resources allocation in the water-energy-food nexus. An outstanding challenge relates to the ownership of the processes and water-energy-food nexus related issues, which needs to adapt to local institutional structures and existing platforms for collaboration. Managing different power relations amongst stakeholders in yet another challenges which special relevance to the nexus, since by definition this topic involves an array of various actors.

AUTHOR CONTRIBUTIONS

Both authors co-wrote the paper; OJ led the organizing and writing and so was designated lead author.

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REFERENCES

AfDB (2016). *Feed Africa: Strategy for Agricultural Transformation in Africa 2016-2025*. African Development Bank (AfDB), Abidjan, Côte d'Ivoire.

Africa Progress Panel (2015). *Power People Planet: Seizing Africa's Energy and Climate Opportunities*: Africa Progress Report 2015, Africa Progress Panel, Geneva.

Alcamo, J. (2008). Chapter six The SAS Approach: combining qualitative and quantitative knowledge in environmental scenarios. *Dev. Integr. Environ. Assess.* 2, 123–150. doi: 10.1016/S1574-101X(08)00406-7

Andersson, L., Olsson, J. A., Arheimer, B., and Jonsson, A. (2008). Use of participatory scenario modelling as platforms in stakeholder dialogues. *Water SA Spec. HELP Ed. Spec.* 34, 439–447. Available online at: http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1816-79502008000400003&lng=en&nrm=iso

Ansoms, A. (2008). *A Green Revolution for Rwanda?: The Political Economy of Poverty and Agrarian Change*. IOB, University of Antwerp.

Arnstein, S. R. (1969). A ladder of citizen participation. *J. Am. Inst. Plann.* 35, 216–224. doi: 10.1080/01944366908977225

Baard, P., Carlsen, H., Edvardsson Björnberg, K., and Vredin Johansson, M. (2011). *Scenarios and Sustainability A Swedish Case Study of Adaptation Tools for Local Decision-Makers*. Working Paper No. 124. Stockholm: National Institute of Economic Research (NIER).

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Bekele, M., and Girmay, Z. (2014). *Reading through the Charcoal Industry in Ethiopia: Production, Marketing, Consumption and Impact (No. FSS Monograph No.9)*. Forum for Social Studies (FSS), Addis Ababa, Ethiopia.

Bierbaum, R., Stocking, M., Bouwman, H., Cowie, A., Diaz, S., Granit, J., et al. (2014). *Delivering Global Environmental Benefits for Sustainable Development (No. Report to the 5th GEF Assembly, Mexico)*. Global Environment Facility, Washington, DC.

Bohunovsky, L., Jäger, J., and Omann, I. (2011). Participatory scenario development for integrated sustainability assessment. *Reg. Environ. Change* 11, 271–284. doi: 10.1007/s10113-010-0143-3

Bradfield, R., Wright, G., Burt, G., Cairns, G., and Van Der Heijden, K. (2005). The origins and evolution of scenario techniques in long range business planning. *Futures* 37, 795–812. doi: 10.1016/j.futures.2005.01.003

Carlsen, H., Dreborg, K. H., and Wikman-Svahn, P. (2013). Tailor-made scenario planning for local adaptation to climate change. *Mitig. Adapt. Strateg. Glob. Change* 18, 1239–1255. doi: 10.1007/s11027-012-9419-x

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. doi: 10.1016/j.esd.2012.07.004

CIA (2016). *The World Factbook [WWW Document]*. Available online at: https://www.cia.gov/library/publications/the-world-factbook/ (Accessed December 13, 2016).

Drigo, R., Munyehirwe, A., Nzabanita, V., and Munyampundu, A. (2013). *Final Report Update and Upgrade of WISDOM Rwanda and Woodfuels Value Chain Analysis as a Basis for the Rwanda Supply Master Plan for Fuelwood and Charcoal*. Kigali: Rwanda Natural Resources Authority (RNRA).

Federal Democratic Republic of Ethiopia (2012). *Ethiopia's Climate-Resilient Green Economy*: *Green Economy Strategy*.

Fiorino, D. J. (1990). Citizen participation and environmental risk: a survey of institutional mechanisms. *Sci. Technol. Hum. Values* 15, 226–243. doi: 10.1177/016224399001500204

Hallding, K., Nykvist, B., and Persson, Å. (2012). "The new geopolitics of environmental constraints, changing ecosystems and resources competition," in *The Emerging Global Security Environment, Strategic Yearbook*, ed B. Huldt (Stockholm: Swedish National Defence College), 301–330.

Harrison, S., and Mort, M. (1998). Which champions, which people? public and user involvement in health care as a technology of legitimation. *Soc. Policy Admin.* 32, 60–70. doi: 10.1111/1467-9515.00086

Hoff, H. (2011). "Understanding the Nexus," *Presented at the Bonn 2011 Nexus Conference* (Stockholm: Stockholm Environment Institute).

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., et al. (2013). Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Change* 3, 621–626. doi: 10.1038/nclimate1789

Interayamahanga, R. (2011). *Citizen's Participation in Democratic Governance in Rwanda*.

Jäger, J., and Patel, N. (2012). "An earth system perspective," in *Fifth Global Environment Outlook: Environment for the Future We Want* (Nairobi: United Nations Environment Programme).

Jones, L., and Carabine, E. (2013). Exploring political and socio-economic drivers of transformational climate policy: early insights from the design of ethiopia's climate resilient green economy strategy. *Overseas Dev. Inst. Work Pap.* doi: 10.2139/ssrn.2646522

Karlberg, L., Hoff, H., Amsalu, T., Andersson, K., Binnington, T., Flores-López, F., et al. (2015a). Tackling complexity: understanding the food-energy-environment nexus in Ethiopia's Lake tana sub-basin. *Water Altern.* 8, 710–734. Available online at: http://www.water-alternatives.org/index.php/alldoc/articles/vol8/v8issue1/273-a8-1-6/file

Karlberg, L., Hoff, H., Flores-López, F., Goetz, A., and Matuschke, I. (2015b). Tackling biomass scarcity—from vicious to virtuous cycles in sub-Saharan Africa. *Curr. Opin. Environ. Sustain.* 15, 1–8. doi: 10.1016/j.cosust.2015.07.011

Kefale, A. (2011). The (un) making of opposition coalitions and the challenge of democratization in Ethiopia, 1991–2011. *J. East. Afr. Stud.* 5, 681–701. doi: 10.1080/17531055.2011.642525

Kok, K., Biggs, R., and Zurek, M. (2007). Methods for developing multiscale participatory scenarios: insights from southern Africa and Europe. *Ecol. Soc.* 13:8. doi: 10.5751/ES-01971-120108

Lee, B., Preston, F., Kooroshy, J., Bailey, R., and Lahn, G. (Eds.) (2012). *Resources Futures*. London: Royal Institute of International Affairs.

Matfess, H. (2015). Rwanda and Ethiopia: developmental Authoritarianism and the New Politics of African Strong Men. *Afr. Stud. Rev.* 58, 181–204. doi: 10.1017/asr.2015.43

Matthew, R. A., Barnett, J., McDonald, B., and O'Brien, K. L. (2010). *Global Environmental Change and Human Security*. Cambridge, MA: MIT Press.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-Being*. Washington, DC: Island Press.

Ministry of Finance and and Economic Development (2010). *Growth and Transformation Plan 2010/11–2014/15, Vol. 2, Policy Matrix*.

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, 75–85. doi: 10.1016/j.esd.2013.01.001

Nakicenovic, N., Alcamo, J., Davis, G., De Vries, B., Fenhann, J., Gaffin, S., et al. (2000). *Special Report on Emissions Scenarios, Working Group III, Intergovernmental Panel on Climate Change (IPCC)*. Cambridge University Press, Cambridge, 595.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2015). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* 42, 169–180. doi: 10.1016/j.gloenvcha.2015.01.004

Pahl-Wostl, C. (2002). Participative and stakeholder-based policy design, evaluation and modeling processes. *Integr. Assess.* 3, 3–14. doi: 10.1076/iaij.3.1.3.7409

Patel, M., Kok, K., and Rothman, D. S. (2007). Participatory scenario construction in land use analysis: an insight into the experiences created by stakeholder involvement in the Northern Mediterranean. *Land Use Policy* 24, 546–561. doi: 10.1016/j.landusepol.2006.02.005

Rahmato, D. (2011). *Land to Investors: Large-Scale Land Transfers in Ethiopia*. Forum for Social Studies, Addis Ababa.

Ravera, F., Hubacek, K., Reed, M., and Tarrasón, D. (2011). Learning from experiences in adaptive action research: a critical comparison of two case studies applying participatory scenario development and modelling approaches. *Environ. Policy Gov.* 21, 433–453. doi: 10.1002/eet.585

Reed, M. S., Kenter, J., Bonn, A., Broad, K., Burt, T. P., Fazey, I. R., et al. (2013). Participatory scenario development for environmental management: a methodological framework illustrated with experience from the UK uplands. *J. Environ. Manage.* 128, 345–362. doi: 10.1016/j.jenvman.2013.05.016

Republic of Rwanda (2007). *Economic Development and Poverty Reduction Strategy: 2008-2012*. Kigali.

Republic of Rwanda (2011). *Green Growth and Climate Resilience: National Strategy for Climate Change and Low Carbon Development*.

Republic of Rwanda (2013). *Economic Development and Poverty Reduction Strategy II: 2013-2018*.

Robinson, J., Burch, S., Talwar, S., O'Shea, M., and Walsh, M. (2011). Envisioning sustainability: recent progress in the use of participatory backcasting approaches for sustainability research. *Technol. Forecast. Soc. Change* 78, 756–768. doi: 10.1016/j.techfore.2010.12.006

Rounsevell, M. D., and Metzger, M. J. (2010). Developing qualitative scenario storylines for environmental change assessment. *Wiley Interdiscip. Rev. Clim. Change* 1, 606–619. doi: 10.1002/wcc.63

Spielmann, M., Scholz, R., Tietje, O., and de Haan, P. (2005). Scenario modelling in prospective LCA of transport systems. Application of Formative scenario analysis (11 pp). *Int. J. Life Cycle Assess.* 10, 325–335. doi: 10.1065/lca2004.10.188

Stein, C. (2013). *How Understanding Social Networks Can Help to Govern the Nexus: a Case from the Blue Nile Basin, SEI Discussion Brief*. Stockholm: Stockholm Environment Institute.

Stirling, A. (2007). "Opening Up" and "Closing Down": Power, Participation, and Pluralism in the social appraisal of technology. *Sci. Technol. Hum. Values* 33, 262–294. doi: 10.1177/0162243907311265

Swart, R., Raskin, P., and Robinson, J. (2004). The problem of the future: sustainability science and scenario analysis. *Glob. Environ. Change* 14, 137–146. doi: 10.1016/j.gloenvcha.2003.10.002

The Economist (2010). Efficiency versus Freedom. *The Economist*. Available online at: http://www.economist.com/node/16743333

United Nations (2013). *Women Secure 64 Per Cent of Seats in Rwandan Parliamentary Elections | ONE UN Rwanda [WWW Document]*. Available online at: http://www.rw.one.un.org/press-center/news/women-secure-64-cent-seats-rwandan-parliamentary-elections (Accessed November 9, 2016).

Uvin, P. (2001). Difficult choices in the new post-conflict agenda: the international community in Rwanda after the genocide. *Third World Q.* 22, 177–189. doi: 10.1080/01436590120043291

van Vliet, M., Kok, K., and Veldkamp, T. (2010). Linking stakeholders and modellers in scenario studies: the use of Fuzzy Cognitive Maps as a communication and learning tool. *Futures* 42, 1–14. doi: 10.1016/j.futures.2009.08.005

Verhoeven, H. (2011). *Black Gold for Blue Gold*?: *Sudan's Oil*, *Ethiopia's Water and Regional Integration*. Chatham House.

Voinov, A., and Bousquet, F. (2010). Modelling with stakeholders. *Environ. Model. Softw.* 25, 1268–1281. doi: 10.1016/j.envsoft.2010.03.007

Voinov, A., and Gaddis, E. J. B. (2008). Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. *Ecol. Model.* 216, 197–207. doi: 10.1016/j.ecolmodel.2008.03.010

Volkery, A., Ribeiro, T., Henrichs, T., and Hoogeveen, Y. (2008). Your Vision or My Model? Lessons from participatory land use scenario development on a European Scale. *Syst. Pract. Action Res.* 21, 459–477. doi: 10.1007/s11213-008-9104-x

World Bank (2009). *The Little Data Book on Africa 2008/2009*. Washington, DC: The World Bank.

Zulu, L. C., and Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. *Energy Sustain. Dev.* 17, 127–137. doi: 10.1016/j.esd.2012.07.007

Zur Heide, F., Woltering, L., Karlberg, L., and Weitz, N. (2015). *Rapid appraisal of the Water-Energy-Food nexus in Zambia (No. Discussion Brief).* GFA Consulting Group GmbH/Stockholm Environment Institute (SEI), Hamburg and Stockholm.

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The Marginalization of Sustainable Charcoal Production in the Policies of a Modernizing African Nation

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Charcoal is the main cooking fuel for urban populations in many African countries. Urbanization and population growth are driving an increase in demand for charcoal, whilst deforestation reduces biomass stocks. Given increasing demand for charcoal, and decreasing availability of biomass, policies are urgently needed that ensure secure energy supplies for urban households and reduce deforestation. There is potential for charcoal to be produced sustainably in natural woodlands, but this requires supportive policies. Previous research has identified policy issues that have contributed to the charcoal sector remaining informal and environmentally destructive. In this paper, we describe how national policies in Tanzania on energy, forests, agriculture, land, and water, consider charcoal, and the degree to which they do, and do not, support sustainable charcoal production. The paper identifies policy gaps and a cross-sector tendency to marginalize natural forest management. By adopting a nexus approach, the paper highlights the inter-connections between sustainable charcoal production, ecosystem services, and trade-offs in the allocation of land, labor, and net primary production. In conclusion, sustainable charcoal production has been marginalized in multiple national policies. As a result, potential benefits of sustainable charcoal production are lost to multiple sectors.

Keywords: charcoal, sustainable forest management, policy analysis, nexus, Tanzania

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INTRODUCTION

Global wood charcoal production has trebled over the last 50 years from 17.3 million tons in 1964 to 53.1 million tons in 2014 (FAO, 2016). Sixty-one percent of current global production occurs in Africa (FAO, 2016), primarily to satisfy demand for cooking fuel from urban and peri-urban households (Mwampamba et al., 2013; d'Agostino et al., 2015). With Africa's population projected to double between 2015 and 2050 (UN, 2015), and with increased rural-urban migration in key producing countries, including Tanzania, Ethiopia, and Nigeria (FAO, 2016), demand for charcoal is projected to increase. Whilst demand for charcoal is projected to increase in Africa (IEA, 2014), the availability of woody biomass is declining due to widespread net deforestation (Hansen et al., 2013).

Charcoal can be produced without permanently deforesting or degrading a forested area, by protecting harvested areas from cultivation, intensive grazing, and fire, thus enabling natural regeneration. We use the term "to deforest," to mean the long-term or permanent removal of forest cover and conversion to a non-forested land use (Watson et al., 2000), whilst we follow the FAO (2003) definition that forest degradation means the long-term reduction of the overall potential supply of benefits from a forest, which includes carbon, wood, biodiversity, and other goods and services. As Chidumayo and Gumbo (2013) have stated, woodlands in many tropical countries, including Tanzania, will regenerate within 8–30 years of trees being cut for charcoal. Similarly, Woollen et al. (2016) found that areas of Mopane woodland in Mozambique, under long term charcoal production, continued to provide most ecosystem services, so long as the woodland species continued to dominate the area.

Sustainable charcoal production requires owners of natural woodland to maintain forest cover over time, rather than converting it to other land uses, such as agriculture. In this paper, we assume that charcoal production is more likely to be sustainable if charcoal-dependent countries adopt, and implement, policies that explicitly support sustainable production and incentivize forest owners to maintain natural woodland for sustainable charcoal production. We assume that sustainable production is more likely to be achieved in woodlands with secure tenure, formalized management, and harvesting plans designed to maintain the broad ecosystem functions of the forest or woodland. This assumption is supported by evidence from Niger and Senegal, where the adoption of formalized, community-based woodfuel production has resulted in an increase in the forest stock (de Miranda et al., 2010). In contrast, in Tanzania and in many of the other top charcoal-producing countries in Africa, charcoal value chains are largely informal with production proceeding in the absence of sustainable harvesting plans (Sander et al., 2013; Schure et al., 2013). The informality of production, particularly the absence of formalized and sustainable harvesting, has contributed to widespread forest degradation and, to a lesser extent, deforestation, particularly in the vicinity of concentrated markets, such as large urban areas (Chidumayo and Gumbo, 2013). The role of national policy, in this context, is to document a nation's intention to manage natural forests for sustainable charcoal production, with lower level policy tools setting out the details of how the policy should be implemented. National policy therefore provides a foundation for the formalization of sustainable charcoal production, and for the allocation of forest lands for that purpose. If these assumptions are correct, then we can infer that embedding sustainable charcoal production in national policy will help to safeguard forests, and the ecosystem services that they provide. However, we also recognize that formalization does not guarantee sustainability (Schure et al., 2013), and that there are examples of government attempts to control supply which have, instead, disrupted supply (Ribot, 1999), and of informal production in which forest ecosystem services are sustained (Ribot, 1999; Woollen et al., 2016). We also recognize that there are currently few examples of formalized, sustainable charcoal production in practice (de Miranda et al., 2010; Zulu and Richardson, 2013). The relevance of including sustainable charcoal production in national policy and the risks of omitting it are explored throughout the paper. Despite the potential benefits of sustainable charcoal production, national policies in many African countries have not embraced the practice even in countries with development programmes, and research, promoting sustainable production [World Bank, 2009; Owen et al., 2013; Sander et al., 2013; CamCo Clean Energy (Tanzania) Limited, 2014].

There are various reasons why sustainable charcoal production has been marginalized in national policies. Mwampamba et al. (2013) identified five misconceptions about charcoal that are held by policy-makers and other stakeholders, despite evidence that runs counter to those perceptions. These include beliefs that: charcoal is an energy source primarily for the poor; that charcoal use for cooking will decrease automatically, as a country becomes more developed; that charcoal production causes deforestation; that the charcoal sector is economically irrelevant; and that improved charcoal cook stoves mitigate deforestation. The authors highlight that a paucity of data on the charcoal trade has confounded attempts to nurture a more nuanced understanding of the trade amongst some policy-makers, and that, as a result, these beliefs have resulted in mis-guided policies. The question of why policy-makers have marginalized sustainable charcoal production in national policy is also explored in this paper.

Various authors, including Mwampamba et al. (2013) and Sander et al. (2013), have highlighted policy-related barriers to improving the sustainability of charcoal production in Tanzania. In this study, we retain their focus on Tanzania whilst defining more precisely those policy-related barriers. We describe how charcoal is currently addressed in energy, forest, agriculture, water, and land policies in Tanzania. We also update previous analyses by bringing in the National Energy Policy, 2015 (URT, 2015b), and the draft National Forest Policy, 2014 (URT, 2014), and broadening the scope of the analysis also to consider the land, agriculture, and water policies. We assess the degree to which different sectoral policies consider sustainable management of natural woodlands for charcoal production. In addition to looking at policy content, we also look briefly at the broader policy cycle in order to identify other factors that have influenced the treatment of charcoal in national policy. By applying nexus thinking, we explore the inter-sectoral implications of current policies. We highlight the inter-connections between sustainable charcoal production, natural woodland management, ecosystem services, and the energy, forest, agriculture, water, and land sectors, particularly when viewed through the lens of climate change.

The paper is focused on policies in Tanzania, the fifth largest charcoal producer in Africa (FAO, 2016). Tanzania stands out in terms of the extent to which charcoal has contributed to deforestation in the country. For example, in a study of 17 countries with the highest deforestation rates globally, the average proportion of deforestation attributable to charcoal was 6.9 ± 2.3%, with the highest proportion occurring in Tanzania at 33.16% (Chidumayo and Gumbo, 2013). However, the assumptions underpinning this estimate are only weakly validated, in terms of the interplay between charcoal and crop production, particularly in areas where charcoal production occurs during a land use transition from forest to cropland. Bailis et al. (2015) estimated that woodfuel harvesting contributed no

Abbreviations: CBFM, Community Based Forest Management; MNRT, Ministry of Natural Resources and Tourism; TFCG, Tanzania Forest Conservation Group; TFS, Tanzania Forest Services Agency; TZS, Tanzanian Shilling; VLFR, Village Land Forest Reserve.

more than 20% of non-renewable biomass harvested in Tanzania. In the paper, we unpick some of the policy-related drivers of deforestation and forest degradation. We also challenge policy makers, in countries such as Tanzania that are undergoing rapid economic and land use change, to re-evaluate the land use trade-offs that are being made between agriculture and natural forests, and to embrace policies that promote sustainable charcoal production and natural woodland management.

Charcoal and the Energy Sector

The nexus between charcoal and the energy sector in many African countries, including Tanzania, centers on its predominance in the national energy supply. Woodfuels including charcoal and fuel wood provide 85–90% of Tanzania's energy supply (World Bank, 2009; URT, 2015b). In urban areas, 71% of households depend on charcoal, whilst fuelwood is predominantly used in rural areas [CamCo Clean Energy (Tanzania) Limited, 2014]. Tanzania's urban population has increased from <1 to 12 million over the last 50 years (FAO, 2016). This growth trend is projected to continue, with a concomitant increase in the proportion of the population using charcoal (Sander et al., 2013).

Charcoal and the Forestry Sector

Perceptions of the charcoal–forest nexus have focused on forests as an input to charcoal production, and the impact, thereof, in terms of deforestation and forest degradation (Msuya et al., 2011; Mwampamba et al., 2013; Owen et al., 2013). Less attention has been paid to the potential for charcoal to generate revenues for sustainable natural woodland management, thereby contributing to the retention of forest cover. This can be attributed to the low level of effort that has been made in managing woodlands sustainably for charcoal production. This has created a "vicious cycle," where the *status quo* of unplanned production is perceived to be the only production model. This leads policy-makers to marginalize, and occasionally attempt to ban charcoal (Mwampamba et al., 2013), thereby missing the opportunity to generate revenues for investment in sustainable management, including in the context of community-based forest management. The lack of investment in forest management perpetuates the unplanned production model, and so reinforces its negative impact on the forest resource base. From a climate change perspective, the absence of sustainable forest management results in the emission of greenhouse gases from the resultant deforestation and forest degradation (Bailis et al., 2015).

Charcoal and the Agriculture Sector

The nexus between charcoal and the agriculture sector centers on the allocation of land, labor, and net primary production. The outcome of the nexus between agriculture and charcoal has important implications for forests, given that agriculture generally results in the conversion of forests to cropland i.e., deforestation, whilst charcoal production is more frequently a driver of forest degradation (Ribot, 1999; Chidumayo and Gumbo, 2013; Woollen et al., 2016). At one level, agriculture and charcoal production compete with each other for land, labor, and net primary production, albeit for the common purpose of feeding people. However, whilst sustainable charcoal production requires post-harvesting regeneration of woodland, crop production results in deforestation. Sustainable charcoal production from natural woodlands is existentially dependent on the continued availability of those woodlands, and, by default, the ecosystem services generated by those woodlands (**Figure 1**).

Although data on the proportion of deforestation attributable to specific drivers is not readily available in many countries (Hosonuma et al., 2012), there is considerable evidence to demonstrate that agriculture is the main driver of deforestation in Africa, even in countries, such as Tanzania, where charcoal has also been identified as a significant deforestation driver (Gibbs et al., 2010; Chidumayo and Gumbo, 2013; Krausmann et al., 2013; Willcock et al., 2016). The question of whether, and how much, deforestation is caused by charcoal production, has been raised by several authors (Ribot, 1999; Mwampamba et al., 2013) and raises complex semantic issues (Lund, 2015), as well as unpicking the spatially heterogeneous inter-play of drivers of land use change. The availability of higher resolution and more frequent remote sensing images is helping to generate a more robust, and finer scale understanding of land use change, including deforestation (Hansen et al., 2013).

Whilst crop production is a major driver of deforestation, it is also dependent on the ecosystem services that forests provide, such as regulation of water quality and flow, protection of soils from erosion, and provision of habitats for pollinators and predators of crop pests (Foley et al., 2005; Ninan and Inoue, 2013). As such, forests play a binding role in the nexus between charcoal and agriculture, particularly when we consider the hydrology of agricultural areas. The linkages between forest cover and the hydrology of an area are complex and vary between catchments (Brown et al., 2005; Price, 2011). Maintaining forest cover reduces the risk and severity of flooding in many catchments (Bradshaw et al., 2007), and sustains base flows in some catchments, particularly those prone to soil hardpan formation and soil compaction, when deforested (Bruijnzeel, 1988; Price, 2011). Deforestation therefore has implications for downstream agricultural production, particularly for areas under irrigation. With climate change, the risks to agricultural production due to fluctuating dry season flows are likely to increase with the longer, drier dry season predicted for parts of Africa, including parts of Tanzania, by some climate models (de Wit and Stankiewicz, 2006; Watkiss et al., 2011). Therefore, policies that promote incentives to maintain forest cover, including sustainable charcoal, may also contribute to safe-guarding dry-season irrigation in downstream agricultural areas.

The nexus between charcoal and crop production is bound further by their common labor force. CamCo Clean Energy (Tanzania) Limited (2014) estimate that 300,000 households are involved in charcoal production in Tanzania.

Most charcoal producers are also farmers who practice charcoal production in the dry season (Zulu and Richardson, 2013). Charcoal production also provides an economic safety net for farmers in case of crop failure or others shocks to a household's livelihood (*ibid*; Jones et al., 2016). This points to the potential for sustainable charcoal production to enhance

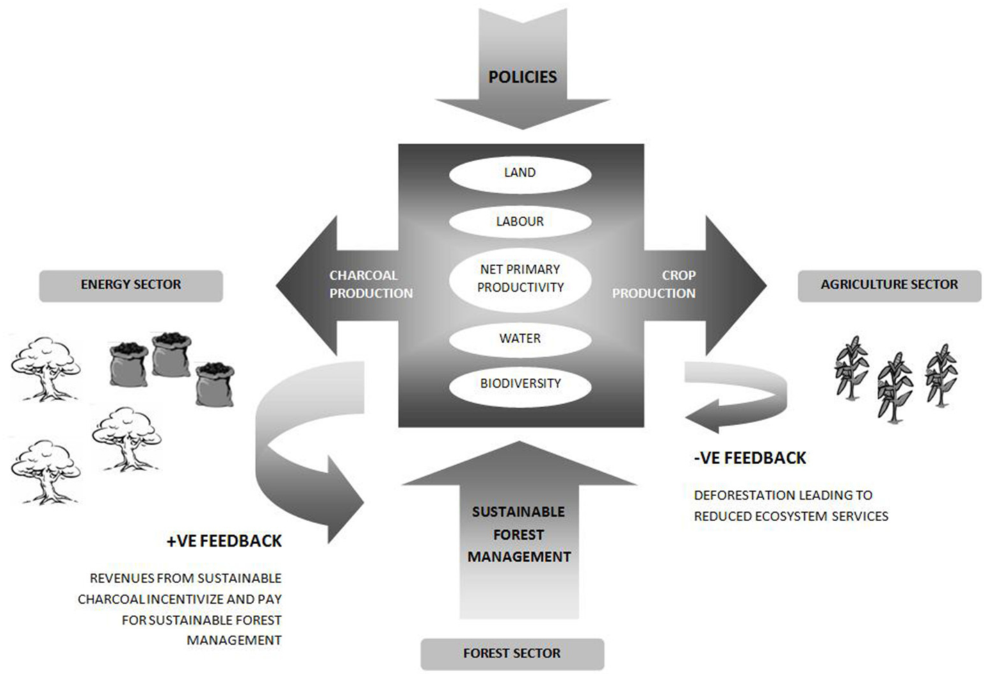

FIGURE 1 | A nexus map for the energy, agriculture and forest sectors highlighting resource trade-offs and feedback loops.

livelihood resilience in rural households vulnerable to climate change-related shocks.

The trade-off between charcoal production and agriculture is also influenced by land policy. Sustainable charcoal production requires national land policies that promote sustainable woodland management as a land use, and promote secure forest tenure, over a timescale proportionate to the 8–30-year woodland regeneration cycle. In this paper, we examine this nexus between charcoal, energy, forests, agriculture, land, and water, and the degree to which these connections are reflected in national policy.

METHODS

We apply an interpretive approach to policy analysis (Yanow, 2007), specifically a close-reading of policy documents. We selected Tanzania as a case study due to its high dependency on charcoal amongst urban households, the high potential for scaling up sustainable charcoal production given extensive areas of woodland in the country, and the authors' familiarity with the charcoal trade in Tanzania through involvement in the ongoing "Transforming Tanzania's Charcoal Sector project" financed by the Government of Switzerland.

We reviewed over-arching national policies including the constitution (URT, 1977), development vision (URT, 1999), and national climate change strategy (URT, 2012). We reviewed the national policies for the energy, forest, agriculture, land, and water sectors. We reviewed each national policy document for references to sustainable charcoal production, natural forest management, charcoal, forest produce, woodfuel, biomass energy, and/or other terms with a similar meaning. For those sectoral policies that referred to any of these terms, we reviewed additional policy instruments including regulations, orders, guidelines, strategies, and plans. Text referring to those terms was compared to identify similarities and differences between policies. We compared the ways in which those terms are, or are not, presented in the policy background descriptions, issues, objectives, and statements. In our comparison, we also looked for statements on inter-sectoral connections related to sustainable forest management and/or the charcoal trade. The list of policy documents that we reviewed is provided in **Table 1**. We focused on charcoal produced from natural woodlands, rather than charcoal from plantations or fuel briquettes. We have followed FAO (2004) in its definitions of charcoal and fuelwood. However, we use a narrow definition of woodfuel to mean solid, direct woodfuels, specifically charcoal and firewood.

By looking at policy content, we focused primarily on the policy formulation and decision-making stage of the policy cycle, and to a lesser degree, the agenda-setting and implementation steps. The policy cycle provides a conceptual framework based on a simplified chronology of the policy process. Jann and Wegrich (2007) present a 5-step policy cycle model comprising: agenda-setting, policy formulation and decision-making, implementation, evaluation, and termination. Agenda-setting is the process by which issues are selected, or rejected, for inclusion in a particular policy. Research on agenda-setting might look at how policy makers select the issues to include in, or exclude from, national policy, and in which policy to include those issues. Research on agenda-setting also addresses political

TABLE 1 | Tanzanian policy documents reviewed.

OVER-ARCHING POLICY DOCUMENTS
The Constitution of the United Republic of Tanzania, 1977, Cap 2 (URT, 1977)
The Tanzania Development Vision 2025 (URT, 1999)
The National 5 Year Development Plan 2016/17–2020/21 (URT, 2016a)
ENERGY
The Rural Energy Act, 2005. Act No. 8 of 2005
The National Energy Policy, 2015 (URT, 2015b)
The National Energy Policy, Draft 2013
The National Energy Policy, 2003 (URT, 2003)
The Biomass Energy Strategy for Tanzania, Draft 2014 [CamCo Clean Energy (Tanzania) Limited (2014)]
Ministry of Energy and Minerals: Strategic Plan 2011/12–2015/16. MEM, 2011 (TFS, 2013b)
AGRICULTURE
The National Agriculture Policy, 2013 (URT, 2013a)
The National Livestock Policy, 2006 (URT, 2006)
LAND
The National Land Policy, Draft 2016 (URT, 2016b)
The National Land Policy, 1997 (URT, 1997b)
The Land Act, 1999. Act No. 4 of 1999. Cap 113
The Village Land Act, 1999. Act No. 5 of 1999. Cap 114
WATER
The National Water Policy, 2002
The Water Resources Management Act, 2009. Act No. 11 of 2009
FOREST
Forest Policies
The National Forest Policy, 1998 (URT, 1998)
The National Forest Policy, Draft 2014 (URT, 2014)
Forest Laws and Regulations
The Forest Act, 2002, Act No. 14 of 2002, Cap 323
The Forest (Amendment) Regulations, GN 324 of 2015
The Forest (Amendment) Regulations, GN 433 of 2013
The Forest (Amendment) Regulations, GN 69 of 2006
Forestry Sector Guidelines and Public Notices
Community-Based Forest Management Guidelines. Forestry and Beekeeping Division, 2007
Joint Forest Management Guidelines. Ministry of Natural Resources and Tourism, 2013
Guidelines for Harvesting in Village Land Forest Reserves. Tanzania Forest Services Agency, 2013 (TFS, 2013a)
Public Notice regarding procedures for trade in forest products. Tanzania Forest Services Agency, 2015
*Mwongozo wa uvunaji endelevu na biashara ya mazao ya misitu yanayovunwa katika misitu ya asili (*Guidelines on sustainable harvesting and trade in forest products from natural forests). Tanzania Forest Services Agency, 2015
National Woodfuel Action Plan. Forestry and Beekeeping Division, 2009. Draft
Tanzania Forest Services Agency Strategic Plan. July 2014–June 19. Tanzania Forest Services Agency, 2013
Other Forestry Sector Reports
Participatory forest management in Tanzania: facts and figures. Ministry of Natural Resources and Tourism, 2012
The National forest resources monitoring and assessment of Tanzania Mainland: main results. Ministry of Natural Resources and Tourism, 2015
Maelezo kuhusu Wakala wa Huduma za Misitu, Tanzania: majukumu, mafanikio, changamoto na mikakati (2011–2015) [Information about the Tanzania Forest Services Agency: responsibilities, achievements, challenges and strategies (2011–2015)]. Ministry of Natural Resources and Tourism, 2016
ENVIRONMENT AND CLIMATE CHANGE
The National Environmental Policy, VPO, 1997 (URT, 1997a)
The Environmental Management Act, 2004. Act No. 20 of 2004. Cap 191
The Draft National Environment Policy 2016 (URT, 2016c)
The National Climate Change Strategy, 2012 (URT, 2012)

questions in terms of whose issues make it onto the policy agenda, and who defines those issues. This flows into the policy formulation and decision-making step, which involves making choices about the purpose of a policy and the broad strategy to be pursued, in order to achieve those objectives. Once policy has been defined, the next step is for it to be implemented, including defining the regulatory, financial, and organizational details and enacting the strategies and plans. Policy implementation research includes looking at the way in which a policy is enacted, including its impact, cost-effectiveness, and inter-play with other policies. The evaluation and termination steps of the policy cycle cover the process of reviewing a policy and the subsequent steps of policy change. In reality, the steps are frequently overlapping, particularly when looking at an issue such as charcoal which cuts across multiple sectors each following its own unique policy cycle. The policy cycle framework has been criticized for being over-simplistic, top-down, and insensitive to context. It has also persisted in policy research, as a heuristic device, within which a plethora of quantitative and qualitative methods may be applied. Whilst recognizing its shortfalls, we find it to be a useful framework within which to position our research.

RESULTS

Tanzania's Development Vision as Determinant of Sector Policies

National policies are designed to guide a sector to play its part in achieving a broader national vision. As context for the paper's review of individual sectors, it is important to understand Tanzania's development vision as a key determinant of policy content. Tanzania's Development Vision 2025 aims at achieving "*a high quality livelihood for its people, attain good governance through the rule of law and develop a strong and competitive economy*" (URT, 1999).

In terms of economic development, it is envisaged that by 2025, "*The economy will have been transformed from a low productivity agricultural economy to a semi-industrialized one...*" In terms of economic targets, the Vision states that by 2025 there will be "*a diversified and semi-industrialized economy with a substantial industrial sector comparable to typical middle-income* *countries*." It is also envisioned that "*fast growth will be pursued while effectively reversing current adverse trends in the loss and degradation of environmental resources (such as forests, fisheries, fresh water, climate, soils, biodiversity)*." The national development vision is further elaborated in Tanzania's current 5 year development plan which includes targets to "*reduce charcoal consumption in urban areas by 30% by 2020/21 and by 60% by 2025/26,*" as well as to "*promote... renewable green energy technologies (biogas, LPG, Solar Energy).*" Overall, the vision equates modernity with a shift away from the *status quo* where 75% of the work force is employed in an agriculture sector dominated by subsistence, small-scale crop production (URT, 2013a) and toward industrialization and a higher quality of life.

Woodfuel and Charcoal in National Policies

We found that, at policy level, no current national policies include objectives, or statements, giving specific directions on sustainable charcoal production. The word "charcoal" appears in the National Forest Policy, 1998 (URT, 1998) ($N = 2$), and the National Energy Policy, 2015 (URT, 2015b) ($N = 5$), seven times. Six of these seven occurrences are in the sector descriptions and outline the general importance of charcoal as an energy carrier in Tanzania, or its role in environmental degradation. One forest policy direction makes specific reference to restricting the export of charcoal. These statements are cited in **Table 2**. The Environmental Policy, 1997, uses the broader term "woodfuel" rather than charcoal, and provides the most comprehensive guidance, including policy objectives to "*minimize woodfuel consumption and develop alternative energy sources and woodfuel energy efficiency and to promote rational exploitation of forest resources accompanied with reforestation and afforestation programmes...for domestic consumption and export...*" The terms charcoal and woodfuel do not occur in the constitution and development vision, nor in the agriculture, livestock, land, or water policies. Overall, there is consistency between the energy, forest, and environmental policies which present charcoal as an environmental problem to be resolved primarily through fuel-switching. **Table 3** provides an overview and timeline of the policies and other key regulatory documents included in this review.

Consideration of cross-cutting issues, including environment, began to be a standard component of national policies in Tanzania after 2003 (URT, 2003). Thus, older policies, such as those for land, forest, and water, do not include sections on cross-cutting issues, whilst the more recent agricultural, livestock, and energy policies include policy objectives and statements related to the environment as a cross-cutting issue.

TABLE 2 | National policy statements that include the term "charcoal."

National Forest Policy, 1998 (URT, 1998)
2.0 Main sectoral problems and opportunities
The main reasons for deforestation are clearing for agriculture, overgrazing, wildfires, **charcoal** burning and over-exploitation of wood resources
4.2.5 Trade in forest products
Internal trade and export of certain forest products such as...**charcoal**..., may be restricted or remain under licensing until the conditions for sustainable forest management and utilization are in place
National Energy Policy, 2013
1.2 Energy situation in Tanzania
The national energy balance indicates dominance of biomass use in the form of **charcoal** and firewood and its contribution to the total national energy consumption is about 85 percent
Charcoal consumption mainly in urban areas has nearly doubled over the past 10 years due to urbanization, high prices or scarcity of other alternatives particularly kerosene, electricity and LPG. It is projected that demand for **charcoal**, without supply and demand side interventions will double by 2030, from approximately 2.3 million tons of **charcoal** in 2012. The Government has been promoting substitution of **charcoal** and firewood by providing tax relief to stimulate the use of LPG in the country

Sustainable Charcoal Production and the National Energy Policy

The focus on fuel-switching is exemplified in the mission of the National Energy Policy, 2015 (URT, 2015b), which is, "To provide reliable, affordable, safe, efficient and environment friendly modern energy services to all while ensuring effective participation of Tanzanians in the sector." Modern energy is defined as "energy that is based on petroleum, electricity or any other energy forms that have commercialized market channels, a higher heating or energy content value than traditional energy." In its policy statements, biomass is only included in relation to the objective of enhancing the utilization of renewable energy resources so as to increase its contribution in diversifying resources for electricity generation (URT, 2015b). A focus on fuel-switching from biomass to other energy carriers has remained consistent in Tanzania's national energy policies over the last 25 years. However, the 2015 policy differs from the 1992 and 2003 energy policies in excluding any objective related to sustainable production of woodfuels, except in the context of electricity generation. For example, the National Energy Policy, 2003 (URT, 2003), included the guiding statement "promote efficient biomass conversion and end-use technologies in order to save resources; reduce rate of deforestation and land degradation; and minimizing threats on climate change."

Between 2010 and 2014, the Government of Tanzania developed a biomass energy strategy and action plan, with financial support from the European Union. The primary goal of the strategy was, "*To make biomass energy sustainable in Tanzania.*" The strategy proposed five activity bundles aimed at "*ensuring that biomass energy is sustainable in Tanzania along the entire value chain,*" including sustainable charcoal production. However, as of May 2017, the strategy had not been adopted. Policies were also drafted for petroleum, natural gas, and renewable energy, of which the natural gas policy was approved, whilst others remained in draft form. These policies were then merged into the National Energy Policy, 2015 (URT, 2015b; Muhongo, 2016). Solid biomass energy was excluded from the National Energy Policy during the final stages of the policy revision process. A consultative draft of the National Energy Policy included a policy objective, "*To enhance production and rational use of solid biomass resources*," and a policy statement, "*Encourage sustainable production of solid biomass*" (URT,

TABLE 3 | Timeline of key policy documents summarizing their position on sustainable charcoal.

1997	The National Environmental Policy, 1997 (URT, 1997a)	Objectives include, "*Minimisation of woodfuel consumption through development of alternative energy sources and woodfuel efficiency*," (Energy); and "*Rational exploitation of forest resources accompanied with reforestation and afforestation programmes shall be promoted*" (Forestry) No specific mention of charcoal
	The National Land Policy, 1997 (URT, 1997b)	Land tenure tenet: "*Rights and title to land...will be based mainly on use and occupation,*" and, "*Development conditions are imposed on holders of land*" Community land rights: "*Village Councils will administer village lands*" No specific mention of charcoal
1999	The Land Act, 1999	Categorizes land as general, village, and reserved land No specific mention of charcoal
	The Village Land Act, 1999.	Grants village councils the "*responsibility for the management of all village land*." Elaborates the definition of village land No specific mention of charcoal
2002	The Forest Act, 2002	Includes charcoal in the category "*forest produce*." Sets the legal requirement that forest management plans be in place prior to harvesting any forest produce; empowers communities to manage, and sustainably harvest from, forests on village land; and grants exemption from Central Government royalties for forest products harvested in village land forest reserves
	The National Water Policy, 2002	Recognizes that "*forests have an important effect on the conservation of water resources*." Deforestation cited as a cause of soil erosion and directs that awareness raising campaigns on good land use practices, be undertaken No specific mention of charcoal
2003	The National Energy Policy, 2003 (URT, 2003)	Charcoal classified as a renewable energy with the objectives, "*Promote efficient biomass conversion and end-use technologies to ... reduce deforestation* (Renewable Energy);" and, "*Promote application of alternative energy sources other than fuelwood and charcoal, in order to reduce deforestation*... (Rural Energy)"
2004	The Environmental Management Act, 2004	Provides a general framework for environmental management and protection No specific mention of charcoal
2006	The Forest (Amendment) Regulations, 2006	Describe the procedures, and responsibilities of different entities, in relation to permits for the production, trade, and transportation of charcoal
2007	Community-Based Forest Management Guidelines, 2007	Include specific references to the integration of charcoal production in the management of village land forest reserves
2013	The Forest (Amendment) Regulations, 2013	Set the royalty for one 90 kg bag of charcoal at TZS 14,400; and the annual registration fee for a charcoal dealer at TZS 256,000
	Guidelines for harvesting in VLFRs, 2013	Provide guidance on how village land forests can be harvested. Primarily focused on timber, although charcoaling of timber off-cuts is mentioned
2015	The Forest (Amendment) Regulations, 2015	Set the royalty for one 75 kg bag of charcoal at TZS 16,600; and the annual registration fee for a charcoal dealer at TZS 256,000
	The National Energy Policy, 2015	Its mission is "*to provide...modern energy services to all*," rather than traditional energy. Biomass energy is included under the objective "*To enhance utilization of renewable energy sources...for electricity generation* (Renewable Energy)"

2015a). During the stakeholder consultation process, Tanzanian Civil Society Organizations asked for the policy to provide even more guidance on charcoal and submitted specific proposals for text to be included in the policy (TFCG, 2015a). However, instead of providing more explicit guidance on charcoal, the objective on solid biomass resources was subsequently narrowed, solely to refer to biomass in the context of electricity generation. The result is a policy that, on the one hand, states that, "*The national energy balance indicates dominance of biomass use in the form of charcoal and firewood and its contribution to the total national energy consumption is about 85 percent*," and, on the other hand, provides no specific guidance on how to manage that energy carrier.

Sustainable Charcoal Production and the National Forest Policy

The National Forest Policy, 1998 (URT, 1998), also recognizes the importance of woodfuels in the national economy whilst promoting fuel-switching, in its direction that, "*The use of alternative affordable sources of energy will be promoted through research and extension*." In addition, the forest policy promotes the "*establishment of private woodlots and plantations for woodfuel production.*" Tanzania's National Forest Policy, 1998 (URT, 1998), has been under review since 2008 when a zero draft was circulated to stakeholders for comments, with another draft circulated for comments in 2014, and a committee formed to finalize the policy in 2017. The lengthy revision process, in part, reflects the intervening transfer of forest management responsibilities from the Forestry and Beekeeping Division to the, more autonomous, Tanzania Forest Services Agency (TFS), which was established in 2010. In this paper, both the 1998 policy, and the 2014 draft policy document, are considered. Although in draft form, the 2014 policy is relevant as an indication of the policy direction being considered.

The four overall objectives of the 1998 policy include the objective, "To ensure sustainable supply of forest products and services by maintaining sufficient forest area under effective management;" and "To ensure ecosystem stability through conservation of forest biodiversity, water catchments and soil fertility." The policy includes policy objectives and statements reflecting a commitment to planned, sustainable forest management as a means to supply various forest products and ecosystem services, including charcoal. The goal of the 2014 draft forest policy, which has remained largely unchanged since 2008, is "enhanced contribution of the forest sector to the sustainable development of Tanzania and the conservation and management of her forest resources for the benefit of the present and future generations." Of its four objectives, the most relevant objective of the 2014 draft policy is, "To ensure sustainable supply of forest products and services by maintaining sufficient forest under effective management." As with the 1998 policy, the draft 2014 forest policy is supportive of community based forest management including sustainable production of charcoal and other forest products.

URT (2002) and supporting regulations, guidelines, and orders provide further policy support for sustainably managed, productive forest reserves, including village land forest reserves. For example, the Forest Act, 2002, empowers Village Councils (through the designated village committee) to establish productive village land forest reserves and to issue permits for the extraction of forest produce including charcoal, provided that sustainable management plans are in place. Since the 1990s, more than 530 Village Land Forest Reserves have been established (TFS, 2012 plus TFCG data), including 2.4 million ha of woodland and forest, however, until 2012, none had integrated sustainable charcoal production into their management plans. In part this can be attributed to a lack of guidelines on policy implementation, with policy guidelines on forest product harvesting in village land forest reserves focusing on timber, rather than on charcoal (TFS, 2013a). Since 2012, a project in Morogoro Region, led by the Tanzania Forest Conservation Group (TFCG), has been piloting sustainable charcoal production embedded in community-based forest management as a demonstration for scaling up to other village land forests.

In the context of woodfuel, the draft 2014 National Forest Policy (URT, 2014) states that, "Establishment of private woodlots and plantations, planting of trees on farm for wood fuel production, efficient wood energy conversion and use technologies and alternative sources of energy will be promoted." As with other policies, there is a focus on fuel-switching and tree planting. Under the forestry sector, Tanzania's 5-year development plan includes a target of increasing forest area by 130,000 ha by 2020/21 and 160,000 ha by 2025 through tree planting, for which it indicates a budget of TZS 150 billion and a target of 280 million trees/year, for implementation by the Government (URT, 2016a). The commitment to expand plantations is also reflected in the TFS strategic plan for 2014/19 which includes a target of 50,000 ha of new plantation by 2019 (TFS, 2013b). The 5-year Development Plan indicates that all other forestry sector activities including capacity building and nature reserve management should be paid for by Development Partners (URT, 2016a). Although the policy promotes planting of trees for wood fuel, in reality, most plantations are targeting the timber market, given a higher price per cubic meter for wood when sold as timber than as charcoal. As such, replacing charcoal from natural woodlands with charcoal from plantations, is only likely to succeed at the point where charcoal becomes a more profitable end product than timber for plantation owners. The profitability of charcoal from plantations and woodlots relative to the profitability of timber and other forest products, is often overlooked by those proposing that planted trees be used in charcoal production.

Sustainable Charcoal Production and the National Agriculture Policy

The 2013 Agriculture Policy's mission is, "to facilitate the transformation of the agricultural sector into a modern, commercial and competitive sector in order to ensure food security and poverty alleviation through increased volumes of competitive crop products" (URT, 2013a). The focus on transforming agriculture from traditional, subsistence crop production to a more intensive, commercialized system is aligned with the National Development Vision. The National Agriculture Policy states that, "by definition the agricultural sector is comprised of the crops, livestock, fisheries, forestry and hunting sub sectors," it then goes on to limit its scope to "crop production." Charcoal production and forestry are not included in the scope of the policy. Whilst the policy is not explicit in promoting the conversion of forests or woodlands to agriculture, it is implicit in its view that 440,000 km^2 of land in Tanzania "are suitable for agricultural production." Similarly, the National Livestock Policy, (URT, 2006), includes 200,000 km^2 of "fallow and forestland" in its estimate of the national rangeland resource. Evidence that this assumes woodland conversion to agriculture is also reflected in the National Land Use Framework Plan for 2013–2033, which includes areas of woodland in the land categories designated for the expansion and intensification of agriculture (URT, 2013b).

As well as implicitly promoting land use change from woodland to agriculture, the National Agriculture Policy includes an objective to expand the area of agricultural land under irrigation from 0.4 to 7.1 million hectares (URT, 2013a). Expanding irrigation is presented as a strategy to mitigate climate change-related risks to agriculture. The dependence of agriculture on forest ecosystem services is recognized under cross-cutting issues and there is one policy statement, "*efficient use of renewable natural resources shall be strengthened*."

Sustainable Charcoal Production and the National Land Policy

Tanzania has retained a land tenure structure that deliberately excludes the concept of "freehold" and is instead based on the principle that all land is public land where tenure is defined in terms of "rights of occupancy." The National Land Policy of 1997 (URT, 1997b) identifies five important characteristics, including development conditions, that are imposed on landholders. The objectives of the policy include, "*Ensuring that land is put to its most productive use to promote rapid social and economic development of the country and protecting land resources from degradation for sustainable development*." The policy is founded on a "use it or lose it" principle where rights of occupancy are tied to development conditions. This is important in the context of understanding the land policy–charcoal nexus since tenure is tied to land use. However, the concept of "use" is not defined either to include, or exclude, sustainable forest management including charcoal production. In contrast, other uses are explicitly covered including agriculture, both for crop cultivation and livestock, mining, and settlements. There are no examples of rights of occupancy being given to private land owners for sustainable charcoal production from natural woodlands.

In 2015, the Tanzanian Government began a revision of the National Land Policy. The draft National Land Policy of 2016 (URT, 2016b) retains important elements of the 1997 policy, including the concept of rights of occupancy and the categorization of land as village, general, and reserved land. The draft policy does not mention sustainable charcoal production, although it does include an objective for the "*effective protection, conservation and sustainable utilization of environmentally sensitive areas*," which are defined to include forests. The policy emphasizes formalization of land tenure including widespread issuing of granted and customary rights of occupancy. The promotion of the privatization of land tenure contrasts with the forest policy's focus on communally-owned village land forest reserves.

Sustainable Charcoal Production and the National Water Policy

The water policy does not mention the term "charcoal," and equates the term "energy" with electricity. The National Water Policy recognizes the forest–water linkages and states that, "*Forests have an important effect on the conservation of water resources.*" The policy goes on to state that with the current population growth rate, Tanzania will shift from having 2,700 m^3/person/year to 1,200 m^3/person/year between 2000/1 and 2025. According to UN criteria, this represents a transition toward water scarcity which is broadly defined as being 1,000 m^3/person/year (Falkenmark et al., 2007).

DISCUSSION

The results of our analysis of Tanzanian policies on energy, forests, agriculture, land, and water, map out the marginalization of sustainable charcoal production across national policies despite the potential economic, social, and ecological benefits of managing natural woodlands sustainably for charcoal production. Our findings systematically document policy gaps related to sustainable charcoal production, and provide an in-depth and updated analysis of the broader policy environment.

The marginalization of charcoal is most starkly apparent in Tanzania's energy policy, wherein the National Energy Policy 2015 (URT, 2015b) defines modern energy as the antonym to woodfuels, as the traditional energy carrier. The policy then deals exclusively with modern energy. This reflects a deep-rooted perception that charcoal is part of the traditional way of life that the national development vision seeks to transform, and has no place in the model of modernity envisaged for the country. The omission of a policy objective or statement on sustainable charcoal production from the National Energy Policy means that for the duration of this policy cycle, there is no high-level commitment to produce charcoal and fuelwood more sustainably, nor to provide strategic oversight regarding its supply or quality. Given projected increases in demand for charcoal, and given that the majority of Tanzanians rely on woodfuel, this policy omission means that the National Energy Policy fails to provide guidance on Tanzania's main energy carrier, a situation that risks perpetuating uncontrolled production and concomitant negative environmental impacts. Even if Tanzania's draft biomass energy strategy were to be revived, in the absence of a policy-level objective on woodfuel, the strategy will have no anchor in national policy, thereby risking continued marginalization. This reinforces findings by Mwampamba et al. (2013) regarding the extent to which deeply rooted misconceptions about charcoal have led policy-makers to select policies that seek to exclude charcoal from the national energy mix, rather than embrace sustainable production techniques.

Economic development inevitably leads to trade-offs between land uses, and requires choices to be made between the conversion of forests into anthropogenic land uses such as agriculture, on the one hand, and maintaining natural forests with their inherent ecosystem services, on the other (Foley et al., 2005). Our review has shown how Tanzania's development vision and sectoral policies have marginalized the sustainable woodland management land use option for village land. That agriculture is valued more highly than natural woodland, in part, reflects systemic challenges in integrating the complex concepts under-pinning ecosystem service valuation in decisions over allocation of land and natural resources (Martinez-Harms et al., 2015). Similarly the economic value of the charcoal trade, estimated at US$ 650 million, is poorly understood and is not communicated in national accounts (Sander et al., 2013). For example, official national figures on government revenues from natural forest products do not distinguish charcoal from other products, including timber. Between 2011/12 and 2014/15, TFS reported TZS 187 billion (~US$ 86.5 million) in natural forest product royalties (TFS, 2016), however, the proportion attributable to charcoal is not stated. Although national figures do not disaggregate revenues from charcoal, at a lower level of government, some TFS Zonal offices disaggregate their revenue by forest product. Zonal government revenue figures indicate that charcoal comprised between 10 and 71% of natural forest product revenues in some zones (TFCG, 2015b, Lukumbuzya and Sianga, 2016). The absence of official figures on the value of the charcoal trade contributes to it being under-valued as a land use option, when compared with crops with well-documented trade data. Thus, whilst charcoal has many similarities with traditional crops, in terms of its requirements for land, labor, and net primary production, it is not considered a crop in the agriculture policy, and it is under-valued when land use tradeoffs are being made between agriculture and woodland on village land.

Similarly, sustainable charcoal production is not recognized explicitly as a land use in the National Land Policy. Given that land tenure is tied to land use in the Tanzanian land policy, the absence of explicit recognition for sustainable charcoal production as a land use category, risks the marginalization of sustainable woodland management in favor of agriculture and other cited land uses, particularly given the current trend to privatize village land.

Optimizing water allocation between sectors is another relevant area for policy makers to consider, in the context of selecting an optimal mix of energy carriers, particularly given projected population increases. Beyond charcoal's dependence on forests and forests' absorption of water, traditional charcoal production places minimal demand on water supplies. In contrast, electricity generation from fossil fuels, as promoted in the National Energy Policy, 2015 (URT, 2015b), consumes water at all stages of the energy production life cycle (Mielke et al., 2010). As such, charcoal production using earth kilns is a more water-efficient energy source than electricity, a relevant consideration in the context of growing water scarcity. The relative water requirements of different energy carriers are not considered by either the national water policy, nor by the National Energy Policy.

Given the 2013 National Agriculture Policy's objective to increase land under irrigation, so the protection of the base flows essential for dry-season irrigation becomes critical for policy implementation. Sustainable woodland management for charcoal production may, therefore, be a useful policy tool for protecting base flows, when compared with conversion of woodland to agriculture in catchment areas. Policies that favor sustainable forest management and provide incentives to communities to safeguard the forest resources on their land, may therefore contribute to securing base flows vital to downstream water users, as well as reducing flooding risks.

Few attempts have been made to look strategically at the potential volume of charcoal production from current natural forests in Tanzania. CamCo Clean Energy (Tanzania) Limited (2014) calculated that 2.3 million tons of charcoal were consumed in Tanzania in 2012. They estimated that this required 350,000 ha of woodland, assuming a mean biomass of 50 m^3/ha and a conversion efficiency of 19%. If we extrapolate this further and assume a 24 year rotation cycle for a sustainable system, it would require 8.4 million ha (24 × 350,000 ha) to be under management for sustainable charcoal production, in order to meet 2012 supply levels over the next 20 years or so. According to MNRT (2015) there are 21.6 million ha of forest on village land of which approximately 10%, or 2.3 million ha, are already included in areas under community-based forest management (CBFM). Of the existing areas under CBFM, a significant proportion is too ecologically sensitive to be appropriate for charcoal production, particularly given a tendency for CBFM projects to prioritize high biodiversity areas. Nonetheless, it shows that a significant proportion of charcoal demand could be met through sustainable production from the 21.6 million ha of woodland remaining on village land, including a portion of the area already under CBFM. Even meeting Tanzania's 5-year development plan target of reducing demand by 30%, would still require most of the remaining woodland on village land to be brought under sustainable production.

Given Tanzania's increasing, and increasingly urban, population, it is clear that sustainable charcoal production alone cannot meet projected urban energy needs. Undoubtedly fuel-switching is also needed. Including sustainable charcoal production in national policies would help to generate the broad political support and stakeholder buy-in that is needed to transform the trade in favor of sustainable production.

The exclusion from national policies of sustainable charcoal production reflects three factors that affect each step in the policy cycle. These are the absence of detailed, accurate data on the charcoal trade; deeply-rooted negative perceptions of the trade; and the weak organizing and advocacy capacity of producers, traders, and consumers. The lack of reliable, current data about many important attributes of the charcoal value chain, as well as deeply held negative perceptions of charcoal amongst policy makers, have been highlighted by various authors (Mwampamba et al., 2013; Owen et al., 2013; Sander et al., 2013). Statements by some Ministers and other policy-makers in the current Government, as reported in the Tanzanian media and/or observed by the authors, generally reinforce the findings of Mwampamba et al. (2013). For example, the belief that charcoal is responsible for much of Tanzania's deforestation, is commonly cited by Ministers as the primary reason for excluding charcoal from Tanzania's energy mix[1,2]. We propose three other reasons as to why policy makers choose to marginalize sustainable production. Firstly, few policy makers understand, or believe, that charcoal can be produced in a sustainable way. This reflects how few practical examples there are of charcoal being produced sustainably. Relatedly, technical expertise in managing natural woodlands for sustainable charcoal production is limited in Tanzania, where higher learning institutions have not embraced it into their curricula. Secondly, we contend that the role of agriculture as the main deforestation driver in Tanzania is poorly known amongst many policy-makers, in part, due to there being inadequate, and inadequately publicized, empirical research on deforestation drivers at a national scale. Given agriculture's primacy in Tanzania's economic development plans, we also speculate that it is politically convenient to apportion blame for deforestation on charcoal, instead of on agriculture. Thirdly, the difficulties of inter-sectoral coordination, required to transform the charcoal market, have hindered change. Undoubtedly, the political economy of the charcoal trade is complex and more in-depth research is needed to understand more fully the dynamics at play during the agenda-setting step of the policy cycle.

Advocacy from actors along the charcoal value chain has been muted in Tanzania. This reflects the informal nature of the sector where producers, transporters, and traders are often poorly educated, poor, and lack coordinating networks for advocacy. This contrasts with the advocacy capacity of stakeholders in the natural gas sector where natural gas prospecting and development companies had the resources, experience, and networks to lobby the Ministry of Energy and

[1]'On March 1, 2017, the Minister for Natural Resources and Tourism, Prof. Jumanne Magembe, banned transportation of charcoal from one district to another to combat what he described as deforestation in the country.' In Kitabu, G. How charcoal ban could work in the absence of viable alternative? The Guardian (Tanzania) 21/03/2017 P. 12. http://www.ippmedia.com/en/features/how-charcoal-ban-could-work-absence-viable-alternative

[2]Jumanne Maghembe, the minister of Tourism and Natural Resources, said in December that cutting wood for charcoal needs to stop because it spurs desertification. In Makoye, K. To save forests, Tanzania considers tax on charcoal. Reuters 23/01/2017. http://www.reuters.com/article/tanzania-forest-charcoal-idUSL5N1F945L

Minerals intensively during the formulation of the Natural Gas Policy and the National Energy Policy. Although some civil society organizations, including the Tanzania Forest Conservation Group, have facilitated meetings to highlight issues around charcoal production and to promote sustainable charcoal production, these efforts were insufficient to persuade the Tanzanian Government on the critical need for the 2015 National Energy Policy to provide direction for sustainable charcoal production (URT, 2015b). The weak voice of charcoal stakeholders has contributed to the National Energy Policy's exclusive focus on fossil fuels and electricity generation.

The review has identified important priorities for research including: quantitative assessments of the relative impact of drivers of deforestation and forest degradation; rigorous comparative studies of the costs and benefits of alternative energy carriers and policy options, taking into consideration inter-sectoral implications; experimentation with different models of sustainable charcoal production; and a strategic environmental assessment and cost-benefit analysis of the Government's tree planting proposals relative to increased investment in natural woodland management.

CONCLUSION

Sustainable charcoal production from natural woodlands has been marginalized as a policy option in all sectors in Tanzania. The marginalization of sustainable charcoal production in the energy and forest sectors is exacerbated by the land policy in providing no explicit recognition of sustainable woodland management as a recognized land use, and by the agricultural policy in promoting the expansion of agricultural land. If woodlands do not generate income for their owners, including communities, the economic rationale to convert woodland to agricultural land is strengthened. Assuming that sustainable charcoal production can incentivize sustainable woodland management, an opportunity is therefore being missed to embed a sustainable financing mechanism into participatory woodland management. Widespread conversion of woodland to agriculture inevitably undermines the ecosystem services generated by those woodlands, with corresponding risks to those sectors that depend on those ecosystem services, particularly agriculture. The marginalization of sustainable charcoal production from national policy is, therefore, a missed opportunity given the potential for it to contribute to more climate-resilient rural livelihoods, urban energy security, and sustainable management of woodlands with their inherent ecosystem services including climate change mitigation.

Based on this review we recommend that policy objectives and statements supporting sustainable charcoal be included in the energy and forest sector policies whilst revising policies on water, agriculture, and land to include objectives and statements that promote sustainable natural forest management and reduce agriculture-driven deforestation. We envisage a charcoal market supplying charcoal from sustainably managed, community- and privately-owned woodlands to urban households. Tax revenues would continue to be retained at village and district level in order to incentivize and finance sustainable management of natural woodlands. The professionalism and organization of charcoal producers would increase with concomitant environmental benefits in terms of compliance with efficiency and sustainability guidelines, as well as improved livelihoods for producers, and other rural development gains.

The benefits of sustainable charcoal production become evident when viewed from the perspectives of multiple sectors. The nexus approach to policy analysis adopted in this paper highlights the need for policy makers to consider the inter-sectoral implications of charcoal production and to develop more robust mechanisms to value ecosystem services when making tradeoffs in the allocation of land and natural resources. The analysis also highlights the need for change throughout the policy cycle, including generating a stronger knowledge base, and valuing the needs and interests of more marginalized stakeholders, including woodland-owning communities and charcoal producers. The lessons learned from Tanzania have implications for other countries dependent on charcoal from natural woodlands including the leading charcoal producers in Africa, the Democratic Republic of Congo, Ethiopia, and Nigeria.

AUTHOR CONTRIBUTIONS

ND: lead author responsible for review concept, research design, drafting of the manuscript. CM: responsible for significant intellectual contributions to review design, inputs, and confirmation of manuscript for submission.

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REFERENCES

Bailis, R., Drigo, R., Ghilardi, A., and Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nat. Clim. Chang.* 5, 266–272. doi: 10.1038/nclimate2491

Bradshaw, C. J. A., Sodhi, N. S., Peh, K. S.-H., and Brook, B. W. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Glob. Chang. Biol.* 13, 1–17. doi: 10.1111/j.1365-2486.2007.01446.x

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *J. Hydrol.* 310, 28–61. doi: 10.1016/j.jhydrol.2004.12.010

Bruijnzeel, J. (1988). (De)forestation and dry season flow in the tropics: a closer look. *J. Trop. Forest Sci.* 1, 229–243.

CamCo Clean Energy (Tanzania) Limited (2014). *Tanzania Biomass Energy Strategy and Action Plan*. Africa-EU Renewable Energy Cooperation Programme.

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. doi: 10.1016/j.esd.2012.07.004

d'Agostino, A. L., Urpelainen, J., and Xu, A. (2015). Socio-economic determinants of charcoal expenditures in Tanzania: evidence from panel data. *Energy Econ.* 49, 472–481. doi: 10.1016/j.eneco.2015.03.007

de Miranda, R. C., Sepp, C., Ceccon, E., Mann, S., and Singh, B. (2010). *Sustainable Production of Commercial Woodfuel: Lessons and Guidance from Two Strategies*. Washington, DC: The World Bank.

de Wit, M., and Stankiewicz, J. (2006). Changes in surface water supply across Africa with predicted climate change. *Science* 311, 1917–1921. doi: 10.1126/science.1119929

Falkenmark, M., Berntell, A., Jägerskog, A., Lundqvist, J., Matz, M., and Tropp, A. (2007). *On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity*. SIWI Policy Brief. SIWI.

FAO (2003). *Proceedings. Second Expert Meeting on Harmonizing Forest-related Definitions for Use by Various Stakeholders*. Rome: FAO.

FAO (2004). *Unified Bioenergy Terminology*. Rome: Food and Agriculture Organization of the United Nations.

FAO (2016). *FAOSTAT. Food and Agriculture Organization of the United Nations*. Rome: FAO. Available online at: http://faostat.fao.org/default.aspx

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science* 309, 570–574. doi: 10.1126/science.1111772

Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., et al. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc. Natl. Acad. Sci. U.S.A.* 107, 16732–16737. doi: 10.1073/pnas.0910275107

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science* 342, 850–853. doi: 10.1126/science.1244693

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., et al. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environ. Res. Lett.* 7:4. doi: 10.1088/1748-9326/7/4/044009

IEA (2014). *International Energy Association. Africa Energy Outlook: A Focus on Energy Prospects in Sub-Saharan Africa*. World Energy Outlook Special Report, 1–237.

Jann, W., and Wegrich, K. (2007). "Theories of the policy cycle," in *Handbook of Public Policy Analysis: Theory, Politics and Methods*, eds F. Fischer, G. J. Miller, and M. S. Sidney (Boca Raton, FL: CRC Press), 43–62.

