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Comparative analysis of key socio-economic and environmental impacts of smallholder and plantation based jatropha biofuel production systems in Tanzania

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ABSTRACT

Two jatropha business models are compared on seven key sustainability areas of concern, which are operationalized into various quantitative and qualitative indicators. The assessment is based on two Tanzanian real-life cases, a wide range of primary and secondary sources are used. Results indicate that both the decentralized smallholder model and the centralized plantation model can lead to positive socio-economic and environmental impacts, but substantial differences are also apparent. The smallholder model scores better on land rights, GHG balance and biodiversity and it reaches more people, whereas the plantation model creates more employment and higher (local prosperity) benefits for smaller numbers of people, and could lead to higher yields. Negative impacts of the smallholder model are minimal, whereas the plantation model could lead to decreased food security, loss of land rights and biodiversity. This could permanently affect the livelihood situation of the local population, but this is not inevitable as there is considerable scope for implementing mitigating policies. The way in which a particular model is implemented in practice, its management and company values, can have a major influence. However, the biggest hurdle towards achieving sustained positive societal impacts in both models is their marginal profitability at current yields, costs and prices. Still, these results are highly sensitive to uncertain yields and oil prices. Better outcomes in the future are therefore not foreclosed. A reliable sustainability assessment requires many location-specific and operational company data. More quantitative indicators are ideally required to improve assessment of social impacts and effects on environment.

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1. Introduction

The use of biofuels can potentially contribute to climate change mitigation, rural development and energy security.

One source for biofuel is jatropha, a perennial shrub that grows pan tropically, whose seeds contain oil that can be used as a diesel substitute. Early this century jatropha attracted a great deal of attention by investors [1–4]. Allegations about

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yields of up to 10 t seeds ha⁻¹ [5], or 5 t seeds ha⁻¹ on average [6], low nutrient requirements, and little need for care in combination with ability to withstand semi-arid conditions raised high expectations regarding its Straight Vegetable Oil (SVO) and biodiesel potential [7]. But the realized plantings have been much more modest. The global financial crisis caused difficulties in financing. More accurate research also emerged, warning that realistic yields from an undomesticated crop would be only around 1000 kg seeds ha⁻¹ [8], and that the crop would not perform in poor conditions without adequate nutrient and water management [9]. Concerns were also raised about socio-economic impacts of large plantations, especially local food security [10,11]. Positive livelihood impacts on smallholders also began to be questioned, mainly due to severely disappointing yields [12].

However, that does not mean that jatropha projects cannot have positive effects at all. So far, study results have remained inconclusive, partial, and in mutual disagreement on many fronts. There is a definite lack of studies assessing project sustainability comprehensively. For instance, although several studies have reviewed agronomic aspects, livelihood impacts and/or the economic viability of several jatropha case studies [7,13–16], they have not examined ecological impacts. Other studies have looked at environmental aspects [17,18] and land rights [19], but without assessing economic viability. Comparisons of the two most common business models, plantations and smallholder systems, are particularly scarce, although some studies suggest major impact differences [7,20,21]. One major obstacle is that big plantations are wary to share key financial performance data. Only a few studies, all focused on Mozambique, have reviewed impacts by large plantations [22–24], but these studies are not comparative since hardly any smallholder projects operate there. Broadhurst's Tanzanian study [25] is a good comparative attempt, but his study lacks an economic viability assessment. Many studies also have not used systematic qualitative and quantitative impact indicators.

This article aims to conduct a methodologically rigorous and detailed comparative assessment of the major socio-economic and environmental impacts caused by two major different jatropha business models, using two projects operating in Tanzania as case studies: a large centralized plantation and a smallholder (hedge) system organized around a central processor. In order to create a comprehensive and yet practically applicable list of sustainability indicators, we identified “seven key areas of concern” that are mentioned by different sustainability certification initiatives. For each of these, qualitative and – as much as possible – quantitative impact indicators were formulated. Data were drawn from a wide range of published and grey literature, company documents, personal interviews, satellite data and own field measurements. A mix of quantitative and qualitative methods was used to assess the impacts of the projects according to the chosen indicators. This included, among others, detailed financial feasibility estimations and GHG estimations, including land use change effects. Primary data collection took place in May–August 2010 at the plantation company and during 2006–2010 at the oil processor that coordinates the smallholder system.

The principles, criteria, indicators and methods used in the analysis are described in Sections 2.1 and 2.2. Then follows a description of the plantation and smallholder-based models

in Section 2.3. Section 3 presents the results of the analysis for each of the seven areas of concern. Section 4 contains the discussion and conclusions. Methodological details and background statistics are provided in the online [supplementary material](#).

2. Approach and methodology

2.1. Selection of principles, criteria and indicators

The principles/criteria and indicators/parameters shown in [Table 1](#) were derived from various certification initiatives, policy documents and scientific literature in which the sustainability of bioenergy systems is researched (see Ref. [26] for a comprehensive review of such initiatives in 2010). In some certification systems a distinction is made between (more general) principles and (more specific) criteria. However, this distinction is often vague; therefore we use a combined category “principles/criteria”.

A large number of certification initiatives are being developed and applied. These initiatives vary with respect to scope, issues addressed, and criteria and indicators included. Our focus is on widely recognized frameworks such as: the Cramer criteria [27,28] operationalized in the NTA8080 [29], the Roundtable on Sustainable Biofuels (RSB) [30] and the Global Bio Energy Partnership (GBEP) [31]. We also examined the Renewable Energy Directive (RED) of the European Commission [32], the Position Paper of the WWF with options to promote sustainability [33] and the Draft National Biofuels Guidelines of Tanzania [34]. The RSB is currently considered as one of the most widely acknowledged and most comprehensive certification schemes [26,35,36]. In July 2011, the European Commission officially recognized its compliance with its Renewable Energy Directive 2009/28/EC [37–39]. The GBEP has compiled 24 sustainability indicators (May 2011) which are currently being operationalized and also widely acknowledged [31,40]. We deliberately did not confine ourselves to using one specific system, as this would be arbitrary and might result in a potentially biased assessment. Moreover, socio-economic impacts of bioenergy production are hardly included in existing initiatives, despite serious concerns [26]. We did want to address socio-economic issues in this study.

First, the areas of concern were identified that are most frequently mentioned in these certification initiatives and in the scientific literature (see [41,117] for an overview of all potentially relevant areas of concern). A few of those, especially water, soil, air and gender issues, could not be taken into account in this study due to data constraints for the two projects in Tanzania and a lack of suitable indicators. For each chosen area of concern one or more principles/criteria were then selected ([Table 1](#)).

For each principle/criterion one or several concrete, measurable indicators were defined or compiled, which are used to evaluate to what extent the principles/criteria are met. For working and labour conditions, only compliance or descriptive indicators were selected because it is not possible to compile measurable indicators for this area of concern (see e.g. Ref. [48] for a discussion about the use of indicators). The selection and formulation of principles/criteria and the definition of indicators are detailed below for each area of concern.

Table 1 – Overview of principles/criteria, indicators/parameters, method of analysis, and data sources used in the analysis (sources: [27,31–34,39–42]).

	Principle/criteria	Indicators/parameters	Analysis	Data collection
	The production of bioenergy shall:			
<i>Socio-economic areas of concern</i>				
1. Economic feasibility	Be financially feasible	NPV [$\$ \text{ha}^{-1}$] ^a , IRR [%] ^a , PBP [yr] ^a , production costs [$\$ \text{l}^{-1}$] ^a . NPV and IRR should be positive and PBP and production costs competitive	Quantitative (economic modelling)	Fieldwork (in 2006–2010) and company documents.
2. Local prosperity ^b	Contribute to the social and economic development of local, rural and indigenous peoples and communities	<i>Wages and employment:</i> Employment opportunities, unemployment rate in the region, additional income for smallholder, wage categories for employees [\$]. <i>Impact on local economy:</i> Total investment costs [\$], total (discounted) costs [\$], investments in health care and education facilities, infrastructure, purchase of local materials, expenses that stay in local economy [%], <i>origin of employees^c:</i> region or nation of origin <i>social wellbeing:</i> perception of local population, risks for population if project is abandoned	Qualitative and quantitative	Company business plans, interviews with the communities, literature including household surveys, and national statistics.
3. Labour and working conditions	Ensure decent work and the well-being of workers	Compliance to and description of: legal issues, child labour provisions, discrimination, forced and compulsory labour, disciplinary practises, safety, freedom of trade union organization, education/training, working hours, secondary benefits ^d	Qualitative	Company documents, literature, visits and interviews with management.
4. Food security ^e	Not endanger food security	Qualitative description of; current food security status, possible threats to decreased food availability, access, stability and utilization and measures taken to increase food security	Qualitative and quantitative	Statistical data, literature and observations.
5. Land ownership and land rights ^f	Not violate land rights	Land procurement procedures; land transferred [ha], compensation payments [\$]; displacement of people; process transparency; risk in case of discontinuation; public opinion	Qualitative	Literature, observations.
<i>Environmental areas of concern</i>				
6. Greenhouse gas balance and carbon stock changes	Contribute to reducing GHG emissions compared to fossil fuels and contribute to reducing fossil fuel use	Above- and below-ground carbon stock; life-cycle GHG emissions [$\text{CO}_2\text{-eq}$]	Quantitative	At plantation site: satellite data calibrated with field measurements.
7. Biodiversity	Shall avoid negative impacts on biodiversity, ecosystems, and areas of high conservation value	Conversion of vegetation; location of production areas related to various biodiversity maps; occurrence of threatened species; species diversity (Shannon, Sørensen index)	Qualitative and quantitative	GIS analysis, observations and literature.

^a A Net Present Value (NPV) > 0 and an Internal Rate of Return (IRR) > the (real) discount rate, constitute minimum requirements for project profitability, as well as a reasonable Pay Back Period (PBP), the number of years needed to recover the initial project investment. The total production costs per litre SVO are useful for comparing efficiency of the two business models. They mainly comprise investments in farming support, processing, storage/transport and general investments. For calculation of the total production costs per litre, fixed investment costs are levelised over the 20 year project period. For formulae, see Ref. [43].

