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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

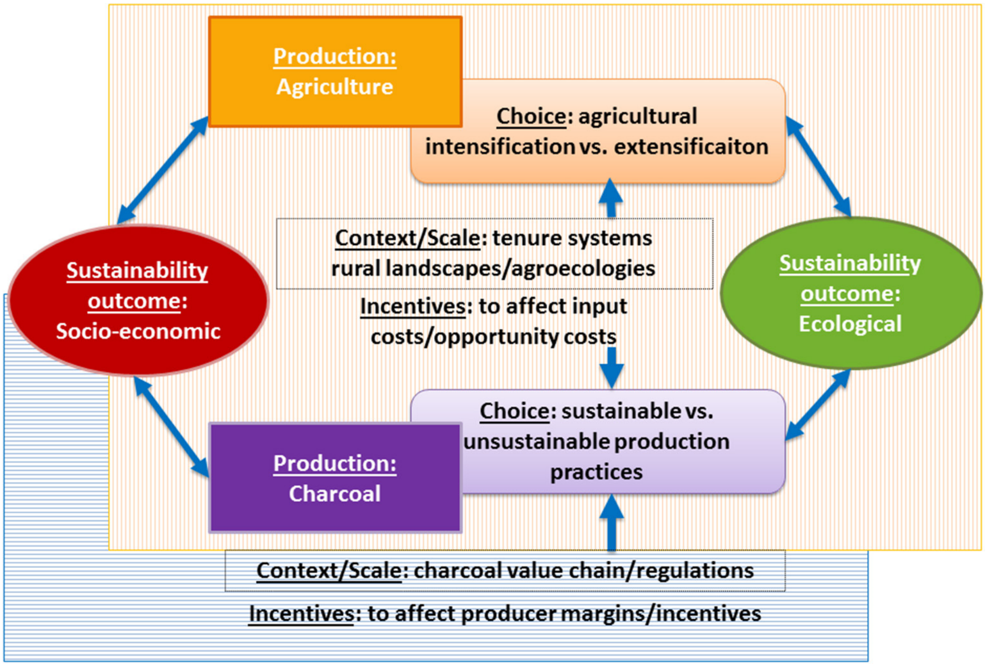

FIGURE 1 | The charcoal-agriculture production nexus.