Jones, D., Ryan, C. M., and Fisher, J. (2016). Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. *Energy Sustain. Dev.* 32, 14–21. doi: 10.1016/j.esd.2016.02.009

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., et al. (2013). Global human appropriation of net primary production doubled in the 20th century. *Proc. Natl. Acad. Sci. U.S.A.* 110, 10324–10329. doi: 10.1073/pnas.1211349110

Lukumbuzya, K., and Sianga, C. (2016). *Revisiting TRAFFIC's Recommendations to Improve Forest Governance in Tanzania*. Cambridge: TRAFFIC.

Lund, H. G. (2015). *Definitions of Forest, Deforestation, Afforestation, and Reforestation*. Gainesville, VA: Forest Information Services. doi: 10.13140/RG.2.1.2364.9760

Martinez-Harms, M. J., Bryan, B. A., Balvanera, P., Law, E. A., Rhodes, J. R., Possingham, H. P., et al. (2015). Making decisions for managing ecosystem services. *Biol. Conserv.* 184, 229–238. doi: 10.1016/j.biocon.2015.01.024

Mielke, E., Anadon, L. D., and Narayanamurti, V. (2010). Water consumption of energy resource extraction, processing, and conversion, a review of the literature for estimates of water intensity of energy-resource extraction, processing to fuels, and conversion to electricity. *Energy Technology Innovation Policy Discussion Paper*, 2010-15. Harvard University.

MNRT (2015). *Ministry of Natural Resources and Tourism*. National forest Resources Monitoring and Assessment of Tanzania Mainland: Main Results.

Msuya, N., Masanja, E., and Temu, E. K. (2011). Environmental burden of charcoal production and use in Dar es Salaam, Tanzania. *J. Environ. Prot.* 2, 1364–1369. doi: 10.4236/jep.2011.210158

Muhongo, S. (2016). "Natural resources and energy development and its contribution to transform Tanzania towards becoming a middle income country by 2025," in *Presentation by the Minister for Energy and Minerals at the Annual Engineers Day*, Mlimani City Conference, Dar es Salaam.

Mwampamba, T. H., Ghilardi, A., Sander, K., and Chaix, K. J. (2013). Dispelling common misconceptions to improve attitudes and policy outlook in developing countries. *Energy Sustain. Dev.* 17, 75–85. doi: 10.1016/j.esd.2013.01.001

Ninan, K. N., and Inoue, M. (2013). Valuing forest ecosystem services: what we know and what we don't. *Ecol. Econ.* 93, 137–149. doi: 10.1016/j.ecolecon.2013.05.005

Owen, M., van der Plas, A., and Sepp, S. (2013). Can there be energy policy in Sub-Saharan Africa without biomass? *Energy Sustain. Dev.* 17, 146–152. doi: 10.1016/j.esd.2012.10.005

Price, K. (2011). Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. *Prog. Phys. Geogr.* 35, 465–492. doi: 10.1177/0309133311402714

Ribot, J. C. (1999). A history of fear: imagining deforestation in the West African dryland forests. *Glob. Ecol. Biogeogr.* 8, 291–300. doi: 10.1046/j.1365-2699.1999.00146.x

Sander, K., Gros, C., and Peter, C. (2013). Enabling reforms: analyzing the political economy of the charcoal sector in Tanzania. *Energy Sustain. Dev.* 17, 116–126. doi: 10.1016/j.esd.2012.11.005

Schure, J., Ingram, V., Sakho Jimbira, M. S., Levangy, P., and Wiersum, K. F. (2013). Formalisation of charcoal value chains and livelihood outcomes in Central- and West Africa. *Energy Sustain. Dev.* 17, 95–105. doi: 10.1016/j.esd.2012.07.002

TFCG (2015a). *Civil Society Organisation Comments on the Draft National Energy Policy 2015. Tanzania Forest Conservation Group*.

TFCG (2015b). *An Analysis of the Ecological and Financial Sustainability of Natural Forest Management in Tanzania*. Tanzania Forest Conservation Group. TFCG Technical Paper 48, 1–49.

TFS (2012). *Participatory Forest Management in Tanzania: Facts and Figures*. MNRT Department of Policy and Planning. Tanzania Forest Services Agency.

TFS (2013a). *Guidelines for Harvesting in Village Land Forest Reserves*, 1–8. Tanzania Forest Services Agency, Dar es Salaam.

TFS (2013b). *Tanzania Forest Services Agency Strategic Plan, July 2014–June 19*. Tanzania Forest Services Agency.

TFS (2016). *Maelezo Kuhusu Wakala wa Huduma za Misitu, Tanzania: Majukumu, Mafanikio, Changamoto Na Mikakati (2011–2015)*. Ministry of Natural Resources and Tourism, Tanzania Forest Services Agency, 1–25.

UN (2015). *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. United Nations (UN), Department of Economic and Social Affairs, Population Division.Working Paper No. ESA/P/WP.241.

URT (1977). *The Constitution of the United Republic of Tanzania. Cap* 2. United Republic of Tanzania.

URT (1997a). *National Environmental Policy*. United Republic of Tanzania.

URT (1997b). *National Land Policy*. United Republic of Tanzania.

URT (1998). *National Forest Polic*y. United Republic of Tanzania.

URT (1999). *The Tanzania Development Vision*. United Republic of Tanzania.

URT (2002). *The Forest Act.* United Republic of Tanzania.

URT (2003). *National Energy Policy*. United Republic of Tanzania.

URT (2006). *National Livestock Policy*. United Republic of Tanzania.

URT (2012). *National Climate Change Strategy*. United Republic of Tanzania.

URT (2013a). *National Agriculture Policy*. United Republic of Tanzania.

URT (2013b). *The National Land Use Framework Plan 2013–33*. United Republic of Tanzania.

URT (2014). *National Forest Policy (Draft)*. United Republic of Tanzania.

URT (2015a). *The Draft National Energy Policy*. United Republic of Tanzania.

URT (2015b). *The National Energy Policy*. United Republic of Tanzania.

URT (2016a). *The National Five Year Development Plan 2016/17–2020/21*. United Republic of Tanzania.

URT (2016b). *National Land Policy (Draft)*. United Republic of Tanzania.

URT (2016c). *National Environmental Policy (Draft)*. United Republic of Tanzania.

Watkiss, P., Downing, T., Dyszynski, J., Pye, S., Savage, M., Goodwin, J., et al. (2011). *The Economics of Climate Change in the United Republic of*

Tanzania. Report to Development Partners Group and the UK Department for International Development.

Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N. H., Verardo, D. J., and Dokken, D. J. (2000). *Land Use, Land Use Change and Forestry*. Cambridge: Cambridge University Press.

Willcock, S. L., Phillips, O. L., Platts, P. J., Swetnam, R. D., Balmford, A., Burgess, N. D. et al. (2016). Land cover change and carbon emissions over 100 years in an African biodiversity hotspot. *Glob. Change Biol.* 22, 2633–2956. doi: 10.1111/gcb.13218

Woollen, E., Ryan, C., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., et al. (2016). Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? *Philos. Trans. R. Soc. B* 371:20150315. doi: 10.1098/rstb.2015.0315

World Bank (2009). *Environmental Crisis or Sustainable Development Opportunity? Transforming the Charcoal Sector in Tanzania*. Policy Note. Environment and Natural Resources Unit for the Africa Region.

Yanow, D. (2007). "Qualitative-interpretive methods in policy research," in *Handbook of Public Policy Analysis: Theory, Politics, and Methods,* eds F. Fischer, G. J. Miller, and M. S. Sidne (Boca Raton, FL: CRC Press), 405–416.

Zulu, L. C., and Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. *Energy Sus. Dev.* 17, 127–137. doi: 10.1016/j.esd.2012.07.007

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Conceptual Analysis: The Charcoal-Agriculture Nexus to Understand the Socio-Ecological Contexts Underlying Varied Sustainability Outcomes in African Landscapes

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The production of charcoal is an important socio-economic activity in sub-Saharan Africa (SSA). Charcoal production is one of the leading drivers of rural land-use changes in SSA, although the intensity of impacts on the multi-functionality of landscapes varies considerably. Within a given landscape, charcoal production is closely interconnected to agriculture production both as major livelihoods, while both critically depend on the same ecosystem services. The interactions between charcoal and agricultural production systems can lead to positive synergies of impacts, but will more often result in trade-offs and even vicious cycles. Such sustainability outcomes vary from one site to another due to the heterogeneity of contexts, including agricultural production systems that affect the adoption of technologies and practices. Trade-offs or cases of vicious cycles occur when one-off resource exploitation of natural trees for charcoal production for short-term economic gains permanently impairs ecosystem functions. Given the fact that charcoal, as an important energy source for the growing urban populations and an essential livelihood for the rural populations, cannot be readily substituted in SSA, there must be policies to support charcoal production. Policies should encourage sustainable technologies and practices, either by establishing plantations or by encouraging regeneration, whichever is more suitable for the local environment. To guide context-specific interventions, this paper presents a new perspective—the charcoal-agriculture nexus—aimed at facilitating the understanding of the socio-economic and ecological interactions of charcoal and agricultural production. The nexus especially highlights two dimensions of the socio-ecological contexts: charcoal value chains and tenure systems. Combinations of the two are assumed to underlie varied socio-economic and ecological sustainability outcomes by conditioning incentive mechanisms to affect the adoption of technologies and practices in charcoal and agriculture productions. Contrasting sustainability outcomes from East Africa are presented and discussed through the lens of the charcoal-agriculture nexus. The paper then concludes by emphasizing the importance of taking into account the two-dimensional socio-ecological contexts into effective policy interventions to turn charcoal-agriculture interactions into synergies.

Keywords: the charcoal-agriculture nexus, socio-ecological contexts, value chain, tenure systems, sustainability outcomes, landscapes, Africa

INTRODUCTION

The production of charcoal is an important socio-economic activity in sub-Saharan Africa (SSA) (Mwampamba et al., 2013; Schure et al., 2014). Charcoal is one of the most important cooking energy sources in SSA, used by the majority of the urban population. It is also one of the most commercialized resources (World Bank, 2011; FAO, 2014).

At the same time, charcoal production is one of the leading drivers of rural land-use changes in SSA (Bailis et al., 2005; Iiyama et al., 2014b). The intensity of impacts on multiple ecosystem goods and services varies considerably across landscapes (Chidumayo and Gumbo, 2012). Some studies attempt to assess the impact of charcoal production on the environment, especially on deforestation. Some of them tend to attribute observed deforestation solely to charcoal production and use (Clancy, 2008; Adanu et al., 2009), without discussing the possibility of other competing activities which might also drive deforestation in a given landscape (Geist and Lambin, 2001). Others argue that charcoal is most often produced as a by-product of displacement for agriculture, which appears to be the most important driver of deforestation (Chidumayo and Gumbo, 2012). Production of charcoal can lead to forest degradation due to large scale tree cutting at the production site level, even when not driving overall forest cover loss (Chidumayo and Gumbo, 2012; Iiyama et al., 2014b, 2015a). Empirical evidence from dryland rural landscapes suggests that charcoal production is indeed causing biodiversity loss, due to selective harvest of indigenous hardwood species (Luoga et al., 2000; Namaalwa et al., 2007; Naughton-Treves et al., 2007; Ndegwa et al., 2016).

To assess the global impacts of woodfuel demand-supply in the tropical regions, Bailis et al. (2015) developed a spatially explicit model that accounted for the impacts of deforestation caused by agriculture and other factors. Their results, which indicated large geographic variations in the degree of woodfuel supply-demand balances, identified East Africa as one of the critical depletion "hotspots" where most demand was unsustainable. The model has proved to be useful in identifying potential areas of woodfuel-driven degradation or deforestation and in informing policy discussions. Charcoal production is however not a simple function of woodfuel demand and supply; it involves a more complicated and dynamic set of processes (Iiyama et al., 2015a). Its impacts on local ecosystem functions vary depending on the choices of (un)sustainable production technologies and practices whose adoption is influenced by site-specific socio-ecological contexts, and are often closely inter-linked with agricultural production. Within a given landscape, charcoal and agricultural productions are closely interconnected as major sources of livelihoods, and both critically depend on the same ecosystem services. The interactions of charcoal and agricultural productions can be more synergistic if there is sustained investment in maintaining the ecosystem functions to sustainably facilitate both systems to support livelihoods. On the other hand, they can result in trade-offs or even vicious cycles if one-off resource exploitation for short-term economic gains permanently impairs ecosystem functions (Iiyama et al., 2015a). Therefore, sustainability outcomes of the charcoal-agricultural production system need to be assessed, both within socio-economic and ecological contexts.

Such sustainability outcomes vary from one site to another due to the heterogeneity of contexts which affect the adoption of technologies and practices in charcoal as well as in agriculture productions. While many empirical studies have attempted to assess the impact of charcoal production on the local environment and beyond, unfortunately very few have either examined its interaction with agricultural production or provided comprehensive contextual information to allow cross-site comparisons (Cerutti et al., 2015; Sola et al., 2017). One possible reason behind this knowledge gap is, as the research topic of this issue argues, "the absence of the nexus approach that examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments in this research arena."

This paper therefore poses an overarching research question—"what are the main causes of heterogeneous, contrasting sustainability outcomes?" In answering to the question, this paper attempts to present a new nexus perspective to understand the contextual mechanisms underlying varied socio-economic and ecological sustainability outcomes of the charcoal-agriculture productions within African landscapes. We first review the conventional "water-energy-food nexus" debates, then introduce key concepts and propose an alternative analytical perspective to understand the charcoal-agriculture nexus. Thereafter, the observations from East African countries, which inspired the authors to develop the proposed charcoal-agriculture nexus approach are presented. The contrasting sustainability outcomes of charcoal production in the cases presented are discussed through the lens of the charcoal-agriculture nexus. The paper concludes with derived policy implications.

CONCEPTUAL APPROACH

The Charcoal-Agriculture Production Nexus

In attempting to provide a new systemic perspective to understanding sustainability outcomes of the interrelations between charcoal and agriculture productions, we first review the conventional "water-energy-food nexus" debates.

In recent years, the notion of a nexus emphasizing the linkages between water, energy, and food has been gaining attention in the scholarly literature due to the increasing interest in policies to achieve and sustain water, energy and food security (Weitz et al., 2014; Wichelns, 2017). While there are several variations by authors, the nexus is mostly presented as a closed cycle in which energy and water interact as the two most important inputs in producing food as an important output (Bazilian et al., 2011; IRENA, 2015; Wichelns, 2017).

Wichelns (2017) extensively reviewed the literature published since 2011 that applied the water-energy-food nexus to addressing issues involving water and energy use in agriculture. He argues that the water-energy-food nexus is not an agreed and tested framework, while it conventionally tends to focus on narrow material flows between inputs and outputs in a closed cycle. He further decries the fact that many authors tend to omit considerations on several critical variables for agriculture, including inputs such as land, labor, capital, etc., as well as issues such as land tenure and externalities, which greatly affect livelihoods and ecosystem functions. Indeed, FAO (2000) had earlier proposed the energy-agriculture nexus concept to address the links between sustainable rural livelihoods and environmental protection. The nexus focusing on agriculture therefore needs to be sufficiently flexible to incorporate the understanding of socio-ecological contexts, including key inputs and issues that simultaneously affect livelihoods and ecosystem functions.

In proposing an alternative approach to addressing charcoal as an entry point, we suggest a specific modification to the energy-agriculture nexus. FAO (2000) stated that, "woodfuel, especially charcoal, is already very much a traded commodity, and farmers can earn extra income from its sale..... (charcoal) is the potential threat to forests and trees outside forests if it is used in an indiscriminate and unsustainable way, which can result in forest degradation or deforestation, deterioration of watersheds, loss of soil fertility as well as biodiversity (FAO, 2000, pp. 49–50)." Indeed, rather than an input as energy to agriculture, the production of charcoal, one of the most commercialized commodities supplied from rural landscapes to urban consumers in SSA (Kambewa et al., 2007; World Bank, 2011; FAO, 2014), is an important source of livelihood along with agriculture (Schure et al., 2014; Jones et al., 2016). At the same time, charcoal and agricultural productions both rely on similar ecosystem services, thus are closely inter-linked via ecological feedback processes of the impacts of the adoption of (un) sustainable technologies/processes by the respective sectors (Iiyama et al., 2015a). Therefore, the charcoal-agriculture nexus approach should be able to simultaneously evaluate two dimensions of the interactions—socio-economic (livelihoods) and ecological sustainability outcomes.

The proposed charcoal-agriculture nexus approach, as conceptualized in **Figure 1**, will facilitate the understanding of the interactions of charcoal and agriculture productions. Below, key concepts and how they are inter-connected are elaborated.

Sustainability Outcomes

According to the definition by United Nations Economic Commission for Africa in its report "Managing Land-Based Resources for Sustainable Development" (UNECA, 2011), there are three pillars of sustainable development—economic, social, and environmental—which are closely interfaced. The economic sustainability concept is to optimize the use of scarce resources to maximize the flow of income that could be generated while at least maintaining a good stock of assets (or capital) which yield these benefits. The social concept of sustainability seeks to maintain the stability and equity of social and cultural systems. The environmental view of sustainable development focuses on the stability of biological and physical systems to adapt to change, and prevent natural resource degradation, pollution and loss of biodiversity from reducing system resilience. Borrowing from these concepts, we define socio-economic (i.e., income, equity aspects) and ecological (impacts on natural resources and biodiversity) dimensions of sustainability outcomes of the charcoal-agriculture nexus.

Socio-Economic Dimension

In SSA, charcoal is mainly supplied from rural landscapes to urban centers, while the rural populations are often too poor to use it (Schure et al., 2014). Charcoal production has pro-poor features because of its low start-up costs and simple technology requiring few skills (Schure et al., 2014; Ndegwa et al., 2016a). It also attracts bigger business because of the high and consistent demand for the product (Kambewa et al., 2007). Indeed, contrary to the long-standing assumption that charcoal production is a "last-resort type of livelihood activity" for those "without much alternative," charcoal production has been increasingly recognized as a part of livelihood diversification strategies (Jones et al., 2016). Income from charcoal provides a safety net for the poorest on one hand, while it supplies capital for large producers to diversify their livelihoods into remunerative farming and/or off-farm business enterprises (Kambewa et al., 2007; Ndegwa et al., 2016a; Smith et al., 2017). From the charcoal-agriculture nexus perspective, charcoal and agricultural production are closely interconnected within a given landscape as major livelihoods as shown on the left part of the **Figure 1**. Charcoal income contributes to supplementing shortcomings in agricultural income or to investing in diversifying livelihoods, including improving agricultural productivity (Kambewa et al., 2007; Ndegwa et al., 2016) and thus protecting producers from poverty. The sustainability of such an income flow, however, indirectly depends on the ecological sustainability of the natural resource basis (Smith et al., 2017) as discussed below.

Ecological Dimension

Charcoal could potentially be a renewable energy if produced with improved kilns and limited to a sustainable supply to allow the rebuilding of tree biomass stocks through natural regeneration or plantation (Kambewa et al., 2007; Chidumayo and Gumbo, 2012; FAO, 2017). In reality, charcoal production in SSA is generally unsustainable with net loss of biomass stocks as it relies on wood, harvested from natural rather than

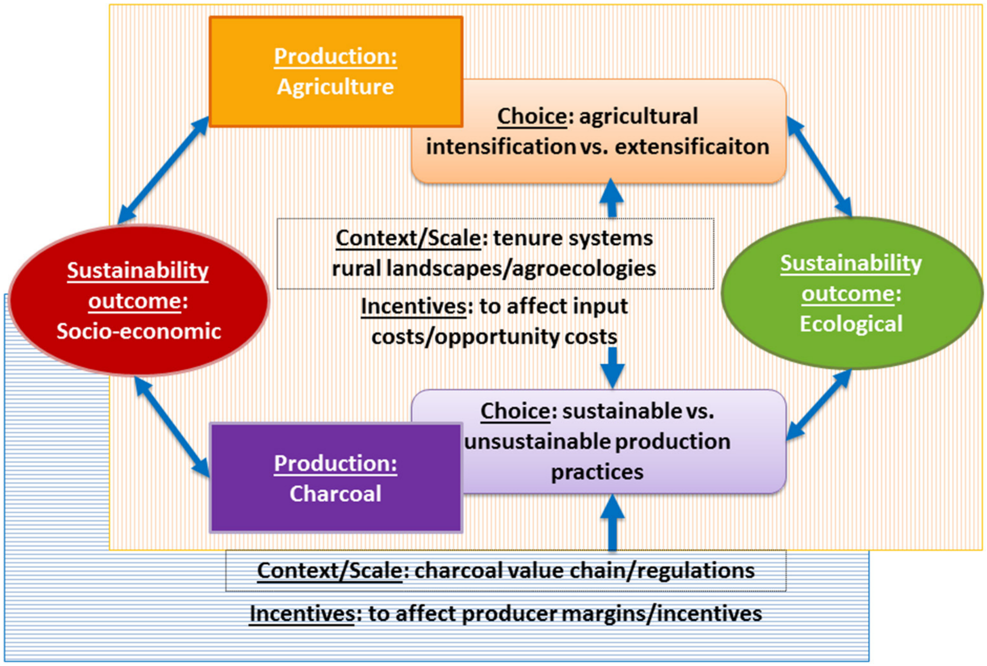

FIGURE 1 | The charcoal-agriculture production nexus.

planted tree stands, which is then converted to charcoal in rudimentary earth kilns with low conversion efficiency (Bailis et al., 2005). While displacement of trees for agriculture still appears to be the most important driver for deforestation with charcoal produced as a byproduct, charcoal production has a significant landscape-level impact on forest degradation due to widespread tree cutting at production site level even when not driving overall forest cover loss (Chidumayo and Gumbo, 2012). With rapid urbanization and population growth in SSA, the negative impacts of charcoal production on forests and woodlands, such as reducing natural regeneration, will increase markedly (Bailis et al., 2005; Iiyama et al., 2014b). The depletion of wood resources by charcoal production can impair ecosystem functions, resilience and productivity (Luoga et al., 2000; Naughton-Treves et al., 2007; Skutsch and Ba, 2010; Iiyama et al., 2015a). Changes in sensitive ecosystems can, in the long run, affect land use patterns, including agriculture productivity, through a complex set of processes and feedback loops (Dale et al., 2011) as shown on the right hand side of **Figure 1**.

Context and Scale

Socio-economic and ecological sustainability outcomes can be more synergistic, or result in trade-offs, and even vicious cycles, widely varying from one site to another, due to the heterogeneity in technologies/practices adopted. In this paper, we assume the heterogeneity in the technology/practice adoption is influenced by site-specific socio-ecological contexts. We especially highlight the importance of understanding two dimensions of the socio-ecological contexts—charcoal value chain and tenure systems—which underline incentive mechanisms to affect technology/practice adoption in charcoal and agriculture productions (Iiyama et al., 2015a).

Charcoal Value Chain

We assume that the price of charcoal determines the income and economic welfare of charcoal-producing households, which in turn influences their decisions to invest in charcoal production technologies and practices, as indicated in the lower part and blue area of **Figure 1**. The price of charcoal can also give rise to a distributional problem across the value chain (Agbugba and Obi, 2013).

The scale of the market and value chain can affect the absolute and relative levels of margins for charcoal producers. Simpler, competitive markets can give relatively higher margins, as high as over 50% of the final retail price, to producers than to other actors, especially with asymmetric information in favor of producers (Agbugba and Obi, 2013). In contrast, and more commonly, complex markets involving many stakeholders and sectors tend to result in inequitable distribution (Sepp, 2008). Frequently, incoherent legislation from different government departments, such as energy, agriculture, environment, natural resource management and local government, which target the same or different sections of the value chain, results in an unclear framework for stakeholders (Sepp, 2008; Schure et al., 2013; Iiyama et al., 2014a). Transport enforcement officers often take advantage of such unclear frameworks by demanding bribes to ignore unsustainable practices (Kambewa et al., 2007; Schure et al., 2013). Increasing rent-seeking activities tend to result in squeezing producers' margins as low as 10–30% of the final retail price, especially for longer value chains with increasing transportation costs (Ribot, 1998; Van Beukering et al., 2007; Shively et al., 2010).

In reality however, the distribution patterns of the charcoal value chain are heterogeneous even within a country. For example, the study on the four largest urban centers which accounted for roughly 90% of the charcoal used in Malawi compared the value chains in Lilongwe and Blantyre, the two largest cities in the country (Kambewa et al., 2007). The proportion of the producer margin as well as that taken as taxes/bribes were higher in Lilongwe (33% for producers, 20% for taxes/bribes) than in Blantyre (21, 12%, respectively), while the relative shares of transporters and retailers were higher in Blantyre (25% for transporters, 33% for retailers) than in Lilongwe (20, 24%, respectively). The study did not report the difference in charcoal production technologies between the two cities while referring to the general adoption of low efficiency kilns across the study sites. As the areas immediately surrounding the cities had already been depleted, Lilongwe's charcoal mainly came from forest reserves, while Blantyre's charcoal came from other districts and Mozambique along with the developed transport infrastructure (Kambewa et al., 2007).

In summary, the distribution patterns of the charcoal value chain are site-specific, while their implications to affect the adoption of technologies/practices in charcoal production are ambiguous depending on their combination with the other socio-ecological contextual mechanism.

Tenure Systems

While there are many studies which focus on the distributional impacts of the charcoal value chain as reviewed above, relatively fewer studies consider the role of local institutions on the sustainability of the charcoal production (Luoga et al., 2000; Iiyama et al., 2015a). We assume that tenure systems evolving along with agricultural intensification are as important as the value chain in influencing the adoption of technologies and practices in charcoal production, as indicated in the center part and orange area of **Figure 1**. For example, in densely populated regions where intensive agriculture is practiced, land is usually already individualized and effectively privatized even without formal title deeds. Formalization could ensure improved tenure security, and provide incentives to invest in longer-term tree planting (Pattanayak et al., 2003).

In some regions, customary tenure systems still prevail and remain functional. The overlapping character of family and collective resource rights to residential, cropping, grazing and common property resources complicates the creation of exclusive property rights (Lawry et al., 2014). As a result, farmers, agro-pastoralists and pastoralists often depend on the same resources in a seamless continuum from woodland, rangeland to farmland (Namaalwa et al., 2007). While individual farming plots are recognized, neighbors are allowed to exploit trees and pastures during fallows, which provide disincentives for landowners to invest in natural resource management including tree planting for charcoal (Luoga et al., 2000; Siri et al., 2006; Iiyama et al., 2015a).

In relatively more extensive pastoral areas with higher degrees of subsistence, land is still held communally (Hosier and Milukas, 1992). On the ground, Privatization or individualization of land rights has been advocated to secure land rights to improve productivity and to avoid resource overexploitation. Yet, a recent review of land reforms across developing regions suggests that strengthening land rights in SSA through formalizing a bundle of overlapping rights customarily distributed through a community into private property could lead to the exclusion and marginalization of large sections of the community, including the poor (Lawry et al., 2014). When the land is sub-divided, land sales or clearance of pasture/natural forests for agriculture by powerful individuals often accelerate with charcoal produced as a by-product, as landowners look for quick returns rather than long-term investment (Bedelian, 2012).

In summary, locally-specific tenure systems evolving along with agricultural intensification can affect the adoption of technologies/practices in charcoal production through affecting direct and opportunity costs of procuring resources.

Interpretations of Case Studies

The proposed charcoal-agriculture nexus stresses the importance of understanding certain socio-ecological contextual mechanisms, namely charcoal value chain and tenure systems, a combination of which underlies varied sustainability outcomes of charcoal production. The following three sections introduce case studies which inspired the authors to develop and conceptualize the charcoal–agriculture nexus approach. They were drawn from the authors' experiences in Kenya, Ethiopia, and Rwanda during the implementation of projects primarily aimed at improving livelihoods by promoting the adoption of natural resource management technologies, including agroforestry, since 2013. Given the background, the presentation of the case studies is more descriptive and qualitative. For each case, the two dimensions of the socio-ecological contexts, i.e., value chain and tenure system, are elaborated and socio-economic vis-à-vis ecological sustainability outcomes are described.

TRANS MARA, KENYA: CHARCOAL AS A BY-PRODUCT OF DEFORESTATION

Context

Charcoal Value Chain

In Kenya, over 80% of urban households rely on charcoal. A national survey estimated that charcoal consumption had risen from 1.6 million t/year in 2004 to 2.3 million t/year in 2013 at a growth rate of 5% per year, higher than the urbanization rate during the same period. The economic value of the charcoal sector was estimated to be comparable to that of the tea industry, the country's major export commodity. The charcoal sector has been estimated to create 0.5–0.7 million jobs across the value chain and to support the livelihoods of 2–2.5 million people (ESDA, 2005; KFS, 2013).

The policies related to the charcoal sector in Kenya are spread across several ministries ranging from agriculture, energy, environment and natural resources and recently created county governments, with overlapping responsibilities (Sepp, 2008;

Iiyama et al., 2014a). The Charcoal Rules of 2009 mandated the Kenya Forest Service (KFS) to grant licenses to groups organized into associations to legally produce sustainable charcoal. However, high transaction costs to screen applications for sustainability have resulted in delayed licensing, thus discouraging potential sustainable producers. The new rule on charcoal was expected to operationalize the law where the national government is charged with formulating a charcoal policy while devolving the responsibility of conservation (such as to promote efficient technologies) to county governments. However, newly established county governments have faced capacity gaps in operationalizing the regulations (Iiyama et al., 2015b). These uncertainties in regulations have made the sector more prone to corruption from the traffic police who capitalize on the confusion by demanding bribes that are factored into the retail price (KFS, 2013; Iiyama et al., 2015b). The 2013 survey revealed that transporters, wholesalers and retailers accounted for 78% (37, 13, 28% respectively) of the final value of a bag of charcoal while the rural actors—wood and charcoal producers—received only 22% (6 and 16% respectively) of the final value (KFS, 2013).

Tenure System

The Maasai Mara National Reserve, which is globally known for its concentration of migratory herbivores, lies in south-western Kenya (**Figure 2**). The Reserve is one of Kenya's top tourist attractions; the direct and indirect contribution of Kenyan tourism to the national economy amounted to 12+% of GDP and 10+% of employment in 2013 with expected steady growth. In turn, the Reserve accounts for less than 10% of the whole Mara Ecosystem, the so-called Trans Mara, most of which is unfenced and surrounded by a mixture of private and communally-owned land historically inhabited by semi-nomadic Maasai communities (Mundia and Murayama, 2009). To the west of the Reserve lies the Oloololo Escarpment, beyond which the land rises to over 2,000 m covered by a mosaic of Afro-montane, semi-deciduous and dry-deciduous forest and acacia savannah woodlands. Nyakweri Forest is the largest remaining forest in the Trans Mara and forms part of the dispersal area of the Reserve. This dense indigenous forest is of high ecological and socio-cultural importance to the Maasai and also an important feeding and breeding ground for large mammals. The forest is dominated by huge trees whose dense vegetation provide a safe haven for elephant mothers to give birth and protect their babies, while forming a habitat for various game species like buffaloes, waterbucks, impalas and leopards, among others (AKTF, 2014). The forest also plays a foundational role in the local climate and rainfall (Iiyama et al., 2015b).

Traditionally, land was owned communally, which enabled the Maasai to practice nomadic pastoralism (Bedelian, 2012). However, because of the government policy aimed at ensuring security of land tenure to facilitate development, the formerly communal rangelands were first demarcated into group ranches. More recently, these group ranches have been internally subdivided into individual plots of about 60 acres (24 ha) for which titles have been allocated to registered members, while a few powerful individuals, such as chiefs, received hundreds of acres (Iiyama et al., 2015b). The sub-division of land paved the way for individual landowners to make land use decisions over cultivation, livestock and wildlife. Previously, individuals did not know which piece of land belonged to whom, thus less tree clearance occurred. After sub-division, surer of which piece of land belongs to them, landowners have started clearing forests for immediate tangible gains from grazing and farming. The community members who failed to get sub-divided plots, on the other hand, have encroached parts of the protected Nyakweri forest by setting up illegal logging camps (AKTF, 2014).

Socio-Economic Vis-à-Vis Ecological Outcomes

The argument behind individualization of tenure was that more secure tenure would result in efficient resource use and improve productivity. However, for this case of a Maasai community which has led subsistence pastoralism without alternative livelihoods, trees on "own" sub-divided land turn out to be "free" resources to earn quick cash incomes with insufficient incentives to invest in conservation for long-term returns. Without realizing the true economic value of tree resources and the social and environmental costs of their depletion, the landowners allow tree felling for agricultural expansion in which charcoal is produced as a by-product (**Figure 2**).

The charcoal value chain provides low margin to landowners. For example, a landowner allows a group of charcoal burners from the neighboring counties to live on his farm, to fell indigenous trees with chainsaws and to make charcoal even with stems, thus completely eliminating the potential for regeneration from re-sprouting. In return, migrant charcoal burners pay US$ 1 per sack of charcoal (45–50 kg) to landowners, then sell a sack to transporters at US$ 4 (Iiyama et al., 2015b). Transporters meet the transaction costs including bribes to law enforcers and finally sell the charcoal in Nairobi, the capital, at US$ 18/sack (Iiyama et al., 2015b). This makes a unit margin to wood producers merely 5% of the final price.

Deforestation may provide landowners with even minimal, one-off charcoal income and agricultural land ready for cultivation. However, it can lead to a vicious cycle of decreasing long-term agricultural productivity due to permanent damage to ecological systems and loss of ecosystem services. Assuming the low efficiency conversion rate of 10–15% of earth mound kilns used, a sack of charcoal (45–50 kg) requires 300–500 kg of (indigenous) wood, yet it is valued at merely US$ 1, which does not reflect the long-term ecosystem services to the community and the whole Mara Ecosystem. Yet, the tenure system fails to internalize the environmental externalities, and hence deforestation continues as long as landowners consider trees as "free."

WESTERN RWANDA: CHARCOAL AS AN INTEGRAL PART OF AGRICULTURAL INTENSIFICATION

Context

Charcoal Value Chain

Rwanda is one of the poorest and most densely populated nations in SSA. While the Government of Rwanda has set the goal

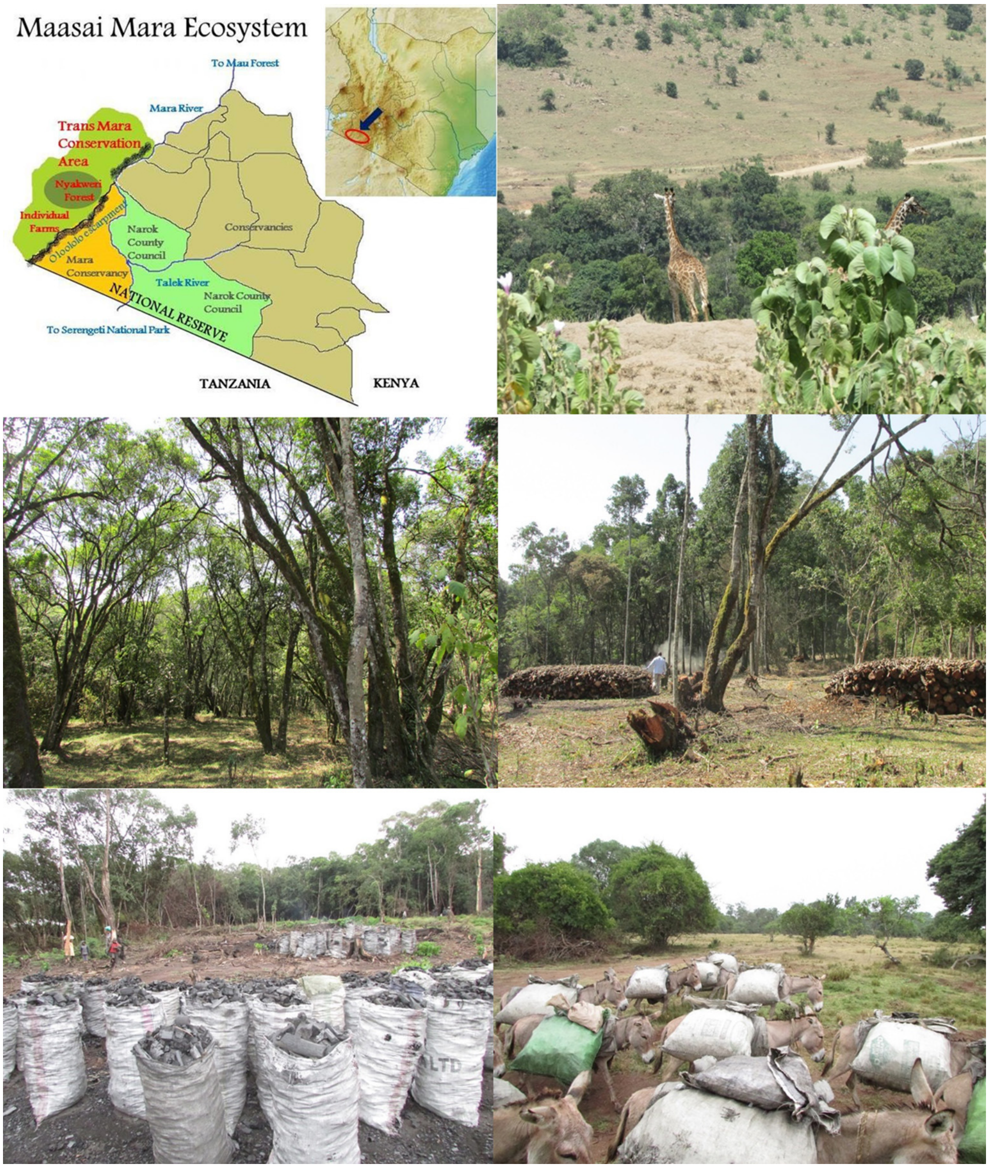

FIGURE 2 | Kenyan site illustration. Over the escarpment of the Mara Triangle lies Trans Mara Conservation Area encompassing recently sub-divided farms and Nyakweri Forest. Indigenous forests have provided multiple ecosystem services over and beyond the Mara Ecosystem. However, trees are felled for agriculture with charcoal produced as a by-product.

of promoting universal access to electricity, the population is still predominantly dependent on biomass energy for cooking. During the period 2010/2011, reliance on wood and charcoal as the primary cooking fuel was still 97% nationwide. Over the last few years the Government and other institutions have supported tree plantations and promoted charcoaling techniques that make more efficient use of the available wood resources and also improve the quality of the produced charcoal. By doing so, the Government has tried to streamline regulations to develop a modern and efficient charcoal value chain in the country by transforming it from an "informal" to "modern" sector, which could contribute to economic development by raising tax revenue (World Bank, 2012).

The charcoal supply regulation in Rwanda today is highly decentralized, with local districts in charge of issuing cutting permits for tree plantations over 2.0 ha and collecting revenue (World Bank, 2012). At the same time, the charcoal business in Rwanda is highly specialized, and farmers usually hire specialized labor to process wood for lumber and charcoal (World Bank, 2012). While it is cumbersome for farmers to apply for a cutting permit, an agent, or a "charcoal master" often takes charge; they handle transactions such as negotiating the price of wood, contacting the local authorities and applying for the necessary cutting permits, cutting trees, carbonizing wood, and transporting (World Bank, 2012).

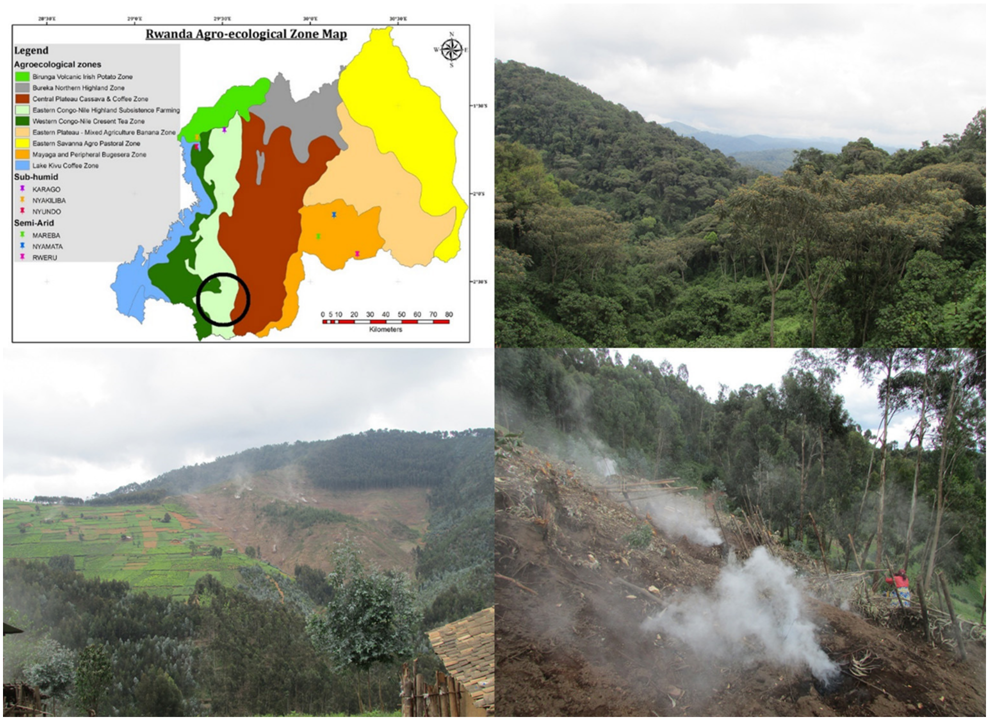

FIGURE 3 | Rwandese site illustration. Nyungwe Forest is the largest block of montane forest in East and Central Africa, home to over 1,000 species, including rare primates, such as chimpanzees, the L'Hoests monkey and Angola Colobus. Nyungwe is also an important water catchment for Rwanda. Western Rwanda is one of the most densely populated regions of the country and at the same time one of the major suppliers of charcoal made from planted Eucalyptus. By ameliorating sloping landscapes and utilizing marginal plots, charcoal production has become an integral part of sustainable agricultural intensification, while creating an income source for farmers, as well as employment opportunities for specialized labor.

Tenure System

In Rwanda, smallholders derive their livelihoods from subsistence agriculture on small farms which are often highly fragmented. The post-genocide Land Law promotes the creation of a private land market through registered titles, combined with a concerted effort to consolidate fragmented plots, hoping to make a dent in the country's tradition of subsistence farming and to unlock its potential for commercial mono-cropping (Pottier, 2006). Given the increasing population pressures against the scarce natural resource base, land use has been quite individualized and intensified. Indeed, the only plausible pathway is sustainable agricultural intensification, including the introduction of priority commercial crops, zero-grazing and agroforestry (Mukuralinda et al., 2016). Rwanda's hilly topography gives rise to diverse agro-ecologies within compact geographical areas and provides environments to the application of diverse pathways for agricultural intensification with trees, with the Government's commitment to expand agroforestry (Mukuralinda et al., 2016).

Socio-Economic Vis-à-Vis Ecological Outcomes

In the past, the production of charcoal in Rwanda was one of the factors that contributed to deforestation, although land clearing for agriculture, for habitation and for creating tea plantations were the leading drivers of the destruction of natural resource bases (World Bank, 2012). In the early 1980s, the region most affected by charcoal production was the eastern part of the country with semi-arid climate.

Today, the western part of the country with more favorable climate is the major charcoal supply region despite extreme land scarcity and fragmentation due to population pressures (**Figure 3**). The area adjacent to the Nyungwe Forest is a charcoal production hot spot. It is estimated that virtually all charcoal in Rwanda is now produced from planted trees, increasing around 2.5% per year, primarily from Eucalyptus woodlots on private as well as community land (World Bank, 2012; Drigo et al., 2013). At the national level, 36–40% of farmers have adopted Eucalyptus woodlots (Ndayambaje et al., 2013).

It is argued that farmers have become aware that with secure land tenure and rising woodfuel prices, it is profitable to invest in tree planting, especially on marginal plots, to produce wood for charcoal along with timber and poles for construction (World Bank, 2012; Mukuralinda et al., 2016; **Figure 3**). The demographic pressure on land forces farmers to exploit marginal areas where it is not profitable to grow crops, but Eucalyptus plantations generate net positive returns due to the low production costs and high demand for wood (World Bank, 2012). The price at the production site was reported at US$ 0.14–0.19/kg, against the retail price of US$ 0.32–0.42/kg in Kigali, the capital city, resulting in a margin of 33–59% at the production site

(World Bank, 2012). The comparatively well specialized charcoal value chain with skilled agents to handle transaction costs for farmers may also provide the positive environment.

By coping with sloping landscapes and utilizing marginal plots through the adoption of Eucalyptus, charcoal production has become an integral part of sustainable agricultural intensification in Rwanda, while supported by the secure tenure system and enabling value chains (Mukuralinda et al., 2016). It is further argued that woody biomass stock from these woodlots can reduce the woodfuel supply-demand gap in the country, thus contributing to reducing pressures on deforestation and degradation (Ndayambaje et al., 2013, 2014). Indeed, it is claimed that there are virtually no illegal charcoal production activities affecting natural forests in Rwanda (World Bank, 2012; Drigo et al., 2013). This is a stark contrast with the situations in other cases reported from SSA where charcoal production is a major driver of degradation of natural woodlands.

CENTRAL ETHIOPIA: CHARCOAL AS A MAJOR CAUSE OF WOODLAND DEGRADATION

Context

Charcoal Value Chain

A national study on biomass energy in Ethiopia reported that by 2000 charcoal had only been consumed in significant quantities in Tigray and Somali regions and hardly in all the other regions (Geissler et al., 2013). However, the past 15 years have seen a massive increase in the consumption of charcoal in all regions from 48,581 tons/year in 2000 to 4,132,873 tons/year in 2013. The report argued that the reasons for this increase could be related to a number of very significant changes in the rural socio-economy. These include, significant increase in rural incomes, proliferation of rural markets, significant reduction in transport costs due to improved roads and increased rural accessibility, and land for tree growing reaching limits around cities or areas with growing demand (Geissler et al., 2013).

The same report stated that charcoal production and marketing in Ethiopia has always been almost entirely informally organized (Geissler et al., 2013). According to the recent national charcoal value chain assessment (MEFCC, 2016), most of the charcoal produced in Ethiopia is traded and supplied to consumers through the following five channels:

Channel 1: Illegal large-scale private producers-private vendors-metropolitan consumers
Channel 2: Illegal large-scale private producers-foreign smugglers-foreign market
Channel 3: Licensed and permitted private/group producers-private vendors-urban consumers
Channel 4: Illegal regular household level producers-local vendors-local consumers
Channel 5: Illegal irregular/sporadic producers directly to road-side buyers or local consumers

Of these, Channel 4—the illegal regular household level charcoal producer to local towns—is the most frequent charcoal production-supply channel covering much of the charcoal-producing regions in Ethiopia, mainly with pastoral/agro-pastoral and mixed farming communities in dry lowlands (MEFCC, 2016), including the example described below. According to the same report, distribution of income and profit sharing in the illegal charcoal production-supply channel in Ethiopia is highly skewed toward the producers who are earning about 75% of the total revenue/bag (MEFCC, 2016).

Tenure System

In Oromia region of Central Ethiopia, trees scattered on farm are prominent features of agro-pastoral livelihoods (Iiyama et al., 2017; **Figure 4**). The land remains state-owned but the constitution affirms the right of access to land for every adult. The recent effort to improve security of land tenure includes land certification through decentralized mechanisms, where the regional government would issue land certificates to individual farmers (Deininger et al., 2008, 2009). Still, in drier parts of Oromia region, access to individual plots is usually not completely exclusive to landowners with neighbors often being allowed to graze livestock as well as to exploit trees and other natural resources after harvesting of crops and during fallows. In such a situation, communal grazing can affect patterns of tree cover on farm. This is because communal grazing causes soil degradation and also affects the survival of tree seeds and seedlings on farm, which could have a negative effect on incentives to intensify or extensify tree management on farms (Gebremedhin et al., 2004; Mekuria and Aynekulu, 2013; Iiyama et al., 2017).

Socio-Economic Vis-à-Vis Ecological Outcomes

The majority of informal charcoal producers are low to middle income or poor pastoral/agro-pastoral and mixed farming households living in the dry lowlands of Ethiopia. These households produce charcoal regularly as their main or additional source of income to support their families (MEFCC, 2016). Wood for charcoal is mostly harvested from trees scattered on farms and landscapes which are available for "free" to households (Iiyama et al., 2017; **Figure 4**). Given the reported high producer unit margin of 75% (MEFCC, 2016) and "free" input costs on the one hand, and the unreliability of income from subsistence/semi-subsistence agro-pastoralism which is subject to climate and other calamities on the other, charcoal production must be among the most rewarding livelihood opportunities to dryland households.

The socio-economic benefits from charcoal production however, have trade-offs. Households in the region are reported to derive multiple benefits from specific tree species, not only to procure free materials for charcoal production, but also to derive ecosystem services, such as shade and climate regulation (Iiyama et al., 2017). Selective tree harvesting at the extraction rate above the capacity for natural regeneration could result in depletion of the wood resources (Iiyama et al., 2017). The degradation and depletion of wood resources from landscapes could undermine the resilience of the semi-arid ecosystems which are already stressed and fragile and of the communities which recurrently

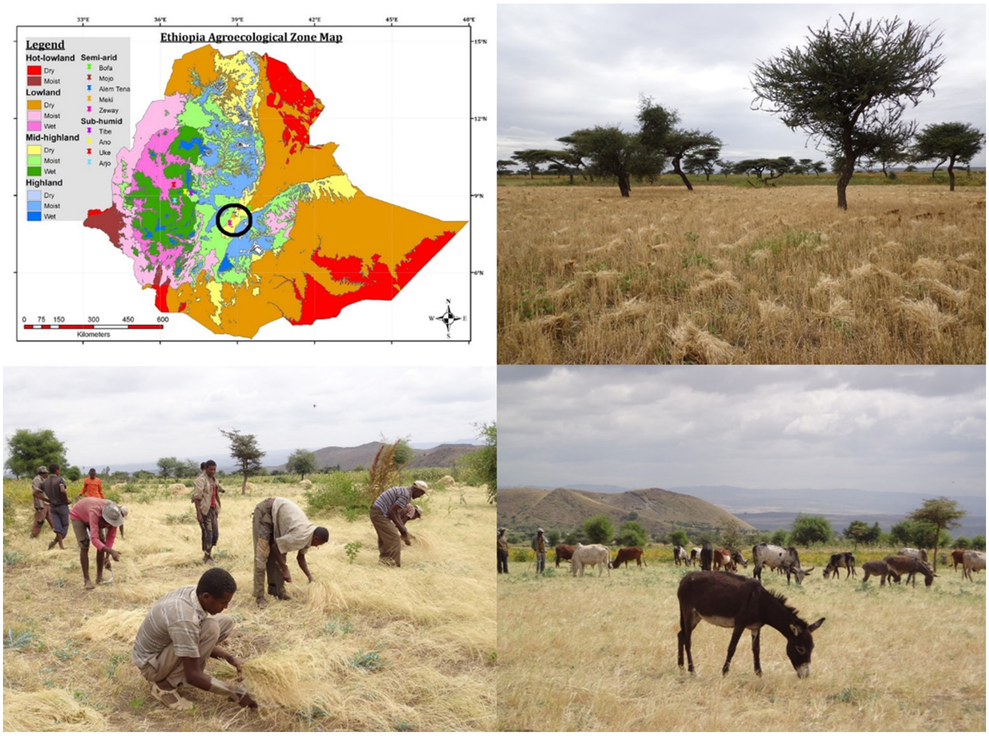

FIGURE 4 | Ethiopian site illustration. Trees on farms are characteristic of a large part of the Ethiopian agricultural landscape where farmers usually retain trees of selected species and minimize impact on the companion crops through occasional lopping and pollarding. While cropping plots belong to individual farmers, neighboring farmers collectively practice harvesting immediately after which communal grazing is practiced.

face food insecurity. Still, farmers have few incentives to plant and grow trees for charcoal for which slow growing indigenous species are preferred (Iiyama et al., 2017). Planting trees is an inherently risky venture where tree survival rates are low, due to not only harsh climatic conditions, but also damages caused by multiple users. Promoting planting of trees or even retaining them on farm through natural regeneration requires reducing risks through some form of institutional arrangements, such as "exclosure" where communities collectively agree to set aside land free from farming and grazing animals for regeneration (Gebremedhin et al., 2004; Mekuria and Aynekulu, 2013; Iiyama et al., 2017).

SYNTHESIS

The above case studies present varied sustainability outcomes due to the heterogeneity in the socio-ecological contexts, as summarized in **Table 1**.

The Kenya and Rwanda cases present contrasting sustainability outcomes while in both cases charcoal has been produced within landscapes with extremely high biodiversity and ecological values. What are the main causes of these contrasting sustainability outcomes?

First, the value chain provides an enabling environment for the adoption of sustainable technologies and practices in western Rwanda while it is discouraged in Trans Mara in Kenya. While there is still room for improvement (World Bank, 2012), the regulations governing the charcoal value chain in Rwanda are relatively streamlined and well decentralized, while highly specialized charcoal masters act to reduce transaction costs for farmers. In contrast, the charcoal value chain in Kenya is severely affected by complicated and overlapping legislations, while local governments lack capacity to control the situation, thus leaving room for corrupt practices (KFS, 2013). In Kenya, inter-sectoral harmonization of policies/regulations is urgently required, while county governments should be empowered to facilitate decentralized monitoring and evaluation on production/transportation sites.

While the value chain may affect charcoal prices, the net profitability of the charcoal production as well as the choice of technologies and practices also depends on how cheaply farmers procure inputs/resources. In Western Rwanda, the integration of planting Eucalyptus in woodlots is not only affordable for farmers, but also enables them to exploit marginal areas where it is not profitable to grow any other crop, supported by exclusive tenure systems (Mukuralinda et al., 2016). In contrast, in the case of Trans Mara, the sub-division of group ranches failed to internalize the ecological value of trees to the communities, the Mara Ecosystem and even beyond. The local communities who led subsistence pastoral livelihoods for years, have marginally benefited from the tourism of the Maasai Mara Reserves, and their decision to deplete trees in Nyakweri Forest has had a destructive impact on the whole Mara Ecosystem. In

TABLE 1 | Comparison of socio-ecological contexts, technologies/practices adopted, and sustainability outcomes of the three case studies.

	Western Rwanda	Oromia/Ethiopia	Trans Mara/Kenya
SOCIO-ECOLOGICAL CONTEXTS			
Value chain	Decentralized regulations, specialized value chain with agents to handle transaction costs, relatively high margins at the production site	Mostly informal markets, high margins to producers for the value chain channel targeting local vendors/ consumers	Unclear frameworks with overlapping and complicated legislations, long value chains prone to corruption and low producer margins
Tenure system	Fragmented and small land holdings yet with recognition of security on individualized, exclusive land rights	Overlapping rights to cropping, grazing and common property resources under customary systems	Sub-division of group ranch to individual plots with skewed distribution in favor of powerful individuals
TECHNOLOGIES/PRACTICES			
Agriculture production	Intensive, well integrated crop-livestock production	(Semi-)subsistence crop-livestock production	Conversion of subsistence pastoralism to agriculture
Charcoal production	Planting eucalyptus in woodlots	Selective cutting of trees scattered on farm, or in communal rangelands, forests, woodlands/state forests	By-product of clearing trees for agriculture land
SUSTAINABILITY OUTCOMES			
Socio-economic	Charcoal as a part of agricultural intensification	Charcoal as a part of livelihood diversification	Charcoal as a one-off cash income for a few individuals
Ecological	Rebuilding of biomass stocks on sloped, marginal land, while reducing pressures of deforestation-degradation	Gradual degradation and biodiversity loss which may lead to the loss of resilience	Permanent loss of the indigenous forest and their ecosystem services
	——Synergy	——Trade-off	——Vicious cycle

such a situation, innovative interventions, such as payment for environmental services (PES), need to complement institutional arrangements to internalize externalities.

The case from Ethiopia provides a more typical example of charcoal as a driver of land degradation, which is widely observed across agro-pastoral landscapes in semi-arid and arid SSA (Luoga et al., 2000; Namaalwa et al., 2007; Naughton-Treves et al., 2007; Iiyama et al., 2008; Kiruki et al., 2017,?; Ndegwa et al., 2016,a,b). Charcoal turns out to be among the most important and reliable cash income sources compared to income from semi-subsistence crop and livestock activities which are subject to climatic and other calamities. Consequently rural agro-pastoralists may continue exploiting native vegetation on their farms and beyond in extensive landscapes as long as wood can be obtained sufficiently cheaply against prices for charcoal, to ensure adequate economic returns (Hosier and Milukas, 1992; Luoga et al., 2000). Lack of an enabling policy environment and non-exclusive tenure conditions interact to provide incentives for over-exploitation of natural trees.

In the above and similar cases, charcoal and agriculture production systems have serious trade-offs, as charcoal allows livelihoods diversification while the depletion of resources leads to undermining the resilience of the ecosystems. It seems quite challenging to turn trade-offs around by controlling production only. In turn, some studies which reveal stratification among charcoal producers and their livelihood diversification patterns give some insights for interventions (Iiyama et al., 2008; Ndegwa et al., 2016a). For example, Ndegwa et al. (2016a), reporting from a community in Eastern Kenya, identified the small-scale producers who seemed "trapped" in perpetual poverty as predominantly relying on income from charcoal and casual labor on the one hand, and the large scale, well-off charcoal producers on the other hand. The latter, produced a large volume of charcoal regularly, and their income allowed them to invest in livelihood diversification and agricultural improvement. Strategically targeting this group to promote the adoption of sustainable charcoal production technologies/practices could potentially lead to synergies in which charcoal production is an integral part of sustainable and resilient crop-livestock-tree integration. Poorer producers need fundamental capacity development to improve their livelihoods (Ndegwa et al., 2016a).

POLICY IMPLICATIONS

In SSA, charcoal is an important energy source for the growing urban populations and an essential source of livelihood for rural populations, therefore it cannot be substituted for many years (FAO, 2017). The critical ecological problem occurs with trade-off or vicious cycle cases where one-off resource exploitation of natural trees for charcoal for short-term economic gains permanently impairs the ecosystem functions. There must be a policy direction to support the adoption of sustainable charcoal production technologies and practices, either establishing plantations, managing existing natural woodlands or encouraging regeneration, whichever is more suitable within the local context. Given the general consumer preference for charcoal with high calorific value, considerations should be given to promoting high biomass forming native and/or exotic tree species that have high calorific value.

This paper has proposed the charcoal-agriculture nexus approach to understand the two dimensions of the socio-ecological contexts, namely charcoal value chains and tenure systems, a combination of which underlies varied socio-economic and ecological sustainability outcomes. In reality, policies aimed at addressing the unsustainability of technologies/practices of charcoal production tend to look at only one dimension, most often the value chain, either attempting to control activities on specific stages such as a ban on production and/or trade, or formalizing regulations. A "one-dimensional intervention" is bound to fail because it ignores the complexity of the charcoal chain (Van Beukering et al., 2007).

For example, formalization is often implemented primarily assuming that controlling illegal charcoal supply could prevent deforestation and degradation, while also aiming to improve tax revenues. Experiences from SSA, however, suggest the ineffectiveness and the "anti-poor" impacts of formalization. Studies from Mozambique (Jones et al., 2016) and Malawi (Smith et al., 2017) argue that the informality of current production practices (including informal tenure regimes) allows poor households to use income from charcoal as a flexible income diversification strategy, thus formalization risks marginalizing the poorest (Schure et al., 2013). The rationale to promote formalization is principally one-sided, and ignores the fact that charcoal is one of the key livelihood activities in rural areas.

In turn, advocating the status quo of the continued adoption of unsustainable charcoal production because of its "pro-poor" nature should not be the ultimate solution. In most occasions the adoption is conditioned by low margins to producers under the non-enabling value chain on the one hand, and by over-exploitation of resources due to externalities under the tenure system on the other. Again, efforts to encourage tree plantations could fail if there are no considerations on "fundamental features of the socio-economy involving labor use, land tenure and usufruct (Dewees, 1989, p. 1959)," as experiences of failed attempts during the "woodfuel-crisis" era had proven (Dewees, 1989). For policies to be effective, a comprehensive approach is needed that recognizes the multitude of dimensions (Van Beukering et al., 2007).

Schure et al. (2013) argue that there is need to tailor interventions for specific socio-ecological contexts with the universal principle to get the "policy/institutional environment right" to provide local communities with incentives to benefit from sustainable tree management for charcoal as an alternative livelihood. More specifically, the key insight learned through the lens of the charcoal-agriculture nexus is to get incentive mechanisms/enabling environment for the adoption of sustainable practices/technologies "right," by streamlining the value chain to improve producers' margins as well as by devising institutional arrangements to internalize externalities which currently condition resource over-exploitation under the existing tenure systems. Proper valuation of resources to reflect economic scarcities combined with right price incentives could lead to socio-economically and ecologically sustainable outcomes of the charcoal-agriculture nexus.

AUTHOR CONTRIBUTIONS

MI led the concept, analysis and overall drafting of the manuscript. HN contributed to the formulating the concept, analyses as well as writing up of several sections. MN contributed to providing materials for the manuscript and refining Discussion. AD contributed to compiling the Ethiopian case study and synthesis section. GN contributed to compiling the Kenyan case study and synthesis section. AM contributed to compiling the Rwanda case study and synthesis section. PD contributed to the refining the conceptual framework and Discussion as well as proof-read. RJ contributed to the drafting of Introduction. JM contributed to drafting of the case studies section and refining the Introduction.

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REFERENCES

Adanu, S. K., Schneider, T., Stimm, B., and Mosandl, R. (2009). Effects of woodfuel production on the environment and people in Adaklu Traditional Area, Ghana. *J. Food Agric. Environ.* 7, 241–247.

Agbugba, I. K., and Obi, A. (2013). Market structure, price formation and price transmission for wood charcoal in South-eastern Nigeria. *J. Agric. Sci.* 5, 77–86. doi: 10.5539/jas.v5n10p77

AKTF (The Anne K. Taylor Fund) (2014). *Threatened Elephant Maternity in the Nyakweri Community Forest*. Montana: MIMEO. Available online at: http://annektaylorfund.org/wp-content/uploads/2013/04/Nyakweri-Forest-Report-8.6.pdf

Bailis, R., Drigo, R., Ghilardi, A., and Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nat. Clim. Change* 5, 266–272. doi: 10.1038/nclimate2491

Bailis, R., Ezzati, M., and Kammen, D. M. (2005). Mortality and greenhouse gas impacts of biomass and petroleum energy future in Africa. *Science* 308, 98–103. doi: 10.1126/science.1106881

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Bedelian, C. (2012). *Conservation and Ecotourism on Privatised Land in the Mara, Kenya: The Case of Conservancy Land Leases*. LDPI Working Paper 9.

Cerutti, P. O., Sola, P., Chenevoy, A., Iiyama, M., Yila, J., Zhou, W., et al. (2015). The socioeconomic and environmental impacts of wood energy value chains in Sub-Saharan Africa. A systematic map protocol. *Environ. Evid.* 4, 12. doi: 10.1186/s13750-015-0038-3

Chidumayo, E. N., and Gumbo, D. J. (2012). The environmental impacts of charcoal production in tropical ecosystems of the world:

a synthesis. *Energy Sustain. Dev.* 17, 86–94. doi: 10.1016/j.esd.2012.07.004

Clancy, J. S. (2008). Urban ecological footprints in Africa. *Afr. J. Ecol.* 46, 463–470. doi: 10.1111/j.1365-2028.2008.01041.x

Dale, V. H., Efroymson, R. A., and Kline, K. L. (2011). The land use–climate change–energy nexus. *Landscape Ecol.* 26, 755–773. doi: 10.1007/s10980-011-9606-2

Deininger, K., Ali, D. A., Holden, S., and Zebenbagen, J. (2008). Rural land certification in Ethiopia: process, initial impact, and implications for other African countries. *World Dev.* 36, 1786–1812. doi: 10.1016/j.worlddev.2007.09.012

Deininger, K., Ayalew, D. A., and Alemu, T. (2009). *Impacts of Land Certification on Tenure Security, Investment, and Land Markets Evidence from Ethiopia. Environment for Development.* Discussion Paper Series April 2009. EfD DP 09–11.

Dewees, P. A. (1989). The woodfuel crisis reconsidered: observations on the dynamics of abundance and scarcity. *World Dev.* 17, 1159–1172. doi: 10.1016/0305-750X(89)90231-3

Drigo, R., Munyehirwe, A., Nzabanita, V., and Munyampundu, A. (2013). "Rwanda supply master plan for firewood and charcoal," in *Support Program to the Development of the Forestry Sector (PAREF-B2) Final Report Update and Upgrade of WISDOM Rwanda and Woodfuels Value Chain Analysis As a Basis for a Rwanda Supply Master Plan for Fuelwood and Charcoal.* AGRICONSULTING S.p.A.

ESDA (Energy for Sustainable Development Africa) (2005). *National Charcoal Survey Summary Report: Exploring the Potential for a Sustainable Charcoal Industry in Kenya*. ESDA.

FAO (Food and Agriculture Organization of the United Nations) (2000). *The Energy and Agriculture Nexus.* Environment and Natural Resources Working Paper No. 4.

FAO (Food and Agriculture Organization of the United Nations) (2014). *State of the World's Forests: Enhancing the Socioeconomic Benefits from Forests*. Rome: FAO.

FAO (Food and Agriculture Organization of the United Nations) (2017). *The Charcoal Transition: Greening Charcoal Value Chain to Mitigate Climate Change and Improve Local Livelihoods*. Rome: FAO.

Gebremedhin, B., Pender, J., and Tesfay, G. (2004). Collective action for grazing land management in crop–livestock mixed systems in the highlands of northern Ethiopia. *Agric. Syst.* 82, 273–290. doi: 10.1016/j.agsy.2004.07.004

Geissler, S., Hagauer, D., Horst, A., Krause, M., and Sutcliffe, P. (2013). *Biomass Energy Strategy Ethiopia*. Eschborn: European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF).

Geist, H. J., and Lambin, E. F. (2001). What drives tropical deforestation? A meta-analysis of proximate and underlying causes of deforestation based on subnational case study evidence. *LUCC Report Series*; 4, University of Louvain.

Hosier, R. H., and Milukas, M. V. (1992). Two African woodfuel markets: urban demand, resource depletion and environmental degradation. *Biomass Bioenergy* 3, 9–24. doi: 10.1016/0961-9534(92)90015-I

Iiyama, M., Chenevoy, A., Otieno, E., Kinyanjui, T., Ndegwa, G., Vandenabeele, et al. (2014a). *Achieving Sustainable Charcoal in Kenya, Harnessing the Opportunities for Cross-Sectoral Integration*. Nairobi: ICRAF-SEI Technical Brief.

