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Impact of land-use change to Jatropha bioenergy plantations on biomass and soil carbon stocks: a field study in Mali

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Abstract

Small-scale Jatropha cultivation and biodiesel production have the potential of contributing to local development, energy security, and greenhouse gas (GHG) mitigation. In recent years however, the GHG mitigation potential of biofuel crops is heavily disputed due to the occurrence of a carbon debt, caused by CO_2 emissions from biomass and soil after land-use change (LUC). Most published carbon footprint studies of Jatropha report modeled results based on a very limited database. In particular, little empirical data exist on the effects of Jatropha on biomass and soil C stocks. In this study, we used field data to quantify these C pools in three land uses in Mali, that is, Jatropha plantations, annual cropland, and fallow land, to estimate both the Jatropha C debt and its C sequestration potential. Four-year-old Jatropha plantations hold on average 2.3 Mg C ha^{-1} in their above- and belowground woody biomass, which is considerably lower compared to results from other regions. This can be explained by the adverse growing conditions and poor local management. No significant soil organic carbon (SOC) sequestration could be demonstrated after 4 years of cultivation. While the conversion of cropland to Jatropha does not entail significant C losses, the replacement of fallow land results in an average C debt of 34.7 Mg C ha^{-1}, mainly caused by biomass removal (73%). Retaining native savannah woodland trees on the field during LUC and improved crop management focusing on SOC conservation can play an important role in reducing Jatropha's C debt. Although planting Jatropha on degraded, carbon-poor cropland results in a limited C debt, the low biomass production, and seed yield attained on these lands reduce Jatropha's potential to sequester C and replace fossil fuels. Therefore, future research should mainly focus on increasing Jatropha's crop productivity in these degraded lands.

Keywords: allometry, biofuel, carbon debt, carbon sequestration, *Jatropha curcas* L., land conversion, root-to-shoot ratio, West Africa

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Introduction

The current demand for reducing greenhouse gas (GHG) emissions, in combination with the depletion of fossil fuel reserves and the growing concern on energy security and independence (Verrastro & Ladislaw, 2007) led to a growing interest in the production of liquid biofuels. In this context, *Jatropha curcas* L., a tropical deciduous shrub, was claimed to provide high oil yields on degraded lands with minimal nutrient and management inputs, thereby avoiding competition with food production (Achten *et al.*, 2010a). However, more recent research has come to disprove these early claims (van Eijck *et al.*, 2014) and a large fraction of Jatropha initiatives failed because of low yields due to insufficient agronomic knowledge (Nielsen *et al.*, 2013; Singh *et al.*, 2014).

Despite this negative experience, small-scale Jatropha cultivation can still play an important role as a local energy source in low-income areas (e.g., Sahel region), thereby contributing to local development, energy security, and GHG mitigation (Achten *et al.*, 2010b; Nielsen *et al.*, 2013; Muys *et al.*, 2014). The latter can be attained through (i) C sequestration in Jatropha biomass and soil during cultivation and (ii) the production of biodiesel to replace fossil fuels (Van Rooijen, 2014). Besides the well-known environmental benefits, GHG mitigation can boost the economic viability of Jatropha projects through C trading mechanisms (Nielsen *et al.*, 2013; Van Rooijen, 2014).

