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

W.M.J. Achten [a,b,g,*], A. Trabucco [a,c], W.H. Maes [d], L.V. Verchot [e], R. Aerts [a], E. Mathijs [f], P. Vantomme [g], V.P. Singh [h], B. Muys [a,i,*]

[a] Division Forest, Nature and Landscape, Department of Earth and Environmental Sciences, University of Leuven, Celestijnenlaan 200E-2411, BE-3001 Leuven, Belgium
[b] Sustainable Assessments of Material Life Cycles, Department of Metallurgy and Materials Engineering, University of Leuven, Kasteelpark Arenberg 44-2450, BE-3001 Leuven, Belgium
[c] Euro-Mediterranean Center for Climate Changes, IAFENT Division, Via E. De Nicola 9, 07100 Sassari, Italy
[d] Laboratory of Plant Ecology, UGent, Coupure Links 653, Bl A, 092 BE-9000 Gent, Belgium
[e] Centre for International Forestry Research (CIFOR), P.O. Box 0113 BOCBD, Bogor 16000, Indonesia
[f] Division of Bioeconomics, Department of Earth and Environmental Sciences, Katholieke Universiteit Leuven, Celestijnenlaan 200E-2411, BE-3001 Leuven, Belgium
[g] Forest Products and Industries Division, Forestry Department, United Nations Food and Agricultural Organization, Viale delle Terme di Caracalla, 00153 Roma, Italy
[h] World Agroforestry Centre (ICRAF), Dev Prakash Shastri Marg Pusa, New Delhi 110012, India
[i] European Forest Institute (EFI), Sant Pau World Heritage Site, S. Antoni Maria Claret 167, 08025 Barcelona, Spain

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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.

* Corresponding authors. Division Forest, Nature and Landscape, Department of Earth and Environmental Sciences, University of Leuven, Celestijnenlaan 200E-2411, BE-3001 Leuven, Belgium. Tel.: +32 16 329721; fax: +32 16 329760.
E-mail addresses: wouter.achten@ees.kuleuven.be (W.M.J. Achten), bart.muys@ees.kuleuven.be (B. Muys).

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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.

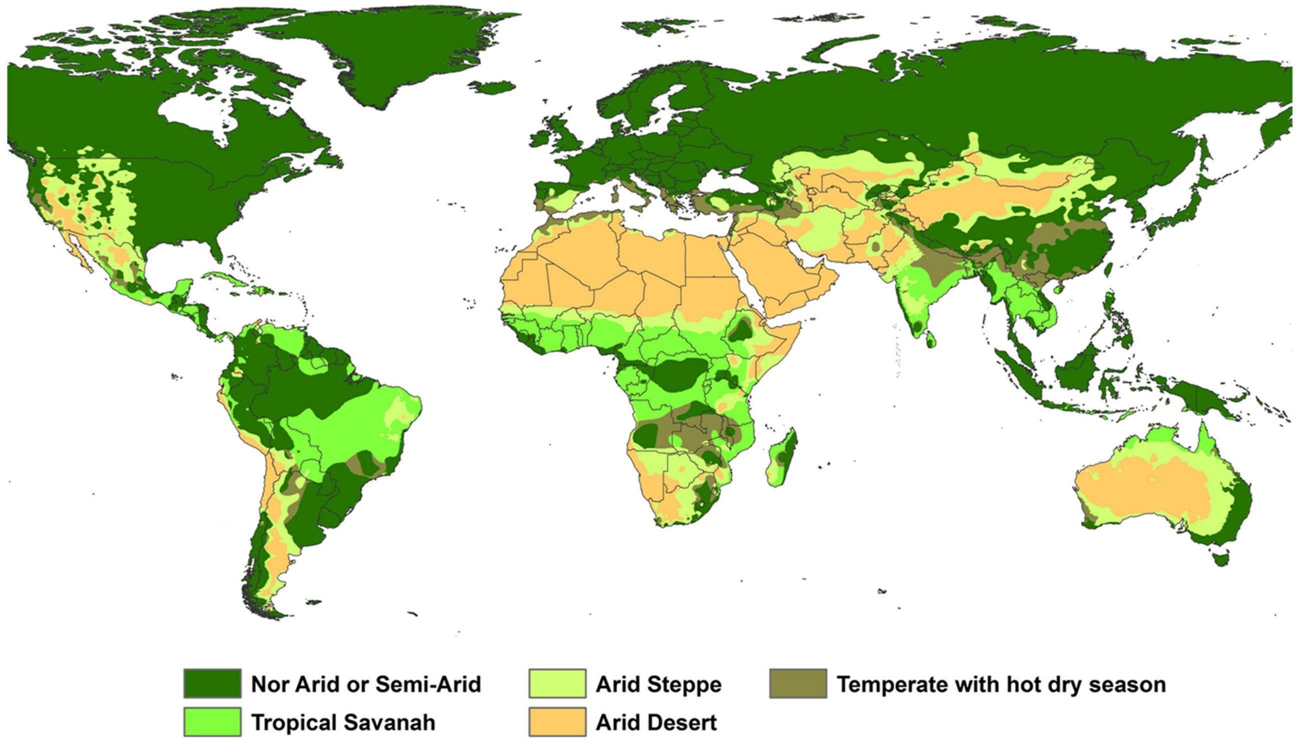

Fig. 1. Map indicating Köppen climate classes (Peel et al., 2007) regrouped for Arid and Semi-Arid climates: Tropical Savannah (Aw), Arid Steppe (BSh; BSk), Arid Desert (BWh; BWk), Temperate with hot dry seasons (CSa; CWa) and Neither Arid or Semi-Arid (all the others).

2.1.2. Biomass carbon stock

In the global carbon ecosystem map produced by Ruesch and Gibbs (2008), spatial distribution of biomass carbon stock [t C ha^{-1}] (aboveground and belowground) was assessed from a combination of land uses, continental boundaries, floristic zones and human disturbance. The spatial estimates of biomass carbon stocks were summerized across the combination of land use categories and climate zones. To indicate the uncertainty on these estimations, and to show the effect of this uncertainty on the final results further calculations were made with the 10th, 50th and 90th percentile of these biomass carbon stock estimates.

