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REVIEW ARTICLE

Assessment of benefits and risks of growing Jatropha (*Jatropha curcas*) as a biofuel crop in sub-Saharan Africa: a contribution to agronomic and socio-economic policies

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Abstract In sub-Saharan Africa (SSA), the main goals behind the development of a biofuel industry are employment creation and income generation. Jatropha (*Jatropha curcas* L.) has emerged as a candidate for biodiesel production. It is a non-edible oil producing, drought-resistant plant that can be grown on marginal land with limited water and low soil fertility. However, these are also attributes that typify weedy and invasive plant species. Adding to these concerns are the general questioning of whether biofuel production will reduce Greenhouse gas (GHG) emissions globally. Currently, there is limited information on the potential invasiveness of many biofuel crops, and in particular, the potential risks of cultivating Jatropha. This paper aims to assess the benefits and risks, especially risks, of growing Jatropha for biodiesel production. Jatropha should be screened through a science-based risk-assessment procedure to predict the risk of becoming invasive before it is released for large-scale commercial cultivation. The net GHG savings can be achieved through the cultivation of Jatropha, considering two main factors: no land-use change and crop management without chemical fertilization.

Keywords Biofuel · Invasive · Jatropha · Risk

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Introduction

In sub-Saharan Africa (SSA), two-thirds (about 620 million) of the total population live without electricity (IEA 2014). This has created growing demand for energy in the region and has opened an opportunity for biofuels-production systems, a new economic opportunity (Mitchell 2011). Consumption of transport fuels in SSA has increased at a rate of 7% per year, as a result of growth in the economic activities within the region (Mulugetta 2008). In rural areas, where a majority of the community may not be able to afford fossil fuel, Jatropha biofuel systems are important energy alternative that can improve smallholder livelihoods, as the oil can be easily extracted with a simple technology and used for cooking in stoves, lighting in lamps, and simple generators (Muys et al. 2013). Bioenergy in SSA becomes even more relevant because of poor access to energy, and vulnerability of agricultural production systems and natural vegetation to climate change. (van Eijck et al. 2012). Furthermore, this region has large tract of land with high capacity for biofuels production (Enweremadu and Alamu 2010). Currently, yields in these vast areas of agricultural land are significantly lower than what is potentially feasible (van Eijck et al. 2012). Therefore, biofuels production can play a significant role in energy security, employment creation, and rural development (Faaij and Domac 2006; Maltsoglou et al. 2013; van Eijck et al. 2014).

The production of biomass for energy generation has gained planetary significance (Barney and DiTomaso 2008; Fletcher et al. 2011) due to its potential to reduce greenhouse gas (GHG) emissions and climate change (Fargione et al. 2008; Buddenhagen et al. 2009; Charles 2009; Kgathi et al. 2012; Koçar and Civaş 2013). The reduction in GHG emissions can be achieved, provided that farmers are not tempted by higher prices for biofuels and do not convert forest and grassland to biofuel crop production (Searchinger et al. 2008). Diverting ecosystems to biodiesel production may create a biofuel carbon debt and increase GHG emissions (Fargione et al. 2008). Biofuels are also perceived to be a strategy for achieving foreign exchange savings, economic growth, and rural development (Gasparatos et al. 2015).

Fossil fuel is the major energy source, constituting 80.3% of the global energy, with 57.7% used in the transport sector (IEA 2006). Fossil fuels are responsible for a significant amount of GHG emissions (Escobar et al. 2009). As a result of these negative consequences, scientists and policymakers have opted for renewable sources of energy. The European Union (EU) has set a target to replace 10% of transport fuel with biofuel by 2020 (Rao et al. 2012). Similarly, the U.S congress instituted a 5% increase in the use of bioenergy (Basili and Fontini 2012). It has been projected that biofuel production could contribute up to 33% of the global energy supply by the year 2050 (van Vuuren et al. 2009; Dornburg et al. 2010). Recently, biofuel crops, such as perennial grasses, woody, and annual crops, are being widely evaluated for biofuels production (Zegada-Lizarazu and Monti 2012).