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In recent years however, the GHG mitigation potential of crop-based liquid biofuels has been heavily debated. In particular, land-use change (LUC) due to biofuel crop establishment may create initial losses in soil and biomass C stocks as a result of increased microbial decomposition and burning. This C debt can have a significant negative impact on the biofuel's GHG balance (Fargione *et al.*, 2008). In the case of Jatropha, multiple studies have been made addressing this particular issue (Struijs, 2008; Bailis & Baka, 2010; Achten & Verchot, 2011; Bailis & McCarty, 2011; Romijn, 2011; Rasmussen *et al.*, 2012; Achten *et al.*, 2013). A wide variety of C debts and associated repayment times have been reported, the latter ranging from a few years up to multiple centuries. The repayment time depends (i) on the C debt created (i.e., the land cover which is replaced by Jatropha) and (ii) on the life cycle CO_2 reduction potential of the biofuel substituting fossil fuel (kg CO_2 ha^{-1} yr^{-1}), indicating a high dependency on local conditions. However, for both aspects data quality (measurements vs. modeled estimation) and assumptions (e.g., assumed yields, fertilizer use, and field emissions) also play an important role. Most studies conclude that GHG mitigation through Jatropha production can only be achieved when it is planted on degraded lands poor in C stocks (Achten & Verchot, 2011; Romijn, 2011). However, the accuracy of these earlier analyses can be questioned, as frequent use is made of default values and nonvalidated estimates of seed yield and C stocks, which are in turn based on little empirical data. This practice can give rise to significant errors in the analysis of Jatropha C debts, as the magnitude and dynamics of C stocks depend strongly on local biophysical conditions (Powers *et al.*, 2011). In addition, assumptions are frequently made which have not been verified in the field (e.g., soil organic carbon (SOC) remaining constant upon LUC), adding more uncertainty to currently available estimates. Therefore, there is an urgent need for more empirical data on Jatropha C stocks compared to other LUs to verify the results reported by the studies mentioned above (Romijn, 2011; Rasmussen *et al.*, 2012).

To answer this call for more empirical data, a field study was set up in Mali with the aim of quantifying soil and biomass C stocks in small-scale Jatropha plantations and comparing these with other LUs. Mali is one of the few sub-Saharan countries explicitly encouraging Jatropha cultivation in its policy, aiming for a 20% replacement of diesel by Jatropha oil by 2023 (Favretto *et al.*, 2012). Whereas traditionally Jatropha was mainly grown as a living fence for local soap production, its cultivation was recently redirected toward small-scale plantations for local energy production. By 2011, this resulted in a total area of almost 5000-ha of Jatropha, mainly situated in the provinces of Koulikoro, Sikasso, and Kayes (Favretto *et al.*, 2012). The gathered C stock data were used to estimate the C debt and associated repayment time of Jatropha-based biofuel and soap production in Mali.

Materials and methods

General setup and study area

The impact of LUC on biomass and soil C stocks was studied using the C stock change method (UNFCCC, 2009), in which C stocks prior to and after LUC are compared. As a monitoring study was practically unfeasible, we applied the ergodic principle, that is, presenting assumed changes over time by comparing different LU classes in space at one point in time. C stocks were measured during summer 2011 in 18 triplets of neighboring fields, each comparing Jatropha, cropland, and fallow LU, thereby assuming that all factors other than the effect of LU are constant within each triplet (spatially paired site design; Conteh, 1999). Sampling sites were equally divided over two distinct ecoregions in Mali: Koulikoro, in the central part of the country and Garalo, a smaller village in the Southern province of Sikasso (Fig. 1). Koulikoro is situated in the Sudanese agro-ecological zone, which is characterized by a semi-arid climate [mean annual temperature (MAT) of 27.6 °C and mean annual precipitation (MAP) of 815 mm; New_LocClim (FAO, Rome, Italy)], dry woodlands (Magin, 2011), and farming systems integrating sedentary livestock rearing with crop production (Coulibaly, 2003). Garalo, belonging to the North-Guinean zone, has a subhumid climate [MAT = 27.0 °C, MAP = 1142 mm; New_LocClim (FAO)] giving rise to a more lush savannah vegetation and a larger diversity of crops (Coulibaly, 2003). Highly degraded soils dominate the landscape in Garalo (Ferric and Plinthic Acrisol), whereas soils in Koulikoro are more productive due to the deposition of Saharan dust (Lixisol) (FAO, 2007). Within each ecoregion, a representative selection of Jatropha fields was made, taking into account various factors as plantation age, management factors (e.g., plant spacing, intercropping), soil conditions, and the presence of neighboring cropland and fallow land. Jatropha plantations were always part of an outgrowers production system managed by a private company (Koulikoro) or local NGO (Garalo).