^b Background indicators used for local prosperity: Gross Domestic Product (GDP); GINI coefficient [44]; Human Development Index (HDI) [44]; % people below the Tanzanian national poverty line; % people below US\$ 2.00 per day [45,55]; % people below the extreme poverty line of US\$ 1.25 (PPP) [44] Multidimensional Poverty Index [44]; Poverty Gap Ratio [46]; minimum wage [\$]; % own-account and contributing family workers in total employment, based on Ref. [46] household possessions; and literacy rate [%]. Definitional details in Appendix B in the online supplementary material.

^c The origin of the employees is analysed to see if the wages earned are likely to be spent in the local economy, or that they are likely to leak out to other countries/regions.

^d These indicators are based on the UN Universal Declaration of Human Rights (1948), which is a requirement by the NTA8080 [29] and the “Tripartite Declaration of Principles concerning Multinational Enterprises and Social Policy”, set up by the International Labour Organization [47]. Other benefits: [42]. Safety is also mentioned by [40,41].

^e Background indicators used for food security: food security situation Tanzania; change in production of main staple crops [%]; food price index, change compared to overall price index [%].

^f Background indicators used for land rights: number of land certificates handed out; number of land conflicts; dissolving rate.

2.2. Description of main indicators and assessment methods

2.2.1. Economic feasibility

In order to assess the economic sustainability of our cases we conduct a Cost Benefit Analysis (CBA), in which the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Pay Back Period (PBP) are used as indicators [49,43]. The CBA is performed assuming similar total cultivation areas of 80,000 ha and a 20 year lifespan for both cases. The 80,000 ha corresponds to the original business plan of the plantation company and is also broadly compatible with the goals set by the processor in the smallholder-based system [72,77]. The 80,000 ha size assumption is also used to assess impacts on local prosperity, food security and the environment.

In the plantation model, the choice of harvesting system is expected to have a large impact on total employment, and thereby on regional economic impacts. Therefore, two harvest-system scenarios are worked out for this model: “semi-manual” and “fully-mechanized”. For the smallholder-based system, two different capacity scenarios are elaborated: a “low” base case (88,000 tons of processed seed/year) and a “high” case (160,000 tons of seeds/year). The “low” scenario assumes a low-input cultivation regime and low per-ha yields for the smallholders, whereas the “high” scenario is compatible with intermediate input cultivation [43].

A sensitivity analysis is performed with respect to CO₂ credit price, SVO price, discount rate, and – for the smallholder model – the purchase price of seeds. In the plantation system various yield scenarios are analysed, as well as a scenario in which proceeds from harvested wood from land clearing are incorporated (as stipulated in the original business plan). A full list of CBA assumptions is contained in [Appendix A in the online supplementary material](#).

2.2.2. Local prosperity

Local prosperity can be increased if household income is increased through employment or increased earnings. The focus in this analysis is on income-effects from employment and their impacts on the local economy. Furthermore, a qualitative description of the impact on social well-being is added. Because the projects had not reached their full size at the time of this assessment, this analysis is partly prospective.

2.2.3. Labour and working conditions

Labour and working conditions relate to the way hired employees are treated, and how smallholders could be influenced in their working conditions. Most of the indicators are compliance indicators: the presence of specific policies on discrimination, disciplinary procedures and the possibility to join a labour union was checked. Various operational company data were used for this.

2.2.4. Food security

It is explored if either model of biofuels production threatens to decrease food security in any way, or, if so, how the scheme proposes to mitigate the threats. The RSB proposes that biofuel producers take measures to “enhance the local food security of the directly affected stakeholders” [50]. Therefore, it is also explored whether the scheme proposes to improve food security beyond current levels. The current status of the case study regions along the spectrum of food insecurity and malnutrition is investigated first. This is done with biometric measures taken from existing data sources: weight-for-age [51,52]; wasting or stunting; and vulnerability. Vulnerability is determined by looking at the five vulnerable livelihood groups that are identified in Tanzania by McKinney [51]; poor-income people (income mostly from crop production), wage labourers, small farmers, remittance dependents and natural resource dependents. Threats to food security arising from the projects are analysed next, by looking at its different dimensions distinguished by FAO: availability, access, stability of supply, and utilization of food for individuals, households, communities and larger population groupings [53,54]. Stability of food supply relates to both availability and access. If groups are affected through big changes in either price or access to supply, then they lack stability and may suffer from food insecurity [55]. Utilization relates to food quality, preparation, and storage, as well as nutritional knowledge and health status of the population [55]. Biofuel activities could affect this through impacts on availability of essential inputs to food preparation, like water and fuel.

2.2.5. Land ownership

In African countries land rights are typically embedded in complex legal frameworks [56]. In Tanzania informal customary land laws co-exist with formal land title deeds, which is why transferring land is complex and sensitive. The main issues are: the land acquisition process (possibly involving deviations from legally established routes); land compensation payments (undervaluing the land); transparency of the process (possibly leading to misunderstandings and disagreements about compensation eligibility); and impacts on livelihoods [56–58]. Furthermore, promises made by projects to villagers are often not written down and therefore cause scepticism amongst farmers when expectations are not met [58]. Therefore the following processes are evaluated: land procurement procedure; change in land access; amount of ha transferred; compensation paid; transparency of process; potential risk in case of project failure; and public opinion in Tanzania. Our main data sources were operational company data and external reports.

2.2.6. GHG balance and carbon stock

Standard GHG methodology is used, e.g. Ref. [59]. In the smallholder system, GHG emissions from changes in

above or belowground biomass, soil organic matter and litter are negligible, assuming jatropha is planted as hedgerows in addition to current crop cultivation, thus avoiding conversion of forest and existing cropland. For (large scale) plantations, the emissions from changes in land use are evaluated by estimating the difference in carbon stock between the prior natural vegetation and the jatropha plantation. The carbon stock of the natural vegetation is estimated as follows:

- *Aboveground biomass* is calculated using remote sensing data in combination with field measurements, as applied by e.g. Refs. [60,61]. A satellite map was used to calculate the Normalized Difference Vegetation Index (NDVI), this is validated by measuring the harvested and dried aboveground biomass of 10 plots (20 × 20 m) for each of the four most common vegetation classes which are woodland, open forest, forest and dense forest (so 40 plots in total). Where available, specific wood densities were used to determine the carbon stock of trees. Shrubs and small trees were weighed and dried in a kiln to calculate the dry biomass per ha. Grass was sampled in subplots of 5 by 5 m, and sundried. The aboveground biomass measurements were linked to the NDVI values from remote sensing by means of a linear regression analysis. Next, the NDVI map was converted into an aboveground carbon map using the regression equation: $NDVI = (NIR - VIS)/(NIR + VIS)$ in which NIR is the near infrared part of the spectrum, and VIS is the visible part of the spectrum of light [62]. This map is used to calculate the total carbon stock of the area assuming all carbon in the biomass is emitted as CO₂ when the land is cleared for the jatropha plantation.
- *Belowground biomass* is estimated using the data on above ground biomass and the default IPCC factors for the above/belowground biomass ratio.
- *Dead organic matter* (dead wood and litter): value taken from literature.
- *Soil organic matter* (carbon in soil): value taken from literature. The timeframe for inclusion of the change in carbon stock is 20 years.

The GHG reduction is then calculated using [formula \(1\)](#) below.

$$GHG_{reduction}(\%) = \frac{F - (-A + B - C - D - E)}{F} * 100 \quad (1)$$

GHG emissions/absorption from:

- A: Removal of original vegetation
- B: Jatropha growth
- C: Transport
- D: Conversion to jatropha oil
- E: Transport to end-user
- F: Application of the jatropha oil/fossil reference

Values from literature are used to determine lower and upper ranges for each item, the timeframe is 20 years. No useful application of the removed vegetation, mainly hulls used as a fertilizer, and seedcake used as a fertilizer, is assumed except for the upper range calculations.

2.2.7. Biodiversity

One of the key strategies to mitigate the risk of bioenergy projects to biodiversity is to conserve areas of significant biodiversity value [63]. The risk of plantation establishment to areas of significant biodiversity value is assessed by identifying the location of national protected areas [64]. Furthermore, additional areas of significant biodiversity value are considered, as identified by Biodiversity Hotspot Areas [65], Key Biodiversity Areas according to Birdlife International [66], and Critical Ecoregions [67]. The location map of the plantation was overlaid with these maps. Overlap indicates potential risk of reduced biodiversity if the land is converted to biofuel cultivation.

The shrub and tree diversity of the planned plantation area are assessed using the Shannon-index [68] to account for abundance and evenness of the species present, and the Sorensen-index [69] to indicate similarities between vegetation types; see [Appendix F in the online supplementary material](#) for the formulae. These two indexes do not have a threshold value but are compared to values reported in the literature, to assess the degree of degradation of the initial vegetation.

Conversion of natural vegetation into plantations containing species with limited distributions could result in (local) species extinction. Therefore, the presence of endangered and endemic species is evaluated by indicating in the 40 plots that were assessed, all trees exceeding a DBH of 10 cm with their Kiswahili names with the help of a local expert followed by identification of their botanical names. The species names are checked with the IUCN Red List of Threatened Species [70].

The indicators used to assess impacts on biodiversity can thus be compared to elements of the concept of a high conservation value (HCV) area initially developed by the Forest Stewardship Council (FSC 1996) in its standard on sustainably managed forests. This concept includes different conservation values of global and national importance that are based on species, sites, ecosystems, and values corresponding to ecosystem services, in particular HCV criteria 1–3 [71].

