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Biofuels in sub-Sahara Africa: Drivers, impacts and priority policy areas

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ABSTRACT

There has been a growing interest in jatropha- and sugarcane-based biofuels across Sub-Sahara Africa. Biofuel expansion in the region reflects policy concerns related to energy security, poverty alleviation and economic development. However, biofuels have also been linked to numerous environmental and socioeconomic impacts such as GHG emissions, water availability/pollution, deforestation, biodiversity loss, poverty alleviation, energy security, loss of access to land and food security to name just a few. Yet there is (a) an insufficient understanding of these impacts (and their synergies) in Sub-Sahara Africa, and (b) a lack of policies that could regulate the biofuel sector and ensure its viability while at the same time preventing its negative impact. The aim of this literature review is to synthesize the current knowledge about biofuel impacts in Africa and to identify priority policy areas that should be targeted for enhancing biofuel sustainability in the continent. The findings of this review indicate that biofuel impacts can be positive or negative depending on several factors such as the feedstock, the environmental/socio-economic context of biofuel production, and the policy instruments in place during biofuel production, use and trade. In most cases there are significant trade-offs but at least part of the negative impacts can be mitigated through careful planning. The incomplete and piecemeal understanding of these trade-offs combined with agronomic, institutional and market failures are currently the most important barriers for the viability and sustainability of biofuel investments in the continent.

Contents

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1. Introduction: biofuel drivers and policies in sub-Sahara Africa

Biofuels were heralded in the early-to-mid 2000s as an important strategy for reducing reliance on fossil fuels and mitigating the associated greenhouse gas emissions. In some national contexts they were perceived as a silver bullet, able to provide a sustainable source of fuel that could be grown in-country but that could also have numerous ancillary benefits on carbon emissions, economic development and poverty alleviation.

Biofuels have consequently received significant attention from governments and the private sector in Sub-Sahara Africa (SSA). Several SSA governments have supported biofuel initiatives as a means of boosting economic growth, rural development and energy security [1–3]. In particular, since 2005 there has been a surge of direct foreign investments[1] in SSA for acquiring large tracks of land to accommodate biofuel expansion [4–9].

The most important driver of biofuel expansion in SSA has been economic development. Investors perceived biofuels to be potentially lucrative commodities, that could be channeled to international markets, and in particular the emerging EU biofuel market following the ratification of the EU Renewables Directive 2009/28/EC (EU-RED). EU-RED sent a strong signal that biofuel/feedstock imports could contribute towards meeting the newly established EU biofuel blending mandates, if production within the EU was insufficient[2] [10,11]. A second market-related circumstance that might have further contributed to biofuel expansion in SSA has been the efforts of Brazil to make ethanol an internationally traded commodity [12–16].

Energy security has been the second major driver of biofuel expansion in SSA as most countries in the region are highly dependent on traditional biomass or imported liquid fossil fuels [19]. Biofuels are particularly appealing to landlocked countries such as Malawi, where fossil fuel imports take a significant toll on trade balances. In fact most pre-2000s biofuel efforts in the continent (e.g. in Kenya, Malawi, South Africa, Zimbabwe), were aiming to increase national energy security and foreign exchange saving by reducing oil imports [1]. Transport has been by a wide margin the main foreseen use for domestically produced biofuels in Southern and Eastern Africa, whilst local energy use (e.g. rural electrification) has been the key use in some West Africa countries.

From an SSA government's perspective, feedstock/biofuel production (whether for exports or domestic use) could potentially boost rural development, having ripple effects on national efforts to alleviate poverty [1–3]. Rural development and "pro-poor" narratives have been very strong in discussions that legitimized biofuels in SSA and influenced the development of early biofuel policies [17,18].

On the other hand, environment-related concerns such as the reduction of greenhouse gases (GHGs) emissions and the improvement of ambient air quality have not been important direct drivers of biofuel expansion in SSA [1–3]. This is not surprising in a region with severe levels of poverty, where economic growth and development are prioritized. Yet concerns over climate change have been, in a way, an indirect driver of biofuel expansion in SSA as the EU, which was the main envisioned market for feedstock/biofuel exports from SSA, promoted biofuels partly as a climate change mitigation measure [11].

The above factors raised high expectations in SSA over biofuels, and catalyzed the significant expansion seen in the second half of the 2000s. The mandatory blending of biofuels into transport fuels has been the main legislative instrument for boosting biofuel uptake in the transport sector in SSA. Several countries in eastern and southern Africa have enacted such blending mandates, but in differing proportions [20], e.g. Angola (E10), Ethiopia (E5), Malawi (E10), Mozambique (E20 by 2021), Sudan (E5), Zambia (E10, B5), and Zimbabwe (E5 increasing to E15). Such mandates are often complemented with an array of policies that stimulate and protect national feedstock/biofuel

[1] Such direct investments were originating both from member (largely EU) and non-member (largely China and India) countries of the Organization for Economic Co-operation and Development (OECD).

[2] This was contrary to the other major biofuel markets at that stage that were either putting barriers for importing feedstock/biofuels (US) or were self-sufficient (Brazil).

production, e.g. tax breaks to facilitate uptake by consumers, price guarantees/subsidies to stimulate domestic production and import tariffs to protect domestic production [1]. On the other hand, countries in western Africa (e.g. Mali) prioritized models of joint biofuel production and use, e.g. for rural electrification where locally produced biofuel replaces conventional fuel in diesel-powered generators that supply village-level electricity grids. Farmers receive cash from growing feedstock, which is essentially money that would have otherwise been spent for importing diesel fuel [21].

At the beginning of the biofuel hype in Africa, Malawi had the only functioning biofuel market in the continent, as it was blending ethanol in gasoline since 1982 [22]. Since then several countries started promoting biofuels either through ambitious state-sponsored programmes (e.g. Ethiopia) or incentivizing the private sector (e.g. Mozambique). Still, this sudden interest in biofuels caught most countries in the region without established policies for promoting and regulating biofuel expansion [1,23–26]. Actually, South Africa was the first country to put in place a formal biofuel plan (2007), followed by Mozambique (2009) [18,19]. Other countries such as Ethiopia, Tanzania and Zambia established biofuel policies, but not coherent overall strategies yet [8]. UN-Energy and FAO-UNEP developed guidance and decision tools for designing comprehensive biofuel/bioenergy strategies in least developed countries, but it is not clear how much such guidance was uptaken by national governments or contributed to the development of biofuel policies [27,28].

However it must be pointed, that while biofuel mandates aim to ensure a biofuel market and reduce risks to biofuel producers, they are rarely accompanied by any measures to reduce the environmental and socioeconomic impacts of biofuel production and use (Section 3). In fact most national biofuel policies that have been enacted in SSA, with the recent exception of Mozambique [18], lack completely provisions for the broader environmental and socioeconomic impacts of biofuel expansion. The lack of such provisions has become particularly evident during the rapid rise and decline of jatropha as a biofuel crop in the region. Dozens of jatropha projects were allocated hundreds of thousands of hectares across Africa [29], with little proof of long-term economic viability or understanding of their environmental and socioeconomic impacts [2,3]. Several of these projects eventually collapsed leaving local communities and ecosystems worse-off [30].

The above suggest that there has been (a) an insufficient understanding of the environmental and socioeconomic impacts that accompany biofuels investments in SSA, and (b) a lack of policies that could regulate the biofuel sector ensuring the viability of biofuel projects while at the same time preventing their negative impact.

The aim of this paper is to synthesize the current knowledge about biofuel impacts in SSA as a first step towards identifying priority policy areas for enhancing the sustainability of biofuel production and use. Section 2 outlines the characteristics of the main biofuel options in SSA. Section 3 identifies key economic, environmental and social impacts associated with jatropha- and sugarcane-based biofuels in SSA, and unravels the mechanisms through which they manifest. The focus is on jatropha and sugarcane, as these have been the two most prominent feedstocks in SSA for biodiesel and bioethanol, respectively. By building on this evidence, Section 4 identifies priority policy areas and offers recommendations for enhancing the sustainability of the biofuel sector in SSA, while Section 5 discusses key lessons learnt through this review. Whereas the impacts discussed in Section 3 relate mainly to jatropha and sugarcane, most of the key policy issues (Section 4) and lessons learnt (Section 5) are to a large extent applicable and to other feedstocks.

2. Biofuel feedstocks and modes of production in SSA

2.1. Biofuel feedstocks

Jatropha (for straight vegetable oil or biodiesel) and sugarcane/molasses (for bioethanol) have dominated proposed biofuel investments in Africa [1,5,29]. Other potential feedstocks include cassava (for bioethanol), palm oil (for biodiesel), sweet sorghum (for bioethanol), tropical sugar beets (for bioethanol), canola oil (for biodiesel) and sunflower oil (for biodiesel) [1,67,145,244]. Second-generation biofuels are unlikely to become an important biofuel option in the short-to-medium term due to the lack of technical expertise, skilled personnel and appropriate infrastructure [31], despite the relatively high feedstock potential in SSA [32].

During the peak of the jatropha hype (2005–2009) almost every country in southern Africa promoted jatropha, as its principal biodiesel crop [30,33], while it also attracted interest in Ghana, Kenya, Tanzania, Senegal, Mali, Burkina Faso and Benin among others [34,35]. This interest largely manifested due to unsubstantiated promises of high yields under adverse growing conditions, e.g. in dry areas with poor soils [30,36]. By 2008, 120,000 ha were acquired for jatropha cultivation in SSA (13% of global total), while it was predicted that by 2015 jatropha production could reach 2 million ha in SSA alone [7]. Such claims were fueled by studies, which suggested that several million hectares of arid and semi-arid land was suitable for jatropha [37]. Recently, the commercial viability of producing jatropha in arid and semi-arid areas has been questioned as relatively high water availability, around 1500 mm/y, is needed to achieve economically viable yields [38]. In fact, most of the "successful" jatropha production occurred in areas of relatively high productivity, including arable land on abandoned plantations (Mozambique, Malawi), existing agricultural land (Zambia, Malawi), savanna ecosystems (Tanzania, Mozambique) or woodland degraded from timber overharvesting (Madagascar) [30,39]. This means that large parts of SSA are likely to be too arid for jatropha production.

Sugarcane production in SSA is still modest by world standards, at ~5.4% of global production [40]. However, large areas are suitable for sugarcane cultivation in SSA, with high production potential in Kenya, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe, with as many as 6 million ha of land being suitable for rain-fed sugarcane agriculture and readily available in just six southern Africa countries [41]. Given that in some of these countries such as Malawi and Tanzania the achieved yields can be in excess of 100 t/ha [40], the raw sugarcane potential in the region is comparable to that of Brazil [42]. This huge untapped potential to produce sugarcane (and sugarcane ethanol) in the region suggests that land is unlikely to be the limiting factor in sugarcane expansion. Currently only Malawi is a significant producer of sugarcane ethanol (Section 1), but this biofuel option is receiving much interest in countries with hundreds of thousands of hectares of land allocated for sugarcane production in countries such as Mozambique, Tanzania, Sierra Leone, Zambia and Zimbabwe [29,40]. Considering the high potential sugarcane yields and energy returns on investment (Section 3.1.2), the domestic ethanol mandates in some of these countries can be met even through modest land conversion [2].

2.2. Modes of production

Depending on the scale of feedstock cultivation and the biofuel end-use, four main distinct biofuel modes of production/use can be identified in SSA (Fig. 1). Types II and IV projects are characterized by the production of feedstock in large plantations (100–

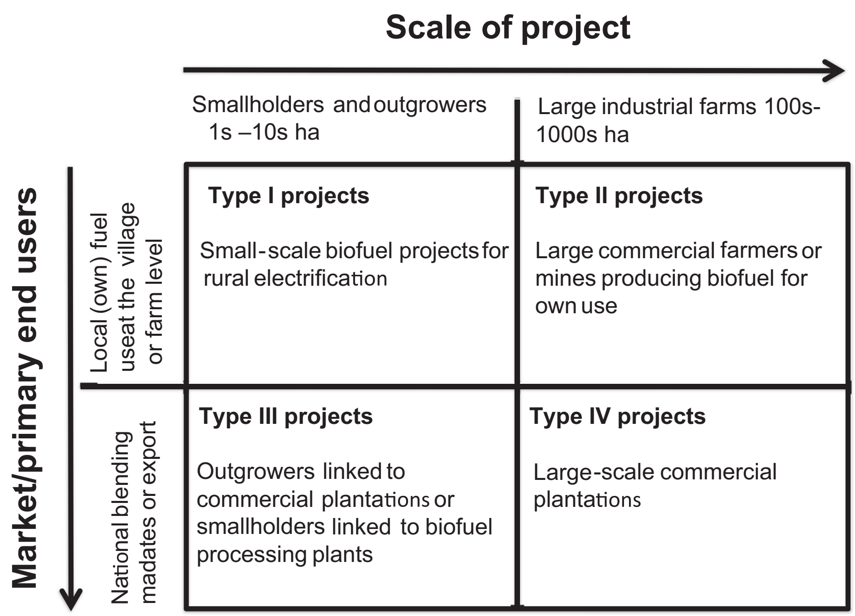

Fig. 1. Typology of feedstock/biofuel projects in Africa.
Source: Adapted from [2,39]

1000 s ha), usually adopting monocultural practices. The appropriation of extensive tracts of land exclusively for feedstock production in Types II and IV projects can compromise, or even displace, previous land uses and has been linked to various negative environmental and socioeconomic impacts (Section 3). On the other hand, Types I and III projects entail feedstock production in smaller scales (1 s–10 s ha).