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

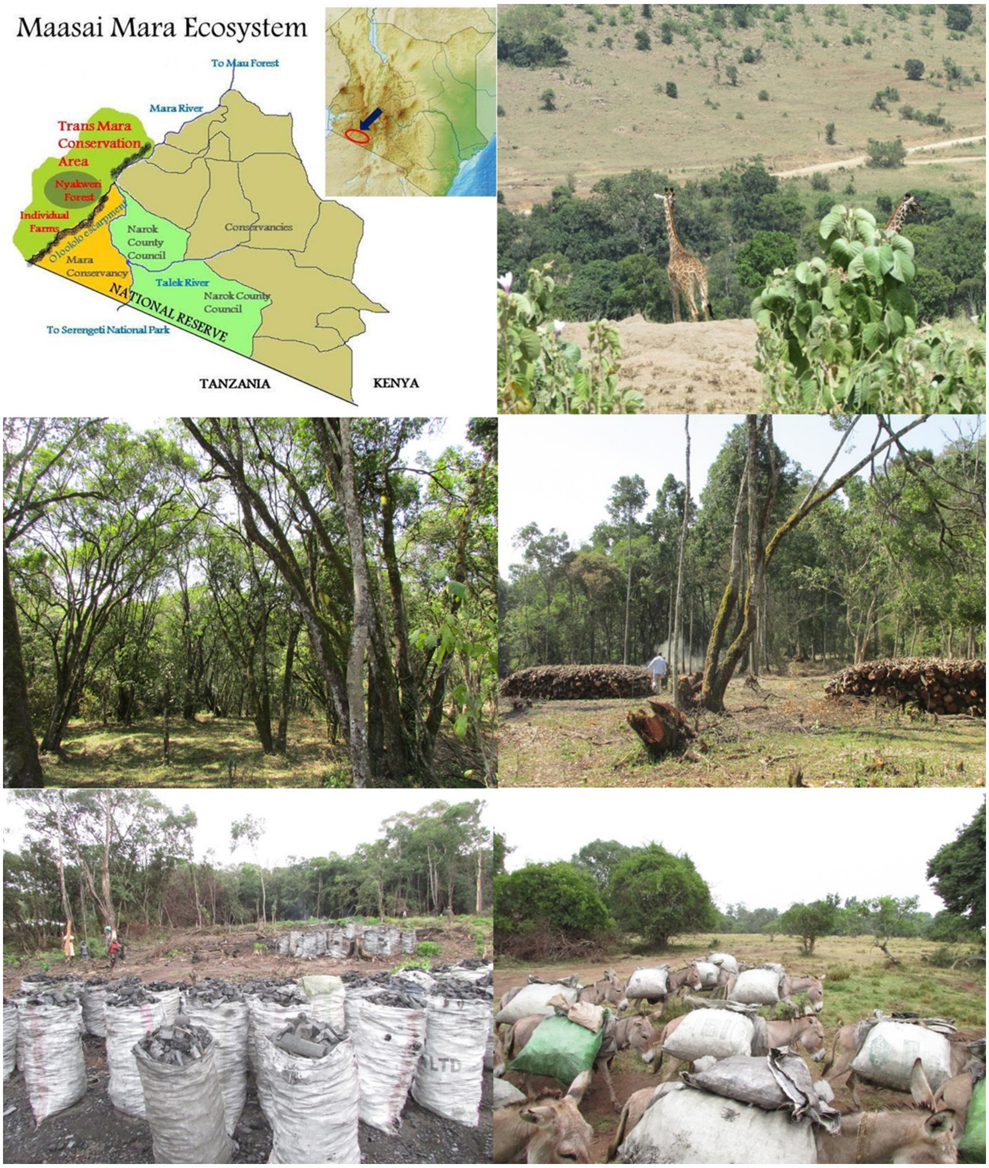

FIGURE 2 | Kenyan site illustration. Over the escarpment of the Mara Triangle lies Trans Mara Conservation Area encompassing recently sub-divided farms and Nyakweri Forest. Indigenous forests have provided multiple ecosystem services over and beyond the Mara Ecosystem. However, trees are felled for agriculture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