2.2. Jatropha in arid and semi-arid lands

2.2.1. Carbon storage in Jatropha plantations

Jatropha plantations are managed in rotations of 20 years. After each rotation the old trees are cut, removed and replaced by new ones. Hence, the average carbon stock in a Jatropha plantation over different rotations was estimated, based on literature data. However, values are scarce. No measured values are available for plantations older than 5 years, which implies making assumptions on the further development of a Jatropha plantation (see supporting information). Similar to the factors affecting yield (Trabucco et al., 2010), biomass production is dependent on the climatic conditions (Achten et al., 2010b). However, insufficient data from different climatic zones are available to make an estimate per climatic zone.

Based on values found in the scientific literature and reasonable assumptions that we describe in detail in the supporting information, we were able to make aboveground biomass estimations. To get insight on how these estimates influence the final results, low medium and high biomass estimations (based on Bailis and Baka, 2010) of the total biomass carbon stock (aboveground and belowground) in a fully grown Jatropha plantation and on the average total biomass carbon stock over different rotations were made. The differences between low, medium and high estimates can be understood as the consequence of differences in management practice, provenance of the planting stock, climate and soil conditions. Unfortunately, the data is not sufficient to differentiate between these factors.

2.2.2. Carbon stock changes

Carbon debts are calculated by subtracting the 10th, 50th and 90th biomass C stock percentiles calculated for different land use types in arid and semi-arid lands (see 2.1.2) from the low, medium and high Jatropha biomass C stocks (see 2.2.1). There is no data on the effects of land conversion to Jatropha on soil C stocks, so we did not take this into account in this assessment.

2.3. Jatropha biodiesel CO_2 reduction rate

Achten (2010) assessed the sensitivity of the greenhouse gas emissions reduction rate [t CO_2-eq ha^{-1} yr^{-1}] of the Jatropha biodiesel to the achieved yields for different Tanzanian regions. A regression analysis between reduction rate and yield was performed on these results (Fig. 2). This analysis demonstrates the high dependency of the greenhouse gas emission reduction rate (GHG_{RR}) on yield [t CO_2-eq ha^{-1} yr^{-1}], in line with Almeida et al. (2011). In the further analysis this regression function is used to calculate the minimum yield needed to repay an eventual carbon debt within a certain period of time.

Note that, if the Jatropha seed yield falls below 0.8 t ha^{-1} yr^{-1} (intercept of regression line of Fig. 2), the greenhouse gas emissions reduction rate drops below zero (i.e. an increase in greenhouse gas emissions).

2.4. Minimum required Jatropha yield

Based on the CO_2 reduction rate [t CO_2-eq ha^{-1} yr^{-1}] and the carbon stock change caused by land conversion to Jatropha [t CO_2-

Box 2. Short description of main GLC 2000 land use typologies (JRC, 2003).

Sparse shrubs and herbaceous sparse vegetation

Sparse Herbaceous or sparse Shrub cover: The main layer consists of sparse herbaceous vegetation and/or sparse shrubs. The crown cover is between 20 and 10 and 1%.

Herbaceous cover, closed to open (>15%). The main layer consists of closed to open herbaceous vegetation. The crown cover is between 100 and 15%.

Bare Areas. Primarily non-vegetated areas containing less than four percent vegetation during at least 10 months a year. The environment is influenced by the edaphic substratum. The cover is natural. Included are areas like bare rock and sands.

Cultivated and managed lands

Primarily vegetated areas containing more than four percent vegetation during at least two months a year. The environment is influenced by the edaphic substratum. The vegetative cover is characterized by the removal of the (semi)natural vegetation and replacement with a vegetative cover resulting from human activities. This cover is artificial and requires maintenance. It is grown with the intention to be managed and/or (partly) harvested at the end of the growing season. Before or after harvest there may be a period without vegetative cover.

Mosaic cropland

Mosaic of Cropland/Tree cover/Other Natural Vegetation. Cultivated and Managed Terrestrial Areas mixed with layers of closed to open trees (crown cover between 100 and 15% and height in the range of 30–3 m) or (semi)natural vegetation which species composition, its environmental and ecological processes are indistinguishable from, or in a process of achieving, its undisturbed state. The vegetative cover is not artificial and does not need to be managed nor maintained.

Mosaic of Cropland/Shrub or Herbaceous cover. Cultivated and Managed Terrestrial Areas mixed with layers of closed to open shrubland (crown cover between 100 and 15%) and/or closed to open herbaceous vegetation (crown cover between 100 and 15%).

Shrubland

The main layer consists of deciduous or evergreen closed to open thicket. The crown cover is between 100 and 15%, height is in the range of 5–0.3 m. It includes the following Land Cover Classes:

- Shrubcover, closed to open (>15%), evergreen (broadleaved or needleleaved)
- Shrubcover, closed to open (>15%), deciduous (broadleaved)

Forest

The main layer consists of closed to open trees. The crown cover is between 100 and 15%, height is in the range of >30–3 m. It includes the following Land Cover Classes:

- Mosaic of tree cover and other natural vegetation (crop component possible),
- Tree cover, broadleaved deciduous, open (15–40%)
- Tree cover, mixed leaftype, closed to open (>15%)
- Tree cover, broadleaved evergreen, closed to open (>15%)
- Tree Cover, broadleaved deciduous, closed (>40%)
- Tree cover, needleleaved evergreen, closed to open (>15%)
- Tree cover, needleleaved decidous, closed to open (>15%)

eq ha^{-1}], it is possible to calculate the repayment time (RT) [years] needed to compensate for the carbon debt, using the method of Fargione et al. (2008). However, since the CO_2 reduction rate depends on the Jatropha yield (see 2.3) and because the Jatropha yields within the geographic areas for which these average carbon debts are calculated, are very variable (Trabucco et al., 2010), we did not calculate the respective repayment times. Instead, the minimum Jatropha seed yields (Y_{Jc}) which would be needed to repay the carbon debt within one human generation (i.e. for RT = 15 and 30 years), were calculated as follows:

$$Y_{Jc} = \left(\frac{CD_{LU\rightarrow Jc}}{RT} + 0.8619\right) \Big/ 0.0011$$

where $CD_{LU\rightarrow Jc}$ is the carbon debt (in t CO_2 ha^{-1} = 44.1/12 t C ha^{-1}) due to change of aboveground biomass stock after conversion of a land use type in arid and semi-arid lands to Jatropha cultivation; and Y_{Jc} is the minimum required Jatropha yield necessary to repay the carbon debt in a certain repayment time (RT = 15 or 30 years).