In India, Southeast Asia, and Africa, Jatropha is emerging as an attractive option for biodiesel production largely because it is perceived as high yielding on marginal lands (von Maltitz et al. 2014; Achten et al. 2015). The production of Jatropha on marginal land suggests that such areas have little value for commercially viable agriculture and would not compete with food production (Brittaine and Lutaladio 2010; Singh et al. 2013a). However, recent literature has revealed that cultivation of Jatropha in marginal land may be associated with low yields, a factor which hampers viability of Jatropha projects.

Jatropha was introduced to Africa as a biofuel feedstock mainly through non-governmental organizations (NGOs) and private companies (Romijn and Caniels 2011; ADB 2012; Muys et al. 2013). These stakeholders viewed Jatropha as miracle crop that can create not only local employment and profit to investors, but also contribute to a reduction in GHGs and energy security (von Maltitz et al. 2014). The global area under Jatropha cultivation was estimated at 900,000 hectares in 2008, with projections of a total of 12.8 million hectares by 2015 (GEXSI 2008). The largest cultivated region, about, 80%, was in Asia, 15% in Africa and the rest in Latin America (Brittaine and Lutaladio 2010). In India, their national mission on biodiesel has promoted Jatropha cultivation on a massive scale (Singh et al. 2013a). In addition, the biodiesel has been certified as a fuel and fuel additive by the Environmental Protection Agency (Debnath and Bisen 2008).

Unfortunately, many plants proposed for biofuels production, including Jatropha, possess attributes for invasiveness (DiTomaso et al. 2007; Buddenhagen et al. 2009; Low et al. 2011). Despite concerns about the adverse environmental impacts of biofuels, Jatropha continues to attract increasing attention worldwide, especially in Asia and Africa where it is expected to be planted on larger scale. However, it is important to assess the potential agricultural and ecological risks that may be associated with the introduction of this exotic species to agro-ecosystems. This article aims to evaluate the benefits and risks of cultivating Jatropha with its high degree of invasiveness, for biodiesel production. Given that one of the main target of biofuel sector progress is reduction in GHGs, this work will also highlight the potential impact of Jatropha cultivation on GHGs.

The choice of Jatropha

Jatropha seed-oil content ranges from 31–35% by weight (Debnath and Bisen 2008; Soo-Young 2011). This high oil content is promising for agro-industrial use because its biodiesel has physical and chemical properties similar to conventional biodiesel (Martinez-Herrera et al. 2006; Abdelgadir and van Staden 2013). In addition, its drought tolerance makes it much more suitable for biodiesel production (King et al. 2009; Biswas et al. 2010; Ricci et al. 2012). The seed oil can be easily extracted and used as biodiesel that meets the international standards (Azam et al. 2005; Tiwari et al. 2007). These desirable properties have prompted investors and governments to consider Jatropha as a substitute for conventional fossil fuels in an attempt to mitigate climate change (Achten et al. 2008).

Almost all of the commercially available biofuels are from first generation crops produced from food crops; for example, grains and sugarcane, as well as from vegetable oils (rapeseed, palm, and sunflower) (Mohr and Raman 2013; Tang and Tang 2014; Ziolkowska 2014). The use of edible crops for biofuels production raises the “fuel versus food” debate as it is likely to affect agricultural production (Kgathi et al. 2012; Koçar and Civaş 2013). However, Jatropha is the exception because it does not compete with food production. Moreover, it can be cultivated on marginal land because of its lower fertilizer and water needs. It is crucial to emphasize that cultivation of Jatropha in marginal land is associated with low potential for commercially viable agriculture and may therefore not compromise food-security issues (Basili and Fontini 2012: Singh et al. 2013a).