Type IV projects are essentially commercial plantations that produce feedstock for national and international markets. Such large-scale feedstock plantations have been established across the continent, e.g. Mozambique (Niqel, D1 Oil), Sierra Leone (Addax), Tanzania (Sun Biofuels, Bioshape, EcoEnergy) and Madagascar (GEM Biofuels, Tozzi Green) and have, in some cases, been linked to outgrower schemes [1,10,39,43–45]. Depending on the feedstock and the production country such plantation can cater to both domestic and international markets.

Type II projects are much less prevalent and entail the joint production of biofuel and its direct use (usually on site), by large farms (e.g. in South Africa) and mines (in Zambia), [39,46]. In any case just a few operational examples of Type IV projects have been reported usually associated with large-scale investments, often foreign-led [30].

Type III projects include feedstock production schemes such as outgrowers linked to large plantations or smallholders linked to feedstock processing plants. In such projects, generally speaking plantations or processing plants provide initial inputs (e.g. capital, seeds, knowledge, fertilizers) with farmers being contractually obliged to grow, harvest sell the feedstock to the company that provides the inputs [47,48]. Such example have been Marli (Zambia) which contracted farmers to allocate up to half of their 10 ha plots for jatropha production [47,48] or BERL (Malawi) that incentivized family farmers to grow jatropha as hedgerows [30]. Given the explicit link between feedstock production and large manufacturers, depending on the feedstock and the production country such plantation can cater to both domestic and international markets.

Type I projects, often-called small-scale projects, entail the local production and consumption of biofuels. Examples include rural electrification projects in Mali, Mozambique and Uganda from straight jatropha oil [49–51]. Type I projects have been promoted across Africa by nongovernmental organizations (NGOs) and development agencies as a way to promote rural development and alleviate poverty, e.g. Folkecenter and Eco-Carbone projects in Mali [21,49] and FACT Foundation project in Mozambique [52]. These benefits are expected to materialize mainly through the local production and consumption of a renewable energy carrier, which can have knock-on effects on income and/or energy provision [2]. Depending on feedstock and local context, Types I and III projects can have very different socioeconomic outcomes (Section 3).

3. Biofuel impacts in sub-Sahara Africa

Impacts commonly associated with biofuel production and use in SSA include: water use, water quality, GHG emissions, atmospheric pollution, soil quality/erosion, biodiversity loss, economic/rural development, energy security, food security and access to land among several others [2,44,45].

As will be explained in the remainder of this section the magnitude of these impacts depends on numerous factors, including:

- feedstock;
- mode of production/use;
- previous land use and agricultural practices adopted during feedstock production;
- location of biofuel production and use (i.e. environmental and socioeconomic context);
- stage of the biofuel's life-cycle; and
- policies in place during biofuel production, use and trade.

Considering the number, geographic distribution and eventual fate of the biofuel projects initiated in SSA in the past decade it is impossible to offer a comprehensive review of all biofuel-related impacts in this section. Instead, the review of the literature focuses on key environmental (Section 3.2) and socioeconomic impacts (Sections 3.1 and 3.3) and unfolds the main mechanisms through which these impacts manifest. For a more comprehensive overview of individual biofuel impacts see [1,2,53–56].

Table 1
Economic impacts of biofuels in Sub-Sahara Africa.

Impact	Feedstock	Mechanism of impact and current state
Economic development (Section 3.1.1)	**Jatropha**	– Potential to contribute to GDP growth and employment generation (***national scale impact***) – Most jatropha projects initially targeted export markets (mainly in the EU) but have re-oriented towards domestic markets partly due to the economic constraints of production (***project-scale impact***) – Current jatropha projects exhibit low profit margins. Most projects are not economically viable while several projects have collapsed (***project-scale impact***)
	Sugarcane	– Potential to contribute to GDP growth and employment generation **(*national scale impact*)** – There are few sugarcane ethanol projects in SSA with most of them targeting domestic markets **(*project-scale impact*)** – High sugarcane yields achieved in parts of SSA suggest that cost-effective sugarcane ethanol production is feasible (***project-scale impact***)
Energy security and foreign exchange savings (Section 3.1.2)	**Jatropha**	– Potentially low-to-moderate EROIs (***project-scale impact***) – Jatropha-based biofuels have not substituted significant amounts of transport fuel in SSA yet **(*national scale impact*)** – Straight jatropha oil has been used in SSA for non-transport uses such as rural electrification **(*local/household scale impact*)**
	Sugarcane	– Potentially high EROIs, especially if bagasse electricity cogeneration is considered (***process scale impact***) – With the exception of Malawi, ethanol blending is currently low in SSA. Bagasse electricity cogeneration is also quite limited **(*national scale impact*)** – Existing blending mandates can be met from relatively moderate land investments considering the high sugarcane productivity across most SSA **(*national scale impact*)** – Ethanol stove programmes in Ethiopia and Mozambique can offer alternative sources of cooking fuel with environmental/social co-benefits, but the penetration of these technologies is still quite low **(household level impact)**

Table 2
Environmental impacts of biofuels in Sub-Sahara Africa.

Impact	Feedstock	Mechanism of impact and current state
Water availability (Section 3.2.1)	**Jatropha**	– Moderate water user when compared to natural vegetation and other agricultural activities in SSA (***local/landscape scale impact***) – Cultivation is largely rain fed in SSA, so water diversion is expected to be low (***local/landscape scale impact***)
	Sugarcane	– In some SSA countries sugarcane is produced under irrigated conditions. Some water diversion is to be expected (***local/landscape scale impact***)
Water quality (Section 3.2.1)	**Jatropha**	– No studies have quantified water pollution from jatropha landscapes in SSA, but it is expected to be low as jatropha projects do not usually use large quantities of agrochemicals (***local/landscape scale impact***)
	Sugarcane	– Sugarcane cultivation in SSA has been associated with water pollution due to the extensive use of agrochemicals (***local/landscape scale impact***)
GHG emissions (Section 3.2.2)	**Jatropha**	– Moderate-to-high GHG emission savings when compared to fossil fuels if LUCC effects are not factored (***global scale impact***) – Significant carbon debts due if LUCC effects are factored, especially if natural vegetation is converted (***global scale impact***)
	Sugarcane	– High GHG emission savings (***global scale impact***) – Relatively low carbon debts due to LUCC effects compared to other biofuels options (***global scale impact***)
Biodiversity loss (Section 3.2.3)	**Jatropha**	– Knowledge about species occurrence in jatropha landscapes is practically non-existent as no biodiversity surveys have been conducted in SSA or elsewhere (***local/landscape scale impact***) – Some jatropha projects have been associated with deforestation (***local/landscape scale impact***) – Jatropha invasiveness is still uncertain in SSA (***local/landscape scale impact***)
	Sugarcane	– Extensive sugarcane monocultures are known to support a relatively limited number of species, but few studies have been undertaken in SSA (***local/landscape scale impact***) – Sugarcane projects in SSA might involve relatively large-scale clearing of indigenous vegetation potentially having a negative impact on biodiversity (***local/landscape scale impact***)

It is important to note that these impacts are scale-specific. For example the impact of GHG emissions (or avoided emissions) from biofuel chains manifests at the global scale. Other impacts such as biofuel-induced biodiversity loss, water availability/quality and loss of access to land can manifest at lower scales (mainly the local scale). Impacts related to economic development, poverty alleviation and energy/food security could manifest at various scales ranging from the local/household scale, to the national and regional scale. To the extent possible the scales that these impacts manifest are differentiated in Tables 1–3 and throughout Section 3.

It should also be noted that with the exception of Malawi (and Zimbabwe in the past), no country in SSA has currently achieved high levels of sugarcane ethanol production [19,22,54,233,234,235]. As a result most of the discussed impacts relate to projects producing sugarcane for sugar and not for ethanol. Yet

Table 3
Social impacts of biofuels in Sub-Sahara Africa.

Impact	Feedstock	Mechanism of impact and current state
Poverty alleviation (Section 3.3.1)	**Jatropha**	– Relatively low employment generation in plantations but the stable salaries offered are usually well-regarded by employees (***local/household scale impact***) – Smallholder/outgrower-based projects can have a large outreach but the offered income is sometimes limited (***local/household scale impact***) – Smallholder/outgrower-based projects can exhibit wider poverty alleviation benefits than large-scale projects (***national scale impact***)
	Sugarcane	– Relatively low employment generation in plantations but the stable salaries offered are usually well-regarded by employees (***local/household scale impact***) – Smallholder/outgrower-based projects can have a large outreach but the offered income is sometimes limited (***local/household scale impact***) – Large-scale sugarcane projects might offer lower poverty alleviation benefits than smallholder-based projects of jatropha/cassava (***national scale impact***)
Food security(Section 3.3.2**)**	**Jatropha**	– Indirect competition with food production (i.e. through competition for labour, land, water and other agricultural inputs) (***local/household/landscape level impact***) – modeling exercises have found varying impacts on national food production but no discernible impact on national food security in SSA (***national scale impact***) – High female involvement in national biofuel programmes might increases food–fuel trade-offs, as women are typically responsible for food production (***national scale impact***) – Involvement in jatropha activities can provide income and have a potentially positive effect on food security (***local/household scale impacts***)
	Sugarcane	– Direct and indirect competitions with food production, i.e. through direct displacement of sugarcane from food uses and competition for labour, land, water and other agricultural inputs (***local/household/landscape level impact***) – Involvement in sugarcane activities can provide income and have a potentially positive effect on food security (***local/household scale impacts***)
Access to land (Section 3.3.3**)**	**Jatropha**	– Large number of large-scale land acquisition requests. In some cases local communities committed almost all of their land in jatropha production (***national scale impacts***) – Communities have lost access to their communal land in several parts of SSA (***household/local level impact***)
	Sugarcane	– Relatively few large-scale land acquisition requests. In some cases local communities committed almost all their land in sugarcane production (***national scale impacts***) – Concerns of losing access to land if certain sugarcane projects proceed to implementation phase (***local/household scale impacts***)

since most of the agricultural practices are the same whether sugarcane is grown for sugar or ethanol, most of the key lessons learnt can be also relevant to sugarcane ethanol projects.

3.1. Economic impacts

3.1.1. Economic growth

Biofuel feedstocks are essentially agricultural commodities whose commercial production can potentially provide economic benefits to rural households and national economies. Except for some Type I projects and most Type II projects (Section 2.2), feedstock cultivation can be considered as a cash crop activity. In this respect feedstock production has been identified to be a potentially important strategy to modernize the agricultural sector in SSA [57]. This can have flow-on effects on national economic growth and poverty alleviation (Section 3.3.1), Table 1.

Macroeconomic studies have shown that biofuel expansion could potentially become an engine of economic growth in countries such as Mozambique and Tanzania [58–61]. For example, general equilibrium modeling (GEM) studies of the Mozambique national economy suggested that biofuel production could contribute approximately 0.37% of national gross domestic product (GDP) and generate 271,000 rural jobs [58,59]. Similar studies in Tanzania suggests significant employment generation and a GDP increase of 0.25–0.37% [60]. However, aggregate economic benefits depend on the adopted modes of biofuel production, with smallholder- and outgrower-based models (Type III) usually offering the largest benefits to the national economy [58–60]. However it must be pointed out that such studies were (are) often based on predicted feedstock yields (especially for jatropha) that predated empirical data from actual on-the-ground studies. For substantial economic benefits to manifest, biofuel ventures (whether Type III or Type IV) need to be economically viable and profitable. Important indicators of viability include achieved yields (land productivity), labour productivity, cost of labour and financial investment.