2.3. Selection and description of the two bioenergy production systems and settings

2.3.1. Case study region

Two Tanzanian cases were chosen for the following reasons: first, in Tanzania there are different jatropha business models in operation which makes the comparison realistic. Second, jatropha projects in this country started as early as 2005, so a lot of experience has accumulated. Third, the Tanzanian government has been working on an enabling environment for biofuels and is distinguishing in its policies between plantations and smallholder schemes [34]. Two real-life jatropha production systems were investigated: a plantation company in the Southeast of Tanzania, BioShape Tanzania Ltd., and a decentralized smallholder system with a central oil processor located in the North of Tanzania, Diligent Tanzania Ltd. The smallholder system covers a much larger sourcing area than the concentrated plantation, see [Fig. 1](#).

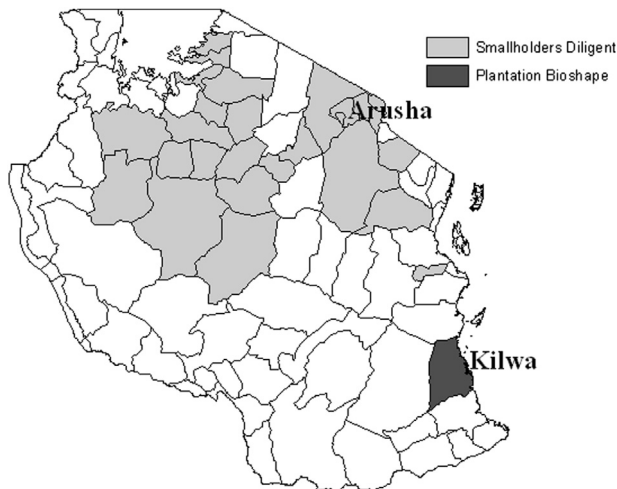


Fig. 1 – Overview of Tanzanian districts that are covered by Diligent Tanzania Ltd. (smallholders) and BioShape (plantation) in 2009.

2.3.2. Smallholder (hedgerow) system

In the smallholder (hedgerow) system, farmers produce for the processing company either under contract (also called outgrowing or contract-farming) or independently. Mostly, family labour is used. The jatropha hedgerows are planted around homesteads or agricultural plots. One farmer can plant the equivalent of around 0.5–1 ha with jatropha, with on average 1000 plants per plot. The seeds are sold to the processor company directly or through a collector who adds a commission to the seed price. Cultivation of jatropha is not very profitable for smallholders, but in many cases it is attractive enough due to low opportunity costs for labour and hedge land [43].

Collection centres run by collectors are located near strategic places such as in a grocery shop, a school or at the house of a well-known farmer. Farmers bring their seeds in bags using bicycles, ox-charts or other local forms of transport. The company organizes onward seed transport to the central processing unit in Arusha, using local transport companies. A “backhaul system” is used for this, utilizing trucks that would otherwise return empty to town after delivering their products upcountry. The processor provides the farmers and collectors with extension services and initial planting material (farming promotion). The processor employs a field team for promotion of the crop, and technical staff in the factory. The processed products are used for the domestic and international market.

Diligent started its activities in 2005 and continued to the end of 2012 when one major investor pulled back. The activities, collection and processing, still continue but under new ownership and name. At the time of study in 2006 the company was working with around 4000 smallholders (reaching 40,000 by 2011), produced around 35,000 l SVO annually and employed around 35 people. The goal at the time of study was to reach 10,000 and ultimately 50–200,000 ha over 20 years; an expansion to 80,000 ha is assumed here to enable comparison with the plantation.

2.3.3. Plantation system

In the plantation system the land is owned by the company BioShape and hired employees cultivate monoculture (block) plantations of 200 ha each. Agricultural equipment and trucks used for cultivation and transport are also owned by the company. Harvesting is done semi-manually, with tree shakers (=our base case scenario). Fully mechanized harvesting is also considered, but these technologies are not yet fully developed. The original business plan envisaged export of unprocessed seeds to Europe, but later plans allowed for

Table 2 – Key characteristics of the two business models used in the analysis.

Business model → Characteristic ↓	Smallholder-based model	Plantation model
Mode of planting	Hedgerows	Monoculture
Type of labour	Family labour or occasional hired labour on the farms, and employees in the processing factory and field team	Employees
Area under cultivation	80,000 ha	80,000 ha
Beneficiaries	80,000–160,000 farmers (each 0.5–1 ha) and employees (≈500est.)	Employees (10–35,000)
Yield	1.1 ton ha ⁻¹ yr ⁻¹ as the base case (‘low’ yield scenario), or 2 ton ha ⁻¹ yr ⁻¹ (‘high’ yield scenario), see Ref. [43]	1.1 ton ha ⁻¹ yr ⁻¹ as the base case; 2, 4 and 6 ^a ton ha ⁻¹ yr ⁻¹ in the sensitivity analysis
Processing capacity	88,000 ton seeds yr ⁻¹ as the base case (low yield scenario) 160,000 ton seeds yr ⁻¹ (high yield scenario)	88,000 ton seeds yr ⁻¹ as the base case; reaching up to 480,000 ton seeds yr ⁻¹ at 6 ton ha ⁻¹ yr ^{-1a} in the sensitivity analysis
Mode of harvesting	Fully manual	Semi-manual (base case) or fully mechanized
Processing	In Tanzania	Initial plan: Western Europe; later changed to Tanzania [34]
Products	Jatropha SVO and biodiesel, seedcake briquettes and charcoal	Jatropha SVO and biodiesel, seedcake briquettes and charcoal, jatropha seeds, harvested wood from plantation

^a Six ton ha⁻¹ yr⁻¹ is the original yield estimate in BioShape’s business plan [72].

domestic seed processing, as requested by the Tanzanian Ministry of Energy and Minerals [34]. At the time of study (2009) BioShape had planted 400 ha, acquired 34,000 ha, and employed around 400 casual and contract workers. It aimed at 80,000 ha under cultivation by 2018 [72]. By the end of 2010 activities halted for various reasons, amongst others the financial crisis. However, the financial model reported here is based on the assumption of a fully executed business plan.

More details about the business models are given in Table 2.

The analysis includes land clearing and preparation (plantation only), the production and transport of the feedstock, conversion into biofuel, and transport to end users.

Table 3 – Main results of the economic analysis.				
System	NPV (US\$ m ha ⁻¹)	IRR (%)	PBP (yr)	Discounted production costs US\$/l SVO
<i>Plantation</i>				
Semi-manual (1 t/h), base case	15	17	13	1.32 ^a
Fully mechanized (1 t/h)	-3	7	≥20	1.45
<i>Processing with smallholders</i>				
Low capacity 82,000 ton seeds, base case	8	14	13	1.28
High capacity 160,000 ton seeds	18	18	12	1.20

^a US\$ 0.87 if wood sales revenues are deducted from production costs.

Applications considered are Straight Vegetable Oil (SVO) for local use and export (both models). Co-products from biofuel production – seedcake and husks – are used as alternatives to wood and/or charcoal, e.g. in boilers, and as a fertilizer. The timeframe of our analysis runs from 2005 to 2025, when both models reach maximum production capacity with mature trees.

3. Results

3.1. Economic feasibility

The results of the economic analysis are presented in Table 3 and Fig. 2. The total investment costs (excluding general expenses) amount to US\$ 11 m for the smallholder model and US\$ 32 m for the plantation. The total (discounted) costs over a 20 year lifetime are US\$ 77–130 m for the smallholder model and US\$ 107–125 m for the plantation.

With (semi)manual harvesting, both business models are marginally profitable. Interestingly, these base case profitability estimations for the two models are quite similar, even though their land, capital and labour configurations differ considerably.

The estimated PBPs of 12–13 years are long especially in the context of developing economies where risks are high, and even more so in view of the lack of commercial experience with jatropha as an energy crop. Both base case models have low IRRs: The low capacity smallholder system with yields of 1.1 ton seeds ha⁻¹ y⁻¹ has an IRR of 14%, and the plantation with the same yield and semi-mechanized harvesting yields 17%. This is dangerously close to the real discount rate of 8.2%. The best IRR of 18% occurs in the “high” scenario of the smallholder model. Fully mechanized harvesting in the plantation model is expected to be unprofitable. However, the plantation profits are much higher if wood sales from land

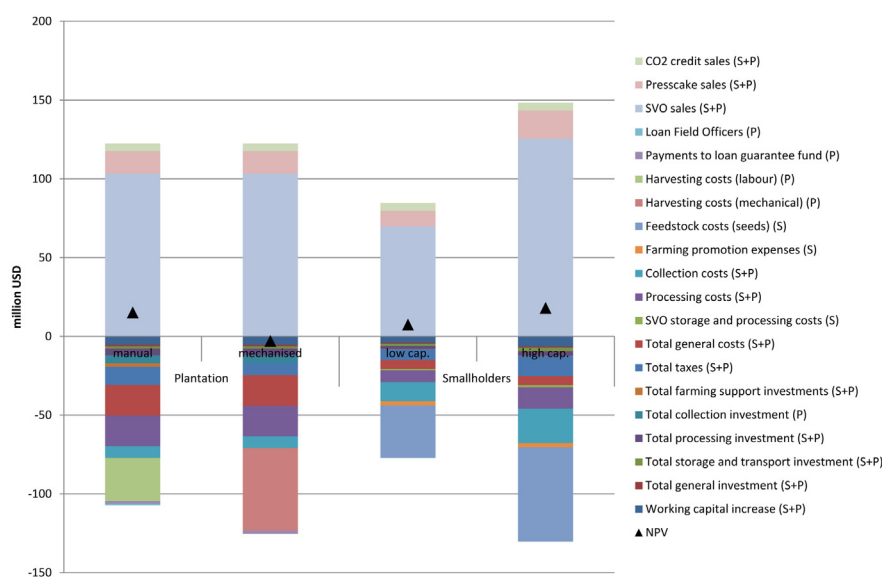


Fig. 2 – Discounted production costs, revenues and NPVs for the two models (2 scenarios each). S indicates cost factors specific to the smallholder model, while P indicates plantation-specific cost factors. S + P means that the relevant cost factors apply to both models.