Jatropha was initially known for ethnomedicine use and as livestock-proof hedgerow (Henning 2004). It is even suggested that it was literally unknown to academia, government and investors globally, especially in southern Africa (von Maltitz et al. 2014). By 2007, 111,000 ha of Jatropha were reported to have been planted in 52 projects within southern Africa (GEXSI 2008). The report further forecasted an increase in hectarage to 2.2 million hectares by 2015. In India, government and international investors promoted commercial cultivation of Jatropha on large plantations (Heller 1996; Kumar et al. 2012). These stakeholders glorified Jatropha as versatile crop that could grow on marginal land to create employment and generate revenue to the local communities and investors (von Maltitz et al. 2014). These claims about the positive performance of Jatropha in poor agricultural land and low inputs are being challenged because they are not based on any credible scientific evidence (Openshaw 2000; Fairless 2007; Achten et al. 2008).

While Jatropha is promoted as an economically and environmentally sustainable feedstock for biofuel production (Renner 2007), there is limited information about its cultivation and management (Achten et al. 2010). For Jatropha to be an economically viable biofuel crop, it is a pre-requisite to develop varieties and other technologies that will address local climatic and agro-ecological constraints (Singh et al. 2013a), since its economic viability as a biomass for biodiesel production under its current state as a wild plant are questionable (Basili and Fontini 2012; Singh et al. 2013a). Experimental studies in India by Singh et al. (2013b) have concluded that for Jatropha to be economically important biodiesel crop it must produce a minimum yield of 4–5 t ha^{-1} with oil content of about 35–40%. Yield assessment of Jatropha plantations in the semi-arid tropical location at International Crops Research Institute for the Semi-arid Tropics (ICRISAT) in Patancheru, indicated that seed yield ranged from 600 kg ha^{-1} at third year to 1560 kg ha^{-1}, influenced mainly by distribution of rainfall during the season (Rao et al. 2012).

Agronomy of Jatropha

Jatropha (Euphorbiaceae) is a multi-purpose and drought-resistant perennial plant, gaining importance as an economically justifiable alternative to conventional diesel (Jones and Miller 1992; Ranade et al. 2008; Sachdeva et al. 2011). There are about 170 different species of Jatropha (Ranade et al. 2008; Basili and Fontini 2012; Sabandar et al. 2013) being distributed worldwide (Schmook and Seralta-Peraza 1997; Deore and Johnson 2008). Even though it can be propagated from seed, seedlings, and cuttings (Misra and Misra 2010; Patil et al. 2015), direct seeding is constrained by low seed germination and cuttings have poor root development (Openshaw 2000; Purkayastha et al. 2010). Its height ranges from two to three meters, but under favourable conditions it can reach a height of ten meters (Achten et al. 2008; Debnath and Bisen 2008). How long Jatropha plants can live largely depends on climatic and agro-ecological regions varying from 40 to 50 years (Kaushik et al. 2007; Achten et al. 2010). The plant takes two to three years to start producing fruits and reach full fruit bearing in the fourth or fifth year (Debnath and Bisen 2008).

Jatropha grows within the temperature range of 15–40 °C (Kumar and Sharma 2008) and is susceptible to frost (Gour 2006; Orwa et al. 2009). The latest studies in Botswana demonstrated that cold weather causes severe damage to Jatropha trees, which delays their sprouting in spring (Inafuku et al. 2013). The plant can be grown on a wide range of soils, but loose soils with good aeration are preferred as they are less likely to be water logged (Foidl et al. 1996; Heller 1996). For example in India, river sand was found to be the best germination medium than vermiculite (Mariappan et al. 2014). Therefore, the plant should not be cultivated in heavy soils (Biswas et al. 2006; Singh et al. 2006), because such soils have poor drainage and aeration that will retard root formation and development (Heller 1996).

Jatropha is still considered a wild plant that grows well under rain-fed conditions from low (250 mm) to high amounts of (3000 mm per annum) rainfall (Foidl et al. 1996). However, there is a gap in knowledge about the management and yield potential of promising clones in different agro-ecological zones (Rao et al. 2012). Seed yields from undomesticated Jatropha plant were reported to be not more than 1 t ha^{-1} (van Eijck et al. 2010).