Indeed most studies have suggested that jatropha (whether in large plantation or smallholder settings) has low profit margins that largely depend on oil prices, labour costs for harvesting/treating (e.g. de-husking, crushing), and fertilization costs [62–67]. In fact the biggest hurdle towards achieving sustained positive societal impacts in both Types III and IV modes of jatropha production, is their marginal profitability at current yields, costs and prices [44,45]. A comparative study of 23 jatropha projects in Mali, Mozambique and Tanzania, showed that plantation- and smallholder-based projects show limited economic viability [237].

Despite the jatropha hype there are hardly any cost benefit analyses, in SSA or elsewhere, and even fewer that were based on real on-the-ground yield data or that did not have methodological discrepancies, e.g. failing to include the full opportunity cost of the converted land [44,45]. One of the few jatropha studies that quantified net-present values (NPV), internal rates of return (IRR), benefit-cost ratios (BCR) and payback periods (PBP) showed that for smallholders in East Africa all family labour settings for cassava and jatropha have positive NPVs and high IRRs and BCRs [67]. However, jatropha production has higher IRRs only in contexts of family labour or low labour opportunity costs [67]. For example, it was found that at in northern Tanzania NPV of jatropha production was negative at a yield of 2 t/ha, becoming only slightly positive at 3 t/ha [63]. In Kenya it was found that only planting jatropha in hedgerows could have a positive IRR, with monocultures being loss making [65]. Labour availability has been identified as an important factor for involvement in jatropha smallholder projects in Zambia and Malawi, as poor and labour-deficient households were less willing to be involved in such schemes [68,69].

On the other hand sugarcane ethanol has a more proven commercial model, especially in countries such as Brazil. The sugar industry in southern Africa operates under favorable climatic conditions (Section 2.1) and is among the few agro-industries where African producers have successfully developed some of their competitive advantages [70]. Thus the sugarcane industry was advanced in some parts of SSA, achieving high yields before the biofuel hype erupted (Section 2.1). In any case there are few published studies that explore the cost-effectiveness of sugarcane ethanol in SSA. A study for Mozambique suggests that the cost-effectiveness of sugarcane ethanol can be highly variable depending on a number of factors such as the agroecological conditions of the production site and the prevalence of infrastructure among several other factors [71].

3.1.2. Energy security and foreign exchange savings

Biofuels are essentially renewable energy carriers. Given that most liquid fossil fuels used in the transport sector (and in some cases electricity generation) across SSA are imported (Section 1), domestically produced biofuels can substitute these imported fuels. This substitution can increase national energy security, and stimulate the economy by generating foreign exchange savings, Table 1. Benefits from improved energy security can be more pronounced where liquid fossil fuels are particularly expensive such as landlocked countries or remote areas. Secondary biofuel uses for cooking stoves, lamps and rural/off-grid electrification can increase energy security at the household/local level, potentially having direct and indirect flow-on effects to poverty alleviation (Section 3.3.1).

A key consideration when evaluating the energy security potential of different biofuel options is the degree to which they provide net-energy gains. A commonly used indicator is the energy return on investment (EROI)[3] achieved during the biofuel's whole life cycle. Table 4 includes energy yields and EROIs of jatropha- and sugarcane-based biofuels as quantified through different life cycle assessments (LCAs). In all reviewed cases, achieved EROIs are higher than 1.[4] This implies that jatropha- and sugarcane-based biofuels can meet the "*net-energy provision*" criterion [73], but also that their EROIs are much lower than those of conventional fossil fuels (approximately 15–20) [74].

However, domestically produced biofuels can decrease fuel imports and thus have a positive effect on trade balance and foreign exchange savings. For example the Brazilian ethanol program has resulted in avoided fuel imports of ~USD 2 billion per year, i.e. as much as 200,000 barrels per day [12]. Malawi has been the only country in SSA consistently blending biofuels since the 1980s. Despite the lack of studies to quantify foreign exchange savings from biofuels, it has been suggested that these savings can be substantial considering the high fuel prices in the country [22].

However, the above figures are not directly comparable and should be interpreted with caution. First of all, there are very few complete biofuel LCAs in SSA. Second, most of the studies in Table 4 were performed in different regional contexts under different agro-ecological, technological and infrastructure conditions. Third, different LCA studies rarely make the same methodological assumptions (e.g. allocation rules, system boundaries), so their results are not directly comparable. Fourth, some of the reviewed studies include biofuel co-products (e.g. bagasse electricity cogeneration, Section 4.2), which can improve significantly the EROIs. Fifth, biofuel EROIs depend a lot on the feedstock yields achieved. Regarding this last point most jatropha LCAs were conducted during the early years of the jatropha hype and tended to make optimistic jatropha yield assumption, that were not observed in the field. This has most likely resulted in inflated EROIs that overestimate the energy security outcomes of jatropha-based biofuels [30,44].

Table 4
Energy yields and EROIs for main biofuel options in SSA.

Feedstock	Region	Energy yield (GJ/ha)	EROI	Source
Jatropha	West Africa	5.7	4.7	[75]
	West Africa	1.4	1.8	[75]
	China	57.9	2.0	[76]
	China	454.0	1.5	[77]
	India	NA	1.5–8.6	[78]
	India	NA	1.2–7.0	[78]
	India	78.7	1.9	[79]
	India	NA	1.8	[80]
	India	17.3	1.4	[81]
	Thailand	103.0	1.4	[82]
Sugarcane	Brazil	132.0	8.5	[83,84]
	Brazil	127.0	3.1	[83,85]
	Brazil	159.0	3.9	[83,85]
	Brazil	140.0	9.3	[86]
	Brazil	130.0	8.2	[87]
	Brazil	130.0	NA	[88]
	Colombia	185.0	NA	[89]
	Mexico	123.0	4.7	[90]
Molasses	Thailand	132.0	0.8	[91]
	Thailand	NA	0.8	[92]
	Nepal	960.0	0.8	[93]

3.2. Environmental impacts

3.2.1. Water quantity and quality

Feedstock production can affect both water availability and water quality, Table 2. Water availability depends on plant physiology and the agricultural practices adopted, e.g. irrigated vs. rainfed agriculture. Water quality is mainly affected by the discharge of hazardous aquatic pollutants associated with feedstock production, feedstock treatment and biofuel production (e.g. fertilizers, pesticides, industrial effluent), which can be a major risk to public health and ecosystem functioning [55].

Regarding water availability, *Jatropha curcas* L is the only species of the jatropha family currently used for biofuel production. It is considered to be a conservative water user due to its high transpiration efficiency [94–96]. Field experiments in South Africa have demonstrated that jatropha on an individual basis is not likely to compete for scarce water resources with indigenous vegetation as it has similar transpiration rates [96,97]. Even though jatropha can grow in arid and semi-arid conditions (Section 2.1), high yields are achieved in wetter conditions [38,98], while economically viable jatropha operations might require irrigated conditions [66,99]. However in non-irrigated conditions in Mozambique, the blue water footprint[5] of high- and medium-yielding jatropha systems was respectively smaller or equal to that of diesel fuel [72]. Conversely, the high transpiration

[3] EROIs are calculated as the ratio of the energy provided during the combustion of the biofuel (Eout), divided by the total energy consumed during biofuel production (Ein).

[4] Another study suggests that the production of straight jatropha oil in Mozambique has favorable energy returns on investment even for low yield scenarios [72].

[5] In water foot-printing studies, "blue" water refers to ground or surface water, "green" water to rainwater and "gray" water to the freshwater needed to assimilate the load of pollutants.

potential of sugarcane (especially under irrigated conditions, e.g. South Africa, Swaziland, Zimbabwe) can result in large blue water footprints. For example, there have been instances of irrigated sugarcane projects (e.g. Tana Delta, Tanzania) that have affected water flow regimes, having subsequent implications for food security [100].

However, there is still a dearth of comparative studies on the water footprint of sugarcane- and jatropha-based fuels, which makes difficult a comparison between the two feedstocks. Furthermore, in water footprint studies, similar to LCA studies (Sections 3.1.2 and 3.2.3), the study assumptions can be an important determinant of the overall result, as it has been shown for jatropha [103–105]. Given this uncertainty regarding the actual water requirement of biofuels in SSA, we speculate that the choice between agricultural practices (i.e. irrigation vs. rain-fed) can be a much more important determinant of the overall water footprint, than the choice between feedstocks (i.e. jatropha vs. sugarcane). This is because both feedstocks lack the ability to tap into deep water sources and desecrate soils as has been observed for tree-species such as Eucalyptus [101,102].

Regarding water quality, to our best knowledge there have not been any studies that have quantifies the water pollution effects of jatropha in SSA, or elsewhere. Jatropha has traditionally been grown in SSA, both in large-scale and smallholder-based schemes, with minimal inputs of agrochemicals and fertilizers. This can reduce potential freshwater quality impacts, but at the same time take a toll on yields [64,66]. On the contrary, there is significant evidence of negative impacts on water quality (and subsequent on ecosystem functioning) due to agrochemical use in sugarcane agriculture in Brazil [107,108]. Water monitoring studies in Swaziland found elevated concentrations for Total Dissolved Solids (TDS), Na and Mg from sugarcane plantations that exceeded the Swaziland guidelines for drinking water and the South African standard for irrigation water [109]. In Kenya (Nzoia sugarcane belt) high current and historical use of pesticides/herbicides (e.g. DDT, aldrin, dieldrin, and endrin), resulted in some cases to concentration levels exceeding the EU limit requirements for drinking water, being thus a potential risk to humans and cattle if untreated [110]. Finally, vinasse (the final by-product of ethanol production) has been shown to have negative impacts on water quality if released untreated [106,247,248].

3.2.2. *Biodiversity loss*

Biofuel expansion has been linked directly to four of the five biodiversity loss drivers identified in the Millennium Ecosystem Assessment (MA); namely land use change, invasiveness, pollution (see Section 3.2.1) and climate change (see Section 3.2.3) [55,111], Table 2. Out of these drivers, land use and cover change (LUCC) has been perhaps the most important driver of biodiversity loss, particularly in feedstock growing areas [112], but few studies have been conducted in SSA [113,114]. Considering that biofuel expansion in the African tropics can become a potentially important driver of land use change, its negative effects on biodiversity can be substantial but difficult to quantify [115].

Feedstock production in SSA usually converts four main types of land: existing agricultural land, abandoned agricultural land, degraded land, and areas of natural vegetation [114,141]. Each of these LUCC effects might contribute directly or indirectly to habitat loss, and can be a feature of both large-scale biofuel projects (Types II and IV) and smallholder-based feedstock production (Typea I and III). For example, there is evidence of clearing biodiverse native miombo forests when establishing jatropha plantations [44,45,116,141]. In the Brong Ahafo region in Ghana, 46% of the area converted to a large-scale jatropha plantation was forested, albeit in some parts degraded from overexploitation [147]. It has been estimated that for each 1000 ha of land converted to jatropha by smallholders, as much as 438 ha of mature forest could be cleared in parts of Zambia [48].

LUCC effects associated with sugarcane expansion pose similar threats to species richness and abundance in SSA. For example, it was found in Kenya that bird density and species richness decreased in areas close to sugarcane plantations [117]. The composition of bird communities also changed with very few forest specialists encountered in farmland (feedstock) habitats [117]. Similarly, sugarcane landscapes were found to harbor lower bee diversity in Kenya [118]. Furthermore, sugarcane projects, such as the proposed SEKAB (a Swedish ethanol producer) project in Rufiji area (Tanzania) were planned to be situated in close proximity to coastal forest areas of high endemism [119,120].

LUCC effects can also have a rather indirect effect on biodiversity. It is well established that poor populations in Africa depend for their livelihoods on the services provided by ecosystems, e.g. wild food, fuelwood/charcoal, timber, non-timber forest products [121–123]. Conversion of natural vegetation for feedstock production may concentrate such resource harvesting in the remaining forested areas. If resource harvesting is confined in ever-diminishing forest areas, it may lead to the overexploitation of commercially valuable species [124]. In this regard overexploitation (not habitat loss) becomes the actual mechanism of biodiversity loss [111].