3. Results

3.1. Potential of arid and semi-arid lands

Global and continental area distributions of existing main land use typologies are shown in Table 1. Globally, arid and semi-arid climates cover 66.5 million km^2 of which 40% is Arid Desert. The remaining 60% (39.9 million km^2) is distributed over Arid Steppe zones (42%), Tropical Savannah zones (41%) and Temperate with hot dry season zones (16%). In these last zones, 29% can be classified as forested area, 26% as sparse shrubs, herbaceous and bare areas and 19% as shrubland. The remaining 26% is mosaic cropland, or cultivated and managed land. Of these climate classes, 34% of the global total is found in Sub-Saharan Africa, 18% in South America, 8% in the Australian area and 7% in South Asia (Table 1).

The spatially averaged biomass carbon stocks (aboveground and belowground) calculated across these land use types by the arid and semi-arid Köppen climate zones are shown in Table 1 as well. Furthermore, Table 1 depicts the 10th, 50th and 90th percentile

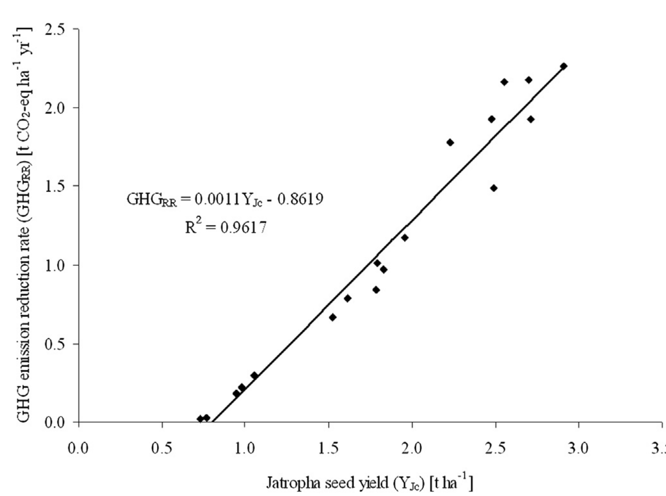

Fig. 2. Regression analysis of the GHG reduction rates [t CO_2 ha^{-1} yr^{-1}] in function of Jatropha seed yields based on life cycle assessment of the Jatropha biodiesel system from field establishment till combustion of the biodiesel, excluding carbon stock change due to land conversion (Achten, 2010)).

Table 1
Global and continental area distributions of existing main land use typologies (GLC 2000 by JRC (2003): [1000 km^2]) and their spatial biomass carbon stock (10th, 50th and 90th percentile) (Ruesch and Gibbs, 2008) [t C ha^{-1}]), by arid/semi-arid climate zoning (see Fig. 1).

	Sparse shrubs, herbaceous and bare areas				Cultivated and managed land				Mosaic cropland				Shrubland				Forest			
	Area [1000 km^2]	C storage [t C ha^{-1}] 10th	50th	90th	Area [1000 km^2]	C storage [t C ha^{-1}] 10th	50th	90th	Area [1000 km^2]	C storage [t C ha^{-1}] 10th	50th	90th	Area [1000 km^2]	C storage [t C ha^{-1}] 10th	50th	90th	Area [1000 km^2]	C storage [t C ha^{-1}] 10th	50th	90th
Global																				
Arid Steppe	8224	1	2	4	2793	5	5	5	755	2	2	20	3516	27	46	47	1639	62	88	115
Temperate with hot dry season	642	2	4	6	2018	5	5	5	216	13	17	45	1132	37	42	42	2454	73	118	142
Tropical Savannah	1482	3	7	8	2747	5	5	5	1924	5	37	99	2904	46	46	46	7437	91	136	186
Total	10,349				7558				2895				7552				11,528			
SubSaharan Africa																				
Arid Steppe	1489	3	4	4	1096	5	5	5	451	2	2	4	1008	46	46	46	310	72	72	134
Temperate with hot dry season	123	4	8	8	241	5	5	5	5	3	3	5	381	46	46	46	1127	86	152	160
Tropical Savannah	493	4	6	8	519	5	5	5	902	2	8	100	1759	46	46	46	3716	75	152	200
South America																				
Arid Steppe	690	1	2	6	63	5	5	5	182	2	2	63	247	7	50	53	263	87	126	128
Temperate with hot dry season	93	2	4	8	174	5	5	5	64	2	4	64	42	50	53	53	193	87	126	128
Tropical Savannah	852	2	8	8	861	5	5	5	858	2	63	97	342	53	53	53	2368	126	128	193
South Asia																				
Arid Steppe	40	1	4	5	437	5	5	5	1	39	39	39	81	39	39	39	58	78	78	78
Temperate with hot dry season	21	1	6	8	627	5	5	5	16	39	53	90	88	39	39	39	197	78	81	180
Tropical Savannah	8	1	1	5	602	5	5	5	20	39	39	90	148	39	39	39	309	78	78	105
Australian Area																				
Arid Steppe	989	2	2	4	295	5	5	5					754	43	43	46	296	96	96	96
Temperate with hot dry season	14	2	4	4	64	5	5	5					24	43	46	46	35	96	96	225
Tropical Savannah	54	4	4	4	1	5	5	5	8	48	85	113	304	46	46	46	251	96	96	96

biomass carbon stock of the main land use typologies, shown per arid/semi-arid climate zone.

