Journal of Arid Environments 98 (2013) 135–145

Contents lists available at SciVerse ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Global greenhouse gas implications of land conversion to biofuel crop cultivation in arid and semi-arid lands – Lessons learned from Jatropha

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ARTICLE INFO

Article history:
Received 16 March 2011
Received in revised form
8 April 2012
Accepted 14 June 2012
Available online 1 September 2012

Keywords:
Annual repayment
Carbon debt
Carbon stock
Climate change mitigation
Jatropha biomass
Land use type

ABSTRACT

Biofuels are considered as a climate-friendly energy alternative. However, their environmental sustainability is increasingly debated because of land competition with food production, negative carbon balances and impacts on biodiversity. Arid and semi-arid lands have been proposed as a more sustainable alternative without such impacts. In that context this paper evaluates the carbon balance of potential land conversion to Jatropha cultivation, biofuel production and use in arid and semi-arid areas. This evaluation includes the calculation of carbon debt created by these land conversions and calculation of the minimum Jatropha yield necessary to repay the respective carbon debts within 15 or 30 years.

The carbon debts caused by conversion of arid and semi-arid lands to Jatropha vary largely as a function of the biomass carbon stocks of the land use types in these regions. Based on global ecosystem carbon mapping, cultivated lands and marginal areas (sparse shrubs, herbaceous and bare areas) show to have similar biomass carbon stocks (on average 4–8 t C ha^{-1}) and together cover a total of 1.79 billion ha. Conversion of these lands might not cause a carbon debt, but still might have a negative impact on other sustainability dimensions (e.g. biodiversity or socio-economics). Jatropha establishment in shrubland (0.75 billion ha) would cause a carbon debt of 24–28 t C ha^{-1} on average (repayable within 30 year with yield of 3.5–3.9 t seed ha^{-1} yr^{-1}). Land use change in the 1.15 billion ha of forested area under arid and semi-arid climates could cause a carbon debt between 70 and 118 t C ha^{-1}. This debt requires 8.6–13.9 t seed production ha^{-1} yr^{-1} for repayment within 30 years. If repayment is required within 15 years, the necessary minimum yields almost double. Considering that 5 t seed ha^{-1} yr^{-1} is the current maximum Jatropha yield, conversion of forests cannot be repaid within one human generation. Repayment of carbon debt from shrubland conversions in 30 years is challenging, but feasible. Repayment in 15 year is currently not attainable.

Based on this analysis the paper discusses the carbon mitigation potential of biofuels in arid and semi-arid environments.

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http://dx.doi.org/10.1016/j.jaridenv.2012.06.015

1. Introduction

Biofuels are regarded as part of the solution for the energy, climate and ecological challenges of the global society. However, their environmental sustainability has been recently under heavy debate. From these discussions it is recommended that biofuels: (1) should not increase greenhouse gas emissions compared to fossil fuel use, (2) should not increase direct or indirect competition with food production for land and resources (Finco and Doppler, 2010; Janaun and Ellis, 2010), (3) should avoid large carbon stock changes through direct and indirect land use changes (Fargione et al., 2008; Searchinger et al., 2008), (4) should not decrease other ecosystem services (e.g. water quantity (Fingerman et al., 2010)), and (5) should avoid impact on biodiversity (Fargione et al., 2010; Wiens et al., 2011).

Arid and semi-arid lands are often seen as a potential place where biofuel production can attain environmental sustainability (Chavez-Guerrero and Hinojosa, 2010), as it is assumed that (1) these lands have a limited contribution to food production and thus a small potential for indirect land use change; and (2) the ecosystems of arid and semi-arid lands generally deliver fewer ecosystem services than those in more humid climates (e.g. in terms of carbon stock and biodiversity) (Constanza et al., 1997). The general aim of this paper is to evaluate the potential of arid and semi-arid lands for environmentally sustainable biofuel production. It is our hypothesis that the abovementioned assumptions on arid and semi-arid land are not necessarily valid and that environmental sustainability of biofuel production in arid and semi-arid lands is not necessarily guaranteed. In that context this paper evaluates the carbon balance of potential land conversion to Jatropha cultivation and biofuel production and use in arid and semi-arid areas.