Data collection

General information on the history and management of each field was gathered using a brief, semistructured interview with the field's owner. Exact field locations and surface areas were recorded using GPS.

Biomass carbon. Only long-term C pools, that is, perennial shrubs and trees, were included in the estimation of biomass C. To determine Jatropha biomass, an allometric equation was first derived from destructive measurements on a representative sample of 46 Jatropha trees originating from within the selected fields and five trees from an additional field in Koulikoro.

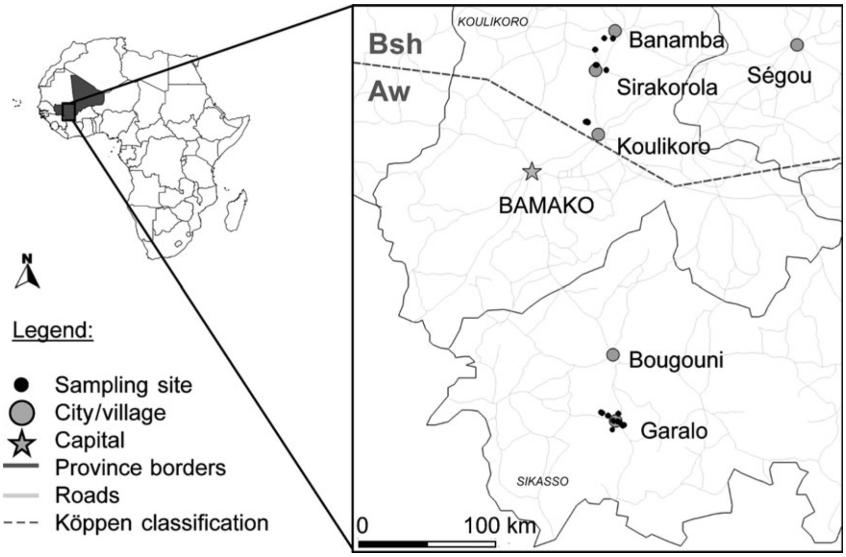

Fig. 1 Location of study sites in relation to Köppen-Geiger climate classification. Bsh, Hot steppe climate and Aw, Tropical savannah climate.

After measuring tree dimensions (i.e., basal stem diameter, tree height, crown diameter in two perpendicular directions, number and diameter of primary branches), the trees were cut down and their woody aboveground biomass (excluding leaves; wAGB) was measured fresh on the field. Subsequently, representative samples of stem and branches were taken, weighed, dried until constant weight (105 °C), and weighed again to calculate the total dry weight of wAGB per tree. Non-linear regression analysis was used to find the most suitable allometric relation. Using the selected equation (see section Jatropha biomass, allometric relation and root-to-shoot ratio, under Results), Jatropha wAGB was then estimated in three square plots per field, each containing nine healthy and representative Jatropha trees, and finally expressed in Mg ha^{-1} using the plot's surface area. Allometric equations for other tree species and shrubs were obtained from the literature (see Box 1). In Jatropha fields and annual cropland, all mature trees and shrubs other than Jatropha were measured individually, whereas a nested sampling design was applied in fallow land, consisting of one 10 × 10 m plot in one 20 × 20 m plot. All trees with a stem diameter exceeding 6 cm were measured in the large plot, while other trees and shrubs were only appraised in the small plot.