3.2. Carbon storage in Jatropha plantations

A 20 year old plantation stores 48–74 t CO_2-eq ha^{-1} (low: 48.4; medium: 65.4 and high: 74.1 t CO_2-eq ha^{-1}) in above-ground biomass (Fig. 3). With a root/shoot ratio of 38.6% (average of literature values, see supporting information) this leads to a total sequestration of 67.1, 90.6 and 102.8 t CO_2-eq ha^{-1} (or 18.2, 24.7 and 28.0 t C ha^{-1}) for low, medium and high sequestration respectively. The low estimation of the time-averaged stock over different rotations is 44.1 t CO_2-eq ha^{-1} (or 12.0 t C ha^{-1}). The medium estimate is 65.5 t CO_2-eq ha^{-1} (or 17.8 t C ha^{-1}), whereas the high estimate indicates an average stock of 78.5 t CO_2-eq ha^{-1} (or 21.4 t C ha^{-1}). These latter values will be used to calculate the carbon stock changes triggered by land conversion from a certain land use type to Jatropha cultivation.

3.3. Jatropha in arid and semi-arid lands

The carbon debt caused by land conversion in the main land use categories to Jatropha in the different arid/semi-arid climate zones is shown in Table 2 (global) and Table A.1 (per subcontinent, see Appendix). Carbon debts are calculated using the estimates of low, medium and high average Jatropha biomass carbon stock. No carbon debts are shown for conversion of 'sparse shrubs, herbaceous and bare areas' and 'cultivated and managed land' because the initial biomass carbon stock is lower that the carbon stored in the Jatropha biomass (not shown in Table 2). Considering the calculations for the 50th percentile of the biomass carbon stock under the original land use and the medium Jatropha biomass carbon stock, carbon debts due to conversion of mosaic cropland range from 0 (in arid steppe and temperate climates with a hot dry season) to 19 t C ha^{-1} in tropical savannah. Establishing Jatropha in shrubland is estimated to cause a carbon debt between 24 and 28 t C ha^{-1}. Converting forests leaves carbon debts ranging from 70 to 118 t C ha^{-1} (Table 2).

The minimum Jatropha yield required to repay the carbon debt of land conversion is shown in Tables 3 and 4 for RT = 15 and 30 years, respectively (Table A.2 and Table A.3 show these results per subcontinent as well).

Repayment of carbon debts triggered by conversion of mosaic cropland largely depends on the climate zone and the geographical location where the conversion occurs. In sub-Saharan Africa conversion of mosaic cropland in arid steppe and temperate zones with hot dry seasons would not trigger a carbon debt, whereas in South Asia it would take a yield of 3.1–4.6 t seed ha^{-1} yr^{-1} to repay the debt within 30 years. Repayment within 15 years would require 5.5–8.1 t seed ha^{-1} yr^{-1}. In South America 30 years repayment requires 5.8 t seed ha^{-1} yr^{-1} in tropical savannah zones (15 years: 10.8 t seed ha^{-1} yr^{-1}) (Appendices Table A.2 and Table A.3).

4. Discussion

4.1. Jatropha in arid and semi-arid lands

Although land use change clearly plays a pivotal role in the overall emission profile of a biofuel, it is often not accounted for in LCA (Muller-Wenk and Brandão, 2010). Even though the biofuel system, from field establishment through combustion of the biodiesel (excluding carbon stock change due to land conversion) can reduce GHG emission, land use and biomass change needed to start such biofuel system can postpone the net GHG reduction for a considerable time (Fargione et al., 2008; Gibbs et al., 2008). The Jatropha case analyzed above illustrates that this risk is also present in arid and semi-arid climates.

Focusing on climate mitigation implications of land conversions to biofuels, our analysis shows that the balance determining the net emissions reductions depends heavily on the biomass carbon stock of the current land use, the average biomass carbon stock of Jatropha rotations and the seed yield of Jatropha. As this analysis aims at making rough estimations of the generic carbon mitigation implications of land use change on a global scale, each of these variables contain uncertainty. To put this uncertainty into perspective and to show the sensitivity of the results to the variability of the carbon data, we calculated final results (minimum yields for a certain repayment period) for 3 biomass carbon stock estimated both in the original land use type (10th, 50th and 90th percentile) and in the Jatropha rotations (low, medium and high estimate). Further, minimum necessary Jatropha yields are calculated for repayment within 15 and 30 year to show the effect of this period choice. The GHG reduction potential is based on a regression function relating GHG reduction with Jatropha yield. This relation is based on LCA assessments of different yield using a generic LCA model (Achten, 2010; Almeida et al., 2011). This function can change by improving the life cycle performance of Jatropha biodiesel.

Allowing 30 years for repayment of the carbon debt created by converting forest would require Jatropha yields ranging from 8.6 to 13.9 t seed ha^{-1} yr^{-1}. Such yields are currently considered

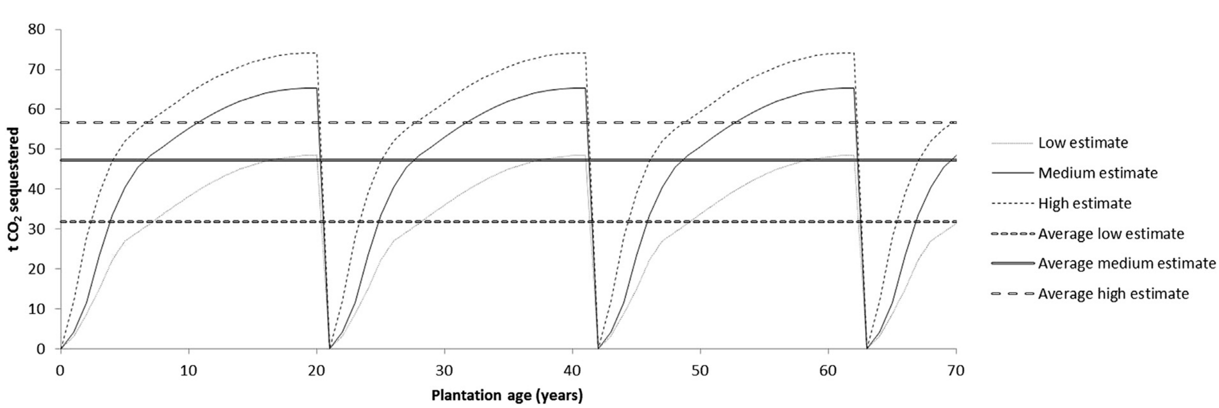

Fig. 3. Estimated CO_2 sequestration in aboveground biomass of a Jatropha plantation over consecutive rotations.