Jatropha has been considered to be a potentially invasive species in SSA that could outcompete the native savannah and miombo vegetation. For example South Africa banned jatropha production preemptively based on this fear but without conclusive evidence [30]. Recent studies in Zambia and Burkina Faso suggest that fears of jatropha's invasiveness might be overhyped [125,126,245].

Finally, different agricultural management practices during feedstock production can have differing effects (positive or negative) on biodiversity (Section 4.9). For example, agrochemical use during sugarcane production is much higher than for jatropha production and can have a proven negative impact on biodiversity (Section 3.2.1). Large jatropha monocultures tend to retain (for the first years at least) an understory of indigenous grasses and forbs [127]. It is therefore possible that some level of biological diversity in maintained in jatropha plantations, as compared to sugarcane plantations that usually undergo complete conversion. However, if such an understory is used then in order to achieve the same overall energy output (Section 3.1.2) more land area will be required to be converted for jatropha than sugarcane, thus offsetting such positive biodiversity effects.

3.2.3. *GHG emissions*

By substituting conventional transport fuel, biofuels can affect the overall GHG and atmospheric pollutant emissions from the transport sector, Table 2. Considering that GHGs are emitted in every stage of the biofuel chain [128], any potential climate change mitigation benefits of biofuels should be assessed after considering the fuel's entire life cycle. Few studies have explored biofuel-related atmospheric emissions in SSA, with most of them focusing on GHG emissions.

Several comparative studies and LCA meta-analyses have identified the consistently high emission savings of sugarcane ethanol when compared to conventional fuel [128–131]. On the other hand the emission savings of jatropha-based biofuels tend to range considerably, Table 5.

Currently few studies that quantify the GHG emissions of biofuel chains in SSA are based on actual observed yields. Depending on agricultural practices, jatropha production in north Mozambique could emit between 25 and 78 g CO_2eq per MJ of jatropha oil, which represents carbon savings of 3–69% compared to conventional diesel [73]. A recent study calculated high overall emissions savings for jatropha biodiesel in Tanzania [136], but seems to have assumed optimistic jatropha yields rarely encountered in most projects in southern Africa [30]. A recent study of sugarcane ethanol in Malawi calculated emissions of 116 g CO_2eq per MJ of ethanol [137]. These emissions were mostly due to the high use of nitrogen fertilizers, diesel and electricity for irrigation, and could be mitigated by adopting different management practices [137].

The above suggests that the GHG emission savings of different biofuel options in Africa could be considerable, but these figures should be interpreted with caution. Apart from the points made in Section 3.2.1, these LCAs exclude GHG arising from direct and indirect LUCC effects. The carbon lost from above/below ground biomass and soils during land conversion can create carbon debts that might take several decades to repay [138–140] (Table 6).

Such effects are not easily captured in current biofuel LCAs but can have a strong effect on the overall carbon balance. For example, if LUCC effects are excluded, then jatropha biodiesel in Brazil can emit 55% less GHG than conventional diesel (Table 5), but if considered then jatropha biodiesel emits 59% more GHGs than conventional diesel [132]. Similarly, an added 77 g of CO_2eq per MJ of ethanol MJ are expected to be emitted, when indirect LUCC effects were factored in a sugarcane ethanol LCA for Malawi [137]. However, even when factoring LUCC effects in LCAs, some biofuel options can exhibit significant net-carbon savings. For example in Tanzania both smallholder and large-scale jatropha projects could provide GHG savings (151% and 2% respectively) over conventional diesel [45].

Table 5
GHG emissions (in gCO_2 eq/MJ) and emissions savings (in %) for jatropha-based biofuels.

Region	Emissions (gCO_2 eq/MJ)	Emission savings (%)	Source
Brazil	40.0	55	[132]
China	17.9	80	[133]
China	52.0	49	[76]
India	74.6	85	[134]
India	NA	50–107	[78]
India	NA	40–93	[78]
India	NA	69	[80]
India	123.7	55%	[81]
Ivory Coast	23.5	72	[75]
Ivory Coast	74.5	11	[75]
Global	50	51	[135]

3.3. Social impacts

3.3.1. Poverty alleviation

Alleged pro-poor benefits have been one of the biggest selling points of biofuels in SSA (Section 1). Biofuels can potentially boost rural development and poverty alleviation directly by providing income from employment in plantations (Type IV projects) or subcontracted selling of feedstock (essentially a cash crop) from smallholders (Type III projects) [2], Table 3. They can also boost rural development indirectly through the provision of locally renewable energy that can boost other productive activities [2]. These indirect effects are usually a feature of small-scale biofuel projects (Type I) and are difficult to delineate. This section focuses on the main direct effects but the interested reader is diverted to other publications for an exposition of indirect poverty alleviation mechanisms [2,49–51]. It should be also mentioned that there are several examples of biofuel poverty alleviation effects (and social impacts in general) being gender-differentiated in SSA, with women less likely to enjoy positive impacts or more likely to face the negative impacts [2,146,147].

3.3.1.1. Employment generation and project outreach. Large plantations (Type IV projects) have been shown to create some employment opportunities, but the magnitude of employment generation is variable between the different stages of biofuel production. Most jobs are created during feedstock production (agricultural phase), which mainly uses low-skilled labor with fewer jobs usually created further down the biofuel chain [55]. Evidence from SSA suggests that jobs during the plantation maintenance phase are more likely to be seasonal rather than permanent [147,148,237]. For smallholder/outgrower-based projects (Type III), the project's outreach (i.e. number of farmers involved) becomes an important determinant of poverty alleviation. The outreach of such projects is highly variable and depends on the feedstock, the agricultural practices and the feedstock-buying capacity of the buyer (e.g. core plantation or biofuel producing facility).

Several jatropha plantations in SSA collapsed before yields stabilized, so the available evidence about employment generation is largely limited to the plantation establishment phase [30,44]. Studies suggest the creation of 0.11–0.21 jobs/ha in Mozambique

Table 6
Carbon payback times for different biofuels options.

Feedstock	Region	Original land use	Payback time (yrs)	Source
Palm oil	Cameroon	Forest	45–53	[81]
Jatropha	Ghana	Mix of open and closed woodland, permanent cropland and fallow land	71–129	[141]
	Zambia	Mix of mature miombo woodland, permanent cropland and allow land	20-NA	[141]
	Mozambique	Mature miombo woodland	187–966	[142]
	Africa	Miombo woodland	33	[116]
	South Africa	Converted savannas	17–36	[43]
	Zambia	Miombo woodland	32–81	[43]
	Mexico	Secondary woodland	60–101	[141]
	Mexico	Mix of secondary forest, fallow land and permanent cropland	72–183	[141]
	Mexico	Mainly agricultural land and pasture with secondary forest	7–30	[141]
	Brazil	Caatinga woodland	10–20	[143]
Sugarcane	Brazil	Cerrado woodland	17	[138]
	Brazil	Grassland	3–10	[144]
	Brazil	Forest	15–39	[144]
Cassava	Mali	Fallow land	37–81	[145]

[10,30] and 0.15 jobs/ha in Ghana [147]. In several cases, the number of jobs eventually generated was much lower than the initial community expectations. For example, Sun Biofuels in Tanzania promised to generate thousands of jobs and minimum wage for local villages, but the project eventually lacked financial viability and closed down in 2011 leaving hundreds of people unemployed [149–151]. Other large-scale jatropha projects in Tanzania, Mozambique and Madagascar have also either fully closed, have encountered financial difficulties or have been sold to new investors resulting in the eventual loss of the generated jobs [30,43].

The sugar industry is one of the largest employers in East Africa, with the sector employing directly over 50,000 employees [152]. Due the sugarcane sector's need to achieve economies of scale, it can attract larger investments than jatropha and become a significant agent of employment generation (in absolute terms). However sugarcane employment density can be equal or even lower than that of jatropha. For example the SEKAB sugarcane project in Tanzania would have created just 0.15 jobs/ha in its full extent (30,000 jobs over 200,000 ha) [46]. Mechanization can have take a toll on employment creation, effectively decimating the high number of poorly paid harvester jobs, as has been witnessed in Brazil [12,83].

Several projects have incentivized smallholders to cultivate jatropha in hedges. The outreach of such projects can be huge (e.g. BERL, Malawi which boasted as many as 30,000 farmers involved) though these farmers would only make a small proportion of their overall income from jatropha, Section 3.3.1.2. Other projects such as Marli (Zambia) and Dilligent (Tanzania) “required” more substantial production commitment from smallholders, eventually including from a few hundred to several thousand farmers [44–46,48]. Studies have shown that jatropha uptake among smallholders depends on a multitude of household characteristics such as external income sources, labour availability and land endowment [68,69].

Sugarcane projects can have even larger outreach to smallholders/outgrowers,. The sugarcane industry in East Africa is estimated to contribute income to over 300,000 farmers [152]. In Kenya, the Mumias Sugar Company was formed in 1973 as an outgrower company now includes 66,000 contracted smallholders cultivating approximately 64,000 ha within a 40 km radius of the sugarcane processing plant [153]. Other sugarcane projects such Illovo/Dwangwa (Malawi) and RSSC/SWADE (Swaziland) involve several hundred farmers.

3.3.1.2. Income generation. Many rural areas in SSA have very limited job opportunities, so even low-waged jobs are highly sought after. For example in the Brong Ahafo region (Ghana) rural households were keen to abandon off-farm income activities (but very few subsistence agriculture) when employed in jatropha plantations [148]. However, the received wages tend to be very low in absolute terms, in most cases reflecting legal minimum wage requirements [237]. For example, workers in some jatropha plantations in Mozambique can earn as little as EUR 44/month [30,154]. Totoma in Mali allegedly paid its plantation workers between CFA 500–750/day (approx. USD 1–1.50/day) [155], while Sun Biofuels in Tanzania GBP42/month [150,151,156]. In Ghana, the average wage for unskilled full-time employees amounted to 75 Ghana Cedi/month (USD 50/month) (about 51% of the average household income in the region) [147]. Another study from Ghana found large variation in plantation salaries, with an average salary of ~100 Ghana Cedi/month (~USD 67/month) [239]. While plantation salaries can rarely offset losses from other income activities they are still considered important by recipients for the livelihoods. This may be because they offer a secure and stable source of income that could consistently cover food, medical, and educational expenses [147,237] or be a much needed source of cash in times of need (e.g. during droughts) [30].

Given the relatively low employment generation potential of Type IV projects (Section 3.3.1.1), few persons usually benefit from plantation wages [45,237,239]. When aiming for broader rural development and poverty alleviation, modeling studies have suggested that smallholder schemes might provide larger overall benefits (Section 3.1.1). For example smallholder cassava schemes (Tanzania) and jatropha (Mozambique), seem to provide more widespread poverty alleviation benefits compared to large-scale sugarcane production [58,60]. These more widespread poverty alleviation effects have also been observed through comparisons of Types III and IV jatropha projects in Tanzania [45]. Still studies in several SSA countries have shown that the actual amount of income received from involvement in smallholder/outgrower jatropha activities was very limited and could only be considered a supplement to other livelihood activities, especially subsistence agriculture [30,48,68,69,237]. In fact such activities were considered by some participating farmers more of investments for the future (i.e. jatropha seen a “pension tree”,[6]) rather than activities able to provide high income benefits immediately [48]. However, on some occasions, income from jatropha activities was used to substitute previously purchased products such as soap or mosquito repellent [183].

Large-scale sugarcane production in Malawi, Mozambique and Zambia seem to have offered some national and local benefits such as employment generation, but the overall wages are also typically low [157]. Conversely, sugarcane outgrower programs in Kenya, Malawi, Tanzania and South Africa seem to have provided substantial rural development benefits and in some circumstances resulted in the development of a relatively prosperous smallholder sector [157,158]. In Uganda, villages closer to the Kinyara Sugar Works Limited (KSWL) factory appeared wealthier than villages closer to the Mabira Forest Reserve [159].[7] In Dwangwa (Malawi) sugarcane outgrowers seemed to have higher incomes than wage laborers at the neighboring Illovo sugarcane estate and significantly higher incomes than households with no involvement in the sugarcane sector at all [160]. However, in a similar manner to jatropha, the income obtained from smallholders' involvement in the sugarcane sector might not be enough to lift recipients out of poverty as was evidenced for the majority of sugarcane farmers at the Nzoia Sugarbelt (Kenya) [161]. In that area, the average farmer obtained a mean monthly income of Kenya Shillings 723 (USD 10) from an average sugarcane field of 0.38 ha, which would not have been enough to meet the basic needs of a family [161].