Iiyama, M., Derero, A., Kelemu, K., Muthuri, C., Kinuthia, R., Ayenkulu, E., et al. (2017). Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agrofor. Syst* 91, 271–293. doi: 10.1007/s10457-016-9926-y

Iiyama, M., Kariuki, P., Kristjanson, P., Kaitibie, S., and Maitima, J. (2008). Livelihood diversification strategies, incomes and soil management strategies: a case study from Kerio Valley, Kenya. *J. Int. Dev.* 20, 380–397. doi: 10.1002/jid.1419

Iiyama, M., Neufeldt, H., Dobie, P., Hagen, R., Njenga, M., Ndegwa, G., et al. (2015a). "Opportunities and challenges of landscape approaches for sustainable charcoal production and use. Chapter 14," in *Climate-Smart Landscapes: Multifunctionality in Practice, Nairobi, Kenya: World Agroforestry Centre (ICRAF)*, eds P. A., Minang, M. van Noordwijk, O. E. Freeman, C. Mbow, J. de Leeuwand, D. Catacutan, 195–209. Available online at: http://asb.cgiar.org/climate-smart-landscapes/chapters/chapter14.pdf.

Iiyama, M., Neufeldt, H., Dobie, P., Jamnadass, R., Njenga, M., and Ndegwa, G. (2014b). The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Curr. Opin. Environ. Sustain.* 6C, 138–147. doi: 10.1016/j.cosust.2013.12.003

Iiyama, M., Njenga, M., and Meriki, S. (2015b). Mara ecosystem threatened by charcoal production in Nyakweri Forest and its environs Call for landscape charcoal governance. *ICRAF Technical Brief 3*. Available online at: http://www.worldagroforestry.org/downloads/Publications/PDFS/BR15044.pdf.

IRENA (The International Renewable Energy Agency) (2015). *Renewable Energy in the Water, Energy & Food Nexus*. Abu Dhabi: IRENA.

Jones, D., Ryan, C. M., and Fisher, J. (2016). Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. *Energy Sustain. Dev.* 32, 14–21 doi: 10.1016/j.esd.2016.02.009

Kambewa, P., Mataya, B., Sichinga, K., and Johnson, T. (2007). *Charcoal: The Reality – a Study of Charcoal Consumption, Trade and Production in Malawi*. Small and Medium Forestry Enterprise Series No. 21. London: International Institute for Environment and Development.

KFS (Kenya Forestry Service) (2013). *Analysis of the Charcoal Value Chain in Kenya*. Nairobi: Camco Advisory Services (Kenya) Limited.

Kiruki, H. M., van der Zanden, E. H., Malek, Z., and Verburg, P. H. (2017). Land cover change and woodland degradation in a charcoal producing semi-arid area in Kenya. *Land Degrad. Dev.* 28, 472–481. doi: 10.1002/ldr.2545

Kiruki, H. M., van der Zanden, E. H., Njuru, P. G., and Verburg, P. H. (2017). The effect of charcoal production and other land uses on diversity, structure and regeneration of woodlands in a semi-arid area in Kenya. *Forest Ecol. Manage.* 391, 282–295. doi: 10.1016/j.foreco.2017.02.030

Lawry, S., Samii, C., Hall, R., Leopold, A., Hornby, D., and Mtero, F. (2014). The impact of land property rights interventions on investment and agricultural productivity in developing countries: a systematic review. *Campbell Syst. Rev.* 2014:1 doi: 10.4073/csr.2014.1

Luoga, E. J., Witkowski, E. T. F., and Balkwill, K. (2000). Economics of charcoal production in miombo woodlands of eastern Tanzania: some hidden costs associated with commercialization of the resources. *Ecol. Econo.* 35, 243–257. doi: 10.1016/S0921-8009(00)00196-8

MEFCC (2016). *The Charcoal Industry Assessment of Ethiopia: Policy and Institutional Restructuring for Sustainable Charcoal*. Addis Ababa: Ministry of Environment, Forest and Climate Change (MEFCC), Supported by Global Green Growth Institute (GGGI).

Mekuria, W., and Aynekulu, E. (2013). Exclosure land management restores soil properties of degraded communal grazing lands in northern Ethiopia. *Land Degrad. Dev.* 24, 528–538 doi: 10.1002/ldr.1146

Mukuralinda, A., Ndayambaje, J. D., Iiyama, M., Ndoli, A., Musana, B., et al. (2016). *Taking to Scale Tree-Based Systems in Rwanda to Enhance Food Security, Restore Degraded Land, Improve Resilience to Climate Change AND Sequester Carbon*. Washington, DC: PROFOR.

Mundia, C. N., and Murayama, Y. (2009). Analysis of land use/cover changes and animal population dynamics in a wildlife sanctuary in East Africa. *Remote Sens.* 1, 952–970. doi: 10.3390/rs1040952

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, 158–170. doi: 10.1016/j.esd.2013.01.001

Namaalwa, J., Sankhayan, P. L., and Hofstad, O. (2007). A dynamic bio-economic model for analyzing deforestation and degradation: an application to woodlands in Uganda. *Forest Policy Econ.* 9, 479–495. doi: 10.1016/j.forpol.2006.01.001

Naughton-Treves, L., Kammen, D. M., and Chapman, C. (2007). Burning biodiversity: woody biomass use by commercial and subsistence groups in western Uganda's forests. *Biol. Conserv.* 134, 232–241. doi: 10.1016/j.biocon.2006.08.020

Ndayambaje, J. D. T., Mugiraneza, T., and Mohren, G. M. J. (2014). Woody biomass on farms and in the landscapes of Rwanda. *Agroforest Syst.* 88, 101–124. doi: 10.1007/s10457-013-9659-0

Ndayambaje, J. D., Heijman, W. J. M., and Mohren, G. M. J. (2013). Farm woodlots in rural Rwanda: purposes and determinants. *Agroforest Syst* 87, 797–814. doi: 10.1007/s10457-013-9597-x

Ndegwa, Nehren, U., Grüninger, F., Iiyama, M., and Anhuf, D. (2016). Charcoal production through selective logging leads to degradation of dry woodlands:

a case study from Mutomo District, Kenya. *J. Arid Land.* 8, 618–631. doi: 10.1007/s40333-016-0124-6

Ndegwa, G., Anhuf, D., Nehren, U., Ghilardi, A., and Iiyama, M. (2016a). Charcoal contribution to wealth accumulation at different scales of production among the rural population of Mutomo District in Kenya. *Energy Sustain. Dev.* 33, 167–175. doi: 10.1016/j.esd.2016.05.002

Ndegwa, G., Iiyama, M., Anhuf, D., Nehren, U., and Schlueter, S. (2016b). Tree establishment and management on farms in the drylands: evaluation of different systems adopted by small-scale farmers in Mutomo District, Kenya. *Agrofor. Syst.* doi: 10.1007/s10457-016-9979-y

Pattanayak, S. K., Mercer, D. E., Sills, E., and Yang, J. C. (2003). Taking stock of agroforestry adoption studies. *Agrofor. Syst.* 57, 173–186. doi: 10.1023/A:1024809108210

Pottier, J. (2006). Land reform for peace? Rwanda's 2005 land law in context. *J. Agr. Change* 6, 509–537. doi: 10.1111/j.1471-0366.2006.00133.x

Ribot, J. S. (1998). Theorizing access: forest profits along Senegal's charcoal commodity chain. *Dev. Change* 29, 307–341. doi: 10.1111/1467-7660.00080

Schure, J., Dkamela, G. P., van der Goes, A., and McNally, R. (2014). *An Approach to Promote REDD+ Compatible Wood-Fuel Value Chains*. Vietnam: SNV.

Schure, J., Ingram, V., Sakho-Jimbira, M. S., Levang, P., and Wiersum, K. F. (2013). Formalisation of charcoal value chains and livelihood outcomes in Central and West Africa. *Energy Sustain. Dev.* 17, 95–105. doi: 10.1016/j.esd.2012.07.002

Sepp, S. (2008). *Shaping Charcoal Policies: Context, Process and Instruments As Exemplified by Country Cases*. Germany: GTZ.

Shively, G., Jagger, P., Sserunkuuma, D., Arinaitwe, A., and Chibwana, C. (2010). Profits and margins along Uganda's charcoal value chain. *Int. Forest. Rev.* 12, 270–283. doi: 10.1505/ifor.12.3.270

Siri, E. F., Gachathi, N., Muok, B., Ochieng, B., and Owuor, B. (2006). "Synergies in biodiversity conservation and adaptation to climate change: the case of hilltop forests in Kitui, Kenya," in *Savannas and Dry Forests: Linking People with Nature*, eds J. Mistry and A. Berandi (Farnham: Ashgate).

Skutsch, M. M., and Ba, L. (2010). Crediting carbon in dry forests: the potential for community forest management in West Africa. *Forest Policy Econ.* 12, 264–270. doi: 10.1016/j.forpol.2009.12.003

Smith, H. E., Hudson, M. D., and Schreckenberg, K. (2017). Livelihood diversification: the role of charcoal production in southern Malawi. *Energy Sustain. Dev.* 36, 22–36. doi: 10.1016/j.esd.2016.10.001

Sola, P., Cerutti, P. O., Zhou, W., Gautier, D., Iiyama, M., Shure, J., et al. (2017). The environmental, socioeconomic and health impacts of woodfuel value chains in Sub-Saharan Africa: a systematic map. *Environ. Evid.* 6:4. doi: 10.1186/s13750-017-0082-2

UNECA (United Nations Economic Commission for Africa) (2011). *Sustainable Development Report on Africa I: Managing Land-Based Resources for Sustainable Development*. Addis Ababa: UNECA. Availabe online at: http://hdl.handle.net/10855/14946.

Van Beukering, P., Kahyarara, G., Massey, E., di Prima, S., Hess, S., Makundi, V., et al. (2007). Optimization of the charcoal chain in Tanzania. *Poverty Reduction and Environmental Management (PREM) Working Paper 07/03.*

Weitz, N., Nilsson, M., and Davis, M. (2014). Approaching interaction in the SDGs – a nexus approach to the Post-2015 agenda: formulating integrated water, energy, and food SDGs. *SAIS Rev. Summ. Fall* 34, 37–50. doi: 10.1353/sais.2014.0022

Wichelns, D. (2017). The water-energy-food nexus: is the increasing attention warranted, from either a research or policy perspective? *Environ. Sci. Policy* 69, 113–123. doi: 10.1016/j.envsci.2016.12.018

World Bank (2011). *Wood-Based Biomass Energy Development for Sub-Saharan Africa: Issues and Approaches*. Washington, DC: The International Bank for Reconstruction and Development.

World Bank (2012). *Establishing a Green Charcoal Value Chain in Rwanda: A Feasibility Study. Sustainable Development Network*. Washington, DC: The World Bank.

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Modeling the Effects of Future Growing Demand for Charcoal in the Tropics

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Global demand for charcoal is increasing mainly due to urban population in developing countries. More than half the global population now lives in cities, and urban-dwellers are restricted to charcoal use because of easiness of production, access, transport, and tradition. Increasing demand for charcoal, however, may lead to increasing impacts on forests, food, and water resources, and may even create additional pressures on the climate system. Here we assess how different charcoal scenarios based on the Shared Socio-economic Pathways (SSP) relate to potential biomass supply. For this, we use the energy model TIMER to project the demand for fuelwood and charcoal for different socio-economic pathways for urban and rural populations, globally, and for four tropical regions (Central America, South America, Africa and Indonesia). Second, we assess whether the biomass demands for each scenario can be met with current and projected forest biomass estimated with remote sensing and modeled Net Primary Productivity (NPP) using a Dynamic Global Vegetation Model (LPJ-GUESS). Currently one third of residential energy use is based on traditional bioenergy, including charcoal. Globally, biomass needs by urban households by 2100 under the most sustainable scenario, SSP1, are of 14.4 mi ton biomass for charcoal plus 17.1 mi ton biomass for fuelwood (31.5 mi ton biomass in total). Under SSP3, the least sustainable scenario, we project a need of 205 mi tons biomass for charcoal plus 243.8 mi ton biomass for fuelwood by 2100 (total of 450 mi ton biomass). Africa and South America contribute the most for this biomass demand, however, all areas are able to meet the demand. We find that the future of the charcoal sector is not dire. Charcoal represents a small fraction of the energy requirements, but its biomass demands are disproportionate and in some regions require a large fraction of forest. This could be because of large growing populations moving to urban areas, conversion rates, production inefficiencies, and regions that despite available alternative energy sources still use a substantial amount of charcoal. We present a framework that combines Integrated Assessment Models and local conditions to assess whether a sustainable sector can be achieved.

Keywords: traditional bioenergy, charcoal, integrated assessment, supply and demand, biomass, dynamic vegetation model, remote sensing

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INTRODUCTION

More than half of the global population now lives in cities, leading to important consequences for energy consumption (Grubler et al., 2012). Urbanization will influence the type of fuels used and also the total energy consumption for different functions, and choice depends on income (Poumanyvong and Kaneko, 2010). Charcoal is the main cooking fuel especially in urban areas in sub-Saharan Africa, South Asia, Latin America and the Caribbean (Ghilardi et al., 2013; Mwampamba et al., 2013; Zulu and Richardson, 2013). Globally, charcoal corresponds to a small fraction of the total energy mix (Bond et al., 2004). However, with continued urbanization charcoal will remain an important fuel locally (Arnold et al., 2006; Ghilardi et al., 2013) and will likely become an important fuel globally, as Africa and South America are major producers and exporters (Hillring, 2006).

The reason for the preference for charcoal by part of the urban dwellers in developing countries is that it has higher energy content than firewood (32–33 MJ/kg in charcoal vs. 18–19 MJ/kg in fuelwood; Wood and Baldwin, 1985), has a more accessible and reliable supply, is easier to transport, is inexpensive, stores more easily, and burns more cleanly, i.e., with less smoke (Zulu and Richardson, 2013). Worldwide, about 1.5 to 2 million deaths per year are caused by indoor air pollution from burning biomass, with the majority of the contribution coming from unprocessed wood rather than charcoal (Torres-Duque et al., 2008). However, depending on the charcoal production method, 3 to 12 kg of biomass are required to produce 1 kg of charcoal. Further, charcoal's non-CO_2 greenhouse gas emissions are 6–13 times higher than traditional woodfuels, which includes the contribution of the emissions during charcoal production phase (Torres-Duque et al., 2008). Charcoal production has many environmental impacts, namely deforestation and forest degradation, followed by erosion impacting the catchment hydrology, and emissions of greenhouse gases. Charcoal production is responsible for 7% tropical forest loss (Chidumayo and Gumbo, 2013), making it important to assess whether there is enough forest to sustain this production at local and global scales, particularly if demand is to increase with further urbanization. Further, charcoal production could affect the microclimate, leading to more extreme temperatures, wind and water erosion even when the kiln-site is no longer in use as regeneration of the ecosystems requires a number of years (Gómez-Luna et al., 2009). Finally, charcoal production may compete with the production of food, reduce water resources, and other services forests provide (Fisher et al., 2011; Chidumayo and Gumbo, 2013). Besides these negative effects, charcoal may also be beneficial as its application to soils contributes to higher organic matter content and soil fertility (Glaser et al., 2002). If managed properly, some researchers have indicated that charcoal could be a renewable energy source with a theoretical net carbon emission close to zero (Piketty, 2015) even becoming a sustainable sector given that good governance is put in place (Neufeldt et al., 2015).

Due to the expected continuation of urbanization trends, demand for charcoal could increase in the coming decades (Mwampamba et al., 2013; Zulu and Richardson, 2013), depending on the competition with other fuels. As such, increasing demand for charcoal may create additional pressures on the climate system (Bailis et al., 2015) challenging policy goals for energy transitions (Zulu and Richardson, 2013), food security (Mwampamba et al., 2013), and biodiversity (Chidumayo and Gumbo, 2013). Alternatively, energy transition from charcoal to renewable fuels such as pellets, bio-ethanol, renewable electricity, etc. needs to account for land use emissions which could arise from maintaining forest areas (Peters et al., 2013). It is therefore important to have a more detailed assessment of the implications of using charcoal as a bioenergy source, i.e., the dynamics of demand and supply of charcoal and its impacts. The nexus approach for charcoal aims to take an integrated consideration of the environmental, societal and economic issues related to charcoal supply and demand. It also aims at understanding how the effects of demand and supply in one sector percolate across other sectors. One way to operationalize the nexus approach is through the use of Integrated Assessment Models (IAM).

Here, we use IAM to project future global and regional demands for energy and estimate the share of charcoal in such projections. We use the energy model TIMER (a part of the IAM IMAGE) to project the demand for secondary energy from fuelwood and charcoal, and the primary biomass "equivalents." We do that by estimating biomass "equivalents" that correspond to a 1:5 conversion for charcoal and 1:1 conversion for other biomass sources. We then compare the demand with the current and over time forest biomass, and use this information to discuss the nexus between charcoal and its coupled sectors, globally and for four tropical regions with high charcoal demand (Central America, South America, Africa and Indonesia).

METHODS

Study System

World charcoal production approached 50 million tones in 2010 (FAO, 2016). Recent estimates suggest that 51% of charcoal production comes from Africa and 35% from South America, but not all the charcoal stays where it is produced and major exports of charcoal occur in Indonesia, Malaysia and China, while major imports occur in Europe, Korea and Japan (Hillring, 2006; http://www.trademap.org). Most of this production is to meet demands for charcoal for cooking and heating. Charcoal production is arguably one of the most ancient human engineering processes, dating from 38,000 year ago. Charcoal is produced by slow pyrolysis, i.e., heating of wood in the absence of oxygen (Antal and Gronli, 2003). This is achieved in its most traditional production way, by stacking wood in a pile, sealing it with a layer of grass and soil, and igniting the wood at the kiln entrance, i.e., the structure produced by the wood stack and soil layer (**Figure 1**).

We used the Integrated Assessment Model IMAGE (Stehfest et al., 2014) to project the demand for residential energy for a number of energy carriers (solids, liquids, gaseous, modern bioenergy, traditional fuels including charcoal, hydrogen, secondary heat, and electricity). To determine the fraction of charcoal in traditional fuels, we assume the proportions of different traditional fuels in Bond et al. (2004) and Fernandes

FIGURE 1 | Charcoal production system in Mexico: **(A)** deforestation for biomass, **(B)** post deforestation, **(C)** biomass for charcoal, **(D)** kiln, **(E)** kiln site post-production, and **(F)** kiln site 5 years post-production.

et al. (2007), which varies between 2 and 30%. We then determine biomass needed to meet charcoal and fuelwood demand by estimating "biomass equivalents," with a 1:5 conversion for charcoal and 1:1 conversion for fuelwood (http://www.fao.org/docrep/x5328e/x5328e02.htm). This demand is determined for three different potential futures as projected in the Shared Socio-economic Pathway scenarios (Riahi et al., 2017; van Vuuren et al., 2017). Second, we compare projected demands with existing above ground biomass estimated using remote sensing (Saatchi et al., 2011; Baccini et al., 2012). Further, with modeled estimates of Net Primary Productivity (NPP) from the Dynamic Global Vegetation Model - LPJ-GUESS we have an estimate if the forest provides enough increase in biomass to fulfill the charcoal demands while other services remain. We do this globally and again for four tropical regions (Central America, South America, Africa, and Indonesia) to assess whether there are differences at global and local scales, and whether there are differences for urban and rural populations.

Projections of Future Energy Demand

The Integrated Model to Assess the Global Environment (IMAGE) has been developed in order investigate the interactions between human and natural systems with the aim of assessing global change. A detailed description of the model can be found in Stehfest et al. (2014). Among other things, IMAGE provides long term (2100) global projections of energy supply and demand, land use and land use change, and consequent effects on the climate system.

In this analysis we primarily use projections of energy demand for the residential sector as represented in IMAGE (Daioglou et al., 2012). Residential energy demand is determined for different end-use functions (cooking, water heating, space heating, lighting and appliances), and different potential energy carriers (traditional fuels, coal, oil, gas, electricity, etc.) that compete with each other based on their relative costs. The model is particularly appropriate as it explicitly takes into account differences in urban and rural energy use, as well as five income quintiles within each of these groups. Furthermore, it explicitly takes into account the access of poor households to modern energy carriers through endogenously modeled electrification rates, consumer discount rates and other price effects. Following, the model was used in order to determine possible future demand levels of traditional fuels and charcoal.

The demand for traditional fuels depends on the household income, and the prices of different energy carriers. Traditional fuels are assumed to have no monetary cost and are thus used by households which cannot afford modern energy carriers either because they are too expensive, or the do not have access to them (i.e., they are not electrified). The model is calibrated in order to reproduce International Energy Agency data (1971–2010; https://www.iea.org/) which provides historic traditional fuel use, as well as modern energy carriers. The demand of traditional fuels is disaggregated among fuelwood, crop residues, dung and charcoal, with the volume of each calibrated to historic data and it is assumed that historic and future charcoal use is limited to urban households (Fernandes et al., 2007). Though the model includes the trade of modern energy carriers, this is not the case for traditional fuels, including charcoal.

Scenario Projections: Shared Socio-Economic Pathways

The IMAGE model has recently been used in order to assess energy and land use pathways for various baseline and climate mitigation pathways based on the Shared Socioeconomic Pathways (Kriegler et al., 2012; Riahi et al., 2017; van Vuuren et al., 2017). The SSPs define distinctly different pathways about future socio-economic developments and are designed to span a wide range of combinations of challenges to mitigation and adaptation to climate change. For this study we use IMAGE results for charcoal demand for the SSP1, SSP2, and SSP3 baselines (van Vuuren et al., 2017). SSP1, also named as *Sustainability*, represents a world with low challenges for climate adaptation and mitigation, with educational and health investments accelerating the demographic transitions, increases in economic welfare and low resource and energy intensity. SSP2, named *Middle of the Road*, represents a world with medium challenges to both mitigation and adaptation, environmental systems continuing to experience degradation, and some improvements and overall the intensity of resource and energy use declines. Global population growth plateaus in the second half of the century and economic inequality improves only slowly. Finally, SSP3, named *Regional Rivalry* represents a world with large challenges to both adaptation and mitigation, with slow economic development, worsening inequality, high population growth and a low priority for addressing environmental concerns. In the context of this study, the SSPs provide divergent storylines for urbanization, economic development, inequality among urban and rural households, and actions toward access and use of improved energy sources. For instance, the lower economic growth, higher economic inequality and population growth in SSP3 tend to increase the demand for lower quality fuels while the opposite effects are observed in SSP1.

Global and Regional Demands for Energy and Biomass under SSPs

We produced outputs at the global scale but also for the four selected regions, Central America, South America, Africa and Indonesia. We focus on these four regions because charcoal is still very important as either the main source of energy (Africa), co-use charcoal along other fuels (Indonesia), continue to use charcoal for cultural reasons despite the dominant use of other fuel sources (Central America), or provide charcoal to other regions of the world (South America; Hillring, 2006; Ghilardi et al., 2013; Mwampamba et al., 2013). We projected global and regional demands for the required biomass across the three SSP scenarios. The demand is measured in biomass, which for comparative purposes is converted by a factor of ½ to Carbon.

Supply of Biomass: Current Biomass

We used the outputs from the GEOCARBON global aboveground biomass at 1 km resolution to estimate the supply of biomass to each of the four regions of the study (https://www.bgc-jena.mpg.de/geodb/projects/Home.php; Saatchi et al., 2011; Baccini et al., 2012). We used this data because it is one of the most recent and finer scale global datasets where biomass is consistently estimated across regions. Given the coarse scale of our analysis we believe that this data product provides sufficient resolution and an accurate figure of standing biomass. There is a more recent pan-tropical map of above ground biomass (Avitabile et al., 2016), that is incorporated into the GEOCARBON map. We chose not to use directly the product of Avitabile et al. (2016) because it does not include Central America and Africa in its full extent. The map combines the biomass estimates of Avitabile et al. (2016) and Santoro et al. (2015) in ton C.ha^{-1}. The map only covers forest areas, i.e., areas with a dominance of tree cover as in the Global Land Cover map of 2000 (Bartholomé and Belward, 2005). On top of these biomass measurements, we excluded IUCN protected areas which cover about 15% of the global terrestrial surface. The spatial extent of global protected areas in 2016 was obtained from World Database on Protected Areas (https://www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas). The biomass values were converted to kg C.m^{-2} to compare with the modeled Net Primary Productivity (see below).

Net above Ground Biomass Accumulation

To calculate the net increase of biomass, we used the LPJ-GUESS model (Lund-Potsdam-Jena General Ecosystem Simulator; Smith et al., 2001), which simulates global vegetation dynamics and biogeochemical cycling for terrestrial ecosystems. The model uses 11 plant functional types (PFTs) to represent the most important vegetation types for temperate, tropical, boreal and grassland biomes. Our simulations focus on natural vegetation only, i.e., all croplands and pastures are not included. Each PFT and biome has its own specific parameterization for plant physiological and biogeochemical processes of carbon and nitrogen (Smith et al., 2001). The occurrence of the PFTs is predicted based on bioclimatic limits and competition for light and soil resources. For tree PFTs the model uses an individual based approach, representing multiple age cohorts that can co-occur in a single stand. Several processes, including mortality and establishment of trees, as well as disturbances are modeled stochastically. Grid cell mean dynamics are based on simulation for 20 replicate sub-grid units ("patches"). The model was run on a global grid of $0.5^{\circ} \times 0.5^{\circ}$ degrees (approximately 50×50 km at the equator) based on climate data from the CRU TS 3.0 data set (Mitchell and Jones, 2005). To initialize the model, we used a spin-up of 500 years to bring vegetation and soil carbon pools approximately at equilibrium, during which a repeated cycle of climate forcing was used, based on the first 10 years of the input dataset.

For our analysis, we were interested in the annual increase of wood in forests. From the simulated average annual carbon fluxes, we used Net Primary Productivity (NPP [$kgC.m^{-2}.year^{-1}$]), which is the net effect of Gross Primary Productivity minus respiration losses. NPP reflects above and below ground biomass, both for all or for selected PFTs. We report total NPP, as well as the values of above ground biomass for NPP total and for the tree PFT (NPP_{tree}). NPP is the sum of NPP_{wood}, NPP_{canopy}, and $NPP_{fine\ roots}$; Malhi et al. (2011) estimated an average of 30% biomass allocated to NPP_{wood}, although the allocation of wood to fine roots is highly variable. Thus we report on NPP by a factor of 0.3 as a representation of the aboveground fraction of NPP. To calculate total available annual NPP_{wood} and NPP_{tree} from forests under future projections, we estimated the change in forest area. We used the global forest projections under the different SSP scenarios for the time slices 2010, 2015, 2030, 2050, and 2100 (van Vuuren et al., 2017) also on 0.5 × 0.5 degree resolution. The extent of land use change and deforestation are taken into account as the different scenarios predict different population growths and therefore different demands for food production and land use.

RESULTS

Projected Energy Demand for Residential Uses

Currently, about one third of residential energy use is based on traditional bioenergy, including charcoal (see **Figures 2D–F**, about 30 EJ from the 90 EJ for traditional bioenergy in 2015). The share of traditional bioenergy in the residential sector reduces rapidly in SSP1 (about 55% of the 2015 values of traditional biofuels by 2020, 18% by 2030, 7% by 2050, and 2.5% by 2100; **Figure 2A**), as urban populations become wealthier and policies are introduced to provide access to modern energy consistent with the Energy for All objectives (Table S1). In contrast, SSP3 projects a traditional energy demand relatively constant (between 78 and 100% of the 2015 values, **Figure 2C**), given the relatively high population projections. The SSP2 projections are in between these two extremes. Most of the projected energy demand from all SSPs is to be used for cooking and only a minor fraction is dedicated to space and water heating (**Figure 2B**).

Biomass Needed to Meet Projected Energy Needs

Globally, under the most sustainable scenario, SSP1, and because it is assumed that as urban populations become wealthier they replace charcoal use by other fuelwood, 14.4 mi ton biomass will be needed for charcoal plus 17.1 mi ton biomass for fuelwood by 2100. In the worst case scenario, SSP3, we project a greater than 10-fold demand compared to SSP1. By 2100, 205 mi tons of biomass for charcoal plus 244 mi ton of biomass for fuelwood will be needed (**Figure 3**).

Currently, two regions contribute the most to the global biomass demand, 1/3 Africa and 1/4 South America (**Figures 3C,D**). In the most sustainable scenario (SSP1), African urban populations are projected to require 5.5 mi ton biomass for charcoal plus 1.7 mi ton for fuelwood. In the SSP1 scenario, South America is projected to require 1.7 mi ton biomass for charcoal plus 0.6 mi ton biomass for fuelwood. In the least sustainable scenario, a total of 189.1 mi ton of biomass would be required for African urban populations (145.3 mi ton of biomass for charcoal, 43.8 mi ton of biomass for fuelwood in urban areas) and a total of 60.6 mi ton of biomass for South America (45.1 mi ton mi ton of biomass for charcoal plus 15.5 mi ton mi ton of biomass for fuelwood). This is because urbanization and population growth are projected to be the highest for Africa (see Table S1), and South America supplies charcoal elsewhere. Indonesia and Central America have the lowest demands (SSP1: a total of 1.3 mi ton biomass for Central America and 3.1 mi ton biomass for Indonesia; SSP3: 31.2 mi ton biomass for Central America, 12.6 mi ton biomass for Indonesia; **Figures 3B,C**). In general, the demand for biomass decreases over time, except for SSP3, and in Africa and Central America. Indonesia shows the relative sharpest decrease in biomass demand, becoming very close to the needs from Central America (**Figure 3**).

Current Forest Aboveground Biomass and Net Primary Productivity

Global estimates of forest aboveground biomass in 2015 were of 43,855.9 mi ton C, of which 25% (11,259.5 mi ton C biomass) was in protected areas (**Table 1**). In 2015, each of the regions we analyzed had aboveground biomass values that varied from 404.4 mi ton C in Central America to 13,653 mi ton C in South America. Demands for biomass for charcoal by 2015 converted to mi ton C show that demand values are relatively small. Most of this demand is from Central America (3% aboveground biomass needed not in protected areas per year) but in all the other regions biomass equivalents for charcoal are around 0.5% per year. The results for 2015 are problematic as these rates already suggest a non-sustainable production system, and it is important to acknowledge that estimated needs for biomass are modeled rather than empirical due to the absence of systematic data collected at the global scale.

We next looked into whether forest growth rates (via NPP) could withstand future demands for biomass "equivalents" (for charcoal and fuelwood). Globally, total NPP is 728.24 mi ton $C.year^{-1}$, and is much higher for South America and Africa, while it is almost one order of magnitude lower for Central America and Indonesia (**Table 2**). However, NPP available for charcoal production (wood or tree PFT) show values about 1/3 smaller than total NPP globally. A comparison of the remote sensing estimates for forest above ground biomass and modeled total NPP are shown in Table S2.

Future NPP under Land Use Change

Depending on the SSP scenario, forests are replaced by other land uses at different rates (Figure S1) and the resulting future NPP is mapped in **Figure 4** for 6 different time slices. Figures

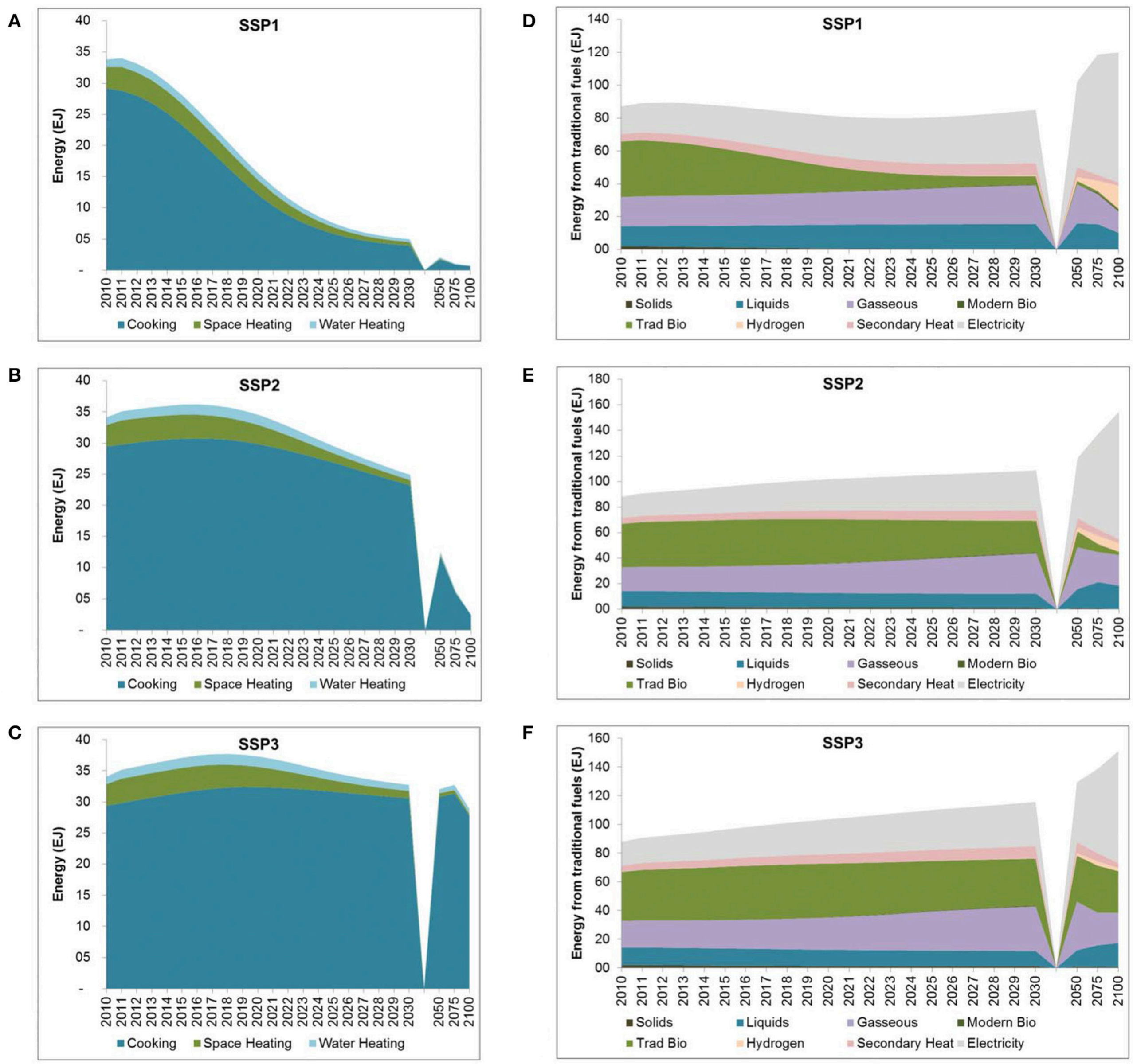

FIGURE 2 | Projections of residential energy demand and the use of traditional energy: **(A–C)** end-uses supplied by traditional bioenergy, and **(D–F)** share by energy carrier in total residential energy use (green is traditional bioenergy).

S2–S5 in the Supplementary material shows the detailed NPP per region for the projected futures. SSP3 projects higher land use change, in which even large parts of the Congo Basin are changed. Under this scenario, the Central Amazon Basin remains as forest, as this area is mostly protected (**Figure 4**). The detailed maps for each region, also follow the same pattern, with greater land use change in SSP3 and therefore 2/3 forest loss for Central America (Figure S2), 1/5 for South America (Figure S3), 1/2 loss in Africa (Figure S4), and 1/6 loss in Indonesia (Figure S5). 45% of forest aboveground biomass is protected in South America, while 34% for Central America, 21% in Indonesia, and 17.5% in Africa.

Demand and Supply Projections

With increasing demand, forest land uses decrease resulting in a lower supply of NPP. In **Figure 5** we plotted the trends of global demand and supply from 2020 to 2100 for the three SSP scenarios. Globally the supply by NPP is always higher than the demand, suggesting that charcoal production is potentially not a large stressor on the system. However, this means that the NPP the forest provides must be harvested in a sustainable way, that ecosystem functioning is not hindered. At a global scale even with the worst case scenario (SSP3) there is two times higher supply than demand (**Figure 5A**; Table S3). The four regions follow the same global trend, with supply being at least a factor 10 greater

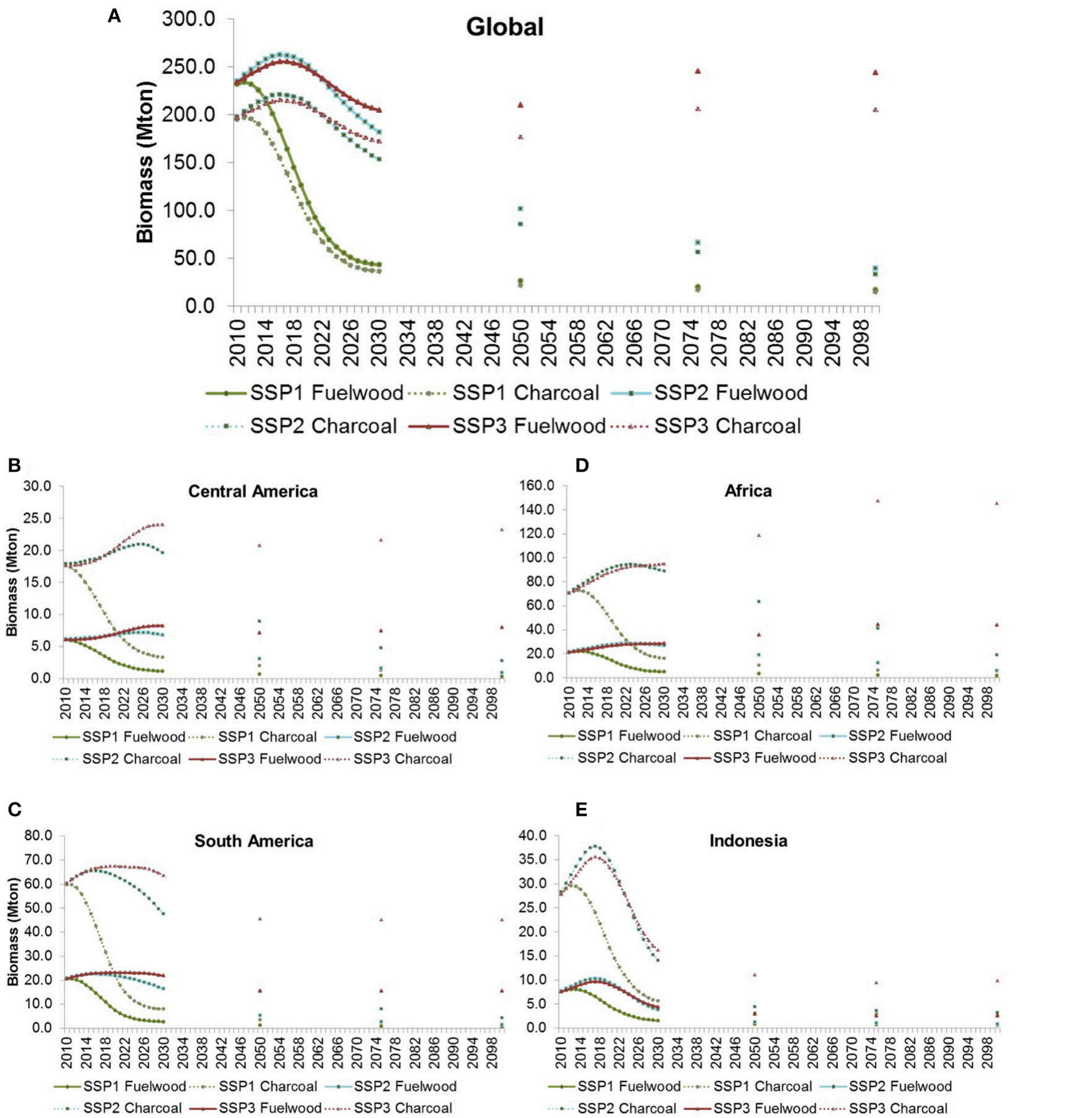

FIGURE 3 | Biomass needs for urban fuelwood and charcoal demands under three SSP scenarios: **(A)** globally, **(B)** Central America, **(C)** South America, **(D)** Africa, and **(E)** Indonesia. Estimates are in million ton of biomass. Charcoal means biomass "equivalents" that equal a 1:5 conversion. SSP1: green (line - fuelwood, dash - charcoal), SSP2: blue (line - fuelwood, dash - charcoal), and SSP3: red (line - fuelwood, dash - charcoal).

than the demand. However, under SSP3 both Central America and Africa supply and demand become closer at the end of the century (not the log scale on the graph).

DISCUSSION

We set to assess whether there is enough forest to sustain charcoal production at local and global scales, using a combination of modeling and observation data. The projected population growth and increasing number of urban dwellers will increase the demand for charcoal, but given that this demand is a small fraction of the total traditional fuels, current global biomass and NPP will be able to meet this demand even under the least sustainable scenarios both globally and for each of the focal regions. Our results, assuming only urban uses for charcoal show that under more sustainable scenarios (SSP1 and SSP2) the demand for charcoal will peak around 2020, and then decrease as other energy sources become available. In the four regions we studied, up to 3% of forested area is needed per year to account for the charcoal demand. In an unsustainable forest

TABLE 1 | Demand and supply of biomass for charcoal in 2015 (mi ton C).

	$SSP1_{2015}$	$SSP2_{2015}$	$SSP3_{2015}$	Forest aboveground $biomass_{2015}$	Forest aboveground $biomass_{2015}$ not in protected areas
C. America	6.95	9.25	9.1	404.4	266.3
S. America	23.85	32.75	33.1	13,652.9	7,567.2
Africa	33.6	41.75	40.4	6,627.9	5,459.5
Indonesia	13.85	18.3	17.15	41,42.9	3,274.7
Global	84.55	109.95	106.9	43,855.9	32,596.4

Demand is for urban areas under three SSP scenarios, and supply in forest aboveground biomass. We chose to display scenario results rather than data because there is no systematic data collected over these regions and globally, and because we can then compare current time with future scenario data.

harvesting regime, this means that all forest are cleared within 30 years. On the contrary at these relative low rates, NPP from 10 to 20% of each of the analyzed regions is able to produce enough biomass, even when accounting for the projected forest losses. We conclude that a sustainable harvesting of the forest for charcoal production is possible as the forest produces enough biomass to meet the demands, but it is dependent on incentives and governance to implement such sustainable regime. The picture, however, is varied for different tropical regions that represent different uses of charcoal.

In Africa, charcoal is still very important as the main source of energy (Mwampamba et al., 2013), and for this continent our results show the lowest ability to meet urban charcoal demands. This is likely because despite a high NPP, the rates of deforestation in Africa are five times higher than the global average (Bowker et al., 2017), and are mostly due to fuel wood consumption (Bailis et al., 2015; Sulaiman et al., 2017). Further, given the very high need for land for food production (Bowers et al., 2017) and the external land grabbing processes that are currently ongoing in the African continent (Johanson et al., 2016; Zoomers et al., 2017), our results may even be underestimates. We estimate that around 0.7% forested land is needed for charcoal production per year. Further it is also clear that the share of protected forested area is in Africa the smallest of the four regions. Finally, this is the continent where projected population growth achieves the highest values. Our results suggest that charcoal supply to urban dwellers will be possible during the twenty-first century, and demand and supply gap will become smaller by the end of the century.

In Central America, charcoal use is mainly for cultural reasons despite the dominant availability and use of other fuel sources (Ghilardi et al., 2013). Alongside with Africa, we found that this region will also face a closing gap between supply and demand by the end of the century, under the least sustainable scenario. Very worrying is that around 3% of forested land is needed for charcoal production per year. Central America is particularly important as charcoal use in this region is by cultural choice as there are other energy carriers in the region that supply for energy needs. Thus reduction of biomass pressure on low NPP forests could be achieved through more efficient charcoal production systems or reduced use.

South America highly productive forests may explain why this region is the one the greatest gap between supply and demand, even in the least sustainable scenario. For current charcoal demand, around 0.4% of forested unprotected area is needed. However, South America is one of the major exporters of charcoal, and internal consumption is still relatively low in contrast to its neighboring Central America (Hillring, 2006).

In Indonesia, like Central America, charcoal is used along with other fuels in an even smaller fraction. This explains why Indonesia supply is able to meet the local demand of biomass. In contrast with the other regions, all our scenarios project a decrease in demand for Indonesia until the end of the century. This is likely why the gap in supply and demand is not comparable to Central America, as Indonesia forests also have among the lowest NPP in comparison to all other regions. Around 0.5% of forested not protected area is needed per year. However, Indonesia is also a large exporter of charcoal (Hillring, 2006; http://www.trademap.org), so these numbers are probably higher. As projected land use change for oil palm and rubber plantations are enormous, it is highly questionable if Indonesia can have a sustainable charcoal production.

Our results suggest that the charcoal sector does not face major supply constraints, as both globally and regionally biomass productivity is able to meet the biomass demands even under the least sustainable scenarios. However, there are a few caveats for this relatively simplistic suggestion. First, our analysis focused on the dynamics of supply-demand assuming that all supply comes from the region where it is produced, and we know that there is charcoal trade, and charcoal exports globally are growing (http://www.trademap.org). Recent estimates suggest that 51% of charcoal production comes from Africa and 35% from South America, but not all the charcoal stays where it is produced and major exports of charcoal occur in Indonesia, Malaysia and China, while major imports occur in Europe, Korea and Japan (Hillring, 2006). Including the dynamics of trade would improve our analysis as it would allow estimating the demand for internal and external needs, and whether trade could meet demands from scarce regions. It would also be important to assess whether trade could be managed to maximize forest protection, and what are the opportunity costs of such approach. Second, we assume an optimal regional use of forest NPP, which might be an unrealistic assumption but a necessary assumption to assess how NPP could provide biomass in the absence of local knowledge on forest NPP use. To contain this assumption we estimated a lower boundary of NPP values by applying a 1/3 multiplier to total NPP, and an upper boundary estimate obtained from tree PFT. We find this is a first order estimate to look into the local capacity to provide biomass for urban dwellers in the studied regions. Future studies can build upon our results to test for differences in regional uses of NPP, and assess optimal allocation strategies. A sustainable harvesting method means that biomass can only be used as long as it meets the aboveground-NPP. This selective thinning should also be optimally placed in space, meaning that the producing industry should have a full rotating scheme around the whole continent, Thirdly, we assume a conversion rate of 1:5 from wood to charcoal; however, we know this factor varies with charcoal production

TABLE 2 | Tree and wood NPP, and average NPP over the last century (1900–2006).

	NPP (mi ton $C.year^{-1}$)	NPP in protected areas (mi ton $C.year^{-1}$)	Average $NPP_{1900-2006}$ ($kg\ C.m^{-2}.year^{-1}$)	NPP_{Wood} (mi ton $C.year^{-1}$)	NPP_{wood} in protected areas (mi ton $C.year^{-1}$)	NPP_{tree} (mi ton $C.year^{-1}$)	NPP_{tree} in protected areas (mi ton $C.year^{-1}$)
C. America	1,667	314	0.58	556	94	302.1	218
S. America	15,527	406	0.73	5,176	1,218	3,182.4	2,954
Africa	15,451	2,257	0.45	5,150	681	2,651.1	1,243
Indonesia	3,639	578	1.12	1,210	173	828.3	441
Global	72,824	11,336	0.45	24,275	3,401	12,573	7,079

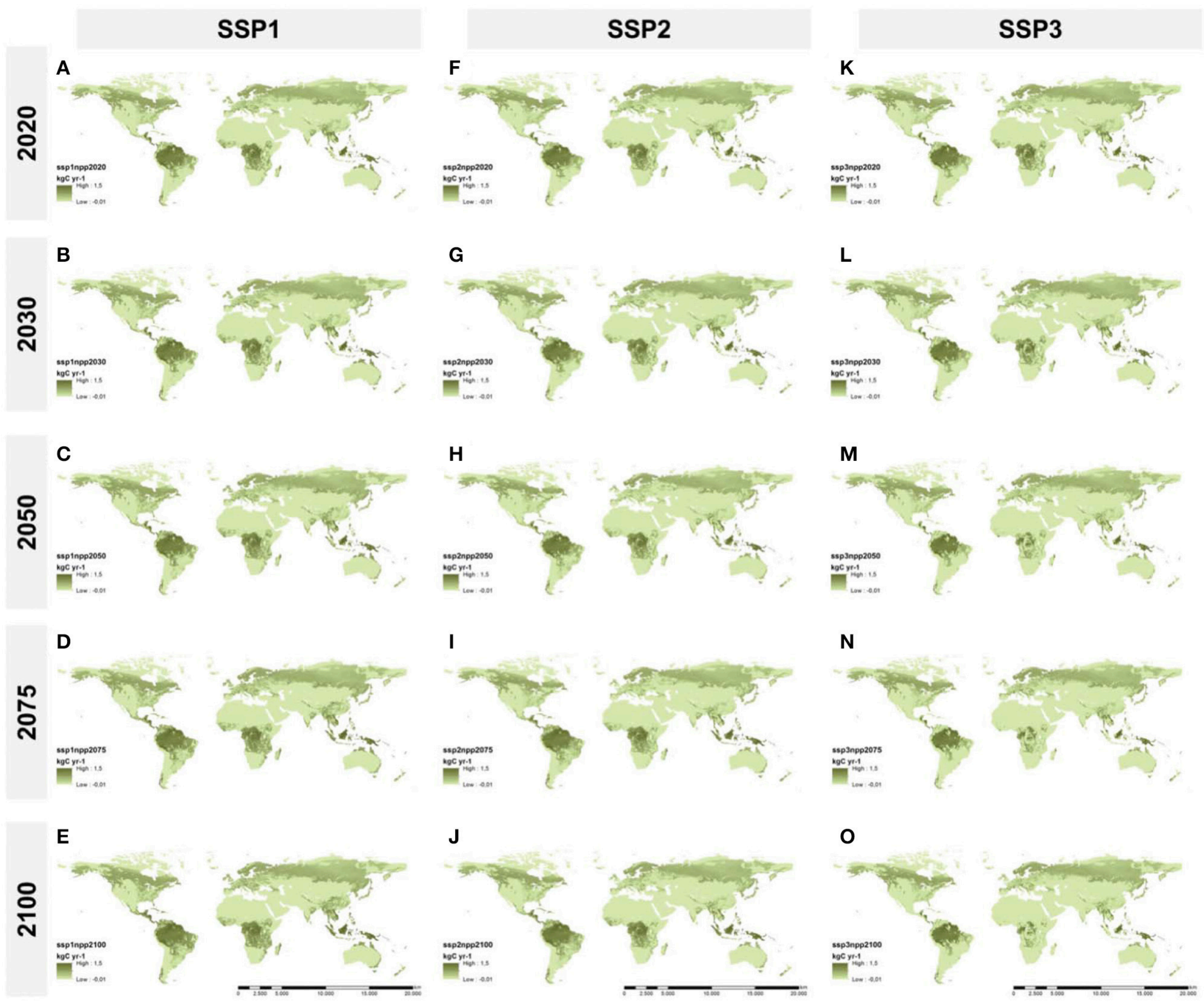

FIGURE 4 | Global future mean Net Primary Productivity under the three SSP scenarios for 2020, 2030, 2050, 2075, and 2100: **(A–E)** SSP1, **(F–J)** SSP2, and **(K–O)** SSP3. See Figures S3–S6 for regional maps for Central America, South America, Africa, and Indonesia. Values displayed are NPP.

technique. A range of 3 to 12 kg of biomass is required to produce 1 kg of charcoal. This suggests that changing production techniques both globally and regionally could be a way forward to make the charcoal sector even more attractive to meet urban residential energy needs. Finally, charcoal is a relatively small fraction of the global and regional energy needs. At least an equal amount of biomass is needed for traditional fuels like fuelwood. Further, other energy carriers may require biomass as primary material or secondary to produce heat to operate the energy production facilities. This means that additional stressors

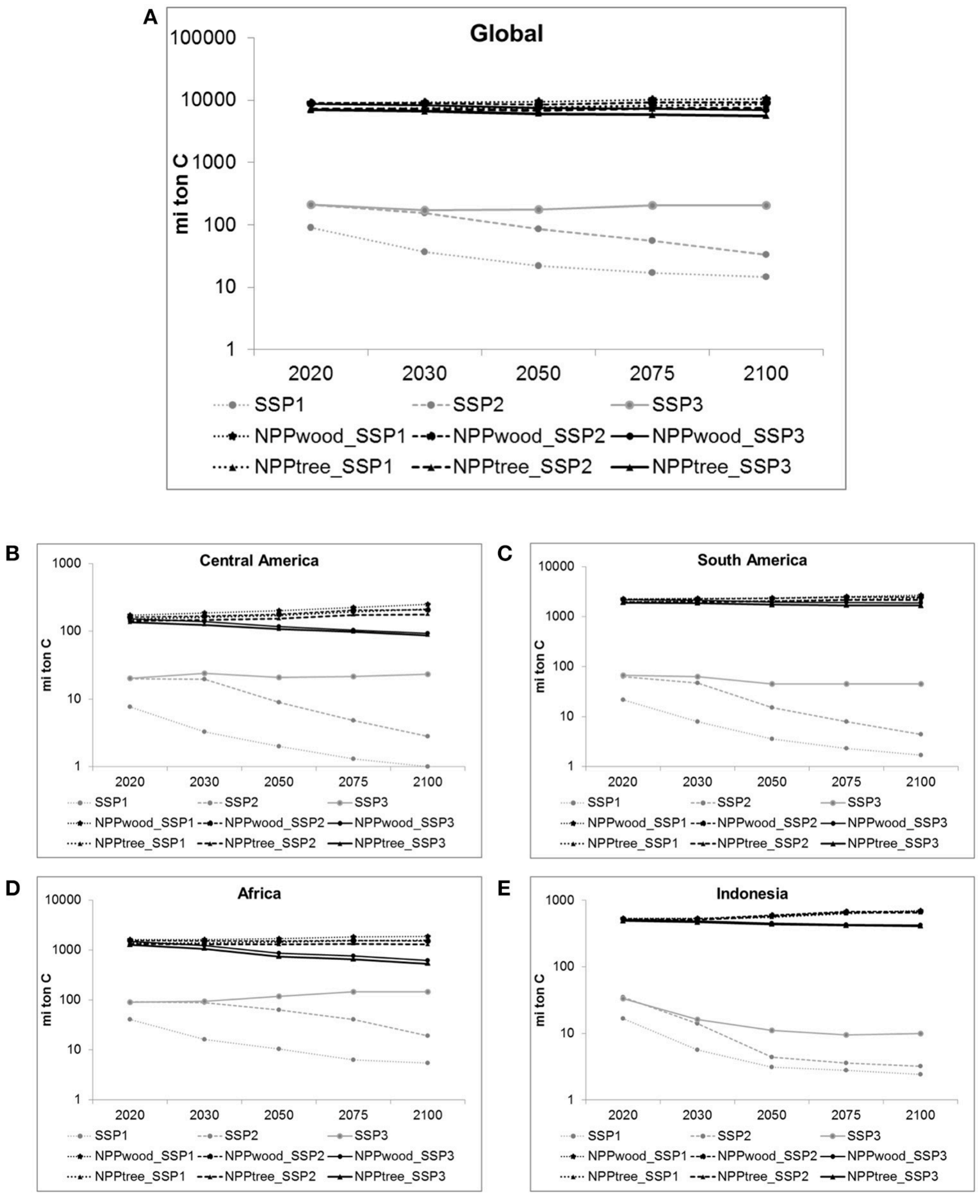

FIGURE 5 | Projected demand and supply of biomass for charcoal (mi ton C) under SSP scenarios for 2020, 2030, 2050, 2075, and 2100. Gray lines are demand and black lines are supply. Full line for SSP3, dashed line for SSP2 and dotted line for SSP1. Globally the supply is always higher than the demand, suggesting that charcoal production is not a large stressor on the system. However, regionally it can be observed that the demand approximates the supply in the case of Central America and Africa under the most unsustainable scenario. **(A)** Globally, **(B)** Central America, **(C)** South America, **(D)** Africa, and **(E)** Indonesia.

on local biomass are present and not accounted for in our analysis.

The future of the charcoal sector is not dire. Wood and Baldwin (1985) estimated that for developing countries about 1 kg of biomass per day gets consumed for every man, woman and child, and this fuel correspond to as much as 95% of the domestic energy. This biomass can be used for either traditional biofuel or charcoal, and the choice of charcoal over fuelwood is a function of supply, transportation, storage, price and convenience (Zulu and Richardson, 2013). Charcoal represents a small fraction of the energy needs, but its biomass demands are disproportionate and in some regions the gap between supply and demand is closing under the least sustainable scenario. We use a novel combination of empirical data, modeling and scenarios to suggest that charcoal for urban dwellers projected demand is not expected to add significant extra pressures on forests, as long as other energy carriers are made more renewable and sustainable, as our models assume a movement away from charcoal due to gross domestic product growth and improved access to modern energy. However, charcoal production can also be made more sustainable. Here we analyzed whether there was sufficient standing biomass and sufficient biomass growth in terms of NPP, but further research is suggested on how meeting charcoal supply might affect other sectors like water, food and biodiversity (Johanson et al., 2016). Our results already suggest a need to cut down massive amounts of forest, under an optimized use of forest NPP. However, it is possible to implement a wood extraction strategy that only requires extracting larger trees, or at larger time intervals (as depicted in **Figure 1**). Burning of charcoal and associated deforestation amounts to 71.2 mi tCO_2 and 1.3 mi tCH_4 being released to the atmosphere (Chidumayo and Gumbo, 2013). Air pollution by atmospheric particulate matter production from wood is two times larger than that from charcoal, and both are still much higher than electricity ($PM_{10,wood}$ = 1,200 $\mu g/m^3$; $PM_{10,charcoal}$ = 540 $\mu g/m^3$; $PM_{10,electricity}$ = 200–380 $\mu g/m^3$; Torres-Duque et al., 2008). Wood combustion also releases twice as many polycyclic aromatic hydrocarbons as charcoal, highly toxic environmental compounds and carcinogenic molecules (Oanh et al., 1999). However, with cleaner production systems and changing production methods, higher efficiency might be achievable with reduced emissions and improved air quality. Deforestation rates are responsible for major biodiversity losses (Ahrends et al., 2012). It would be important, however, to determine which woody species are most suited for charcoal production, and target extraction toward those or complement biomass needs with directed intensive plantations. The identified research needs can provide important information to better integrate between global models and local conditions to fully understand whether local sustainable optimal pathways in the charcoal nexus can be achieved.

AUTHOR CONTRIBUTIONS

MS: designed the experiment, collected the data, wrote the manuscript. SD: designed the experiment, wrote the manuscript. VD and MB: collected the data, edited the manuscript. Dv: edited the manuscript

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REFERENCES

Ahrends, A., Burgess, N. D., Milledge, S. A. H., Bulling, M. T., Fisher, B., Smart, J. C. R., et al. (2012). Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proc. Nat. Acad. Sci. U.S.A.* 107, 14556–14561. doi: 10.1073/pnas.0914471107

Antal, M. J., and Gronli, M. (2003). The art, science, and technology f charcoal production. *Ind. Eng. Chem. Res.* 42, 1619–1640. doi: 10.1021/ie0207919

Arnold, J. E. M., Kohlin, G., and Persson, R. (2006). Woodfuels, livelihoods, and policy interventions: changing perspectives. *World Dev.* 34, 596–611. doi: 10.1016/j.worlddev.2005.08.008

Avitabile, V., Herold, M., Heuvelink, G., Lewis, S. L., Phillips, O. L., Asner, G. P., et al. (2016). An integrated pan-tropical biomass maps using multiple reference datasets. *Glob. Change Biol.* 22, 1406–1420. doi: 10.1111/gcb.13139

Baccini, A., Goetz, S. J., Walker, W. S., Laporte, N. T., Sun, M., Sulla-Menashe, D., et al. (2012). Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Change* 2, 182–185. doi: 10.1038/nclimate1354

Bailis, R., Drigo, R., Ghilardi, A., and Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nat. Clim. Change* 5, 266–272. doi: 10.1038/nclimate2491

Bartholomé, E., and Belward, A. S. (2005). GLC2000: a new approach to global land cover mapping from Earth observation data. *Int. J. Rem. Sens.* 26, 1959–1977. doi: 10.1080/01431160412331291297

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J. H., and Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *J. Geophys. Res.* 109, 1–34. doi: 10.1029/2003jd003697

Bowers, S., Ryan, C., and Jones, X. H. (2017). *Understanding Agricultural Drivers of Deforestation Through Remote Sensing*. IIED Working Paper. IIED, London.

Bowker, J. N., de Vos, A., Ament, J. M., and Cumming, G. S. (2017). Effectiveness of Africa's tropical protected areas for maintaining forest cover. *Conserv. Biol.* 31, 559–569. doi: 10.1111/cobi.12851

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. doi: 10.1016/j.esd.2012.07.004

Daioglou, V., van Ruijven, B. J., and van Vuuren, D. (2012). Model projections for household energy use in developing countries. *Energy* 37, 601–615. doi: 10.1016/j.energy.2011.10.044

FAO (2016). Available online at: http://faostat.fao.org/Portals/_faostat/documents/pdf/wood%20charcoal.pdf

Fernandes, S. D., Trautmann, N. M., Streets, D. G., Roden, C. A., and Bond, T. C. (2007). Global biofuel use, 1850-2000. *Global Biogeoch. Cycles* 21, 1–15. doi: 10.1029/2006GB002836

Fisher, B., Lewis, S. L., Burgess, N. D., Malimbwi, R. E., Munishi, P. K., Swetnam, R. D., et al. (2011). Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. *Nat. Clim. Change* 1, 161–164. doi: 10.1038/nclimate1119

Ghilardi, A., Mwampamba, T., and Dutt, G. (2013). What role will charcoal play in the coming decades? Insights from up-to-date findings and reviews. *Energy Sustain. Dev.* 17, 73–74. doi: 10.1016/j.esd.2013.02.007

Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biol. Fert. Soils* 35, 219–230. doi: 10.1007/s00374-002-0466-4

Gómez-Luna, B. E., Rivera-Mosqueda, M. C., Dendooven, L., Vázquez-Marrufo, G., and Olalde-Portugal, V. (2009). Charcoal production at kiln sites affects C and N dynamics and associated soil microorganisms in *Quercus* spp. temperate forests of central Mexico. *Appl. Soil Ecol.* 41, 50–58. doi: 10.1016/j.apsoil.2008.08.007

Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D. J., Ichinose, T., et al. (2012). "Urban energy systems," in *Global Energy Assessment – Toward a Sustainable Future*, eds T. B. Johansson, N. Nakicenovic, A. Patwardhan, and L. Gomez-Echeverri (Cambridge, UK; New York, NY: Cambridge University Press; Laxenburg: The International Institute for Applied Systems Analysis), 1307–1400.

Hillring, B. (2006). World trade in forest products and wood fuel. *Biomass Bioenergy* 30, 815–825. doi: 10.1016/j.biombioe.2006.04.002

Johanson, E. L., Fader, M., Seaquist, J. W., and Nicholas, K. A. (2016). Green and blue water demand from large-scale land acquisitions in Africa. *Proc. Natl. Acad. Sci. U.S.A.* 113, 11471–11476. doi: 10.1073/pnas.1524741113

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., et al. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new approach based in shared socio-economic pathways. *Global Environ. Change* 22, 807–822. doi: 10.1016/j.gloenvcha.2012.05.005

Malhi, Y., Doughty, C., and Galbraith, D. (2011). The allocation of ecosystem net primary productivity in tropical forests. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 366, 3225–3245. doi: 10.1098/rstb.2011.0062

Mitchell, T. D., and Jones, P. D. (2005). An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Clim.* 25, 693–712. doi: 10.1002/joc.1181

Mwampamba, T. H., Ghilardi, A., Sander, K., and Chaix, K. J. (2013). Dispelling misconceptions to improve attitudes and policy outlook on charcoal in developing countries. *Energy Sustain. Dev.* 17, 75–85. doi: 10.1016/j.esd.2013.01.001

Neufeldt, H., Langford, K., Fuller, J., Iiyama, M., and Dobie, P. (2015). *From Transition Fuel to Viable Energy Source: Improving Sustainability in the Sub-saharan Charcoal Sector*. ICRAF Working Paper No. 196. Nairobi, World Agroforestry Centre.

Oanh, N. T. K., Reutergardh, L. B., and Dung, N.,T. (1999). Emission of polycyclic aromatic hydrocarbons and particulate matter from domestic combustion of selected fuels. *Environ. Sci. Technol.* 33, 2703–2709. doi: 10.1021/es980853f

Peters, G. P., Andrew, R. M., Boden, T., Canadell, J. G., Ciais, P., Le Quere, C., et al. (2013). The challenge to keep global warming below 2°C. *Nature Clim. Change* 3, 4–6. doi: 10.1038/nclimate1783

Piketty, T. (2015). *Carbon and Inequality: from Kyoto to Paris. Trends in the Global Inequality of Carbon Emissions (1998-2013) and Prospects for An Equitable Adaptation Fund*. Paris: Paris School of Economics.

Poumanyvong, P., and Kaneko, S. (2010). Does urbanization lead to less energy use and lower CO2 emissions? A cross-country analysis. *Ecol. Econ.* 70, 434–444. doi: 10.1016/j.ecolecon.2010.09.029

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., et al. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environ. Change* 42, 153–168. doi: 10.1016/j.gloenvcha.2016.05.009

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., et al. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proc. Natl. Acad. Sci. U.S.A.* 108, 9899–9904. doi: 10.1073/pnas.1019576108

Santoro, M., Beaudoin, A., Beer, C., Cartus, O., Fransson, J. E. S., Hall, R. J., et al. (2015). Forest growing stock volume of the northern hemisphere: spatially explicit estimates for 2010 derived from Envisat ASAR. *Rem. Sens. Environ.* 168, 316–334. doi: 10.1016/j.rse.2015.07.005

Smith, B., Prentice, I. C., and Sykes, M. T. (2001). Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Glob. Ecol. Biogeogr*. 10, 621–637. doi: 10.1046/j.1466-822X.2001.00256.x

Stehfest, E., van Vuuren, D., Bouwman, L., and Kram, T. (2014). *Integrated Assessment of Global environmental Change with IMAGE 3.0: Model Description and Policy Implications*. Den Hague: Netherlands Environmental Assessment Agency (PBL).