Interestingly, because it is adapted to marginal soils with low nutrient content, Jatropha can be used to rehabilitate degraded land (Openshaw 2000; Jongschaap et al. 2007; Garg et al. 2011). Furthermore, it is capable of producing seed yields of good quality under minimum water requirements compared to other crops (Kheira and Atta 2009). Seed yield is quite variable and varies from 0.2 to >2 kg seeds from a single plant or 0.4–12 t ha^{-1} (Francis et al. 2005; Achten et al. 2008; Wani et al. 2012). The variation in seed yield is strongly linked to diverse environments where it is cultivated (Behera et al. 2010; Srivastava et al. 2011). In Tanzania, large-scale Jatropha oil production, seed yield of 2–5.4 t ha^{-1} a^{-1} were obtained under optimum conditions, i.e. fertilizer and good soil (Segerstedt and Bobert 2013).

Lands in arid and semi-arid areas have always been favored as ideal places for biofuel production, as it is doubtful that any significant contribution to food production can be made (Achten et al. 2013). Jatropha is well adapted to arid and semi-arid conditions where it is used to protect soil from erosion, rehabilitate land, and serve as a livestock-proof hedgerow (Martinez-Herrera et al. 2006;

Abdelgadir and van Starden 2013). However, yields under arid and semi-arid areas were found to be significantly lower than expected (Sanderson 2009). Romijn (2011), quoting personal communication with Y. W. Franken reported that in Honduras, Mali and Mozambique, oil yields ranged from more than 1250 L ha^{-1} a^{-1} in favorable conditions to a meager 250 L ha^{-1} a^{-1} based on minimal water supply and low soil fertility.

Uses of Jatropha

About 69% of the world's poorest people rely on biomass for their daily energy needs, and Jatropha is the principal crop for biofuels production (ENDA 2008). The main sources of energy in these poor communities are fuelwood and charcoal (Wiskerke et al. 2010). Because Jatropha oil properties are similar to those of conventional diesel (Berchmans and Hirata 2008) and when combined with an uncomplicated extraction methodology, such biofuel is an ideal option for poor countries and can be used directly in cooking, lighting, and simple generators. In view of these desirable oil properties, biodiesel from Jatropha has turned into very suitable energy choice for the remote areas in SSA, where fossil fuel is expensive and its supply unreliable (Basili and Fontini 2012; Muys et al. 2013).

According to Muys et al. (2013), economic models postulated that when Jatropha biofuel systems are economically viable, they could result in oil prices of $\geq$\$70 US dollars per barrel. The same source also cautioned that even when the oil prices were higher than the baseline price, there was no viable Jatropha projects as poor returns resulted in abandonment of most large-scale commercial plantations.

Jatropha was first commercialized by exportation of its seed oil from Cape Verde to Portugal for soap production and lamps (Gübitz et al. 1999). The seeds are highly harmful as they contain several toxins (phorbol esters, curcin, trypsin inhibitors, lectins and phytates) as well as allergic proteins (Abdu-Aguye et al. 1986; Lioglier 1990; Becker and Makkar 1998; Maciel et al. 2009). However, after detoxification, the seed cake can provide a highly nutritious and cheap protein (50–60%) supplement for animal feed (Makkar et al. 1998). The seed cake contains more nutrients than both chicken and cattle manure (Francis et al. 2005), and can be used as an organic fertilizer and the organic waste products can be used in the production of biogas (Lopez et al. 1997; Staubmann et al. 1997; Gübitz et al. 1999).