Table 4 – Sensitivity of profitability to changes in CO₂ credit revenue, SVO price, discount rate, seed purchase price, seed yield and the inclusion of wood sales (Pl = plantation model, Sm = smallholder-based model).

Change in variable	Scenarios	NPV [M\$]		IRR [%]		PBP [yr]		Production costs [\$ l ⁻¹]	
		Pl.	Sm.	Pl.	Sm.	Pl.	Sm.	Pl.	Sm.
	Business models								
	Semi manual – low capacity	15	8	17	14	13	13	1.32	1.28
	Mechanized – high capacity	–3	18	7	18	>20	12	1.45	1.20
Reduction of CO ₂ revenue from US\$ 350,000 yr ⁻¹ to US\$ 0.	Semi manual – low capacity	11	4	15	11	14	16	Same	
	Mechanized – high capacity	–7	14	5	16	>20	13		
Unchanged SVO price at US\$ 2,000 \$ ton ⁻¹ , instead of decrease over time to US\$ 1,000 \$ ton ⁻¹	Semi manual – low capacity	49	35	26	23	11	11	1.28	1.35
	Mechanized – high capacity	32	68	19	27	14	11	1.41	1.31
Increase in discount rate from 8.2% to 15%	Semi manual – low capacity	2	–1	17	14	16	>20	Same	
	Mechanized – high capacity	–9	3	7	18	>20	16		
Increase in seed purchase price from smallholders from US\$ 0.16 to US\$ 0.20 kg ⁻¹	Low capacity		2		10		16		1.38
	High capacity		8		13		14		1.30
Yield increase in the semi-manual plantation system from 1.1 to 2, 4 and 6 ton ha ⁻¹ yr ⁻¹	2 ton /ha ⁻¹ / yr ⁻¹	41		22		11		1.13	
	4 ton ha ⁻¹ yr ⁻¹	98		26		10		1.06	
	6 ton ha ⁻¹ yr ⁻¹	155		27		10		1.04	
Inclusion of wood sales of 12.7 m ² of harvestable timber/ha from original vegetation at plantation.	US\$ 61.70 gross margin of timber sales per cubic meter	42		91		3		0.87	

clearing during the first 11 years of the project (approximately US\$ 27 m) are included. If these revenues are deducted from the costs of production, the cost per litre SVO falls spectacularly from US\$ 1.32 to US\$ 0.87. However, this scenario is not informative about the profitability of jatropha cultivation as such.

The results discussed above still include uncertain benefits from carbon credits. Voluntary Credits (VCAs) are being traded at other jatropha plantations, but their price can sink to a low US\$ 2–3 per ton. Therefore, in the sensitivity analysis (Table 4), the effect on profitability of the removal of the CO₂ credits has been assessed. The sensitivity analysis also assesses effects from variations in seed yield and the oil sales price, as these are also uncertain.

Profitability is apparently sensitive to the SVO price. In the original estimation, that price is assumed to decrease over time from US\$ 2000 to US\$ 1000 per ton. This was assumed because the market for jatropha oil is still immature, with limited supply in relation to demand. One might expect the price to decrease over time to a competitive level comparable to fossil diesel (of around US\$ 0.80–1.00 l⁻¹ [43]). If the SVO price was to remain at US\$ 2000 ton⁻¹ ($\approx 1.91 \$ l^{-1}$) until 2025, the projects' financial prospects would be substantially better. In practice, the SVO price will depend closely on the fossil fuel price. If the latter rises over time due to structural high demand on world oil markets, the SVO price may remain well above US\$ 1000 per ton.

An increase in the purchase price of seeds from the smallholders and an increased discount rate have smaller influences on profitability. An improved yield per ha would have major positive effects on the plantation project, but this might only be possible against higher input costs (these effects not assessed here).

3.2. Local prosperity

All general background prosperity indicators considered for this study indicate that Tanzanian material living standards

are extremely low. A large proportion of the population live below the international and national poverty lines: 97% earns less than US\$ 2 PPP (2000–'07), 68% is below US\$ 1.25 PPP (2000–'09) and 33% is below the national poverty line (2000–'09). Average income in 2009 was a mere US\$ 548 per capita. Just 55% of households own a radio, a mere 2.0% own a mobile phone, 5.8% a wheelbarrow, 43% a bicycle, and 1.1% a TV [73]. There are also notable differences in poverty between regions and groups (GINI₂₀₁₁ = 37.6), which means that some regions and groups are even worse off; see Appendix B for more poverty statistics.

The impacts on local prosperity by the smallholder system and plantation system are detailed in Table 5.

Especially given the extreme poverty in rural Tanzania, the overall impact on local prosperity can be considered quite positive for both models. They both generate employment and income. The plantation generates higher profits per beneficiary, while the smallholder system has many more beneficiaries but generates lower revenues per person. All wages are above the minimum salary range set by the Tanzanian Government (US\$ 49–245₂₀₁₀ [79]). The salary scales for higher skilled labour in the two companies are comparable. In the smallholder system the occurrence of middlemen is an issue, since they could pay seed sellers below the minimum price set by the processor. This has occurred a few times in practice. On the other hand, higher than factory gate prices also have been paid in times of high seed demand.

The plantation company offers more investments in education and health facilities, while the farmers in the smallholder model receive more training, and the use of local transport stimulates local entrepreneurs. In a fully manual harvesting regime, employment requirements at the plantation would exceed available employment in the region which would cause migration of people, this could be a threat to both food and water supplies in the region.

Both models also affect the local economy by purchasing tools and materials locally. Not all the expenditures are local,

Table 5 – Comparison of local prosperity effects of the two business models.

Local prosperity Comparison	Indicator	Smallholder-based model	Plantation model
Wages and employment	Employment	126 field officers, and part time occupation for 80,000–160,000 self-employed farmers	81 field officers and 10,000–35,000 employees, mostly low skilled for harvesting, see Ref. [72]; 6000 employees if harvesting is fully mechanized ^a .
	Wages	Above minimum wage for employees; Farmer seed sales revenue: US\$ 70–140/year, based on US\$ 0.14/kg ^b . Occurrence of middlemen and low seed payments are issues	Above minimum wage
Impact on local economy	Total investment costs	US\$ 11 m	US\$ 32 m
	Total costs (discounted) (20 yrs)	US\$ 77–130 m (US\$ 33–59 is spent on purchasing seeds from farmers and US\$ 4.8 m on transport within region)	US\$ 107–125 m
	Education and health investments	No foundation established yet, but plans exist	Through foundation: maternity ward, classrooms, vegetable garden. With land acquisition money: classrooms, tractor, see Ref. [75]
Origin of employees	Local purchases	Large complex equipment imported, all else purchased locally	Small equipment, tools and stationery purchased locally or elsewhere in Tanzania, all large equipment imported
	% of costs related to processing	11%	18–20%
	Management functions by local population	1 out of 4 management positions fulfilled by expats, foreign shareholders	Unskilled from the region, skilled from outside, 7 out of 18 management positions fulfilled by expats, foreign shareholders
Social wellbeing	Perceptions about project, incl. perception of risk when project would be abandoned	Extension service to farmers and facilitation of credit access fosters farmers' perceptions of increased wellbeing and trust; see Ref. [76]. Skepticism possible if project would be abandoned	Not studied. Increased income might lead to increased social wellbeing, but high levels of skepticism/anger if project is abandoned ^c
	Impact if project fails	Possible to take up 'old lives' again, little change in daily routine	Difficult/impossible to go back to 'old lives', major disruption

^a Fully mechanized harvest requires around 180 harvesters with 3 workers per harvester, so around 540 workers instead of 24,400 if 88,000 tons of seed production is harvested with an efficiency of 40 kg person⁻¹ day⁻¹ [74] for 90 days per year.

^b If the price of seeds is 0.14 \$ kg⁻¹, a total amount of 15 kg would have to be collected daily to earn on the poverty line of 2 \$ day⁻¹. An average is 40 kg day⁻¹ [74], so this seems achievable for around 25 days per year even without other income.

^c This actually happened in 2010, when the Dutch holding of BioShape went bankrupt, and all activities in Tanzania stopped, included the activities of the social benefits foundation, see Ref. [78,83].

however. Salaries of non-Tanzanians will (partly) end up abroad, furthermore, since both companies have Dutch holdings it is very likely that the profits after tax deductions will (partly) go abroad as well. All advanced equipment is imported from other countries due to sheer unavailability in Tanzania. The location of processing would have a major influence on the occurrence of local spin-off effects; originally the plantation company wanted to process the seeds abroad, this would mean low capacity building and value added creation inside Tanzania.

Perhaps the greatest risk for social wellbeing emanating from the projects arises from the risk of project failure. This could induce high scepticism in the local population due to unkept promises [78]. In the plantation model, the entirely basis of people's livelihoods would also be disrupted; it

might not be easy or even possible to revert back to prior livelihoods based on subsistence farming. In comparison, disruptions to livelihoods of the outgrowers in the smallholder model would be much less drastic as *jatropha* hedge cultivation is an incremental activity for farmers with low risks.

3.3. Labour and working conditions

Child labour is common in Tanzania, although prohibited under Tanzanian law. The 2002 Population and Housing Census classifies almost 40% of 9 million children in Tanzania as economically active for most of the twelve months prior to the census reference month. Among those, 16% were classified as doing unpaid work, 12% as working for own benefit and

12% as doing paid work. Even among children aged 5–9 years old, 29% were classified as economically active, of which 40% (363,000 children) on usual status [80].

Neither at the plantation nor at the processor was any child labour observed; worker age was verified by checking ID-cards. In the smallholder system children do usually help with household and agricultural tasks, as is common in low-income rural societies, and observed by Mitchell [81], but the money earned by selling seeds is sometimes used for school fees. Helping with farm work does not imply that children do not attend school. All Diligent's outgrowers state that their children attend school regularly. This is in fact a condition for production on contract. But it is more difficult to detect and prevent excessive and exploitative child labour in a smallholder system than in a plantation system. Table 6 gives a full comparison of labour and working conditions.