Sulaiman, C., Abdul-Rahim, A. S., Mohd-Shahwahid, H. O., and Chin, L. (2017). Wood fuel consumption, institutional quality, and forest degradation in sub-Saharan Africa: evidence from a dynamic panel framework. *Ecol. Ind.* 74, 414–419. doi: 10.1016/j.ecolind.2016.11.045

Torres-Duque, C., Maldonado, D., Perez-Padilla, R., Ezzati, M., and Viegi, G. (2008). Biomass fuels and respiratory diseases: a review of the evidence. *Proc. Am. Thorac. Soc.* 5, 577–590. doi: 10.1513/pats.200707-100rp

van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., van den Berg, M., Harmsen, M., et al. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environ. Change* 42, 237–250. doi: 10.1016/j.gloenvcha.2016.05.008

Wood, T. S., and Baldwin, S. (1985). Fuelwood and charcoal use in developing countries. *Ann. Rev. Energy* 10, 407–429. doi: 10.1146/annurev.eg.10.110185.002203

Zoomers, A., van Noorloos, F., Otsuki, K., Steel, G., and van Westen,. G. (2017). The rush for land in an urbanizing world; from land grabbing towards developing safe, resilient, and sustainable cities and landscapes. *World Dev.* 92, 242–252. doi: 10.1016/j.worlddev.2016.11.016

Zulu, L. C., and Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. *Energy Sustain. Dev.* 17, 127–137. doi: 10.1016/j.esd.2012.07.007

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Integrating Food-Water-Energy Research through a Socio-Ecosystem Approach

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The nexus approach helps in recognizing the link between water, energy, and food production systems, emphasizing the need to manage them in a more integrated way. The socio-ecosystem (SES) approach, however, goes beyond that, by incorporating the regulation and supporting services in the management equation. Changes in ecosystem integrity affect the delivery of ecosystem services to society, which affects local people's well-being, creating a feedback mechanism regarding management strategies. The SES approach makes explicit the "human-bio-physical" nature of our interaction with ecosystems, highlighting the need for a more integrated and interconnected social-ecological research perspective. In addition, the SES approach makes more explicit the multi-scale character of the ecological processes that structure and maintain social-ecological systems. Water dynamics have an important role in shaping ecosystem's structure and functioning, as well as determining the systems capacity for delivering provisioning services. The tropical dry-deciduous forest (TDF), is particularly useful in studying water-food-energy trade-off interactions. Recently, a category 5 hurricane landed in the study area (Mexico's Pacific coast), triggering various social and ecological problems. This event is challenging the current forest management strategies in the region. The extreme hydrometeorological event created an excellent opportunity to test and promote the SES approach for more integrated food-water-energy research. By using the SES approach within our long-term socio-ecological research project, it was easier to identify opportunities for tackling trade-offs between maintaining the transformation of the system and a more sustainable alternative: promoting the maintenance of the ecosystem's integrity and its capacity to deliver provisioning and regulating services.

Keywords: nexus, social-ecological systems, transdisciplinary research, trade-offs, LTER, LTSER, Chamela

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INTRODUCTION

An international group have been studying the ecosystem implication of biomass extraction for charcoal production in tropical Africa and Latin America (Ghilardi et al., 2013; Mwampamba et al., 2013; Santos et al., 2017). Their main concern is that this extended practice has been a slow, but persistent, pressure on the forest biomass resources. The group has recently adopted the "nexus approach" (*sensu lato* Hanlon et al., 2013), which seeks a stronger understanding of the interdependencies among food, water, and energy production systems to secure a more sustainable production process. By using simulation models, they have projected the demand for fuel-wood and charcoal for different socio-economic pathways, showing the disproportionate biomass demands that in some regions will require using a large fraction of forest (Santos et al., 2017). By adopting a nexus approach, the group is facilitating the understanding of the socio-economic and ecological interactions of charcoal and agricultural production, especially by highlighting two dimensions of the socio-ecological contexts: charcoal value chains and tenure systems (Iiyama et al., 2017). In addition, the interconnections between sustainable charcoal production in Tanzania, ecosystem services, and trade-offs in the allocation of land, labor, and net primary production have been documented (Doggart and Meshack, 2017).

The aim of this perspective article is to discuss the socio-ecosystem (SES) approach as a conceptual tool for guiding integral food-water-energy research. With the experience gained at the Chamela Mex-LTER Group, which belongs to the International Long-Term Ecological Research (ILTER) network, I will describe ecosystem's water dynamics as an entry point for showing the interconnected nature of the ecological processes. I will then describe the possible effect of management activities on these ecosystems' water dynamics. This analysis helps in recognizing trade-offs between obtaining provisioning ecosystem services (e.g., water, crops, and charcoal) and the conservation of the supporting and regulating ecosystem services. This is also important since the maintenance of an ecosystem's integrity is required to sustain the delivery of such products. Finally, I discuss how the effects an extreme hydrometeorological events is inducing us to define new research questions and hypotheses following a SES approach.

THE SOCIO-ECOSYSTEM (SES) APPROACH

System thinking has been essential for recognizing the existence of biotic and abiotic components interacting and conforming ecosystems at different and multiple hierarchical scales (systems within systems; **Figure 1**). Ecosystem ecologists are also helping in identifying the natural processes behind the delivery of provisioning and regulating ecosystem services that sustain human social-economic development. The millennium ecosystem assessment (MA) was successful in documenting the importance of these services and the urgency of conserving and restoring the natural ecosystem behind them. This international initiative (Millennium Ecosystem Assessment, 2005) not only documented the fragility of Earth's life support system, but also the severity of knowledge fragmentation and the difficulties of the scientific system in conducting interdisciplinary research (Norgaard, 2008). System thinking has changed the way we appreciate and understand our world (Ackoff, 1999; Capra and Luisi, 2014), now conceptualizing it as social-ecological systems resulting from humans and ecosystems interacting in time and space at different hierarchical scales (Berkes and Folke, 1998). This SES view is also an attempt to recognize our "human-bio-physical" nature in a completely integrated and interconnected way (**Figure 1A**; Maass, 2012).

Socio-ecosystem research requires a shift from viewing humans as external drivers of natural systems to that of agents acting within socio-ecological systems (Grimm et al., 2000; Redman et al., 2004; Haberl et al., 2006). Dealing with SES also requires new epistemic approaches, and the long-term, site-based, bottom-up, and transdisciplinary approach has been suggested as the key ingredient for conducting SES research for sustainability (Carpenter et al., 2012; Fischer et al., 2015; Maass and Equihua, 2015; Balvanera et al., 2017). On these grounds, an "Integrative Science for Society and the Environment" research initiative has been proposed to elevate LTER science to a new level of integration, collaboration, and synthesis necessary for addressing current and emerging environmental research challenges (Collins et al., 2011). This approach has also been the response of some of the ILTER network groups to deal with this endeavor (Maass et al., 2016).

WATER AS AN INTEGRAL COMPONENT OF ECOSYSTEM PROCESSES

Water participates in most energy fluxes and mass recycling ecosystem's processes (Baird and Wilby, 1999; Chaplin, 2001); therefore, water dynamics have an important role in shaping the ecosystem's structure and functioning, as well as determining the system's capacity to deliver provisioning services, such as drinking water, food crops, and fuel-wood biomass. Water availability has been identified as one of the major limiting factors for sustaining terrestrial ecosystem productivity (Chapin et al., 2002). Therefore, maintaining natural water dynamics is a key ecosystem management component and a requirement for reaching sustainable productivity. With this in mind, I will describe the role of water in many ecological processes as an entry point to recognizing the trade-offs between obtaining provisioning ecosystem services and the conservation of the ecological processes that sustain the delivery of such products (also conceived as supporting and regulating services).

Depending on its phase water's presence in the ecosystem highly affects the ecosystem's albedo (the surface short-wave solar reflectivity). For example, while liquid water has an albedo of <20%, a cloud can reach albedos >90%. In addition, significant albedo changes (>25%) can occur within hours when a light-colored soil becomes darker after a rainfall. Albedo is a key ecosystem process since it affects net solar radiation (Q^*) entering the ecosystem. Between 80 and 85% of Q^* is used either to heat the air through sensible heating fluxes (Q_h) or to evaporate water through latent heating fluxes (Q_e). The proportion of each flux is known as Bowen's ratio (Q_h/Q_e). Only a small fraction of Q^* (1–3%) is captured through photosynthesis, whereas water evaporation and transpiration processes (Q_e fluxes) usually consume >50% of Q^* in most forested ecosystems. Transpiration acts as "transportation band," moving dissolved nutrients in the soil solution to the canopy through a continuous water column flowing from the roots to the stems and branches (Chapin et al., 2002). This high energy consumption process is driven by solar

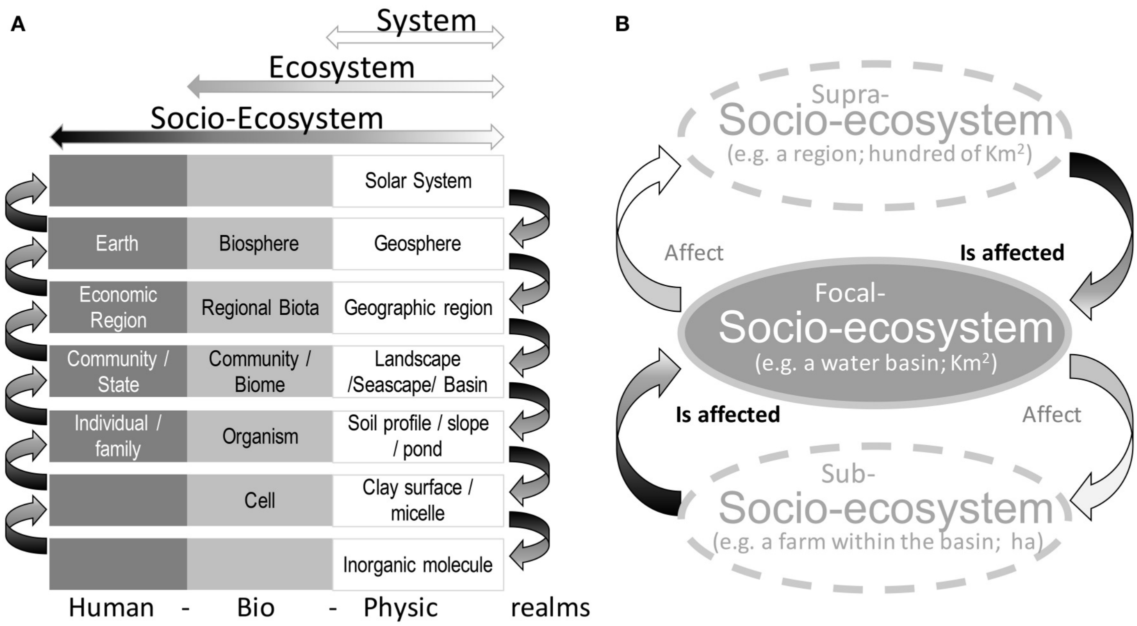

FIGURE 1 | (A) Nested and hierarchical character of socio-ecosystems (SES), with management that always requires a detailed analysis of **(B)** the factors "affecting" and "being affected" by the supra- and sub-SES.

energy, heating the atmosphere, and maintaining the relative humidity gradient (between the stomata and the air) required to sustain transpiration. Water's physical-chemical process (i.e., oxidation, dissolution, evaporation, freezing, etc.) are also the main forces behind rock weathering and nutrient release to the soil solution. Likewise, water moves large quantities of minerals off the land through infiltration, leaching, and erosion. This important "integration character" of water makes its dynamics a key aspect determining ecosystem functioning, as well as a major controlling factor determining ecosystem productivity, including food and biomass production.

Human needs for energy, food, and water have promoted ecosystems' transformations. In fact, at least in tropical areas, regionally distinct modes of agricultural expansion, wood extraction, and infrastructure extension have been identified as the prevailing proximate causes of deforestation (Geist and Lambin, 2002). Deforestation entails nearly total destruction of forest structure and composition, as well as disruption of key ecosystem functions, including its water dynamics (Maass, 1995). Changes in forest cover induce a Bowen's ratio increase (through Q_e reduction) and a change in the ecosystem energy balance (through albedo modification). In fact, albedo and Bowen's ratio modification have been identified as a major drivers of climate change, along with green-gas emissions which are also promoted by land use change (Eltahir, 1998). Further land degradation and water dynamic disruption occurs when management practices, such as induced fire or tilling, expose bare soil to direct impact of raindrops. Although small, raindrops are strong enough to break soil clods into small particles that clog soil pores, creating a surface crust which significantly reduces soil infiltration. The soil crusting process has been identified as a major cause of soil erosion, not only inducing land degradation through fertility reduction, but also as the main source of water pollution and siltation in river beds, lakes, and dams (Pimentel, 2006). Infiltration reduction also changes the main route water takes to reach the valley bottomlands, promoting faster overland runoff and floods, and reducing underground water recharge and stream flow during the dry season (Bruijnzeel, 2004). All these water-related trade-offs emerge when natural ecosystems are transformed and should be at the core of any ecosystem management discussion.

Charcoal is an important cooking energy source in rural areas (Ghilardi et al., 2013; Iiyama et al., 2017). Its production promotes forest degradation and, in the long run, can produce a complete deforestation process (Santos et al., 2017) and its consequences in terms of albedo changes, soil crusting, water and wind erosion, floods and droughts. Even biodiversity loss has been detected as a result of the selective harvest of indigenous hardwood species (Naughton-Treves et al., 2007). Charcoal, however, can be produced in more sustainable ways by avoiding deforestation or a permanently degrading process, as well as by protecting harvested areas from cultivation, intensive grazing, and fire, thus enabling natural regeneration (Doggart and Meshack, 2017). This has been the case in Mozambique areas where even under long-term charcoal production they continued to provide ecosystem services (Woollen et al., 2016).

ECOSYSTEM SERVICES AND ECOSYSTEM INTEGRITY

Ecosystem transformation to obtain water, energy, and food production not only generates a trade-off between these provisioning ecosystem services, but also with cultural, regulating and, most importantly, supporting services (the basic ecological processes behind the maintenance of all services; Daily et al., 1997). Dealing with these trade-offs, and with the delayed effects of ecosystem manipulation, is a complicated task. One way to do it is by recognizing that natural ecosystems are our best reference of sustainability. Working with nature, understanding and respecting the natural processes behind the ecosystem services is becoming a better strategy than transforming nature at will (Jordan, 1998). Through the maintenance of the "ecosystem integrity," we can reduce the possibility of unsuspected and long-term effects. Therefore, it is important to link food-water-energy provisioning services with the particular configurations of supporting ecosystem processes that provide those services, using natural ecosystems as sustainable references (Garcia-Alaniz et al., 2017). Equihua et al. (2014) define ecosystem integrity as "*the condition where its structure and functions are not impaired and auto-organization dynamics alone are driving the system*" and can be measured by how different an actual ecosystem is from some original and desired condition. Changes in integrity take place through ecosystem degradation, and one is the mathematical complement of the other. Since the specific setting of abiotic environment in a given area establishes the context for the compositional, structural, and functional ecosystem attributes, these settings can be measured to infer "ecosystem integrity" status (Garcia-Alaniz et al., 2017). At ILTER, we suggest doing this by using ecosystem integrity and human well-being as key response variables in the analyses of how these variables change under different ecosystem management regimes and in diverse socio-ecological settings (Maass et al., 2016).

CLIMATE CHANGE, LTER, AND RESEARCH OPPORTUNITIES

The study of SES responses to intense hydrometeorological phenomena (e.g., drought, flood, frost, etc.) is becoming extremely important under the current climate change scenarios, which are forecasting an increase in their intensity (IPCC's, 2014; Knutson et al., 2015). Extreme hydrometeorological events generate complex management issues such as insect pests, plant mortality, fuel load and fire increase, and CO_2 emissions (Shaver et al., 2000; Held and Soden, 2006; Álvarez-Yépiz and Martínez-Yrízar, 2015). In turn, these problems also generate indirect social-economic effects (e.g., tree mortality reduces wood supply) (Walker et al., 1999). Species of TDF have evolved under these highly variable conditions and are adapted to extreme droughts (Holbrook et al., 1995). Land use change, however, increases SES vulnerability and lowers the resilience capacity to these extreme hydrometeorological events (Gavito et al., 2014). Under perturbed conditions, exotic, and invader species resistant to drought and fire (like buffelgrass) also increase (Búrquez-Montijo et al., 2002).

LTER is helping to evaluate the effect of hydrometeorological events by analyzing the risk with more precision (Gavito et al., 2014). LTER also brings information useful to better designing management policies under climate change scenarios. As Collins et al. (2011) have pointed out, pulses and pressures (natural and human-induced) drive ecosystem dynamics, which affects the structure and functioning of natural ecosystems. In turn, the delivery of ecosystem services decreases depending on how much ecosystem integrity has changed. Variation in ecosystem service delivery has an impact on local peoples' well-being, creating a feedback mechanism on management strategies, resulting into pulses or pressure on the ecosystem. In other words, to properly manage this adaptive management cycle, identifying, and understand trade-off among different management alternatives is crucial. Those alternatives that better maintain an ecosystem's integrity will produce higher ecosystem services.

THE CHAMELA MEX-LTER RESEARCH SITE

At Chamela's Mex-LTER site, in the Mexican Pacific Coast (105°W, 20°N), we have been studying the structure and functioning of the tropical dry-deciduous forest (TDF) within the Chamela-Cuixmala Biosphere Reserve (Maass et al., 2002). The ecosystem's water dynamics, energy fluxes and nutrient cycling have been studied for decades (>35 years). TDF has a strong seasonal character in which 65% of the yearly rain falls in 3 months, creating a strong dry-wet ecosystem dynamic. Inter-annual rainfall is also highly variable in the study region (from 340 to 1,329 mm year^{-1}). Extended droughts alternate with heavy rainstorms creating highly unpredictable climate conditions. Dry periods of 8 consecutive months without any rain are common in the area. Native species are adapted to these extreme conditions. Introduced species under a highly transformed ecosystem, however, become highly vulnerable to these extreme hydrometeorological events. Subsistence agriculture and cattle ranching are the main productive activities in the area. Most stakeholders are not native farmers; they recently colonized the region (in 1960s), arriving from areas other than TDF (Castillo et al., 2005). "Traditional" land management consists of clear-cutting the forest, growing corn for 1–2 years and then converting the agricultural land into induced pasture fields (De Ita, 1983). Soil erosion, compaction, and infiltration reduction are the result of poor management practices, creating a vulnerable environment for the local settlers who suffer from recurrent crop failures because of the lack of sufficient rain during critical moments in the production cycle (Maass, 1995).

In addition, excess rainfall for short periods creates occasional floods with harmful consequences for the settlers at the lower section of the basin. During the last 15 years, a more socio-ecological approach has been conducted (Castillo et al., 2005, 2007; Maass et al., 2005), and currently, a transdisciplinary approach (Spangenberg, 2011) is in the process of being established, promoting appropriate conditions for different stakeholders' participation, not only in our research activities but, most importantly, in the definition of our research program.

In October 2011, Hurricane Jova hit the region and, recently (October 2015), Hurricane Patricia (category 4–5) crossed the Chamela-Cuixmala Reserve, seriously disrupting its forest

TABLE 1 | Processes, impacts, and management opportunities as a result of Hurricane Patricia affecting the tropical dry-deciduous forest at the Chamela-Cuixmala Biosphere Reserve.

Process ***(to study & monitor)***	***Impact (to prevent, mitigate)***	**Opportunity (of management)**
Increase in fuel load (dead trees and branches)	Fire risk increase	*Harvest wood for multiple use, including charcoal production*
Fence destruction	Tree cutting to repair fences	*Identify better tree species to use as "living fences"*
Reduction in Evapotranspiration (Et) and Runoff (Q) increase	Soil erosion and floods	*Increase water availability and ground water recharge*
Increase of organic matter inputs to the soil (leaf litter and branch decomposition)	Nitrification and N leaching promoting nitrate inputs to ground water system	*Develop a "participatory monitoring system" for water quality of local sources*
Orchard tree mortality	Market losses and interest reduction in orchard industry	*Promote management practices for "resistant trees" (mango and tamarind) and "resilience trees" (papaya and banana)*
Increase in new tissue (sprouts and bud growth)	Pest increase in management systems	*Identify species interactions to develop "biological control"*
Reduction in native bird population	Increase in insect pests	*Recognize and promote "ecosystem services" from local fauna*
Reduction of large carnivores (puma and jaguar) crossing the lowlands	Increase of small fauna and zoonosis sprouts in the region	*Recognize and promote "ecosystem services" from local fauna*
Increased exposure to vectors diseases (insects) as a result of roof and window destruction	Increase in dengue and chikungunya cases	*Request higher responses from local and state health authorities in the area*
Problems in accessing woodlands and cost increase of extracting forest products	New access using bulldozers	*Review and develop better "access and extraction" of forest products*
Spatial damage heterogeneity	Social imbalance	*Review "land planning" and promote "sense of of community"*
Lack of coordination between local, regional, and federal governments	Inefficient process, injustice, impunity, and corruption	*Promote local and "polycentric governance"*
Official recognition of the disaster	Abuse of help permits and concessions	*Promote monitoring policies (creation of a "citizen observatory")*
Efficiency of governmental response	Apathy and reduction of the alert response from local settlers	*Promote "adaptive management"*
Local news covered on mass media	Interest reduction in visiting the area (by tourists) and revenue reduction	*Use media attention to talk about the area (beyond the disaster) and stimulate investment to help local economy.*
Destruction of tourism infrastructure	Lost interest from foreign invertors	*Promote the establishment of "risk prevention" and "mitigation policies" with local business*
Roof blown off by the wind in most houses	Roof restoration with asbestos sheets	*Promote the concept of "sustainable building" in the region*
Deterioration of reserve's "core land"	Reduction in ecosystem services requiring large preserved areas (e.g., regulating services)	*Promote "restoration ecology research" within the biosphere reserve and trigger restoration efforts outside the reserve's core areas*

structure and functioning. This has created an opportunity for triggering a transdisciplinary research under the SES approach. Workshops with local stakeholders allowed us to identify their major concerns after the hurricane landfall in their village and croplands. By consulting with local settlers' views, concerns and interests, our research agenda deviated from the traditional approach, in which the scientific hypotheses are defined strictly on either ecological or social aspects as a separate issue. The exercise helped us link social-ecological process with two possible response scenarios: the "business as usual" response and the "conservation" alternative. The latter pushes forward a more sustainable SES approach. Inspired by the stakeholders input, I identified those social-ecological processes we must evaluate and monitored them after the disturbance (see column one in **Table 1**). In addition, I identified the most likely response of local settlers to hurricane effects (column two in the same table). Finally, an effort was undertaken to define the type of actions we may need to implement for preventing or mitigating those problematic and likely responses, as a way toward finding of a more hypothetical socio-ecological alternative (last column).

By using this SES approach, it was easier to identify opportunities for tackling trade-offs between continuing to transform the system and a more preserving alternative, which imply the protection of the ecosystem's integrity. For example, it has been suggested the identification of resilient native species to be used as living fences (instead of the traditional use of dead trunks or artificial poles). Likewise, there is a proposal to grant authorization of the removal of dead boles to produce charcoal (traditionally forbidden in the protected areas) as a management strategy to reduce the fire risk that resulted from the the increase of fuel load after the hurricane. In addition, we identify an opportunity for launching a community-based water monitoring system, to promote a better understanding by local people about the importance of conserving their forest land to maintain a good quality of their water sources. See more examples in **Table 1**.

FINAL THOUGHTS

The SES approach not only aids in linking energy, nutrient, and water processes in a natural ecosystem, but it also connects these supporting services with provisioning services, such as food, charcoal, and clean water. The SES approach also helps to recognize the importance of preserving ecosystem integrity and its link with local people's well-being. With this connection in mind, it is easier to identify and deal with the trade-offs between preserving and transforming natural ecosystems. Furthermore, the SES approach highlights the multi-scale (nested and hierarchical) character of the social-ecological processes that structure and maintain SES (**Figure 1A**), which permits recognizing the high uncertainty that large-scale processes generate in the management practice. To deal with such multi-scale complexity, the manager should focus on one particular scale and analyze its link with the immediate upper (supra system) and lower (sub system) scales; see **Figure 1B**. This multi-scale character of SES also shows the importance of focusing on local processes as a strategy for facilitating the adaptive management cycle. Finally, the need for promoting long-term and site-based research (i.e., academic groups anchoring their research on specific sites for many years) has become evident for developing not only a better understanding of the local ecosystem, but also the necessary trust between researchers and the local community for efficient transdisciplinary research.

ETHICS STATEMENT

Table 1 was prepared using statements from different stakeholders affected by the hurricane's impact on their homes and agricultural lands. No particular names are included in the table. All workshop participants attended by invitation and knew its objectives and the intention of using the obtained information in the publication of scientific papers.

AUTHOR CONTRIBUTIONS

MM is the sole author of this article. It was prepared under the invitation of Dr. Tuyeni Heita Mwampamba, editor of the special research topic "Charcoal, Food, and Water Production in the Tropics: Applying Nexus Thinking to Improve Research and Policy Approaches in Complex Landscapes" to be included in Frontiers in Environmental Science, in the section Agroecology and Land Use Systems.

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REFERENCES

Ackoff, R. L. (1999). *Ackoff's Best: His Classic Writings on Management*. New York, NY: John Wiley and Son.

Álvarez-Yépiz, J. C., and Martínez-Yrízar, A. (2015). *Huracanes, Sequías y Heladas: Eventos Climáticos Extremos en México*. Available online at: http://web.ecologia.unam.mx/oikos3.0/index.php/articulos/fracturacion-hidraulica/8-articulos/165-eventos-climaticos-extremos-y-sus-impactos-en-los-socio-ecosistemas-de-mexico.

Baird, A. J., and Wilby, R. L. (1999). *Eco-Hydrology*. New York, NY: Routledge.

Balvanera, P., Daw, T. M., Gardner, T. A., Martín-López, B., Norström, A. V., Ifejika Speranza, C., et al. (2017). Key features for more successful place-based sustainability research on social-ecological systems: a programme on ecosystem change and society (PECS) perspective. *Ecol. Soc.* 22:14. doi: 10.5751/ES-08826-220114

Berkes, F., and Folke, C. (1998). *Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience*. Cambridge: Cambridge University Press.

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: not seeing the soil for the trees? *Agric. Ecosyst. Environ.* 104, 185–228. doi: 10.1016/j.agee.2004.01.015

Búrquez-Montijo, A., Miller, M., and Martínez-Yrízar, A. (2002). "Mexican grasslands, thornshrub, and the transformation of the Sonoran Desert by invasive exotic buffelgrass (*Pennisetum ciliare*)," in *Invasive Exotic Species in the Sonoran Region*, ed B. Tellman (Tucson, AZ: University of Arizona Press), 126–146.

Capra, F., and Luisi, P. L. (2014). *The System View of Life: A Unifying Vision*. New York, NY: Cambridge University Press.

Carpenter, S. R., Folke, C., Norström, A., Olsson, O., Schultz, L., Agarwal, B., et al. (2012). Program on ecosystem change and society: an international research strategy for integrated social–ecological systems. *Curr. Opin. Environ. Sustain.* 4, 134–138. doi: 10.1016/j.cosust.2012.01.001

Castillo, A., Magaña, A., Pujadas, A., Martínez, L., and Godínez, C. (2005). Understanding the interaction of rural people with ecosystems: a case study in a tropical dry forest of mexico. *Ecosystems* 8, 630–643. doi: 10.1007/s10021-005-0127-1

Castillo, A., Pujadas, A., and Schroeder, N. (2007). "La reserva de la biosfera Chamela-Cuixmala, México: perspectivas de los pobladores rurales sobre el bosque tropical seco y la conservación de ecosistemas," in *Hacia una Cultura de Conservación de la Diversidad Biológica*, *Vol. 6*, eds G. Halffter, S. Guevara, and A. Melic (Zaragoza: Monografías Tercer Milenio), 245–254.

Chapin, T. S. III., Matson, P. A., and Mooney, H. A. (2002). *Principles of Terrestrial Ecosystem Ecology*. New York, NY: Springer.

Chaplin, M. F. (2001). Water: its importance to life. *Biochem. Mol. Biol. Educ.* 29, 54–59. doi: 10.1111/j.1539-3429.2001.tb00070.x

Collins, S. L., Carpenter, S. R., Swinton, S. M., Orenstein, D. E., Childers, D. L., Gragson, T. L., et al. (2011). An integrated conceptual framework for long-term social–ecological research. *Front. Ecol. Environ.* 9, 351–357. doi: 10.1890/100068

Daily, G. C., Alexander, S., Ehrlich, P., Goulder, L., Lubchenco, J., Matson, P. A., et al. (1997). Ecosystem services: benefits supplied to human societies by natural ecosystems. *Issues Ecol.* 2, 1–16.

De Ita, C. (1983). *Patrones de producción agrícola en un ecosistema tropical en la costa de Jalisco*, Tesis de Licenciatura, Facultad de Ciencias; Universidad Nacional Autónoma de México, 183.

Doggart, N., and Meshack, C. (2017). The marginalization of sustainable charcoal production in the policies of a modernizing african nation. *Front. Environ. Sci.* 5:27. doi: 10.3389/fenvs.2017.00027

Eltahir, E. A. B. (1998). A soil moisture–rainfall feedback mechanism 1. Theory and observations. *Water Resour. Res.* 34, 765–776. doi: 10.1029/97WR03499

Equihua, M., García-Alaniz, N., Pérez-Maqueo, O., Benítez, G., Kolb, M., Schmidt, M., et al. (2014). "Integridad ecológica como indicador de la calidad ambiental," in *Bioindicadores: Guardianes de Nuestro Futuro Ambiental. Instituto Nacional de Ecología y Cambio Climático -El Colegio de la Frontera Sur*, eds C. A. González Zuarth, A. Vallarino, J. C. Pérez-Jiménez, and A. M. Low Pfeng. (México: El Colegio de la Frontera Sur, Instituto Nacional de Ecología y Cambio Climático), 779.

Fischer, J., Gardner, T. A., Bennett, E. M., Balvanera, P., Biggs, R., Carpenter, S., et al. (2015). Advancing sustainability through mainstreaming a social–ecological systems perspective. *Curr. Opin. Environ. Sustain.* 14, 144–149. doi: 10.1016/j.cosust.2015.06.002

Garcia-Alaniz, N., Equihua, M., Pérez-Maqueo, O., Equihua Benítez, J., Maeda, P., Pardo Urrutia, F., et al. (2017). The mexican national biodiversity and ecosystem degradation monitoring system. *Curr. Opin. Environ. Sustain.* 26–27, 62–68. doi: 10.1016/j.cosust.2017.01.001

Gavito, M.E., Martínez-Yrízar, A., Ahedo, R., Araiza, S., Ayala, B., Ayala, R., et al. (2014). La vulnerabilidad del socio-ecosistema de bosque tropical seco de Chamela, Jalisco, al cambio global: un análisis de sus componentes ecológicos y sociales. *Invest. Ambiental Ciencia y Política Pública* 6, 109–126. Available online at: http://www.revista.inecc.gob.mx/article/view/236#.WX4aBtM1-Rs

Geist, H. J., and Lambin, E. F. (2002). Proximate causes and underlying driving forces of tropical deforestation tropical forests are disappearing as the result of many pressures, both local and regional, acting in various combinations in different geographical locations. *Bioscience* 52, 143–150. doi: 10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2

Ghilardi, A., Mwampamba, T., and Dutt, G. (2013). What role will charcoal play in the coming decades? Insights from up-to-date findings and reviews. *Energy Sustain. Dev.* 17, 73–74. doi: 10.1016/j.esd.2013.02.007

Grimm, N. B., Grove, J. G., Pickett, S. T. A., and Redman, C. L. (2000). Integrated approaches to long-term studies of urban ecological systemsurban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory. *Bioscience* 50, 571–584. doi: 10.1641/0006-3568(2000)050[0571:IATLTO]2.0.CO;2

Haberl, H., Winiwarter, V., Andersson, K., Ayres, R. U., Boone, C., Castillo, A., et al. (2006). From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. *Ecol. Soc.* 11, 13. doi: 10.5751/ES-01786-110213

Hanlon, P., Madel, R., Olson-Sawyer, K., Rabin, K., and Rose, J. (2013). *Food, Water and Energy: Know the Nexus. GRACE Communications Foundation Water and Energy Programs*, New York, NY. Available online at: http://www.gracelinks.org/media/pdf/knowthenexus_final_051513.pdf.

Held, I. M., and Soden, B. J. (2006). Robust responses of the hydrological cycle to global warming. *J. Clim.* 19, 5686–5699. doi: 10.1175/JCLI3990.1

Holbrook, N. M., Whitbeck, J. L., and Mooney, H. A. (1995). "Drought responses of Neotropical dry forest trees," in *Seasonally Dry Tropical Forests*, eds S. H. Bullock, H. A. Mooney, and E. Medina (New York, NY: Cambridge University Press), 243–276.

Iiyama, M., Neufeldt, H., Njenga, M., Derero, A., Ndegwa, G. M., Mukuralinda, A., et al. (2017). Conceptual analysis: the charcoal-agriculture Nexus to understand the socio-ecological contexts underlying varied sustainability outcomes in african landscapes. *Front. Environ. Sci.* 5:31. doi: 10.3389/fenvs.2017.00031

IPCC (2014). *Climate Change 2014.* Synthesis Report Summary for Policymakers, Available online at: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

Jordan, C. F. (1998). *Working with Nature: Resource Management for Sustainability*. Amsterdam: Taylor and Francis.

Knutson, T. R., Sirutis, J. J., Zhao, M., Tuleya, R. E., Bender, M., Vecchi, G. A., et al. (2015). Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *J. Clim.* 28, 7203–7224. doi: 10.1175/JCLI-D-15-0129.1

Maass, J. M. (1995). "Tropical deciduous forest conversion to pasture and agriculture," in Seasonally Dry Tropical Forests, eds *S. H. Bullock, H. A. Mooney, and E. Medina* (New York, NY: Cambridge University Press), 399–422.

Maass, J. M. (2012). "El manejo sustentable de socio-ecosistemas," in *Cambio Climático y Políticas de Desarrollo Sustentable, Tomo 14 de la Colección Análisis Estratégico Para el Desarrollo*, ed J. L. Calva(Coord) (México: Editorial Casa Juan Pablos-Consejo Nacional de Universitarios), 267–290.

Maass, J. M., Balvanera, P., Castillo, A., Daily, G. C., Mooney, H. A., Ehrlich, P., et al. (2005). Ecosystem services of tropical dry forests: insights from long-term ecological and social research on the Pacific coast of Mexico. *Ecol. Soc.* 10:17. doi: 10.5751/ES-01219-100117

Maass, M., Balvanera, P., Bourgeron, P., Equihua, M., Baudry, J., Dick, J., et al. (2016). Changes in biodiversity and trade-offs among ecosystem services, stakeholders, and components of well-being: the contribution of the international long-term ecological research network (ILTER) to programme on ecosystem change and society (PECS). *Ecol. Soc.* 21:31. doi: 10.5751/ES-08587-210331

Maass, M., and Equihua, M. (2015). "Earth stewardship, socio-ecosystems, the need for a transdisciplinary approach and the role of the international long term ecological research network (ILTER)," in *Earth Stewardship: Linking Ecology and Ethics in Theory and Practice*, eds R. Rozzi, F. S. Chapin, J. B. Callicott III, S. T. A. Pickett, M. E. Power, J. J. Armesto, and R. H. May Jr. (Dordrecht: Springer). 217–233.

Maass, M., Jaramillo, V., Martínez-Yrízar, A., García-Oliva, F., Pérez-Jiménez, A., and., Sarukhán, Y. J. (2002). "Aspectos funcionales del ecosistema de selva baja caducifolia en Chamela, Jalisco," in *Historia Natural de Chamela*, eds F. A. Noguera, J. H. Vega-Rivera, A. N. García-Aldrete, and M. Quesada-Avendaño (México: UNAM), 525–542.

Millennium Ecosystem Assessment (2005). *Ecosystems and Human Well-Being: Synthesis.* Washington, DC, Island Press.

Mwampamba, T. H., Ghilardi, A., Sander, K., and Chaix, K. J. (2013). Dispelling common misconceptions to improve attitudes and policy outlook in developing countries. *Energy Sustain. Dev.* 17, 75–85. doi: 10.1016/j.esd.2013.01.001

Naughton-Treves, L., Kammen, D. M., and Chapman, C. (2007). Burning biodiversity: woody biomass use by commercial and subsistence groups in western Uganda's forests. *Biol. Conserv.* 134, 232–241. doi: 10.1016/j.biocon.2006.08.020

Norgaard, R. B. (2008). Finding hope in the millennium ecosystem assessment: an essay. *Conserv. Biol.* 22, 862–869. doi: 10.1111/j.1523-1739.2008.00922.x

Pimentel, D. (2006). Soil erosion: a food and environmental threat. *Environ. Dev. Sustain.* 8, 119–137. doi: 10.1007/s10668-005-1262-8

Redman, C. L., Grove, J. M., and Kuby, L. H. (2004). Integrating social science into the long-term ecological research (lter) network: social dimensions of ecological change and ecological dimensions of social change. *Ecosystems* 7, 161–171. doi: 10.1007/s10021-003-0215-z

Santos, M. J., Dekker, S. C., Daioglou, 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. doi: 10.3389/fenvs.2017.00028

Shaver, G. R., Canadell, J., Chapin, I. F. S., Gurevitch, J., Harte, J., Henry, G., et al. (2000). Global warming and terrestrial ecosystems: a conceptual framework for analysis ecosystem responses to global warming will be complex and varied. Ecosystem warming experiments hold great potential for providing insights on ways terrestrial ecosystems will respond to upcoming decades of climate change. documentation of initial conditions provides the context for understanding and predicting ecosystem responses. *Bioscience* 50, 871–882. doi: 10.1641/0006-3568(2000)050[0871:GWATEA]2.0.CO;2

Spangenberg, J. (2011). Sustainability science: a review, an analysis and some empirical lessons. *Environ. Conserv.* 38, 275–287. doi: 10.1017/S0376892911000270

Walker, B. H., Steffen, W. L., Canadell, J., and Ingram, J. S. I. (eds.). (1999). *The Terrestrial Biosphere and Global Change. Implications for Natural and Managed Ecosystems*. Cambridge: Cambridge University Press.

Woollen, E., Ryan, C., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., et al. (2016). Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? *Philos. Trans. R. Soc. B* 371:20150315. doi: 10.1098/rstb.2015.0315

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METHODS
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Multi-Scale Integrated Analysis of Charcoal Production in Complex Social-Ecological Systems

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We propose and illustrate a multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) as a tool to bring nexus thinking into practice. MuSIASEM studies the relations over the structural and functional components of social-ecological systems that determine the entanglement of water, energy, and food flows in a complex metabolic pattern. MuSIASEM simultaneously considers various dimensions and multiple scales of analysis and therefore avoids the predicament of quantitative analysis based on reductionism (one dimension and one scale at the time). The different functional elements of society (the parts) are characterized using the concept of "processor," that is, a profile of expected inputs and outputs associated with the expression of a specific function. The processors of the functional elements of the social-ecological system can be either scaled-up to describe the metabolic pattern of the system as a whole, or scaled-down by considering the characteristics of its lower-level parts—i.e., the different processors associated with the structural elements required to express the specific function. An analysis of functional elements provides insight in the socio-economic factors that pose internal constraints on the development of the system. An analysis of structural elements makes it possible to study the compatibility of the system with external constraints (availability of natural resources and ecological services) in spatial terms. The usefulness of the approach is illustrated in relation to an example of the use of charcoal in a rural village of Laos.

Keywords: charcoal, metabolic pattern, relational analysis, social-ecological system, MuSIASEM

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INTRODUCTION

Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) is a general accounting framework for the analysis of the metabolic pattern of social-ecological systems (Giampietro et al., 2009, 2014). MuSIASEM allows the simultaneous consideration of water, energy, and food flows over various hierarchical scales of analysis, and therefore is a potentially powerful tool to bring nexus thinking into practice. Indeed, according to UNU-FLORES (https://flores.unu.edu/en/research/nexus) a nexus approach "examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments." The potential use of MuSIASEM to study water-energy-food nexus problems has been explored earlier (Giampietro et al., 2014), but not in relation to charcoal production in tropical social-ecological systems. In this work we illustrate a refinement of the MuSIASEM approach as recently developed in the EU Horizon2020 project MAGIC. This particular approach relies on the use of software and the creation of an *ad-hoc* database. For reasons of space, these technical aspects are not presented here. However, detailed technical descriptions of other pilot case studies, representing various types of social-ecological systems at different hierarchical scales, are available in deliverable D4.1 of MAGIC (http://magic-nexus.eu/).

Charcoal production plays an important role as a source of energy and cash income for populations of many developing countries, notably in Africa. However, charcoal production is increasingly being associated to deforestation and environmental degradation (Mwampamba et al., 2013) and therefore is now often included in the list of "dangerous" activities (Zulu, 2010). In order to seek sustainable solutions, it is important to recognize that charcoal production forms an integral part of a complex network of activities that operates at different scales establishing a bridge between ecosystem services and the supply of key resources such as food, energy, and water (Chidumayo and Gumbo, 2013). Moreover in many socio economic circumstances charcoal production is associated with a rich diversity of stakeholders across its supply chain (Butz, 2013; Ghilardi et al., 2013; Zulu and Richardson, 2013). These various aspects make charcoal production a perfect case study for MuSIASEM.

In this work, we adapt the MuSIASEM approach to study the water–energy–food nexus in charcoal-producing rural systems. We use a novel concept, that of "processor" (defined below) that brings the relations among the system's elements into sharper focus. The concept of processor has been specifically developed by the second author within the context of the project MAGIC for the application of the MuSIASEM accounting scheme to the water-energy-food nexus. Using this idea of processor, we show in this paper how to characterize the metabolic pattern of water, energy and food of charcoal-producing systems by establishing a relation—in qualitative and quantitative terms—among: (1) the various functional components (e.g., subsistence production, cash crop production, charcoal production, off-farm work) associated with the survival/reproduction of the village (guaranteeing food, energy, and water security); and (2) the related structural elements (e.g., typologies of land-uses, aquifers, off-farm jobs) used to express the functions.

In the next section, we first provide the basic features of MuSIASEM. In the following Sections The Idea of Processors, Relational Analysis Over Functional Elements, and Relational Analysis Over Structural Elements we go more into the details of the methodological approach, and in Section Discussion and Conclusions we discuss the approach in relation to the specific problematics of charcoal-producing systems using a case study in Laos as an example.

GENERAL FEATURES OF MULTI-SCALE INTEGRATED ANALYSIS OF SOCIETAL AND ECOSYSTEM METABOLISM

The MuSIASEM accounting framework organizes quantitative information in reference to different dimensions of analysis—i.e., social, economic, technical, biophysical, ecological—and different hierarchical scales of analysis referring to both socio-economic narratives and an ecological narratives (Madrid-López and Giampietro, 2015). In this way, the information generated can be used to check three dimensions of sustainability:

1. *Feasibility*—This dimension sees the system (society) as a black-box interacting with its context. Feasibility thus refers to the compatibility of the metabolic system as a whole with processes beyond human control, that is, external constraints imposed by the availability of natural resources and ecosystem services. This dimension involves (i) checking whether the metabolism of the system (seen as a black box) is compatible with the boundary conditions, and (ii) checking the level of openness of the system in terms of trade with other social-ecological systems (the extent of externalization to or dependence on other social-ecological systems);
2. *Viability*—This dimension looks at the workings inside the black-box to check the interactions among its parts. Viability thus addresses the compatibility of the system in relation to processes under human control (e.g., economic viability, technical viability) by checking whether the interaction of the parts inside the black box is compatible with available technology and know-how;
3. *Desirability*—This dimension checks whether the characteristics of the metabolic pattern are acceptable to those living inside the system (the desirability of the metabolic pattern directly affects the stability of the social fabric).

MuSIASEM basically consists of a relational analysis of the functional and structural elements of a social-ecological system that together determine its metabolic pattern of water, energy, and food. The concept of metabolism is commonly associated to the human body to represent the complex processes converting food into the energy and building blocks required to maintain its structure and functions. However, the concept of metabolism can also be and indeed has been applied to social-ecological systems (Ostwald, 1907, 1911; Lotka, 1922, 1956; Soddy, 1926; Zipf, 1941; White, 1943; Cottrell, 1955). Complex societies exhibit a mechanism of reproduction and maintenance similar to that of the human body. They extract and use a mix of energy and material inputs from their environment to express the functions required for preserving their identity. Along these premises, a new scientific field has emerged that is based on the study of "societal (or social) metabolism" (Wolman, 1965; Martinez-Alier, 1987; Fischer-Kowalski and Hüttler, 1998; Daniels, 2002; Swyngedouw, 2006; Giampietro et al., 2009; Broto et al., 2012; Giampietro, 2014). Metabolic pattern refers to the expected profile of inputs (taken from the environment) and outputs (discharged into the environment) associated to the set of functions required to reproduce the identity of a given social-ecological system (Giampietro et al., 2011). The concept of metabolic pattern neatly shows that the nexus between water, energy, and food is determined by forced relations among the structural and functional elements of a complex system. The term "relational analysis" (Rosen, 1958, 1985; Louie, 2009, 2013) indicates the existence of expected patterns of relations over the elements of metabolic networks that are capable of self-reproduction and self-maintenance. It implies a distinction

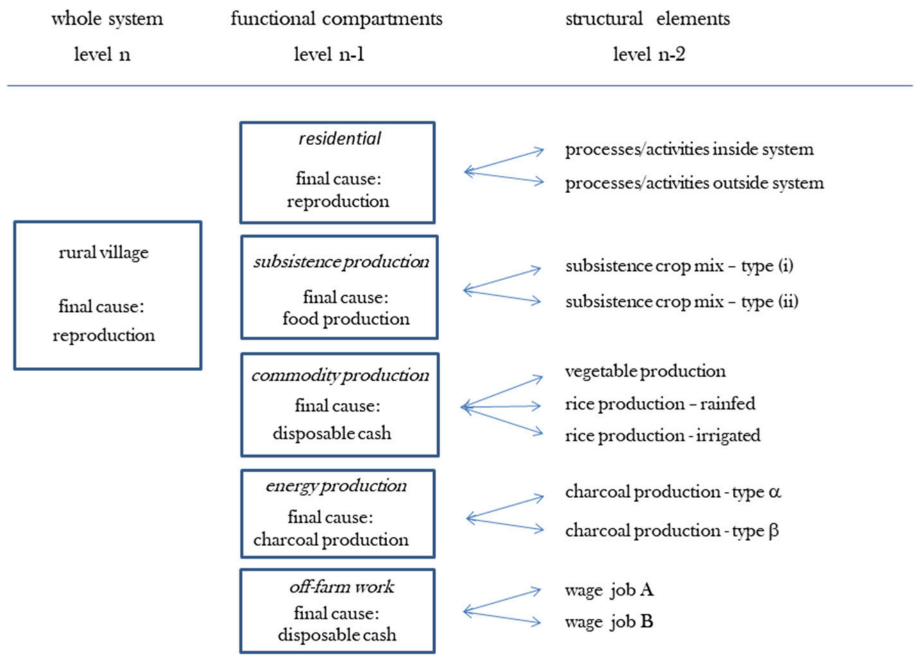

FIGURE 1 | Hierarchical organization of the system: the definition of the function of the whole (on the left) translates into a definition of functions for the functional compartments in the middle, using structural elements to carry out their tasks at the level n-2 (on the right).

between: (i) inputs and outputs remaining inside the self-organizing system; and (ii) inputs and outputs exchanged with the context. MuSIASEM also borrows from hierarchy theory (Koestler, 1968; Whyte et al., 1969; Allen and Starr, 1982; Salthe, 1985; Ahl and Allen, 1996) in that it explains the complex and impredicative relations among structural and functional elements across different hierarchical levels of organization. In particular, we consider functional elements as the parts of the "black-box" that define the interaction with the embedding context (black-box is *level n*, functional parts are at *level n−1*, the context is *level n +1*). Each functional compartment is determined by a series of structural elements that are not necessarily homogenous or similar in their biophysical processes (see **Figure 1**). For example, a functional compartment (vegetable production) may be composed of different combinations of structural elements (processes producing tomatoes, egg-plants, zucchini).

The assignment of structural elements to a given functional element is a semantic decision: the structural elements must share the same final objective (final cause in the jargon of relational analysis) with the functional element to which it is assigned. For example, in **Figure 1**, vegetable production and rice production belong to the same functional compartment (cash crop production). Different structural elements—that is, processes associated with a defined land-use typology—mapping onto the same final cause will be accounted in the same functional compartment. The structural elements are considered as sub-parts of the functional components as described in **Figure 1** (structural parts are defined at *level n−2*, functional parts at *level n−1*, and the black-box at *level n*).

Note that the semantic definition of the relation between structural and functional compartments is subject to a certain level of ambiguity. For example rice production can be mapped onto two different functional compartments, "subsistence production" and "cash crop/commodity production"; charcoal production can be mapped onto "energy production" or "cash crop/commodity production." In the same way, the final cause—getting disposable cash—can be obtained in two different ways, relating to two structural elements of different nature: on-farm production requiring land use allocation and off-farm work not requiring land allocation within the system boundaries. All these "bifurcations" can be handled by the accounting framework of MuSIASEM. In fact, MuSIASEM accounting entails a constraint of congruence to avoid double counting (and a messy representation). The sum of the relative sizes of the flows (energy, water, food, and money) and the funds (hours of human activity and hectares of land use) associated with the functional compartments and structural elements (defined at levels n−1 and level n−2, respectively) must be equal to the total amount of flow and fund elements defined at level n. For example, when the process of charcoal production generates an input (energy flow) consumed by the village, we must include the funds and the flows associated with this production to the final cause of producing energy. On the contrary if the charcoal is sold on the market then the funds and flows associated with this process are included in the functional compartment "getting disposable cash." In fact, when charcoal is produced and sold it does not belong to the energetic metabolism of the village, it becomes just a commodity. In relation to this point, the conditions of congruence—the size of all the flows and funds must remain the same when moving across different levels of analysis—guarantee coherence in the analysis.

Thus, an important feature of MuSIASEM is that the simplification of the information space in a given set of categories of accounting—required to generate a quantitative representation—is not semantically closed, as is the case with conventional models. The framework of accounting allows an exploration of the option space generated by the complex set of *impredicative* relations between structural and functional elements across hierarchical levels and scales: it does not deny the existence of chicken-egg paradoxes or ambiguities in the definition of the parts and sub-parts, rather it handles them. MuSIASEM deals with impredicativity through the use of grammars, that is, a set of expected relations over functional and structural elements that is semantically open. In fact, it may be that changes in external constraints will affect the characteristics of internal processes (top-down causality) or that changes in the internal characteristics of the system will redefine the external constraints (bottom-up causality). In this sense, we prefer the term *quantitative storytelling* over quantitative analysis to stress that numbers generated in this way only have meaning if properly contextualized in relation to: (i) the special characteristics of the environment; (ii) the special history of the social-ecological system in question; and (iii) the special research question considered.

MuSIASEM can be used in a diagnostic mode, by analyzing the actual metabolic pattern of a system, or in simulation mode, by examining scenarios (e.g., population growth, technical innovation, changing terms of trade).

In conclusion the innovative features of this approach are:

1. It is based on an analysis of relations over *patterns* (processors are profiles of expected inputs and outputs) and not on relations over numbers (e.g., inputs or output) as is the case in conventional models;
2. It integrates quantitative information referring to different hierarchical scales (describing and combining relevant aspects of the system originating from non-equivalent descriptive domains);
3. It integrates quantitative attributes defined according to different dimensions of analysis (economic, social, technical, ecological) and allows the use of geographic information systems;
4. It handles "impredicativity," that is the ambiguous relation between structural and functional types (chicken-eggs paradox) typically encountered in the analysis of the functioning of complex self-producing systems.

THE IDEA OF PROCESSORS

An important novel aspect of the approach proposed here compared to earlier work is the use of processors to assign an identity to the metabolic elements of the system. Any metabolic element of a social-ecological system, whether a functional compartment or a structural element, is an open system in itself that expresses an expected pattern of "behavior" in terms of: (i) consumption of inputs; (ii) expression of a useful function coinciding with the supply of useful output(s); and (iii) generation of unwanted by-products. The semantic analog of the "processor" of social-ecological systems is the enzyme for biochemical systems or the production function for economic analysis. The basic idea is that a specific pattern of inputs can be associated to the generation of a specific pattern of outputs. Depending on the scale considered, the expected behavior may be either: (i) reproducing itself (if we are considering the metabolic system as a whole); (ii) expressing a useful function needed to stabilize the larger metabolic system to which the element belongs (if we are considering a functional element); or (iii) transforming a profile of inputs into an expected profile of outputs (if we are considering a structural element making up a functional element). Metabolic elements can be defined as functional elements, when their characteristics are determined by processes taking place on the level above (top-down causality), or structural elements, when their characteristics are determined by processes taking place on the level below (bottom-up causality).

Thus, we describe each metabolic element (either functional or structural) as a processor that establishes a relation between: (i) internal inputs and internal outputs, and (ii) external inputs and external outputs. "Internal" refers to two different typologies of elements that are consumed or produced (flows) and maintained (funds) by the society (societal metabolism). In the jargon of life cycle analysis (LCA), internal elements are described as operating in the "technosphere" and therefore they refer to inputs and outputs determined by processes that are under human control and remaining within the borders of the socio-economic systems. "External" refers to flows that are produced or received by processes outside human control, that is, natural processes and ecosystem services (ecosystem metabolism). In the jargon of LCA these flows are considered as "coming from" or "going to" the biosphere.

As illustrated in **Figure 2** a processor is therefore associated with five sets of inputs/outputs:

- n_1: Internal inputs—required flows under human control (e.g., electricity, fuels, blue water, food, monetary flows):
- n_2: Internal inputs—required funds under human control (e.g., hours of human labor, hectares of land use, power capacity):
- n_3: External inputs—required flows extracted from ecosystems (e.g., green water, water extracted from aquifers to generate blue water, ecological services):
- n_4: External outputs—flows that must be discharged into ecosystems (e.g., pollutants, nitrogen from fertilizers, solid waste, GHG emissions):
- n_5: Internal outputs—useful flows or funds generated by metabolic elements and used by other elements in the technosphere (e.g., the useful products of functional and structural elements—supply of charcoal, rice, disposable cash).

The terminology funds and flows refers to the flow-fund model of Georgescu-Roegen in relation to bioeconomic analysis (Mayumi, 2002). A processor (**Figure 3**), is made of fund elements (inputs of human activity, managed land, power capacity), and this amount of fund elements will remain constant over the time duration of analysis (usually on a year basis). This information

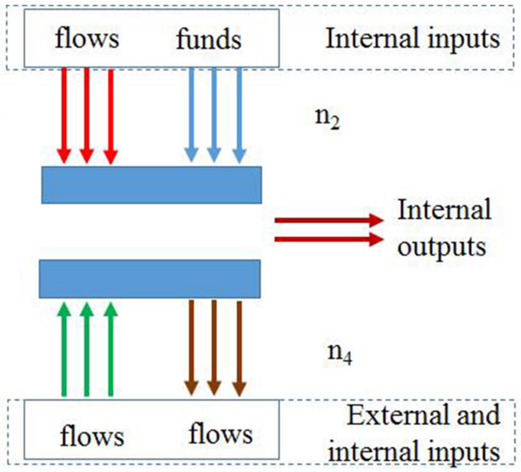

FIGURE 2 | Conceptualization of the expected pattern of inputs and outputs in a processor. Inputs and outputs remaining in the technosphere are internal, those getting from and to the biosphere are external.

can be used to define the size of the processor. The flow elements describe what the processors do: consuming and producing inputs and outputs (energy, food, water, monetary flows). Flows either appear or disappear during the analysis. Therefore, by using the concept of processor we can define: (1) the size of the functional and structural elements looking at quantities of fund elements; and (2) the qualitative characteristics of these elements (benchmark values) looking at the values of flow/fund ratios—e.g., energy per hour of labor, food per hour of labor, etc.

A representation based on processors makes it possible to describe social-ecological systems across different scales. In fact, the characteristics of the different processors of functional elements can be scaled-up to describe the characteristics of the whole village. This translates into defining a higher-level processor by scaling-up the relative quantities of inputs and outputs. The characterization of the given set of relations across scales is illustrated in **Figure 4**. In order to obtain the scaling, it is essential that the sum of the sizes of funds and flows described in the functional elements is equal to the size of funds and flows (per category) described at the level of the whole. The identification and definition of functional elements requires assigning an identity to the different socio-economic sectors or activities (a definition of why are they needed).

RELATIONAL ANALYSIS OVER FUNCTIONAL ELEMENTS

In **Figure 5** we propose a set of functional elements associated with a charcoal producing village. As discussed earlier (see also **Figure 1**), functional elements describe the social-ecological system top-down. They explain what the system does in terms of socio-economic activities (what/why): charcoal production (either energy supply or getting disposable cash through commodity production), off-farm work (getting disposable cash through wages), and residential activities (reproducing the fund element "people"). Since this method of representation is semantically open, other functional elements may be added to this set (e.g., cultural, religious activities). What is important is to re-adjust, after the introduction of a new set of functional and structural element, the profile of allocation of funds and flows in order to maintain the congruence of the relative sizes and relative paces and densities across the different representations across levels. As a matter of fact, the "identity" of the social-ecological system in terms of a set of functional elements should be defined on the basis of participatory processes involving the inhabitants of the system.

The definition of the set of functional elements, the definition of their relative sizes, and the definition of the metabolic profile of the various flows (e.g., water, energy, money) in each of the functional elements generate *mutual information* in the system, also called a "Sudoku effect" in analogy with the Sudoku game (Giampietro and Bukkens, 2015). Sudoku is a popular number puzzle in which one can infer the solution based on a set of congruence constraints and the information already given. Note that the size of the funds and the flows in the processor of the different functional compartments must be compatible with the size and the flows of the set of processors making up the whole (system closure). The quantification of the characteristics of the various processors in relation to the processor of the whole (after considering imports and exports) permits us to study the existence of sets of forced relations ("playing the Sudoku game").

Using the concept of processor, we can define the total size of the funds, in this example: total human activity measured in hours per year (THA = population × 8,760) and total available land within the geographic boundaries (TAL), measured in hectares (see **Figure 5**). This is the overall size of the village (at level n) should be divided among the lower-level functional elements (level n−1). Both THA and TAL must be distributed over the different functional elements (the categories of human activity and land uses associated with the different processors) in accordance with the socio-economic organization. This entails a competition for the use of these funds across different functional compartments. Therefore, each investment in any one of the functional elements can be considered to have an "opportunity cost" for society (the same amount of funds could be used for a different purpose).

An additional constraint is represented by the qualitative characteristics of the functions expressed by the functional elements. For instance, crop production can only take place on arable land. So additional categories, such as managed land (land uses) and non-managed land, need to be used for organizing the accounting (see **Figure 5**). This explains why an analysis of functional elements requires also a simultaneous analysis of structural elements carried out to a finer grain (at a smaller scale). The same applies for the fund human activity: Human beings need a given amount of sleep and personal care (non-working time), heavy work requiring a high level of power can only be carried out by male adults or animal power, etc. It should be noted that by looking at the analysis of functional elements, we can get a diagnostic analysis of the relations between funds and flows inside and across different functional elements. For

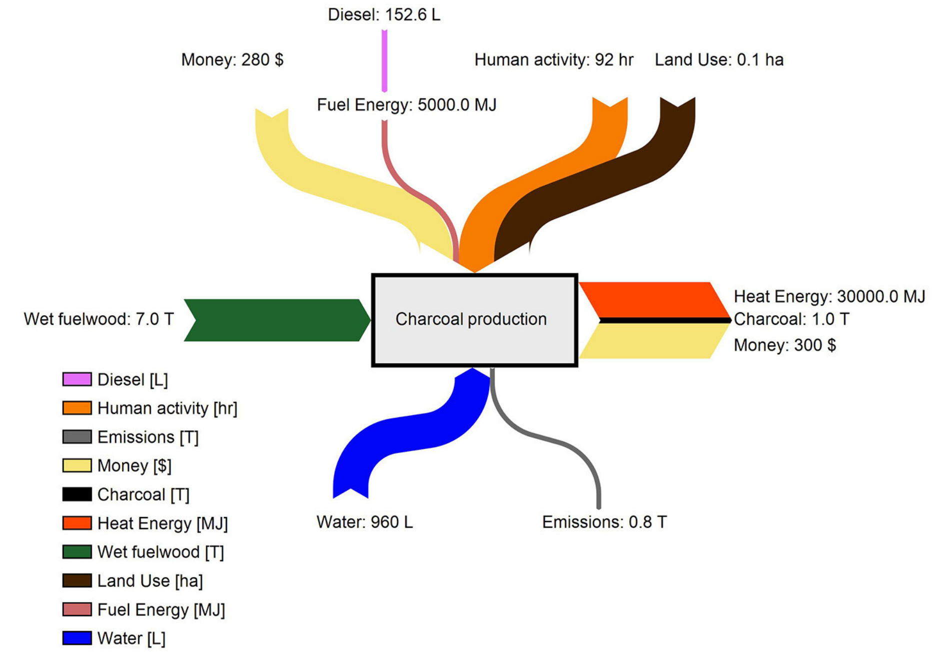

FIGURE 3 | Schematic representation of the charcoal production processor. Data are made up for the purpose of illustration.

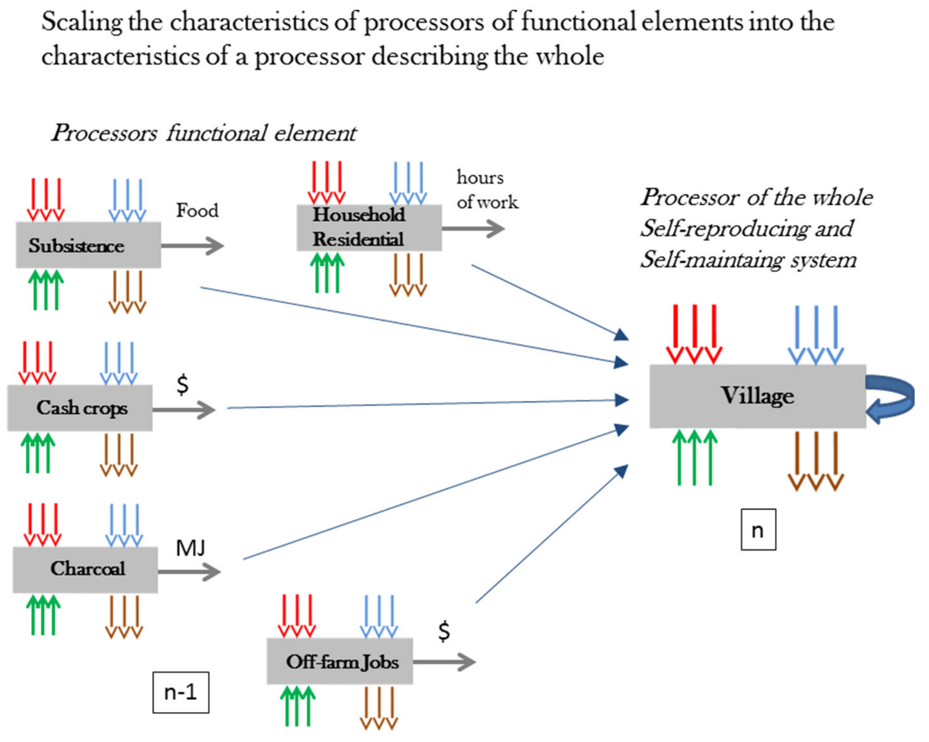

FIGURE 4 | The characteristics of a processor describing the whole society (on the right) are explained using the characteristics of the processors describing functional elements (on the left).

example, one can calculate how much water (flow), managed land (fund), and human labor (fund) is required or how much pollution is generated by a given processor. However, on the basis of a relational analysis of functional elements only, one cannot define the exact location of the associated activities. To have the exact location in space of a specific biophysical process (described

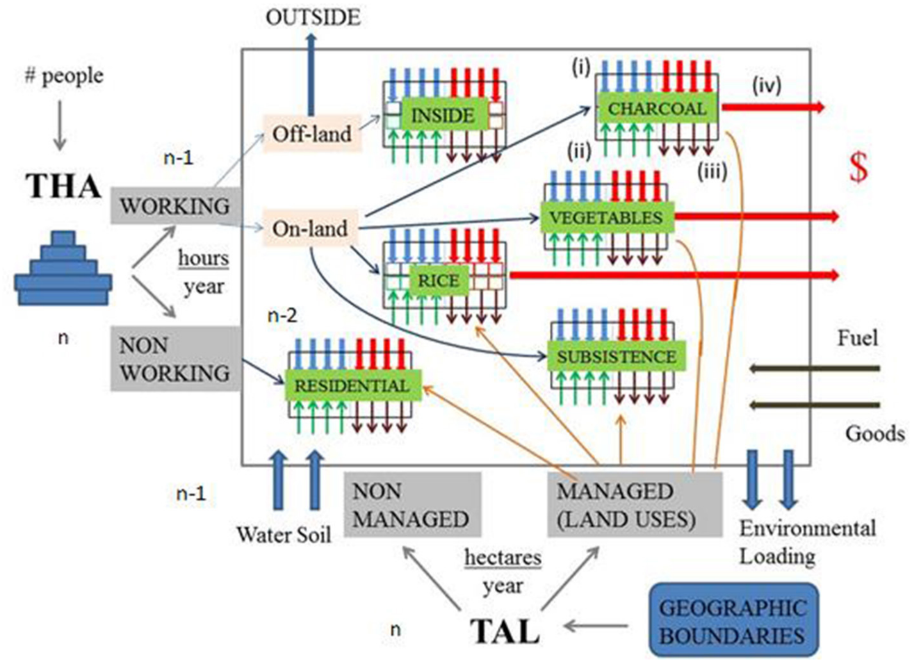

FIGURE 5 | Representation of the functional elements for a charcoal-producing village. Each activity is associated with a processor determining a set of expected relations between inputs, outputs, wastes and emissions. The overall metabolic pattern can be assessed against the constraints provided by the limited availability of human activity (THA) and available land (TAL).

by its specific processor) we should look at the corresponding structural element(s). This can be achieved using a layer in GIS of all the land uses (e.g., typologies of crop production) mapping onto a same functional type (e.g., commodity production). In this way, we can handle a typical predicament of integrated assessment: (i) the accounting of economic flows (internal inputs and outputs coming and going into the techno sphere) can be "translated" into economic variables considering the costs and revenues—prices. But this accounting is not directly associated to specific locations; (ii) the assessment of environmental impacts requires us to locate the exact position of the land use.

In **Figure 5** we can also see the inflows and outflows resulting from market transactions. Note that this graph is just a skeleton for the organization of the accounting. The various flows are indicated in semantic terms, but can be quantified adopting different choices of proxy variables. For instance, food may be quantified in terms of kg of food products (potatoes, beef, papaya, etc.) or kcal of nutrients (proteins, carbohydrates, calories). The same applies to water (blue water and green water) or energy (charcoal, gasoline, or wood). In MuSIASEM, benchmarks, such as charcoal produced per hour of labor, money earned per hectare, food required per person per day, water extraction from the aquifer per day, are used to assess the relative flows. In this way it becomes possible to summarize the balance of the system (whole vs. the sum of all the functional elements—see **Figure 4**) in relation to the chosen metric for quantifying energy, food, water, human activity, land use, and money flows. This balance has to consider the distinction between flows derived from inside the village and those from outside (imports). This diagnostic analysis is a good starting point to have the big picture of the factors (drivers, states) determining the sustainability on the socio-economic side.

RELATIONAL ANALYSIS OVER STRUCTURAL ELEMENTS

Structural elements are elements expressing an expected metabolic pattern of inputs and outputs associated with a known process. They have an external referent independent of their function guaranteeing the reliability of the expression of the pattern (e.g., a common blueprint or know-how determining the characteristics of the process). Examples of structural elements are: a hectare of rice cultivated with a given technology, a job providing a known wage, a pattern of behavior of members of a household when out of work. Structural elements are associated with the expression of a specific typology of process and therefore with the expression of an expected profile of inputs and outputs at a given scale. In general the scale of the structural elements is smaller than that of the corresponding functional type.