Its nitrogen content ranges from 3.2 to 3.8% (Kumar and Sharma 2008). A fertilizer trial by Henning (2004) on pearl millet indicated that the this crop reached its maximum potential yield in Jatropha oil cake (5 t ha^{-1}) compared with farm-yard manure (5 t ha^{-1}) and NP fertilizer (100 kg ammonium phosphate and 50 kg urea ha^{-1}). Nitrogen-based fertilizers based on Jatropha seedcake are likely to reduce N_2O emissions (Basili and Fontini 2012). Jatropha plants can easily regenerate from cuttings and are therefore mostly planted as a hedge to protect homesteads and fields as it is too poisonous and unpalatable to be browsed by cattle or other animals (Henning 2004; Martínez-Herrera et al. 2006). It can also be used to control soil erosion, and to rehabilitate agricultural wastelands (Francis et al. 2005).

Jatropha species are traditionally used for treatment of several diseases in Africa, Asia and Latin America (Burkill 1994; Abdelgadir and van Staden 2013). In Senegal, Nigeria, Congo, and East Africa, stem sap or dried powdered plant is applied on fresh wounds to stop bleeding (Abdelgadir and van Staden 2013). In Congo, dried sap is also used as "penicillin." Jatropha oil seed is known for its laxative effect, which heals digestive system symptoms such as abdominal pains and looseness of the bowels (Sabandar et al. 2013). However, Lioglier (1990) advised to the contrary and warned that the seeds of *Jatropha* species are highly toxic and should not be considered for herbal medicine. The seeds contain curcin, a phytotoxin that causes vomiting, bloody diarrhea, and central nervous system depression (Abdu-Aguye et al. 1986). It is stated that the seeds can cause nausea, vomiting and dizziness, and in extreme conditions, even death (Becker and Makkar 1998). Other uses of Jatropha include the manufacture of lubricants, soaps and candles, astringents and coloring dye (Jain 1991; Ambasta 1994).

While Jatropha is widely used in traditional medicine in most regions of Africa, a review on the uses of different parts of Jatropha plants in folk and traditional medicine by Abdelgadir and van Staden (2013) did not indicate any medicinal uses in Southern Africa. However, Henning (2004) reported the main uses of Jatropha in Southern Africa as medicinal and animal-proof hedgerow. It was practically unknown to academics and governments in Southern Africa until 2000, when it started to be promoted as a biodiesel crop (von Maltitz et al. 2014). While it is also being promoted as an energy crop in the region, it is banned in South Africa because it is considered a noxious weed (Blanchard et al. 2011).

Risks associated with Jatropha cultivation and production

Jatropha has been praised on unproven claims of high oil yields without any scientific backing (Das et al. 2012; von Maltitz et al. 2014). For example, the large-scale Jatropha cultivation was carried out without use of improved varieties, on-farm evaluation, and assessment of appropriate management practices (Edrisi et al. 2015). Large-scale cultivation and investments pose socio-economic and environmental hazards (Achten et al. 2010, 2015). In view of this uncertainty, it is imperative to examine potential dangers that might arise out of large-scale cultivation of Jatropha.

Invasiveness risk

One of the main challenges to this booming industry is how to meet biofuel demands efficiently and sustainably on the scarce land, while at the same time avoiding negative environmental consequences, such as the risk of invasiveness (Robertson et al. 2008). A significant number of crops proposed for biofuels production have the potential to become invasive (Buddenhagen et al. 2009; Barney and DiTomaso 2011; von Maltitz et al. 2014). This concern stems from the fact that desirable traits for an ideal biofuel crop—such as high productivity, tolerance to abiotic stress, low-input requirements and wide habitat breath—are the same physiological traits that facilitate invasiveness (Raghu et al. 2006; Barney and DiTomaso 2011; Flory et al. 2012).