3.3.2. Access to land

Feedstock production in SSA is usually located in previous agricultural land, abandoned agricultural land, degraded land or natural vegetation (Section 3.2.2). In most SSA countries such areas are under some form of customary tenure, often legally recognized as “communal lands” with no individual private ownership. Communal agricultural land is mainly used for subsistence agriculture, while communal rangelands and forests for livestock grazing and harvesting a wide range of woodland products such as wild food, timber, fuelwood and medicinal herbs. Access to such woodland products is important to the livelihoods of poor and

[6] See also video at: www.biodiversity.ox.ac.uk/biofuel_landscapes.

[7] It should be mentioned that households pursued different livelihood strategies and invested in different components of wealth so it is unclear whether the benefits of sugarcane cultivation outweighed the environmental costs of forest loss [159].

marginalized groups, while loss of access can drive these groups into deeper poverty [121,162,163].

Biofuel-related loss of access to communal land has been usually associated with large-scale (Type IV), rather than smallholder-based (Type III) projects [44,45,239]. It is largely linked to how communal land is transferred to a biofuel venture, the compensation mechanisms enacted, and the actual level of influence that the community has on this land, during and after project implementation [164], Table 3. The particular procedures of land transfer vary among SSA countries. However, those lands set to be converted for feedstock production that are previously managed and used by local communities, have to be converted first into state land before being leased to biofuel investors. [149,165]. This is a formal process where tenure is permanently transferred to the state, which subsequently leases the land to investors [166]. Though legislation differs between countries, lease fees would typically go to the state, with the community members receiving some sort of compensation (but not always and not usually enough) and job opportunities [164,166]. If an investment project fails (e.g. collapse of jatropha projects) then this land typically remains state land rather than reverting back to the community [165]. The situation therefore can potentially arise that a community loses both their traditional access to land, as well as the employment benefits they had expected to obtain. The transfer of land rights and the conversion of communal lands for large-scale feedstock production has often been considered largely unfair to local communities and has crystallized into the "land-grabbing" debate [167,168].

Online land acquisition databases suggest that several million hectares have been acquired in SSA for large-scale agricultural projects, often related to biofuels [29,169].[8] Many of these large-scale land acquisitions have been driven from the private sector, and are often foreign-led targeting good agricultural land [172]. Due to the economies of scale involved in sugarcane production the land requirements for sugarcane projects tend to be on average higher than that of jatropha. Still, the number of land acquisition requests for sugarcane-based projects have been less than that of jatropha, e.g. only two out of 24 large-scale land acquisitions requests in Tanzania were aimed at sugarcane production [124]. However, there are underway some large-scale sugarcane ethanol investments in Kenya, Mozambique, Sierra Leone and Tanzania [29,169].

There are several documented examples in SSA (and elsewhere) where poor people lost access to their land due to biofuel expansion. This included the displacement of poor families, elite capture of land, loss of land rights through coercion (or provision of false/selective information) or even aggressive land seizures [5]. Loss of access to land and lack of compensation has also been a characteristic of large-scale jatropha projects in Ghana [239]. The loss of access to land has often severe negative effects on household livelihoods [147,239], especially following the collapse of jatropha projects (e.g. Sun Biofuels, D1 Oils, GEM Biofuels, Bioshape) [30].

On the other hand issues of loss of access to land are not a characteristic of smallholder-based projects (Type III), as the land (or right to use it) is not transferred to a company. In these cases the main land-related issue associated with household livelihoods is the opportunity cost of the land dedicated for feedstock production [173], which can be related to income loss (Section 3.3.1.2) or reduction of food security (Section 3.3.3).

[8] In reality most of these acquisitions have (a) not progressed beyond the planning stage or (b) the land actually converted was only a fraction of the acquired land [8]. Furthermore, the robustness of land-grabbing datasets has been questioned [170,171].

3.3.3. Food security

Most SSA countries exhibit low levels of national food security, with rural areas often being the poorest and most food insecure, especially during drought [174]. Ironically this food insecurity persists despite high agricultural potentials in many countries in the continent [40]. In fact crop yields lag well behind the true agricultural potential due to low agricultural inputs and a reliance on small-scale farming [175].

Biofuels' impact on food security is another highly contentious issue that has crystalized in the food-versus-fuel debate [176]. Even though there is some consensus that biofuel expansion has contributed to international food price increases during the 2007–2008 food crisis, the actual magnitude of this effect is far from agreed; reportedly ranging between 3 and 30% [177–180]. Interestingly, it has been argued that biofuels have not contributed to food price increases in SSA [181].

In fact, as a non-food/feed and non-fibrous crop, jatropha does not compete directly with food crops and fodder. In other words as jatropha cannot be used for food or feed (jatropha oilseeds are toxic), using jatropha for energy purposes does not divert the crop from food-related uses. On the other hand sugarcane is used extensively in the food industry, and in this sense the diversion of sugarcane to ethanol production (rather than sugar production) can have direct effects on food production, i.e. displacement from food-related uses. However, both jatropha and sugarcane can compete indirectly with food production through competition for land, labour, water and other agricultural inputs, Table 3.

Macroeconomic studies have suggested that national food security will not be affected (or will slightly decrease if no new land is brought under cultivation) in SSA countries that undergo biofuel expansion, as feedstock will most likely compete with food crops destined for export, rather than domestic food consumption [58,61]. Yet, stronger trade-offs between biofuels and food security might emerge when female labor is used intensively, as women are drawn away from food production [59].

However, actual involvement in biofuel activities (e.g. as paid labour in plantations, smallholder) can have radically different food security outcomes at the household/local level. Since biofuel expansion in SSA often happens in poor rural areas that mainly host subsistence agricultural activities, it is imperative to understand these household dynamics, if the real effect of biofuel on food security is to be understood.

At the household level there are two different mechanisms at play. On the one hand feedstock production competes for land, labour and agricultural inputs (Type III projects) while employment in plantations (Type IV projects) can divert labour from subsistence agricultural activities. This diversion of land, labour and agricultural inputs can have a negative effect to household food security. Conversely, smallholder feedstock production (as a cash crop) or employed work in plantations can provide income (Section 3.3.1.2), which can be used to buy food or agricultural inputs. In this respect household involvement in biofuel activities can potentially have a positive impact on household food security [30,237].

Regarding land competition, there have been reports of large-scale jatropha projects (Type IV) displacing subsistence agricultural activities [147,150,239], Section 3.3.2.[9] Such displacement, effects, apart from reducing the total amount of cropland, they can result in shifts of farming patterns [239] or relocation to areas with less favorable farming conditions [124]. They can also result in the loss of access to woodlands used for sourcing food [44,45,147]. Lower crop yields and loss of access to forest products due to land displacement can increase household dependency on external

[9] It should be mentioned that land displacement is not always a feature of large-scale biofuel project [237].

Table 7
Appropriate feedstocks and modes of production for each drivers of biofuel expansion in SSA.

Aim	Scale	Mode of production	Feedstock
Economic development	National	Type IV	Sugarcane
Poverty alleviation	National, local	Type III	Sugarcane and/or jatropha
Energy security	National	Type IV	Sugarcane
	Local	Type I–II*, or other biofuel end-uses such as cooking	Jatropha and/or sugarcane

*Few examples of successful Type I and Type II projects.

food sources, reducing thus food security at the household level [147]. When it comes to smallholder-based projects (Type III), land competition becomes immediately obvious as the land under feedstock production becomes immediately unavailable for food crop production. However, there are cases of smallholders that have been aware of this land competition and have acted conservatively when planting jatropha to avoid reducing their food production. For example, in Zambia despite suggestions to farmers to allocate 5 ha to jatropha production, most farmers allocated less than 2 ha [47,48]. In order to minimize such land competition effects, schemes in Malawi, Mozambique and Senegal have incentivized smallholders to grow jatropha in hedgerows on field boundaries rather than dedicating block areas within their fields [30,35,52]. Yet our experience from visiting such projects shows that some land is lost from food crop production.[10]

Regarding labour diversion, competition for labour may be a limiting factor in those smallholder households that maintain large areas for both jatropha and food crops [47]. Labour availability becomes a significant factor of whether households decide to be (or continue being) involved in smallholder feedstock production [68,69]. In parts of Ethiopia farmers already had live jatropha fences so jatropha projects could be seen as a new source of income, which would have had anyway some short of opportunity cost due to the diversion of labour [243]. When it comes to paid work in plantations, workers in Mozambique jatropha plantations have reported that they will simply hire additional labour to support their food crop production if their plantation work prevents them from having enough time to work on their food gardens [175,237].

Regarding income, as already mentioned the income obtained through paid work in plantations or through involvement in smallholder schemes can be important, particularly in remote rural areas where there are limited other income opportunities, Section 3.3.3. This income might contribute positively to food security especially after events that have reduced household food production (e.g. droughts) or if it comes at a point that any other harvesting activity had seized [30,44,45]. Such positive food security outcomes can be one of the largest benefits of biofuel expansion in SSA, but so far little available empirical evidence exists [182], as they are notoriously difficult to be captured [30].

4. Priority policy areas for sustainable biofuels in Africa

4.1. Align biofuel policies with national realities and wider policy objectives

When designing biofuel policies in SSA (and developing world contexts in general) it is important to have a clear understanding of (a) why biofuel promotion is pursued and (b) what is the true benefits that the available biofuel options can actually have. Different biofuel options can have radically different outcomes for economic growth, local/national energy security and poverty alleviation (Section 3). The evidence presented in Section 3, suggests that no single biofuel option currently available in SSA can meet simultaneously all these aims (Table 7). In this respect, carefully designed bioenergy/biofuel strategies will be needed in order to balance the, sometimes, conflicting policy drivers of biofuel expansion [1,27,28].

4.1.1. Economic development through feedstock export

Economic growth through the export of feedstock/biofuels to external markets (particularly the EU) has been an important driver of biofuel expansion in SSA (Section 1). To achieve this aim the development of an export-oriented production model must be seen as a priority. In this respect feedstocks and management practices that create economies of scale, increase yields and maximize returns on economic investment appear to be more appropriate, i.e. large plantations (Type IV projects) using proven feedstock such as sugarcane (Table 7).

For example the pre-eminence of the Brazilian sugarcane ethanol program has been linked to the constant consolidation and economic efficiency of large-scale sugarcane production, particularly in the state of Sao Paulo [12,13]. While, large-scale sugarcane ethanol production has shown some signs of success in Malawi (and Zimbabwe in the past), it has been largely confined towards supplying national markets. Export-oriented production models such as the large-scale production of sugarcane ethanol circumnavigating sugar production (e.g. Addax in Sierra Leone) are an exception. They pose a different business approach and should be monitored closely during their implementation in the coming years to ascertain whether they can be viable options in other parts of Africa [184].

On the other hand Type IV projects, using unproven feedstocks such as jatropha can pose significant production risk and be counterproductive in efforts to achieve economic growth through feedstock export. This has become evident following the collapse of several large-scale jatropha ventures across SSA that aimed to export to the EU, e.g. SUN biofuels (Tanzania), D1 Oil (Mozambique), GEM Biofuels (Madagascar) and Tozzi Green (Madagascar) among several others [30]. Other projects that initially aimed the EU market eventually reoriented to domestic markets when factoring the low yields, logistic costs and sustainability concerns, (e.g. Niqel in Mozambique) [30]. Recent studies further corroborated that large-scale jatropha production in Tanzania for domestic use and (certified) exports, will require high yields only possible at good soils and high fertilization inputs, and will be too expensive to compete with conventional diesel or rapeseed oil from the EU [64].

4.1.2. Rural development and poverty alleviation

A second driver of biofuel expansion in SSA has been the perceived potential of biofuels to catalyze poverty alleviation

[10] Although feasible to accommodate large numbers of jatropha hedgerows in typical smallholder settings in SSA, evidence from Zambia suggests farmers only created hedges around new fields carved out in the grazing commons [246]. This raises questions on the acceptability and scalability of such feedstock production methods.

through the generation of income and rural employment (Section 1). However, there are considerable uncertainties regarding the employment and income opportunities of the current biofuel pathways in SSA (Section 3.3.1).

Feedstock plantations offer employment and income (albeit both modest) to rural households (Section 3.3.1). Labour costs are key determinants of the profitability of plantations (Type IV projects), so in order to increase their economic viability they would need to either lower labour costs or increase harvest per unit time [62,64]. This would most likely disadvantage plantation laborers either through reduced wages or through reduced employment opportunities.