Risks arising from possible project failure loom large in the plantation model. In fact, major problems have arisen here in reality. After the bankruptcy of the Dutch BioShape Holding in April 2010, all 400 daily workers were suddenly sent home, while the contract workers were kept on for six more months, for which they were never paid. Despite the existence of national regulations to prevent these situations, no employment stability or social security was observed. A law suit has been filed in Dar es Salaam High Court trying to retrieve the unpaid salaries of over 90 contract workers [83,84]. Failure of the processor company in the smallholder system would have more limited effects. The workers in the factory and the field team would stop receiving benefits and

the smallholders would lose their market for seeds, although other seed buyers/processors may fill that gap in some regions. The impact of market loss on total household income would be minor.

In sum, both systems formally have similar labour and working conditions (although it is difficult to verify the conditions in smallholder households), but there are large differences in the set-up and the manner of implementation of the two systems, which affect how things work out on the ground. The processor firm in the smallholder system places considerable emphasis on providing employee skill training, more so than the plantation. Perhaps the latter could have organized this under the wing of its foundation, but it never reached this stage due to its bankruptcy.

Many issues discussed above – poverty, wages and employment, prices and rural development, also have a close relationship with the next topic of food security.

3.4. Food security

3.4.1. Background information

In Tanzania roughly 15% of households are considered food insecure, with a similar proportion considered highly vulnerable [51]. Regional variability in food insecurity varies between 5% to above 50% of households (see Appendix C in the online supplementary material), but all regions suffer from high rates of stunting among children under five, indicative of chronically low nutrient intake. Thus, food security is a concern in all regions. Households relying mainly on small

Table 6 – Labour and working conditions in the two business models.

	Smallholder-based model	Plantation model
Legal issues	Obeying all relevant ILO and national regulations	Obeying all relevant ILO and national regulations, however, very poor exit strategy (lawsuits ongoing), contravening article 26 of ILO
Child labour provisions (children in employment and hazardous work)	None employed (farmers might ask their children to help)	None employed
Discrimination	Field officers from all tribes, substantial number of female employees	Based on skills and talent, not on tribe or gender, although preference is given to local people
Forced and compulsory labour	None	None
Disciplinary practices	Warning system before dismissing	Warning system before dismissing (in practice not always applied)
Safety	Protective wear provided to factory employees	Safety regulations (but unclear and no processing took place yet)
Freedom of trade union organization	Freedom of association/right to organize; contacts with labour unions	Freedom of association/right to organize; contacts with labour unions
Education/training	Courses provided depending on skills (computer, human resource, also HIV/AIDS)	No specific training programme but training on the job
Working hours	Normally 5.5 days a week, over time is paid 150% or 200% (Sunday). Over time and night shifts do occur occasionally	No working allowed before 7:00 and after 17:00 (danger of wildlife encounters). Possible exception: work performed on the camp site and at office
Secondary benefits	Provision of meals Coverage of medical cost Provision of education for 1 child per employee	Provision of meals Coverage of medical cost Provision of housing for staff outside the area

The indicators are based on Refs. [29,40–42,47], see Methodology section. Sources: fieldwork, company business plans [72,82].

farming and wage labour are more likely to be food insecure than skilled labourers and traders [51]. Chronic malnutrition is common, affecting over 30% of children under 5 [51]. Acute malnutrition, which is indicative of recent or current food shocks, is less prevalent with fewer than 6% of children affected nationwide in 2006, although 10–14% in some districts affected by drought at that time [51].

National food production figures show a change in food production from 2007 to 2009: millet, maize and cassava production decreased, while rice, wheat flour, beans, banana and sweet potato production increased [80]. The reason for this decline however, is not biofuel production but ‘unfavourable weather’ [80]. The food price index increased every year since 2001, but only marginally when compared to the overall price index which also increased [80].

In any business model, food security may increase if household incomes increase [85]. A study of more than 100 smallholders observed that those connected to the jatropha seeds processor reported higher levels of food security and lower incidences of food shortages compared to other smallholders, but the exact reasons could not be verified [76]. A FAO study indicates that smallholder-based biofuel systems are most effective in increasing household income [85]. It indicates that the key factor to increase food security is to increase agricultural yields [85]. Biofuel investments could catalyse this if they invest in increasing local communities’ knowledge to achieve this. In our study, the plantation company’s efforts in this respect were limited to encouragement of a school garden through its foundation. The processor was making good efforts with agricultural extension services. However, increased public spending will be also necessary to increase access to knowledge, fertilizer, improved seeds and water, and reduce input prices [85].

3.4.2. Availability and access

The area targeted for jatropha production by the plantation was not actively in use for crop production or grazing, so food availability was not directly affected. However, communities used it for hunting and possibly firewood gathering, charcoal making, medicinal plant gathering etc. If community members are paid for the reduced access caused by the plantation, then they can compensate for the loss of those resources; however there is evidence that in some cases compensation has not reached affected individuals (Section 3.5). Wage income – if stable – could compensate for the loss of traditional food access. The wages per household (especially for females) should be higher than the market value of the food produced on household plots. However, after the discontinuation of the plantation in 2010, no wages have been paid while land access is still restricted. A report by a Tanzanian NGO [75] also indicated that the production of food in Kilwa decreased during the time that the company was active. This might be due to employees’ time reduction for household food plot cultivation. The company did try to limit food price increases by buying the staple food for employees (maize and beans) in the main city Dar es Salaam.

In the smallholder hedge model, food availability and access to resources are not directly affected. A potential knowledge benefit arises from the agricultural extension

work, which could help increase food crop yields. However, the timing of initial weeding requirements of jatropha can conflict with those of food crops [81]. Seed harvesting seems to cause fewer conflicts on labour demand.

3.4.3. Stability

Sudden one-off shocks are unlikely to be caused by biofuel operations, except when they fail. However, in the plantation model seasonal (harvesting) shocks may occur, particularly as a result of the influx of seasonal job-seekers, self-employed service providers and dependents. For an estimated 10,000 employees, this could involve 50,000 people [72,86], whereas the current population of the five communities providing land to the plantation is less than 7000. The company acknowledged that food demand will be monitored and “food supply will have to increase to service the influx” [[72] p. 45], and that it will establish “farms to service this need” [[72] p. 45], but nothing concrete was planned. A Strategic Impact Assessment noted that the company needs to strengthen monitoring systems. Therefore, the establishment of a large plantation in a sparsely populated region in which 30% of the population is classified as either “food insecure” or “highly vulnerable” to insecurity is likely to induce instability in supply (due to sudden large in-migration) and poses risks to food security. In contrast, schemes such as Diligent’s outgrower model rely primarily on family labour and involve little, if any seasonal labour movement.

3.4.4. Utilization

The plantation system was meant to replace 80,000 ha of forest and woodland (map in Appendix E), so ensuring fuel supplies for cooking would become a major issue for the nearby communities and seasonal migrants. Yet, the company business contains no plan to ensure adequate fuel supplies, so food security also could be threatened through lack of access to cooking fuel. Such threats are unlikely to arise in the smallholder production system. Smallholders were never observed to replace live fences containing fuelwood species entirely with jatropha. The processor also produced seedcake-based alternatives for charcoal and wood for use in urban areas: solid fuel briquettes, pellets and biogas from the seedcake [74,87]. In contrast, the initial plantation model foresaw 100% oil extraction in Europe, with the seedcake to be utilized as a solid fuel in European power plants [72]. It remained unclear how the seedcake would be used if domestic processing were to occur after all, likely as fertilizer for the jatropha field.

Finally, local food security can be increased by improved (road) infrastructure, by making regions more accessible and cheapening transport to and from there (see Appendix C for major recent infrastructure improvements effected in Tanzania). However, neither company contributed to improved local infrastructure. BioShape’s initial plans to upgrade Kilwa harbour were only meant for seed export (but those plans did not materialize).

In sum, food security can be affected in many ways in both business models (see Table 7 for a compilation of all factors discussed above), but risks are likely to be much greater in the plantation model due to the high influx of labourers. However, there are various measures that can be taken to prevent

Table 7 – Comparison of the food security impact by the two business models.

	Smallholder-based model	Plantation model
Food availability and access (production in region)	Not affected, but labour competition can arise ^a	Decreased but could be compensated by wages and compensation money. Effect on local food prices unclear ^b . Compensation for loss of resources might not reach targeted group
Food stability	No impact	Large influx of employees and job seekers might affect
Utilization	No impact	Possible loss of wood resourced is threat to cooking fuel provision
Measures to increase food security	Increase income Extension services to increase food production Jatropha co-products used as energy source (biogas, solid fuel briquettes or pellets)	Increase income Revitalize harbour (not executed)

^a Observed by Mitchell [81] who interviewed jatropha growers from the smallholders company, that weeding of jatropha can interfere with labour requirements of food crops. However, weeding is only required in the initial years of jatropha cultivation.

^b Food was bought within the region (mostly meat, fish and vegetables) but the staple food (maize and beans) was obtained in Dar es Salaam in order to prevent an increase in local food prices.

adverse effects or even improve the food security situation. For example, the management can regulate working hours so that some daytime is left for workers to cultivate their own food plots too. It can also prioritize food production on part of the plantation itself. Initial labour (weeding) constraints in a smallholder system are in any case limited to 2–3 years, but farmers should also be advised to keep prioritizing food production.

3.5. Land rights

More land titles were issued and more village land certificates were handed out in Tanzania in 2009 compared to 2008 but there are also more disputes reported. However, most disputes involve areas close to cities like Dar es Salaam and Mwanza rather than truly rural areas, were our companies operated [80]. See Appendix D for details about land issues.