Indeed, several structural types can feed into one functional type. For instance, as illustrated in **Figure 6**, all the hectares of crop-land used to cultivate rice with a specific technique (e.g., rain fed) and all the hectares of crop-land used to cultivate rice with another technique (e.g., irrigated) can be aggregated into another category of accounting that is "rice production." In turn, the two structural elements "rice production" and "vegetable production"—referring to actual

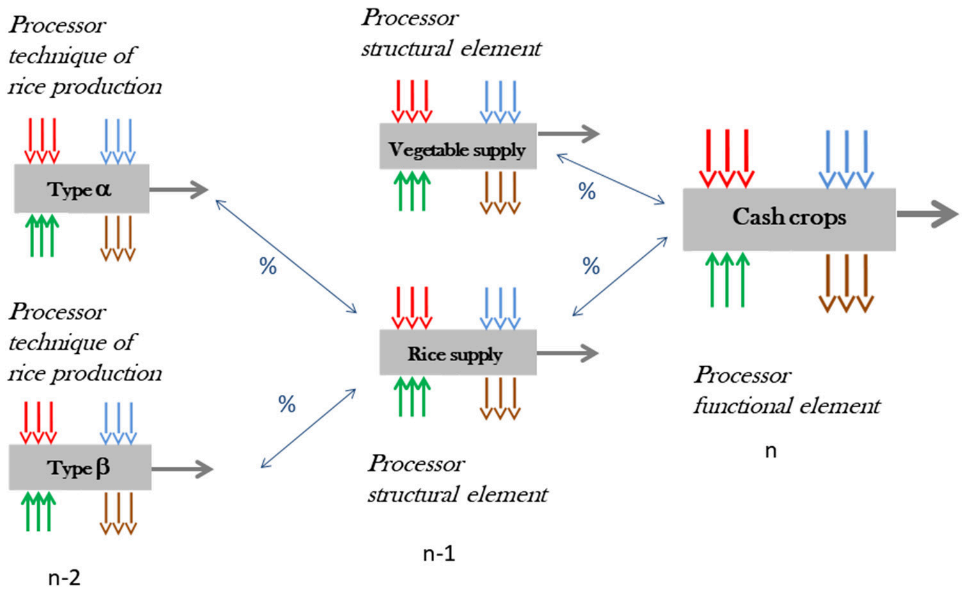

FIGURE 6 | Scaling the representation starting from the characteristics of production techniques (on the left) scaled into the characteristics of structural elements (in the middle) scaled to the characteristics of functional elements (on the right). The scaling can go in the two directions.

processes taking place in specific locations (hectares of land use) with known modalities (yields and labor productivity)—can be aggregated into the functional element "cash crop production."

For the operation of scaling down (moving from right to left in **Figure 6**) it is necessary to obtain information on the characteristics of the structural elements at the local scale. In this way it becomes possible to generate the analysis shown in **Figure 6** in which different land uses map onto a same category of structural elements. This procedure allows us to study the existence of external constraints—availability and suitability of land, availability of water, effect of pollution, destruction of habitat, etc.

Vice versa, in order to be able to interpret the information given by technical coefficients defined at the local level of land uses—the characteristics of structural elements defined by processors—we have to scale them up to the level of functional elements (moving from left to right in **Figure 7**. For instance, in this way we can examine how the flows observed at the local level of structural elements "translate" into economic flows associated with imports and exports of inputs and outputs at the level of the whole village. At this point, the importance of handling impredicativity becomes evident. We can use the established set of relations either: (i) to assess the characteristics that would be required by the mix of processors of structural elements (the pattern of production) to achieve the economic performance required by the functional elements, or (ii) to assess what type of economic performance can be achieved by the functional element, given the characteristics and the mix of lower-level structural elements.

The multi-scale analysis permits us to elucidate the nature of costs and benefits at the local scale (e.g., between different technologies to extract water: water pumps powered by wind or diesel), the relevance of these costs in the overall budget of the households at a mesoscale, to finally arrive at how the different performances of households affect the characteristics of the whole village.

In simulation mode, processors can be used to compare the effect of changes in the relative size of structural types that feed into the same functional type. For example, we can compare the profiles of inputs and outputs associated with 1 ton of rice produced by different techniques (α vs. β) and make projections on how a different mix of the production techniques will affect the land use and overall flows of energy, water, food at the village level. Trade-offs (e.g., 1 ton of rice α requires more energy than rice β, but less water) can then be evaluated within a larger analysis of the metabolic pattern in relation to the indirect effects that an adjustment in one functional element (rice production) can have on the others in terms of changes in the allocation of land-use, overall production of food for self-consumption or generation of cash income.

An analysis based on structural types and land-use analysis makes biophysical constraints better visible (Serrano-Tovar and Giampietro, 2014). For example, flooded areas are good only for rice production but not for vegetable production. Also, distance to the fields is an important factor in determining labor productivity because commuting diminishes the time available for other activities. Finally an analysis of land use and structural elements allows us to better appreciate how the flows of energy, water, and biomass metabolized by processes under human control affect (in negative ways) the ability of the embedding natural ecosystems to express their metabolic pattern of flows of energy, water, and biomass (Lomas and Giampietro, 2017).

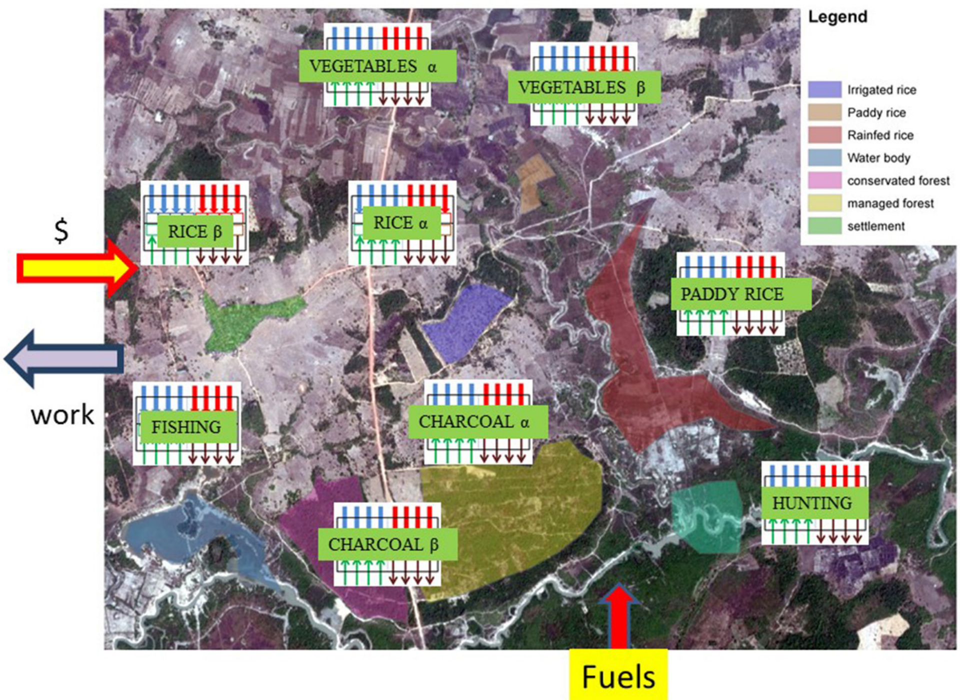

FIGURE 7 | Representation of structural elements (green squares) for a hypothetical charcoal-producing village. For each activity, we show different typologies having different input requirements.

DISCUSSION AND CONCLUSIONS

In relation to charcoal production in rural villages MuSIASEM can result extremely useful in that it characterizes the functional elements in relation to human time (activity) allocation (the hours of labor/activity required to express the different functions). In many charcoal-producing subsistence villages the opportunity-cost of human time is a key factor determining the observed pattern of activities. Examples are the trade-offs between subsistence vs. cash-crops, and child labor vs. education.

For instance, in the case of the Dong Khuai village in Laos (Yokoyama et al., 2014), an increasing share of the villagers goes working outside the village to bring money inside. The same final cause "getting disposable cash" can be obtained from two different functional elements: producing commodities (that may include charcoal!), something requiring land-uses, or working outside the village, not requiring land uses. Population growth and the movement to a market economy reduce the amount of land available inside the village to collect wood and produce charcoal and increase the opportunity cost of labor. When pressured by these two drivers, villagers tend to invest relatively more human time in earning money through off-farm work and then use the money generated in this way to buy LPG gas. The trade-offs of this substitution can also be assessed by considering the final cause of the functional element "producing energy" and comparing the two structural processes "charcoal production" vs. "generation of income to purchase LPG" that can fulfill the same function. Buying LPG has a much lower opportunity cost of human time than making charcoal, but it increases the dependence on the availability of off-farm jobs and the risk in case of fluctuations in gas prices. These two conditions are beyond the control of the villagers and therefore this trade-off can only be properly assessed at a larger hierarchical level considering a larger scale (the relation between the village and its socio-economic context). The same dilemma is faced in relation to food security. Abandoning self-sufficiency, obtained through the functional compartment "subsistence production," in favor of a fully monetarized economic process—getting cash through wages to buy food—may provide an improvement in living conditions but it may also increase the risks for the villagers.

In this example, we see that the production of charcoal and food can be considered in relation to different perspectives ("food and energy" vs. "disposable cash"). The analysis of the resulting trade-offs depends on the set of relations between the size and the characteristics of the structural and functional elements in the metabolic pattern. How much charcoal and food can be sold, what is the "opportunity cost" of the land, labor and other inputs to be invested in their production, how much land and labor is available. The internal competition for production factors can be related to the problem of children forced to help their parents to collect wood (Yuichiro et al., 2009). When the time of the children is needed to collect wood, we deal with a community constrained by the requirement of labor to remain at a low level of education and leisure.

In conclusion, we illustrated that the main logic of the approach consists in establishing a relation among different hierarchical levels and different dimensions of analysis. Characterizing functional elements in relation to the whole system (levels n+1, n, n−1) the approach bridges the biophysical and economic dimension of sustainability. Characterizing structural elements (levels n−2, n−1, n) the approach links the technical and ecological dimension of sustainability. The proposed quantitative representation organized over a specified set of functional and structural elements forces the analyst to address the "why, what and how questions": What is produced and consumed? How are goods and services produced and consumed and by whom? Why these goods and services and why these modalities? Why does the society express this specific pattern of functions and not another? A transparent analysis of the what, how and why questions represent an effective application of nexus thinking in the form of quantitative story-telling and a good starting point to improve research and policy approaches in complex landscapes.

AUTHOR CONTRIBUTIONS

MG developed the MuSIASEM methodology. RG applied the methodology to charcoal producing systems.

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REFERENCES

Ahl, V., and Allen, T. F. H. (1996). *Hierarchy Theory: A Vision, Vocabulary, and Epistemology.* New York, NY: Columbia University Press.

Allen, T. F. H., and Starr, T. B. (1982). *Hierarchy Perspectives for Ecological Complexity.* Chicago, IL: University of Chicago Press.

Broto, V. C., Allen, A., and Rapoport, E. (2012). Interdisciplinary perspectives on urban metabolism. *J. Ind. Ecol.* 16, 851–861. doi: 10.1111/j.1530-9290.2012.00556.x

Butz, R. J. (2013). Energy for Sustainable Development Changing land management : a case study of charcoal production among a group of pastoral women in northern Tanzania. *Energy Sustain. Dev.* 17, 138–145. doi: 10.1016/j.esd.2012.11.001

Chidumayo, E. N., and Gumbo, D. J. (2013). Energy for Sustainable Development The environmental impacts of charcoal production in tropical ecosystems of the world : a synthesis. *Energy Sustain. Dev.* 17, 86–94. doi: 10.1016/j.esd.2012.07.004

Cottrell, F. (1955). *Energy and Society: The Relation between Energy, Social Changes, and Economic Development.* New York, NY: McGraw-Hill.

Daniels, P. L. (2002). Approaches for quantifying the metabolism of physical economies: a comparative survey: Part II: review of individual approaches. *J. Ind. Ecol.* 6, 65–88. doi: 10.1162/108819802320971641

Fischer-Kowalski, M., and Hüttler, W. (1998). Society's metabolism. *J. Ind. Ecol.* 2, 107–136. doi: 10.1162/jiec.1998.2.4.107

Ghilardi, A., Mwampamba, T., and Dutt, G. (2013). Energy for Sustainable Development What role will charcoal play in the coming decades? Insights from up-to-date fi ndings and reviews. *Energy Sustain. Dev.* 17, 73–74. doi: 10.1016/j.esd.2013.02.007

Giampietro, M. (2014). "The scientific basis of the narrative of societal and ecosystem metabolism," in *Resource Accounting for Sustainability: The Nexus between Energy, Food, Water and Land Use,* eds M. Giampietro, R. Aspinall, J. Ramos-Martin, and S. G. F. Bukkens (New York, NY: Routledge), 250.

Giampietro, M., Aspinall, R., Ramos-Martin, J., and Bukkens, S. G. F. (2014). *Resource Accounting for Sustainability Assessment: The Nexus between Energy, Food, Water and Land Use.* New York, NY: Routledge.

Giampietro, M., and Bukkens, S. G. F. (2015). Analogy between Sudoku and the multi-scale integrated analysis of societal metabolism. *Ecol. Inform.* 26, 18–28. doi: 10.1016/j.ecoinf.2014.07.007

Giampietro, M., Mayumi, K., and Ramos-Martin, J. (2009). Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): theoretical concepts and basic rationale. *Energy* 34, 313–322. doi: 10.1016/j.energy.2008.07.020

Giampietro, M., Mayumi, K., and Sorman, A. H. (2011). *The Metabolic Pattern of Societies: Where Economists Fall Short.* New York, NY: Routledge.

Koestler, A. (1968). *The Ghost in the Machine.* New York, NY: Macmillan.

Lomas, P. L., and Giampietro, M. (2017). Environmental accounting for ecosystem conservation: linking societal and ecosystem metabolisms. *Ecol. Modell.* 346, 10–19. doi: 10.1016/j.ecolmodel.2016.12.009

Lotka, A. J. (1922). Contribution to the energetics of evolution. *Proc. Natl. Acad. Sci. U.S.A.* 8, 147–151. doi: 10.1073/pnas.8.6.147

Lotka, A. J. (1956). *Elements of Mathematical Biology.* New York, NY: Dover Publications Inc.

Louie, A. (2009). *More Than Life Itself: A Synthetic Continuation in Relational Biology (Categories)* Vol. 1. Berlin: Walter de Gruyter.

Louie, A. H. (2013). *The Reflection of Life.* New York, NY: Springer.

Madrid-López, C., and Giampietro, M. (2015). The water metabolism of socio-ecological systems: reflections and a conceptual framework. *J. Ind. Ecol.* 19, 853–865. doi: 10.1111/jiec.12340

Martinez-Alier, J. (1987). *Ecological Economics: Energy, Environment and Society.* Oxford: Basil Blackwell.

Mayumi, K. (2002). *The Origins of Ecological Economics: The Bioeconomics of Nicholas Georgescu-Roegen.* New York, NY: Routledge.

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, 75–85. doi: 10.1016/j.esd.2013.01.001

Ostwald, W. (1907). The modern theory of energetics. *Monist* 17, 481–515. doi: 10.5840/monist190717424

Ostwald, W. (1911). Efficiency. *Independent* 71, 867–871.

Rosen, R. (1958). A relational theory of biological systems. *Bull. Math. Biophys.* 20, 245–260. doi: 10.1007/BF02478302

Rosen, R. (1985). "Organisms as causal systems which are not mechanisms: an essay into the nature of complexity," in *Theoretical Biology and Complexity,* eds I. W. Richardson, A. H. Y. Louie, and R. Rosen (Orlando, FL: Academic Press), 165–203. doi: 10.1016/B978-0-12-597280-2.50008-8

Salthe, S. N. (1985). *Evolving Hierarchical Systems: Their Structure and Representation.* New York, NY: Columbia University Press.

Serrano-Tovar, T., and Giampietro, M. (2014). Multi-scale integrated analysis of rural Laos: studying metabolic patterns of land uses across different levels and scales. *Land Use Policy* 36, 155–170. doi: 10.1016/j.landusepol.2013.08.003

Soddy, F. (1926). *Virtual Wealth and Debt: The Solution of the Economic Paradox.* London: George Allen & Unwin.

Swyngedouw, E. (2006). Circulations and metabolisms: (Hybrid) Natures and (Cyborg) cities. *Sci. Cult.* 15, 105–121. doi: 10.1080/09505430600707970

White, L. A. (1943). Energy and the evolution of culture. *Am. Anthropol*. 45, 335–356. doi: 10.1525/aa.1943.45.3.02a00010

Whyte, L. L., Wilson, A. G., and Wilson, D. (1969). *Hierarchical Structures*. New York, NY: Elsevier Science.

Wolman, A. (1965). The metabolism of cities. *Sci. Am*. 213, 178–190. doi: 10.1038/scientificamerican0965-178

Yokoyama, S., Okamoto, K., Takenaka, C., and Hirota, I. (2014). *Integrated Studies of Social and Natural Environmental Transition in Laos.* Tokyo: Springer.

Yuichiro, N., Okamoto, K., and Boulidam, S. (2009). Time-geographic analysis on natural resource use in a village of the vientiane plain. *Southeast Asian Stud*. 47, 426–450. doi: 10.11518/hgeog.2008.0.509.0

Zipf, G. K. (1941). *National Unity and Disunity*. Bloomington, IN: The Principia Press, inc.

Zulu, L. C. (2010). The forbidden fuel: charcoal, urban woodfuel demand and supply dynamics, community forest management and woodfuel policy in Malawi. *Energy Policy* 38, 3717–3730. doi: 10.1016/j.enpol.2010.02.050

Zulu, L. C., and Richardson, R. B. (2013). Energy for sustainable development charcoal, livelihoods, and poverty reduction : evidence from sub-Saharan Africa. *Energy Sustain. Dev*. 17, 127–137. doi: 10.1016/j.esd.2012.07.007

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A Spanner in the Works: Human–Elephant Conflict Complicates the Food–Water–Energy Nexus in Drylands of Africa

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The two major conservation issues for drylands of Africa are habitat loss or degradation and habitat fragmentation, largely from agriculture, charcoal production, and infrastructural development. A key question for management is how these landscapes can retain their critical ecological functions and services, while simultaneously supporting resilient livelihoods. It is a clear nexus question involving food (agriculture), water, and energy (fuelwood), which is complicated by human–wildlife conflicts. While these could appear disparate issues, they are closely connected in dryland forest landscapes of Africa where elephants occur close to areas of human habitation. For instance, crop failure, whether due to weather or wildlife damage, is a key driver for rural farmers seeking alternative livelihoods and incomes, one of the commonest being charcoal production. Similarly, heavy reliance on wood-based energy often leads to degradation of wildlife habitat, which heightens competition with wildlife for food and water, increasing the possibility of crop-raiding. So, for multifunctional landscapes where elephants occur in close proximity with humans, any food–water–energy nexus activities toward achieving sustainability and resilience should consider human–elephant conflicts (HECs). Here, we broach these food–water–energy nexus issues with a focus on dryland areas of Africa and HECs. We highlight an ongoing study attempting to address this nexus holistically by employing a climate-smart agriculture (CSA) and agro-forestry based design, augmented by an elephant deterrent study and an eco-charcoal production venture.

Keywords: climate-smart agriculture, human–wildlife conflict, integrated landscapes, Kasigau corridor, Tsavo ecosystem

OVERVIEW OF THE NEXUS IN DRYLANDS

Humanity requires food and water for existence, while energy is a primary driver for economic development. A growing human population, rapid economic growth and increasing prosperity and consumerism are driving up demand for food, water, and energy globally (Ozturk, 2015). The ability of existing food, water, and energy systems to meet this growing demand is constrained by the competing needs for limited resources across the different sectors. Increasingly, it has been shown that issues in the food, water, and energy sectors are closely interwoven and cannot be managed effectively without cross-sectoral integration. In South Asia for instance, Rasul (2014) demonstrated a high degree of dependency of downstream communities on upstream ecosystem services for dry-season water for irrigation and hydropower, drinking water, and soil fertility and nutrients. Globally, agriculture is the largest consumer of water, while energy is required to produce and distribute water and food; energy production such as, hydropower also requires water. As such, exploiting synergies and balancing trade-offs between food production systems and water and energy use is critical for ensuring security across the three spheres (WWAP, 2014). The nexus as used in this paper describes the point food, water, and energy systems intersect.

At this intersection, actions related to one system can, and often will, impact one or both of the other systems, making it useful to take a nexus (holistic) approach when implementing such actions. Indeed, there is increasing evidence that improved food, water, and energy security can be achieved through a nexus approach that integrates management and governance across sectors and scales, which decreases negative economic, social, and environmental externalities (Hoff, 2011). This approach recognises the interdependencies of food, water, and energy production systems, providing a good framework for assessing resource use and improving sustainability by managing trade-offs and enhancing synergies (Hellegers et al., 2008; Bazilian et al., 2011; Biggs et al., 2015). It enables decision-makers and practitioners consider cross-sectoral impacts, where co-benefits and trade-offs are made explicit, and appropriate safeguards put in place to reduce the risk that progress toward one goal will undermine progress toward another (WWAP, 2014).

Moreover, major changes are occurring with important implications for the status of the food–water–energy interface (Hellegers et al., 2008). Changing land use systems and climate variability will increase stresses on the entire nexus at multiple spatial scales, while water shortages are expected to worsen with climate change, forest loss, and growing urbanisation (Tidwell, 2016). However, the role of the food–water–energy nexus in adaptation to climate change effects has perhaps not yet been fully recognised (Rasul and Sharma, 2016). The Sustainable Development Goals (SDGs) ultimately target achieving sustainable agricultural practices, water, and energy security; indeed, the food–water–energy nexus was central to discussions regarding the development and subsequent monitoring of the SDGs (UN, 2014). This nexus underscores the linkages and relationships between the natural and human systems, particularly in the development of economically and environmentally feasible food and energy production systems. In the drylands of Africa, human–wildlife conflicts (HWCs) lie at the heart of these human–natural systems' interface (Johansson, 2008).

A recent global assessment of drylands, which cover over 40% of Earth's land surface and support close to the same proportion of the human population, found that multifunctionality was positively and significantly related to plant species richness (Maestre et al., 2012). Still, almost all of the tropical dry forests today are exposed to a variety of threats including habitat loss and climate change (Miles et al., 2006; Bestelmeyer et al., 2015). Habitat loss and degradation is driven by a combination of factors, all relevant in the food–energy–water nexus. Agricultural production (both livestock and crops) coupled with fuelwood dependence (firewood and charcoal) can result in depleted water resources (e.g., see Rasul, 2016 for impact of agriculture on water and energy). Further, the co-occurrence of humans and elephants in these dryland ecosystems sets up the potential for conflict (**Figure 1**).

HOW DO WE RECONCILE THIS?

A fundamental issue here is the direct competition for resources: watching an elephant feed, move, or drink, one wonders just how they will survive in human-dominated and increasingly agricultural landscapes, even in the absence of poaching. While the circumstances under which it happens and its ramifications have long been debated (Caughley, 1976; Western, 1989), there is clear evidence of elephant destruction of forests and woodlands (e.g., Ben-Shahar, 1993; de Beer et al., 2006; Asner and Levick, 2012; de Boer et al., 2015; cf. Chamaillé-Jammes et al., 2009). These are the same resources required not only for fuelwood and charcoal, but also for climate moderation. Besides, elephants need up hundreds of litres of water a day, just for drinking; as rainfall patterns change, humans, and wildlife are also competing for diminishing water resources.

Historically, across multiple continents, megafauna are hardest hit by the combined impacts of climatic changes and human activities, since they typically are species with low reproductive rates and rely on high adult survival (Barnosky et al., 2004; Gibbons, 2004; Burney and Flannery, 2005; Barkham, 2016; van der Kaars et al., 2017). Crucially, the human population within the countries making up the elephant range in Africa (**Figure 1**) mostly live in rural areas (Martin, 2016). In most of these elephant range countries, the minimum human density for elephant co-existence (Parker and Graham, 1989) has been exceeded, resulting in population declines and severe range contraction of elephants (Douglas-Hamilton, 1987; Bouché et al., 2011; de Boer et al., 2013; Chase et al., 2016).

For the food–water–energy nexus, the germane question is whether the multiple goals can be attained in the midst of megaherbivores like elephants. In the face of the global concern and campaign to save the elephant, this is a socio-politically sensitive question to ask. Farmers in many parts are also feeling the pressure: they are unable to articulate their interests and fears, or indeed defend their crops and resources for fear of repercussions (e.g., Woodroffe et al., 2005). This is a major determinant for the nexus' success in drylands of Africa, and calls for holistic solutions that explicitly incorporate human–elephant conflict (HEC) into the frame.

RE-CASTING THE NEXUS PROBLEM FOR AFRICAN DRYLANDS

Humans and elephants are consummate competitors; competition theory maintains that such species cannot exist in sympatry (Parker and Graham, 1989). Indeed, with expanding permanent agriculture, HEC appears to be increasing in many African ecosystems as the agricultural interface with

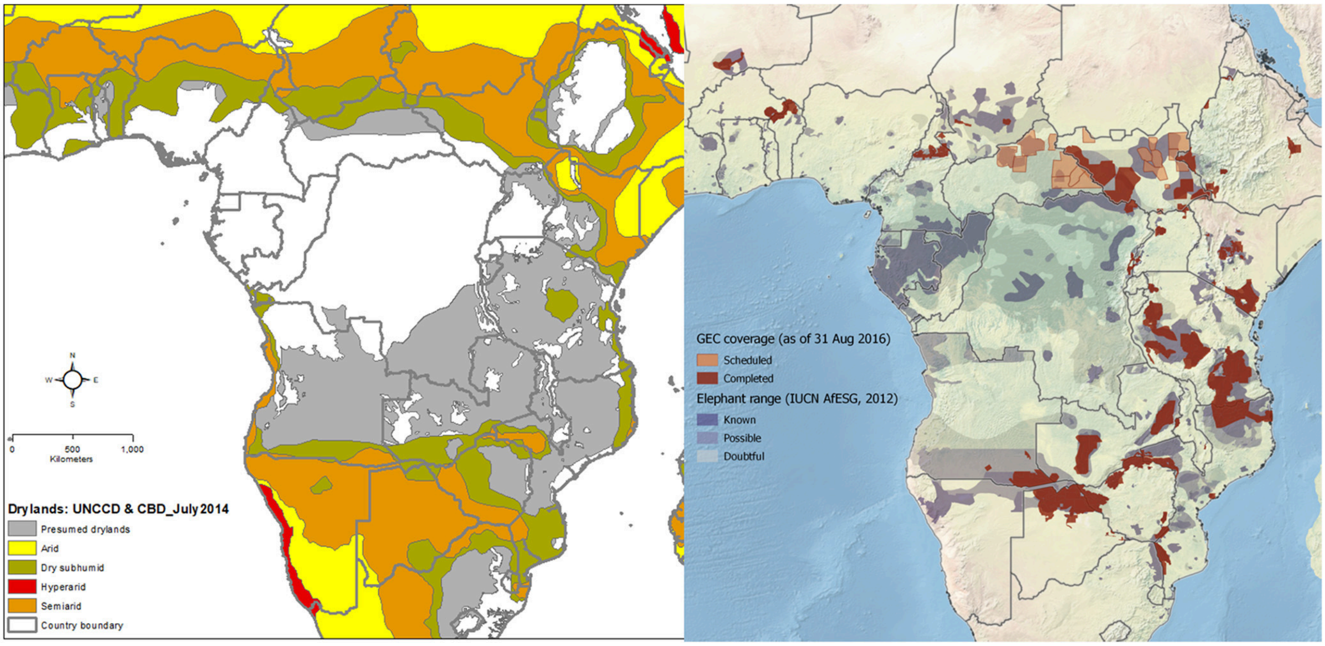

FIGURE 1 | African drylands and present-day elephant range; the drylands map adopted from UNEP-WCMC (2007), and the known elephant range map reproduced from Chase et al. (2016) and Thouless et al. (2016).

elephant range expands (Hoare, 1999; King et al., 2017). Yet, seemingly, many studies addressing food, water, and energy issues simultaneously do not consider human–wildlife conflict as a critical factor determining the outcome of any proposed solutions, for areas like the drylands of Africa where humans co-exist with elephants. This is exemplified in the following excerpt from a recent publication on drylands agriculture and climate change: *Against a backdrop of increasing climate change, a primary challenge for decision makers in the world's dry lands will be helping rural communities to earn a living and produce food securely in a situation where land is degraded, water scarce, and rainfall and temperature patterns increasingly unpredictable. Viable options and interventions exist today. They include using: improved crop varieties and livestock breeds; farming approaches to reduce risk and improve nutrition; making farming for communities living in on marginal lands more resilient; and methods for making the best possible use of the scarce water available* (Pedrick et al., 2012).

Likewise, in another seminal tome on multifunctionality in climate-smart landscapes—i.e., those that simultaneously support climate, agriculture, and conservation objectives (Scherr et al., 2012), wildlife hardly features; there are only few mentions of HWCs and their role in shaping land use outcomes in these human–natural ecosystems and landscapes (Minang et al., 2015). Although Minang and his colleagues highlight several examples of climate-smart landscapes where wildlife habitats or corridors are maintained in an otherwise agricultural matrix, only once do they mention that such diverse landscape objectives *could also influence each other negatively when wild animals damage crops grown by the farmers/agropastoralists.*

While the point of focus in these and similar publications is on the conflict for resources across the three sectors (food, water, and energy), we argue here that HEC deserves more than a cursory mention. In some situations, HEC is crucial in shaping the rest of the nexus. For instance, the scaling problem seen through low adoption or failure of farmers taking up climate-smart agriculture (CSA) and associated practices, even when they are demonstrated to have clear yield and productivity benefits (e.g., Lin, 2011; Kaczan et al., 2013), is a recurring theme. Usually, it can be traced back to HWC, and the fear or unwillingness of farmers to put effort and money toward crop production in the face of likely destruction by wildlife, especially elephants (e.g., Gupta, 2013).

Many nexus studies also recommend that landscapes and production systems could, perhaps should, be managed for multiple end uses, including habitat for wildlife and other ecosystem services (Bennett and Balvanera, 2007), yet few explain how the system will actually function on the ground (cf. Smajgl et al., 2016). Likewise, the integrated landscape management (ILM) approach seeks to achieve multiple objectives from a landscape, including agricultural production, provision of ecosystem services, and protection of biodiversity (Scherr et al., 2013). This calls for different stakeholders to weigh competing demands and balance trade-offs between diverse land uses and objectives. It has been suggested that, within such integrated landscapes: *Sustainably managed and lightly used habitat for native plants, birds, bees and beasts provides critical ecosystem services like pollination, pest predation, and wildfire and land slip* *protection, along with being culturally significant, beautiful and valuable in its own right* (LPFN, 2015).

Besides no mention of potential problems with this set up, it is also unclear how it is to be implemented on the ground. The outlined recommendations for action (LPFN, 2015) do not indicate how to resolve the thorny HWC issues that would often accompany these landscapes, if they are successfully established. For elephants in particular, there are numerous examples in Africa and elsewhere of the economic and social losses to human societies associated with living in close proximity with them. These range from economic (mainly crop-related) losses (Sitati et al., 2003; Sitienei et al., 2014), social (Naughton et al., 1999), health (Jadhav and Barua, 2012), and sometimes multiple effects (Mackenzie and Ahabyona, 2012).

As such, it is worth asking: for whom is the landscape being structured (e.g., Githiru, 2007). The farmer will almost always see elephants as a nuisance; a dangerous and destructive pest (Twine and Magome, 2008). If farmers perceive an inordinate risk of crop damage by wildlife, farming could be altered or abandoned entirely despite suitable technology, seeds, etc. (see e.g., Williams, 2009; Gupta, 2013; McGuinness and Taylor, 2014; Vidija, 2017). What then would be their motivation to build a multifunctional landscape that jeopardises their fields even whilst conserving wildlife and wildlife habitats? At a policy level, this could also be seen from the perspective of revenue-sharing regarding the commons (sensu Hardin, 1968), whereby elephants destroy the farmer's *own* crops, but the bulk of tourism revenues go to the *State* before trickling back to the community (also in the collective sense), if they do.

We postulate that, if the integrated landscape idea was written by a farmer, it would have a very different design. Perhaps the reason HWC hardly features in these conversations, besides perhaps an inadvertent underrating of the magnitude and ramifications of the problem, is the thorny nature of any solutions (e.g., Hoare, 2012). Nonetheless, we believe that the problem should be brought to the fore in conversations around the food–water–energy nexus in drylands of Africa, if we are to have a more complete picture of trade-offs, and a better understanding of the reasons for poor uptake of certain recommendations by farmers and government agencies.

CASE EXAMPLE: ELEPHANTS AND CSA, SE KENYA

In the expansive Tsavo ecosystem, SE Kenya, we have recently begun an initiative that hopes to explicitly build-in the HEC issue into some elements of the food–water–energy nexus. The primary goal of the project is working out how the dryland forest ecosystem and surrounding agricultural matrix along the Kasigau Corridor REDD+ project[1] landscape can retain their critical ecological functions and services, including the vital wildlife corridor function, whilst simultaneously supporting resilient livelihoods. The major drivers of deforestation justifying the REDD+ project were identified as charcoal production and slash-and-burn agriculture (WWC, 2011). While the later happens in frontier areas typically prone to HEC, there are additional HEC issues for more established farms due to increased degradation of elephant habitat and reduced connectivity especially due to mega-infrastructure projects. As such, though a key point of entry into the food–water–energy nexus in this context is charcoal production, both social (income source) and biological (habitat degradation) aspects, dealing with this issue demands looking at root causes. An important root cause here is HEC's influence on farming decisions and impact on yields. Consequently, the ongoing study is moulded around the following objectives related to the nexus and HEC:

- Food, Water, and Energy: Develop the applied science of sustainable intensification of crop production using CSA, mainly involving crop diversification and agro-forestry for multiple benefits including better yields, improved water use and retention, as well as provision of fuelwood[2].
- Food and HEC: Assess the effectiveness of various low-technology deterrents, working independently or in combination, in reducing both crop damage and averting HECs.
- Biodiversity conservation and HEC: Investigate how elephant ecological research and monitoring can contribute to mitigating for HEC. This involves collecting and collating elephant population, movement, and behaviour data, which will lay the scientific foundation for an early warning system disseminated through SMS alerts and a system of warning lights.

This study hopes to give recommendations for improved food production under CSA, such as, the use of different crops or crop varieties, agro-forestry, and water retention methods like conservation agriculture, and how this can be combined with energy production and a reduction in HEC-related losses. We hope to help design a system where farmers can produce more on their farms by needing or using less water and adequately guarding against HEC, but also satisfy their energy needs from the same food production system. From the food–water–energy nexus perspective, it aspires to stop the vicious cycle where poor crop production leads to low income, which leads to habitat attrition for charcoal production, in turn leading to increased HEC and even lower yields.

CONCLUSION

It is worth reiterating here that the core thrust of this paper mainly concerns the drylands of Africa where agricultural lands lie adjacent to wildlife areas and are prone to human–wildlife conflict, especially as pertains to elephants. Perfect-looking solutions for the food–water–energy nexus in these areas e.g., integrated landscapes involving increasing tree cover and crop diversification that help increase productivity and conserve

[1] The REDD+ project area covers 2,000 km^2 of *Acacia-Commiphora* dryland forest, with a human population of about 100,000 living adjacent to this area (WWC, 2010, 2011).

[2] Alongside this is a separate effort developing a simple eco-charcoal production technology that the farmers can apply on their farms to make charcoal and briquettes for subsistence and small-scale commercial use.

water resources, will remain under or un-implemented if they contribute to, or are perceived by the farmers to contribute to, increased HWC. While poaching remains an extremely emotive subject, loss of habitats, and associated HEC are perhaps more insidious, relentless, and remorseless. As the human population in Africa grows, our ability and willingness to share land and the life-supporting resources with this megaherbivore will be frequently and severely tested. If multifunctional landscapes are to stand a chance, the whole food–water–energy nexus for drylands of Africa will need to be recast, considering the elephant in the room.

AUTHOR CONTRIBUTIONS

MG: Contributed to all aspects of the work including conception and design, fieldwork for case study and interpretation of community views, drafting the work and revising it critically. He gave a final approval of the version to be submitted, and consented to be accountable for all aspects of the work. UM: Contributed to conception and design, drafting the work and revising it critically. He gave a final approval of the version to be submitted, and consented to be accountable for all aspects of the work. SK: Contributed to fieldwork for case study and interpretation of community views, drafting the work and revising it critically. He gave a final approval of the version to be submitted, and consented to be accountable for all aspects of the work. BS: Contributed to conception and design, drafting the work and revising it critically. He gave a final approval of the version to be submitted, and consented to be accountable for all aspects of the work.

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REFERENCES

Asner, G. P., and Levick, S. R. (2012). Landscape-scale effects of herbivores on treefall in African savannas. *Ecol. Lett.* 15, 1211–1217. doi: 10.1111/j.1461-0248.2012.01842.x

Barkham, P. (2016). *Elephants Are the End of a 60m-Year Lineage – Last of the Megaherbivores*. Available online at: https://www.theguardian.com/environment/2016/aug/12/elephants-are-the-end-of-a-60-million-year-lineage-the-last-of-the-megaherbivores

Barnosky, A. D., Koch, P. L., Feranec, R. S., Wing, S. L., and Shabel, A. B. (2004). Assessing the causes of late Pleistocene extinctions on the continents. *Science* 306, 70–75. doi: 10.1126/science.1101476

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Bennett, E., and Balvanera, P. (2007). The future of production systems in a globalized world. *Front. Ecol. Environ.* 5:540. doi: 10.1890/1540-9295(2007)5[191:TFOPSI]2.0.CO;2

Ben-Shahar, R. (1993). Patterns of elephant damage to vegetation in northern Botswana. *Biol. Conserv*. 65, 249–256. doi: 10.1016/0006-3207(93)90057-8

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., et al. (2015). Desertification, land use, and the transformation of global drylands. *Front. Ecol. Environ.* 13, 28–36. doi: 10.1890/140162

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M. A. Horsley, J., Pauli, N., et al. (2015). Sustainable development and the water–energy–food nexus: a perspective on livelihoods. *Environ. Sci. Policy* 54, 389–397. doi: 10.1016/j.envsci.2015.08.002

Bouché, P., Douglas-Hamilton, I., Wittemyer, G., Nianogo, A. J., Doucet, J. L., Lejeune, P., et al. (2011). Will elephants soon disappear from West African Savannahs? *PLoS ONE* 6:e20619. doi: 10.1371/journal.pone.0020619

Burney, D. A., and Flannery, T. F. (2005). Fifty millennia of catastrophic extinctions after human contact. *Trends Ecol. Evol.* 20, 395–401. doi: 10.1016/j.tree.2005.04.022

Caughley, G. (1976). The elephant problem–an alternative hypothesis. *Afr. J. Ecol.* 14, 265–283. doi: 10.1111/j.1365-2028.1976.tb00242.x

Chamaillé-Jammes, S., Fritz, H., and Madzikanda, H. (2009). Piosphere contribution to landscape heterogeneity: a case study of remote-sensed woody cover in a high elephant density landscape. *Ecography* 32, 871–880. doi: 10.1111/j.1600-0587.2009.05785.x

Chase, M., Schlossberg, S., Griffin, C., Bouché, P. J., Djene, S. W., Elkan, P. W., et al. (2016). Continent-wide survey reveals massive decline in African Savannah elephants. *PeerJ* 4:e2354. doi: 10.7717/peerj.2354

de Beer, Y., Kilian, W., Versfeld, W., and van Aarde, R. J. (2006). Elephants and low rainfall alter woody vegetation in Etosha National Park, Namibia. *J. Arid Environ.* 64, 412–421. doi: 10.1016/j.jaridenv.2005.06.015

de Boer, W. F., Oort, J. W. A., Van Grover, M., and Peel, M. J. S. (2015). Elephant-mediated habitat modifications and changes in herbivore species assemblages in Sabi Sand, South Africa. *Eur. J. Wildl. Res*. 61, 491–503. doi: 10.1007/s10344-015-0919-3

de Boer, W. F., van Langevelde, F., Prins, H. H. T., de Ruiter, P. C., Blanc, J., Vis, M. J. P., et al. (2013). Understanding spatial differences in African elephant densities and occurrence, a continent-wide analysis. *Biol. Conserv.* 159, 468–476. doi: 10.1016/j.biocon.2012.10.015

Douglas-Hamilton, I. (1987). African elephants: population trends and their causes. *Oryx* 21, 11–24. doi: 10.1017/S0030605300020433

Gibbons, R. (2004). Examining the extinction of the pleistocene megafauna. *Anthropol. Sci. Spring* 22–27.

Githiru, M. (2007). Conservation in Africa: but for whom? *Oryx* 41, 119–120. doi: 10.1017/S0030605307001937

Gupta, A. C. (2013). Elephants, safety nets and agrarian culture: understanding human-wildlife conflict and rural livelihoods around Chobe National Park, Botswana. *J. Polit. Ecol*. 20, 238–254. Available online at: http://jpe.library.arizona.edu/volume_20/Gupta.pdf

Hardin, G. (1968). The tragedy of the commons. *Science* 162, 1243–1248. doi: 10.1126/science.162.3859.1243

Hellegers, P. J., Zilberman, D., Steduto, P., and McCornick, P. (2008). Interactions among water, energy, food and environment: evolving perspectives and policy issues. *Water Policy* 10, 1–10. doi: 10.2166/wp.2008.048

Hoare, R. (1999). Determinants of human-elephant conflict in a land-use mosaic. *J. Appl. Ecol.* 36, 689–700. doi: 10.1046/j.1365-2664.1999.00437.x

Hoare, R. (2012). Lessons from 15 years of human–elephant conflict mitigation: management considerations involving biological, physical and governance issues in Africa. *Pachyderm* 51, 60–74. doi: 10.1080/10871209.2015.1005855

Hoff, H. (2011). "Understanding the nexus," in *Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus* (Stockholm).

Jadhav, S., and Barua, M. (2012). The elephant vanishes: impact of human-elephant conflict on people's wellbeing. *Health Place* 18, 1356–1365. doi: 10.1016/j.healthplace.2012.06.019

Johansson, T. (2008). *Beasts on Fields. Human-Wildlife Confl icts in Nature-Culture Borderlands*. Department of Geography, Faculty of Science, University of Helsinki, Helsinki.

Kaczan, D., Arslan, A., and Lipper, L. (2013). *Climate-Smart Agriculture? A Review of Current Practice of Agroforestry and Conservation Agriculture in Malawi and Zambia*. Rome: FAO.

King, L. E., Lala, F., Nzumu, H., Mwambingu, E., and Douglas-Hamilton, I. (2017). Beehive fences as a multidimensional conflict-mitigation tool for farmers coexisting with elephants. *Conserv. Biol.* 31, 743–752. doi: 10.1111/cobi.12898

Lin, B. B. (2011). Resilience in agriculture through crop diversification: adaptive management for environmental change. *Bioscience* 61, 183–193. doi: 10.1525/bio.2011.61.3.4

LPFN (2015). *Landscape Partnerships for Sustainable Development: Achieving the SDGs through Integrated Landscape Management*. Washington, DC: EcoAgriculture Partners.

Mackenzie, C. A., and Ahabyona, P. (2012). Elephants in the garden: financial and social costs of crop raiding. *Ecol. Econ.* 75, 72–82. doi: 10.1016/j.ecolecon.2011.12.018

Maestre, F. T., Quero, J. L., Gotelli, N. J., Escudero, A., Ochoa, V., Delgado-Baquerizo, M., et al. (2012). Plant species richness and ecosystem multifunctionality in global drylands. *Science* 335, 214–218. doi: 10.1126/science.1215442

Martin, R. (2016). *Lifting Africans from Poverty is the Only Way to Save Elephants.* Available online at: https://www.theguardian.com/environment/2016/oct/01/debate-can-legal-ivory-trade-save-elephants

McGuinness, S., and Taylor, D. (2014). Farmers' perceptions and actions to decrease crop raiding by forest-dwelling primates around a rwandan forest fragment. *Hum. Dimens. Wildl.* 19, 179–190. doi: 10.1080/10871209.2014.853330

Miles, L., Newton, A. C., DeFries, R. S., Ravilious, C., May, I., Blyth, S., et al. (2006). A global overview of the conservation status of tropical dry forests. *J. Biogeogr.* 33, 491–505. doi: 10.1111/j.1365-2699.2005.01424.x

Minang, P. A., van Noordwijk, M., Freeman, O. E., Mbow, C., de Leeuw, J., and Catacutan, D. (eds.). (2015). *Climate-Smart Landscapes: Multifunctionality in Practice*. Nairobi: World Agroforestry Centre (ICRAF).

Naughton, L., Rose, R., and Treves, A. (1999). *The Social Dimensions of Human-Elephant Conflict in Africa: A Literature Review and Case Studies from Uganda and Cameroon*. Gland: IUCN.

Ozturk, I. (2015). Sustainability in the food-energy-water nexus: evidence from BRICS (Brazil, the Russian Federation, India, China, and South Africa) countries. *Energy* 93, 999–1010. doi: 10.1016/j.energy.2015.09.104

Parker, I. S. C., and Graham, A. D. (1989). Men, elephants and competition. *Symp. Zool. Soc. Lond.* 61, 241–252.

Pedrick, C., Devlin, M., and Timmermann, T. (2012). *Strategies for Combating Climate Change in Drylands Agriculture*. Doha: The International Center for Agricultural Research in the Dry Areas (ICARDA) and CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Rasul, G. (2014). Food, water, and energy security in South Asia: a nexus perspective from the hindu kush himalayan region. *Environ. Sci. Policy* 39, 35–48. doi: 10.1016/j.envsci.2014.01.010

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the sustainable development goals in South Asia. *Environ. Dev* .18, 14–25. doi: 10.1016/j.envdev.2015.12.001

Rasul, G., and Sharma, B. (2016). The nexus approach to water–energy–food security: an option for adaptation to climate change. *Clim. Policy* 16, 682–702. doi: 10.1080/14693062.2015.1029865

Scherr, S. J., Shames, S., and Friedman, R. (2012). From climate-smart agriculture to climate-smart landscapes. *Agric. Food Secur.* 1:12. doi: 10.1186/2048-7010-1-12

Scherr, S. J., Shames, S., and Friedman, R. (2013). *Defining Integrated Landscape Management for Policy Makers*. Washington, DC: EcoAgriculture Partners.

Sitati, N. W., Walpole, M. J., Smith, R. J., and Leader-Williams, N. (2003). Predicting spatial aspects of human-elephant conflict. *J. Appl. Ecol.* 40, 667–677. doi: 10.1046/j.1365-2664.2003.00828.x

Sitienei, A. J., Jiwen, G., and Ngene, S. M. (2014). Assessing the cost of living with elephants (*Loxodonta africana*) in areas adjacent to Meru National Park, Kenya. *Eur. J. Wildl. Res.* 60, 323–330. doi: 10.1007/s10344-013-0789-5

Smajgl, A., Ward, J., and Pluschke, L. (2016). The water–food–energy Nexus – realising a new paradigm. *J. Hydrol.* 533, 533–540. doi: 10.1016/j.jhydrol.2015.12.033

Thouless, C. R., Dublin, H. T., Blanc, J. J., Skinner, D.P., Daniel, T. E., Taylor, R. D., et al. (2016). African Elephant Status Report 2016: An Update from the African Elephant Database. Gland: IUCN.

Tidwell, T. L. (2016). Nexus between food, energy, water, and forest ecosystems in the USA. *J. Environ. Stud. Sci.* 6, 214–224. doi: 10.1007/s13412-016-0367-8

Twine, W., and Magome, H. (2008). "Interactions between Elephants and People," in *Elephant Management*: *A Scientific Assessment for South Africa*, eds R. J. Scholes and K. G. Mennell (Johannesburg: Wits University Press), 206–240.

UN (2014). *Introduction and Proposed Goals and Targets on Sustainable Development for the Post 2015 Development Agenda*. United Nations Online.

UNEP-WCMC (2007). *A Spatial Analysis Approach to the Global Delineation of Dryland Areas of Relevance to the CBD Programme of Work on Dry and Subhumid Lands*. Cambridge.

van der Kaars, S., Miller, G. H., Turney, C. S. M., Cook, E. J., Nürnberg, D., Schönfeld, J., et al. (2017). Humans rather than climate the primary cause of Pleistocene megafaunal extinction in Australia. *Nat. Commun.* 8:14142. doi: 10.1038/ncomms14142

Vidija, P. (2017). *Beehives Keep Invasive Jumbos Off Farms in Tsavo*. Available online at: http://www.the-star.co.ke/news/2017/02/10/beehives-keep-invasive-jumbos-off-farms-in-tsavo_c1490278

Western, D. (1989). The ecological role of elephants in Africa. *Pachyderm* 12, 42–46.

Williams, A. C. (2009). *Where Should the Elephants Go?*. Avaliable online at: http://news.bbc.co.uk/2/hi/science/nature/7828251.stm

Woodroffe, R., Thirgood, A., and Rabinowitz, S. (2005). *People and Wildlife: Conflict or Coexistence?* Cambridge: Cambridge University Press.

WWAP (2014). *The United Nations World Water Development Report 2014: Water and Energy*. Paris.

WWC (2010). *The Kasigau Corridor REDD Project Phase I–Rukinga Sanctuary*. Wildlife Works Carbon.

WWC (2011). *The Kasigau Corridor REDD Project Phase II - The Community Ranches*. Wildlife Works Carbon.

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Applying the Water-Energy-Food Nexus to the Charcoal Value Chain

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Globally, natural resources are increasingly under pressure, especially due to population growth, economic growth and transformation as well as climate change. As a result, the water, energy, and food (WEF) nexus approach has emerged to understand interdependencies and commonly manage resources within a multi-scale and multi-level framework. In Sub-Saharan Africa, the high and growing consumption of traditional biomass for cooking purposes - notably fuelwood and charcoal—is both a key source of energy and contributor for food security as well as a pressure on natural resources. Improving the bioenergy value chains is essential for limiting environmental degradation and for securing the livelihoods of millions of people. Although the WEF nexus approach entails large potential to address the complex problems arising along the bioenergy value chains, these are currently not considered. Based on the WEF nexus approach, we analyze the different steps within the charcoal value chain in Sub-Saharan Africa and highlight the respective interdependencies and the potential for improving overall socio-economic and environmental sustainability. We emphasize the water, energy and food related implications of vicious and virtuous production cycles, separated by value chain segments. We discuss the potential and major challenges for implementing more sustainable value chains. Furthermore, we underline the necessity of applying WEF nexus approaches to these value chains in order to optimize environmental and social outcomes.

Keywords: WEF, nexus, value chain, traditional biomass, sustainability, Sub-Saharan Africa, wood energy

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THE WATER-ENERGY-FOOD NEXUS

Since 1980, the planet has lost about 50% of its biodiversity (WWF, 2016), with 33% of land moderately to highly degraded (FAO, 2015) and water resources overexploited in more than 30 countries (UNEP, 2008). Pressure on these natural resources rises with rising populations and demand for various natural-resource-dependant products. Global demand for water (Foresight, 2011), energy (IEA, 2013), and food (FAO, 2009) is expected to increase between 60 and 85% in the coming decades, especially in fast growing, underdeveloped countries. Developments for these resources and the linked sectors are intimately interwoven.

In response, the WEF (Water, Energy, Food) nexus approach has emerged as a concept for the analysis and management of the complex global resource systems (World Economic Forum, 2011; FAO, 2014; Yumkella and Yillia, 2015). It acknowledges that the joint understanding and sustainable management of water, energy, and food is critical for maintaining the provision of ecosystem services and thus achieving livelihood security (Beisheim, 2013; Schomers and Matzdorf, 2013; Spiegelberg et al., 2015). Therefore, the WEF nexus approach is multi-dimensional, integrating management and governance systems across sectors and scales (Hoff, 2011). Overcoming silo thinking (Hussey and Pittock, 2012; Rasul, 2016) is its main aim (FAO, 2014) and cross-sectoral linkages, costs and benefits are therefore an integral analytical focus (Ringler et al., 2013; Semertzidis, 2015). Hoff (2011) outlines the three central guiding principles as (1) investing to sustain ecosystem services; (2) creating more with less; and (3) accelerating access and integrating the poorest.

With this article we argue that the WEF nexus approach is an especially well suited concept for tackling a major and strongly disputed economic, social, and environmental issue in SSA: charcoal production. With a WEF perspective, we look at the entire charcoal value chain and summarize the socio-economic and environmental issues and potential technical, political, and institutional solutions. Through this integrated approach, we link an old issue to a variety of new international developments, including the ecosystem service concept, new food security approaches, the bio-economy move and the SDGs, which start to trigger a host of new national policies and funding initiatives.

CHARCOAL IN SUB-SAHARAN AFRICA

Charcoal plays an extremely large but often overlooked role in many developing countries. Food security for up to three billion individuals (Jagger and Shively, 2014; Urmee and Gyamfi, 2014) depends on bioenergy for cooking (Makungwa et al., 2013), with wood based bioenergy accounting for roughly 10% of global primary energy (Bailis et al., 2015). In SSA, up to 90% of the primary energy consumption are based on wood (Sosovele, 2010), representing up to 3% of national GDP, with charcoal being the preferred choice of urban households (Santos et al., 2017). For Dar es Salaam for instance, it is calculated that a 1% increase in urbanization leads to a 14% increase in charcoal demand (Hosier et al., 1993). Although rather old, this figure is substantiated by the reported growth of charcoal consumption in Tanzania as published by Peter and Sander (2009) (one million tons in 2009) and CAMCO (2014) (2.3 million tons in 2012). In SSA in total, the charcoal value chain employs up to 13 million people (Openshaw, 2010) and generates $8 billion in economic activity annually (UNCCD, 2015).

The discussion whether and to which extent charcoal production contributes to deforestation and forest degradation (DFD) (Butz, 2013; Chidumayo et al., 2013; Sander et al., 2013; Schure et al., 2013; Zulu and Richardson, 2013; Smith et al., 2015; Ndegwa et al., 2016) or not (Minten et al., 2013; Mwampamba et al., 2013; Owen et al., 2013) is ongoing. In a recent meta-study FAO (2017) summarizes that "*where demand is high, mainly in [SSA] [. . .], unsustainable wood harvesting and charcoal production contribute to forest degradation and deforestation [. . .]*" (p. 2). We follow this assessment and include this negative consequence in our analysis even though context specificity remains essential. Nevertheless: Politically, claimed DFD remains an important argument against constructive charcoal policies and projects. The importance of the value chain is overlooked, neglected, or evaded by national governments (Doggart and Meshack, 2017), donors and implementing agencies (Kees and Feldmann, 2011). If at all, usually only partial attempts were made to intervene into the charcoal value chain, often with a biased attitude toward it. Prominent examples include efforts to plant wood lots as a substitute for forest harvesting (Chamshama et al., 2010), to improve the efficiency of cooking (Hanna et al., 2012), to regulate the sector with central government control (Schure et al., 2013), and to substitute wood energy (Bazilian et al., 2011).

However, many of these efforts were relatively unsuccessful, and most were insufficient to change the negative public image of charcoal. But given its huge present and future importance, renewed efforts to improving this value chain are imperative if not only minor energy and resource challenges but arguably one of the largest WEF ones is to be tackled.

WEF NEXUS AND CHARCOAL IN SSA

This perspective article argues that it is urgent to anew tackle the charcoal issue as one of the key challenges for energy, food, and water security in SSA. The WEF nexus approach applied to the charcoal value chain resumes not only its problems but also its strengths and positive provisions. The wider ecosystem services approach looks beyond WEF and also takes on board other services of trees and forests such as biodiversity and climate regulation. We want to demonstrate that these new concepts are especially well-suited to address and overcome existing multi-dimensional challenges and to support the development of sustainable charcoal value chains. This new perspective is argued to accommodate recent political multi-dimensional initiatives, notably the Agenda 2030. However, traditional bioenergy including charcoal does not play a role in WEF nexus and ecosystem services approaches yet and we therefore urge researchers and policy makers to apply them to charcoal value chains on all scales to close this gap and therewith help to solve challenges that have been present for many decades. In sum, we aim to implement a paradigm shift toward joint research and political action between ministries, programs, and policies. The analysis is based on a literature review.

ANALYSIS OF VALUE CHAIN ELEMENTS

WEF nexus aspects and dimensions of sustainability along the charcoal value chain in SSA are analyzed and discussed as outlined in **Figure 1**. Major analytical trajectories are separated into (**Figure 1A**) socio-economic and (**Figure 1B**) environmental spheres.

(1) Production/Harvesting

Charcoal in SSA is mainly produced via informal/illegal extraction and carbonization of wood resources from forested areas (Kwarteng, 2015; FAO, 2017) although the role of trees outside forests remains unclear (Neufeldt et al., 2015). Wood cutting for charcoal is commonly associated with DFD (**Figure 1B**) even though this effect is questioned by researchers. In the prevailing charcoal production system, the harvesting of

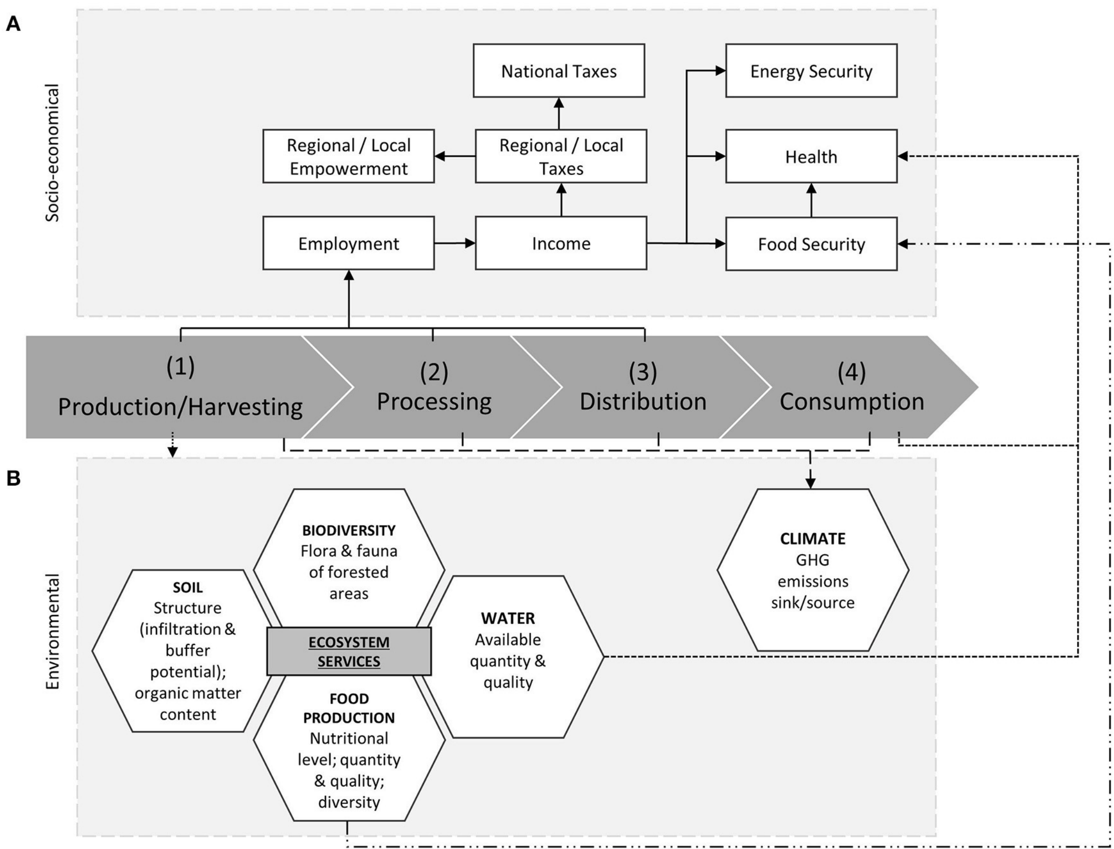

FIGURE 1 | Analytical framework for charcoal value chain assessment with focus on sustainability dimensions (**A**: socio-economical; **B**: environmental) and WEF nexus analysis (adapted from Peter and Sander, 2009).

wood resources occurs in close proximity to the kiln (Luoga et al., 2000), thus resulting in potentially harmful effects being local. As larger log pieces are preferred for charcoal production, the composition of age classes in the affected forested areas shifts toward smaller and younger trees. Selective tree cutting also occurs as some tree species are better suited for charcoal production than others (Ndegwa et al., 2016). These processes result in reduced biodiversity and lowered biomass input into soils. There are potentially further negative consequences for water quality and quantity (Lele, 2009) and biota and bioturbation, leading to poorer soil quality. Consequently, soil erosion takes place (Zimmermann et al., 2006; Mohammad and Adam, 2010) which might also affect crop production negatively.

In the prevailing—potentially extractive—system of charcoal production, neither reforestation nor afforestation occurs; thus neither relevant job opportunities nor downstream effects are created (**Figure 1A**). Due to the de facto unregulated character of charcoal production in most SSA countries, negligible taxes are paid and the governments do not receive any revenues. However, food security is increased temporarily as overall household income rises. Positive environmental effects are also widely absent (**Figure 1B**).

Sustainable management of (natural) forests or the implementation of locally adapted agro-forestry systems is more positive as biodiversity and water flows are largely maintained. However, the implementation of joint food/wood production in locally adapted agroforestry systems is critical for long-term success, especially when focusing on the WEF nexus—even though the adaptation of sustainable agroforestry systems is already challenging (Pollini, 2009; Jerneck and Olsson, 2013). A careful implementation of agroforestry systems could also create rural job opportunities, with higher and more diversified incomes Leakey (2014) (**Figure 1A**).

On the environmental side (**Figure 1B**), agroforestry systems can improve local soil and water quality, the available water quantity, biodiversity in the agroforestry landscapes and food production (Sanchez, 2002, 2010; Mugo and Ong, 2006).

Charcoal production represents a significant transfer of financial resources from urban to rural areas and is perceived as an "*engine of economic growth*" (p. 297) from Van Der Plas and Abdel-Hamid (2005). Thus, sustainable charcoal production can be understood as a pro-poor development measure because it increasing and stabilizing incomes, especially in rural areas (Ahrends et al., 2010; **Figure 1A**).

(2) Processing

Currently, carbonization mainly takes place in traditional earth mound kilns with low conversion efficiencies (e.g., Tabuti et al., 2003; Peter and Sander, 2009). This low conversion factor is due to insufficient drying of wood, non-uniformity of input material and often due to lacking experience of the producers (Kammen and Lew, 2005). Kiln performance directly affects environmental conditions, as the choice of the technology and the knowledge of the producer regulates the amount and the composition of trees used (**Figure 1B**). However, directly at the kiln site, remaining charcoal particles might improve soil fertility and water holding capacity and therefore food production ("Terra Preta") (Barrow, 2012).

In an optimized system, knowledge on improved production techniques could be disseminated and respective training measures could be applied. Improved charcoal production processes can reach carbonization rates of up to 30% (Iiyama et al., 2014), thereby minimizing energy losses. The latter will most likely contribute positively toward woody resources, biodiversity conservation and climate change (**Figure 1B**). Furthermore, leftover particles might be used more effectively for soil improvement when e.g., being spread on farms.

Productivity and subsequent income opportunities for charcoal producers would also increase, thereby decreasing food insecurity, especially during times of poor harvests (**Figure 1A**).

(3) Distribution

Distribution of charcoal in the current system is mainly organized by the most influential group of wholesalers and vehicle transporters (Sander et al., 2013), who receive the majority of profits (Mwampamba et al., 2013). A smaller quantity of transport is also realized via bicycles. In Malawi, for example, 13% of the 92,000 people involved in the charcoal business are bicycle transporters (Kambewa et al., 2007). Thus, this transportation pathway is a factor for livelihood and food security, at least in semi-urban areas.

Looking at the environmental effects of distribution (**Figure 1B**), current transportation relies mainly on trucks driven by fossil fuels, but Gmünder et al. (2014) report that, "*transportation plays a small role in charcoal's climate impact*" (p. 82). Thus, the environmental optimization potential of the transportation sector is rather limited. Data on the labor effects and working conditions of individuals involved in charcoal distribution is absent.

Legalized charcoal transport, wholesale and retail, however, may not alter material flows substantially, but it would generate tax revenues that could be used to support social services, including food security programs (**Figure 1A**). Whether a change of the current status for wholesalers and retailers occurs depends on the strategy applied, operating official trading points seem promising.

(4) Consumption

Charcoal is the major fuel in larger settlements: in East Africa, up to 90% of urban households rely on it (UNCCD, 2015), even though high levels of indoor air pollution (IAP) result (Dherani et al., 2008). Charcoal can be used in either traditional charcoal cooking stoves or in improved cooking stoves (ICS). The type of stove commonly used depends on a variety of factors, especially the (former) existence of stove dissemination programs (Ruiz-Mercado et al., 2011), including the cultural and social fitting of stove design (Bielecki and Wingenbach, 2014; Confino and Paddison, 2014), and the price of charcoal (Mobarak et al., 2012; Guta, 2014). Thus, adoption rates and rationales are highly site-specific and no conclusive overall analyses are available (Johnson and Bryden, 2012; Lewis and Pattanayak, 2012). An improved charcoal value chain must nevertheless include ICS, as their successful application most likely results in substantially reduced charcoal consumption.

In particular, the emissions and fuel efficiency of stoves are important with regard to the environmental effects (**Figure 1B**). Combustion characteristics and efficiency rates differ due to differing stove designs (Maccarty et al., 2010). The potential of ICS to improve the efficiency of charcoal use is assessed differently but Kshirsagar and Kalamkar (2014) as well as Hutton et al. (2006) report fuel savings of 30–34% which might be accepted as close-to-real value.

Synopsis of Improved Value Chain

An improved value chain that simultaneously addresses sustainability challenges of the charcoal value chain related to water, energy, and food must necessarily include sustainable wood production, preferable in agroforestry systems. Harvesting procedures should be optimized by applying locally adapted harvesting techniques in adequate areas. The widespread utilization of improved charcoal kilns and ICS is likewise important for long-term success. Improvements to the value chain should also include reliable and balanced taxation systems as this is likely to harmonize minimal ecological impacts with specific stakeholder needs (**Figure 1A**). In order to ensure that higher incentives do not lead to unsustainable harvests, harvesting rates must be regulated depending on local conditions. Additionally, patches of old forest should be conserved to foster soil protection and natural regrowth of particularly vulnerable or precious pieces of land (Hoffmann et al., 2016).

Water, energy, and food related implications of vicious and virtuous production cycles as well as biodiversity and climate issues are summarized in **Table 1**.

DISCUSSION AND CONCLUSION

The wood-energy sector is politically neglected in SSA (Doggart and Meshack, 2017) though it is huge and projected to increase. Thus, pressures on natural resources will increase too, even if the extent of its contribution to overall resource degradation is debated. We have collected arguments and evidence that charcoal value chains can be organized in a sustainable and inclusive way. To truly enhance the sustainable development of this sector, it must move up the political agenda. Both science and policy must acknowledge its environmental, social, and economic importance and its status as the most important renewable energy source in SSA for now and for decades to come. The establishment of sustainable charcoal value chains is essential for limiting environmental degradation that might

TABLE 1 | Summary of water, energy and food related implications of vicious and virtuous production cycles, separated by value chain segments.

