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Greenhouse gas and energy balance of Jatropha biofuel production systems of Burkina Faso

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ABSTRACT

Jatropha curcas has been introduced as a low-cost energy crop in Burkina Faso for the production of straight vegetable oil (SVO) and biodiesel. It is cultivated in different plantation systems including smallholder inter-plantings with annual crops, large-scale monoculture, afforestation on marginal land, in traditional hedge systems along contour stone walls, and in living fences. We performed Life Cycle Assessment of these Jatropha systems using empirical data on yields and carbon stocks, and accounting for changes in agro-ecosystem provisioning and regulating services that occurred after the land conversion to Jatropha. The study found that all *J. curcas* production pathways substantially reduced greenhouse gas emission (68–89%) and saved energy (65–90%) compared to diesel fuel. Highest values are achievable under the assumption that by-products (husks, seed cake, glycerin) are used for energy generation. The decentralized production of SVO supplied by feedstocks from intercropping and hedgerow systems seems to be most promising option. However, very low land-use efficiency (6.5–9.5 GJ ha^{-1} production) characterized Jatropha intercropping and monoculture plantations, rendering the plant a competitor to food crops and increasing the risk of conversion of savanna land to Jatropha cultivation. Jatropha plantings on marginal lands largely failed. High labor requirements constrain integration of Jatropha plantation systems within small farmholdings. Currently, the traditional hedge systems show the lowest land-use replacement potential and labor needs while providing multiple ecosystem services, but alone cannot satisfy rural energy needs. In order to reach energy supply targets without claiming more land and compromising other ecosystem services, the *J. curcas* plantation systems in Burkina Faso need to be made more efficient through plant breeding and improved agronomic management.

Introduction

More than 80% of energy consumption in Burkina Faso is from the traditional use of biomass. With a growing population, the consumption of the biomass now exceeds the capacity of its re-growth, leading to soil erosion and land degradation (Arevalo, 2016; Hanff et al., 2011). The national energy deficit for transportation and electricity generation is covered by imported petroleum fuels amounting to 50% of the national trade balance (Arevalo, 2016; Tatsidjodoung et al., 2012). Burkina Faso struggles to exploit alternative renewable energy sources (e.g., solar energy, biogas, biofuel) to satisfy the growing energy demand, decrease the dependency on imported fossil fuel, and reduce environmental degradation associated with the traditional use of biomass (Dabat and Blin, 2011; Hanff et al., 2011; Laude, 2011).

Jatropha curcas is being promoted as a biofuel crop in Burkina Faso (Baumert, 2014) to supply different sectors of the economy. The following local and national scale scenarios have been elaborated for *J. curcas* biofuel production in Burkina Faso: (i) The cultivation of *J. curcas* on 2.4% of the arable land would enable the production of biodiesel to replace 100% of fossil fuels in the thermal power stations of the national electricity company (Hanff et al., 2011), thus reducing dependency on fossil oil imports; (ii) The local use of straight vegetable oil (SVO) from Jatropha in stationary diesel engines for off-grid electricity could contribute to the alleviation of energy scarcity in rural areas (Blin et al., 2013); (iii) In the long term, *J. curcas* biodiesel can be an alternative to conventional diesel in the transport sector (Tatsidjodoung et al., 2012).

It is generally agreed that sustainable bioenergy systems must provide net energy gains as well as environmental and local socio-economic benefits, and be producible in large quantities without compromising food production (Fritsche et al., 2005; Mangoyana, 2009). Also, the production chain is expected to be carbon neutral or mitigate climate change, taking into account agro-inputs in energy crop production and CO_2 losses due to conversion of carbon-dense ecosystems to energy crops (Fargione et al., 2008). Life Cycle Assessment (LCA) is a common tool to evaluate the energy efficiency, carbon neutrality, and policy-relevant issues of biofuel production systems (Gnansounou et al., 2009; Thornley et al., 2015). To date, no LCA

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has been conducted for *J. curcas* in Burkina Faso, where its biofuel production proceeds without knowledge of environmental consequences of the various production systems.

Over-optimistic *J. curcas* yield estimations were stated as a major source of error in LCAs (Almeida et al., 2014; Gasparatos et al., 2012). For instance, the LCA of *J. curcas* for West Africa by Ndong et al. (2009) did not include C-stock changes due to land conversion, and assumed seed yields >100% higher than reported in Burkina Faso (Baumert and Khamzina, 2015). Land-use and land-cover changes have often been overlooked in LCA calculations (Reinhardt et al., 2008) but need to be considered due to changes in ecosystem soil and biomass C-stocks associated with the introduction of biofuel crops (Mangoyana, 2009; Reinhardt et al., 2008). Furthermore, the energy needs for human labor are not part of most LCA methodologies (Grimsby et al., 2012) but can be substantial in the manually managed, labor-intensive systems of the small farmers in West Africa (Ndong et al., 2009).

This study aims to evaluate the production of *J. curcas* SVO and biodiesel (Jatropha methyl ester, JME) in Burkina Faso using the LCA methodology, with focus on greenhouse gas (GHG) emissions, fossil energy use and environmental impacts of Jatropha introduction. To this end, we applied empirical data from *J. curcas* farming systems characteristic for Burkina Faso (their yields and carbon stocks) and accounted for changes in agro-ecosystem provisioning and regulating services that occurred after the transition of land use to *J. curcas* cultivation.