3.5.1. Plantation

At the time of study, BioShape had acquired the first 34,000 ha of the planned ultimate 81,000 ha. This was previous “village land” that had been transferred into central government-owned “general land” [3,56] for the purpose of enabling a foreign investor to lease it. However, BioShape did not acquire the lease through the official route, namely the Tanzanian Investment Centre, but rather through the “services” of employees in another ministry [88]. When this fact came out, it was not good for the company’s reputation within Tanzania. The minister in question was later removed from office in connection with corruption.

According to one field study involving one of the involved villages [3] the village still had spare land left, such as settlement areas and Village Land Forest Reserves. The local communities were also satisfied with the company’s approach, although they also mentioned that in one village compensation money had not been received – possibly due to a conflict between village and district council over the division of the compensation money [3].

The total amount of money that was paid varies in different sources from US\$ 20–30 ha⁻¹ or US\$ 0.5–1 m for

34,000 ha [86,89]. The money was paid through the district authorities, which kept part of it to allegedly support the development of social services in villages in the district [3]. This was something that the village authorities had not counted on, and its legitimacy was questioned by them. It is also unclear whether the remaining share of the money that was destined for the village communities, has been distributed by the village councils to the actual villagers. Since BioShape went bankrupt it is also unclear whether villagers will ever regain their land rights, as there is no legal precedent of turning general land back into village land. Villagers surrounding another jatropha company that went bankrupt in Tanzania are facing the same issue [78].

3.5.2. Smallholders

In a smallholder-based model, land issues are less prominent because no land ownership transfers take place [56]. In principle, farmers decide whether or not they want to plant jatropha and/or stop cultivating other crops on their own land. However, vulnerable groups can be affected. An additional use for land like this can worsen already existing pressures on the land, and can thus bring latent conflicts to the surface. Landowners for example, sometimes oppose to the planting of jatropha because they fear their tenants will then claim more permanent tenure rights [90], an issue observed between the pastoralist Masai tribe and Arusha airport authority. However, with the majority of the smallholders associated with the smallholder company no conflicts were found. Rather, a positive effect from jatropha was noted in the form of resolution of land conflicts. In some regions in Tanzania it was observed that farmers liked to plant jatropha as a fence because it limited conflicts with neighbours. This was also observed in Mali [19]. One qualification to make is that the regions in which the smallholder company is active are familiar with jatropha cultivation and the plants have been used as fences since decades. In other locations this might be different. Hence, it could take longer to learn to cultivate it, or that lives would change more significantly than in our case study.

Table 8 summarizes the land rights impacts from the two business models.

Table 8 – Summary of impacts of the two companies on land rights.

	Smallholder	Plantation
Land acquisition procurement, change in land access	No major impacts, weaker groups could have difficulties. Expanding into prior uncultivated land can be an issue. ^a	Village land transferred into general land and after this transferred to the company. Villages have lost access and legal rights to (part of) their land. ^{b,c}
Amount of ha land transfer	0 ha	34,500 ha ^{b,c}
Compensation for reduction	N.A.	Around 30 \$ ha ⁻¹ for local authorities and villagers, conflicts on commercial value and division of money. ^d
Displacement of people	N.A.	13 people ^e
Transparency of the process	N.A.	Unclear, it is not clear whether stakeholders consultations have taken place, also unknown whether documentation was made available in Swahili.
Potential risk in case of project failure	Low, hedgerows will not gain income but other production just continues.	High, land rights are transferred to central government, no clause in contract that land is returned to villagers if company fails. ^f
Public opinion	Good, no land right changes involved. Some increased and lowered conflicts on land boundaries.	Medium, foreign companies are seen as 'land grabbers' by some, but others are keen to see development in their area because they think they can profit.

^a When land tenure systems are weak, the rural population might experience difficulties sustaining their land access [7,19]. Furthermore, Wahl et al. [91] observed that only a few smallholders hold official land ownership certificates in Northern Tanzania. Mitchell [81] indicated that more than 93% of the 74 jatropha outgrowers she interviewed perceived expanding their land, for multiple reasons, as problematic. Wahl et al. [91] observed in the same region that 76–86% of the households use their maximum amount of land for agricultural production, this was based on the National Sample Census of Agriculture 2002/2003.

^b Ref. [3].

^c Ref. [56].

^d The company paid around 30 \$ per hectare as a compensation payment, which is a total of 2.76 M\$ (for 92,500 ha) and of these revenues 40% went to the district government, 30% to the village and 30% to the central government [86]. Other sources mention other figures, such as 676,000 \$ for 34,000 ha [89].

^e This is mentioned in [92], however no further information was revealed.

^f A report by a Tanzanian NGO mentions several unsatisfied villagers, mainly after the company had stopped operations early 2010 [75].

It is clear that land rights are much more impacted by the plantation model than by the smallholder model. Unrelated to bioenergy production as such are the procedures to acquire land, determine its value, and ensure that villagers get adequate compensation, all of which are quite unclear.

3.6. GHG balance

A significant correlation was found between the NDVI values and the aboveground carbon content samples ($p < 0.001$), linear regression explained 51%. The most common vegetation type is forest (39 tC ha⁻¹) while the second most common type is open forest (11 tC ha⁻¹), see Fig. 3.

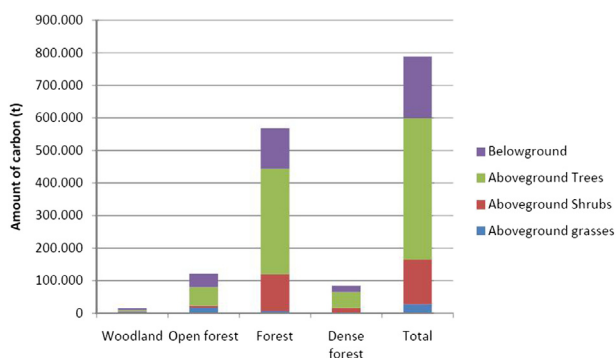


Fig. 3 – The total above and belowground carbon (t) in the plantation area per vegetation type.

Woodland (5 tC ha⁻¹) and dense forest (44 tC ha⁻¹) are less common. The total carbon stock in the area is estimated at 788,700 tC or on average 25.6 tC ha⁻¹. A carbon map of the plantation area is in Appendix E (App. Fig. 5).

The carbon content of the soil (SOC) is estimated to vary between 31 and 40 tC ha⁻¹ (values derived from existing studies; details in Appendix E) [93,94]. The carbon storage in jatropha plantations depends a lot on the pruning regime, and is estimated to be 13 tC ha⁻¹ [94,95] which also tallies with the average of the range of 8–17.5 tC ha⁻¹ reported by other studies [96,97]. It is assumed that jatropha planted as hedgerows in the smallholders system hardly replaces other land uses.

See Table 9 for a comparison of all estimated emissions in the two business models.

The largest contributing factors to the GHG balance by far are the removal of the original vegetation (–) and the carbon sequestration in the jatropha (+). All other factors only have a marginal influence. The smallholder model generates highly favourable GHG results (151% reduction), whereas the plantation model only approximates carbon neutrality (2% reduction) over a 20-year period. If an economic allocation method instead of one based on energy would be used (in which 92% of emissions would be allocated to the SVO, instead of 42%) the emission reduction would decrease to –114% (so an increase) for the plantation model and a further reduction to more than 200% in the smallholder model. The uncertainties are very large, but the smallholder model definitely performs much better than the plantation model.

Table 9 – GHG balance for jatropha oil from plantation (semi manual harvesting) including upper and lower ranges and smallholders (low capacity scenario). Depreciation period is 20 years.

Emission component	Smallholders ^a emissions (kg CO ₂ - eq ha ⁻¹ yr ⁻¹)	Plantation ^b emissions (kg CO ₂ -eq ha ⁻¹ yr ⁻¹)	Most positive estimate plantation emissions (kg CO ₂ -eq ha ⁻¹ yr ⁻¹)	Most negative estimate plantation emissions (kg CO ₂ -eq ha ⁻¹ yr ⁻¹)
(A) Removal of original vegetation	0	4,533 ^c	3,562 ^d	4,569 ^e
(B) Jatropha growth:				
Carbon stock jatropha	-1283 ^f	-2383 ^g	-3208 ^h	-1467 ⁱ
ΔCarbon stock soil ^j	0	-293 ^k	0	-293 ^k
Fertilizer use (N ₂ O)	142	604 ^l	142 ^m	604 ⁿ
Use of agricultural machinery	0	434 ^o	159 ^p	488 ^q
CO ₂ , N ₂ O, CH ₄ indirect (fertilizer production)	178	259 ^r	178 ^s	1365 ^t
(B) Jatropha growth (total)	-963	-1379	-2729	1283
Land use change (A + B)	-963	3154	833	5852
Transport	26 ^u	186 ^u	26 ^t	186 ^v
Conversion	16 ^w	31 ^x	16 ^w	31 ^x
Transport to end user	0	0		
Allocation to oil (excluding residues and co-products) [%] ^y	42	42	42	42
Total	-387	1416	367	2549
Reference fossil fuel	753 ^z	1448 ^{aa}	753	1448
Emission reduction (%)	151%	2%	51%	-76%

^a Hedgerow planting, no removal of original vegetation, no use of machinery, yield of 1 ton ha⁻¹ yr⁻¹, depreciation period 20 yr.

^b Semi manual harvesting, yield 2 tons ha⁻¹ yr⁻¹, depreciation period 20 yr.

^c Carbon stock 25.6 tC ha⁻¹ (based on field measurements), in formula: carbon stock times CO₂/C-molar mass ratio (44/12) divided by the depreciation period is 4693 CO₂-eq. In addition emissions from burning biomass and from the use of land clearing machines are estimated to be 96–131 and a reduction of 256 kg CO₂-eq ha⁻¹ yr⁻¹ is applied due to the decrease of forest fires and denitrification. No useful application of the vegetation is assumed.

^d Useful application of the vegetation (furniture), therefore only 33% of the emissions are allocated to jatropha instead of 42%, here the value for 100% is depicted.

^e The highest range (44 kg CO₂-eq ha⁻¹ yr⁻¹) for emissions from land clearing machines is used [98].