Table 2
Global carbon debts provoked by introducing Jatropha cultivation in existing main land use typologies (GLC 2000 by JRC (2003) [t C ha^{-1}]. Carbon debts are calculated for the 10th, 50th and 90th biomass carbon stock of Mosaic Cropland, Shrubland and Forest and for three levels of Jatropha carbon stocks.

	Mosaic cropland				Shrubland				Forest			
	Area [1000 km^2]	Carbon debt [t C ha^{-1}] percentile			Area [1000 km^2]	Carbon debt [t C ha^{-1}] percentile			Area [1000 km^2]	Carbon debt [t C ha^{-1}] percentile		
		10th	50th	90th		10th	50th	90th		10th	50th	90th
Global												
Arid Steppe	755	2	2	20	3516	27	46	47	1639	62	88	115
Low Jc carbon stock		–	–	8		15	34	35		50	76	103
Medium Jc carbon stock		–	–	2		10	28	29		44	70	98
High Jc carbon stock		–	–	–		6	24	25		40	66	94
Temperate with hot dry season	216	13	17	45	1132	37	42	42	2454	73	118	142
Low Jc carbon stock		1	5	33		25	30	30		61	106	130
Medium Jc carbon stock		–	0	27		19	24	24		55	100	124
High Jc carbon stock		–	–	23		16	21	21		52	96	121
Tropical Savannah	1924	5	37	99	2904	46	46	46	7437	91	136	186
Low Jc carbon stock		–	25	87		34	34	34		79	124	174
Medium Jc carbon stock		–	19	81		28	28	28		74	118	169
High Jc carbon stock		–	15	78		24	24	24		70	114	165

unrealistic, even with optimal fertilizer and irrigation. Repayment within 15 year would require 16.4–27.0 t seed ha^{-1} yr^{-1}. To repay the carbon debts caused by conversion of shrublands in 30 years would require Jatropha yields ranging from 3.5 to 3.9 t seed ha^{-1} yr^{-1}. These yields fall among the highest end of the current maximal yield estimations. Reviews of measured yields (Achten et al., 2008; Trabucco et al., 2010) report that Jatropha yields mostly range between 1 and 3 tons per ha, and exceptionally to 4 tons per ha. Repayment within 15 years makes minimal yields between 6.2 and 7.0 t seed ha^{-1} yr^{-1} necessary. Repaying the transformation of mosaic cropland into Jatropha within 30 years requires a minimum yield of 2.9 t seed ha^{-1} yr^{-1} (5.0 t seed ha^{-1} yr^{-1} in case only 15 years are allowed). In the areas where no carbon debt is created, as in cultivated and managed land, areas with sparse shrubs, and herbaceous and bare areas a net GHG emission reduction could be attained if the yield is higher than 0.8 t ha^{-1} yr^{-1} (cfr. Fig. 3 and Section 2.3).

4.2. Biofuels in arid and semi-arid lands

The decision to convert land to biofuel crop cultivation in arid and semi-arid lands is a complex issue. A balance has to be found between (1) biofuel species' fitness to provide yield under a given climate (e.g. water availability), (2) the opportunity cost and social impact of replacing other land use systems, and (3) the carbon stored in the preceding land use system.

The available area distribution is given per land use typology, providing the possible area for biofuel activities. The degree of environmental suitability for biofuel farming over these lands varies according to climate, roughly reflected in the Köppen classification. The establishment of biofuel crops over land use typologies associated with agricultural production could fully (i.e. for "cultivated and managed land") or partially (i.e. for "mosaic cropland") interfere with food production. Furthermore, the conversion of these lands into biofuels could lead to indirect land use change effects by the displacement of the food production to other areas. However, the threat of indirect effects is related to the extent and relative importance of agricultural area in a given region. In principle this threat would be negligible in regions where large amounts of non-agricultural land climatically suitable for biofuel cropping are still available. Still, it is very important to recognize that a large portion of these non-agricultural lands are already performing important functions for local communities, in particular for provision of grazing area and energy for traditional biomass

Table 3
Minimum Jatropha yield [t dry seed ha^{-1} yr^{-1}] necessary to repay the carbon debt caused by land use change (for the 10th, 50th and 90th biomass carbon stock of Mosaic Cropland, Shrubland and Forest and for three levels of Jatropha carbon stocks) within 15 years.

	Mosaic cropland				Shrubland				Forest			
	Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]			Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]			Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]		
		10th	50th	90th		10th	50th	90th		10th	50th	90th
Global												
Arid Steppe	755				3516				1639			
Low Jc carbon stock				2.53		4.23	8.29	8.55		11.84	17.66	23.81
Medium Jc carbon stock				1.23		2.94	7.00	7.26		10.55	16.36	22.52
High Jc carbon stock						2.14	6.20	6.46		9.75	15.56	21.72
Temperate with hot dry season	216				1132				2454			
Low Jc carbon stock		0.93	1.99	8.07		6.41	7.46	7.46		14.40	24.35	29.76
Medium Jc carbon stock				6.77		5.12	6.17	6.17		13.11	23.06	28.47
High Jc carbon stock				5.97		4.32	5.37	5.37		12.31	22.26	27.66
Tropical Savannah	1924				2904				7437			
Low Jc carbon stock			6.25	20.21		8.29	8.29	8.29		18.47	28.31	39.61
Medium Jc carbon stock			4.96	18.92		6.99	7.00	7.00		17.18	27.01	38.32
High Jc carbon stock			4.16	18.11		6.19	6.19	6.19		16.38	26.21	37.52

Table 4
Minimum Jatropha yield [t dry seed ha^{-1} yr^{-1}] necessary to repay the carbon debt caused by land use change (for the 10th, 50th and 90th biomass carbon stock of Mosaic Cropland, Shrubland and Forest and for three levels of Jatropha carbon stocks) within 30 years.