In response to the potential invasiveness risk of biofuel crops, international organizations, such as Global Invasive Programme (GISP) and International Union for Conservation of Nature (IUCN), have produced a white paper to guide the selection of biofuel feedstocks and management strategies, including regulatory and policy reforms, created to prevent widespread invasion (Quinn et al. 2013). Both organizations recommend that plant protection officers to be consulted before biofuel feedstocks are introduced (GISP 2007; IUCN 2009). Most biofuel crops are cultivated in areas outside their geographical origin, thus exacerbating the potential risk of future invasions (Barney and DiTomaso 2008). For example, the United States is evaluating miscanthus hybrids (*Miscanthus* × *giganteus*) as a potential biomass crop (Lewandowski et al. 2003; Jørgensen 2011) which is native to Eastern Asia (Stewart et al. 2009). Similarly, Jatropha originates in South America and Mexico (Makkar and Becker 2009; Achten et al. 2010), but is currently widely promoted for biodiesel production in India, Southeast Asia, and Africa.

Invasive plants are those ones that grow vigorously when introduced into an exotic ecosystem, occupy large tracts of land and out-compete native species, destroying plant diversity and ecosystem services (IUCN 2009). Invasive species are only surpassed by habitat destruction in terms of their threat to biodiversity (Randall 1996; Vitousek et al. 1997; Mack et al. 2000; Wittenberg and Cock 2001; Clout and Williams 2009). The economic costs of invasive species to the economy can be significantly high. The negative impact of invasive species is projected to be more than US \$1.4 trillion, which is equivalent to five percent of the global economy (Pimentel et al. 2001). Since Jatropha is classified as invasive crop (GISP 2008), its cultivation was forbidden in Australia (Royal Botanic Gardens Sydney 2008) and South Africa (Blanchard et al. 2011; von Maltitz et al. 2014). Conversely, most sub-Sahara African countries consider it as an important biofuel crop (Spaan et al. 2004).

The proposed large-scale cultivation, transport, processing, and breeding for high-yielding varieties provide opportunities for successful "escape" and invasion of nearby agro-ecosystems (Richardson and Blanchard 2011; Barney 2014). The success of invasion however, is largely determined by the amount of seeds or other reproductive structures dispersed into that system (Lockwood et al. 2005). The risks of invasiveness therefore increase with increasing number of propagules (Holle and Simberloff 2005). The anticipated large-scale of Jatropha plantings implies that it has many opportunities to escape because of high propagule pressure (Low et al. 2011). Experimental studies in Zambia on Jatropha demonstrated that its seeds or cuttings were not able to escape and spread significantly from deliberate plantings (Negussie et al. 2013a). However, the plant has been predicted to be highly invasive when cultivated in regions where it does not naturally occur (Negussie et al. 2013b). Such contradictory reports call for the importance of studies focusing on risk assessment of large-scale cultivation of Jatropha.

Another key concern is about whether biofuel crops can produce enough fuel to meet energy needs and become profitable on the domestic or international markets (Fargione et al. 2008; Scharlemann and Laurance 2008). In Tanzania, the price for Jatropha seed in 2007–2009 ranged from 0.14 to 0.18 \$ kg^{-1} (Loos 2008; Mitchell 2008), whereas, in Kenya it ranged from 0.12–0.18 \$ kg^{-1}. Still in Tanzania, Wiskerke et al. (2010) found that the production cost of Jatropha oil makes it too expensive to be used as a substitute for fuelwood and concluded that smallholder Jatropha oil production as an alternative fuel for household cooking is not economically attractive.

Segerstedt and Bobert (2013) used an economic land-evaluation assessment for large-scale Jatropha oil production in Tanzania, which showed that more fertilizer and as well as more labor are needed to achieve high seed yields (2–5.4 t ha^{-1}). These high input costs will elevate the price of production and thus render the Jatropha biodiesel production system unprofitable (Achten et al. 2015). Market failures can contribute significantly to the risk of Jatropha invasiveness. Many plantations were unsuccessful, due to lack of markets for the seeds (Sanderson 2009) or poor yields (Euler and Gorriz 2004; Ariza-Montobbio and Lele 2010). These low returns resulted in abandonment of commercial large-scale plantings with the risk of plant escapes into adjacent land use systems.