^f Carbon stock jatropha 7 tC ha⁻¹ [99], depreciation period 20 yr, based on hedges grown in Tanzania with 40 cm spacing, the same formula as c.

^g Carbon stock jatropha 13 tC ha⁻¹ based on belowground 8–10 tC ha⁻¹ [94] and the same root/shoot ratio as [95] which leads to 11–14 tC ha⁻¹ averaged as 13 tC ha⁻¹, depreciation period 20 yr, the same formula as c.

^h Carbon stock jatropha 17.5 tC ha⁻¹ [97], depreciation period 20 yr, the same formula as c.

ⁱ Carbon stock jatropha 8 tC ha⁻¹, depreciation period 20 yr, the same formula as c. This is an average of 7.8 tC ha⁻¹ according to [96] and 8.1 tC ha⁻¹ according to [100].

^j Ryan et al. [105] have calculated the amount of carbon in the soil of miombo woodland in Mozambique, and found the values varying from 32 to 133 tC ha⁻¹. Depending on the severeness of depletion, the study by Romijn [118] uses a range of 49–81 tC ha⁻¹ for African miombo woodland. The conversion from Caatinga woodland to jatropha (rather similar to miombo to jatropha) is estimated as 29 tC ha⁻¹ by [94] while a reduction due to the clearing of the biomass was estimated as 24 tC ha⁻¹ by the same study. The high values for clearing original vegetation are furthermore confirmed by Achten [95], who estimated the effect of removal of original vegetation from tropical savannah to forest between 24 and 118 tC ha⁻¹.

^k Based on BioShape estimate of 1.6 tC ha⁻¹ carbon storage, fruits are left on the field, the same formula as c.

^l 6.4 kg N₂O ha⁻¹ yr⁻¹, N₂O is 296 times stronger than CO₂, it is assumed that fruit hulls are brought back to the plantation area.

^m [101], emission factor 0.01 kg N₂O kg N⁻¹ [93] or 2.96 kg CO₂-eq kg N-fertilizer⁻¹, application rate [102]; diesel use 55–141 l ha⁻¹ yr⁻¹, emissions 159–407 kg CO₂-eq ha⁻¹ yr⁻¹, assumed that preparation of the land is included, emissions between 142.1 and 417.4 kg CO₂-eq ha⁻¹.

ⁿ Emission factor 0.01 kg N₂O kg N⁻¹ [93] or 2.96 kg CO₂-eq kg N-fertilizer⁻¹, application rate; (BioShape tool); diesel use 150 l ha⁻¹ yr⁻¹, emissions 453–488 kg CO₂-eq ha⁻¹ yr⁻¹ of which 9–44 for the preparation of land and 444 for jatropha growth, emissions between 332–604 kg CO₂-eq ha⁻¹.

^o Use of machinery for growing jatropha 5419 MJ ha⁻¹ assuming mechanized harvesting, diesel use 150 l ha⁻¹, density of diesel is 0.85 kg l⁻¹, energy content 42.5 MJ kg⁻¹. Direct and indirect CO₂ emissions from diesel use respectively: 0.07–0.01 kg CO₂-eq ha⁻¹ yr⁻¹.

^p [102]; diesel use 55–141 l ha⁻¹ yr⁻¹, emissions 159–407 kg CO₂-eq ha⁻¹ yr⁻¹, assumed that preparation of the land is included.

^q Diesel use 150 l ha⁻¹ yr⁻¹, emissions 453–488 kg CO₂-eq ha⁻¹ yr⁻¹ of which 9–44 for the preparation of land and 444 for jatropha growth.

^r Yield assumed 2 ton ha⁻¹ yr⁻¹, fertilizer need N–P–K: 68–4–12 kg ha⁻¹, emission factors NPK: 3.7–0.7–0.5.

^s [101]; only nitrogen fertilizers, based on nutrient removal between 48–141 kg ha⁻¹, emission per kg produced fertilizer are 3.7–6.69 kg CO₂-eq kg⁻¹ fertilizer using the BioShape tool or Senternovem CO₂ tool. [103] respectively, emissions between 178–943 kg CO₂-eq ha⁻¹ yr⁻¹.

^t Only nitrogen fertilizers, application rate at plantation is assumed 112–204 kg ha⁻¹ nitrogen fertilizer, emission per kg produced fertilizer are 3.7–6.7 kg CO₂-eq kg fertilizer⁻¹ using the BioShape tool or Senternovem CO₂ tool [103] respectively, emissions between 414–1365 kg CO₂-eq ha⁻¹ yr⁻¹.

^u Truck max 10 t within Tanzania, 450 km, seeds are processed in Tanzania, 1 ton seeds per ha, 0.08 kg CO₂-eq MJ⁻¹, truck: 0.73 MJ ton km⁻¹.

^v 2 types of transport, first truck max 35 t within Tanzania (60 km), and 15,000 t ship to Rotterdam (12,600 km), seeds are processed in Netherlands, 2 ton seeds per ha, 0.08 kg CO₂-eq MJ⁻¹, truck: 0.45 MJ ton km⁻¹, ship: 0.09 MJ ton⁻¹ km⁻¹ [104].

^w Conversion efficiency 0.26 ton jatropha oil per hectare, crushing is 36 MJ ton seeds⁻¹ (3.8 ton), pressing is 72 MJ ton seedcake⁻¹ (2.8 ton) and refining 45 MJ ton oil⁻¹ (1 ton), 0.16 kg CO₂-eq MJ⁻¹.

^x Conversion efficiency 0.5 ton jatropha oil per hectare, crushing is 36 MJ ton seeds⁻¹ (3.8 ton), pressing is 72 MJ ton seedcake⁻¹ (2.8 ton) and refining 45 MJ ton oil⁻¹ (1 ton), 0.16 kg CO₂-eq MJ⁻¹.

^y 42% allocation to the oil (energy content).

^z 0.26 ton oil ha⁻¹ yr⁻¹, 36.2 GJ ton⁻¹, 0.08 kg CO₂-eq MJ⁻¹.

^{aa} 0.5 ton oil ha⁻¹ yr⁻¹, 36.2 GJ ton⁻¹, 0.08 kg CO₂-eq MJ⁻¹.

Paz and Vissers [106] made GHG calculations for a jatropha plantation in Mozambique. Although their result (48% GHG reduction) is much more favourable than the plantation results reported here, they are mutually consistent because their estimate did not need to take account of land use change emissions, as jatropha was cultivated on an old tobacco estate. IFEU calculated GHG reductions for the same smallholder system in Tanzania and came to a saving of 444 kg CO₂-eq ha⁻¹ (68% GHG reduction) [107].

3.7. Biodiversity

The original vegetation in the area targeted to be cleared for the plantation consists of Eastern African Coastal Forest and Eastern miombo woodland; see Appendix F (App Fig. 6). In this area, seven tree species were found that are listed in the IUCN Red List of threatened species; see Appendix F (App Table 9). The plantation area is largely part of the so-called Northern Zanzibar-Inhambane coastal forest mosaic which is classified both as Critical Ecoregion and Biodiversity Hotspot. The southernmost part of the plantation is part of the Eastern miombo woodlands, which is also a Biodiversity Hotspot area. In the Northwest and Southeast, the plantation areas are bordered by forest reserves which belong to the Kilwa District Coastal Forest, which is classified as Key Biodiversity Area for its high degree of bird endemic species. The calculated Shannon and Sørensen indexes are shown in Table 10.

From these indexes it can be concluded that ‘forest’ has the highest biodiversity value and ‘woodland’ the lowest. The floristic composition of the sampled miombo woodlands is most similar to that of ‘open forest’, while the ‘forest’ and ‘dense forest’ categories also resemble each other. The average Shannon index of 2.18 for woodlands is relatively high, compared to the average value of 1.9 for largely undisturbed miombo woodlands found in Mozambique [108]. This is an indication that the woodlands investigated in this study are probably not ‘degraded’ in terms of biodiversity. For old-

growth miombo woodlands in northern Zambia for example, Shannon index values of 2.17–2.19 were reported, while miombo coppice showed decreased values of 1.36–1.54 [109]. Considering the large share of plant species in the Eastern miombo Woodland ecoregion of 54% which is endemic for that region, it is important to preserve this ecoregion [82]. The plantation company is planning to clear ultimately 80,000 ha. No trees, except Baobabs, will be left standing. This will result in a strong decrease of local biodiversity and in a largely fragmented habitat, with expected negative impacts on the regional biodiversity, including unique ecosystems and species with restricted ranges.

There was no evidence found of threats to biodiversity if jatropha is planted in hedgerows of live fences. In Central America live fences can contribute to biodiversity, more than 160 species of birds, bats, dung beetles and butterflies were recorded, furthermore “live fences offer a means of increasing tree cover in fragmented agricultural landscapes that can be readily adopted by farmers” [110]. Windbreaks can significantly enhance the local deposition of tree and shrub seeds within the agricultural landscape by attracting seed-dispersing birds from nearby forests [111]. However the specific value of jatropha trees in hedgerows in Tanzania would have to be further researched.

4. Discussion and conclusions

4.1. Comparison of the two business models

The key results of the comparison of the two jatropha business models are summarized in Table 11. These results convey that the choice of business model affects the socio-economic and environmental performance in many ways. The smallholder model scores much better on land rights, GHG balance and biodiversity and it reaches more people, whereas the plantation model creates more employment and higher (local prosperity) benefits for smaller numbers of people, and could

Table 10 – Biodiversity results for the plantation model.

	Nr of IUCN Red list species per class	Nr of IUCN Red list individuals per class	Shannon index	Sørensen index		
Woodland	3	12	2.18			
Open forest	2	5	2.52	0.55		
Forest	4	27	3.65	0.13	0.3	
Dense forest	4	11	3.33	0.11	0.16	0.52

Table 11 – Summary of the impacts on sustainability from the two business models.