Actually as discussed in Section 3.3.1, overall broader rural development benefits might emerge through smallholder feedstock production (Type III) due to higher outreach or small-scale projects (Type I) or using jatropha for non-fuel purposes, e.g. soap-making [1,2,51,58,60]. On the other hand smallholder schemes have been blamed as passing the production risks to the smallholder [173]. For example, it has been demonstrated that the main reason behind the failure of the Senegalese biofuel program was the initial design, in which smallholders were encouraged to adopt jatropha with almost no extension support, poor quality planting material, and uncertain market prospects [185].

The above suggest that there cannot be a silver-bullet solution about which biofuel strategy could offer the greatest poverty alleviation benefits in a given local context. However there is some evidence to suggest that the more widespread poverty alleviation effects come from projects involving smallholders and/or the promotion of the local use of jatropha-derived goods (whether fuel or soap) when adequate technical and financial support is provided.

It would appear from the above that policies supporting smallholder-based feedstock production (Type III projects) will be key if biofuels are to become agents of poverty alleviation in SSA. Even though some large-scale plantations will be necessary to ensure the existence and stability of biofuels markets (Section 4.2), the policy environment should ensure that an active small-producer core supports the biofuel industry. Policy instruments could include small producer quotas, tax-relief based on small producer contributions or legislation requiring small producer contributions, e.g. [1].

4.1.3. National and local energy security

The third major driver of biofuel expansion in SSA has been energy security (Section 1). When aiming to enhance national energy security through biofuel use in the transport sector, then biofuels with high EROIs should be preferred (Section 3.1.2). Sugarcane and jatropha-based biofuels exhibit EROIs over 1, which suggests that both can offer net-energy gains and as an extension contribute to national energy security (Table 4). However, as a first-order approximation sugarcane ethanol seems to be a safer option when considering (a) the consistently higher EROIs of sugarcane ethanol (Table 4) and that (b) jatropha LCAs have often assumed optimistic yields potentially overestimating EROIs (Section 3.1.2).

Yet, diesel is a highly preferred fuel in SSA as a large proportion of transport energy consumption comes from non-passenger uses, e.g. freight transport and heavy machinery [17]. At the same time a large portion of the population across the continent has minimal access to modern fuels, depending almost exclusively on fuelwood and charcoal. This suggest that increasing biofuel use in the transport sector as a means of boosting energy security might not be the most effective (or socially desirable) approach. In contexts where local energy security overrides national energy security (e.g. poor and/or remote areas where modern fuels are very expensive), the deployment of biofuels for cooking (Section 4.10) or the development of small-scale biofuel projects for decentralized rural electrification (Type I projects) might be more appropriate.

Type I projects can theoretically improve local energy security and alleviate poverty if implemented properly in remote areas (or far from electricity grids) where fuel imports can be extremely costly. For example, the rural electrification Folkecenter Garalo project (Mali) used straight jatropha oil providing electricity to 350 homes (50% of Garalo village) and small local business stimulating the local economy, e.g. electricity sewing machine, powered tools for furniture makers, and training technicians [186]. A cost-recovery pricing system for the provided electricity was designed to allow long-term viability, but NGO support was supposed to cover operational expenditures in the early stages [52,187]. This support was removed in 2010 but sourcing sufficient local jatropha feedstock to run the project has proved problematic and it is not clear if the project was still operational at the time of writing this paper. Other similar projects have been operating in several other parts of Africa [49–52,188,231,232,237]. Despite their widespread publicity there is no evidence any of these projects has remained fully operational on biofuel when initial support ceased.

There are a few initiatives that have promoted biofuels as low-cost replacements to traditional biomass fuels. Such examples include ethanol stoves that could replace charcoal stoves in urban centres, e.g. Cleanstar (Mozambique) and GAIA Foundation (Ethiopia). Such projects could in theory increase the access of poor households to reliable sources of modern fuel having at the same time environmental and social co-benefits (Section 4.10). However the reality is different as such initiatives struggle to make a discernible large-scale impact.

The above suggest that on the one hand, projects that aim to promote local energy security do not need to have strong profit-oriented motives and basically need to only recover operating costs. On the other hand if they cannot achieve it without external support (usually from NGOs) they are bound to collapse in the long-run when this support is no longer available. Furthermore, such projects are sensitive to several factors, including feedstock yields, petroleum prices, labour costs and user preferences, with many of these parameters lying outside the control of investors [189]. Donors and local/national governments aiming to promote Type I projects or alternative biofuel uses, need to weigh carefully these parameters, as the collapse of such projects (apart from a waste of resources) might potentially have the negative social impacts witnessed in Types III and IV projects.

4.2. Develop viable markets for biofuels and their co-products

4.2.1. National markets

Strong national and regional agricultural markets are seen as a fundamental pre-requisite for developing African agriculture [57]. The lack of mature biofuel markets has been a key impediment to biofuel expansion in SSA [1], while it might have contributed to the collapse of large-scale jatropha projects in countries such as Zambia, Madagascar and Tanzania [30]. There are also several reports of smallholders farmers investing capital, labour and land into jatropha cultivation, but eventually being left stranded with unmet expectations and a trouble finding markets for their jatropha seeds [48,148,190,191].

Creating stable biofuel markets in SSA will be key if biofuels are to contribute to economic development and energy security. Biofuel mandates (Section 1) are powerful mechanisms for establishing biofuel markets, as they create a steady biofuel demand. By securing demand, mandates essentially reduce production risks to foreign investors and local producers. However, if mandates are to fulfill their potential as market creation mechanism, then appropriate infrastructure should also be in place to dispense effectively the biofuel across the producing country.

In any case the public sector is a major player for the development of national agricultural markets not the least through stimulating private sector investment through a conducive business environment, and developing infrastructure [192]. In contexts where greater private involvement is desirable then Public Private Partnerships (PPPs) can be effective means of promoting biofuel market creation [192].

Markets for biofuel co-products can further increase the economic viability of biofuel production. For example it has been suggested that the financial viability of jatropha biodiesel in Tanzania can increase if co-products are used to create additional revenue streams [236]. At this stage, the most promising biofuel co-product is sugarcane bagasse for electricity cogeneration in sugar mills.[11] For example, it has been suggested that increasing bagasse electricity cogeneration in Tanzania could contribute large amounts of energy, thus compensating for fossil fuels and reducing GHG emissions [194]. Apart from using this cogenerated electricity in the sugarcane mill, it can be sold (a) to local off-grid customers, or (b) to the national grid as surplus electricity from independent power producers [42]. To achieve this it is essential to provide incentives to sugar mills to invest in cogeneration technology and allow them to supply excess electricity to the public network through appropriate national policies such as attractive feed-in tariffs.

4.2.2. International markets

Biofuel policies in Africa are largely designed at the national level [1,20]. Yet such "introverted" biofuel markets can take a toll on the actual potential of biofuels expansion in the region. For example, countries such as Mozambique, Zambia and Zimbabwe have high sugarcane production potential [41] and can easily exceed their existing ethanol targets. However, their small vehicle fleets confine the size of their national biofuel markets. On the other hand, South Africa has by far the largest private vehicle fleet in SSA while at the same time has relatively low sugarcane productivity compared to some of its neighboring countries and has banned the jatropha production (Section 3.2.2). This means that there is huge potential for South Africa to import feedstock/biofuels from neighboring countries such as Mozambique and Zimbabwe. Furthermore to achieve high ethanol penetration regionally, the promotion of flex-fuel vehicles would be necessary (e.g. as in Brazil [12]), something that would be economically forbidding for most countries in the region to achieve in isolation.

Considering that Africa is moving towards greater economic integration, regional biofuel/feedstock trade could become an avenue for establishing viable biofuel markets [195]. This would require the development of appropriate trade policies through regional multi-lateral institutions such as the Southern African Development Community (SADC), the East African Community, the Common Market for Eastern and Southern Africa and the African Union. Furthermore, the development of regional biofuel markets could make technologically and economically feasible the modernization of vehicle fleets in small and poor biofuel-producing countries [196].

[11] Other promising biofuel co-products include jatropha seedcake (for fertilizer, methane production and fodder if detoxified), sugarcane residues (for fodder) and the multiple waste streams of cassava production [193]. Less promising is vinasse as a fertilizer. However, these by-products are usually low-value and returning them to farmers (or other users) might require complicated logistics that can reduce the overall cost-effectiveness of biofuel production [30].

4.3. Base feedstock selection on proper agronomic knowledge

Despite high initial expectations and an aggressive expansion phase, the jatropha hype has fizzled in SSA [30,44,65,197]. The key reason behind these unmet expectations has been the low yields achieved by several projects, as jatropha is practically an undomesticated crop. It has been suggested that lack of understanding of jatropha physiology and growing conditions resulted to the communication of incomplete knowledge to investors, governments and local communities, and played a major role to the subsequent widespread collapse of jatropha in SSA [30,198,249].

Thus, the improvement of seed quality and quantity is an important breeding goal, but efforts for the improvement of jatropha germplasm and trait characteristics are still in their infancy [199,250]. Most (if not all) jatropha projects in SSA used wild and unimproved jatropha varieties which in our view it will take a toll on the yields of the projects that have not already collapsed for years to come.

Taking the above into consideration, if biofuels are indeed the preferred means to support agroindustrial development in SSA (see Section 4.1), then well-proven crops such as sugarcane should be prioritized before crops whose potential is uncertain such as jatropha, (e.g. see [249] for other crops). These alternative crops should only be prioritized once their potential is proven, which will require significant research and development efforts (Section 4.4). Towards this end, policies should "demand" national-level testing as well as stimulate the breeding of new feedstock varieties in order to ensure that planting stock is of a standard that can ensure adequate yields in the long-term. As an extension, it is prudent to reconsider the promotion and the allocation of land to jatropha until sufficient data demonstrate that a jatropha-based biofuel industry will be technically, financially and ecologically viable, even if based on more moderate expectations [30,237]. Finally, the provision of agricultural extension activities to smallholders can be key to allow them adopt effectively a new crop. Many individual biofuel projects (or even national policies) failed because farmers were not given enough information to get the best from their land and crops, e.g. [185].

4.4. Foster innovation in the biofuel sector

Technological innovation both in the supply- and the demand-side has been an important catalyst for the success of sugarcane ethanol in Brazil [200]. Certain innovations in the supply-side have also contributed to the success of the sugarcane ethanol sector in Malawi [22]. Thus, technological innovation could be crucial for unlocking the true potential of biofuels in other SSA countries. This applies to existing first generation (including underutilized biofuels, Section 2.1), as well as second-generation biofuels [192]. Some key target areas for innovation in the biofuel sector include:

- maximize feedstock production from biofuel landscapes;
- optimize biofuel recovery from feedstock (and waste);
- develop cheap and cost-efficient alternative biofuel uses for the rural and urban poor (Section 4.10); and
- develop novel production approaches, increasing equity and ownership in the entire value chain (Section 4.7).

Research and Development (R&D) activities should focus on the development of feedstock varieties that are suited in the specific agroecological zones of SSA and can produce high yields. This is pressing not only for jatropha (Section 4.3), but also for other underutilized feedstocks that are gaining attention (Section 2.1), [249]. Strategies to combat feedstock crop diseases in a preemptive and cost-efficient manner will further reduce production risks to feedstock producers [201]. Another interesting aspect will be to develop integrated biofuel production platforms that optimize biofuel production from feedstock and waste streams [193,202]. A potentially rewarding R&D activity could be to harness non-toxic jatropha varieties, as this might allow the direct use of jatropha seedcake as a co-product, livestock feed, potentially increasing the economic competitiveness of jatropha production (Section 4.2).

Whatever are the R&D priorities in SSA, the development of successful R&D systems[12] would most certainly require increasing R&D spending and coordinated actions between national governments, industry and academia. Currently, it will be challenging to mobilize the needed resources as biofuels have been the only renewable energy sector that reduced consistently its R&D expenditure following the 2008 financial crisis with so signs of reversing this trend [20]. However, PPPs might be a successful arrangement to mobilize financial resources to drive scientific research and innovations in SSA [192].

Another way to promote biofuel innovation, at least for sugarcane ethanol, can be through the stronger bilateral cooperation with Brazil. Brazil is actively working towards making ethanol a global agricultural commodity. This entails boosting sugarcane ethanol production in other parts of the world[13] through the transfer of technical expertise and technology, including in SSA countries such as Ghana, Angola, Mozambique and Kenya [15,16]. Stronger cooperation between African and Brazilian actors could allow the transfer of ethanol technology and know-how, which could allow SSA countries to leapfrog their sugarcane ethanol production capabilities.