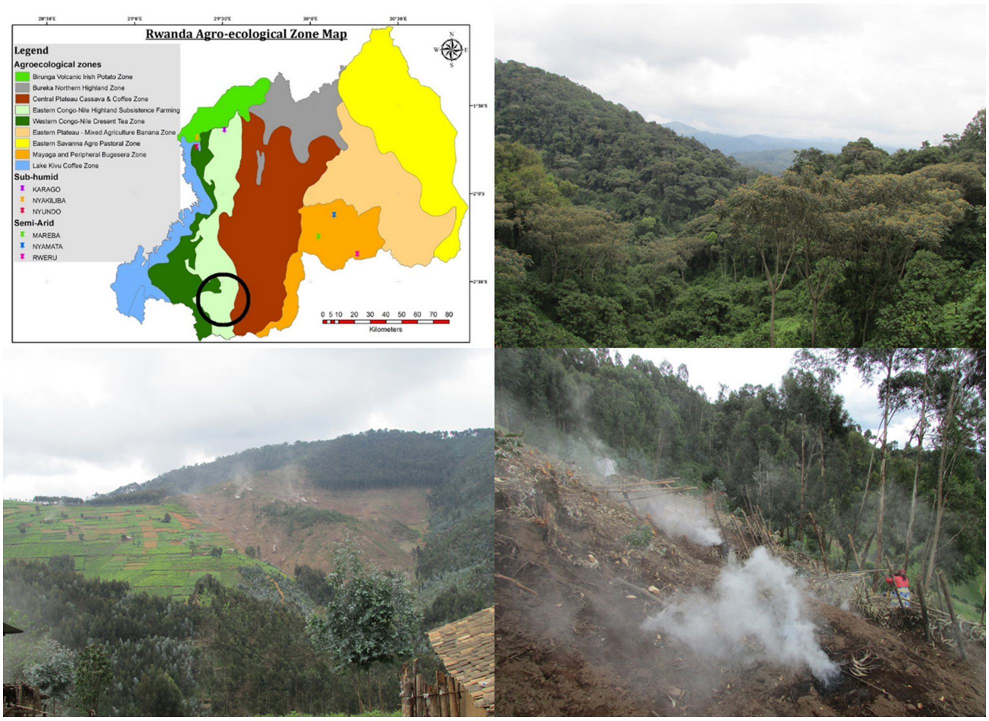

FIGURE 3 | Rwandese site illustration. Nyungwe Forest is the largest block of montane forest in East and Central Africa, home to over 1,000 species, including rare primates, such as chimpanzees, the L'Hoests monkey and Angola Colobus. Nyungwe is also an important water catchment for Rwanda. Western Rwanda 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

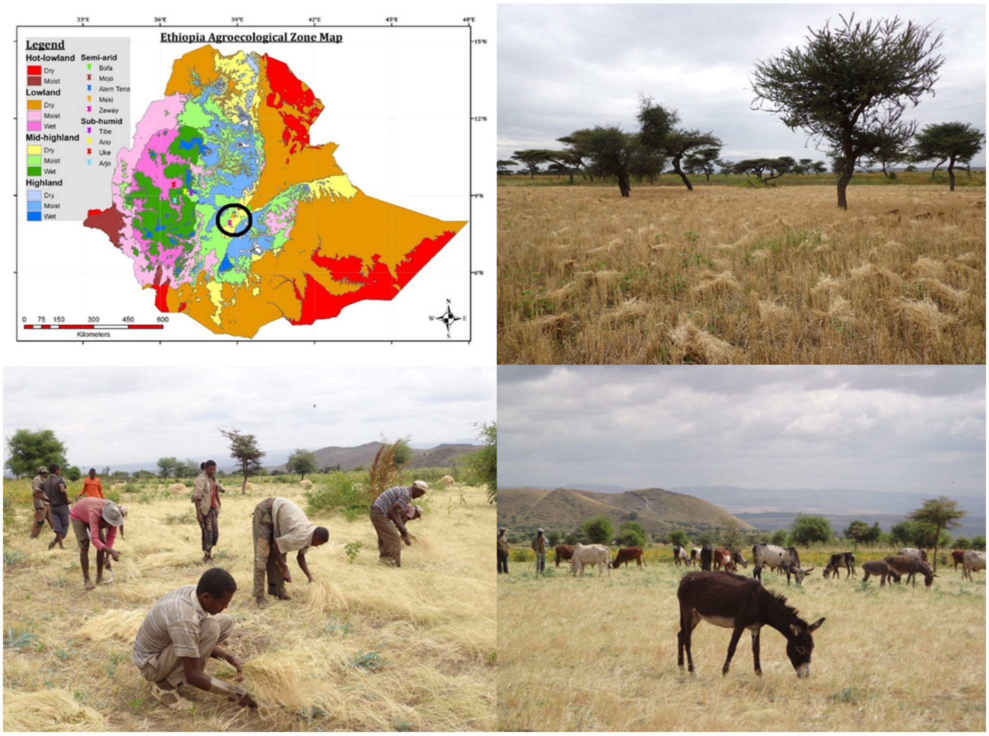

FIGURE 4 | Ethiopian site illustration. Trees on farms are characteristic of a large part of the Ethiopian agricultural landscape where farmers usually retain trees of selected species and minimize impact on the companion crops through occasional lopping and pollarding. While cropping plots belong to 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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