Vicious cycle—current system			Virtuous cycle—improved system	
Socio-Economic	**Environmental**		**Socio-Economic**	**Environmental**
No additional job creation, no additional downstream activities No taxes (at regional, local or national level) No regional and local empowerment No adequate revenue share, pot. negative effect on food production	Forest degradation and deforestation, soil erosion, reduction of soil organic matter content Decreases in water quality and quantity Increasing climate change Selective cutting (reduction of biodiversity, older trees and charcoal prone tree species)	**Production/ Harvesting**	Job opportunities Higher and more stable (additional) income opportunities for rural population, trees as flexible cash crops Increased income and sustained livelihoods, improved food security Increased tax payments	Improved soil and water quality and quantity Increased biodiversity Carbon sequestration Nutrient replenishment Locally adopted cutting system Reduction of siltation, patches of old forest can remain
No tax payment Low quality jobs	Reduced biodiversity Reduced water quality and quantity Contribution to climate change (low kiln efficiency) Potentially positive: “Terra preta” (locally)	**Processing**	Increased income generation and food security Increased tax payments	Reduced resources consumption Reduced climate change emissions (higher efficiencies of kilns)
Highly unequal power and revenue sharing No tax payments	Fossil fuels use (trucks)	**Distribution**	Increased tax revenues More equal power & revenue sharing Increased income for producers and processors → increased food security	Depending on system applied, potentially no substantial changes
High level of indoor air pollution (IAP)	Low combustion efficiency → high levels of resource consumption	**Consumption**	Reduced level of IAP by using improved cooking stoves (ICS)	Decreasing emissions and resource consumption by using ICS

occur. Research approaches and development strategies that truly integrate and harmonize all sectors and scales throughout the charcoal value chain simultaneously should be prioritized as the respective sectoral and scale interdependencies remain excluded from governmental strategies so far.

We show that the WEF nexus approach offers a promising toolbox to do so: it can function as an intellectual bridge to overcome the separation of scales, sectors, and political spheres along the charcoal value chain, thus helping to improve its understanding and sustainable management. Recent international developments and initiatives invite to such a multi-dimensional approach: The Agenda 2030 requests to have integrate views on its sustainable development goals (SDGs) of which many can be directly linked to the charcoal value chain as we have shown: poverty (SDG 1), food security (SDG 2), health (SDG 3), energy (SDG 7), decent work (SDG 8), industry and innovation (SDG 9), sustainable cities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life on land (SDG 15), and partnerships (SDG 17) (United Nations, 2015). There are new efforts to link the three Rio environmental conventions on biodiversity, climate change, and desertification and produce joint environmental and social co-benefits. New public and private funds are set up to finance sustainable energy and development projects and usually have to show (more or less stringent) multi-dimensional positive impacts and due diligence for negative ones (DIE/GDI, 2017).

While all these new initiatives promise to support exactly the type of development-friendly charcoal production we have shown to be possible, charcoal value chains have not been studied within the context of WEF nexus approaches and concepts so far. Currently, WEF nexus projects mainly focus on urban areas and middle-income classes in rising (Asian) developing countries (Spiegelberg et al., 2015) while the overall challenges associated with sustainable bioenergy provision mainly occur in SSA. In line with this, Endo et al. (2017) report that <4% of actors involved in WEF nexus projects are African. Furthermore, current WEF nexus frameworks are largely applied from a water-centric perspective (Smajgl et al., 2016; Endo et al., 2017). However, the guiding principles of the WEF nexus approach, as outlined by Hoff (2011), entail very promising contact points with the charcoal sector in SSA: The implementation of sustainable wood production value chains represents a major contribution to sustaining ecosystem service (1st WEF nexus principle). Creating more with less (2nd WEF nexus principle) is mirrored in approaches to increase the efficiency of the existing charcoal production and consumption systems. As charcoal production is often the domain of socially marginalized groups (Khundi et al., 2011; Zulu and Richardson, 2013; Jones et al., 2016), efforts to allocate more financial resources to producers via implementation of inclusivity contribute toward integrating the poorest (3rd WEF nexus principle).

In conclusion, the development of environmentally sound, socially inclusive and economically charcoal value chains—an old, large and unsolved challenge particularly in SSA—could gain new impetus in a new political setting which requests integrated multi-dimensional solutions. The WEF and extended environmental service approach can organize the evidence and arguments in a comprehensive way.

AUTHOR CONTRIBUTION

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

Ahrends, A., Burgess, N. D., Milledge, S. A. H., Bulling, M. T., Fisher, B., Smart, J. C. R., et al. (2010). Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proc. Natl. Acad. Sci. U.S.A.* 107, 14556–14561. doi: 10.1073/pnas.0914471107

Bailis, R., Drigo, R., Ghilardi, A., and Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nat. Clim. Change* 5, 266–272. doi: 10.1038/nclimate2491

Barrow, C. J. (2012). Biochar: potential for countering land degradation and for improving agriculture. *Appl. Geography* 34, 21–28. doi: 10.1016/j.apgeog.2011.09.008

Bazilian, M., Cordes, L., Nussbaumer, P., and Yager, A. (2011). Partnerships for access to modern cooking fuels and technologies. *Curr. Opin. Environ. Sustain.* 3, 254–259. doi: 10.1016/j.cosust.2011.05.004

Beisheim, M. (2013). *Der Nexus Wasser-Energie-Nahrung. Wie mit vernetzten Versorgungsrisiken umgehen?* Berlin: Stiftung Wissenschaft und Politik.

Bielecki, C., and Wingenbach, G. (2014). Rethinking improved cookstove diffusion programs: a case study of social perceptions and cooking choices in rural Guatemala. *Energy Policy* 66, 350–358. doi: 10.1016/j.enpol.2013.10.082

Butz, R. J. (2013). Changing land management: a case study of charcoal production among a group of pastoral women in northern Tanzania. *Energy Sustain. Dev.* 17, 138–145. doi: 10.1016/j.esd.2012.11.001

CAMCO (2014). *Biomass Energy Strategy (best) Tanzania. Tanzania Biomass Energy Strategy and Action Plan*. Final report. 138. Dar es Salaam: euei pdf - European Union Energy Initiative Partnership Dialogue Facility.

Chamshama, S., Savadogo, P., and Marunda, C. (2010). "Plantations and Woodlots in Africa's Dry Forests and Woodlands," in *The Dry Forests and Woodlands in Africa. Managing for Products and Services,* eds E. N. Chidumay, and D. J. Gumbo (London, Washington, DC: Earthscan), 205–230.

Chidumayo, E. N., and D. J., Gumbo (2013). The environmental impacts of charcoal production in tropical ecosystems of the world: a synthesis. *Energy Sustain. Dev*, 17, 86–94. doi: 10.1016/j.esd.2012.07.004

Confino, J., and Paddison, L. (2014). *Cookstove Designs are Failing the Poorest Communities.* London, UK: Guardian News & Media Ltd. Available online at: http://www.theguardian.com/sustainable-business/cookstoves-design-poor-communities-refugees-unhcr-ikea (Accessed Sept 12, 2015).

DIE/GDI (2017). *Green Finance*. Available online at: http://www.die-gdi.de/green-finance/ (Accessed Oct 02, 2017).

Dherani, M., Pope, D., Mascarenhas, M., Smith, K. R., Weber, M., and Bruce, N. (2008). Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. *Bull World Health Organ* 86, 390–398C. doi: 10.2471/BLT.07.044529

Doggart, N., and Meshack, C. (2017). The marginalization of sustainable charcoal production in the policies of a modernizing African Nation. *Front. Environ. Sci.* 5:27. doi: 10.3389/fenvs.2017.00027

Endo, A., Tsurita, I., Burnett, K., and Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *J. Hydrol.* 11, 20–30. doi: 10.1016/j.ejrh.2015.11.010

FAO (2009). *How to Feed the World in 2050.* Rome: FAO - Food and Agriculture Organization of the United Nations.

FAO (2014). *The Water-Energy-Food-Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*. Rome: FAO - Food and Agriculture Organization of the United Nations.

FAO (2015). *Status of the World's Soil Resources.* Rome: FAO - Food and Agriculture Organization of the United Nations.

FAO (2017). *The Charcoal Transition: Greening the Charcoal Value Chain to Mitigate Climate Change and Improve Local Livelihoods*. Rome: FAO - Food and Agriculture Organization of the United Nations.

Foresight (2011). *The Future of Food and Farming*. Final Project Report. London: The Government Office for Science.

Gmünder, S., Zah, R., Rainhard, J., and Charron-Doucet, F. (2014). *Transforming Tanzania's Charcoal Sector*. *Life Cycle Assessment Component,* Zurich: Quantis Switzerland/Germany.

Guta, D. D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. *Energy Policy* 75, 217–227. doi: 10.1016/j.enpol.2014.09.017

Hanna, R., Duflo, E., and Greenstone, M. (2012). "Up in Smoke: The influence of household behavior on the long-run impact of improved cooking stoves," in *Working Paper Series* (Cambridge, MA: MIT - Massachusetts Institute of Technology; Department of Economics), 12–10.

Hoff, H. (2011). "Understanding the Nexus," in *Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus* (Stockholm: SEI - Stockholm Environment Institute).

Hoffmann, H., Brüntrup, M., and Sander, K. (2016). *At the Wooden Cross-Road, in: Rural 21*. Frankfurt: DLG-Verlag GmbH.

Hosier, R. H., Mwandosya, M. J., and Luhanga, M. L. (1993). Future energy development in Tanzania: the energy costs of urbanization. *Energy Policy* 21, 524–542. doi: 10.1016/0301-4215(93)90039-I

Hussey, K., and Pittock, J. (2012). The energy–water Nexus: managing the links between energy and water for a sustainable future. *Ecol. Soc.* 17:31. doi: 10.5751/ES-04641-170131

Hutton, G., Rehfuess, E., Tediosi, F., and Weiss, S. (2006). *Evaluation of the Costs and Benefits of Household Energy and Health Interventions at Global and Regional Level*. Geneva: WHO - World Health Organization.

IEA (2013). *World Energy Outlook 2013.* Paris: IEA - International Energy Agency.

Iiyama, M., Neufeldt, H., Dobie, P., Njenga, M., Ndegwa, G., and Jamnadass, R. (2014). The potential of agroforestry in the provision of sustainable woodfuel in sub-Saharan Africa. *Curr. Opin. Environ. Sustain.* 6, 138–147. doi: 10.1016/j.cosust.2013.12.003

Jagger, P., and Shively, G. (2014). Land use change, fuel use and respiratory health in Uganda. *Energy Policy* 67, 713–726. doi: 10.1016/j.enpol.2013.11.068

Jerneck, A., and Olsson, L. (2013). More than trees! Understanding the agroforestry adoption gap in subsistence agriculture: Insights from narrative walks in Kenya. *J. Rural Stud.* 32, 114–125. doi: 10.1016/j.jrurstud.2013.04.004

Johnson, N. G., and Bryden, K. M. (2012). Energy supply and use in a rural West African village. *Energy* 43, 283–292. doi: 10.1016/j.energy.2012.04.028

Jones, D., Ryan, C. M., and Fisher, J. (2016). Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. *Energy Sustain. Dev.* 32, 14–21. doi: 10.1016/j.esd.2016.02.009

Kambewa, P., Mataya, B., Sichinga, K., and Johnson, T. (2007). *Charcoal: the Reality. A Study of Charcoal Consumption, Trade and Production in Malawi,* London, UK: IIED - International Institute for Environment and Development.

Kammen, D. M., and Lew, D. J. (2005). *Review of Technologies for the Production and Use of Charcoal: Renewable and Appropriate Energy Laboratory Report*. Golden: National Renewable Energy Laboratory.

Kees, M., and Feldmann, L. (2011). The role of donor organisations in promoting energy efficient cook stoves. *Energy Policy* 39, 7595–7599. doi: 10.1016/j.enpol.2011.03.030

Khundi, F., Jagger, P., Shively, G., and Sserunkuuma, D. (2011). Income, poverty and charcoal production in Uganda. *For. Policy Econ.* 13, 199–205. doi: 10.1016/j.forpol.2010.11.002

Kshirsagar, M. P., and Kalamkar, V. R. (2014). A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. *Renewable Sustain. Energy Rev.* 30, 580–603. doi: 10.1016/j.rser.2013.10.039

Kwarteng, E. (2015). *Fuelwood Value Chain Analysis Literature Review Report., The USAID/Ghana Sustainable Fisheries Management Project (SFMP)*. Narragansett, RI: Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island and SNV Netherlands Development Organization.

Leakey, R. R. B. (2014). The role of trees in agroecology and sustainable agriculture in the tropics. *Ann. Rev. Phytopathol.* 52, 113–133. doi: 10.1146/annurev-phyto-102313-045838

Lele, S. (2009). Watershed services of tropical forests: from hydrology to economic valuation to integrated analysis. *Curr. Opin. Environ. Sustain.* 1, 148–155. doi: 10.1016/j.cosust.2009.10.007

Lewis, J. J., and Pattanayak, S. K. (2012). Who adopts improved fuels and cookstoves? A Systematic Review. *Environ. Health Perspect.* 120, 637–645. doi: 10.1289/ehp.1104194

Luoga, E. J., Witkowski, E. T. F., and Balkwill, K. (2000). Economics of charcoal production in miombo woodlands of eastern Tanzania: some hidden costs associated with commercialization of the resources. *Ecol. Econ.* 35, 243–257. doi: 10.1016/S0921-8009(00)00196-8

Maccarty, N., Still, D., and Ogle, D. (2010). Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy Sustain. Dev.* 14, 161–171. doi: 10.1016/j.esd.2010.06.002

Makungwa, S. D., Epulani, F., and Woodhouse, I. H. (2013). Fuelwood supply: a missed essential component in a food security equation. *J. Food Security* 1, 49–51. doi: 10.12691/jfs-1-2-6

Minten, B., K., and Sander, and, D., Stifel (2013). Forest management and economic rents: evidence from the charcoal trade in Madagascar. *Energy Sustain. Dev*. 17, 106–115. doi: 10.1016/j.esd.2012.08.004

Mobarak, A. M., Dwivedi, P., Bailis, R., Hildemann, L., and Miller, G. (2012). Low demand for nontraditional cookstove technologies. *Proc. Natl. Acad. Sci. U.S.A.* 109, 10815–10820. doi: 10.1073/pnas.1115571109

Mohammad, A. G., and Adam, M. A. (2010). The impact of vegetative cover type on runoff and soil erosion under different land uses. *CATENA* 81, 97–103. doi: 10.1016/j.catena.2010.01.008

Mugo, F., and Ong, C. (2006). "Lessons from eastern Africa's unsustainable charcoal trade," in *ICRAF Working Paper* (Nairobi: ICRAF - World Agroforestry Center.

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, 75–85. doi: 10.1016/j.esd.2013.01.001

Ndegwa, G. M., Nehren, U., Grüninger, F., Iiyama, M., Anhuf, D. (2016). Charcoal production through selective logging leads to degradation of dry woodlands: a case study from Mutomo District, Kenya. *J. Arid Land* 8, 618–631. doi: 10.1007/s40333-016-0124-6

Neufeldt, H., Dobie, P., Iiyama, M., Njenga, M., Mohan, S., and Neely, C. (2015). *Developing Sustainable Tree-Based Bioenergy Systems in Sub-Saharan Africa: ICRAF Policy Brief 28*. Nairobi: ICRAF - World Agroforestry Centre.

Openshaw, K. (2010). Biomass energy: employment generation and its contribution to poverty alleviation. *Biomass Bioenergy* 34, 365–378. doi: 10.1016/j.biombioe.2009.11.008

Owen, M., Der Plas, R. V., and Sepp, S. (2013). Can there be energy policy in Sub-Saharan Africa without biomass? *Energy Sustain. Dev*. 17, 146–152. doi: 10.1016/j.esd.2012.10.005

Peter, C., and Sander, K. (2009). *Environmental Crisis or Sustainable Development Opportunity? Transforming the Charcoal Sector in Tanzania. A policy note*. Washington, DC: The World Bank.

Pollini, J. (2009). Agroforestry and the search for alternatives to slash-and-burn cultivation: from technological optimism to a political economy of deforestation. *Agric. Ecosyst. Environ.* 133, 48–60. doi: 10.1016/j.agee.2009.05.002

Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environ. Dev*. 18, 14–25. doi: 10.1016/j.envdev.2015.12.001

Ringler, C., Bhaduri, A., and Lawford, R. (2013). The nexus across water, energy, land and food: potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain.* 5, 617–624. doi: 10.1016/j.cosust.2013.11.002

Ruiz-Mercado, I., Masera, O., Zamora, H., and Smith, K. R. (2011). Adoption and sustained use of improved cookstoves. *Energy Policy* 39, 7557–7566. doi: 10.1016/j.enpol.2011.03.028

Sanchez, P. A. (2002). Soil fertility and hunger in Africa. *Science* 295, 2019–2020. doi: 10.1126/science.1065256

Sanchez, P. A. (2010). Tripling crop yields in tropical africa. *Nat. Geosci.* 3, 299–300. doi: 10.1038/ngeo853

Sander, K., Gros, C., and Peter, C. (2013). Enabling reforms: analyzing the political economy of the charcoal sector in Tanzania. *Energy Sustain. Dev*. 17, 116–126. doi: 10.1016/j.esd.2012.11.005

Santos, M. J., Dekker, S. C., Daioglou, 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. doi: 10.3389/fenvs.2017.00028

Schomers, S., and Matzdorf, B. (2013). Payments for ecosystem services: a review and comparison of developing and industrialized countries. *Ecosyst. Services* 6, 16–30. doi: 10.1016/j.ecoser.2013.01.002

Schure, J., Ingram, V., Sakho-Jimbira, M. S., Levang, P., and Wiersum, K. F. (2013). Formalisation of charcoal value chains and livelihood outcomes in Central- and West Africa. *Energy Sustain. Dev.* 17, 95–105. doi: 10.1016/j.esd.2012.07.002

Semertzidis, T. (2015). Can Energy Systems Models Address the Resource Nexus? *Energy Procedia* 83, 279–288. doi: 10.1016/j.egypro.2015.12.182

Smajgl, A., Ward, J., and Pluschke, L. (2016). The water–food–energy Nexus – Realising a new paradigm. *J. Hydrol.* 533, 533–540. doi: 10.1016/j.jhydrol.2015.12.033

Smith, J. U., Fischer, A., Hallett, P. D., Homans, H. Y., Smith, P., Abdul-Salam, Y., et al. (2015). Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. *Renewable Sustain. Energy Rev.* 50, 903–917. doi: 10.1016/j.rser.2015.04.071

Sosovele, H. (2010). Policy challenges related to biofuel development in Tanzania. *Africa Spectrum* 45, 117–129. Available online at: http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:gbv:18-4-2505

Spiegelberg, M., Baltazar, D. E., Sarigumba, M. P. E., Orencio, P. M., Hoshino, S., Hashimoto, S., et al. (2015). Unfolding livelihood aspects of the Water–Energy–Food Nexus in the Dampalit Watershed, Philippines. *J. Hydrol*. 11, 53–68. doi: 10.1016/j.ejrh.2015.10.009

Tabuti, J. R. S., Dhillion, S. S., and Lye, K. A. (2003). Firewood use in Bulamogi County, Uganda: species selection, harvesting and consumption patterns. *Biomass Bioenergy* 25, 581–596. doi: 10.1016/S.0961-9534(03)00052-7

UNCCD (2015). *Fuel for Life. Securing the Land-Energy Nexus*. Bonn, Germany: UNCCD -United Nations Convention to Combat Desertification.

UNEP (2008). *Vital Water Graphics*. Nairobi: United Nations Environment Programme.

United Nations (2015): *Resolution adopted by the General Assembly on 25 September 2015,* New York, NY: United Nations.

Urmee, T., and Gyamfi, S. (2014). A review of improved Cookstove technologies and programs. *Renewable Sustain. Energy Rev.* 33, 625–635. doi: 10.1016/j.rser.2014.02.019

Van Der Plas, R. J., and Abdel-Hamid, M. A. (2005). Can the woodfuel supply in sub-Saharan Africa be sustainable? The case of N'Djaména, Chad. *Energy Policy* 33, 297–306. doi: 10.1016/j.enpol.2003.08.001

World Economic Forum (2011). *Water Security. The Water-Food-Energy-Climate Nexus*, Washington, DC: World Economic Forum.

WWF (2016). *Living Planet Report 2016, Risk and Resilience in a New Era.* Gland: WWF International.

Yumkella, K. K., and Yillia, P. T. (2015). Framing the Water-energy Nexus for the Post-2015 Development Agenda. *Aquatic Procedia* 5, 8–12. doi: 10.1016/j.aqpro.2015.10.003

Zimmermann, B., Elsenbeer, H., and De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: implications for runoff generation. *For. Ecol. Manag.* 222, 29–38. doi: 10.1016/j.foreco.2005.10.070

Zulu, L. C., and Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. *Energy Sustain. Dev*. 17, 127–137. doi: 10.1016/j.esd.2012.07.007

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Nexusing Charcoal in South Mozambique: A Proposal To Integrate the Nexus Charcoal-Food-Water Analysis With a Participatory Analytical and Systemic Tool

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Nexus analysis identifies and explores the synergies and trade-offs between energy, food and water systems, considered as interdependent systems interacting with contextual drivers (e.g., climate change, poverty). The nexus is, thus, a valuable analytical and policy design supporting tool to address the widely discussed links between bioenergy, food and water. In fact, the Nexus provides a more integrative and broad approach in relation to the single isolated system approach that characterizes many bioenergy analysis and policies of the last decades. In particular, for the South of Mozambique, charcoal production, food insecurity and water scarcity have been related in separated studies and, thus, it would be expected that Nexus analysis has the potential to provide the basis for integrated policies and strategies focused on charcoal as a development factor. However, to date there is no Nexus analysis focused on charcoal in Mozambique, neither is there an assessment of the comprehensiveness and relevance of Nexus analysis when applied to charcoal energy systems. To address these gaps, this work applies the Nexus to the charcoal-food-water system in Mozambique, integrating national, regional and international studies analysing the isolated, or pairs of, systems. This integration results in a novel Nexus analysis graphic for charcoal-food-water relationship. Then, to access the comprehensiveness and depth of analysis, this Nexus analysis is critically compared with the 2MBio-A, a systems analytical and design framework based on a design tool specifically developed for Bioenergy (the 2MBio). The results reveal that Nexus analysis is "blind" to specific fundamental social, ecological and socio-historical dynamics of charcoal energy systems. The critical comparison also suggests the need to integrate the high level systems analysis of Nexus with non-deterministic, non-prescriptive participatory analysis tools, like the 2MBio-A, as a means to increase sensitivity to the specifics of charcoal systems while keeping the practical benefits of Nexus as a high level policy design tool. In conceptual terms, this integration promotes open, participatory, integrated, comprehensive and creative analysis and exploration of the Nexus across scales, disciplines and sectors, providing thus, a strong base to design inclusive, sound and robust policies, projects and strategies relating/integrating charcoal, food and water security.

Keywords: participatory nexus analysis, charcoal, 2MBio, mozambique, systems thinking, analytical frameworks

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INTRODUCTION

In recent years, the Nexus approach has gained considerable and increasing professional, academic and political attention as a relevant systems approach to inform and shape policy, funding and research on integrated energy, natural resources and environmental management (Kurian and Ardakanian, 2015; Boas et al., 2016; Wichelns, 2017).

The nexus' basic argument is that fundamental systems (or economic sectors) like water, energy and food/agriculture, are intrinsically interdependent and, thus, must be addressed through integrated approaches (Boas et al., 2016; Al-Saidi and Elagib, 2017). Addressing a system/sector in isolation and ignoring Nexus synergies and trade-offs can produce misleading results and are inadequate to provide basic services to the poorest and fail to adequately cope with climate change (Brouwer et al., 2018). Hence, rather than looking into systems in isolation, nexus approaches promote the trans-disciplinary and trans-sectorial joint analysis, assessment, modeling and management of the multi-faceted linkages and interactions between systems (Howartha and Monasterolo, 2016). While many systems composition and denominations exist, this study focuses on the well-known nexus Energy-Food-Water (from here on, the Nexus).

The Nexus puts emphasis on the dangers of scarcity and is seldom justified by a number of different drivers or influencing factors that, through direct or indirect feedback and feed-forward loops, can result in unsustainable depletion of resources (Allouche et al., 2015). These drivers tend to be interrelated and generally include (e.g., Biggs et al., 2015; Keairns et al., 2016): climate change and extreme events (e.g., floods, drought); socio-economic trends (e.g. demographic trends); ecological impacts; and institutional systems. Therefore, Nexus provides a conceptual framework to analyse how a specific interest focus (e.g., natural resources management) relates with: the interactions (trade-offs, synergies and linkages) between water, food and energy systems and associated "security"; the drivers or influencing factors pressing the dynamics those interactions and "security"; and specific aspects affecting and being affected by those interactions (**Figure 1**).

As a systems analysis, the Nexus has been included in policy goals such as circular economy, low-carbon economy, resource efficiency, sustainable development, access to clean water and social welfare (Yillia, 2016; Brears, 2018; Brouwer et al., 2018). Remarkably, such deterministic and modular Nexus framework, facilitates mathematical modeling of systems as resources, i.e., (sources of) water, (forms of) energy, and (specific) food crops. Consequently, it is possible to model and quantify resource demand, costs and trends for each isolated resource/system, as well as, the dynamic interaction between different resource/system, i.e., how a stress in one Nexus system can create pressures on the other systems (Gulati et al., 2013; Kling et al., 2017). Formally, these models link different knowledge sets (models) to support evidence-based adaptive strategies (Scott et al., 2015), identify and minimize trade-offs (Pittock et al., 2015; Kurian, 2017), and maximize synergies, efficiency, while reduce risks and improve resource governance (FAO, 2014; Gallagher et al., 2016).

Despite these objectives and potential, the Nexus has been considered a "new development buzzword" (Dupar and Oates, 2012) which is not exactly new, generating a "somewhat misplaced [enthusiasm]" (Wichelns, 2017) and presenting serious implementation challenges, particularly evident on Nexus modeling, both isolated for each systems or in integrated Nexus analysis. The most relevant Nexus modeling drawbacks include the lack of (Kaddoura and El Khatib, 2017; Kling et al., 2017; Liu et al., 2017): data in quantity, quality and consistency; systematic identification, analysis and exploration of synergies, trade-offs and impacts simultaneously across scales and levels of detail; aggregation methods "sensitive" to local specificities; incorporation of human and systems adaptation and behavior; methods to evaluate and compare models. Another critique of the Nexus refers to the existence of institutional and communication barriers across sectors and disciplines that hinder dramatically the applicability in real institutional settings (Conway et al., 2015; Endo et al., 2015; Leck et al., 2015; Wichelns, 2017). Finally, Allouche et al. (2015) also see the Nexus as part of the "neoliberal policy [that hides issues such as] resource inequality and access [...] the manufacture of scarcity and international political economy and geopolitics."

For the purpose of this work relevant gaps in Nexus research include: the water-centric focus (Endo et al., 2015; Smajgl et al., 2016); the general absence of analysis of charcoal energy systems (CES) or Sub-Saharan Africa contexts (Ferroukhi et al., 2015); and the lack of studies critically comparing nexus analysis with other systems approaches. These gaps are particularly relevant as CES are fundamental for many developing countries through multidimensional interactions with crucial socio-economic aspects (Mirzabaev et al., 2015; Martins et al., 2018). To address these Nexus research gaps, this work focuses on the Nexus for charcoal presenting a relational graphic (**Figure 3**) displaying the interactions between charcoal, water and energy for the case of Mozambique (section Uncovering The Nexus Charcoal-Food-Water In Mozambique). These compared results are then compared with a similar analytical exercise conducted with a novel systems analytical tool, the 2MBio-A (based on the design tool 2MBio, Martins et al., 2018), developed specifically for bioenergy and applied to the case of Mabalane district in southern Mozambique (section Charcoal Centred Systems Analysis For Mozambique). The critical comparison exposes the analytical limitations of Nexus and options are presented to integrate Nexus analysis with non-deterministic and non-normative tools, like the 2MBio-A or 2MBio, to amplify the analytical capabilities and comprehensiveness of Nexus analysis with more participatory and specific insights (section Constructive Discussion: Proposal For An Integrated Design Approach). The conclusion (section Conclusion) resumes the discussion and analysis of outcomes of the work and presents possible future work.

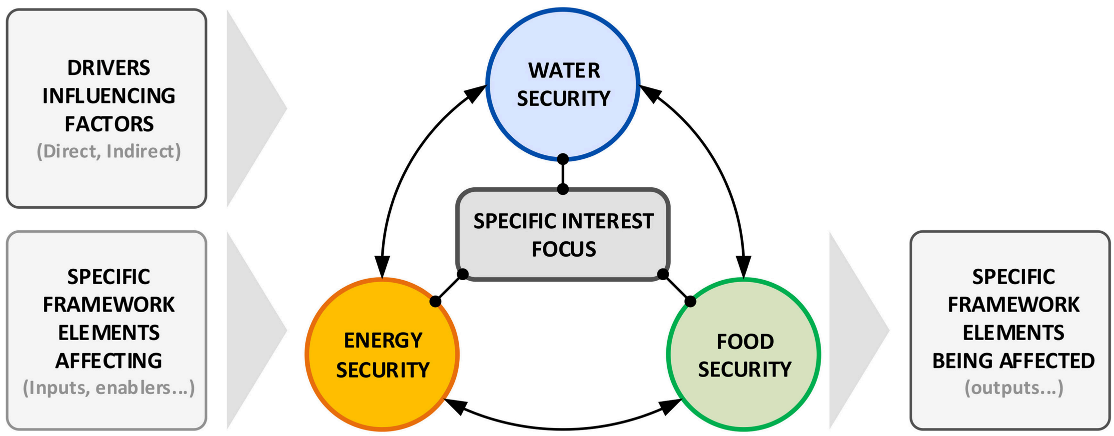

FIGURE 1 | Generic graphical representation of the Nexus analytical framework (the names and definition of the components might differ slightly depending on the author).

UNCOVERING THE NEXUS CHARCOAL-FOOD-WATER IN MOZAMBIQUE

Mozambique, a Sub-Saharancountry, has been for decades among the 20 least developed countries in the world (UNDP, 2016). Mozambique has more than 50% of its population experience chronic or periodic episodes of food insecurity (Batidzirai et al., 2006), and droughts and flood episodes related, directly or indirectly with climate change (e.g., Bullock and Hülsmann, 2015). Mozambique is highly dependent on wood fuel energy systems for cooking, mostly charcoal in cities and firewood in rural areas. An estimated 96% of the population (over 25 million people) rely on wood fuel (IEA, 2014), which represents 2.2% of total GDP (van der Plas et al., 2012), 76.5% of all national energy demand and over 15 $\times$ 10^6 tons of wood (worth 700million US$) taken from Mozambican forest every year (Ryan et al., 2016). Simultaneously around 51% of Mozambican population (45% in rural areas and 8% in cities) have no access to improved water sources (WHO/UNICEF, 2014) and large portions of the country are arid or semi-arid (Turton et al., 2008). At the policy level, the Government of Mozambique had long established clear policies for food security, including a main national strategy Plan for the Reduction of Absolute poverty (PARPA in Portuguese) and the 1991 Law of Water. However, and remarkably, charcoal is virtually absent from Mozambican policy while 98% of charcoal business is informal (Cumbe et al., 2005). Furthermore, issues with water, charcoal and food tend to be addressed by separated Ministries, with inexistent or poor effective inter-ministerial coordination. The policies relating water with food production exist, but highly criticized by their lack of suitable social and political considerations (van der Zaag et al., 2010; Alba et al., 2016; Ducrot, 2017). Therefore, Mozambique presents an interesting research opportunity to explore the Nexus focusing on charcoal in a socio-ecological context marked by climate change, poverty, water and food scarcity, and the absence of specific policies for charcoal or linking charcoal with water and food security.

The first task proposed by this research is to make explicit the Nexus water-charcoal-food and associated drivers in Mozambique. This task presents two important challenges: the scarcity of work on the Nexus applied to charcoal or Mozambique; and the existence of relevant Nexus research not identified as such. Hence, to support a comprehensive analysis and avoid a possible bypass of relevant information, this review includes: the work explicitly mentioning the Nexus on Mozambique (section Explicit Nexus Analysis Made On Mozambique, and Southern Africa); and "Nexus like" analysis linking water and/or food with charcoal energy systems or bioenergy in contexts similar to Mozambique (section Nexus And Systems Analysis Relevant For CES And Mozambique).

Explicit Nexus Analysis Made on Mozambique, and Southern Africa

The review of the workthat explicitly mentions the nexus and Mozambique (Bullock and Hülsmann, 2015; Nielsen et al., 2015) revealed an essentially water centric Nexus analysis, i.e., water is the main focal point of analysis and intervention. Bullock and Hülsmann (2015) identify a high, but unevenly distributed, potential for sustainable development based on hydropower for Mozambique and several vulnerabilities. Currently, hydropower supplies over 98% of the national electrical consumption, but the availability of water might refrain further growth. Nine of Mozambique's 11 main rivers are trans-boundary, which makes the country particularly dependent on neighboring countries' water policies, strategies and availability. Climate change intensified drought in the region and Mozambique further reducing rivers' downstream flow. Finally, population, industrialization and agriculture growth increased water usage for drinking processing and irrigation. Therefore, hydropower is presented as a synergetic solution, controlling river flow (and reducing flood effects), storing water, facilitating irrigation and improving, geographically, quantitatively and qualitatively, the availability of electrical supply for productive uses. Moreover, for Bullock and Hülsmann (2015), emphasize the role of Integrated

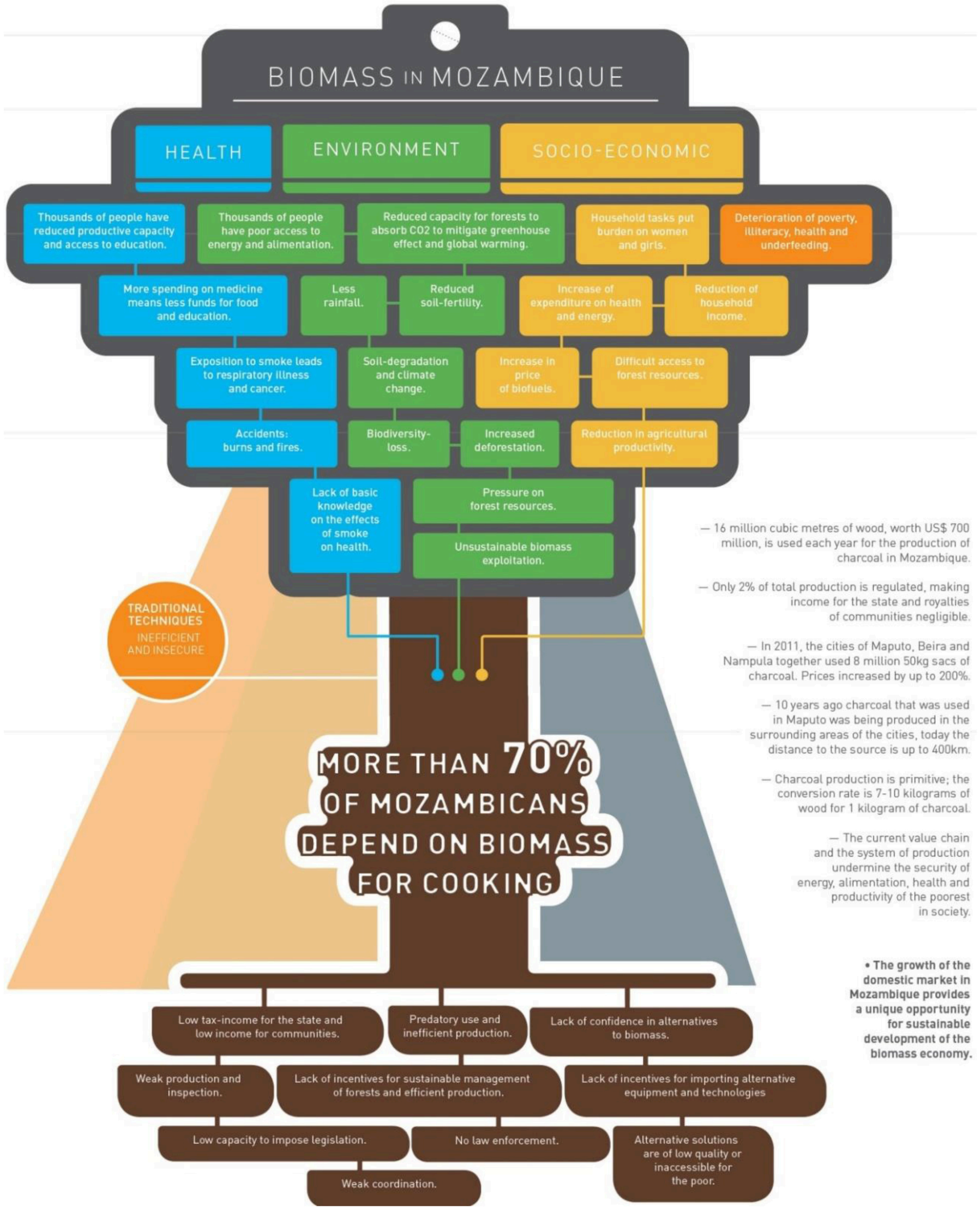

FIGURE 2 | Biomass Tree of Problems, created in a National Expert's Workshop at Maputo (Source: SNV, 2007).

DRIVERS OR INFLUENCING FACTORS

- ☐ **Climate change** (ENSO) **and extreme events** (floods, droughts, cyclones)
- ☐ **Soil scarcity and erosion**
- ☐ **Competing and combined uses of resources**
- ☐ **Deforestation**
- ☐ **Poverty; Urbanization; Population growth**
- ☐ **Energy intensification; Increased demand for woodfuels**
- ☐ **Globalised economy** (aid, capital/technology transfer)
- ☐ **Changing livelihood patterns** (energy, food, consumption)
- ☐ **Lack of suitable infrastructures and tecnology**
- ☐ **Governance** (week or absent law enforcement, Informality, lack of political coordination, corruption)
- ☐ **Power relations** (discrimination, structures and networks)
- ☐ **Geopolitics** (downstream location, conflict)

	WATER	CHARCOAL/BIOCHAR	FOOD
WATER		• Water availability and quality ➔ CHP operation (steam, refrigeration) → energy security and irrigation cost and intensity • Water availability and quality ➔ Growth of dedicated crops for charcoal (and GHG emissions)	• Irrigation ➔ Crops (more harvests, crop diversity and yields) ➔ Food security → income • Irrigation ➔ Labour market (off-farm income vs abandon food production vs geographic concentration of food production and consumption) ➔ Income and food security • Water availability and quality ➔ Health (water bourn deceases, sanitation) ➔ food security
CHARCOAL/BIOCHAR	• CHP ➔ Afects water avalability (more vs overexploitation) • CHP ➔ Diversify water uses (drinking vs irrigation) • CHP ➔ Afects water quality (pollution vs desalination, heating, cooling) • CHP ➔ Water supply (extraction, pumping, treatment and purification, distribution) • Deforestation from charcoal ➔ Soil quality (erosion) and Climate change (less rainfall) ➔ Water availability (less underground water, droughts, less water retention on soils) • Income from charcoal ➔ Funds irrigation (e.g. acquisition, operation, maintenance) • CHP projects ➔ Equity on water entitlement and rights • Dedicated crops for charcoal making ➔ Water availability for other crops • Availability and quality of CHP electrical power ➔ irrigation and water treatment systems options • Dedicated energy crops (plantations) ➔ Pollute Water (fertilizers), • Biochar ➔ Increases water retention (less irrigation) • Biochar ➔ Treat wastewater for irrigation (cadmium and lead removal)		• CHP and charcoal sterilise and boil water ➔ Food security • CHP based irrigation ➔ see above • CHP and charcoal heat ➔ Food processing and conservation and cash-crops ➔ Food security → Income • CHP and charcoal heat ➔ Small industry (e.g. brick making) ➔ income → Food security • Lack of charcoal ➔ Cooking habits (e.g. Less nutritious food eaten row, uncooked or prepared fast) ➔ Food security • Charcoal production ➔ Heath (e.g. respiratory deceases, fires, accidents) ➔ Less time, labour and income for food • Charcoal production ➔ Soil quality (natural soil regeneration vs deforestation effects, see left) ➔ Diet and food security • Charcoal income ➔ Socio-economic environment (reinvested in productive uses vs exacerbate previous prevailing social inequity in access and use of resources vs abandon of food production vs availability of other valuable resources like construction wood or firewood) ➔ Income → Food security • Dedicated crops for charcoal ➔ Agriculture systems (land, water and labour availability vs nitrogen fixation) ➔ Food security and prices
FOOD	• Increased food production ➔ Water overexploitation and pollution ➔ Water cost and time spent to collect • Deforestation from farming ➔ Soil quality (erosion) and Climate change (less rainfall) ➔ Water availability (less underground water, droughts, less water retention on soils) • Agroforestry ➔ Water retention	• Food habits and urbanization ➔ increased demand for charcoal and CHP • Cultural habits ➔ Preference for charcoal and unavailability of economically viable alternatives • Increases agriculture production ➔ available cheap animal and agriculture wastes to compete with charcoal for energy • Agroforestry ➔ Trees/wood residue for charcoal/firewood	

FIGURE 3 | Relational table detailing the Nexus drivers and interactions (CHP- combined heat and power technology based on woody biomass or charcoal; ➔ Direct link; → indirect link; Sources: see sections Explicit Nexus Analysis Made On Mozambique, and Southern Africa–Uncovering The Nexus Charcoal-Food-Water In Mozambique).

Water Resources Management to bring about synergetic effects on the nexus.

Nielsen et al. (2015) conducted a nexus analysis on Mozambique to identify trade-offs. Interactions and possible synergies to justify and model the effect of a number of specific interventions in the nexus. Mozambican agriculture is characterized for: being virtually all rain-fed and presenting the lowest yields in SADC, underdeveloped extension services and limited access to inputs (e.g., fertilizers). Conversely, weak distribution network for products and inputs, hinder the development of a sustainable market and food security. In this context, wide variations in rain fall, increasingly frequent and intense floods and droughts, extreme dependence on upstream countries for water quantity and quality, uneven distribution of groundwater, inefficient use of water sources, lack of suitable infrastructures and distribution network, lack of skills and political coordination present major challenges for and water security and, in particular, for irrigation. In this regard, while hydropower could increase food security through irrigation, it might also compete with agriculture for water and significant water losses through evaporation of reservoirs are possible, which poses a threat to water security. Since Mozambique exports around 80% of its hydropower and, Nielsen et al. (2015) only around 20% of the population, and less than 8% of rural households, have access to electricity, the microlevel effects of hydropower in energy security are minimal. Still on the energy sector, Nielsen et al. (2015) acknowledges the overwhelming presence of firewood and charcoal for cooking, as well as, their possible impacts in the nexus. Respiratory diseases resulting from smoke emissions, and time and resources spent collecting firewood and producing charcoal affects the capacity to work and/or reduces the availability to engage in other on-farm or off-farm paid work opportunities, affecting ultimately food security. This "time link" and "health link" might have a gender dimension since women are responsible for collecting wood, cooking and usually spend more time in farms than men. Charcoal (more than firewood) is also linked with deforestation, which is, in turn, linked with soil erosion and water retention in soils. According to Nielsen et al. (2015), high urbanization rates, lack of suitable technological alternatives and political involvement form national governments drive the increasing demand for charcoal leading to increasing pressure on forest resources, soil erosion and poor watershed management. Nielsen et al. (2015) also evaluate the effects of agroforestry (the practice of planting crops together with woody plants) on the nexus. Nitrogen-fixing trees and the decomposition of leaves, fruits, and other biomass and residues produced by those trees, act as organic fertilizer with low ecologic impact, increasing soil fertility, reducing soil erosion from wind and water and resulting in higher agricultural output. The possibility to have fruit trees or legumes can also contribute to more food availability and dietary diversity. Mozambique had success history of intercrop of cashew trees (introduced by Portuguese from India) with cassava or maize by small farmers in almost one-third of the Mozambique. However, Civil war, the lack of renewal of trees and pressure from donors (notably the World Bank) resulted in the deterioration of the cashew sector in the 1980–1990s, with serious impacts on household income and food security at local level (Hanlon, 2000).

Remarkably, many of these water-centric analysis and conclusions are also in Nexus studies done for Southern Africa Development Community (SADC) and Southern Africa Region:

- Climate change will affect water availability, food production, livelihoods, electricity supplies and basic infrastructure. The ENSO (El Niño Southern Oscillation) is expected to produce an increasing frequency, intensity and unpredictability of extreme climate events, including the massive floods (465,000 people displaced between 2001 and 2008) and chronic droughts and cyclones (Obasi, 2005; Ward, 2010; Conway et al., 2015).
- Charcoal is absent of analysis or, if considered, is considered a problem to be solved by other forms of energy or technologies favored by existing institutional arrangements, e.g., centrally planned hydropower projects and "improved" or "modern" technological solutions (Schreiner and Baleta, 2015; Mabhaudhi et al., 2016; Muller, 2016).

These results are combined with section Nexus And Systems Analysis Relevant For CES And Mozambique in the nexus interaction graphic in section Nexus Causal Relations for Mozambique.

Nexus and Systems Analysis Relevant for CES and Mozambique

To complement the review on Nexus analysis explicitly mentioning Mozambique (section Explicit Nexus Analysis Made On Mozambique, and Southern Africa), a review was conducted focusing on studies that included: (1) systemic analysis linking charcoal with water and/or food in Mozambique; (2) relevant nexus analysis of bioenergy or CES in developing countries.

One of the few systemic analysis of CES from a "nexus like" perspective was developed by SNV (2007) in a workshop with Mozambican experts' (**Figure 2**). In this analysis, CES is perceived as a problem rooted in weak or unsuitable institutional and technological systems, high demand ("70% of Mozambicans depend on charcoal for cooking") and free easily accessible forest wood. These root problems could be understood as drivers for the Nexus with deep health, environmental and socio-economic effects.

Regarding the consequences, from a Nexus perspective, three interdependent dynamics are visible:

- Unsustainable CES promote deforestation, which degrades the soil and promotes climate change, reducing rainfall, which further increases soil degradation. These direct and indirect roots for soil degradation result in lower fertility and, thus, less food availability and lower income (e.g., to buy food).
- The inefficient technology used on charcoal production and consumption is associated with accidents, burns and fires and respiratory diseases, decreasing the household health, availability to work and, thus, income availability for food due to increasing spend on health care and decreasing work productivity, which may lead to food insecurity.
- The combination of the two dynamics above and the absence of strong, enforcing and suitable institutional and policy framework result in informal and unsustainable forest management, progressive scarcity of wood or increase of wood prices, leading to poverty and malnourishment, with higher impact on women and girls.

Some other studies complement this analysis highlighting a number of trade-offs, linkages and drivers or influencing factors relevant for the Nexus.

On the linkage charcoal-deforestation, Sitoe et al. (2016) and (Woollen et al., 2016) perceive deforestation as a multi-dimensional phenomenon, which includes land clearance for farming as an important factor.

Ryan et al. (2016)while linking deforestation with the breakage of nutrient cycle (e.g., nitrogen cycle), also considers that charcoal production, when part of shifting cultivation, boosts fertility on inherently infertile soils. Deforestation can also facilitate soil erosion, increasing the amount of sediments on rivers and lakes, thus reducing the water quality and affecting fish productivity (Ryan et al., 2016). Furthermore, deforestation reduces water infiltration in the soils reducing ground water recharge, dry season flows and precipitation, which has a negative impact on food production (Ryan et al., 2016). Over extraction of wood can also promote a decline in competitive wood-land-specific uses (e.g., firewood, medicines, construction materials), with possible welfare losses, especially for the most vulnerable (Woollen et al., 2016).

The scarcity of water and wood energy increases the time and income spent on acquiring those goods and reduces the investment on healthcare and/or in irrigation technology and water storage facilities, which in turn reduces food production, hygiene, and income generation (Cairncross and Cuff, 1987; Ng'ang'a et al., 2012; Magombeyi et al., 2013). Sanitation is included as healthcare. Indeed, areas subjected to drought, away from irrigation networks or low underground water levels are associated with food insecurity and poverty (Mabhaudhi et al., 2016). Conversely, the lack, or the price increase, of charcoal can also affect household's cooking habits. Protein-rich "hard" meals (e.g., with beans or meat) may be avoided or undercooked to conserve energy and families may rely heavily on low-protein "soft" foods (e.g., grains and greens) which can be prepared quickly (Brouwer et al., 1997). In other cases, families may stop boiling drinking water when faced with an energy shortage (Plummer, 1999).

In rural areas of Mozambique marked by extreme poverty, constant and intensive natural hazards, with few income generation options and with insufficient agriculture production, charcoal is a main poverty coping strategy (Clover, 2007; Brida et al., 2013; Jones et al., 2016). In southern Mozambique, after the 2000's massive floods and intensive drought, 60–70% of farmers engaged in off-farm activities for extra-income (Brida et al., 2013). Notably, 90% of households in that area are involved in charcoal making (Ng'ang'a et al., 2012) since this is the most profitable off-farm activity (Nhantumbo, 2010). The income resulting from charcoal, if reinvested on food production (e.g., working capital, invest in field opening and clearance, buy agricultural inputs or equipment), or irrigation systems can reinforce and multiply growth in the agricultural sector increasing food availability or surplus for sale (Mather, 2012; Djoudi et al., 2015; Jones et al., 2016; Ducrot, 2017). However, very few farmers do these investments and several irrigation programs implemented in Mozambique revealed to promote political centralization, reduce local participation, be poorly coordinated, promote inequality and threaten natural resource management (Eriksen and Silva, 2009; van der Zaag et al., 2010; Djoudi et al., 2015; Alba et al., 2016; Ducrot, 2017).

In the case of charcoal, an important Nexus driver and influencing factor is the institutional framework around forest in Mozambique. Alongside the land and water, forest belong to the state, but local communities' rights and resource management practices are considered while a charcoal production license system (supposedly) based on forest capability is in force. However, local institutions have been considerably reduced in post-independency and during the civil war (Pihale, 2003), governmental institutions are incapable to monitor or reinforce the law and the license price is considered unsuitable and the requirements unrealistic (Eriksen and Silva, 2009; Jones et al., 2016). Consequently, forest resources are seen as monetary free open-to-all resource, charcoal is a business running on informal and illegal channels, and most producers are unable to govern their resources due to weak institutional capacities (Baumert et al., 2016). Simultaneously, the lack of financial and public services, access to markets and knowledge (including technology and electricity) strongly reduce the options to increase productivity and diversify coping strategies to climate change and household income generation (Ng'ang'a et al., 2012; Ducrot, 2013). Definitely, the lack of options and the perceived cost-free benefit from charcoal making and growing demand from increasing number of urban poor, the need for cash income pushes farmers away from more resilient (but less profitable) agricultural strategies toward others that carry a greater degree of risk for capital-poor, small-scale farmers (Silva et al., 2010). Notably, these practices have implications on: the diversity, availability and access to other forest uses (Ryan et al., 2016); vulnerability to climate change, food security, land and soil quality (Ng'ang'a et al., 2012; Gomiero, 2016; Woollen et al., 2016).

Another data set and knowledge to inform the Nexus analysis on charcoal is research done on Nexus analysis focused on CES and/or bioenergy in developing countries.

A possible CES to consider is the combined heat and power technology, CHP, based on charcoal supplied by dedicated wood plantations or forest residues (e.g., Wetterlund et al., 2013; Sowlati, 2016; Tidwell, 2016) coupled with the relevant aspects of nexus analysis applied to biofuels in developing countries (Guta et al., 2015; Mirzabaev et al., 2015; Brears, 2018) and biochar (carbon-rich charcoal) production for soil remediation (Belmonte et al., 2017). This approach allowed to identify:

- Linkages water-charcoal/biochar: water for CHP (e.g., refrigeration, steam production); CHP for water supply (extraction, pumping, treatment and purification, distribution); effects of CHP on water quality (e.g., heating, cooling, desalination); biochar can treat wastewater for irrigation (cadmium and lead removal); CHP and biochar can pollute the water; energy effects on water entitlement rights and availability (e.g., overexploitation); the effect dedicated plantations on water (e.g., use of fertilizers); the overexploitation of trees (deforestation) on water cycles through soil erosion and land degradation; enhanced soil with biochar increases water retention and reduces irrigation requirement.
- Linkages food-water: water for agriculture; off-farm jobs linked with irrigation, and health improvement (e.g., sanitation, clean water, water-borne deceases), which affects work productivity and thus food security; the effect of agriculture on water quality (e.g., fertilizers).
- Linkages Charcoal/ biochar-food: CHP for food processing (e.g., conservation and storage); energy plantation for agroforestry might affect land quality to generate synergies (e.g., nitrogen fixation, more harvests per year, higher yields, diversification); biochar can increase crop productivity; CHP/charcoal/biochar might increase income (small business, agriculture), influencing food security and facilitating reinvestments in food/energy production; plantation might create resource competition (e.g., labor, land, water) or degradation of food resources (e.g., soil erosion, land degradation, water scarcity, oversupply of nutrients); charcoal production can generate accidents resulting in less working power.

While relevant for a comprehensive analysis, this combination of technological options (CHP and plantations) is still not a reality in Mozambique, mostly characterized by the use of firewood in rural areas and the production of charcoal from forest wood on local mold kilns to supply urban consumers.

Finally, there are two studies that explicitly relate the Nexus with Charcoal: Githiru et al. (2017) and González-López and Giampietro (2017). Githiru et al. (2017) poses the possibility that human-elephant conflicts could change the risk perception by farmers, changing their income strategies which include charcoal production. While a relevant and interesting element to be considered, there is no Nexus analysis explicating the possible interaction wildlife-charcoal-water-food. González-López and Giampietro (2017) uses a general accounting framework for the analysis of the metabolic pattern of social-ecological systems using the multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) model to study the Nexus in relation with charcoal production in a rural village in Laos. The MuSIASEM applies a metabolic perspective to simulates human decisions in face of trade-offs and synergies between charcoal production and different activities under a scenario of limited availability of human activity and available land. While "metabolic patterns" and "relational analysis" are mentioned they are not presented, and thus, it is not possible to derive explicit interactions for the Nexus charcoal-water-food.

Nexus Causal Relations for Mozambique

To make the Nexus explicit in a schematic format, the results from section Explicit Nexus Analysis Made On Mozambique, and Southern Africa and Nexus And Systems Analysis Relevant For CES And Mozambique were collected and integrated in **Figure 3**, to show the drivers and effects that the system in the far left column have on the system on the top column. While not much different from other Nexus analysis representations (e.g., Biggs et al., 2015; Brears, 2018) **Figure 3** is the first integrated and comprehensive Nexus analysis centered on CES made for Mozambique.

CHARCOAL CENTRED SYSTEMS ANALYSIS FOR MOZAMBIQUE

In this section, a participatory analytical tool, the 2MBio-A, is presented for comparative purposes with the Nexus analysis (section Uncovering The Nexus Charcoal-Food-Water In Mozambique) and applied to the case of Mabalane, a charcoal production district in the south of Mozambique. The comparative results will be critically explored and discussed in section Constructive Discussion: Proposal For An Integrated Design Approach.

The 2MBio-A, a Systems Analysis for Charcoal Energy Systems

To assess comprehensiveness and depth of analysis of the Nexus focused on CES (section Uncovering The Nexus Charcoal-Food-Water In Mozambique) this work proposes the 2MBio-A as a tool to support an alternative systems analysis on the same system. The 2MBio-A is, in fact, the analytical version of the 2Mbio, a participatory design tool developed by the author and successfully used to facilitate the design of a creative synergetic firewood/food system from scratch in different settings, from rural communities to engaged groups of experts and academics (Martins, 2014; Martins et al., 2018).

The 2MBio is an ontological metamodel, i.e., a graphical illustration that makes explicit the basic elements (concepts, constructs and rules of interaction) of the bioenergy systems design. Moreover, the 2MBio theoretical basis considers design a continuous reflexive analytical activity (Schön, 1983). Furthermore, the 2MBio was specifically developed for the wood fuel energy systems (and bioenergy systems in general). These three structural aspects of the 2MBio made it naturally adaptable for the task of analysing CES possible interactions, simply by truncating the design process at its design stage. Therefore, while the 2MBio analyses the problem to design a grounded solution, the analytical version, the 2MBio-A, simply analyses the problem. Therefore, like the 2MBio, the 2MBio-A (**Figure 4**), offers a visual, explicit and formal platform representing 13 basic elements necessary and sufficient to produce comprehensive and meaningful analytical specification of any bioenergy system. The 2MBio-A is easy to use, non-normative and non-prescriptive and effectively allows a wide range of actors to develop contextualized, comprehensive and meaningful analysis of bioenergy systems.

Moreover, like the 2MBio, the 2MBio-A does not compel normative visions of efficiency or sustainability, instead, allows for users alone, or together with additional people, draw on their creativity, knowledge, experience, perspectives, by exploring the full extent of bioenergy systems analysis space represented by 13 basic elements organized as boxes on a piece of paper (see **Figure 4**). Each of the 13 basic elements are well defined, easy to understand and explicit, and are provide the space for users to write and draw directly on paper their ideas and perspectives. Thus, the proposed tool works as an interactive and common ground where participants make explicit their creativity in the participatory conceptual analysis of CES. In other words, the 2MBio-A promotes sense-making across different users, since, once filled, the 13 basic elements serve to translate abstract, tacit, implicit and individual mental models and views into concrete, explicit and common written/drawn specifications, making it available for others to discuss. As a result, through the 2MBio-A, users can establish a structured and constructive dialogue/debate while exploring, understanding, learning and refining their views on CES analysis. Significantly, being a low-tech, low cost tool, and allowing for drawing on it, the 2MBio-A facilitates wider participation of people from areas with low or no literacy, low electricity access and lack of computers.

Applied Contextualization: the Case of Mabalane

The 2MBio-A could be used on generic way, however, to contextualize the tool, the analysis will be carried in Mabalane, a district that presents a highly stress nexus situation, marked by water scarcity, low food production and high charcoal production under an overall scenario of poverty and climate change vulnerability.

Located in Gaza Province, Mabalane occupies 9,580 km^2 of the upper part of the Mozambican Limpopo Basin (**Figure 5A**). Around 98% of the families are engaged on subsistence agriculture mostly rain fed and, thus, extremely dependent on natural conditions, which are extremely unfavorable hazardous (Brida et al., 2013; Ducrot, 2017). The soils are very poor for agriculture, classed as loamy sand (82% sand, 13% silt, 5% clay), with a low carbon and nutrient content (0.4% C, 0.05% N) (Woollen et al., 2016). In practical terms, the options are between farming the sandy soil at the uplands, with a high risk of crop failure in drought years, or the fertile soil close to the Limpopo River with a high risk of floods (Brida et al., 2013;

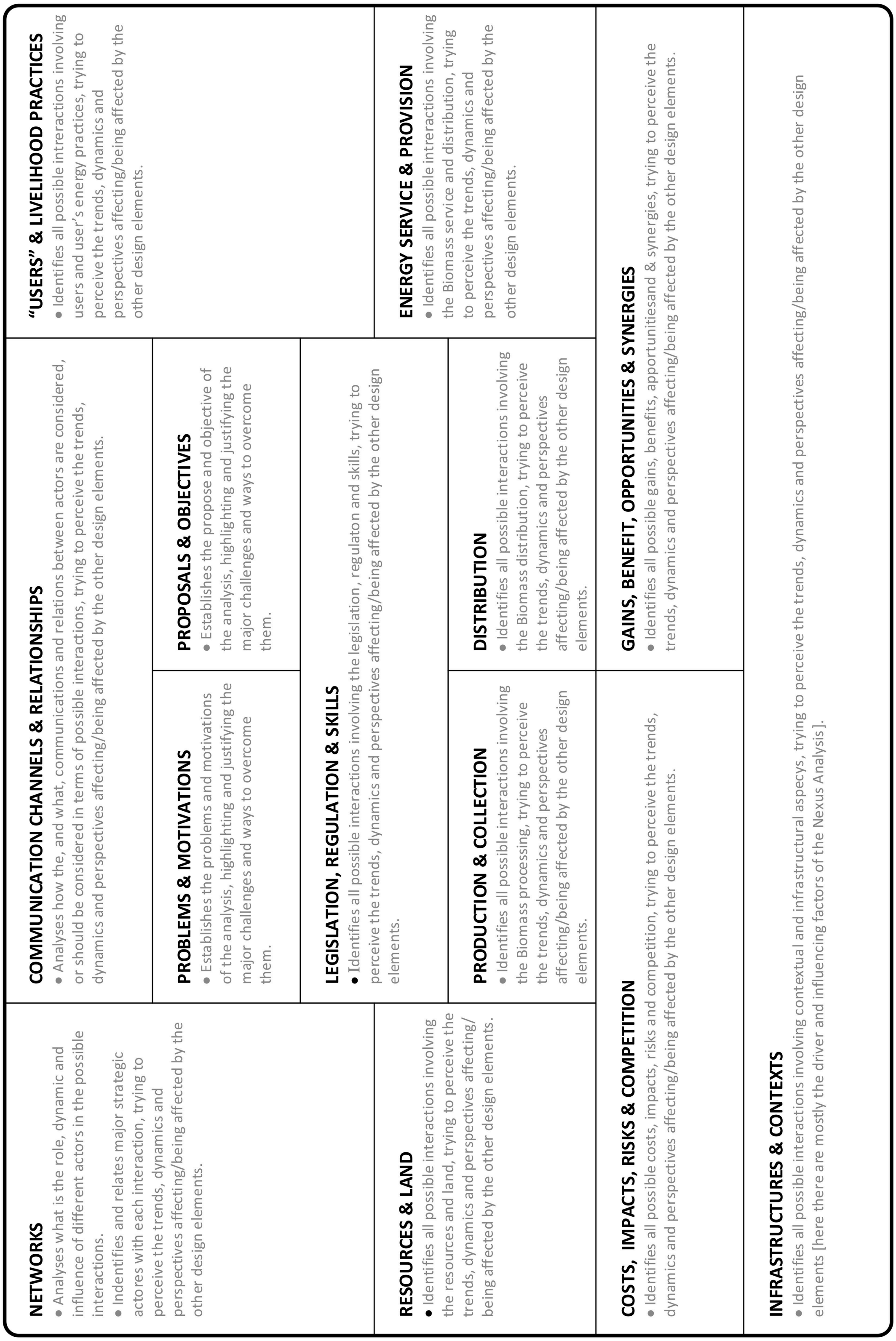

FIGURE 4 | The 2MBio-A layout including description of every basic element (Source: based on Martins, 2014).

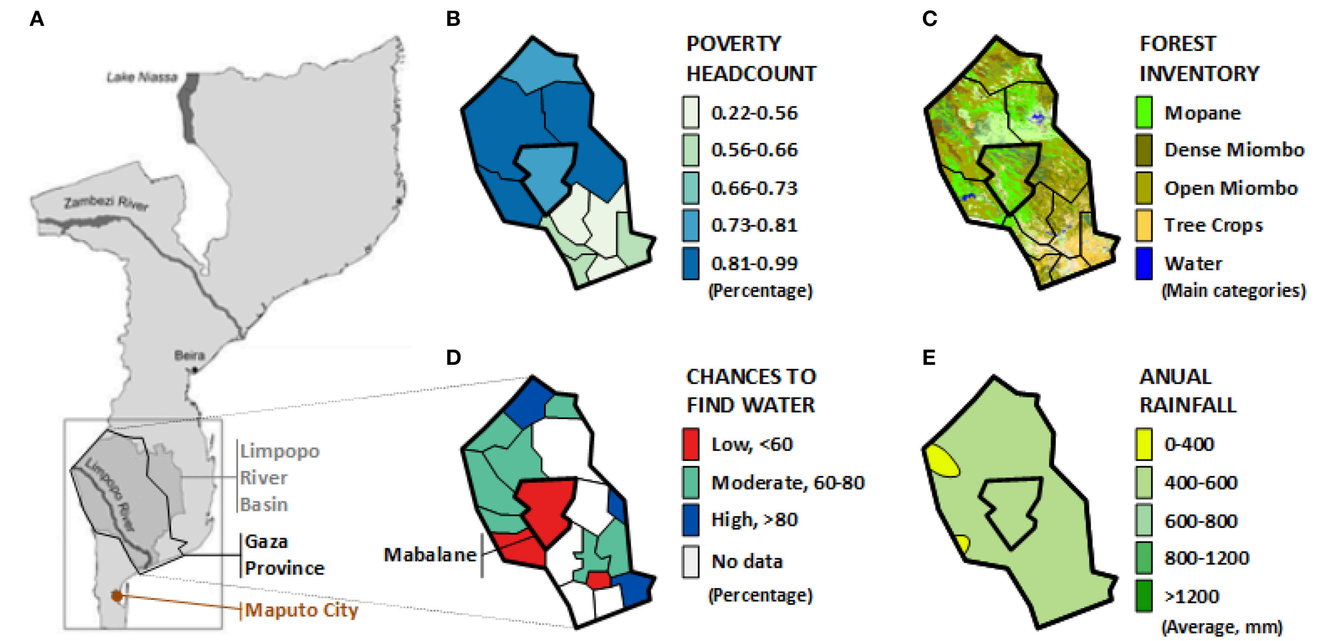

FIGURE 5 | Maps showing the relative location of the Limpopo River Basin, Gaza Province, Mabalane District and Maputo City in Mozambique, as well as, water, poverty and forest data [Source and full maps, **(A,E)**- (Ng'ang'a et al., 2012); **(B)** (Simler and Nhate, 2005); **(C)** (JICA, 2016); **(D)** (Ducrot, 2013)].

Ducrot, 2017). Moreover, following climate change tendencies in the region, drought periods become more extended, chronic and severe (Turton et al., 2008). Therefore, in the context of projected climatic changes and increases in climate variability, food security in those areas is at risk (Brida et al., 2013). According to the official ranking based on nutrition, food security and access to public good indicators, Mabalane is in the 4th quartile of the poorest districts of Mozambique, with around 72% of the population living below the national poverty line (**Figure 5B**) and one third to half of the households suffering from a food shortage period (Ducrot, 2017) which can last between 3 and 5 months depending on the year and the zone (FEWSNET, 2014).

A crucial issue in the district is water access. Around and 75% of the district area is already arid or semi-arid land with and annual rainfall between 400–470 mm and between 20–31 mm in the dry season (April to September) (Ng'ang'a et al., 2012; Ducrot, 2017) (**Figure 5E**). Between September and December, the Limpopo River is dry due for upstream water extraction and the management of the catchment area (Ducrot, 2017). Furthermore, Mabalane is one of the country's districts with the hardest access to good quality underground water. The boreholes should have more than 75 m, the rate of successful drilling is below 60%, and if successful there is a 70% chance to find water with an average salinity of 2,650 µS/cm while the limit is 2,500 µS/cm (**Figure 5D**; Ducrot, 2013). At the regional level, there is evidence that water resources of the Limpopo Basin are already stressed under today's climate conditions (Zhu and Ringler, 2012).