Belowground biomass (BGB) was estimated using root-to-shoot ratios. A region-specific value was obtained for Jatropha through destructive measurements of 17 Jatropha trees. After measuring plant dimensions, these trees were uprooted and their dry BGB was determined in a similar way as described above for wAGB. For other species, the literature values were used, that is, 0.28 and 0.56 for trees in subtropical dry forest with more and <20 Mg AGB ha^{-1}, respectively, and 0.32 for scrubland in subtropical steppe (Eggleston *et al.*, 2006). The resulting biomass estimates were converted to C stocks in Mg ha^{-1} using C content data from the literature: 0.46 for Jatropha (based on Firdaus *et al.*, 2010; Torres *et al.*, 2011; Firdaus &

Box 1

Literature-based allometric equations for aboveground biomass

1) Shea tree (*Vitellaria paradoxa* C.F. Gaertner): (Nouvellet *et al.*, 2006)

$$AGB = ((a \times G) - b)) \times \mathrm{wD} \qquad (1)$$

with AGB = aboveground biomass [Mg] of an individual tree, G = girth at breast height [m], wD = wood density (=0.85 Mg m^{-3}; Louppe, 1994); a = 2.4612 (DBH > 0.63 cm) or 0.6868 (DBH < 0.63 cm); b = 1.5130 (DBH > 0.63 cm) or 0.1314 (DBH < 0.63 cm).

2) Trees of dry tropical forest (generic): (UNFCCC, 2006)

$$AGB = \exp[-1.996 + (2.32 \times \ln(\mathrm{DBH}))] \times 10^{-3} \qquad (2)$$

with AGB = aboveground biomass [Mg]; DBH = diameter at breast height [cm].

3) Shrubs (generic): (UNFCCC, 2006)

$$AGB = \sum\left(\frac{\pi}{3} \times \mathrm{BA}_i \times H \times \mathrm{wD}\right) \qquad (3)$$

with AGB = aboveground biomass [Mg]; BA$_i$ = basal area of branch i [m^2]; H = height of shrub [m]; wD = wood density (=0.62 Mg m^{-3}; UNFCCC, 2006).

Husni, 2012; Hellings *et al*., 2012) and 0.50 for other tree species (Eggleston *et al*., 2006).

Soil carbon. Four soil layers were sampled in each field, that is, 0–5, 5–10, 10–20, and 20–30 cm, for which both SOC concentration and bulk density were determined to calculate SOC stocks in Mg ha^{-1} (see Eqn 4).

$$\mathrm{SOC_{stock}} = \frac{\mathrm{SOC}}{100} \times \mathrm{BD} \times \left(1 - \frac{G}{100}\right) \times d \times 10 \qquad (4)$$

with SOC$_{\mathrm{stock}}$ = SOC stock [Mg ha^{-1}]; SOC = SOC mass percentage [g C (100 g soil)$^{-1}$]; BD = bulk density [kg m^{-3}]; G = mass percentage of coarse fragments (>2 mm) [g (100 g soil)$^{-1}$] and d = depth of soil layer [m].

Jatropha fields were sampled most intensively to study the spatial variability of SOC (3 plots × 2 sampling locations per field; Fig. 2). In each Jatropha plot, sample A_1 was mixed with B_1 and A_2 with B_2, yielding two BD samples and two SOC samples for each soil layer per plot. In cropland, three samples were taken per field for both SOC and BD per depth. In each fallow plot (10 × 10 m), six SOC samples, situated on three transects, were taken. These samples were bulked per transect and depth, yielding three SOC samples and one BD sample per depth.

SOC samples were air-dried, passed through a 2-mm sieve, ground, and homogenized with a mortar, oven-dried at 60 °C and analyzed using the automated dry combustion method (Carlo Erba 1110 Elemental Analyzer, Carlo Erba Instruments, Rodano, Italy). As nitrogen levels are determined in the same analysis, these results were also used to calculate the C/N ratio. BD was determined using the gravimetric method, that is, drying samples with a fixed volume of 100 cm^3 overnight (105 °C) and weighing them on a precision balance. These samples were then passed through a 2-mm sieve to calculate the mass fraction of gravel in the soil. Finally, soil texture was measured through laser diffraction analysis (Beckman Coulter – LS 13 320 Laser Diffraction Particle Size Analyzer, Beckman Coulter, Miami, FL, USA) and pH-H_2O was determined using an electrode (Van Reeuwijk, 2002) on one mixed sample per field.