	Mosaic cropland				Shrubland				Forest			
	Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]			Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]			Area [1000 km^2]	Yield [t dry seed ha^{-1} yr^{-1}]		
		10th	50th	90th		10th	50th	90th		10th	50th	90th
Global												
Arid Steppe	755				3516				1639			
Low Jc carbon stock				1.65		2.51	4.54	4.67		6.31	9.22	12.30
Medium Jc carbon stock				1.01		1.86	3.89	4.02		5.67	8.57	11.65
High Jc carbon stock						1.46	3.49	3.62		5.27	8.17	11.25
Temperate with hot dry season	216				1132				2454			
Low Jc carbon stock		0.86	1.38	4.42		3.60	4.12	4.12		7.59	12.57	15.27
Medium Jc carbon stock				3.78		2.95	3.48	3.48		6.95	11.92	14.62
High Jc carbon stock				3.38		2.55	3.07	3.07		6.54	11.52	14.22
Tropical Savannah	1924				2904				7437			
Low Jc carbon stock			3.52	10.50		4.53	4.54	4.54		9.63	14.54	20.20
Medium Jc carbon stock			2.87	9.85		3.89	3.89	3.89		8.98	13.90	19.55
High Jc carbon stock			2.47	9.45		3.49	3.49	3.49		8.58	13.50	19.15

use (Maes and Verbist, 2012); hence, their conversion to either biofuel or cropland could cause other direct and indirect land use changes.

With respect to climate change mitigation, new biofuel farming activities may trigger loss of existing biomass carbon stocks, which varies according to land use, climate zones and geographic location (Table 1). Therefore, non-agricultural land with low biomass carbon stocks ("marginal land"), but still high biofuel crop suitability, fits best for biofuels to achieve a swift net GHG reduction. However, it must be emphasized that in this study lands were classified as marginal based on carbon content and agricultural activity (i.e. food production). Other services (e.g. grazing land, biodiversity, fuelwood provision) are not regarded. Therefore conversion of the marginal lands can have impacts other than carbon emissions which must be considered as well (Rossi and Lambrou, 2008; Arnold et al., 2006; Maes and Verbist, 2012). As such, the real area available for land use conversion might be considerably smaller.

In arid steppe climates, biofuel plantations could potentially occupy large quantities of marginal land (8.2 million km^2) if either irrigation would be provided, or if planted crops would be adapted to thrive in suboptimal precipitation conditions. Irrigation could increase yield, but will increase GHG emissions as well (e.g. running pumps). Therefore, in terms of climate change mitigation an optimum could be found. Irrigation could also increase the water footprint of the biofuel (the amount of water required to produce 1 GJ of energy) (Yeh et al., 2011) and as such, increases the water competition with other water usages (e.g. by local communities, for food production or ecosystem services). As water is the restricting factor in arid and semi-arid lands, this is an important impact to consider. However, the water balance and footprint of many biofuel crops are still not well understood (cfr. discussion about Jatropha water footprint in Gerbens-Leenes et al., 2009; Jongschaap et al., 2009; Maes et al., 2009b).

Lands with temperate climates with hot dry season and with low biomass carbon stocks are for largely already allocated to cropland production. Scarcity of marginal lands in these climates (0.65 million km^2) suggests a limited potential for large biofuel initiatives. Tropical savannah zones include a larger amount of marginal land (1.5 million km^2, mainly located in South America 0.9 million km^2). However, these areas also hold biomass carbon stocks (on average 9 t C ha^{-1}) which are higher than carbon stocks in annual crops (Table 1). Biofuel trees or perennial crops would therefore probably result in a low carbon debt compared to annual biofuel crops.

5. Conclusions

When biofuel production is considered to help achieve climate change mitigation goals, it is desirable that they result in net reduction of GHG emission soon after introduction. Therefore repayment times have to be kept as short as possible. Repayment times can be reduced (1) by reducing carbon debt through land conversion to biofuels; and (2) by using a biofuel crop which can attain a high GHG emission reduction rate.

The evaluation of Jatropha in arid and semi-arid lands shows that avoiding high land use conversion carbon debts, would drive the biofuel cultivation towards lands which are currently fully or partially used for food production or other services. Conversion of these lands might not impede or postpone net GHG emission reduction, but might have a negative impact on other sustainability dimensions. This indicates that the potential area for sustainable biofuel production in arid and semi-arid lands is already considerably restricted by current carbon stocks. Consideration of other sustainability indicators (e.g. social indicators) will even further restrict the area available and suitable for sustainable biofuel production.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jaridenv.2012.06.015.

Appendices

Table A.1
Global carbon debts provoked by introducing Jatropha cultivation in existing main land use typologies (GLC 2000 by JRC (2003) [t C ha^{-1}]. Carbon debts are calculated for the 10th. 50th and 90th biomass carbon stock of Mosaic Cropland. Shrubland and Forest and for three levels of Jatropha carbon stocks