Despite these hard conditions, Mabalane is well endowed with easily accessible hard wood from the extensive forest of Mopane (Colophospermum mopane) (**Figure 5C**). Mopane is a dense hardwood species, which produces highly appreciated high-quality, slow-burning charcoal. In this scenario of generalized poverty, lack of opportunities and easy and free access to resources, charcoal production is major way to generate cash income. Indeed, Gaza is the region of the country with the higher number of licenses conceded, reaching a total annual volume of 542,203 allowed charcoal bags (around 43,000 tons) (MITANDER, 2016).

Finally, while 600 km away the Capital City Maputo, the two locations are linked by a road 80% paved with good quality tar and a cargo train running three times per week. Not surprisingly, Mabalane is currently the major charcoal producer district in the south, and virtually all its production is to supply the growing urban population of Maputo.

Applying the 2MBio-A on Mabalane: Unveiling and Expanding Linkages

The 2MBio-A was designed, and achieves the best results, when used in participatory exercises, however, to assure a common base of comparison with the Nexus analysis made above (section Uncovering The Nexus Charcoal-Food-Water In Mozambique) the 2MBio-A will be applied as a supporting tool for individual analysis by the author (**Figure 6**). The purpose is to use the 2MBio-A to identify relevant interactions (trade-offs, synergies, logical effects) for each basic element of the 2MBio-A (the "boxes") and among them. In other words, the purpose is to perceive how each basic element affects, and is affected by, the other design elements within a predefined systems analysis. For the presented case, CES was considered as a socio-ecological

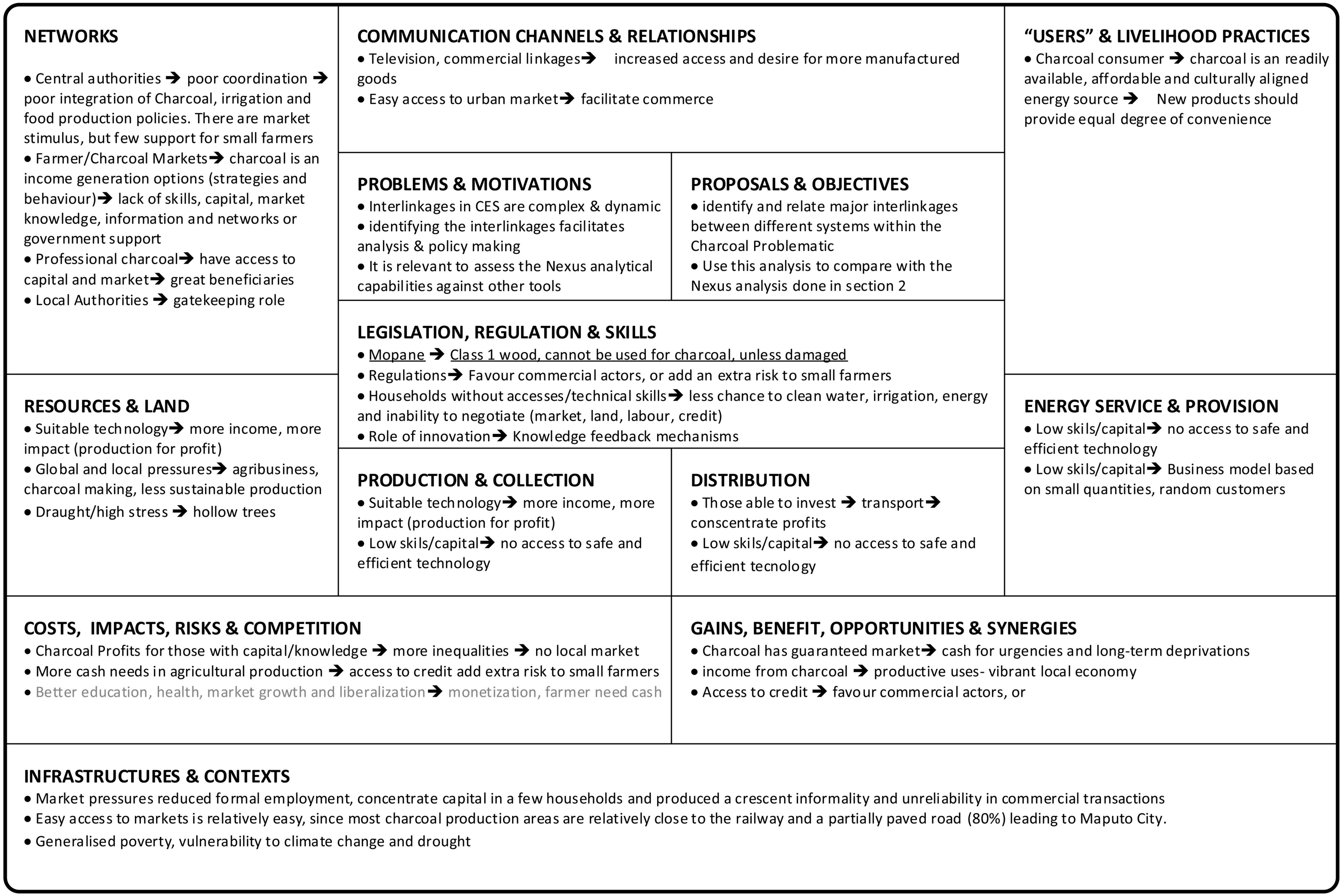

FIGURE 6 | The 2MBio-A fully described after one fast initial iteration.

system (or social-ecological system see: Martins, 2014; Homer-Dixon et al., 2015) and the interactions were written directly on the body of the 2MBio-A (**Figure 6**). This interactions represent the result of the author's experience and research conducted in the Mabalane area during 2015–2016, and display the first interaction with the 2MBio-A. Further analysis by the author and/or other user could result in higher refinement.

Before advancing for a deeper discussion on the use of the 2MBio-A in the nexus analysis, to be conducted on section Constructive Discussion: Proposal For An Integrated Design Approach, it is important to mention two aspects on the use of the 2MBio-A carried above (section Applying The 2MBio-A On Mabalane: Unveiling And Expanding Linkages above).

First, while not presented for economy of space, all the elements considered in Nexus analysis (**Figure 3**) are also included in **Figure 6**. Indeed, what is presented in **Figure 3** as drivers and influencing factors is what the 2MBio-A designates by Infrastructure and Context (the bottom box). Likewise, since most of the Nexus analysis have been developed around specific technologies, these technologies and their interaction within the Nexus could also be included along the supply chain section of the 2MBio-A, i.e., the central row comprising the elements (boxes) Resources and Land, Production and Collection, Distribution, and Energy Service and Provision. However, rather than an interaction water-energy, what would be presented would be, how that technology would interact with water, food and energy.

Secondly, while belonging to a specific element (box), the interactions identified in **Figure 6** might affect and be affected by other elements or interactions with other elements. Therefore, the 2MBio-A (as the 2MBio) relies on harrows to show such inter-basic elements interactions. In fact, methodologically, to assure coherency and comprehensiveness, the use of the 2Mbio-A requires that each aspect identified in each and every single basic element, must have correspondence (linkage) with all the others elements.

CONSTRUCTIVE DISCUSSION: PROPOSAL FOR AN INTEGRATED DESIGN APPROACH

Critical Discussion on the Nexus as a Viable Tool to Analyse Charcoal Energy Systems

The basic premises and application of the nexus approach to the water-charcoal-food in Mozambique is valid and potentially useful, however presents a number of gaps, challenges and problems.

Probably the most notorious gap of the Nexus approach to Mozambique and charcoal is the absence of the forest as a Nexus component. The Nexus studies on Mozambique identify deforestation, the possible competitive use of forest resource, and the effect of dedicated plantations on water and food systems (**Figure 3**), but in every case, forest is part of system or resource, not a complex and dynamic socio-ecologic system. Nevertheless, Mopane forest is crucial for charcoal production, a source of welfare, food and resources and crucial for the water system (Bila and Mabjaia, 2012), and throughout Southern Africa, the Miombo forest supports directly the livelihood for over 100 million people in both urban and rural areas (Campbell et al., 2007; Syampungani et al., 2009). The lack of nature is, actually, also a common critique of the current Nexus formulation (Krchnak et al., 2011; Allouche et al., 2015).

Another gap detected is the often mentioned absence of social systems and concerns in Nexus approach (Ringler et al., 2013; Allouche et al., 2015; Foran, 2015; Leck et al., 2015). In the Nexus analysis (section Uncovering The Nexus Charcoal-Food-Water In Mozambique), poverty, livelihoods patterns, geopolitics and socio-economic phenomena are mentioned as Nexus drivers, but the actual linkage with the water-food-energy security is focused on how those drivers affect the physical and economic "availability" of resources. However, "availability" also includes "access to resources, the capacity to utilize resources as well as dynamics of social power relations and the strength of institutions" (Biggs et al., 2015), which are contextual, dynamic, complex and produced historically (Ringler et al., 2013; Foran, 2015). Remarkably, the need to understand the local perceptions and copping strategies within the context of differential social access to wood fuel has long been identified as gap in natural resources management in Southern Africa (Katerere, 1999; Moyo and Sill, 1999).

Likewise, for the case of food systems, the Nexus analysis identified fertilizer use as a driver (Nielsen et al., 2015), but affecting the Nexus through economic perspectives involving quantifiable linkages and assumptions, missing thus the cultural, social and political insight involved. On the other hand, the systems analysis proposed allowed the exploration of interaction between water and charcoal systems with critical inputs like land tenure, access to agriculture extension and financial services or rural labor market and dynamics. This incomplete economic analysis is also part of more generic criticism (Wichelns, 2017).

The gaps identified above, result from the specific combination of elements and drives selected for the Nexus approach, as well as, how Nexus analysis frames resource management. Since the Nexus is essentially a systems approach, the resulting analysis is dependent on the boundaries set, purpose and conceptualization applied. Remarkably, boundary setting is a highly subjective and political task (Ulrich, 2003; Chang et al., 2016), and what the system does not see (outside limits or vision) the system does not analyse. In fact, the definition of appropriate boundaries is critical, since the results will differ, depending on Garcia and You (2016): the number of systems considered; the combinations of systems chosen; the size, kind and number of spatial and temporal scales used; and the actors involved.

This focus on quantification is defined from the origin, since the Nexus aims to support modeling with quantifiable, optimizable and grounded on data models (section Introduction). Furthermore, the current analytical focus is on natural resource management from a deterministic, technocratic and economic perspective, favoring pre-defined visions of sustainability, resource use, security and better technological solutions. The purpose of analysis is to provide strong evidence based on mathematical equilibrium models, in which resource allocation can be optimized and efficiency improved (Allouche et al., 2015; Garcia and You, 2016). Even the trade-offs identified, rather than express multiple perspectives on the interactions, present the multiplication of deterministic assumptions, i.e., cause, effects and mutual interactions belong all to a limited set of pre-determined possibilities. Notably, this perspective promotes the commodification of resources and the parameterization of interactions bypassing, oversimplifying or simply ignoring situations, options or interactions that cannot be "quantifiable," e.g., social dynamics, perceptions, innovative capacities and behaviors (Ringler et al., 2013; Foran, 2015).

The solution so far has been the use of qualitative methods (e.g., interviews), or the use of agent based simulation, which try to simulate real humans behaviors (Garcia and You, 2016). However, even if these techniques capture the complexity of human behavior, at some point the data must be aggregated or extrapolated across scales, losing its richness and, if improperly done, leading to erroneous research conclusions and misguided policy (Nielsen et al., 2015). Consequently, the Nexus tends to favor economical, technological views such as hydropower and other "clean renewable energy," by-passing social and ecological considerations and "backwards and informal" technologies, such as charcoal.

On the other hand, the 2MBio-A instead of forcing the focus on a somewhat arbitrary number of systems applies systems and design thinking to identify which would be the basic elements of analysis of a given energy system. This ontological approach, focused on basic elements of analysis has many advantages. The 2MBio-A is not dependent on the purpose of the user. Many Nexus analysis have been proposed comprising different combinations of systems, interests and even sequences of the same systems. This diversity renders any comparison exercise difficult if not impossible. However, what is lost in "comparability" is not gained in depth or creativity of analysis. Conversely, the basic elements approach, allows for a necessary and sufficient number of blocks to be used for analytical and design purposes, facilitates comparison across models and modelers, and being non-normative and non-deterministic, allows for total freedom of analysis. Note that while the Nexus forces the view on its elementary systems, the 13 block layout of the 2MBio-A invites the users to navigate at their will to whatever systems they want, the way they wanted, as long as they check each box and relate every box. In any case, the modular nature of the 2MBio-A facilitates the addition of new elements without losing comparability because the reference set is already identified. Therefore, explicitly including nature (Resources and Land), livelihoods and socio-cultural behavior ("Users" and Livelihood Practices), and deliberately seeking for social, political and cultural dimensions of each interaction it was possible to address the complexity of charcoal systems, identify and contextualize multiple perspectives relevant for the definition of suitable, integrated and situated analysis for charcoal.

Particularly relevant was the effect that climate conditions have on Mopane and, consequently, on the legal nature of charcoal making. This finding, another undetected interaction in the Nexus, refers to the fact that, while legally forbidden to be used for charcoal making, since most Mopane trees are hollow, i.e., defective, they can actually be used for charcoal. In a fieldwork to Mabalane conducted in 2015 the author collected samples of 81 Mopane trees of different legal diameters in Mabalane-Sede and Combumune (two main charcoal production points) and identified 76% of trees as hollow. An empirical observation of the wood piled in the train station in Mabalane-Sede ready to be sent to Maputo also confirms these numbers. The reason why so many trees are hollow seem to be a common phenomenon in several ecosystems (Ruxton, 2014; Sheil et al., 2017). Studies suggest that this is an adaptation mechanism with microbial or animal consumption of interior wood producing nutrients to feed new growth via the trees roots or, in an alternative explanation, such loss of wood comes at very little cost to the tree and so investment in costly chemical defense of this wood is not economic (Ruxton, 2014). Interestingly, the lack of water is presented as the local explanation and the fact is used to legitimize the mono-exploration of Mopane. In practical terms, this interaction exposes how a biological adaptation, combined with an unsuited legal framework, generates the institutional and legal basis that legitimize an economic activity.

This being said, it is not the intention of this work to claim that the 2MBio-A or 2MBio are better approaches that the Nexus analysis. The point is that presented as an integrated all-encompassing analysis, the Nexus "forces" the analysis into a narrow set of knowledge and experiences, imposes a quantification on complex interactions that cannot be easily understood, communicated and even less quantified. To a certain point, by focusing on a certain approach and set o systems, the Nexus becomes "blind" to relevant elements, interactions and dynamics. Considering the scales involved, the disciplinary diversity required and creative and innovative approaches required to address trade-off (e.g., Ringler et al., 2013), it is possible that, posed as it is, the Nexus may become a sterile exercise unable to fulfill the task it was set to achieve. At least by itself.

Beyond the Nexus With the Nexus: Toward the Integrated and Participatory Nexus

Considering any Nexus as complex socio-ecological systems, three major challenges emerge as fundamental to propose more comprehensive, integrated and encompassing analysis: the challenge of identifying and analysing the interlinkages, trade-offs and synergies among the Nexus Systems (e.g., Liu et al., 2017); communicate that analysis across disciplines, sectors and cultures (e.g., Wichelns, 2017); and promote creativity (Ringler et al., 2013). More than improve modeling techniques (which has its merit, Kling et al., 2017; Veldhuis and Yang, 2017), arguably it is necessary to promote participation and dialogue (e.g., Mirzabaev et al., 2015; Howartha and Monasterolo, 2016; Kling et al., 2017; Veldhuis and Yang, 2017). Sometimes under other denominations, like "co-decision" (Veldhuis and Yang, 2017) or "transdisciplinary […] knowledge co-production" (Kling et al., 2017) the purpose is to Promote the "active engagement of stakeholders from different sectors in all the phases of knowledge development to acquire a clearer picture of their needs and expertise in the decision making process" (Howartha and Monasterolo, 2016). Therefore. More than simple passive consultation, it is necessary to refocus the politics and philosophy of the Nexus toward a more inclusive and democratic process (Allouche et al., 2015; Leese and Meisch, 2015). Acknowledging the nexus as a complex problem that cannot be solved solely by high-level, top-down determinist and technocratic approaches, this political shift calls for plurality, diversity and multiplicity in "nexused challenges" (Allouche et al., 2015). Besides considering social and ecological dimensions, the nexus analysis should involve, value and acknowledge multiple criteria, scales, actors, perspectives, knowledge and ways of knowing and understanding problems and solutions (Allouche et al., 2015; Leese and Meisch, 2015; Pittock et al., 2015). Importantly, within the nexus analysis, natural resources management should also include contextualized definitions of development, and address rights, equity and power relations (Allouche et al., 2015; Foran, 2015; Leese and Meisch, 2015). Therefore, recognizing the political nature of decision-making in nexus, the purpose is to promote more democratic, adaptive, deliberative and reflexive forms of understanding and act upon the challenges posed by nexus (Stein et al., 2014; Allouche et al., 2015).

In practical terms, the implementation of this perspective it is necessary to create tools that promote active and creative participation; dialogue; and are adapted to the users' context.

Participation is repeatedly considered a basic element/process in nexus analysis. Acknowledging the complex and transdisciplinary nature of Nexus analysis, the active engagement of scientists and non-experts from different sectors in all stages and scales of decision-making is required to capture lessons emerging from different experiences (Kurian, 2017), build a clearer picture of needs and expertise (Howartha and Monasterolo, 2016) and explore and test different perspectives (Pittock et al., 2015). Participation is also considered a process to bring the nexus analysis, its challenges and trade-offs, to concrete actors in real contexts (Stein et al., 2014). For Leck et al., (2015), stronger processes of co-production between researchers and nexus stakeholders are crucial to overcome the institutional barriers that affect nexus implementation, while the absence of participation is a cause for the lack of ownership and consequent failure of nexus based projects in Southern Africa (e.g., Prasad et al., 2012). In Mozambique, in nexus related studies, participation is considered to be useful to blend equity perceptions of politicians, technicians and population and better integration of natural resources management in the planning process (Ducrot, 2013), or to identify perceptions otherwise overlooked by aggregating processes (Nielsen et al., 2015).

Closely related with participation, dialogue is a central element in FAO's perspective on the nexus linking the resource base with the goals (FAO, 2014). In this framework, dialogue makes explicit the different goals, interests and uses of resource base of stakeholders', shares the understanding each actor holds on the nexus problems and solutions, implements and coordinates action, while offering a process to reconcile differences and build common ground (FAO, 2014; Pittock et al., 2015; Smajgl et al., 2016). Therefore, implicitly, dialogue also favors learning, inclusive and participatory dynamics.

Regarding the adaptability to the user contexts, it is relevant to mention two practical aspects. First, the need to focus on the user and its context, particularly if the purpose is to address CES in developing countries. Each actor involved in the nexus analysis has its own framings, different definitions of the problem, and particular histories, languages and cultures (Allouche et al., 2015; Leck et al., 2015). Secondly, the importance of visual knowledge as motivator of creativity and interaction. Visualization has long been useful to tackle complex problems (Conklin, 2005). In the nexus analysis, particularly when combined with participatory modeling, facilitate discussion and joint learning, allow for rapid data collection (Stein et al., 2014; Legrand, 2015). The main benefit of visualization is the "making explicit" of tacit relationships, assumptions and expectations allowing, thus, actors from different backgrounds to engage in structured discussions and exploration as part of the nexus analysis (Stein et al., 2014; Kurian, 2017).

Since the 2MBio-A (as well as the 2MBio) fulfills these design criteria, this research proposes an integrated and participatory Nexus approach based on those tools. However, the Nexus modeling toolkit, the Nexus social network mapping (Stein et al., 2014) or the Nexus Games (Mochizuki et al., 2017) might be interesting options.

The use of the 2MBio to design Nexus based approaches, or the 2MBio-A, to analyse the Nexus, is quite intuitive, has 3+1 steps and is depicted in **Figure 7**:

1. Setup- Definition of the groups for the participatory analysis workshop. Care should be taken to make groups with a wide selection of relevant and representative array of perspectives, interests or ideas.
2. Composition- In the participatory analysis workshop, the participants decide upon which components should be part of the nexus to analyse (A in **Figure 7**). If the purpose is specifically the Nexus, an option should be given to include extra components. This initial choice will express the users' particular concerns and perceptions on the chosen Nexus.
3. Specification- With the nexus components chosen, the users will perform the nexus analysis in each of the DEs (boxes) having the respective DE as the center of the analysis. For instance, if the nexus charcoal-food-water was selected in 1, in the DE "Resources and Land", the nexus is charcoal-water-food-forest-land and all the interactions should be considered according to the users perspectives (e.g., social, economic, cultural). The relations are written or drawn in the DE, indicating with arrows which component affects which and how. In each DE the users should also include pertinent remarks or comments, e.g., meta-information on choices, drivers, historical tendencies.
4. Consolidation- Since the 2MBio-A is an ontological and modular tool, it is always possible to compare, combine and/or integrate side-by-side, DE-by-DE two or more different specified 2MBio-A. If any of these processes is done within the same region or case study, this represent a case-study consolidation. If any of these processes is done across administrative borders (e.g., between a village and a national 2MBio-A), the consolidation is across geographical scales.

Note that the use of the 2MBio-A does not "make" the Nexus Modelling and complete analysis. What the 2MBio-A provides is an entry-level platform for the Nexus analysis. By entry level it is, by no means, to say basic or simple, since it can be rather

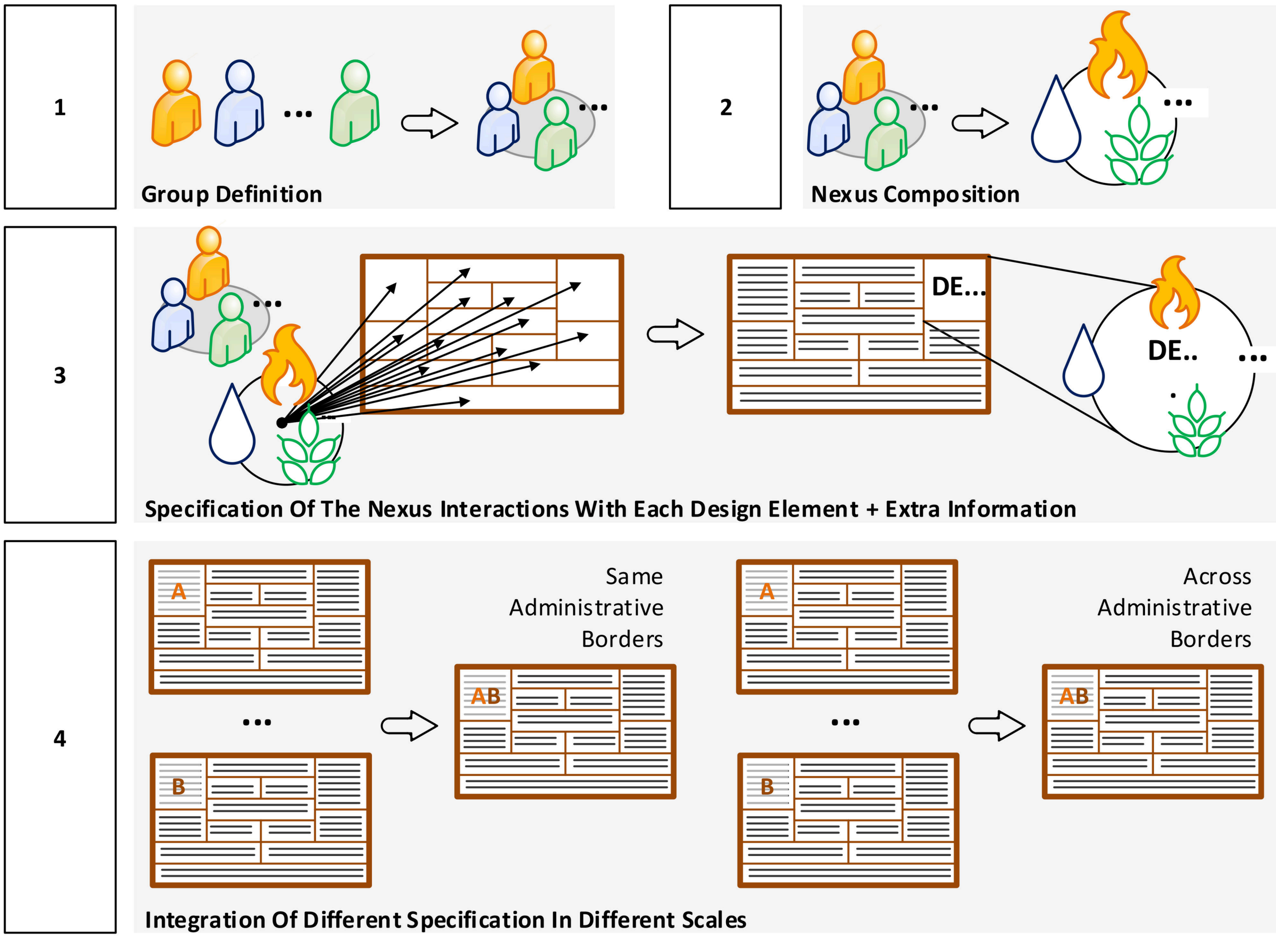

FIGURE 7 | Schematic representation of the 2MBio-A used as a focused Nexus Charcoal-Water-Food tool with the different steps and some possible applications (Source: the Author).

deep and sophisticated. The meaning of entry-level is to highlight the interface nature of the proposed integration based on the 2MBio-A. This participatory, dialogue and visual approach has the potential to orient the modeling, design and analysis effort faster and more effectively to otherwise blind spots of Nexus analysis.

CONCLUSION

Charcoal energy systems, CES, is a complex socio-ecological system dynamically interwoven into other systems, including, the water, the food and the energy systems. On this regard, the Nexus (charcoal-food-water) does provide an interesting and potential useful conceptual support an integrated analysis of resource management linking data research to policy-making. The relevance of this analysis for policy-making is clear when it is realized that over 70% of the population relies exclusively on charcoal and firewood, extreme climate disasters (e.g., floods, droughts) are common and still there is no real law enforcement on the subject.

However, nexus approaches seem to drive on normative and prescriptive political agendas based on technical knowledge and, surprisingly, there is no Nexus analysis focused on CES. Likewise, there are no comparative study between a Nexus analysis and any other systems approach for the some purpose. To bridge this gap, a Nexus analysis was made for Mozambique based on relevant existing studies. For comparison purposes, a participatory bioenergy systems conceptual design tool developed by the author, the 2MBio, was adapted to perform the same kind of analysis on the CES defined for Mabalane, a major charcoal production area in South Mozambique. Nexus approach failed to identify relevant links with ecology and livelihoods culture and social dynamics. In particular, Nexus was blind to the inequalities in rural areas, to the effect of dry climate and soil on the biology of trees and how these links affected the legitimacy of charcoal makers under present legal framework. Thus, overly focused on three systems the Nexus seems to replicate the problems of the centralized strategies on a different level.

Recognizing, however, the potential provided by the systems thinking behind the Nexus to detect interlinkages, synergies and trade-offs in charcoal problematics, this research proposed an integrated approach based on the 2MBio-A. The 2MBio-A keeps the modular, simple to use, intuitive and visual structure of the 2MBio to promote a non-deterministic, non-prescriptive and structured dialogue to further analysis and exploration of the nexus. While charcoal-centric, the 2MBio-A provides users with the liberty to define the composition of the nexus, identify and register (i.e., make explicit and available to discussion) in a participatory way the interactions drivers and any other useful information to facilitate analysis of the chosen Nexus. Since the 2MBio provides a structured, comprehensive platform for analysis, the result is a contextualized, participatory and comprehensive specification of Nexus analysis. Moreover, and still relying on the modular structure of the 2MBio, the 2MBio-A approach provides the possibility to compare different specifications defined for different contexts, promoting thus, integration across scales. Furthermore, the 2MBio-A provides a comprehensive platform for deep analysis, from which more detailed and formalized Nexus modeling can be built.

While further work is necessary to implement and test the 2MBio-A in real settings to refine and improve the process. The integration proposed, acknowledges the relevance of diverse knowledge, the need to align policy with reality, the existence of multiple uncertainties and, the fact that resource management is a political process, to present an approach that supports participation, dialogue, openness while providing a structured but non-normative platform for comparison and integration across scales.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

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REFERENCES

Alba, R., Bolding, A., and Ducrot, R. (2016). The politics of water payments and stakeholder participation in the Limpopo River Basin, Mozambique. *Water Altern.* 9, 569–587.

Allouche, J., Middleton, C., and Gyawali, D. (2015). Technical veil, hidden politics: Interrogating the power linkages behind the nexus. *Water Altern.* 8, 610–626.

Al-Saidi, M., and Elagib, N. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Sci. Total Enviro.* 574, 1131–1139. doi: 10.1016/j.scitotenv.2016.09.046

Batidzirai, B., Faaij, A., and Smeets, E. (2006). Biomass and bioenergy supply from mozambique. *Energy Sustain. Develop.* 10, 54–81. doi: 10.1016/S0973-0826(08)60507-4

Baumert, S., Luz, A., Fisher, J., Vollmer, F., Ryan, C., Patenaude, G., et al. (2016). Charcoal supply chains from mabalane to maputo: who benefits? *Energy Sustain. Develop.* 33, 129–138. doi: 10.1016/j.esd.2016.06.003

Belmonte, B., Benjamin, M., and Tan, R. (2017). Biochar systems in the water-energy-food nexus: the emerging role of process systems engineering. *Curr. Opin. Chem.* Eng. 18, 32–37. doi: 10.1016/j.coche.2017.08.005

Biggs, E., Bruce, E., Boruff, B., Duncan, J., Horsley, J., Pauli, N., et al. (2015). Sustainable development and the water-energy-food nexus: a perspective on livelihoods. *Environ. Sci. Policy* 54, 389–397. doi: 10.1016/j.envsci.2015.08.002

Bila, J., and Mabjaia, N. (2012). Crescimento E Fitossociologia De Uma Floresta Com Colophospermum Mopane, Em Mabalane, Província De Gaza, Moçambique. *Braz. J. For. Res.* 32, 421–427. doi: 10.4336/2012.pfb.32.72.421

Boas, I., Biermann, F., and Kanie, N. (2016). Cross-sectoral strategies in global sustainability governance: towards a nexus approach. *Int. Environ. Agreem.* 16, 449–464. doi: 10.1007/s10784-016-9321-1

Brears, R. (2018). "The green economy and the water-energy-food nexus," in *The Green Economy And The Water-Energy-Food Nexus*, ed R. Brears (London: Palgrave Macmillan), 23–50.

Brida, A.-B., Owiyo, T., and Sokona, Y. (2013). Loss and damage from the double blow of flood and drought in mozambique. *Int. J. Glob. Warm.* 5, 514–531. doi: 10.1504/IJGW.2013.057291

Brouwer, F., Avgerinopoulos, G., Fazekas, D., Laspidou, C., Mercure, J.-F., Pollitt, H., et al. (2018). Energy modelling and the nexus concept. *Ener. Strat. Rev.* 19, 1–6. doi: 10.1016/j.esr.2017.10.005

Brouwer, I., Hoorweg, J., and van Liere, M. (1997). When households run out of fuel: responses of rural households to decreasing fuelwood availability, Ntcheu District, Malawi. *World Develop.* 25, 255–266. doi: 10.1016/S0305-750X(96)00100-3

Bullock, A., and Hülsmann, S. (2015). "Strategic opportunities for hydropower within the water-energy-food nexus in mozambique," in *Working Paper nr. 4, United Nations University Institute for Integrated Management of Material Fluxes and of Resources (Unu-Flores)* (Dresden).

Cairncross, S., and Cuff, J. L. (1987). Water use and health in mueda, Mozambique. *Trans. R. Soc. Trop. Med. Hyg.* 81, 51–54. doi: 10.1016/0035-9203(87)90280-X

Campbell, B., Angelsen, A., Cunningham, A., Katerere, Y., Sitoe, A., and Wunder, S. (2007). Miombo Woodlands-Opportunities *a*nd Barriers To Sustainable Forest Management. Bogor Barat: CIFOR, Center for International Forestry Research.

Chang, Y., Li, G., Yao, Y., Zhang, L., and Yu, C. (2016). Quantifying the water-energy-food nexus: current status and trends. *Energies* 9:65. doi: 10.3390/en9020065

Clover, J. (2007). *Framing Issues of Environmental Security in Angola & Mozambique- the Nexus of Land, Conflicts and Sustainable Livelihoods in Post-Conflict Situations.* Doctoral Thesis, University of the Witwatersrand, Johannesburg.

Conklin, J. (2005). *Dialogue Mapping: Building Shared Understanding of Wicked Problems.* New York, NY: John Wiley & Sons.

Conway, D., van Garderen, E., Deryng, D., Dorling, S., Krueger, T., Landman, W., et al. (2015). Climate And Southern Africa's water-energy-food nexus. *Nat. Clim. Change* 5, 837–846. doi: 10.1038/nclimate2735

Cumbe, F., Sharma, D., and Lucas, C. (2005). The status of "Clean Cooking Fuels," in Sydney, NSW: University of Technology. Available online at: www.saee.ethz.ch (September 2009).

Djoudi, H., Vergles, E., Blackie, R., Koame, C., and Gautier, D. (2015). Dry forests, livelihoods and poverty alleviation: understanding current trends. *Int. Forest. Rev.* 17, 54–69. doi: 10.1505/146554815815834868

Ducrot, R. (2013). *Pro-Poor Mechanisms for Water and Land Access and Uses in the Upper Limpopo Basin, Mozambique.* Final report: Project: CPWF Limpopo Basin: Water Governance, International Centre for Water Economics and Governance in Africa, Universidade Eduardo Mondlane, Gestión de L'Eau, Actoers, Usage, Maputo.

Ducrot, R., (2017). Is small-scale irrigation an efficient pro-poor strategy in the upper Limpopo Basin in Mozambique? *Phys. Chem. Earth A/B/C* 100, 383–392. doi: 10.1016/j.pce.2016.06.001

Dupar, M., and Oates, N. (2012). *Getting to Grips With the Water-Energy-Food 'Nexus'.* London: Climate and Development Knowledge Network. Available online at: https://cdkn.org/2012/04/getting-to-grips-with-the-water-energy-food-nexus/?loclang=en_gb (Accessed May 2017).

Endo, A., Tsurita, I., Burnett, K., and Orencio, P. (2015). A review of the current state of research on the water, energy, and food nexus. *J. Hydrol.* 11, 20–30. doi: 10.1016/j.ejrh.2015.11.010

Eriksen, S., and Silva, J. (2009). The vulnerability context of a savanna area in mozambique: household drought coping strategies and responses to economic change. *Environ. Sci. Policy* 12, 33–52. doi: 10.1016/j.envsci.2008.10.007

FAO (2014). *The Water-Energy-Food Nexus, a New Approach in Support of Food Security And Sustainable Agriculture.* Rome: Food and Agriculture Organisation of the United Nations.

Ferroukhi, R., Nagpal, D., Lopez-Pe-a, A., Hodges, T., Mohtar, R., Daher, B., et al. (2015). *Renewable Energy in the Water, Energy & Food Nexus.* Abu Dhabi: International Renewable Energy Agency.

FEWSNET (2014). *Mozambique Livelihood Zone Descriptions, Report by the Famine Early Warning Systems Network.* Maputo: FEWSNET.

Foran, T. (2015). Node and regime: interdisciplinary analysis of water-energy-food nexus in The Mekong Region. *Water Altern.* 8, 655–674.

Gallagher, L., Dalton, J., Bréthaut, C., Allan, T., Bellfield, H., Crilly, D., et al. (2016). The critical role of risk in setting directions for water, food and energy policy and research. *Curr. Opin. Environ. Sustain.* 23, 12–16. doi: 10.1016/j.cosust.2016.10.002

Garcia, D., and You, F. (2016). The water-energy-food nexus and process systems engineering: a new focus. *Comp. Chem. Eng.* 91, 49–67. doi: 10.1016/j.compchemeng.2016.03.003

Githiru, M., Mutwiwa, U., Kasaine, S., and Schulte, B. (2017). A spanner in the works: human–elephant conflict complicates the food–water–energy nexus in Drylands of Africa. *Front. Environ. Sci.* 5:69. doi: 10.3389/fenvs.2017.00069

Gomiero, T. (2016). Soil degradation, land scarcity and food security: reviewing a complex challenge. *Sustainability* 8:281. doi: 10.3390/su8030281

González-López, R., and Giampietro, M. (2017). Multi-scale integrated analysis of charcoal production in complex social-ecological systems. *Front. Environ. Sci.* 5:54. doi: 10.3389/fenvs.2017.00054

Gulati, M., Jacobs, I., Jooste, A., Naidoo, D., and Fakir, S. (2013). The water-energy-food security nexus: challenges and opportunities for food security in South Africa. *Aquat. Proc.* 1, 150–164. doi: 10.1016/j.aqpro.2013.07.013

Guta, D., Jara, J., Adhikari, N., Qiu, C., Gaur, V., and Mirzabaev, A. (2015). "Decentralized energy in water-energy-food security nexus in developing countries: case studies on successes and failures," in *Discussion Papers on Development Policy No. 203, Center For Development Research (ZEF)* (Bonn).

Hanlon, J. (2000). Power without responsibility: the World Bank & Mozambican Cashew Nuts. *Rev. Afr. Polit. Econ.* 27, 29–45. doi: 10.1080/03056240008704431

Homer-Dixon, T., Walker, B., Biggs, R., Crépin, A., Folke, C., Lambin, E., et al. (2015). Synchronous failure: the emerging causal architecture of global crisis. *Ecol. Soc.* 20:6. doi: 10.5751/ES-07681-200306

Howartha, C., and Monasterolo, I. (2016). Understanding barriers to decision making in the UK energy-food-water nexus: the added value of interdisciplinary approaches. *Environ. Sci. Policy* 61, 53–60. doi: 10.1016/j.envsci.2016.03.014

IEA (2014). *World Energy Outlook Special Report, a Focus on Energy Prospects In Sub-Saharan Africa, Africa Energy Outlook*. Paris: International Energy Agency.

JICA (2016). *Maps for the National Land Use Inventory, Direcção Nacional De Florestas, Ministério Da Terra*, *Ambiente E Desenvolvimento Rural.* Maputo: JICA.

Jones, D., Ryan, C., and Fisher, J. (2016). Charcoal as a diversification strategy: the flexible role of charcoal production in the livelihoods of smallholders in central Mozambique. *Ener. Sustain. Develop.* 32, 14–21. doi: 10.1016/j.esd.2016.02.009

Kaddoura, S., and El Khatib, S. (2017). Review of water-energy-food nexus tools to improve the nexus modelling approach for integrated policy making. *Environ. Sci. Policy* 77, 114–121. doi: 10.1016/j.envsci.2017.07.007

Katerere, Y. (1999). "Biomass planning: how to meet future energy requirements," in *Energy Policy and Planning in Southern Africa*, eds S. Moyo, S., M. Sill, and P. O'Keefe (Harare: SARIPS and SAPES), 33–52.

Keairns, D. L., Darton, R. C., and Irabien, A. (2016). The energy-water-food nexus. *Ann. Rev. Chem. Biomol. Eng.* 7, 239–262. doi: 10.1146/annurev-chembioeng-080615-033539

Kling, C., Arritt, R., Calhoun, G., and Keiser, D. (2017). Integrated assessment models of the food, energy, and water nexus: a review and an outline of research needs. *Ann. Rev. Res. Econ.* 9, 143–163. doi: 10.1146/annurev-resource-100516-033533

Krchnak, K., Smith, D., and Duetz, A. (2011). "Putting nature in the nexus: investing in natural infrastructure to advance water-energy-food security," in *Bonn2011 Conference: The Water, Energy and Food Security Nexus-Solutions for the Green Economy, Background Papers for the Stakeholder Engagement Process* (Bonn).

Kurian, M. (2017). The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. *Environ. Sci. Policy* 68, 97–106. doi: 10.1016/j.envsci.2016.11.006

Kurian, M., and Ardakanian, R. (2015). "The nexus approach to governance of environmental resources considering global change," in *Governing The Nexus, Water, Soil And Waste Resources Considering Global Change, UNU-Flores*, eds M. Kurian and R. Ardakanian (New York, NY: Springer International Publishing), 3–13.

Leck, H., Conway, D., Bradshaw, M., and Ree, J. (2015). Tracing the water-energy-food nexus: description. *Theory Pract. Geogr. Compass* 9/8, 445–460. doi: 10.1111/gec3.12222

Leese, M., and Meisch, S. (2015). Securitising sustainability? Questioning the 'water, energy and food-security nexus'. *Water Altern.* 8, 695–709.

Legrand, C. (2015). *Participatory Simulation to Raise Awareness About Integrative Planning for Small Water Infrastructures and Drought Control in Semi-Arid Mozambique,* Master Thesis, Wageningen Univeristy, Wageningen.

Liu, J., Yang, H., Cudennec, C., Gain, A., Hoff, H., Lawford, R., et al. (2017). Challenges in operationalizing the water-energy-food nexus. *Hydrol. Sci. J.* 62, 1714–1720. doi: 10.1080/02626667.2017.1353695

Mabhaudhi, T., Mpandeli, S., Madhlopa, A., Modi, A., Backeberg, G., and Nhamo, L. (2016). Southern Africa's water-energy nexus: towards regional integration and development. *Water* 8:235. doi: 10.3390/w8060235

Magombeyi, M., Taigbenu, A., and Barron, J. (2013). "Rural poverty and food insecurity mapping at district level for improved agricultural water management in the limpopo river basin," in *CPWF Research for Development (R4D) Series 6, CGIAR Challenge Program on Water and Food* (Colombo).

Martins, R. (2014). *2MW, The Wood Fuel Energy Systems Conceptual Design Metamodel, a Novel Approach to Participatory Design Contextualised to the Case of Mozambique*. PhD Thesis, Imperial College London.

Martins, R., Cherni, J., and Videira, N. (2018). 2MBio, A novel tool to encourage creative participatory conceptual design of bioenergy systems-the case of wood fuel energy systems in South Mozambique. *J. Clean. Prod.* 172, 3890–3906. doi: 10.1016/j.jclepro.2017.05.062

Mather, D. (2012). *Determinants of Crop Income in Rural Mozambique.* Report 71E, Direcção de Economia, Ministério Da Agricultura de Moçambique, Maputo.

Mirzabaev, A., Guta, D., Goedecke, J., Gaur, V., Börner, J., Virchow, D., et al. (2015). Bioenergy, food security and poverty reduction: trade-offs and synergies along the water-energy-food security nexus. *Water Int.* 40, 772–790. doi: 10.1080/02508060.2015.1048924

MITANDER (2016). *Relatório Anual da 2016 Direcção Nacional De Florestas,* Ministério Da Terra, Ambiente E Desenvolvimento Rural, Maputo.

Mochizuki, J., Magnuszewski, P., and Linnerooth-Bayer, J. (2017). "Games for aiding stakeholder deliberation on nexus policy issues," in DNC2017 *Position Paper* (Dresden: UNU-FLORES).

Moyo, S., and Sill, M. (1999). "Introduction," in *Energy Policy and Planning in Southern Africa*, eds S. Moyo, M. Sill, and P. O'Keefe (Harare: SARIPS and SAPES), 1–12.

Muller, M. (2016). "Virtual water and the nexus in national development planning," in *Building Climate Resilience Through Virtual Water and Nexus Thinking in the Southern African Development Community*, eds A. Entholzner and C. Reeve (Cham: Springer International Publishing), 87–105.

Ng'ang'a, S., Maute, F., Notenbaert, A., Herrero, M., and Moyo, S. (2012). "Coping strategies and vulnerability to climate change of households in Mozambique," in *CCAFS Working Paper Nr. 28, CGIAR Research Program on Climate Change* (Copenhagen: Agriculture and Food Security (CCAFS)).

Nhantumbo, I. (2010). "Payment for environmental services: forest policy issues in Mozambique," in *Payment For Environmental Services, Laying the Ground Work, Case Studies From Eastern and Central Africa*, eds H. Mogaka, J. Okeyo-Owuor, and A. Kipkoech (Junja: ASARECA), 23–39.

Nielsen, T., Schünemann, F., McNulty, E., Zeller, M., Nkonya, E., Kato, E., et al. (2015). *The Food-Energy-Water Security Nexus, Definitions, Policies, and Methods in An Application to Malawi and Mozambique.* IFPRI

Discussion Paper 01480, International Food Policy Research Institute, Washington, DC.

Obasi, G. (2005). "The impacts of ENSO in Africa," in *Climate Change And Africa,* ed P. Low (Cambridge: Cambridge University Press), 218–230.

Pihale, E. (2003). *The Environmental Impact of the Armed Conflict in Southern Mozambique, 1977-1992.* Master Thesis, University of Cape Town, Cape Town.

Pittock, J., Orr, S., Stevens, L., Aheeyar, M., and Smith, M. (2015). Tackling trade-offs in the nexus of water, energy and food. *Aquat. Proc.* 5, 58–68. doi: 10.1016/j.aqpro.2015.10.008

Plummer, M. (1999). To fetch a pail of water. *Natl. Hist.* 108, 56–65.

Prasad, G., Boulle, M., Boyd, A., Rahlao, S., Wlokas, H., and Yaholnitsky, I. (2012). *Energy, Water and Climate Change in Southern Africa: What are the Issues That Need Further Investment And Research?* Cape Town: Energy Research Centre, University of Cape Town.

Ringler, C., Bhaduri, A., and Lawford, R. (2013). The nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain.* 5, 617–624. doi: 10.1016/j.cosust.2013.11.002

Ruxton, G. (2014). Why are so many trees hollow? *Biol. Lett.* 10:20140555. doi: 10.1098/rsbl.2014.0555

Ryan, C. M., Pritchard, R., McNicol, I., Owen, M., Fisher, J. A., and Lehmann, C. (2016). Ecosystem services from Southern African woodlands and their future under global change. *Philos. Trans. R. Soc. B* 371, 1–16. doi: 10.1098/rstb.2015.0312

Schön, D. (1983). *The Reflective Practitioner*. London: Temple Smith.

Schreiner, B., and Baleta, H. (2015). Broadening the lens: a regional perspective on water, food and energy integration in SADC. *Aquat. Proc.* 5, 90–103. doi: 10.1016/j.aqpro.2015.10.011

Scott, C., Kurian, M., and Wescoat Jr,. J. (2015). "The water-energy-food nexus: enhancing adaptive capacity to complex global challenges," in *Governing The Nexus, Water, Soil And Waste Resources Considering Global Change*, *UNU-Flores*, eds M. Kurian and R. Ardakanian (New York, NY: Springer International Publishing), 15–39.

Sheil, D., Eastaugh, C. S., Vlam, M., Zuidema, P. A., Groenendijk, P., van der Sleen, P., et al. (2017). Does biomass growth increase in the largest trees? Flaws, fallacies and alternative analyses. *Funct. Ecol.* 31, 568–581. doi: 10.1111/1365-2435.12775

Silva, J., Eriksen, S., and Ombe, Z. (2010). Double exposure in Mozambique's Limpopo River Basin. *Geograph. J.* 176, 6–24. doi: 10.1111/j.1475-4959.2009.00343.x

Simler, K., and Nhate, V. (2005). *Poverty, Inequality, and Geographic Targeting: Evidence From Small Area Estimates In Mozambique,* FCND Discussion Paper 192, International Food Policy Research Institute, Washington, DC.

Sitoe, A., Remane, I., Ribeiro, R., Falcão, M., Mate, R., Nhamirre, J., et al. (2016). *Identificação E Análise Dos Agentes E Causas Directas E Indirectas De Desmatamento E Degradação florestal Em Moçambique,* Relatório Final, Centro de Estudos de Agricultura e Gestão de Recursos Naturais, Maputo.

Smajgl, A., Ward, J., and Pluschke, L. (2016). The water-food-energy nexus, realising a new paradigm. *J. Hydrol.* 533, 533–540. doi: 10.1016/j.jhydrol.2015.12.033

SNV (2007). *The Biomass Tree* of Problems. Maputo: SNV.

Sowlati (2016). "Modeling of forest and wood residues supply chains for bioenergy and biofuel production," in *Biomass Supply Chains for Bioenergy and Biorefining,* eds J. Holm-Nielsen and E. Ehimen (Amsterdam: Woodhead Publishing), 167–190.

Stein, C., Barron, J., Nigussie, L., Gedif, B., Amsalu, T., and Langan, S. (2014). "Advancing the water-energy-food nexus: social networks and institutional interplay in the Blue Nile," in *WLE Research for Development (R4D) Learning Series 2, International Water Management Institute (IWMI), CGIAR Research Program on Water, Land and Ecosystems (WLE)* (Colombo).

Syampungani, S., Chirwa, P., Akinnifesi, F., Sileshi, G., and Ajayi, O. (2009). The miombo woodlands at the cross roads: potential threats, sustain-able livelihoods, policy gaps and challenges. *Natl. Res. Forum* 33, 150–159. doi: 10.1111/j.1477-8947.2009.01218.x

Tidwell, T. (2016). Nexus between food, energy, water, and forest ecosystems in the USA. *J. Environ. Stud. Sci.* 6, 214–224 doi: 10.1007/s13412-016-0367-8

Turton, A., Ashton, P., and Jacobs, I. (2008). *The Management Of Shared Water Resources In Southern Africa*, CSIR Report No. CSIR/NRE/WR/ER/2008/0400/C, IMIS Contract No. 2009UNA073263853111, United Nations Economic Commission for Africa-Southern Africa (UNECA-SA) (Lusaka).

Ulrich, W. (2003). Beyond methodology choice: critical systems thinking as critically systemic discourse. *J. Operat. Res. Soc.* 54, 325–342. doi: 10.1057/palgrave.jors.2601518

UNDP (2016). *Human Development Report 2016, Human Development for Everyone.* New York, NY: United Nations Development Programme.

van der Plas, R., Sepp, S., Pigaht, M., Malalane, A., Mann, S., and Madon, G. (2012). Mozambique Biomass Energy Strategy, *ECO-Consult and MARGE International for European Union Energy Initiative Partnership Dialogue Facility and Ministry of Energy of Mozambique.* Maputo: European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF), Mozambique Ministry of Energy.

van der Zaag, P., Juizo, D., Vilanculos, A., Bolding, A., and Post Uiterweer, N. (2010). Does The Limpopo River basin have sufficient water for massive irrigation development in the plains of Mozambique? *Phys. Chem. Earth* 35, 832–837. doi: 10.1016/j.pce.2010.07.026

Veldhuis, A., and Yang, A. (2017). Integrated approaches to the optimisation of regional and local food–energy–water systems. *Curr. Opin. Chem. Eng.* 18, 38–44. doi: 10.1016/j.coche.2017.09.001

Ward, P. J., Beets, W., Bouwer, L. M., Aerts, J. C. J. H., and Renssen H., (2010). Sensitivity of river discharge to ENSO. *Geophys. Res. Lett.* 37:L12402. doi: 10.1029/2010GL043215

Wetterlund, E., Leduc, S., Dotzauer, E., and Kindermann, G. (2013). Optimal use of forest residues in Europe under different policies—second generation biofuels versus combined heat and power. *Biomass Conv. Bioref.* 3, 3–16. doi: 10.1007/s13399-012-0054-2

WHO/UNICEF (2014). *Progress On Sanitation And Drinking-Water, 2014 Update, WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation.* Geneve: World Health Organization.

Wichelns, D. (2017). The water-energy-food nexus: is the increasing attention warranted, from either a research or policy perspective? *Environ. Sci. Policy* 69, 113–123. doi: 10.1016/j.envsci.2016.12.018

Woollen, E., Ryan, C. M., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., et al. (2016). Charcoal production in the mopane woodlands of mozambique: what are the trade-offs with other ecosystem services? *Philos. Trans. R. Soc. B* 371:20150315. doi: 10.1098/rstb.2015.0315

Yillia, P. (2016). Water-energy-food nexus: framing the opportunities, challenges and synergies for implementing the Sdgs. *Österreichische Wasser-und Abfallwirtschaft* 68, 86–98. doi: 10.1007/s00506-016-0297-4

Zhu, T., and Ringler, C. (2012). Climate change impacts on water availability and use in the Limpopo River Basin. *Water* 4, 63–84. doi: 10.3390/w4010063

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Incorporating Ecohydrological Processes Into an Analysis of Charcoal-Livestock Production Systems in the Tropics: An Alternative Interpretation of the Water-Energy-Food Nexus

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In the tropics, livestock grazing usually occurs simultaneously with charcoal production, yet empirical understanding of the combined activities remains poor, especially in terms of their effects on hydrological functions. Given predicted growth in both charcoal and beef production in Sub-Sahara Africa, South East Asia, and Central and South America, understanding the potential effects of maintaining this dual production system on local and landscape level hydrological dynamics is paramount for ensuring long-term ecosystem sustainability. Based on a synthesis of existing literature, we propose a theoretical and conceptual framework for analyzing the interlinks between charcoal, livestock, and hydrological processes where they co-exist. As a silo approach, we first analyze the isolated effects of charcoal production and livestock on hydrological processes before exploring their combined effects (systemic approach). Given the scarcity of studies that explicitly address the influence of traditional small-scale charcoal production on hydrological processes, we base our findings on existing knowledge about deforestation, forest fire and grazing impacts on hydrology. We find that exclusion of the effects of companion activities and omission of information on the intensity of biomass harvesting (i.e., pruning branches, selective harvest, clear cutting, uprooting tree stumps) can lead to over-attributing changes in hydrological processes to charcoal, thus exaggerating the effects on ecosystems which might lead to inappropriate interventions. We also find that, in the case of livestock keeping, impacts on hydrological processes are highly dependent on grazing intensity, with low intensity grazing possibly having negligible or even positive effects on forest regrowth and thereby restoration of hydrological processes. Thus, the charcoal-livestock-water nexus may have a wide range of outcomes for hydrological processes from negligible to highly profound effects, depending on key decisions in management and practice. To test these findings, however, field studies are needed that explicitly treat the combined effects of different biomass harvesting practices and grazing intensities on hydrological processes across different scales. Albeit conceptual at this stage, we believe that our approach is a necessary first step in the process of diagnosing potential shortcomings of past approaches for studying charcoal production systems and developing new understanding of this three-way nexus.

Keywords: biomass energy, charcoal, ecohydrology, grazing, nexus

INTRODUCTION

One third (2.4 billion) of global population depends on traditional woodfuels (charcoal and firewood) for most of their cooking and heating requirements (FAO, 2017). For 29 countries primarily in sub-Saharan Africa (SSA), woodfuel constitutes more than 50% of total national energy supply (FAO, 2014). It is estimated that worldwide, approximately half of the wood extracted from forests is used as woodfuel, 17% of which is converted to charcoal (FAO, 2017). Forests are central for regulating local, regional, and global hydrological cycles (Bradshaw et al., 2007). In woodfuel-dependent nations, over-extraction of woody biomass to supply the energy sector can jeopardize the status of forests and their ability to fulfill their regulatory functions (Bazilian et al., 2011).

The water-energy-food (WEF) nexus is usually presented as the point of interaction of the three resources with a tradeoff often implied between two or all components (Bazilian et al., 2011; Hoff, 2011; Endo et al., 2017). Typically, the energy component depicted in descriptions of this nexus is electrical, sourced either from hydropower, nuclear, petroleum or from biofuels derived from crops. The obvious tradeoff, in these examples, tends to be about securing sufficient water for energy production when it is also needed to produce food. In the case of traditional charcoal production, as is conducted by millions of small-scale producers in SSA, Central and South America, the Caribbean and South East Asia, natural forests and shrublands supply most of the biomass (FAO, 2017). In this context, the water-energy link is ecohydrological with the central question being: Does charcoal production negatively impact local and regional hydrological dynamics?

Most tropical landscapes are managed for multiple co-occurring activities (DeFries and Rosenzweig, 2010) whose combined effects on system-level functioning are insufficiently understood (Uriarte et al., 2011). Charcoal producing landscapes are no exception. Cattle, goats, sheep, donkeys and horses are often released in the forests and woodlands where charcoal is made to graze and forage on grass, shrubs, trees, and coppicing stumps. Livestock grazing in the form of pastoral, agro-pastoral and silvopastoral systems supplies 24% of global meat production; 50% of global beef is produced in developing countries under such grazing systems. Nevertheless, a recent global review of the current state of research of the WEF nexus identified 37 projects that addressed two or more nexus components (Endo et al., 2017). Of these, 23 addressed energy and food; none, however, addressed traditional woodfuel (charcoal and firewood) production systems. In the same review, 25 research projects addressed the combination of food and water (with and without energy), but only one addressed meat and dairy production as the food component, with the focus being on crop production for livestock. Global demand for livestock is expected to increase substantially in the coming decades (Herrero et al., 2009) yet, grazing is virtually absent from nexus research.

Multiple interaction effects invoked by co-occurring activities may be imperceptible if each activity is studies in isolation (Hoff, 2011). We are not aware of published studies that have specifically looked at the ecohydrological effects of charcoal production. Studies do exist, however, on the effects of grazing in forests on hydrological functions. Along with studies on the effects of deforestation, forest degradation, and wildfires on watershed function, they lay the groundwork for developing a conceptual understanding of how charcoal production and livestock might affect site- to watershed-level hydrological processes and functions. To do this, we first describe the charcoal production and the extensive livestock system individually. We follow this with an analysis of how each land use activity—in isolation—influences hydrological processes (the silo approach), before we explore the effects of their co-occurrence (systemic approach). Albeit conceptual at this stage, we believe that our approach is a necessary first step in the process of developing systemic understanding of charcoal production systems that takes into account co-occurring activities. It is also useful in identifying information and knowledge gaps for addressing integrated landscape management challenges in the tropics. By illustrating the added value gained from exploring system-level interaction dynamics, we hope that our paper encourages other researchers and practitioners to conduct similar exercises in their own study areas.

CHARCOAL PRODUCTION

Despite transitions to cleaner and more fuels such as gas and electricity, charcoal is still a highly significant source of energy for many urban and peri-urban households in sub-Saharan Africa (SSA), South-east Asia and Latin America (Picos and Valero, 2009; FAO, 2017). Affordability and cultural preference for charcoal, compounded by high rates of population growth and urbanization in these regions suggest that, for the next three to five decades, demand will continue to grow before it begins to drop (FAO, 2017; Santos et al., 2017). Since charcoal is mostly sourced from natural forests (Chidumayo and Gumbo, 2013; FAO, 2017), meeting this growing demand is already posing challenges for the energy, forestry, and environmental sectors in the tropics.

Charcoal production can have severe consequences for ecosystems and ecological processes. Biomass removal and biomass burning can result in habitat depletion and associated biodiversity loss (Ferraro et al., 2011; Fontodji et al., 2011; Sodhi et al., 2011; Specht et al., 2015), contributing to greenhouse gas (GHG) emissions (Pennise et al., 2001; Bailis, 2009; Bailis et al., 2015) and reduction of carbon storage and sequestration capacity of terrestrial forest biomes (Mwampamba, 2007; Chidumayo and Gumbo, 2013). At the kiln site, where the biomass is converted to charcoal, long-term and seemingly non-reversable effects on soil biodiversity and soil physicochemical properties have been reported (Oguntunde et al., 2008; Fontodji et al., 2009; Nigussie and Kissi, 2011). These and earlier studies on charcoal contributed to setting the tone of international policies and interventions for tropical forests, and national forest and energy policies: that charcoal production is environmentally unsustainable; it should be curtailed; cleaner fuels must be sought (Mwampamba et al., 2013; Zulu and Richardson, 2013; Doggart and Meshack, 2017).

In the past decade, increased accessibility and quality of satellite imagery have drastically improved current understanding of charcoal production systems, prompting renewed interest in assessing the broader effects of charcoal production on forests and ecosystems (Ahrends et al., 2010; Ghilardi et al., 2016; Sedano et al., 2016; Bailis et al., 2017). Importantly, newer studies distinguish two dominant pathways through which charcoal in the tropics is produced. In the first pathway, forests are managed specifically to produce charcoal, making it the primary objective of the management system. Under this pathway, felled areas are left to regenerate, and a rotational cycle is maintained, albeit a seemingly arbitrary cycle in cases where informal forest management prevails (FAO, 2017). In the second pathway, trees are harvested for other land use objectives such as to produce timber or to clear new land for agriculture. In this pathway, charcoal making is a by-product that makes use of woody residues unsuitable for timber or fallen and uprooted trees that hinder agricultural activities. While forest degradation (in terms of species richness, genetic and structural diversity, and biomass density) tends to be the most likely outcome in the first pathway, complete forest loss (deforestation) is more probable in the second.

Seldom do studies on charcoal production specify which of these two pathways prevails in their study areas, making it difficult to discern which process is more prominent globally and regionally. Nevertheless, attributing forest degradation rather than deforestation to charcoal production has probably contributed to fundamental shifts in attitudes toward charcoal (and woodfuels) by policymakers and the donor community. This is especially that case in SSA, where there has been a visible upsurge in recent years in government and donor funded interventions aimed at producing charcoal more sustainably, a complete turnaround from previous prohibition and elimination interventions. Examples include the Swiss government support for a charcoal project in Tanzania (2014), German government support to wood charcoal industry in Namibia (2017), FAO's publication of how to green the charcoal value chain (FAO, 2017), and The Nature Conservancy's request for a study on the economics, policy and investment opportunities for sustainable charcoal in East Africa (2017). However, due to shortcomings in existing research, these new projects—which will apply state of the art knowledge of charcoal production systems—could encounter critical implementation challenges.

As research approaches have become more systemic and interdisciplinary, it is becoming increasingly obvious that charcoal production studies have made two important omissions about production systems in the tropics. First, that charcoal is rarely the only activity occurring on the land on which it is produced. Anecdotal evidence from researchers and practitioners working in charcoal production systems often cite timber harvesting, grazing, hunting, and collection of medicinal plants, wild foods and firewood as typical activities co-occurring in the same physical space and at the same time as charcoal is being produced (Eckholm et al., 1984; Maass et al., 2005; Mwampamba, 2009; Randriamalala et al., 2016; Woollen et al., 2016; Castillo-Hernández, 2017). Few of these studies, however, explicitly quantify the effects of these co-occurring activities on ecosystems. This makes the specific impact of charcoal making on forests and forest processes a challenge to single out and easy to over or underestimate. Secondly, the forests and woodlands from which charcoal is derived have a regulating role in local and regional hydrological dynamics *in addition to* the carbon cycle regulation that is more often emphasized.

Where Charcoal Meets Livestock

Among companion activities, livestock keeping is probably the most common, occurring virtually everywhere that charcoal is produced, from goat grazing in Madagascar (Randriamalala et al., 2016) to cattle in Kenya (Owen, 2013), Ethiopia (Gezahegn, 2018), Mexico (Castillo-Hernández, 2017), and Argentina (Abril and Bucher, 1999; Clark et al., 2010). In fact, some landowners in the tropics consider grazing an ideal complementary activity for charcoal production and vice versa. They actively prune (Owen, 2013) or selectively cut (Castillo-Hernández, 2017) trees to maintain desirable levels of pasture while converting the resultant biomass into charcoal. Alternatively, they incorporate livestock into forests and woodlands to keep grasses low to prevent the spread of wildfires (Castillo-Hernández, 2017). Due to complex process interactions it is likely that charcoal and livestock production co-occurring in an area will affect hydrological dynamics distinctly different than if each activity were occurring separately. At the very least, current understanding of charcoal production effects on vegetation and soils in the tropics would need to be reassessed in light of the possible effects that livestock may also be having on the system. Similarly, studies of livestock impact on vegetation that omitted the co-occurrence of charcoal in management systems would probably have misinterpreted the effects. Failure to address some of these inherent complexities of charcoal production systems may partially explain a history of frustrations with policy interventions in the sector, particularly in SSA (Mwampamba et al., 2013; Zulu and Richardson, 2013; Doggart and Meshack, 2017).

Studies that explicitly recognize land use activities that co-occur with charcoal making or which document, measure, and explore their singular and combined effects are few and only just emerging (e.g., Randriamalala et al., 2016; Woollen et al., 2016; Castillo-Hernández, 2017). Where companion activities exist, pinpointing the singular effects of charcoal is complicated by the fact that other activities exert their own effects on ecosystems by interacting directly with the vegetation and with the substrate on which vegetation depends. Livestock, for example, could affect woody biomass supply for charcoal by enhancing or inhibiting biomass recovery processes, such as natural regeneration. A silo approach to understanding the effects of livestock or charcoal ignores the multiple interactions taking place between vegetation and livestock, between livestock and charcoal production, and between charcoal production and vegetation. It also excludes the effects of these interactions on other higher-level ecological processes such as regulation of the carbon and hydrological cycles.

Incorporating companion activities to the charcoal production system drastically changes how charcoal effects are understood and how charcoal as a "problem" can be addressed through policy and practice. Indeed, doing so changes the charcoal issue from a seemingly tame or relatively simple problem to an "extraordinarily complex" or "wicked" one (Lach et al., 2005). Or, one that has "multiple and conflicting criteria for defining solutions," whose "solutions create problems for others," and where "no rules exist for determining when problems can be said to be solved" (Rittel and Webber, 1973). Given the rise in recent years of meat production in the tropics to meet global shifts toward higher meat consumption (McAlpine et al., 2009; Henchion et al., 2014; Lobato et al., 2014), where livestock keeping coincides with charcoal, an integrated understanding of their combined effects would ensure that adequate policies and practices are developed.

The Water Dimension

Known feedbacks exist between vegetation and hydrological processes (Ludwig et al., 2005; Dekker et al., 2007; Asbjornsen et al., 2011) that are affected by biomass removal, a fundamental feature in charcoal production. The absence of hydrological studies in charcoal production systems is particularly relevant and oddly surprising given the tendency for charcoal making to occur in water-limited ecosystems. Tropical dry forests and woodlands (e.g., *Miombo* and *Mopane* woodlands in SSA and the *sahel* woodlands of W Africa), tropical savannas (e.g., the *cerrado* ecosystems of Brazil), and tropical shrublands (e.g., *chacos* in Argentina, *matorral* in Mexico) provide most of the biomass used to produce charcoal (FAO, 2017). If charcoal production affects hydrological processes, compounded effects would be expected in these water-stressed ecosystems where changes in hydrological processes could have cascading and disproportional effects on overall system resilience.

The Charcoal-Livestock—Water-Nexus

Omitting these two attributes of typical tropical charcoal production, i.e., the co-occurrence with companion activities and the feedbacks with hydrology, systems puts "sustainable" charcoal projects at risk of being fundamentally flawed in terms of their ecological understanding of system-wide responses to charcoal production. Additionally, implementation barriers may arise due to conflicts between land users who have not been adequately acknowledged.

Thus, the confluence of charcoal, livestock keeping, and hydrological processes presents an intriguing and unexplored nexus that urgently needs unraveling. Here, we provide a theoretical and conceptual framework for analyzing the interlinks between charcoal, livestock, and hydrological processes where they co-occur.