Jatropha curcas L. is a small tree producing oil bearing seed (oil content: 27–40%; Achten et al., 2007), general rule of thumb: 250 g oil per kg seeds) suitable for biodiesel production. It is native to Mexico and central continental America, but is currently distributed and cultivated all over the tropics. The extraction efficiency of Jatropha oil is between 60 and 99%, depending on applied extraction technology. Based on several positive claims (see Box 1) Jatropha has been promoted as a sustainable biodiesel crop for arid and semi-arid lands resulting in large investments and land conversions (Achten et al., 2008). Though widely promoted, yields in arid and semi-arid regions are often below expectations (e.g. Sanderson, 2009), partly because the plant originally grows in more humid tropical savannah and monsoon climates (Maes et al., 2009a) and has a lower production in more arid conditions (Li et al., 2010; Trabucco et al., 2010).

Box 1. The main Jatropha claims behind its promotion (as compiled by Achten et al. (2008)).

- Jatropha produces toxic oil and does not compete with food consumption;
- Jatropha can make use of arid and semi-arid lands that are unsuitable for agriculture without additional irrigation and fertilization and thus does not compete with land for food production.
- Jatropha can grow on degraded, eroded, so-called "wasteland" and does not compete with ecosystem conservation
- Jatropha yields enough oil to reduce greenhouse gas emissions and enhance rural socio-economic development.

Whereas reducing fossil energy dependency and climate change mitigation are the main arguments for Jatropha expansion in arid and semi-arid lands, several studies have focused on quantifying the energy and carbon balances of Jatropha biodiesel. Some studies have also focused on other environmental impacts. Life cycle assessment studies on Jatropha biodiesel have shown a reduction in greenhouse gas (GHG) emissions of 49–72% (Achten et al., 2010a; Almeida et al., 2011; Lam et al., 2009; Ndong et al., 2009; Ou et al., 2009) and non-renewable energy use (>70%) compared to fossil diesel use (Achten et al., 2010a; Ou et al., 2009), but an increase in eutrophication, acidification and land exploitation (Achten et al., 2010a; Almeida et al., 2011). These studies cover the system from crop establishment in the field through combustion of the biodiesel in the engine, but do not include carbon stock changes due to land conversion to the biofuel crop. Several studies show that land use change prior to the biodiesel production can lead to carbon debts which can negate the positive carbon balance for large periods and, as such, postpone net greenhouse gas reduction (Achten and Verchot, 2011; Fargione et al., 2008). Depending on the carbon stock of the land use type that is converted to Jatropha and on the potential Jatropha yield on that location, carbon debt repayment times are calculated ranging from one decade to several centuries (Achten and Verchot, 2011; Achten, 2010; Bailis and McCarthy, 2011; Romijn, 2011).

Aiming to evaluate Jatropha's potential to produce environmentally sustainable biofuel in arid and semi-arid regions, we confront Jatropha's life cycle greenhouse gas (GHG) reduction potential with the carbon storage services delivered by different land use types in the arid and semi-arid lands globally present. We evaluate whether Jatropha cultivation can deliver more climate change mitigation services than the systems currently occupying these lands. To do so we (1) make an analysis of the biomass carbon stocks of different land use types in different arid and semi-arid zones of the globe, (2) calculate the carbon stock change due to land conversion to Jatropha (i.e. carbon debt, cfr. Fargione et al., 2008) and (3) compare this carbon stock change with the life cycle GHG reduction potential of the Jatropha biodiesel system to calculate the minimum Jatropha yield necessary to repay an eventual carbon debt within one human generation. The analyses are based on data available in publicly available databases and in the scientific literature.

Based on that information, we discuss the carbon mitigation potential of biofuels in arid and semi-arid environments and formulate general recommendations on the further development and promotion of biofuels in these climatic zones.

2. Material and methods

2.1. Potential of arid and semi-arid lands

The effective land surface availability and biomass carbon stocks are analyzed for different arid and semi-arid climate zones according to the Köppen classification and for different available land use typologies.

2.1.1. Land use availability

We regrouped the Köppen bio-climate classification (Peel et al., 2007) to distinguish the following arid and semi-arid climate strata: Tropical Savannah (Köppen label Aw), Arid Steppe (BSh; BSk), Arid Desert (BWh; BWk), Temperate with hot dry seasons (CSa; CWa) and Neither Arid or Semi-Arid (all the others) (Fig. 1). Areas of available land use in arid and semi-arid climates were calculated by overlaying this revised climate map with the main land use typologies (GLC 2000 by JRC (2003)) to calculate areas of available land use by arid and semi-arid climate zones. A short description of the land use typologies is given in Box 2.