	Mosaic cropland				Shrubland					Forest		
	Area [1000 km^2]	Carbon debt [t ha^{-1}] percentile			Area [1000 km^2]	Carbon debt [t ha^{-1}] percentile			Area [1000 km^2]	Carbon debt [t ha^{-1}] percentile		
		10th	50th	90th		10th	50th	90th		10th	50th	90th
SubSaharan Africa												
Arid Steppe	451	2	2	4	1008	46	46	46	310	72	72	134
Low Jc carbon stock		–	–	–		34	34	34		60	60	122
Medium Jc carbon stock		–	–	–		28	28	28		54	54	116
High Jc carbon stock		–	–	–		25	25	25		51	51	113
Temperate with hot dry season	5	3	3	5	381	46	46	46	1127	86	152	160
Low Jc carbon stock		–	–	–		34	34	34		74	140	148
Medium Jc carbon stock		–	–	–		28	28	28		68	134	143
High Jc carbon stock		–	–	–		25	25	25		65	131	139
Tropical Savannah	902	2	8	100	1759	46	46	46	3716	75	152	200
Low Jc carbon stock		–	–	88		34	34	34		63	140	188
Medium Jc carbon stock		–	–	82		28	28	28		57	134	182
High Jc carbon stock		–	–	79		25	25	25		54	131	179
South America												
Arid Steppe	182	2	2	63	247	7	50	53	263	87	126	128
Low Jc carbon stock		–	–	51		–	38	41		75	114	116
Medium Jc carbon stock		–	–	45		–	32	35		69	108	110
High Jc carbon stock		–	–	42		–	29	32		66	105	107
Temperate with hot dry season	64	2	4	64	42	50	53	53	193	87	126	128
Low Jc carbon stock		–	–	52		38	41	41		75	114	116
Medium Jc carbon stock		–	–	46		32	35	35		69	108	110
High Jc carbon stock		–	–	43		29	32	32		66	105	107
Tropical Savannah	858	2	63	97	342	53	53	53	2368	126	128	193
Low Jc carbon stock		–	51	85		41	41	41		114	116	181
Medium Jc carbon stock		–	45	79		35	35	35		108	110	175
High Jc carbon stock		–	42	75		32	32	32		105	107	172
South Asia												
Arid Steppe	1	39	39	39	81	39	39	39	58	78	78	78
Low Jc carbon stock		27	27	27		27	27	27		66	66	66
Medium Jc carbon stock		21	21	21		21	21	21		60	60	60
High Jc carbon stock		18	18	18		18	18	18		57	57	57
Temperate with hot dry season	16	39	53	90	88	39	39	39	197	78	81	180
Low Jc carbon stock		27	41	78		27	27	27		66	69	168
Medium Jc carbon stock		21	35	72		21	21	21		60	63	162
High Jc carbon stock		18	31	69		18	18	18		57	60	159
Tropical Savannah	20	39	39	90	148	39	39	39	309	78	78	105
Low Jc carbon stock		27	27	78		27	27	27		66	66	93
Medium Jc carbon stock		21	21	72		21	21	21		60	60	87
High Jc carbon stock		18	18	69		18	18	18		57	57	84
Australian Area												
Arid Steppe					754	43	43	46	296	96	96	96
Low Jc carbon stock						31	31	34		84	84	84
Medium Jc carbon stock						25	25	28		78	78	78
High Jc carbon stock						22	22	25		75	75	75
Temperate with hot dry season				24	43	46	46	35	96	96	225	
Low Jc carbon stock						31	34	34		84	84	213
Medium Jc carbon stock						25	28	28		78	78	207
High Jc carbon stock						22	25	25		75	75	204
Tropical Savannah	8	48	85	113	304	46	46	46	251	96	96	96
Low Jc carbon stock		36	73	101		34	34	34		84	84	84
Medium Jc carbon stock		30	67	95		28	28	28		78	78	78
High Jc carbon stock		27	63	91		25	25	25		75	75	75

Table A.2
Minimum Jatropha yield [t dry seed ha^{-1} yr^{-1}] necessary to repay the carbon debt caused by land use change (for the 10th. 50th and 90th biomass carbon stock of Mosaic Cropland. Shrubland and Forest and for three levels of Jatropha carbon stocks) within 15 years

	Mosaic cropland			Shrubland			Forest		
	Minimum yield [t dry seed ha^{-1} yr^{-1}]			Minimum yield [t dry seed ha^{-1} yr^{-1}]			Minimum yield [t dry seed ha^{-1} yr^{-1}]		
	10th	50th	90th	10th	50th	90th	10th	50th	90th
SubSaharan Africa									
Arid Steppe									
Low Jc carbon stock				8.36	8.36	8.36	14.15	14.15	27.96
Medium Jc carbon stock				7.06	7.06	7.06	12.86	12.86	26.67
High Jc carbon stock				6.26	6.26	6.26	12.05	12.05	25.87
Temperate with hot dry season									
Low Jc carbon stock				8.36	8.36	8.36	17.28	31.97	33.84
Medium Jc carbon stock				7.06	7.06	7.06	15.98	30.67	32.55
High Jc carbon stock				6.26	6.26	6.26	15.18	29.87	31.75
Tropical Savannah									
Low Jc carbon stock			20.38	8.36	8.36	8.36	14.80	31.97	42.66
Medium Jc carbon stock			19.09	7.06	7.06	7.06	13.51	30.67	41.36
High Jc carbon stock			18.29	6.26	6.26	6.26	12.71	29.87	40.56
South America									
Arid Steppe									
Low Jc carbon stock			12.14		9.25	9.92	17.49	26.17	26.62
Medium Jc carbon stock			10.85		7.96	8.62	16.20	24.88	25.33
High Jc carbon stock			10.05		7.15	7.82	15.39	24.08	24.53
Temperate with hot dry season									
Low Jc carbon stock			12.37	9.25	9.92	9.92	17.49	26.17	26.62
Medium Jc carbon stock			11.07	7.96	8.62	8.62	16.20	24.88	25.33
High Jc carbon stock			10.27	7.15	7.82	7.82	15.39	24.08	24.53
Tropical Savannah									
Low Jc carbon stock		12.14	19.60	9.92	9.92	9.92	26.17	26.62	41.10
Medium Jc carbon stock		10.85	18.31	8.62	8.62	8.62	24.88	25.33	39.81
High Jc carbon stock		10.05	17.51	7.82	7.82	7.82	24.08	24.53	39.00
South Asia									
Arid Steppe									
Low Jc carbon stock	6.80	6.80	6.80	6.80	6.80	6.80	15.48	15.48	15.48
Medium Jc carbon stock	5.51	5.51	5.51	5.51	5.51	5.51	14.19	14.19	14.19
High Jc carbon stock	4.70	4.70	4.70	4.70	4.70	4.70	13.39	13.39	13.39
Temperate with hot dry season									
Low Jc carbon stock	6.80	9.80	18.16	6.80	6.80	6.80	15.48	16.15	38.20
Medium Jc carbon stock	5.51	8.51	16.86	5.51	5.51	5.51	14.19	14.86	36.91
High Jc carbon stock	4.70	7.71	16.06	4.70	4.70	4.70	13.39	14.06	36.11
Tropical Savannah									
Low Jc carbon stock	6.80	6.80	18.16	6.80	6.80	6.80	15.48	15.48	21.50
Medium Jc carbon stock	5.51	5.51	16.86	5.51	5.51	5.51	14.19	14.19	20.21
High Jc carbon stock	4.70	4.70	16.06	4.70	4.70	4.70	13.39	13.39	19.40
Australian Area									
Arid Steppe									
Low Jc carbon stock				7.69	7.69	8.36	19.49	19.49	19.49
Medium Jc carbon stock				6.40	6.40	7.06	18.20	18.20	18.20
High Jc carbon stock				5.59	5.59	6.26	17.40	17.40	17.40
Temperate with hot dry season									
Low Jc carbon stock				7.69	8.36	8.36	19.49	19.49	48.22
Medium Jc carbon stock				6.40	7.06	7.06	18.20	18.20	46.93
High Jc carbon stock				5.59	6.26	6.26	17.40	17.40	46.13
Tropical Savannah									
Low Jc carbon stock	8.80	16.93	23.17	8.36	8.36	8.36	19.49	19.49	19.49
Medium Jc carbon stock	7.51	15.64	21.88	7.06	7.06	7.06	18.20	18.20	18.20
High Jc carbon stock	6.71	14.84	21.07	6.26	6.26	6.26	17.40	17.40	17.40