Jatropha seeds have been reported to be dispersed mainly anthropogenically and by gravitational force (Hannan-Jones and Csurhes 2008). Plant features can enhance its growth aggressiveness (Pyšek and Richardson 2007); for example: larger and more prolific species naturally attract more dispersal agents and therefore ensuring its spreading (Jelbert et al. 2015). Animals usually disperse seeds by consuming and ejecting them later through their digestive tract. However, the toxins in the Jatropha fruits and seeds make them inedible and unattractive food source for animals and therefore less likely to be dispersed by them (Negussie et al. 2013b).

Rejmánek and Richardson (1996) showed that seed weight correlates negatively with dispersal distance. Large seeds are too heavy to be dispersed and would therefore require large animals and strong winds to be successfully dispersed physically (Kelly 1995). Jatropha seeds are quite large and range from $1.69 \times 1.4 \times 0.84$ mm to $1.84 \times 1.31 \times 0.85$ mm as length, width and breadth, respectively (Misra and Misra 2010). Given that for an invasion to occur, seeds or reproductive structures must be dispersed to suitable sites (Burns et al. 2013; Lewis et al. 2014); however, the risks of invasiveness associated with Jatropha cultivation might be low, owing to its large seed which would be too heavy to be dispersed.

Seeds and seedlings predation occurs mostly around the parent where seeds and seedlings are concentrated (Peres et al. 1997; Hulme 1998; Willson and Traveset 2000). In Zambia, rodents and shrews were reported to be consuming Jatropha seeds (Negussie et al. 2013a). Given that Jatropha seeds may not be dispersed further away from the parent plant, they are more likely to be destroyed by predators and pathogens. Furthermore, experimental studies in Botswana by Inafuku-Teramoto et al. (2013) demonstrated that Jatropha trees are susceptible to frost damage and can lose all their leaves when conditions become too cold. In China, Liang et al. (2007) observed that Jatropha is susceptible to chilling stress, especially at seedling stage. Additionally, the loss of leaves will delayed sprouting in spring. This observation substantiates the suggestion that risks of invasiveness from Jatropha cultivation would be low.

Jatropha susceptibility to low temperatures suggests that its recruitment from stumps or coppicing will be slow and further limit its invasiveness. The seeds of Jatropha are reported to have low viability (Rakkimuthu et al. 2011), suggesting that germination rates from seed banks will be reduced over time. Once the seed bank is built, it gives the species opportunity to germinate and establish when conditions are favorable (Rejmánek 2000), making control and eradication difficult (Lewis et al. 2014). However, it is unlikely that this will be the case with Jatropha seed bank, given its low seed viability.

Recent studies have challenged the production efficiency of biofuels crops and have called attention to the need of a large cultivation area, besides water use for irrigation. Such combined aspects would not be compensated as biofuel production is still low (Steer and Hanson 2015). There is also a chance of biofuels production becoming more profitable, tempting growers to convert agricultural land to biofuel crop cultivation. Another point would be the failure in producing economic yields of biofuel, leading its cultivation to be carried out in fertile arable areas (Fargione et al. 2008). This scenario could occur with Jatropha due to its poor performance on marginal lands.

Impact on greenhouse gas emissions

Most studies have demonstrated that replacing traditional fossil fuel with biofuels will reduce GHG emissions (Fargione et al. 2008; Gallagher 2008; Naik et al. 2010), because the growing biofuel crop sequesters carbon (Osamu and Carl 1989; Scarlat and Dallemand 2011). The GHG balance is largely influenced by the type of biofuel feedstock used, the crop management during cultivation, and whether there are land-use changes (Quirin et al. 2004; Larson 2006; Dornburg et al. 2010). Therefore, in the assessment of carbon debt or credit resulting from land-use change, the carbon benefits of using land for biofuels should be taken into consideration, including carbon costs, carbon storage, and sequestration forfeited by converting land from its current uses (Searchinger et al. 2008).