In our view in national contexts that smallholder projects are prioritized (Section 4.1) “technology delivery” innovation systems should be avoided. In such innovation systems producers are mere recipients of better seeds (or knowledge) from experts, with their knowledge considered an exogenous factor to the innovation process. On the other hand, integrated innovation systems such as the “capacity to innovate”, can offer greater benefits as they involve in the innovation process public and private actors with vested interests in biofuel production [205].

It is worth mentioning that biofuels can become a driver of innovation (eco-innovation) in their own right, as has been the case of ethanol in Brazil, e.g., neat ethanol and flex-fuel vehicles [200]. However, this would require developing substantial absorptive capacity nationally (Section 4.2) and competences for export success (Section 4.1.1). With the possible exception of South Africa, the current potential of biofuel-driven eco-innovation in SSA is negligible [206].

4.5. Prevent speculative and predatory corporate behavior

It seems that some of the risky investments associated with the jatropha hype of the mid-2000s, have been the result of speculative/predatory corporate behavior. Most likely this speculative behavior can be linked to the expectation of high profits despite the inadequate understanding of the plant's physiology and lack of commercial cultivation experience (Section 4.3). This was eventually a key reason behind the eventual collapse of most large-scale investment in the region such as D1 Oils, Sun Biofuels, and GEM Biofuels among several others [30]. In other cases, biofuel production might have been just an excuse to cover other activities, e.g. illegal hardwood harvesting as was allegedly the case for Bioshape in Tanzania [124].

This speculative behavior was not only confined to large-scale projects, but was also a feature of smallholder-based projects, which eventually left farmers hold the majority of the risk. A comparative study of smallholder-based sugarcane projects found that land rights were poorly negotiated, contracting agreements were in some instances informal and there was an unbalanced power between workers and companies [157]. Specific corporate practices have been highly criticized [48]:

- approach potential outgrowers with high expectations and minimal awareness of the possible risks associated with returns on investment;
- draft one-sided contractual obligations (i.e. agreements signed by farmers but not the company); and
- require farmers to keep land under jatropha for 30 years and sell only to Marli allowing the company to set prices unilaterally.

Such speculative and predatory corporate behavior had demonstratedly negative impacts to the livelihoods of local communities (Section 3.3.2), caused direct financial losses to the shareholders of collapsed ventures and might have even led to a complete discredit of potentially viable biofuel projects, e.g. Bedford Biofuels in Kenya [238].

Policies at the national level should ensure that future biofuel ventures, particularly foreign-led, must concretely exhibit their future economic viability before being allocated land and commence operations. This means that SSA governments need to strike a fine balance between providing incentives for attracting foreign investment in the agricultural sector (e.g. Section 4.1), and at the same time ensure that these investments will fulfill their promised potential.

Overall a better regulation of the biofuel sector (and aligned sectors such as agriculture, transport, forestry) will be needed. Drafting appropriate national biofuel plans can be a good starting point as it has been suggested that such governance frameworks could increase transparency for investors by (a) providing clear guidance on the design of biofuel investment proposals, and (b) by facilitating transparent and timely handling of proposals by the government [18,207]. Although such frameworks may restrict specific business activities, they may also improve the investment climate by being explicit about minimum requirements and consequences of non-compliance [18,207]. Considering that access to financing is a major barrier to bioenergy project in SSA [208], such governance frameworks can include economic/financing incentives to biofuel ventures that demonstrate their true potential.

The above instruments can be complemented by the mandatory use of independent audit mechanisms that can scrutinize the viability of the proposed business plans based on the best available evidence and a clear compensation regime in the event that biofuel projects fail. In any case the strong enforcement and monitoring of these proposals can go a long way towards curbing speculative corporate behavior and reducing the risk of exposing poor households to the failure of biofuel projects.

[12] Perhaps the only successful biofuel innovation system has been that of Brazilian sugarcane ethanol. The system is centered in Sao Paulo State and has been largely privatized since the 1990s [203]. It resulted in a three-fold increase of ethanol recovery per sugarcane hectare; i.e. from 2000 L/ha in the late 1970s, to more than 6000 L/ha nowadays [204]. Key innovations include the development of sugarcane varieties better suited to Brazilian climatic conditions, the cogeneration of power from bagasse and improvements in sugar extraction, vinasse recovery and alcohol fermentation [203]. Simultaneous innovations in the automotive industry such as the development or neat ethanol and flex fuel-vehicles further catalyzed the penetration of sugarcane ethanol in the Brazilian transport sector [12].

[13] Brazil as the largest global ethanol exporter has for long aimed to export sugarcane bioethanol in the protected US market under favorable terms. This would require the formation of an international ethanol market, which essentially entails the diversification of ethanol production to other countries [13,14].

4.6. Include broader sustainability considerations in biofuel policies

Most of the priority policy areas discussed above (e.g. Sections 4.1.1 and 4.2–4.5) essentially aim to enhance the economic viability of biofuel investments. Economic viability is certainly an important factor that can affect the overall sustainability of biofuel projects,[14] as it reduces risks associated to the collapse of biofuel projects that can ultimately leave local communities and investors worse off. Yet, environmental and social concerns are largely absent from biofuel policies in SSA (Section 1), despite the fact that their importance has been acknowledged by certification schemes such as the Roundtable on Sustainable Biomaterials and Bonsucro [209,210].

This review has gone at great lengths to unravel the multiple environmental and social impacts linked to biofuel expansion in SSA (Sections 3.2 and 3.3). In fact it is not uncommon for decision makers and local communities in SSA to articulate broader sustainability concerns related to the environmental and social performance of biofuel projects [18,198,211], even though, such sustainability framings are different between stakeholders along biofuel chains and can change over time [211].

The above suggest that it is important to articulate broader environmental and social criteria in biofuel policies across SSA. These criteria should be chosen according to the specific national context and the other overarching policy objectives (Section 4.1). Good starting points would be to include policy provisions that aim to:

- protect the land rights of local communities (Sections 3.3.2 and 4.7),
- minimize food–fuel competition (Sections 3.3.3 and 4.8) and
- phase out and ban harmful environmental practices (Sections 3.2.2 and 4.9)

A precautionary bias for key issues such as food security, land tenure and ecological degradation can be a powerful mechanism to avoid negative biofuel impacts in SSA when evidence is lacking.[15] Enforcing strong monitoring mechanisms during the implementation of current biofuel projects/policies can go a long way towards capturing the occurrence of secondary impacts and unintended consequences, whether positive and negative.

Additionally, there should be efforts to adopt a life-cycle mentality in biofuel policies, as some biofuel impacts manifest in different stages of the biofuel chain (e.g. Sections 3.2.1 and 3.2.3). We believe that a life cycle mentality will make clearer to decision-makers the trade-offs associated with biofuel production and use. Even though it might be possible to achieve win-win solutions, stakeholders should be aware (and have the capacity to be informed) that this might not always be the case. Demanding the life cycle-based understanding of the environmental and socioeconomic impacts of biofuel projects can provide the basis for transparent and evidence-based decision-making.

Finally, apart from inclusive (i.e. include economic, environmental and social provisions), biofuel policies should be reflexive and able to deal with unintended consequences that may be an outcome of even the best of policy intentions.

4.7. Safeguard land rights and minimize the potential for land-grabbing

Biofuel projects can compromise the access of local communities to agricultural or forest land (Section 3.3.3). The process of transferring communal land rights to private interested for large-scale feedstock production (Type IV projects) has been identified as particularly problematic (Section 3.3.3).[16]

Customary landowners that face the greatest risk tend to be in countries where land transfers entail [166]:

- the conversion of customary to state land (in these contexts the initial land negotiations inadvertently shape future livelihood outcomes);
- no upper limit of land area acquired (in these contexts land is locked for outside users, irrespective of its economic use or the area actually planted); and
- leaseholds of long duration

Land tenure policies in SSA countries should be amended so as to allow for the appropriate compensation of communities that transfer land for the establishment of large-scale biofuel projects [172], or to regain land tenure if such projects fail. The latter can be particularly contentious but must be a pre-requisite in those countries that promote untested and collapse-prone feedstocks such as jatropha (Section 4.3).

Another option would be to allow lease agreements directly with local communities rather than with national governments.[17] In these cases there is a need to ensure that local communities have access to good information and are in a position to negotiate under favorable terms with biofuel investors [164]. Mechanisms such as village land trusts or equity-based joint ventures may be appropriate for this purpose [124].

Regulating the maximum size and time of lease of the core estate in large-scale biofuel projects [166], and requiring part of their production to be met by outgrowers (e.g. Dwangwa sugarcane project, Malawi) can also reduce potential problems with land tenure. Finally, it is worthwhile to explore novel feedstock production business models that go beyond the prevailing land acquisition paradigm [241]. For example there have been examples of farmers pooling their land to establish private commercial ventures (becoming shareholders themselves in the process) and sharing the dividends of what becomes large-scale feedstock production scheme (Type IV), e.g. SWADE sugarcane project in Swaziland.

4.8. Minimize food–fuel competition

Dealing with the root causes of food insecurity in SSA is a priority development target, but at the same time it is fair to say that most of the food insecurity problems in SSA predate the period of biofuel expansion. However, there is no doubt that all current biofuel options in SSA can compete directly or indirectly with food production, thus having potentially negative effects on national and local food security (Section 3.3.3). On the other hand the income received through involvement in biofuel activities such as paid work in plantations or selling of feedstock as a cash crop can increase household food security by preventing rural households from selling their subsistence crop production when cash is needed, or even allow them buy food in times of need [237]. Yet we must be also conscious that biofuel-related food security outcomes can be felt differently across different societal groups.

[14] e.g. Principle 2 of the Roundtable on Sustainable Biomaterials (RSB) certification criteria [209].

[15] An example of precautionary reasoning in biofuel policy has been the ban of jatropha in South Africa over fears of its invasiveness (Section 3.2.2).

[16] It is important to note that issues related to land tenure and loss of access to land are not confined to biofuels. In fact they tend to be a common feature of most large-scale agro-agricultural investments in Africa, biofuels included [242].

[17] It should be pointed that local elites may not always play a constructive role in such negotiations. For example local chiefs by playing their traditional roles in the acquisition of land and as arbitrators were in most instances the cause to land-related conflicts associated with large-scale jatropha projects in Ghana [240].

For example even moderate changes in domestic food prices can affect severely the food security of poor urban households.

In this respect the actual food security outcomes of biofuels can be positive or negative depending on a series of factors and local circumstances (Section 3.3.3). Detailed food security studies at the local/household level in SSA are largely missing or are incomplete [182,237]. Yet, while it is difficult to delineate the links between biofuels and food security, at the same time it is important in the face of this uncertainly to ensure that biofuel expansion will not affect food security in SSA.

At the national level, biofuel policies must include explicit provisions that prohibit (or restrict the level of) feedstock production in high quality agricultural land unless the long-term economic viability of biofuel investment and the positive food security spill-over effects are concretely shown. In tandem, there should be coordinated efforts to increase agricultural productivity both in the food and the biofuel sector. Foreign exchange savings and earnings from biofuel trade could potentially contribute funding towards this end, e.g. by assisting the purchase of agricultural inputs (fertilizers, tractors) in food insecure areas or fostering national biofuel innovation systems (Section 4.4). Food security can also be linked to securing the land rights of customary landowners so policies that strengthen these rights are essential (Section 4.7). Furthermore, modeling studies have suggested that only modest improvements in female education and food crop yields can increase food security and ensure broad-based benefits from biofuels investments [59].

Measures at the individual project level can also enhance local food security. For example in areas of high dependence on subsistence agriculture and high food insecurity, biofuel companies can hire only one person per household, making thus sure that there will be sufficient labour to tend to family farms. Biofuel firms can also allow their workers to have more flexible schedule during important periods of the crop calendar (e.g. cultivation, harvesting). In smallholder projects some feedstocks such as jatropha could be grown as hedges at the boundaries of farms, reducing but not completely removing, land competition with subsistence agricultural production. Finally information should be made available in advance about the actual food security outcomes of household involvement in biofuel chains, particularly smallholder feedstock production (Type III projects). For example it has been suggested that enterprise diversification can increase the food security of sugarcane smallholders in the Nyando District (Kenya) [213].