THEORETICAL UNDERPINNING OF INTERACTIONS BETWEEN VEGETATION AND HYDROLOGICAL PROCESSES

There is long-term recognition by both hydrologists and ecologists of the importance of vegetation (and forests in particular) in modulating key hydrological processes (Asbjornsen et al., 2011; Henchion et al., 2014). From reducing the direct impact of precipitation on bare surfaces to determining infiltration into soils, vegetation (along with climatic, geographical and geological factors) determines the amount of water available in the landscape to replenish surface and underground reservoirs (Ludwig et al., 2005). Nevertheless, studies that explore interlinks between vegetation and hydrology in charcoal production systems are virtually nonexistent.

Four stages in the charcoal production cycle are likely to be the most relevant for hydrological processes (**Figure 1**). These stages represent key changes in vegetation and soil properties that, given what is understood of vegetation-water dynamics, should influence hydrological processes. The mature forest phase consisting of trees forming a closed or partially closed canopy represents the natural forest type in the area and its main characteristics in terms of tree size and shape, tree density, and tree species composition. Depending on forest type, a mix of sapling trees, shrubs, herbs, and grass would be expected in the understory vegetation.

The biomass harvesting phase captures key elements about how the vegetation is removed, specifically, whether biomass is obtained from felling entire trees, pruning branches, or from thinning sprouts and suckers. It also outlines whether clear felling (i.e., all trees are felled regardless of size and/or species) or selective harvesting (only specific species of specific size are felled) is practiced. In most forests or woodlands managed for charcoal production, 50–90% of standing trees are felled (Chidumayo, 1991; Chidumayo and Gumbo, 2013). Removing >10% of forest cover is technically deforestation (FAO, 2010). The biomass harvesting stage also clarifies whether uprooting is involved. As outlined earlier, uprooting would indicate that other land use motives are at play (e.g., agricultural expansion) in which charcoal making would be a by-product (pathway one).

The biomass recovery phase is a period lasting 9–30 years (FAO, 2017) and is generally characterized by resprouting (or coppicing) of tree stumps and gradual recovery of aboveground vegetation toward mature forest status. Coppicing is a widely recognized functional trait of tropical forest tree species and the primary mechanism through which they regenerate (Murphy and Lugo, 1986; McLaren and McDonald, 2003). It is also a key shared worldwide characteristic of trees preferred for charcoal making (Chidumayo and Gumbo, 2013; FAO, 2017).

Finally, a parallel recovery process takes place on abandoned kiln sites. Kiln sites are areas where biomass was stacked, insulated, and ignited to convert it to charcoal. The site represents an area that has experienced extreme heat (>400°C)

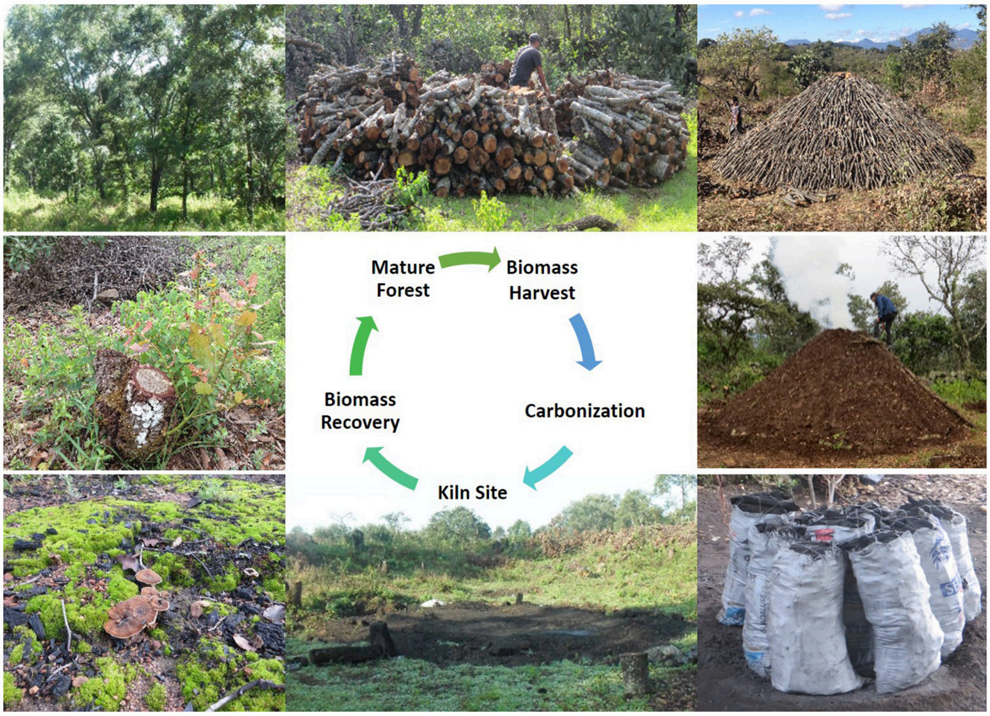

FIGURE 1 | Key stages in a typical traditional system in which forests or woodland are managed for (among other things) charcoal production. Clockwise from upper left corner: Wood is harvested from mature forests, different sized logs are stacked above or below-ground to form a rectangular or conical kiln that is insulated with locally available material such as, grass and earth. Once lit, the process of carbonization converts the wood to charcoal which is subsequently packed into sacks that are sold to intermediaries. With time (>20 years), the kiln site recovers some vegetation. In felled areas, tree stumps coppice in 2–4 weeks to initiate the biomass recovery period which lasts from 8 to 30 years before the cycle is repeated. Livestock are typically an integral part of this system, present in all or only some of the stages. Photos courtesy of THM.

for 5–21 days and sometimes more (FAO, 2017). It can take on a rectangular or circular shape typically occupying a surface area of 20–100 m^2. In traditional charcoal production systems, the kiln site moves in response to biomass availability (FAO, 2017). Depending on numerous factors, among which are tree density of desired species, ability, and willingness to move logs to kiln site, and ease of finding ideal conditions for locating kilns, several (dozens, scores) kiln sites might be concentrated in a given area or dispersed across a larger surface. Generally, the total kiln site surface area tends to be about 5% of the total harvested area, but this varies considerably across forest types and other factors (Chidumayo and Gumbo, 2013). Some kiln sites are reused in subsequent harvest cycles (Voorhoeve, 2017), but more often than not, new sites are developed with each harvesting cycle.

For the purpose of our analysis, we grouped hydrological processes into four main groups based on the impact of processes on different components of the water balance (**Figure 2**): (i) aboveground rainfall distribution (interception, stemflow, and throughfall); (ii) distribution of infiltration and water storage in the soil (i.e., the water that remains in the local environment and is available for vegetation recovery); (iii) evapotranspiration (i.e., the sum of water that is released from the soil surface and vegetation into the atmosphere), and; (iv) runoff and percolation to groundwater (i.e., water which is lost from the topsoil and is no longer available for evapotranspiration). Granted, this is a gross simplification of the systems, since all these processes are highly interlinked and dependent on one another.

Silo Approach I: The Potential Effects of Charcoal Production on Hydrological Processes

Review of Hydrological Processes in a Mature Forest

In mature forests, trees affect how water (i.e., rainfall) is distributed to the forest floor, how it infiltrates into the soil, and how it moves as surface runoff or subsurface flow to catchment-scale discharge. Worldwide, the influence of forests on hydrological processes is variable because they are contingent on geological properties and river network topography on the one hand, and on forest type, forest age, and climatic conditions on the other (Zhang et al., 2001; Bonell and Bruijnzeel, 2005; Levia et al., 2011). In mature forests, the "double funneling effect" of trees plays a fundamental role for the distribution of rainfall to evaporation, infiltration, and surface runoff (Johnson and Lehmann, 2006). The first funneling effect refers to aboveground distribution of rainfall by tree canopies. Forest canopies can intercept a relatively large proportion of precipitation, 10–50% of season-long or annual rainfall (Carlyle-Moses and Gash, 2011). The remaining rainfall makes its way to the forest floor, either as throughfall or along stems and branches (Llorens and Domingo,

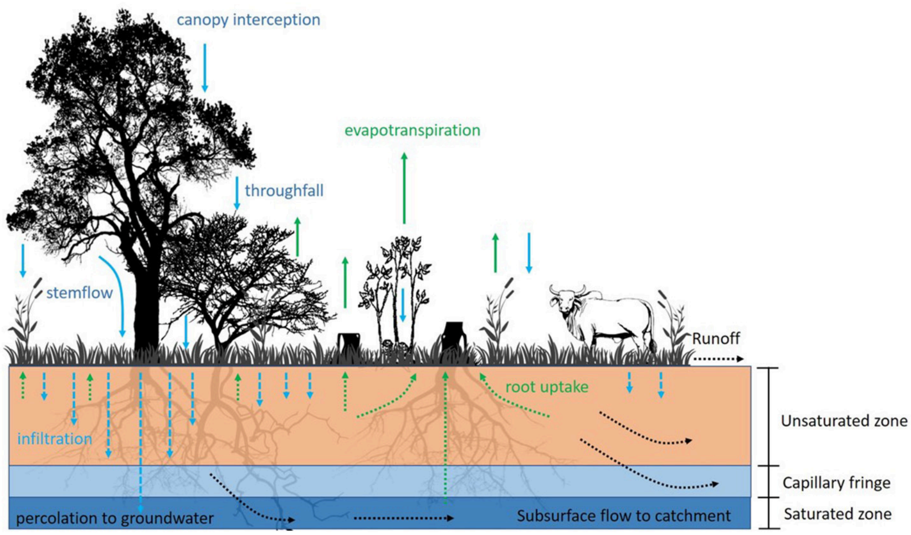

FIGURE 2 | Hydrological processes most relevant for exploring the effects of charcoal production and livestock on hydrological functioning. Illustration by THM.

2007). The degree of funneling by trees depends strongly on the tree species (Llorens and Domingo, 2007; Návar, 2011), canopy architecture (Bialkowski and Buttle, 2015), stand density and forest age and can range from negligible funneling ratios for some species to extreme funneling ratios for others (Levia et al., 2010; Zou et al., 2015).

The second funneling effect refers to the impact of tree root systems on belowground distribution of water. In the vicinity of tree roots, enhanced soil fauna abundance and activity in the root system increases soil macroporosity (Lozano-Parra et al., 2016), which can lead to very high infiltration capacity near tree stems. Indeed, due to this second funneling effect, infiltration rates are observed to decrease exponentially with increasing distance from tree stems (Pressland, 1976). The high overall infiltration capacity of mature forests ensures that most of the rain that reaches the forest floor percolates into the soil, thus contributing to soil moisture and groundwater recharge (Návar, 2011) and making surface runoff or erosion highly unlikely (Bonell and Bruijnzeel, 2005; Farrick and Branfireun, 2014).

In forests, the water which is intercepted by the vegetation as well as a large part of the infiltrated water is used for evapotranspiration. Generally, evapotranspiration from forests is higher than from other vegetation types (Bosch and Hewlett, 1982) and this difference increases with increasing annual precipitation (Zhang et al., 2001). In dryland forests, such as the *Miombo* and *sahel* woodlands from which most charcoal in SSA originates, the absolute difference between evapotranspiration in forests and other vegetation types is not that high, however, in such water-limited ecosystems even small differences in the water balance are important (Zhang et al., 2017). Forests can also affect the temporal dynamics of evapotranspiration. Forest evapotranspiration can remain higher than that of shrubs or grasses during warm and dry spells because the forest root systems can obtain water from deeper soil layers (Lozano-Parra et al., 2016). Through this mechanism, forests can have a positive effect on the feedback between soil moisture and precipitation, even during warm and dry spells (Bonan, 2008).

Catchment-scale discharge from mature forests is usually produced mainly by subsurface runoff to streams (rather than surface runoff, see Farrick and Branfireun, 2014), either through rapid subsurface stormflow or slower groundwater flow (Dias et al., 2015). At the watershed scale, this ensures slower and more continuous discharge from forested areas, a stark contrast to the fast discharge with larger amplitudes associated with croplands (Dias et al., 2015). It is through this ability to regulate flow that forests can provide important flood protection during heavy local rainfall events in summertime (Bradshaw et al., 2007).

Effects of Biomass Harvest on Hydrological Processes

In the following paragraphs we summarize the effects of deforestation on hydrological dynamics. As mentioned in the introduction this is one prevalent pathway for producing charcoal in parts of the tropics, including in Brazil (Swami et al., 2009) and parts of Tanzania (Beukering et al., 2007), where the primary motivation however is agricultural expansion. Deforestation studies can be misleading if applied to the first pathway of charcoal production in which other biomass harvesting methods are used and tree stumps are left intact to regenerate. In the absence of research that has investigated the hydrological effects of biomass harvesting methods in forests or woodland maintained for charcoal making (by pruning branches, selective felling or clear cutting), we can only hypothesize that significant discrepancies can be expected in the influence of the different harvesting methods on the hydrological processes. Thus, we provide a description of how hydrological processes might vary theoretically if charcoal were bring produced under the different pathways.

Whether clearcut or selective harvest is undertaken, the biggest impact that tree removal has is to alter rainfall distribution to the different water balance components through the removal of the double funneling effect of trees. Due to vegetation removal, rainfall is distributed homogeneously on the soil surface and lands on the soil surface with more force (Levia and Frost, 2003), which may increase the susceptibility of soil to erosion. Additionally, vegetation removal changes the infiltration capacity of soils, which in turn influences water distribution to infiltration or runoff processes (Johnson and Lehmann, 2006). When biomass removal occurs, and especially when it includes uprooting of trees, the soil structure—including its macroporosity—is destroyed, resulting in increased surface runoff. Destruction of the macroporosity effect, in fact, explains the oft-reported erosion effects of deforestation (Bosch and Hewlett, 1982; Bruijnzeel, 2004). Under a scenario of pathway one charcoal production, the first funneling effect of vegetation removal could be minimal (in low intensity pruning) or very similar to that of deforestation (in clear cut). But because roots are maintained in pathway one production, the soil structure *per se* remains undisturbed even if the direct impact of raindrops intensifies. The second funneling effect, therefore, might be minimally affected (and could even stay intact, in some cases) compared to the deforestation scenario, thus only minimally influencing the mean infiltration.

Apart from changes in mean annual runoff sums, runoff dynamics also change to much faster flow rates during and shortly after rainfall events after vegetation removal (Ward et al., 2007). This is most evident in clearcutting for agriculture. Conversion of forest to soy bean agriculture, for example, resulted in a strong increase in both the total discharge and the amplitude in discharge (Dias et al., 2015), meaning more extreme high and low flows. Similarly, a review on the effects of deforestation on catchment scale discharge in East Africa found that total discharge increased as did the peaks of discharge; however decrease in low flows was only significant in 31–35% of the studied catchments (Guzha et al., 2018). Under pathway one production, changes to runoff dynamics would be substantially lower not only due to maintenance of intact root systems, but also because the litter layer and undergrowth vegetation generally remains intact (albeit trampled) and would buffer soils from the intensified power of raindrops arriving on the soil surface. The exceptions could be on steep slopes or with recent fire events that removed the buffer effect of undergrowth vegetation and litter.

In addition to infiltration, evapotranspiration volumes and dynamics can also be (temporarily) affected by tree removal for charcoal production. Trees draw water from deeper layers than shrubs and grasses do, which generally contain more shallow roots and have limited access to deeper sources of soil moisture in dry months (Lozano-Parra et al., 2016). Consequently, tree transpiration can continue for a longer period than transpiration of undergrowth vegetation. In addition to more homogeneous rainfall distribution due to vegetation removal, the absence of branches and leaves to intercept the rain removes shade. Its removal would enhance undergrowth, intensify undergrowth evapotranspiration of the undergrowth and quicken the drying of the top soil layer. Thus, biomass harvesting not only results in an absolute change in the water balance components, it mainly also affects the temporal dynamics of hydrological processes. Depending on the scale of land use change in the area, this local vegetation-soil moisture interaction may lead to a macro scale feedback (Dekker et al., 2007; Seneviratne and Stöckli, 2008), whereby large-scale deforestation influences temperature and precipitation regimes of the region (Chambers and Artaxo, 2017), small scale changes however are too small to influence rainfall patterns (D'Almeida et al., 2007). Due to the complex nature of forest-atmosphere feedbacks and the influence of patch size, a general conclusion on the influence of forest removal on local climate conditions cannot be made (Bonan, 2008; Chambers and Artaxo, 2017).

Thinning and selective logging of up to 70% has been shown to have a modest effect on rainfall partitioning and an even smaller effect on soil water and streamflow (probably due to the increased vigor of remaining vegetation) (Bruijnzeel, 2006). Hence, as long as the biomass harvesting method ensures that the soil structure remains intact for the most part, the direct influence of biomass harvesting for charcoal on infiltration is expected to be negligible. This example highlights the importance of studying the specific effects of different biomass harvesting procedures on hydrological processes. In a deforestation scenario, we can deduce from the literature, that infiltration and evapotranspiration strongly decrease, and surface runoff increases after deforestation (Bosch and Hewlett, 1982), especially if there is a complete change of land use to agriculture (crop) or pasture (Alegre and Cassel, 1996).

Hydrological Processes During Biomass Recovery

In a scenario in which forests are cleared for agriculture at large scales, the resulting changes in temporal dynamics of evapotranspiration and runoff as well as influence on the climate would remain. Under pathway one production, which is generally small scale and temporary, with rapid regrowth of the coppices, the influence of harvesting on the yearly sums as well as temporal dynamics of the different water balance components might be minimal and rapidly restore to pre-harvesting values.

Biomass recovery begins immediately after biomass harvest and lasts 9–30 years (FAO, 2017). During this period, infiltration, runoff and evapotranspiration can recover to their initial states (Hassler et al., 2011), although the time to recovery may vary depending on the severity of deforestation, the type of alternative land use (Colón and Lugo, 2006), soil properties (D'Almeida et al., 2007; Hassler et al., 2011), and local climatic conditions (Aide et al., 1996; Chazdon, 2003). After a clear-cut, fine scale biological responses in roots are key to determining vegetation recovery. The fine-root biomass of recovering trunks, for example, undergo three key phases during recovery: a rapid increase up to a maximum of fine-root biomass; a decrease during maturation of the stand; and a steady-state in mature stands (Claus and George, 2005). The hydrological implications of this is that water use by vegetation changes dramatically with stand age (Vertessy et al., 2001). Resprouting tree trunks demand the most water in the early stages of vegetation recovery and during forest maturation, but this demand decreases and then stays relatively steady in mature stands (**Figure 3**). Importantly, water that is taken up undergoes evapotranspiration and is unavailable for discharge from the catchment.

As the vegetation changes from stumps to bushy shrubs to high canopy trees, raindrop impact on soil surfaces becomes less forceful with increasing vegetation cover and rainfall distribution to surface layers diversifies to once again include stemflow and throughfall (**Figure 2**). A decrease in surface temperature and increase in humidity under the canopy due to increased shade from regrowth reduces direct soil water evaporation (Negrete-Yankelevich et al., 2007). Consequently, soil moisture patterns feedback to affect vegetation dynamics through their effects on plant establishment and growth (Breshears and Barnes, 1999), competitive interactions and successional processes (Booth et al., 2003; Asbjornsen et al., 2004).

Hydrological Dynamics at Kiln Sites and Surrounding Area

Studies of the influence of fire on hydrological processes may help deduce what occurs at kiln sites. After fires, runoff and erosion increase strongly, but then slowly decrease in the following years if revegetation of sites occurs (Cerdá and Doerr, 2005). The increase in runoff and erosion is not only due to vegetation removal, but also often attributed to a hydrophobicity of the top soil caused by the fire (Doerr et al., 2000). Additionally, under severe fires (such as can be expected at kiln sites) the soil structure (macroporosity) is destroyed as is the soil fauna, which is responsible for building a large part of soil structure (Certini, 2005). Whether or not soil infiltration recovers and runoff and soil erosion decrease to pre-fire states depends mainly on whether revegetation happens at kiln sites (Cerdá and Doerr, 2005). Revegetation of kiln sites, however, is an understudied phenomenon, with contradicting findings. While some studies report little to no vegetation recovery of abandoned kiln sites (Boutette and Karch, 1984; Chidumayo and Gumbo, 2013), others show that revegetation occurs, although sites have distinct characteristics (soil properties, species composition) from surrounding areas, even hundreds of years after abandonment), at least in temperate regions (Nelle, 2003; Carrari et al., 2016).

After vegetation regrowth, infiltration capacity may recover rapidly and surpass that of pre-burn levels. Studies conducted specifically on the impact of charcoal kilns on soil properties often report soils under kilns to have lower bulk density, higher porosity and higher saturated conductivity (Oguntunde et al., 2008; Nigussie and Kissi, 2011; Wahabu et al., 2015). This higher conductivity contradicts the decreased infiltration (and therefore increased runoff) mentioned earlier and reported by studies on natural forest fires. It is possible that the effects on hydrology, such as water repellency, which is detected in post-fire landscapes diminishes over time. As soil structure is reconstructed and even improved, compared to pre-fire conditions, this can be followed by soil development in the opposite direction (high porosity). These mechanisms could help explain the apparent contradiction between the effects of fire and what has been recorded for kiln sites. Improved soil conditions at kiln sites is an oft-reported phenomenon associated with increased biodiversity (Carrari et al., 2016) and more lush vegetation on long abandoned kiln sites (Glaser et al., 2002; Oguntunde et al., 2004).

Kiln sites are often discussed as the area where biomass was burned, but they do, in fact, represent a larger impacted surface area. Removal of trees, undergrowth and grass to develop the kiln site exposes soils. In sloped areas, sometimes the ground is leveled by cutting into the slope. Additionally, the earth used to insulate the kiln is obtained from the periphery of the cleared site or at close proximity (<15 m). This generates ditches and piles of lose soil. These practices imply that the most notable impact of kilns on hydrological processes in probably through the redistribution of rainfall to the soil surface. The bare ground becomes susceptible to the direct impact of raindrops, which increases runoff and exposes soils to erosion effects (Chidumayo and Gumbo, 2013). Runoff at kiln sites is exacerbated by the added fact that, in the area surrounding the kilns, the cleared woodland also modifies rainfall partitioning as described above (Levia and Frost, 2003) affecting water infiltration into the soil (Hamilton and King, 1983) and thereby, modifying evapotranspiration and runoff more generally (Chidumayo and Gumbo, 2013).

The ditches and gaping holes from which soil was extracted to build the kiln are a kiln-related feature that is virtually, understudied. These holes are, in fact, shallow troughs in which water can accumulate after a rainfall event to percolate into surface layers and affect vegetation dynamics downslope. Whether effective or not, ditches (200 cm long × 50 cm wide × 50 cm deep) are often intentionally dug out in forest restoration sites in Mexico with the belief that they conserve soils and improve soil moisture (SAGARPA, 2009; Perevochtchikova et al., 2012). Research is needed to understand the significance of kiln-derived ditches to ecohydrological processes in charcoal production systems.

Silo Approach II: The Effects of Livestock on Hydrological Processes

Cattle can be important agents of geomorphological change (Trimble and Mendel, 1995). Livestock grazing impacts forests in two principal ways: by altering vegetation cover and through the mechanical action of their hooves which is compounded by the weight of the animals (Mwendera and Mohamed Saleem, 1997; Blanco-Sepúlveda and Nieuwenhuyse, 2011). Studies linking the impact of grazing on hydrological processes have focused primarily on the latter, and specifically on the soil compaction effects on infiltration rates and surface runoff. Research has shown that, generally, soil compaction increases soil bulk density and decreases porosity which, in turn, decreases water infiltration rates and, subsequently, increases surface runoff (Rauzi and Hanson, 1966; Hanson et al., 1970; Gifford and Hawkins, 1978; Mwendera and Mohamed Saleem, 1997). Although these processes can affect site-level nutrient cycles, soil moisture patterns, erosion and sediment yields, downstream water quality, and on-site productivity (Gifford and Hawkins, 1978), for the most part, they have been assumed rather than measured directly.

The impact of herbivory and its subsequent effects on other hydrological processes beyond those of infiltration and erosion is

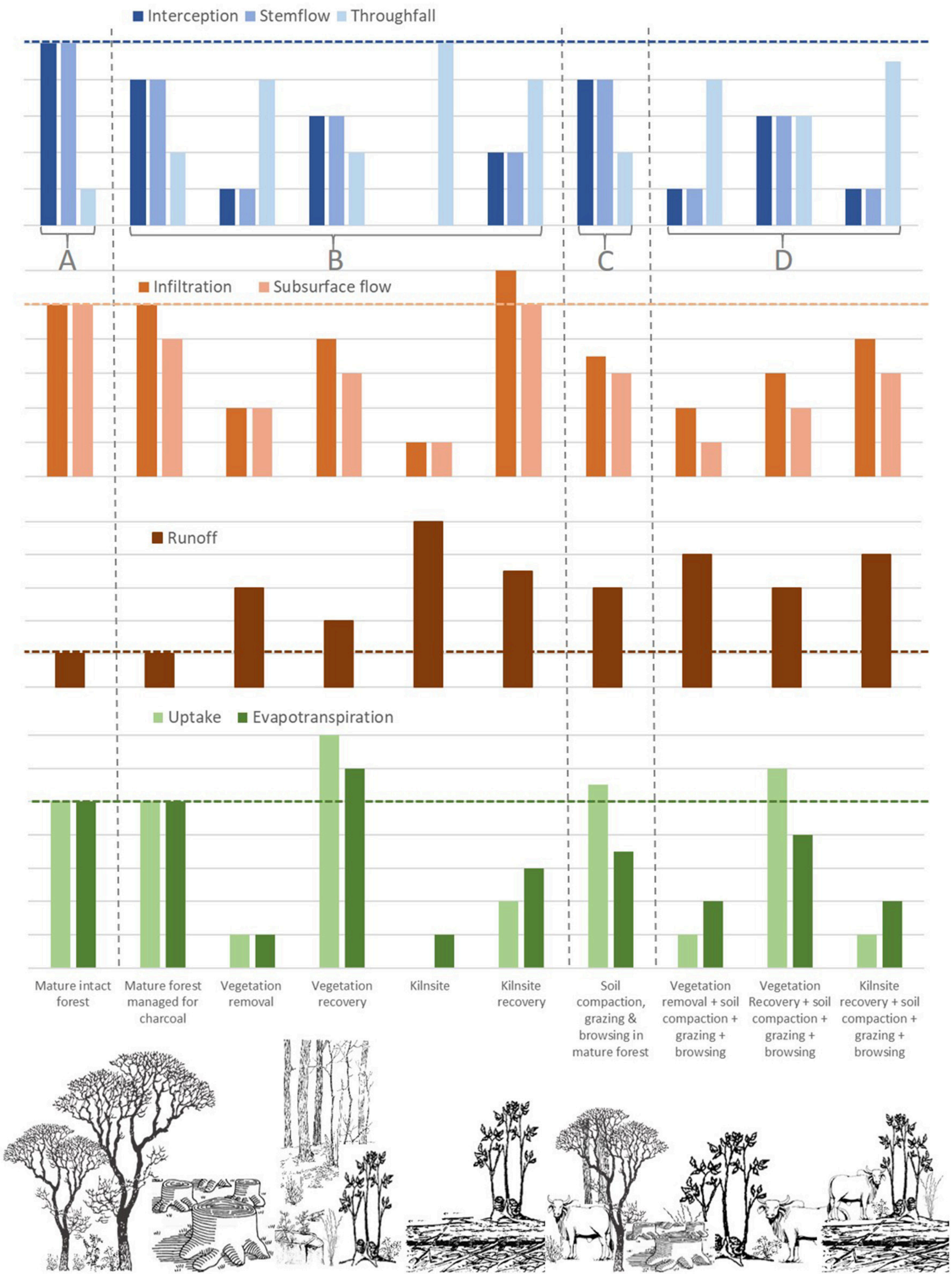

FIGURE 3 | Hypothetical comparison of how key hydrological processes would change relative to **(A)** mature intact forests (far left bars), **(B)** during each stage of the production cycle in forests managed solely for charcoal (next five bars), **(C)** in forests managed only for livestock, and **(D)** in forests managed for both charcoal and livestock. Changes in hydrological processes are assessed relative to levels in mature forests (horizontal dotted line) and not relative to each other. Grazing intensity is assumed to be medium to high.

understudied. We know even less about the effects of browsing (foraging on branches and understory shrubs) than those caused by grazing (consumption of grasses and herbaceous plants). We can deduce that removal or reduction of herbaceous vegetation would expose forest soils to the impact of rain events, increase erosion, reduce the horizon layer and if considered in light of compaction effects, would make it more difficult for seeds and saplings to establish. Low-intensity grazing and browsing, however, avoid many of these impacts (Randriamalala et al., 2016) and rather, maintain vegetation at a constant state of recuperation, which on the other hand, may increase water uptake.

Agro-silvo-pastoral systems can be harmonious and sustainable if the pressure of the different components are kept in a good balance, as is the case for the Meditarranean "Dehesa" landscapes (Schnabel et al., 2009). Surpassing sustainable grazing intensity levels decreases the recovery rate of trees and leads to landscape degradation (Schnabel et al., 2009). Intensive grazing and overgrazing have also been shown to cause irreversible conversion of forests to shrubland (Murphy and Lugo, 1986; Eliason and Allen, 1997; Trejo and Dirzo, 2000) and desertification (Geist and Lambin, 2004). Shrublands imply a drastic change in plant morphology from that of forests, which also leads to a change in volume and fluctuations in evapotranspiration (Sun et al., 2016). How this goes on to affect other hydrological processes remains unclear.

The Systemic Approach: A Three-Way Nexus Between Charcoal, Livestock, And Water

The systemic approach requires considering the effects on hydrological processes when charcoal production co-occurs with livestock keeping. To do so consists of a three-step process: understanding charcoal-livestock dynamics and its effects on soils and vegetation; overlaying those effects on the hydrological system, and finally, considering how hydrological changes influence charcoal and livestock processes. Charcoal-livestock dynamics would exacerbate some hydrological processes or inhibit them from occurring.

A woodland exposed to charcoal and livestock simultaneously undergoes removal of forest canopy for charcoal, soil compaction from the weight of cattle, destruction of the soil structure from the direct impact of hooves, and vegetation suppression or over-compensation from browsing and grazing by cattle. These processes have the largest effect on infiltration rates, which decrease with biomass removal for charcoal production, but this drop is exacerbated if soils (in the mature forest) have experienced the treading stress of livestock or if livestock are introduced immediately after biomass harvest (Arevalo et al., 1998; Godsey and Elsenbeer, 2002). Consequently, the co-occurrence of charcoal production and grazing increases surface runoff, and thereby, erosion. The repercussion of this is that areas where both activities occur could have less water available for vegetation regrowth such that the growth spurts observed in the early phases of recovery in charcoal-only systems are suppressed or severely hampered. Compared to livestock-only systems in which trees are maintained, most of the rainfall distribution attributes of mature forest would be conserved making the effects of compaction less severe.

The direct effects of grazing and browsing on resprouting tree stumps probably affects vegetation recovery rates and intensity, and through this, evapotranspiration, subsurface runoff, and catchment discharge. Browsing of coppicing tree trunks may keep sprouts from growing beyond a certain size while over-browsing could altogether stunt the recovery process (Plieninger et al., 2011). Alternatively, herbivory may cause vegetation to compensate with intense growth which would increase water demand. The consistent regrowth of biomass would result in high evapotranspiration rates and the subsequent decrease and tapering off of evapotranspiration expected with forest maturity might not occur. The compacted soils in harvested areas and kiln sites might also make it difficult for seeds to establish (Pedraza and Williams-Linera, 2003) as soil erosion would have swept off the seedbank and the litter and the first horizon layers necessary for healthy seedling establishment and growth.

DISCUSSION

Despite intuitive interlinks between forests and water, wood-based energy such as charcoal and firewood are underrepresented in discussions and research on the food-water-energy nexus. Similarly, livestock keeping—and in particular grazing in natural forests—is rarely depicted in the food component of the nexus. In tropical regions such as SSA, however, and in countries where large volumes of charcoal are produced, extensive livestock grazing tends to coincide spatiotemporally with charcoal production bringing novel dimensions to the nexus, primarily ecological in nature. The step by step hypothetical exploration we have conducted in this review of how different hydrological processes would play out in charcoal-livestock systems provides a preliminary analysis of the nexus. It facilitates identification of potential tradeoffs, synergies, and critical knowledge gaps.

We have brought together current understanding of the ecohydrological effects of deforestation, forest degradation and livestock to develop a preliminary cognitive model of the nexus highlighting its components, their interactions, and how these might vary under different management regimes. This conceptualization exercise serves several purposes. First it is used to identify and compare the influence of the two different pathways of charcoal production on hydrological processes: aboveground rainfall distribution, infiltration and soil water storage, evapotranspiration and, runoff and groundwater. It ecomes very clear here that the influence of the charcoal production where true deforestation takes place and land use changes to agriculture has a very large and permanent influence on the different hydrological processes, however in case of relatively small scale charcoal production with removal or thinning of coppices without uprooting trees, the influence on the hydrological processes is likely much smaller and with proper consideration of rapid regrowth potential, might be reduced to a negligible and only short lived local influence.

The second purpose that our conceptualization serves is to highlight the stages of the charcoal-livestock system that are key to understanding the nexus in terms of its hydrological effects. A typical charcoal value chain of the first pathway outlines seven to eight stages between the forest where biomass is sourced and the final charcoal consumer (FAO, 2017). In such a life cycle approach to understanding charcoal, the production stages are depicted as two main processes: sourcing of the biomass and carbonization. If the central question, however, is "How do charcoal and livestock, together, affect local and regional hydrology?" more detailed understanding of the production phase is required, necessitating finer subdivisions of the production process into four central processes: the forest before it is cut, the biomass harvesting stage, and the process of recovery of the stand where biomass was harvested, and of the kiln site where carbonization took place. This framing downplays carbonization and focuses instead on the effect it leaves behind at the kiln site. Consequently, we emphasize the need for explicit research programs which study the influence of the different production processes to appreciate their possible effects on ecohydrological dynamics. By doing so, we provide a simple and effective starting point for understanding this nexus and the interactions therein. Such understanding, albeit preliminary and conceptual at this stage, is necessary for flagging key issues of the charcoal-livestock system that could lead to undesired consequences for system-level dynamics. It also pinpoints knowledge gaps that are worthy of further research. These are discussed in more detail in the following paragraphs.

At first glance—and with only lay understanding of ecohydrology—it would seem evident that charcoal production and livestock keeping, whether occurring independently or conjointly *should* impact local hydrological processes negatively through their effect on vegetation and soil substrate. Our exercise, however, revealed that a range of impacts are possible, from negligible to highly profound, depending on several management characteristics of both land use activities. In the case of charcoal, the intensity of biomass harvesting is key: pruning of branches might have imperceptible effects to the hydrological system while selective harvesting and clear cutting could alter the system significantly. Our review suggests that as long as pruning and selective harvesting maintain 30% canopy cover or more, the effects on rainfall distribution and soil erosion can be minimal. For this to apply, however, livestock keeping would need to be maintained at low grazing intensities so that soils are unexposed. Indeed, the key management criteria for livestock keeping *is* grazing intensity. Studies repeatedly show that, whether it is goats or cattle, low grazing intensities avoid a cascade of effects on vegetation, hydrological processes and soil substrates.

The review process highlighted shortcomings in the charcoal research and literature that require immediate attention. Despite recognition of the two production pathways of charcoal, published studies on charcoal rarely describe with sufficient detail which of these pathways is prevalent in their study sites. This makes it a challenge to determine which biomass harvest strategy is practiced (deforestation with uprooting vs. pruning, selective harvest, and clearcutting with stem maintenance) and to deduce from existing studies how hydrological dynamics are affected by charcoal. Assigning a production pathway in the field or from remote sensing is challenging, however. A clear-cut forest in which all trees are used to produce charcoal would, in the short term, display most of the characteristics of deforestation for agriculture or other land use. To determine the motivations for forest clearing would require waiting 6 months to one year to see if tree stumps ultimately regenerate. Even so, observing regeneration after one year does not "proove" the original motivations for clear cutting since those could have changed with time. Furthermore, since livestock can be a temporary or permanent element of the system, it is possible to completely miss or overlook their role or to over-attribute their importance, respectively. Long-term field studies as outlined by Maass (2017) in this special issue, frequent field visits combined with time-series analysis of satellite imagery are needed to pinpoint production pathways and to outline the management practices at the level required for evaluation of hydrological implications.

Throughout our undertaking of this analysis we have mainly focused on local influences of charcoal production and livestock, trying to understand how processes occurring at the level of individual trees and surrounding soils scale up to affect site-level biophysicochemical interactions, and the implications of all this on catchment discharge. In case we assume a large homogeneous landscape in which all the land is dedicated to charcoal production, continuous biomass harvesting for charcoal would maintain a constant fraction of the patches with trees in a state of regrowth, consuming large volumes of water and never reaching the tapering off of evapotranspiration associated with mature forests (Vertessy et al., 2001). High demand for water by recovering vegetation might occur at the expense of catchment recharge. In a scenario whereby charcoal production co-occurs with high intensity grazing, grazing would exacerbate the effect on hydrological processes, through higher runoff (due to soil compaction by animal hooves), low soil water storage and low evapotranspiration implying a loss in the cooling effect of forests. It follows from this that, even if trees stumps are maintained and soil structure remains relatively undisturbed, a catchment used for charcoal production in co-occurrence with grazing could alter catchment level hydrological dynamics. The effects would be substantially more negative if livestock were incorporated at high intensity grazing.

Projected growth in demand for charcoal and meat indicate expansion or intensification of existing production systems in the tropics, including silvopastoral systems such as those analyzed in this review (Herrero et al., 2009; McAlpine et al., 2009; Henchion et al., 2014; Lobato et al., 2014). Specifically, for this system, we can expect biomass harvesting and grazing to intensify. In the case of charcoal, clear cutting becomes the dominant form of biomass harvesting as has already been observed when charcoal demand increases (e.g., Ahrends et al., 2010; Chidumayo and Gumbo, 2013). Rotational cycles might also be shortened implying that mature forest status is never attained. In terms of livestock, more cattle per unit area is expected and year-round stocking might become commonplace. This combination of factors might acerbate hydrological dynamics and push previously sustainable systems into unsustainable pathways. Addressing the research gaps that we have highlighted throughout this paper would help identify how to avoid costly tradeoffs.

CONCLUSIONS

Charcoal production and livestock keeping in the tropics have been demonized by poor understanding of how, precisely, they affect ecosystems and perhaps even wrongly attributing their effects on hydrological processes. There are several pressing environmental challenges facing society today where ecohydrology can contribute to scientific understanding of the complex interactions between multiple resources for developing sound management and policy solutions. By applying ecohydrological science to this three-way nexus, we have contributed to improving current understanding of how charcoal and livestock might—in isolation and conjointly—affect hydrological dynamics from local to catchment scale. We see that the degree to which charcoal production influences hydrological processes depends strongly on what kind of biomass harvesting method is used and on the scale of harvesting. We recognize that there are usually many other potential drivers and stressors that may also affect the charcoal-livestock-water dynamics.

AUTHOR CONTRIBUTIONS

TM was involved with the development of the manuscript topic, literature review, writing and the illustrations. NvS contributed to development of the manuscript topic, especially of the hydrological processes, literature review and writing. LC conducted literature review.

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REFERENCES

Abril, A., and Bucher, E. H. (1999). The effects of overgrazing on soil microbial community and fertility in the Chaco dry savannas of Argentina. *Appl. Soil Ecol.* 12, 159–167. doi: 10.1016/S0929-1393(98)00162-0

Ahrends, A., Burgess, N. D., Milledge, S. A., Bulling, M. T., Fisher, B., Smart, J. C., et al. (2010). Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proc. Natl. Acad. Sci. U.S.A.* 107, 14556–14561. doi: 10.1073/pnas.0914471107

Aide, T. M., Zimmerman, J. K., Rosario, M., and Marcano, H. (1996). Forest recovery in abandoned cattle pastures along an elevational gradient in Northeastern Puerto Rico. *Biotropica* 28, 537–548. doi: 10.2307/2389095

Alegre, J. C., and Cassel, D. K. (1996). Dynamics of soil physical properties under alternative systems to slash-and-burn. *Agric. Ecosyst. Environ.* 58, 39–48. doi: 10.1016/0167-8809(95)00654-0

Arevalo, L. A., Alegre, J. C., Bandy, D. E., and Szott, L. T. (1998). The effect of cattle grazing on soil physical and chemical properties in a silvopastoral system in the Peruvian Amazon. *Agroforest Syst*. 40, 109–124. doi: 10.1023/A:1006075114659

Asbjornsen, H., Goldsmith, G. R., Alvarado-Barrientos, M. S., Rebel, K., Van Osch, F. P., Rietkerk, M., et al. (2011). Ecohydrological advances and applications in plant-water relations research: A review. *J. Plant Ecol*. 4, 3–22. doi: 10.1093/jpe/rtr005

Asbjornsen, H., Vogt, K. A., and Ashton, M. S. (2004). Synergistic responses of oak, pine and shrub seedlings to edge environments and drought in a fragmented tropical highland oak forest, Oaxaca, Mexico. *For. Ecol. Manage.* 192, 313–334. doi: 10.1016/j.foreco.2004.01.035

Bailis, R. (2009). Modeling climate change mitigation from alternative methods of charcoal production in Kenya. *Biomass Bioenergy* 33, 1491–1502. doi: 10.1016/j.biombioe.2009.07.001

Bailis, R., Drigo, R., Ghilardi, A., and Masera, O. (2015). The carbon footprint of traditional woodfuels. *Nat. Clim. Change* 5, 266–272. doi: 10.1038/nclimate2491

Bailis, R., Wang, Y., Drigo, R., Ghilardi, A., and Masera, O. (2017). Getting the numbers right: revisiting woodfuel sustainability in the developing world. *Environ. Res. Lett.* 12:115002. doi: 10.1088/1748-9326/aa83ed

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., et al. (2011). Considering the energy, water and food nexus: towards an integrated modelling approach. *Energy Policy* 39, 7896–7906. doi: 10.1016/j.enpol.2011.09.039

Beukering, P. J. H., Kahyararab, G., Masseya, E., di Primaa, S., Hessa, S., Makundi, V., et al. (2007). *Optimization of the Charcoal Chain in Tanzania. PREM [Poverty Reduction and Environmental Management Working Paper] 07/03.* Amsterdam: Institute for Environmental Studies.

Bialkowski, R., and Buttle, J. M. (2015). Stemflow and throughfall contributions to soil water recharge under trees with differing branch architectures. *Hydrol. Process.* 29, 4068–4082. doi: 10.1002/hyp.10463

Blanco-Sepúlveda, R., and Nieuwenhuyse, A. (2011). Influence of topographic and edaphic factors on vulnerability to soil degradation due to cattle grazing in humid tropical mountains in northern Honduras. *Catena* 86, 130–137. doi: 10.1016/j.catena.2011.03.007

Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. *Science* 320, 1444–1449. doi: 10.1126/science.1155121

Bonell, M., and Bruijnzeel, L. A. (2005). *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management. International Hydrology Series.* Cambridge: Cambridge University Press.

Booth, M. S., Caldwell, M. M., and Stark, J. M. (2003). Overlapping resource use in three Great Basin species: implications for community invasibility and vegetation dynamics. *J. Ecol.* 91, 36–48. doi: 10.1046/j.1365-2745.2003.00739.x

Bosch, J. M., and Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J. Hydrol*. 55, 3–23. doi: 10.1016/0022-1694(82)90117-2

Boutette, F. I., and Karch, E. G. (1984). *Charcoal: Small Scale Production and Use.* Eschborn: Deutsche Gesellschatf fü Technische Zusammenarbeit (GTZ)

Bradshaw, C., Sodhi, N., Peh, K., and Brook, B. (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world. *Glob. Change Biol.* 13, 2379–2395. doi: 10.1111/j.1365-2486.2007.01446.x

Breshears, D. D., and Barnes, F. J. (1999). Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: A unified conceptual model. *Landsc. Ecol.* 14:465. doi: 10.1023/A:1008040327508

Bruijnzeel, L. A. (2004). Hydrological functions of tropical forests: not seeing the soil for the trees? *Agric. Ecosyst. Environ.* 104, 185–228. doi: 10.1016/j.agee.2004.01.015

Bruijnzeel, L. A. (2006). *Hydrological Impacts of Converting Tropical Montane Cloud Forest to Pasture with Initial Reference to Northern Costa Rica*. Final Technical Report DFID-FRP Project No. R7991. Amsterdam; Aylesford: VU University Amsterdam; Forestry Research Programme of the UK Department for International Development.

Carlyle-Moses, D. E., and Gash, J. H. C. (2011). "Rainfall interception loss by forest canopies," in *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*. eds D. F. Levia, D. Carlyle-Moses, and T. Tanaka (Dordrecht: Springer Netherlands), 407–423. doi: 10.1007/978-94-007-1363-5_20

Carrari, E., Ampoorter, E., Verheyen, K., Coppi, A., and Selvi, F. (2016). Former charcoal kiln platforms as microhabitats affecting understorey vegetation in Mediterranean forests. *Appl. Veg. Sci*. 19, 486–497. doi: 10.1111/avsc.12238

Castillo-Hernández, L. A. (2017). *Sinergias y Compensaciones Entre Servicios Ecosistémicos Múltiples: el Caso de la Ganadería y las Plantas útiles en Bosques de Encino Manejados Para Producir Carbón Vegetal*. Master's thesis, Universidad Nacional Autónoma de México, Morelia, MX.

Cerdá, A., and Doerr, S. H. (2005). Influence of vegetation recovery on soil hydrology and erodibility following fire: an 11-year investigation. *Int. J. Wildland Fire*. 14, 423–437. doi: 10.1071/WF05044

Certini, G. (2005). Effects of fire on properties of forest soils: A review. *Oecologia* 143, 1–10. doi: 10.1007/s00442-004-1788-8

Chambers, J. Q., and Artaxo, P. (2017). Deforestation size influences rainfall. *Nat. Clim. Chang.* 7:175. doi: 10.1038/nclimate3238

Chazdon, R. L. (2003). Tropical forest recovery: legacies of human impact and natural disturbances. *Perspect. Plant Ecol. Evol. Syst.* 6, 51–71. doi: 10.1078/1433-8319-00042

Chidumayo, E. N. (1991). Woody biomass structure and utilisation for charcoal production in a Zambian miombo woodland. *Bioresour. Technol.* 37, 43–52. doi: 10.1016/0960-8524(91)90110-6

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. doi: 10.1016/j.esd.2012.07.004

Clark, M. L., Aide, T. M., Grau, H. R., and Riner, G. (2010). A scalable approach to mapping annual land cover at 250 m using MODIS time series data: A case study in the Dry Chaco ecoregion of South America. *Remote Sens. Environ.* 114, 2816–2832. doi: 10.1016/j.rse.2010.07.001

Claus, A., and George, E. (2005). Effect of stand age on fine-root biomass and biomass distribution in three European forest chronosequences. *Can. J. For. Res.* 35, 1617–1625. doi: 10.1139/x05-079

Colón, S. M., and Lugo, A. E. (2006). Recovery of a subtropical dry forest after abandonment of different land uses. *Biotropica* 38, 354–364. doi: 10.1111/j.1744-7429.2006.00159.x

D'Almeida, C., Vörösmarty, C. J., Hurtt, G. C., Marengo, J. A., Dingman, S. L., and Keim, B. D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *Int. J. Climatol*. 27, 633–647. doi: 10.1002/joc.1475

DeFries, R., and Rosenzweig, C. (2010). Toward a whole-landscape approach for sustainable land use in the tropics. *Proc. Natl. Acad. Sci. U.S.A.* 107, 19627–19632. doi: 10.1073/pnas.1011163107.

Dekker, S. C., Rietkerk, M., and Bierkens, M. F. P. (2007). Coupling microscale vegetation-soil water and macroscale vegetation-precipitation feedbacks in semiarid ecosystems. *Glob. Chang. Biol.* 13, 671–678. doi: 10.1111/j.1365-2486.2007.01327.x

Dias, L. C. P., Macedo, M. N., Costa, M. H., Coe, M. T., and Neill, C. (2015). Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. *J. Hydrol. Reg. Stud*. 4, 108–122. doi: 10.1016/j.ejrh.2015.05.010

Doerr, S. H., Shakesby, R. A., and Walsh, R. P. D. (2000). Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Sci. Rev*. 51, 33–65. doi: 10.1016/S0012-8252(00)00011-8

Doggart, N., and Meshack, C. (2017). The marginalization and sustainable charcoal production in the policies of the modernizing African Nation. *Front. Environ. Sci*. 5:27. doi: 10.3389/fenvs.2017.00027

Eckholm, E., Foley, G., Barnard, G., and Timberlake, L. (1984). Fuel *Fuelwood: The Energy Crisis That Won't Go Away*. London: Earthscan.

Eliason, S. A., and Allen, E. B. (1997). Exotic grass competition in suppressing native shrubland re-establishment. *Restorat. Ecol.* 5, 245–255. doi: 10.1046/j.1526-100X.1997.09729.x

Endo, A., Tsurita, I., Burnett, K., and Orencio, P. M. (2017). A review of the current state of research on the water, energy, and food nexus. *J. Hydrol.* 11, 20–30. doi: 10.1016/j.ejrh.2015.11.010

FAO (2010). *Global Forest Resources Assessment 2010, Terms and Definitions*. Forestry Department, Food and Agriculture Organization of the United Nations, Rome.

FAO (2014). *State of the World's Forests 2014*. FAO, Rome.

FAO (2017). *The Charcoal Transition: Greening The Charcoal Value Chain To Mitigate Climate Change And Improve Local Livelihoods*. Food and Agriculture Organization of the United Nations, Rome.

Farrick, K., and Branfireun, B. (2014). Infiltration and soil water dynamics in a tropical dry forest: it may be dry but definitely not arid. *Hydrol. Process.* 28, 4377–4387. doi: 10.1002/hyp.10177

Ferraro, P. J., Hanauer, M. M., and Sims, K. R. (2011). Conditions associated with protected area success in conservation and poverty reduction. *Proc. Natl. Acad. Sci. U.S.A.* 108, 13913–13918. doi: 10.1073/pnas.1011529108

Fontodji, J., Mawussi, G., Nuto, Y., and Kokou, K. (2009). Effects of charcoal production on soil biodiversity and soil physical and chemical properties in Togo, West Africa. *Int. J. Biol. Chem. Sci.* 3:1051. doi: 10.4314/ijbcs.v3i5.51051

Fontodji, J. K., Atsri, H., Adjonou, K., Radji, A. R., Kokutse, A. D., Nuto, Y., et al. (2011). "Impact of charcoal production on biodiversity in Togo (West Africa)," in *The Importance of Biological Interactions in the Study of Biodiversity*, ed J. L. Pujol (London: InTech). doi: 10.5772/22969

Geist, H. J., and Lambin, E. F. (2004). Dynamic causal patterns of desertification. *AIBS Bull.* 54, 817–829. doi: 10.1641/0006-3568(2004)0540817:DCPOD2.0.CO;2

Gezahegn, A. K. (2018). *Characterization of Rangeland Resources and Dynamics of the Pastoral Production Systems in the Somali Region of Eastern Ethiopia*. Doctoral dissertation, University of the Free State.

Ghilardi, A., Bailis, R., Mas, J. F., Skutsch, M., Elvir, J. A., Quevedo, A., et al. (2016). Spatiotemporal modeling of fuelwood environmental impacts: towards improved accounting for non-renewable biomass. *Environ. Model. Softw.* 82, 241–254. doi: 10.1016/j.envsoft.2016.04.023

Gifford, G. F., and Hawkins, R. H. (1978). Hydrologic impact of grazing on infiltration: a critical review. *Water Resour. Res*. 14, 305–312. doi: 10.1029/WR014i002p00305

Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal–a review. *Biol. Fertil. Soils* 35, 219–230. doi: 10.1007/s00374-002-0466-4

Godsey, S., and Elsenbeer, H. (2002). The soil hydrologic response to forest regrowth: a case study from southwestern Amazonia. *Hydrol. Process.* 16, 1519–1522. doi: 10.1002/hyp.605

Guzha, A. C., Rufino, M. C., Okoth, S., Jacobs, S., and Nóbrega, R. L. B. (2018). Impacts of land use and land cover change on surface runoff, discharge and low flows: evidence from East Africa. *J. Hydrol. Reg. Stud.* 15, 49–67. doi: 10.1016/j.ejrh.2017.11.005

Hamilton, L. S., and King, P. N. (1983). *Tropical Forested Watersheds: Hydrologic and Soils Response to Major Uses or Conversions*. Boulder, CO: Westview Press.

Hanson, C. L., Kuhlman, A. R., Erickson, C. J., and Lewis, J. K. (1970). Grazing effects on runoff and vegetation on western south dakota rangeland. *J. Range Manage*. 23, 418–420. doi: 10.2307/3896312

Hassler, S. K., Zimmermann, B., Breugel, M., Hall, J. S., and Elsenbeer, H. (2011). Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. *For. Ecol. Manage*. 261, 1634–1642. doi: 10.1016/j.foreco.2010.06.031

Henchion, M., McCarthy, M., Resconi, V. C., and Troy, D. (2014). Meat consumption: trends and quality matters. *Meat Sci.* 98, 561–568. doi: 10.1016/j.meatsci.2014.06.007

Herrero, M., Thornton, P. K., Gerber, P., and Reid, R. S. (2009). Livestock, livelihoods and the environment: understanding the trade-offs. *Curr. Opin. Environ. Sustain.* 1, 111–120. doi: 10.1016/j.cosust.2009.10.003

Hoff, H. (2011). *Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus*. Stockholm: Stockholm Environment Institute.

Johnson, M. S., and Lehmann, J. (2006). Double-funneling of trees: stemflow and root-induced preferential flow. *Ecoscience* 13, 324–333. doi: 10.2980/i1195-6860-13-3-324.1

Lach, D., Rayner, S., and Ingram, H. (2005). Taming the Waters: strategies to domesticate the wicked problems of water resource management. *Int. J. Water* 3, 1–17. doi: 10.1504/IJW.2005.007156

Levia, D. F., Carlyle-Moses, D., and Tanaka, T. (2011). *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*. New York, NY: Ecological Studies; Springer. doi: 10.1007/978-94-007-1363-5

Levia, D. F., and Frost, E. E. (2003). A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *J. Hydrol.* 274, 1–29. doi: 10.1016/S0022-1694(02)00399-2

Levia, D. F., Van Stan, J. T., Mage, S. M., and Kelley-Hauske, P. W. (2010). Temporal variability of stemflow volume in a beech-yellow poplar forest in relation to tree species and size. *J. Hydrol.* 380, 112–120. doi: 10.1016/j.jhydrol.2009.10.028

Llorens, P., and Domingo, F. (2007). Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe. *J. Hydrol.* 335, 37–54. doi: 10.1016/j.jhydrol.2006.10.032

Lobato, J. F., Freitas, A. K., Devincenzi, T., Cardoso, L. L., Tarouco, J. U., Vieira, R. M., et al. (2014). Brazilian beef produced on pastures: sustainable and healthy. *Meat Sci.* 98. 336–345. doi: 10.1016/j.meatsci.2014.06.022

Lozano-Parra, J., van Schaik, N. L. M. B., Schnabel, S., and Gómez-Gutiérrez, Á. (2016). Soil moisture dynamics at high temporal resolution in a semiarid Mediterranean watershed with scattered tree cover. *Hydrol. Process.* 30, 1155–1170. doi: 10.1002/hyp.10694

Ludwig, J. A., Wilcox, B. P., Breshears, D. D., Tongway, D. J., and Imeson, A. C. (2005). Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86, 288–297. doi: 10.1890/03-0569

Maass, J. M., Balvanera, P., Castillo, A., Daily, G. C., Mooney, H. A., Ehrlich, P., et al. (2005). Ecosystem services of tropical dry forests: insights from longterm ecological and social research on the Pacific Coast of Mexico. *Ecol. Soc.* 10, 1–23. doi: 10.5751/ES-01219-100117

Maass, M. (2017). Integrating food-water-energy research through a socio-ecosystem approach. *Front. Environ. Sci.* 5:48. doi: 10.3389/fenvs.2017.00048

McAlpine, C. A., Etter, A., Fearnside, P. M., Seabrook, L., and Laurance, W. F. (2009). Increasing world consumption of beef as a driver of regional and global change: a call for policy action based on evidence from Queensland (Australia), Colombia and Brazil. *Global Environ. Change* 19, 21–33. doi: 10.1016/j.gloenvcha.2008.10.008

McLaren, K. P., and McDonald, M. A. (2003). Coppice regrowth in a disturbed tropical dry limestone forest in Jamaica. *For. Ecol. Manage.* 180, 99–111. doi: 10.1016/S0378-1127(02)00606-0

Murphy, P. G., and Lugo, A. E. (1986). Ecology of tropical dry forest. *Annu. Rev. Ecol. Syst.* 17, 67–88. doi: 10.1146/annurev.es.17.110186.000435

Mwampamba, T. (2007). Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability. *Energy Policy* 35, 4221–4234. doi: 10.1016/j.enpol.2007.02.010

Mwampamba, T. (2009). *Forest Recovery and Carbon Sequestration Under Shifting Cultivation in the Eastern Arc Mountains, Tanzania: Landscape and Landuse Effects*. Dissertation, University of California, Davis, CA.

Mwampamba, T. H., Ghilardi, A., Sander, K., and Chaix, K. J. (2013). Dispelling common misconceptions to improve attitudes and policy outlook in developing countries. *Energy Sustain. Dev.* 17, 75–85. doi: 10.1016/j.esd.2013.01.001

Mwendera, E. J., and Mohamed Saleem, M. A. (1997). Hydrologic response to cattle in the Ethiopian highlands. *Agric. Ecosyst. Environ.* 64, 33–41. doi: 10.1016/S0167-8809(96)01127-9

Návar, J. (2011). Stemflow variation in Mexico's northeastern forest communities: its contribution to soil moisture content and aquifer recharge. *J. Hydrol.* 408, 35–42. doi: 10.1016/j.jhydrol.2011.07.006

Negrete-Yankelevich, S., Fragoso, C., Newton, A. C., and Heal, O. W. (2007). Successional changes in soil, litter and macroinvertebrate parameters following selective logging in a Mexican Cloud Forest. *Appl. Soil Ecol.* 35, 340–355. doi: 10.1016/j.apsoil.2006.07.006

Nelle, O. (2003). Woodland history of the last 500 years revealed by anthracological studies of charcoal kiln sites in the Bavarian Forest, Germany. *Phytocoenologia* 33, 667–682. doi: 10.1127/0340-269X/2003/0033-0667

Nigussie, A., and Kissi, E. (2011). Effect of charcoal production on soil properties in Southwestern Ethiopia. *Middle East J. Sci. Res.* 9, 807–813.

Oguntunde, P. G., Abiodun, B. J., Ajayi, A. E., and Giesen, N. (2008). Effects of charcoal production on soil physical properties in Ghana. *J. Plant Nutr. Soil Sci.* 171, 591–596. doi: 10.1002/jpln.200625185

Oguntunde, P. G., Fosu, M., Ajayi, A. E., and Van De Giesen, N. (2004). Effects of charcoal production on maize yield, chemical properties and texture of soil. *Biol. Fertil. Soils* 39, 295–299. doi: 10.1007/s00374-003-0707-1

Owen, M. (2013). *The Legally Compliant Charcoal Industry and its Barriers to Growth in Kenya. Final Report in Support to Forest Sector Reform in Kenya.* NIRAS Finland, 42.

Pedraza, R., and Williams-Linera, G. (2003). Evaluation of native tree species for the rehabilitation of deforested areas in a Mexican cloud forest. *N. Forests* 26:83. doi: 10.1023/A:1024423511760

Pennise, D. M., Smith, K. R., Kithinji, J. P., Rezende, M. E., Raad, T. J., Zhang, J., et al. (2001). Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. *J. Geophys. Res. Atmos.* 106, 24143–24155. doi: 10.1029/2000JD000041

Perevochtchikova, M., Tamayo, O., and Milena, A. (2012). Avances y limitantes del programa de pago de servicios ambientales hidrológicos en México, 2003-2009. *Revista Mexicana de Ciencias Forestales* 3, 89–112. Available online at: http://www.scielo.org.mx/scielo.php?pid=S2007-11322012000200008&script=sci_arttext

Picos, J., and Valero, E. (2009). "Forest land resources," in *Forests and Forest Plants-Volume I,* eds Owens and Lund (Paris: UNESCO-EOLSS), 66.

Plieninger, T., Schaich, H., and Kizos, T. (2011). Land-use legacies in the forest structure of silvopastoral oak woodlands in the Eastern Mediterranean. *Reg. Environ. Change*. 11:603. doi: 10.1007/s10113-010-0192-7

Pressland, A. J. (1976). Possible effects of removal of mulga on rangeland stability in south western Queensland. *Aust. Rangeland J.* 1, 24–30. doi: 10.1071/RJ9760024

Randriamalala, J. R., Radosy, H. O., Razanaka, S., Randriambanona, H., and Hervé, D. (2016). Effects of goat grazing and woody charcoal production on xerophytic thickets of southwestern Madagascar. *J. Arid Environ.* 128, 65–72. doi: 10.1016/j.jaridenv.2016.01.002

Rauzi, F., and Hanson, D. L. (1966). Water intake and runoff as affected by intensity of grazing. *J. Range Manage.* 19, 351–356. doi: 10.2307/3895570.

Rittel, H. W. J., and Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sci.* 4:155. doi: 10.1007/BF01405730

SAGARPA (2009). *Tinas Ciegas*. Especialidad de Hidrociencias del Colegio de Postgraduados, Montecillos, Estado de México.

Santos, M. J., Dekker, S. C., Daioglou, 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. doi: 10.3389/fenvs.2017.00028

Schnabel, S., Gutiérrez, A., and Contador, J. F. (2009). "Grazing and soil erosion in dehesas of SW Spain," in *Avances en Estudios Sobre Desertificación. Contributions to the International Conference in memory of Prof. Johm B. Thornes*, eds F. Romero-Díaz, F. Belmonte Serrato, S. Alonso, and F. López Bermúdez (Murcia: Editum Universidad de Murcia), 725–728.

Sedano, F., Silva, J. A., Machoco, R., Meque, C. H., Sitoe, A., Ribeiro, N., et al. (2016). The impact of charcoal production on forest degradation: a case study in Tete, Mozambique. *Environ. Res. Lett.* 11:094020. doi: 10.1088/1748-9326/11/9/094020

Seneviratne, S., and Stöckli, R. (2008). "The Role of Land-Atmosphere Interactions for Climate Variability in Europe," in *Climate Variability and Extremes during the Past 100 Years. Advances in Global Change Research,* eds S. Brönnimann, J. Luterbacher, T. Ewen, H. Diaz, R. Stolarski, and U. Neu (Dordrecht: Springer), 179–193.

Sodhi, N. S., Butler, R., Laurance, W. F., and Gibson, L. (2011). Conservation successes at micro-, meso-and macroscales. *Trends Ecol. Evol.* 26, 585–594. doi: 10.1016/j.tree.2011.07.002

Specht, M. J., Pinto, S. R. R., Albuquerque, U. P., Tabarelli, M., and Melo, F. P. (2015). Burning biodiversity: fuelwood harvesting causes forest degradation in human-dominated tropical landscapes. *Global Ecol. Conservat.* 3, 200–209. doi: 10.1016/j.gecco.2014.12.002

Sun, G., Domec, J. C., and Amatya, D. M. (2016). "Forest evapotranspiration: measurements and modeling at multiple scales," in *Forest Hydrology: Processes, Management and Assessment,* eds D. Amatya, T. Williams, L. Bren, and C. de Jong (Boston, MA: CABI Publishers), 19, 32–50.

Swami, S. N., Steiner, C., Teixeira, W. G., and Lehmann, J. (2009). "Charcoal making in the Brazilian Amazon: economic aspects of production and carbon conversion efficiencies of kilns," in *Amazonian Dark Earths: Wim Sombroek's*

Vision, eds W. I. Woods, J. Lehmann, L. Rebellato, C. Steiner, W. G. Teixeira, and A. WinklerPrins (Berlin: Springer), 411–422.

Trejo, I., and Dirzo, R. (2000). Deforestation of seasonally dry tropical forest: a national and local analysis in Mexico. *Biol. Conserv*. 94, 133–142. doi: 10.1016/S0006-3207(99)00188-3

Trimble, S. W., and Mendel, A. C. (1995). The cow as a geomorphic agent—a critical review. *Geomorphology* 13, 233–253. doi: 10.1016/0169-555X(95)00028-4

Uriarte, M., Yackulic, C. B., Lim, Y., and Arce-Nazario, J. A. (2011). Influence of land use on water quality in a tropical landscape: a multi-scale analysis. *Landscape Ecol.* 26:1151. doi: 10.1007/s10980-011-9642-y

Vertessy, R. A., Watson, F. G. R., and O'Sullivan, S. K. (2001). Factors determining relations between stand age and catchment water balance in mountain ash forests. *For. Ecol. Manage*. 143, 13–26. doi: 10.1016/S0378-1127(00)00501-6

Voorhoeve, J. (2017). *Modelling effects of charcoal production on the carbon Budget in managed oak forest of Central Mexico*. Master's thesis. Utrecht University, Utrecht.

Wahabu, S., Fosu-Mensah, B. Y., and Nyame, F. K. (2015). Impact of charcoal production on physical and chemical properties of soil in the central gonja district of the Northern region, Ghana. *Environ. Nat. Resour. Res*. 5, 11–18. doi: 10.5539/enrr.v5n3p11

Ward, S. E., Bardgett, R. D., McNamara, N. P., Adamson, J. K., and Ostle, N. J. (2007). Long-term consequences of grazing and burning on northern peatland carbon dynamics. *Ecosystems* 10, 1069–1083. doi: 10.1007/s10021-007-9080-5

Woollen, E., Ryan, C. M., Baumert, S., Vollmer, F., Grundy, I., Fisher, J., et al. (2016). Charcoal production in the mopane woodlands of mozambique: what are the trade-offs with other ecosystem services? *Philos. Trans. R. Soc. Lond. B Biol. Sci*. 371, 653–660. doi: 10.1098/rstb.2015.0315

Zhang, L., Dawes, W., and Walker, G. (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resour. Res.* 37, 701–708. doi: 10.1029/2000WR900325

Zhang, M., Liu, N., Harperc, R., Li, Q., Liu, K., Wei, X., et al. (2017). A global review on hydrological responses to forest change across multiple spatial scales: importance of scale, climate, forest type and hydrological regime. *J. Hydrol.* 546, 44–59. doi: 10.1016/j.jhydrol.2016.12.040

Zou, C. B., Caterina, G. L., Will, R. E., Stebler, E., and Turton, D. (2015). Canopy interception for a tallgrass prairie under juniper encroachment. *PLoS ONE* 10:e0141422. doi: 10.1371/journal.pone.0141422

Zulu, L. C., and Richardson, R. B. (2013). Charcoal, livelihoods, and poverty reduction: evidence from sub-Saharan Africa. *Energy Sustain. Dev*. 17, 127–137. doi: 10.1016/j.esd.2012.07.007

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