As with other biofuel crops, one of the most appealing aspects for Jatropha biofuel is to reduce GHG emissions. Tilman et al. (2009) recommended that plants that grow in degraded lands not suitable for agricultural production that also absorb carbon dioxide from the atmosphere should be considered for biofuel production. Jatropha meets these requirements and its cultivation does not induce land-use change (Basili and Fontini 2012) and thus will result in net GHG savings (Gallagher 2008). However, the application of nitrogen fertilizers can negate the net GHG savings through the emission of nitrous oxide (N_2O) (Crutzen et al. 2008), given that the nitrogen-based fertilizers will emit significant amount of N_2O (IPCC 2006). It is recommended that instead, seedcake, a by-product from Jatropha oil extraction, be used as an organic fertilizer (Basili and Fontini 2012).

Life cycle assessment (LCA) studies on Jatropha biodiesel, covering the system from crop cultivation in the field through burning biodiesel in generators and engines, are generally in agreement that there is a reduction in GHG emissions (Tobin and Fulford 2005; Ndong et al. 2009; Achten et al. 2010; Kumar et al. 2012). LCA studies have demonstrated that replacing petroleum diesel with Jatropha biodiesel will reduce net GHG emissions by up to 62% (Whitaker and Heath 2008). Such reductions though, will only be achieved when both direct and indirect land-use change are avoided and by-products, such as seedcake, are used as organic fertilizer (Muys et al. 2013). Achten et al. (2013) assessed the carbon balance of potential land-use change to Jatropha cultivation and found more carbon debt (70–118 t C ha^{-1}) in 1.15 billion ha of forested areas under arid and semi-arid climates than in 0.75 billion ha shrubland (24–28 t C ha^{-1}). Importantly, they projected that the carbon debts will be repaid within 30 years, with a seed yield of 3.5–3.9 and 5 t ha^{-1} a^{-1} in shrubland and forested areas, respectively.

Kritana and Gheewala (2006) investigated GHG emissions from Jatropha production in Thailand using LCA and concluded that GHG emissions from Jatropha biodiesel production was 77% lower than in production and use of fossil diesel. Similarly, in West Africa, Jatropha biodiesel production saved 72% in GHG emissions compared with conventional diesel fuel (Ndong et al. 2009).

Romijn (2011) used data from extant forestry and ecology of Miombo Woodland to estimate GHG emissions resulting from the introduction of large-scale Jatropha cultivation in these woodlands. The study concluded that Jatropha cultivation in these ecosystems will lead to emissions of considerable amounts of GHG that will subsequently undermine any GHG savings from the whole of the production chain, resulting in carbon debt. With the current potential seed yield of 5 t ha^{-1} a^{-1}, it will take about 30 years to repay that debt (Achten et al. 2008, 2013).

Conclusion

Jatropha is a promising biofuel feedstock that can contribute to sustainable rural development and employment creation, especially in Southern Africa. However, for it to be economically and environmentally sustainable, a standard set of practices for diverse environmental conditions needs to be developed. Jatropha's low performance in marginal areas suggests that like any other crop, it needs fertilizer and water to attain economic yield.

The risks of invasion resulting from Jatropha being introduced for biodiesel production have received little attention. The potential invasive risks seem to be quite low; however, its cultivation should be regulated given the expected large–scale cultivation. To minimize the risk of invasiveness, it is recommended that Jatropha be classified as a noxious weed so that farmers or investors are obliged to request permission from plant protection officers before planting. This is essential to regulate and monitor Jatropha cultivation.

Large-scale cultivation of Jatropha will create increased propagule pressure and increase the risk of invasiveness. Jatropha as a new crop should be therefore subjected to a proven scientific risk-assessment protocol to determine if it will become invasive in areas of introduction. Governments should develop regulations on the cultivation of Jatropha for biodiesel production to curb its spread into other land-use systems, given the risks associated with large-scale cultivation, transportation, and seed processing. The rules should ensure that plantations are not abandoned without adequate management and eradication.

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