Data analysis

Throughout this study, statistical analyses were conducted in SPSS 17.0 (IBM, Chicago, IL, USA), and a significance level (α) of 0.05 was used, unless stated otherwise. Whenever appropriate, the data were lognormal-transformed to meet the criteria of parametric statistical tests. In general, differences between LUs, soil types, or ecoregions were assessed using ANOVA in combination with Tukey *post hoc* tests. To determine the impact of LUC on SOC using all gathered data, mixed ANOVA was used in which LU was included as a fixed factor and a unique field ID as a random factor, nested in LU to account for subsampling. This analysis was conducted in SAS 9.3 (SAS Institute Inc., Cary, NC, USA) using the MIXED procedure.

The total C debt was calculated as the difference between the total carbon stock (biomass + soil) of the previous land use and the total carbon stock of the Jatropha plantation at year 0 (Fargione *et al*., 2008). The latter was approximated by subtracting the amount of newly sequestered carbon in Jatropha biomass and soil from the total carbon stock measured in the Jatropha plantation. The associated repayment time, that is, the time it takes before the initial C emissions are compensated through the substitution of fossil fuels by Jatropha biodiesel, is calculated by dividing the C debt by the yearly C reduction potential, which is in turn derived from the comparison of the global warming potential (GWP) of Jatropha-based biofuel with the GWP of the fossil fuel reference system. The GWP of both fuels are obtained from a life cycle analysis (LCA) conducted in Koulikoro (Almeida *et al*., 2014).

Results

Description of fields

With the exception of one missing fallow land in Koulikoro, nine fields of each LU type were visited in each ecoregion. The Jatropha plantations under study are 3–5 years old and most frequently established on former cropland. In Koulikoro, Jatropha is always mixed with other crops and wide planting distances of 5 × 2 m are frequently used, whereas in Garalo intercropping is rare and smaller planting distances of 3 × 3 and 4 × 3 m are applied. Furthermore, Jatropha fields are generally ploughed once a year and receive no irrigation or pruning. Cropland most frequently consists of monocultures and is ploughed once a year. In both ecoregions, crops are mainly cultivated in agroforestry parkland systems, where some mature, widely spaced

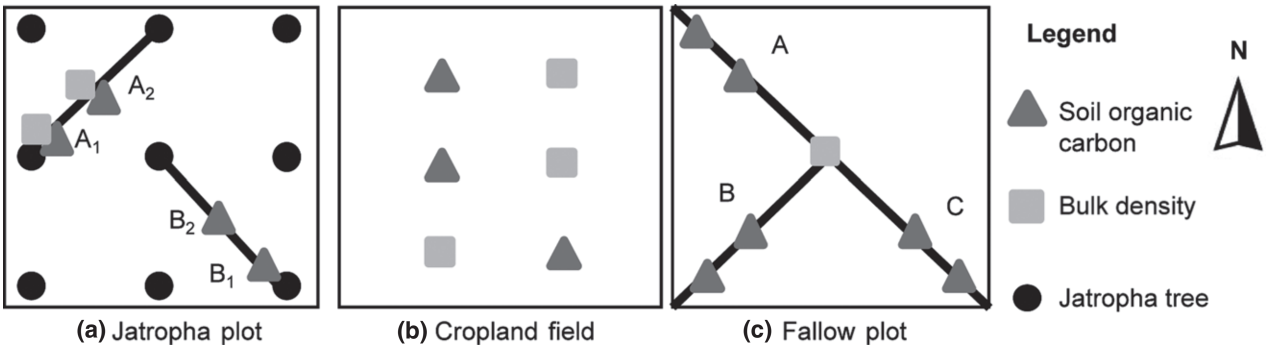

Fig. 2 Soil sampling locations per land-use type (letters represent sampling transects, while numbers refer to sampling locations).