Materials and methods

Jatropha systems in Burkina Faso

In Burkina Faso *Jatropha curcas* is commonly planted in hedgerows to demarcate property, protecting fields from roaming animals, and serving as windbreaks for erosion control (Soulama, 2008). Since 2009, *J. curcas* has been promoted by the government for biofuel production to supply the national electricity and transport sectors. To this end, *J. curcas* has been predominantly introduced in intercrop systems with annual crops and on abandoned degraded soils (Table 1) to avoid possible loss in food production. A maximum of 500,000 ha of land for bioenergy production has been targeted so far (MMCE, 2009). An inventory of *J. curcas* cultivation systems in Burkina Faso (Baumert, 2014) distinguished five main types, as summarized in Table 1. Of these, afforestation systems on marginal lands were not considered in the present study as these were poorly maintained and consequently did not show any biofuel production potential due to low survival rates, stunted plant growth, and lack of fruit yield.

Goal and scope

The main research objective was to assess the climate regulation and energy provision potential of *J. curcas* biofuel production systems in Burkina Faso by evaluating their GHG emissions and energy consumption. System boundaries encompassed the complete life cycle of *J. curcas* oil and biodiesel (Fig. 1a,b)—from cultivation through seed processing to biofuel storage ('Well-to-Tank')—and considered the terrestrial C-stock changes associated with the land use change. Furthermore, the results were compared to the life cycle of diesel fuel. In the end, sustainability of *J. curcas* biofuel was defined by GHG emission reduction and fossil energy savings. The LCA study is defined by a set of ISO norms (ISO 14040, 2006; ISO 14044, 2006) to assess potential environmental impacts throughout the product life cycle.

Functional units

The overall GHG budgets of the *J. curcas* systems were calculated by adding GHG savings or emissions arising from changes in carbon stocks due to land use conversion (ΔC_{LUC}), annualized over the 20-year life cycle of *J. curcas*, GHG emissions arising on- and off-farm (C_f, C_i), and avoided emissions (C_a) through the substitution of energy carriers: $C_{budget} = \pm \Delta C_{LUC}/20 + (C_f + C_i) - C_a$.

Carbon was expressed in CO_2 by multiplying by the factor 44/12. GHG emissions comprised carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). All emissions were converted into carbon dioxide equivalents (kg CO_2e) using the 100-year Global Warming Potentials (GWP) with CO_2: 1, CH_4: 23, and N_2O: 296 (BioGrace, 2013). The functional unit for GHG analysis is area based (kg CO_2e per hectare and year) and output based (kg CO_2e per gigajoule of *J. curcas* SVO or JME).

The cumulated auxiliary energy demand for the production of *J. curcas* biofuel was calculated by summing all energy requirements along the production pathway (Fig. 1a,b). The functional unit for energy analysis is area based (GJ per hectare and year) and output based (MJ per GJ of SVO or MJ per GJ of JME). The Net Energy Ratio (NER) between the quantity of renewable energy attained and the quantity of fossil fuel consumed provides information on the efficiency of the fossil energy in the production of one unit of biofuel (Prueksakorn and Gheewala, 2008). With NER > 1, the fuel can be considered as renewable.

Table 1
Jatropha curcas cultivation systems in Burkina Faso.
(modified from Baumert et al. (2016) and Baumert and Khamzina (2015)).

Cultivation system	System characteristics	Agro-ecological conditions	Average seed yield
Small-scale intercropping 34 plantations visited and 277 plants measured. Age: 1–4 years.	*J. curcas* interplanted with annual crops on small scale (1.8 ± 0.15 ha). Common spacing 4 m × 4 m. Indirect, low-intensity management through maintenance of intercrops, i.e., irregular fertilization (0–150 kg of NPK and 0–100 kg ha^{-1} y^{-1} of urea for the intercrop), manual management, ox-plow, no pruning.	Sudanian agro-ecological zone (AEZ) with annual rainfall 950 mm from May to October. Main soil types *ferric lixisols* and *leptosols*.	0.81 ± 0.2 t h^{-1} (4 years after planting)
Afforestation on marginal land 6 plantations visited and 70 plants measured. Age: 1–2 years.	Land previously abandoned from agricultural activities. No management.		None
Intensely managed plantation 4 plantations visited and 40 plants measured. Age: 3–4 years.	Intercropping or monoculture on a larger scale (50–70 ha). Common spacing 4 m × 4 m. High-intensity management of *J. curcas* trees through regular fertilization (~150 kg of NPK and ~100 kg ha^{-1} y^{-1} of urea), irrigation, motorized soil tillage, pesticide application.		1.25 ± 0.3 t ha^{-1} (4 years after planting)
Living fence 40 stands visited and 148 plants measured. Age: 1–25 years.	Dense plantings around field for protection from browsing animals. 900 trees ha^{-1}. Indirect, low-intensity management through maintenance of adjacent crop.	Sudano-Sahelian AEZ with annual rainfall 860 mm from May to October. Deep *lixisols*.	0.72 ± 0.06 t ha^{-1} (>7-year-old stands)
Contour hedge 6 plantations visited and 55 plants measured. Age: 2–3 years.	Plantings along contour stone walls with wider spacing than in living fences. 200 trees ha^{-1}. Indirect, low-intensity management through maintenance of adjacent crop.	Sahelian AEZ with average annual rainfall 650 mm from June to September. Mainly *cambisols*.	0.11 ± 0.02 t ha^{-1} (2 years after planting)