Table A.3
Minimum Jatropha yield [t dry seed ha^{-1} yr^{-1}] necessary to repay the carbon debt caused by land use change (for the 10th. 50th and 90th biomass carbon stock of Mosaic Cropland. Shrubland and Forest and for three levels of Jatropha carbon stocks) within 30 years

	Mosaic cropland			Shrubland			Forest		
	Minimum yield [t dry seed ha^{-1} yr^{-1}]			Minimum yield [t dry seed ha^{-1} yr^{-1}]			Minimum yield [t dry seed ha^{-1} yr^{-1}]		
	10th	50th	90th	10th	50th	90th	10th	50th	90th
SubSaharan Africa									
Arid Steppe									
Low Jc carbon stock				4.57	4.57	4.57	7.47	7.47	14.37
Medium Jc carbon stock				3.92	3.92	3.92	6.82	6.82	13.73
High Jc carbon stock				3.52	3.52	3.52	6.42	6.42	13.33
Temperate with hot dry season									
Low Jc carbon stock				4.57	4.57	4.57	9.03	16.37	17.31
Medium Jc carbon stock				3.92	3.92	3.92	8.38	15.73	16.67
High Jc carbon stock				3.52	3.52	3.52	7.98	15.33	16.27
Tropical Savannah									
Low Jc carbon stock			10.58	4.57	4.57	4.57	7.79	16.37	21.72
Medium Jc carbon stock			9.94	3.92	3.92	3.92	7.15	15.73	21.07
High Jc carbon stock			9.54	3.52	3.52	3.52	6.75	15.33	20.67
South America									
Arid Steppe									
Low Jc carbon stock			6.46		5.02	5.35	9.14	13.48	13.70
Medium Jc carbon stock			5.82		4.37	4.70	8.49	12.83	13.06
High Jc carbon stock			5.42		3.97	4.30	8.09	12.43	12.65
Temperate with hot dry season									
Low Jc carbon stock			6.57	5.02	5.35	5.35	9.14	13.48	13.70
Medium Jc carbon stock			5.93	4.37	4.70	4.70	8.49	12.83	13.06
High Jc carbon stock			5.53	3.97	4.30	4.30	8.09	12.43	12.65
Tropical Savannah									
Low Jc carbon stock		6.46	10.19	5.35	5.35	5.35	13.48	13.70	20.94
Medium Jc carbon stock		5.82	9.55	4.70	4.70	4.70	12.83	13.06	20.29
High Jc carbon stock		5.42	9.15	4.30	4.30	4.30	12.43	12.65	19.89
South Asia									
Arid Steppe									
Low Jc carbon stock	3.79	3.79	3.79	3.79	3.79	3.79	8.13	8.13	8.13
Medium Jc carbon stock	3.14	3.14	3.14	3.14	3.14	3.14	7.49	7.49	7.49
High Jc carbon stock	2.74	2.74	2.74	2.74	2.74	2.74	7.09	7.09	7.09
Temperate with hot dry season									
Low Jc carbon stock	3.79	5.29	9.47	3.79	3.79	3.79	8.13	8.47	19.49
Medium Jc carbon stock	3.14	4.65	8.82	3.14	3.14	3.14	7.49	7.82	18.85
High Jc carbon stock	2.74	4.25	8.42	2.74	2.74	2.74	7.09	7.42	18.45
Tropical Savannah									
Low Jc carbon stock	3.79	3.79	9.47	3.79	3.79	3.79	8.13	8.13	11.14
Medium Jc carbon stock	3.14	3.14	8.82	3.14	3.14	3.14	7.49	7.49	10.49
High Jc carbon stock	2.74	2.74	8.42	2.74	2.74	2.74	7.09	7.09	10.09
Australian Area									
Arid Steppe									
Low Jc carbon stock				4.24	4.24	4.57	10.14	10.14	10.14
Medium Jc carbon stock				3.59	3.59	3.92	9.49	9.49	9.49
High Jc carbon stock				3.19	3.19	3.52	9.09	9.09	9.09
Temperate with hot dry season									
Low Jc carbon stock				4.24	4.57	4.57	10.14	10.14	24.50
Medium Jc carbon stock				3.59	3.92	3.92	9.49	9.49	23.86
High Jc carbon stock				3.19	3.52	3.52	9.09	9.09	23.46
Tropical Savannah									
Low Jc carbon stock	4.79	8.86	11.98	4.57	4.57	4.57	10.14	10.14	10.14
Medium Jc carbon stock	4.15	8.21	11.33	3.92	3.92	3.92	9.49	9.49	9.49
High Jc carbon stock	3.75	7.81	10.93	3.52	3.52	3.52	9.09	9.09	9.09

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