trees (e.g., *Vitellaria paradoxa* C.F. Gaertner, *Parkia biglobosa* (Jacq.) R. Br. ex G. Don and *Mangifera indica* L.) are kept on the field. These provide nutrients to the crops and an extra income to the farmer through the selling of nonwood tree products such as mango fruit and Shea nuts. Major crops are corn, cotton, and sesame in Garalo and corn, sorghum and millet in Koulikoro. Fallow vegetation consists in both ecoregions of bushes combined with mature trees up to 15 m high. Detailed metadata for each field can be found in Table S1.1 in the Supporting information (Data S1). Examples of the three LUs are presented in Figure S1.1 in the Supporting information (Data S1).

Soil conditions

In both ecoregions, two soil types can be distinguished based on hierarchical cluster analysis: sandy vs. loamy soils in Koulikoro and gravel vs. nongravel soils in Garalo. The mean values of the clustering variables for these soil types are presented in Table 1. The loamy soils in Koulikoro closely resemble the nongravel soils in Garalo. The soil variables given in Table 1 were compared between the three LUs for each ecoregion separately using ANOVA analysis. No significant differences were found between the LUs over all triplets of fields (not shown). Although the similarity in soil conditions between individual fields within each triplet cannot be statistically assessed (only one measurement of soil texture available per field), this outcome does provide a good indication that field selection meets the criteria of a paired site sampling design.

Biomass carbon

Jatropha biomass, allometric relation, and root-to-shoot ratio. A summary of plant dimensions and biomass measurements of individual Jatropha trees is given in Table 2. Nonlinear regression analysis resulted in the crown area (in m²) to be selected as the best predicting variable for wAGB ($R^2 = 0.803$; see Eqn 5 and Fig. 3). The average root-to-shoot ratio for Jatropha amounts to 0.48 (Table 2).

$$\mathrm{wAGB} = 0.897 \times \mathrm{CA}^{1.244} \tag{5}$$

with wAGB = woody aboveground biomass in kg and CA = crown area in m².

Biomass carbon stocks in the different land uses. Mature trees, although low in abundance, represent the largest share of biomass C in all LU types (Fig. 4). On average, only 18.6% of the total biomass stock in a Jatropha plantation is in Jatropha trees. The partitioning of the biomass C stock among the different vegetation elements is similar in both ecoregions (not shown), with

Table 1 Mean values of edaphic variables for the soil types in both ecoregions (0–30 cm depth)

Ecoregion	Soil class	# Jatropha fields assessed	% Sand	% Silt	% Clay	% Gravel	pH	% C	% N	BD (g cm^{-3})
Koulikoro	Sandy	2	76.7 (7.4/6)	17.3 (5.8/6)	6.0 (2.1/6)	0.0 (0.0/6)	4.9 (0.4/6)	0.25 (0.11/24)	0.02 (0.01/24)	1.39 (0.05/20)
	Loamy	7	42.1 (7.00/20)	45.4 (5.7/20)	12.5 (3.5/20)	0.0 (0.0/20)	5.2 (0.5/20)	0.58 (0.25/73)	0.04 (0.02/73)	1.34 (0.07/72)
Garalo	Gravel	6	45.3 (11.4/18)	43.1 (7.2/18)	11.6 (4.9/18)	60.8 (14.3/18)	5.1 (0.4/18)	0.72 (0.20/72)	0.05 (0.01/72)	1.46 (0.09/60)
	Non-gravel	3	43.7 (12.5/9)	42.8 (6.4/9)	13.5 (7.7/9)	1.1 (2.2/9)	5.1 (0.2/9)	0.55 (0.19/36)	0.04 (0.01/36)	1.41 (0.1/30)

BD, bulk density.

Numbers in brackets represent the standard deviations and number of samples, respectively.