4.9. Phase out and gradually ban harmful environmental practices

Some agricultural management practices associated with sugarcane and jatropha production, including the large-scale conversion of natural habitats, agricultural burning and agrochemical use, have been shown to be dangerous to ecosystems and public health [2,55], Sections 3.2 and 3.3. For example, excessive fertilizer use in sugarcane farms in Kenya resulted on elevated heavy metal concentration on topsoil, above international standards [214]. Dangerous pesticides residues (e.g. DDT, HCHs) in sugarcane plantations in Tanzania were linked to past agricultural practices [215], while erosion risk was found to depend on crop management practices (particularly planting and harvesting) [216]. On the other hand it has been suggested that some management practices such as growing feedstock in hedgerowns (jatropha) can harbor higher levels of biodiversity when compared to block plantations (jatropha/sugarcane) [44,118].

As a means of increasing the environmental performance of biofuel projects, producers should be incentivized to phase out and gradually ban harmful agricultural practices. Some key policy provisions could include the ban of dangerous agrochemicals or to require large-scale biofuel projects (Type IV projects) to protect areas of high conservation value within their estates. Exploring the invasive risks posed by jatropha in areas of potential expansion will also be necessary, even though cost-effective risk assessment tools to decide it ex-ante are largely missing [126].

Such provisions can be supported by the mandatory use of strategic environmental assessment (SEA), environmental impact assessment (EIA) and social impact assessment (SIA), particularly when large-scale biofuel projects are established. Even though such instruments are required in several SSA countries for large-scale biofuel projects, they are sometimes poorly implemented. For example, biofuel EIAs have been blamed as failing to consider important local issues or meaningfully involve local communities [164]. EIAs of jatropha and sugarcane projects in Tana Delta (Tanzania) have been blamed for dealing inadequately with local hydrological, biodiversity and socioeconomic issues [100].

Efforts to enhance the environmental performance of biofuel projects could be further boosted by providing incentives to certify feedstock/biofuel through independent third-party certification schemes such as the Roundtable on Sustainable Biomaterials (RSB) or Bonsucro [209,210]. Certification can ensure the adoption of some short of environmentally benign feedstock production practices and is becoming a requirement for biofuel/feedstock exports in the EU. Yet it is not standard practice for the feedstock/biofuel set to be consumed domestically in SSA producing countries.

However, reducing some of these harmful environmental practices might entail socioeconomic trade-offs. For instance switching from sugarcane burning (responsible for large atmospheric emissions) to mechanical harvesting, might reduce job opportunities [12,83]. Understanding such trade-offs is important when designing biofuel policies that include broader sustainability considerations (Section 4.6).

4.10. Promote biofuel end-uses that have social and environmental co-benefits

Non-transport biofuel uses such as cooking and lighting could have important environmental and social co-benefits [217]. These co-benefits largely manifest through the displacement of conventional cooking fuels such as fuelwood and charcoal, which are the main energy sources of the urban and rural poor in SSA [17,218,219]. However these traditional fuels also pose a major public health hazard, as they degrade indoor air quality causing an estimated 400,000 deaths annually in Africa [218]. Ethanol (both straight and gel) combustion does not cause the respiratory problems associated with paraffin, charcoal, and firewood [220]. Studies in Ethiopia have shown significant decreases in the emissions of PM2.5 (84%) and CO (76%) from ethanol stoves when compared to conventional stoves [221]. Considering the safety and health co-benefits of ethanol stoves, middle- and high-income households in Ethiopia were willing to pay small premia [222]. Regarding lighting, substituting paraffin in lamps with jatropha-based fuel can reduce emissions for some pollutants but increase the emissions of others [223].

Charcoal and fuelwood are also significant drivers of deforestation in SSA, contributing to biodiversity loss and GHG emissions through LUCC effects [224,225,226], Sections 3.2.2 and 3.2.3. Switching from such environmentally destructive cooking fuels to ethanol (both in urban and rural settings) could potentially decrease deforestation with ripple biodiversity conservation co-benefits. For example, at current production/conversion rates an estimated 60,000–80,000 ha of sugarcane would be sufficient to provide the ethanol that could replace the entire charcoal market in Tanzania, which is responsible for about 400,000 ha of deforestation per year [227].

A few pilot projects have promoted such alternative biofuel uses in Ethiopia, Tanzania and Mozambique [222,228]. However more significant and coordinated policy intervention would be required to facilitate a large-scale transition from charcoal and fuelwood, to biofuels for cooking and lighting.

If the benefits of biofuel expansion in SSA are to be maximized, such environmental and social co-benefits should be identified and promoted to the extent possible through appropriate policy instruments. The main biofuel policies in SSA are blending mandates (Sections 1 and 4.2), which are indifferent or even act as a hindrance to establish strong demand for non-transport biofuel end-uses (Section 4.2).

This would require a different approach to the development of biofuel mandates. A first step would be to identify which of these end-use technologies can meet actual local needs, and the product-specific and socioeconomic factors that can enable or prohibit their large-scale uptake [222]. This is particularly important, as the factors that influence the uptake of improved fuel stove technologies can be multiple and not easily delineated [229]. As second step would be to establish appropriate incentives for the uptake of these technologies, as high capital cost are usually the key barrier for their effective introduction [230]. Low-income households are also extremely sensitive not only to higher stove prices, but also to increases in fuel costs even when efficiency is improved [222]. Removing taxes from stove ethanol fuel as well as supporting the distribution of stoves through state-sponsored programmes could boost their uptake. Incentivizing through tax breaks (or other financial incentives), large-scale ethanol producers to disseminate stoves as a corporate social responsibility strategy (e.g. Mumias Sugar Industries, Kenya) could further facilitate the uptake of ethanol as a clean cooking fuel.

5. Key lessons learnt

Despite the strong policy imperatives such as energy security, poverty alleviation and economic development that have driven biofuel expansion in SSA (Sections 1 and 4.1), it seems that biofuels have so far underperformed. The jatropha system has almost completely collapsed in the region while sugarcane ethanol is taking a much longer period to make an impact. The type and the magnitude of biofuels' environmental and socioeconomic impacts have largely been context-specific, varying significantly across Africa (Section 3). Yet, some salient observation can be derived from the present study.

First, is that the post-2000 biofuel expansion in Africa has largely been stimulated through direct foreign investment for jatropha projects. These biofuel ventures initially aimed to export feedstock to overseas markets, mainly in Europe, but eventually shifted their focus to domestic markets as the biofuel production in SSA became either uncompetitive or failed to meet the sustainability criteria raised by European consumers (e.g. GHG emissions, deforestation).

Second, is that biofuel expansion in most SSA countries happened without any established policies to regulate it. There were few binding provisions to regulate biofuel investments while the institutions that were supposed to safeguard communal land rights were rather weak. This seems to have encouraged speculative and predatory corporate behavior, with the subsequent collapse of most early jatropha projects having negative impacts on local communities. This means that SSA governments need to strike a fine balance between providing incentives for attracting foreign investment in the agricultural sector, and at the same time, ensure that these ventures are economically viable, will provide the expected local jobs/income, and will respect land tenure agreements with local communities.

Third, is that biofuel expansion in most SSA countries was spearheaded by jatropha. There was no commercial experience with jatropha growing in the region, while there were major knowledge gaps about the expected yields, optimal growing conditions, pests and economics of production. This lack of information plagued most, if not all, jatropha projects and has been a major contributor to the collapse of the jatropha industry in SSA. In retrospect these project collapses have been the most catastrophic aspect of biofuel expansion in SSA and in our opinion they will cast a heavy shadow on any future biofuel efforts in the continent.

Fourth, is the immaturity of viable biofuel markets in SSA. Biofuels/feedstocks (whether for domestic use or exports) were essentially new commodities in SSA. As a result, markets for biofuels (and their co-products) were not in place, which meant that there was a process of experimentation. This market development phase (particularly for jatropha) is not uncommon for industrial crops but raises important questions about the fairness of who should face the risks for this experimentation period. In several cases these risks were left to smallholders. Yet, the collapse or underperformance of most smallholder-based projects in Zambia, Tanzania, Malawi, Senegal, Mali and elsewhere has shown that there can be huge opportunity costs for local communities during the creation of biofuel markets.

Fifth, is the high reliance of rural populations in SSA on ecosystem goods and services. This implies that understanding the environmental impact of biofuels is a pre-requisite for understanding their true poverty alleviation potential. Some of the emerging trade-offs are likely to be complex, with potentially non-obvious feedbacks that can manifest in different spatial scales (e.g. household, local or national scales).

Sixth, is the lack of comparative studies of biofuel impacts in the region. Our review identified not only the incomplete understanding of certain biofuel impacts, but also the critical lack of comparative studies between different biofuel feedstocks and modes of production. Such studies are necessary for identifying the emerging biofuel trade-offs in SSA. We recommend (a) to synthesize the currently available knowledge in an integrated manner and (b) to develop appropriate tools for assessing the impacts of biofuel projects [212]. Developing this knowledge basis will be essential if we are to unravel successfully the actual impacts of biofuel production and use in the region.

Seventh, is the need to involve multiple actors in efforts to develop effective biofuel sustainability strategies. Involving multiple actors during the different stages of the development of governance framework is essential for the credibility, legitimacy and relevance of the governance process among the different actors.

Eighth, is the role of the academic community. Academics seem not to have been fully prepared for providing appropriate policy advice about the feasibility and impacts of biofuel expansion in SSA, particularly for jatropha. Most of the early academic studies about the potential benefits of jatropha were highly optimistic at best, or deeply misleading at worst. Macroeconomic and LCA studies made use of highly inflated jatropha yields, suggesting high positive development benefits [30]. In retrospect academics should have been better tuned with the early biofuel developments in the continent and more involved during the development of biofuel policies.

Ninth, biofuel sustainability is a multi-faceted concept that requires the development of intricate policy frameworks (e.g. Phased Biofuel Development Strategies, [1]) across several government ministries. Such policy frameworks must not only target the development of the appropriate infrastructure or provide the incentives for biofuel production, but must also foster technological innovation and include provisions for curbing the potential negative aspects of biofuels on the environment and society. However, there are high uncertainties and knowledge gaps for certain biofuel impacts, as well as a lack of appropriate integrated and policy-relevant assessment tools [55,212].

6. Conclusions

There has been a large interest for jatropha- and sugarcane-based biofuels in SSA since the mid-2000s. Biofuel expansion was driven across Africa by strong policy imperatives such as energy security, poverty alleviation and economic development. Different stakeholders ranging from national governments, to international development agencies, NGOs and the private sector have had strong vested interests in biofuel development. These competing interests largely dictated the different feestocks (i.e. jatropha, sugarcane), modes of production (i.e. large plantations, smallholder/outgrower schemes) and end-uses (i.e. transport, rural electrification, cooking) eventually adopted.

At the same time biofuel expansion had a number of environmental and socioeconomic impacts such as GHG emissions, water availability/pollution, deforestation, biodiversity loss, poverty alleviation, energy security, loss of access to land and food security to name just a few. The nature and the magnitude of these impacts has largely been context-specific and has varied significantly across SSA.

Factors that have influenced the environmental and socioeconomic performance of biofuel projects, include among others: (a) the feedstock, (b) the mode of biofuel production/use, (c) the previous land use and the agricultural practices adopted during feedstock production; (d) the location of biofuel production and use (i.e. environmental and socioeconomic context), (e) the stage of the biofuel's life-cycle and (g) the policies in place during biofuel production, use and trade.

However, it seems that biofuels have so far underperformed in SSA. The jatropha system has almost completely collapsed while sugarcane ethanol is taking a much longer period to make an impact. Through this extensive review of the literature, we identify ten priority policy areas that should be targeted if the sustainability of biofuel production and use is to be enhanced in SSA:

- align biofuel policies with national realities and wider policy objectives;
- develop viable markets for biofuels and their co-products;
- base feedstock selection on proper agronomic knowledge;
- foster innovation in the biofuel sector;
- prevent speculative and predatory corporate behavior;
- include broader sustainability considerations in biofuel policies;
- safeguard land rights and minimize the potential for land-grabbing;
- minimize food–fuel competition;
- phase out and gradually ban harmful environmental practices;
- promote biofuel end-uses that have social and environmental co-benefits.

As a final note, it is imperative for African policymakers to acknowledge the national and local context within which biofuel production and use is going be pursued. Acknowledging this context, the competing interests at stake and the tradeoffs involved, can go a long way toward designing effective biofuel policies to unlock the true potential of biofuels for Africa.

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