	Smallholder-based model		Plantation model	
<i>Socio-economic areas of concern</i>				
1. Economic viability performance	Positive but relatively low NPV (8–18 M\$ ha ⁻¹), IRR (14–18%), PBP (12–13 y) and production costs between 1.10 and 1.14 \$ l ⁻¹	+–	Except when harvest is fully mechanized (–3 M\$ ha ⁻¹), the NPV is positive but relatively low; 15–41 M\$ ha ⁻¹ , IRR 17–91%, or 7% when harvest is mechanized). PBP 3–>20 y, production costs 1.10–1.24 \$ l ⁻¹)	+–
2. Local prosperity	Large outreach but lower contribution per person, more non-economic impacts. 126 field jobs, 80,000–160,000 farmers 140 \$ year ⁻¹ . Total investment 11 M\$, total expenses 77–130 M\$, 11% of costs related to processing	+	Contribution to employment can be substantial. 10,000–35,000 jobs. Total investment 32 M\$, total expenses 107–125 M\$, 18–20% of costs related to processing	+
3. Labour and working conditions	Difficult to regulate at farmers level, no irregularities observed	+	Possible to regulate, no irregularities observed except in exit strategy	+
4. Food security	Major issue in Tz; impact depends largely on household income	+	Major issue in Tz; impact depends largely on household income	+
5. Land ownership and land rights	Low direct effects	+	Large risk of negative impacts, 34,500 ha of land transferred, compensation paid but low at 20–30 \$ ha ⁻¹ (limited positive impact), also unclear whether money arrived at targeted group, 13 people displaced, loss of land rights after discontinuation (very negative)	–
<i>Environmental areas of concern</i>				
6. Greenhouse gas balance and carbon stock changes	Hardly any land use change effects 151% reduction if no replacement or original vegetation	+	Previous land use is the major issue, which is strongly location specific, 2% reduction but large uncertainty due to influence of removal of original vegetation	+–
7. Biodiversity	Increased if planted as a new hedge, but more research required	+	Very location specific, in this case strong decrease in on-site biodiversity, habitat fragmentation and decreased connectivity. 7 threatened tree species, Shannon index 2.18	–
+ : Positive impact, +– : neutral impact or both positive and negative, – : negative impact.				

possibly obtain higher yields. Risks of substantial negative impacts of the smallholder model are modest, whereas the plantation model could lead to decreased food security, loss of land rights and biodiversity. This could permanently affect the livelihood situation of the local population. The low GHG savings for the plantation system are due to the clearing of original vegetation; results would be much better if forest and woodland areas are avoided. A smallholder system seems to give farmers a better feeling of participation and can stimulate local entrepreneurship. On the other hand, permanent employment opportunities at a plantation model are higher, and rural development can be stimulated.

The economic analysis shows similar (low) rates of profitability with current yields, and the larger upfront investment that is required by a jatropha plantation model makes such investments currently risky.

The downside of the smallholder model for the processor is that there is no secured supply even with contracted out-growers, since honouring contracts is challenging in a developing country like Tanzania. The best approach is to pay an attractive price to farmers. This can be made possible by investing in efficient processing and adding value through selling of by-products.

Except for the financial feasibility and the environmental analysis, the comparison between these business models

could also apply to other feedstocks that are used in hedges or plantations. Issues with for example land rights in Tanzania are generic to large land transfers in general in Africa. GHG balance and biodiversity calculations apply to the specific crop and location we have chosen; in a different location, the results will be different. Location specific data about yields, profits, employment requirements, poverty situation, labour availability and land use will always be required for this. Furthermore, the implementation of the models can influence the performance of the systems. Implementation aspects are project specific such as vision and strategies of management team, company values, and so on. Also the policy environment is an important factor for the implementation of potentially successful business models. Both companies that we used to represent the two models were focussed on the European market and therefore on the European sustainability regulations, e.g. RED. This might have been a reason for them to make sure that they applied a relatively sustainable business model.

4.2. Framework accuracy

The assessment framework is useful for early flagging of potential major areas of concern for implementation of plantations and smallholder (hedge) models, at a stage when

corrective actions are still possible. However, the usefulness of indicators is partly constrained by limits on availability of data; while in certain other areas more/better indicators would be required to further operationalize the framework and obtain more accurate results. Locally practicable – not over-complex and/or overly expensive – indicators for monitoring soil, water, and air impacts are especially required. Ongoing pilot tests of the GBEP indicators and the RSB framework are expected to contribute to developing these. Furthermore, performing repeated measurements over time will provide more details on the performance of projects. Capturing wider and longer-term impacts from bioenergy projects also requires a longer-term view of the interaction with its broader development setting, taking account of factors such as policy changes, large regional development projects (e.g. infrastructure) and natural disasters such as floods or droughts. Furthermore, it will be useful to extend comparisons to other business models, especially those aiming at increasing local rural energy access, as this will assist governments and other organizations in determining which model is most or least suitable for specific locations. However, we also need to keep in mind that more extensive analysis – in whatever direction – can also reduce the framework's practicability.

4.3. Value of the framework for practice

One major lesson arising from the analysis is that the speed of change is a factor that requires attention. A very rapid increase in the number of people employed on a plantation as envisaged in our plantation case could cause food, fuel and water prices to rise, as local (isolated) markets have insufficient time to adjust. Both business models are expected to grow to 80,000 ha, this is a large area for cultivation of a plant that began to be grown commercially only recently. For these two reasons a gradual expansion trajectory is preferred for both models, which enables adequate time for adaptations and learning by doing. Moreover, the government should require realistic, socially acceptable exit strategies to be incorporated in the business plans, including a guarantee of re-transfer of land rights to local communities (for plantations), and cooperation agreements with other local organizations that can guarantee the market for jatropha seeds (for smallholder systems). Mandating clear communication with the local population, documented in writing in the local language for reasons of transparency, can help involve local communities and could minimize negative public perceptions and confusion. Organizing farmers into supply cooperatives groups could be a helpful model to make sure that farmers understand the value of honouring contracts and receive proper training and adequate payment in a smallholder model; it may also create a sense of social belonging and increase their bargaining power. Local governments should make sure that contracts do not repress farmers, could play a role in the establishment of farmer cooperatives and channel their own extension services through these.

The issue of food security is highly complex and our analysis cannot pretend to go beyond identifying key differences in risks and opportunities between the two models with a broad brush approach. Still, useful insights for action arise from it: in addition to boosting incomes, there are other

actions that biofuel operators may take to improve food security [55]. For example, biofuel operators could provide extension services that introduce improved farming techniques, crop diversification, and/or post-harvest processing and storage. Furthermore plantations can offer flexible working hours to ensure that household subsistence food production is not compromised. Large companies using costly inputs like inorganic fertilizers could sell these on to farmers at bulk prices, or allow their earth-working equipment to be used by local farming communities. They can help to connect small farmers to micro credit facilities. The maintenance of community woodlots could help provide fuelwood, and jatropha by-products could be made available as energy sources [13]. Finally, contributions to infrastructural development lead to easier market access, provide wider opportunities for regional development and create public goodwill.

4.4. Economic viability issues

There are still large uncertainties surrounding jatropha production (especially concerning feasible yields) because the commercial use of jatropha is still new. Most large scale plantation companies assume much higher yields in their business plans than what was assumed in the 'base case' estimate of our plantation model of 1 ton seeds per ha (against BioShape's own 6 tons). Therefore, most business plans have strategically predicted much more positive results in order to attract support from financial institutions, host governments, etc., whereas we wanted to show as much as possible the actual situation with current yields, costs and prices. Currently, only farmers with low opportunity costs for family labour can profit financially from jatropha cultivation, and then only if they use a low-input regime [43]. Processors, who are still struggling to reach their own break-even point, cannot (as yet) afford to pay them more remunerative seed prices.

It is to be expected that, like other crops at the beginning of their commercial cultivation, efforts in jatropha breeding will lead to higher yielding, more reliable varieties which will increase financial feasibility. Several breeding research initiatives are currently ongoing such as those by JATROPT [112] and QUINVITA, but results are only expected after several years. Efforts to improve harvesting efficiency (on plantations) and improve valorization of by-products could also boost profitability, such as experiments to use jatropha seedcake as an animal feed. Until results from these efforts materialize, the viability of jatropha cultivation in large plantation settings seems doubtful.

4.5. Inevitability of sustainability trade-offs

Business models that would generate no risks and no negative impacts on any area of concern would of course be preferred, however in practice such models do not exist. Compromises are always necessary, arising from sustainability trade-offs. In very poor regions, it is often a matter of hosting a large biofuel investor with all its pros and cons, or having no investment projects at all. This could mean a big tension between generating employment and incomes, or maintaining biodiversity. In the smallholder model, there is no less tension between ensuring adequate remuneration of farm labour on the one

hand, and striving for an acceptable IRR/NPV of processing companies on the other. The value that is placed on each area of concern is location and actor-specific and is embedded in a cultural and political mindset. Hence there are no easy choices that everyone can readily agree on. A shift from the status quo will always result in winners and losers. However, the status quo is certainly also unsustainable because of severe poverty. In the light of this, sustainability certification schemes such as the RSB and NTA8080 can be viewed as extremely demanding, as they require a positive (or at least neutral) impact in all areas, whereas this can be impossible to achieve in reality.

Still, the application of our framework shows that measures can often be identified to either prevent unsustainable outcomes, or ensure that already unsustainable situations improve over time. For instance, domestic processing is very important for impacts on local prosperity, and this is something that governments can influence. Tanzania's experiences show the value of tightening export regulation and introducing some monitoring of foreign investors [113,114]. Proper land use planning that can prevent future land conflicts and introducing a strong regulatory framework for land are also key government intervention areas, also identified by Habib-Mintz [115]. The Tanzanian government is discussing agro ecological zoning for better land use planning [116], in the realization that the development of domestic biofuel activities – both smallholder-driven and plantation-based – should be embedded in sustainable agricultural development and land use planning.

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Appendix A to F. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.biombioe.2013.10.005>.

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