Table 2 Averages of measurements on individual Jatropha trees, grouped per ecoregion and soil type

Ecoregion	Soil type	Age (years)	Basal area (cm²)	Height (m)	# primary branches	Crown area (m²)	wAGB (kg)	BGB (kg)	R/S
Koulikoro	Loamy	3.45 (0.64/203)	91.98 (55.45/203)	1.70 (0.47/203)	4.16 (1.86/203)	2.97 (2.33/203)	2.55 (2.39/11)	2.14 (0.69/2)	0.46 (0.25/2)
	Sandy	3.50 (0.50/54)	127.57 (44.63/54)	1.80 (0.30/54)	5.69 (1.79/54)	3.43 (1.65/54)	2.67 (1.59/6)	2.35 (-/1)	0.59 (-/1)
Garalo	Gravel	4.55 (0.50/164)	120.25 (47.70/164)	1.89 (0.31/164)	4.14 (1.55/164)	3.09 (1.80/164)	3.58 (2.46/20)	1.57 (1.13/11)	0.44 (0.11/11)
	Non-gravel	4.00 (0.00/81)	99.43 (42.73/81)	1.74 (0.30/81)	4.26 (1.28/81)	2.57 (1.47/81)	3.28 (2.15/9)	2.69 (1.18/3)	0.61 (0.13/3)
All	–	3.90 (0.02/502)	106.25 (2.23/502)	1.78 (0.02/502)	4.33 (0.07/502)	3.00 (0.09/502)	3.16 (0.34/46)	1.88 (0.27/17)	0.48 (0.04/17)

wAGB, dry woody aboveground biomass per tree; BGB, dry belowground biomass per tree; R/S, root-to-shoot ratio.

Numbers in brackets represent standard deviation and number of samples, respectively. 'All' stands for the total mean and standard deviation calculated according to stratified random sampling design.

the exception of the fraction of shrub biomass in fallow land being higher in Garalo (31.4%) compared to Koulikoro (11.4%).

LU has a pronounced effect on the biomass C stock in both ecoregions (Table 3). A significant difference was found between fallow and Jatropha on the one hand ($P = 0.026$ for Garalo and $P = 0.020$ for Koulikoro) and fallow and cropland on the other hand ($P = 0.004$ for Garalo and $P = 0.010$ for Koulikoro). Biomass C stocks in Jatropha plantations are not significantly different from those under annual cropland. This is explained by a similar presence of mature trees in both LUs. Depending on the density and dimensions of these scattered trees in the landscape, the variability in biomass C stocks within each LU is high, implying that the impact of LUC is highly variable as well (see section Total C stock, C debt and C repayment time).

Soil carbon

Soil organic carbon concentrations. SOC concentrations measured in Garalo generally show a logarithmic decrease with depth, being most pronounced in fallow land, followed by Jatropha and cropland (Fig. 5). In Koulikoro, cultivated soils are found to be more homogeneous and are more depleted in organic matter at the surface as compared to Garalo. The latter difference is only found significant for Jatropha ($P = 0.004$). SOC concentrations in fallow land are similar between the two ecoregions. Although SOC concentrations are higher under fallow compared to cropland and Jatropha in all soil layers (Fig. 5), the difference is found to be only significant in the upper 5 cm for Garalo and 10 cm for Koulikoro (see Table S2.1 in the Supporting Information, Data S2).

Soil carbon stocks in the different land uses. SOC stocks are found to follow the same trend as biomass C, that is, being largest under fallow and without significant differences between cropland and Jatropha (Table 3). The effect of LUC is primarily visible in the upper soil layers (Fig. 6).

Spatial variability. A paired t-test was conducted to look for significant differences in SOC between the two sampling locations within Jatropha plantations, that is, directly underneath the shrubs vs. in between the shrubs (Fig. 2). A significant difference is only found for the third soil layer (10–20 cm), where values are larger underneath the shrubs (4.72 Mg ha^{-1}) compared to between the shrubs (4.35 Mg ha^{-1}).

Finally, the within-field spatial variability of SOC, expressed by means of the coefficient of variation (CV), is compared to the between-field variability (Table 4).

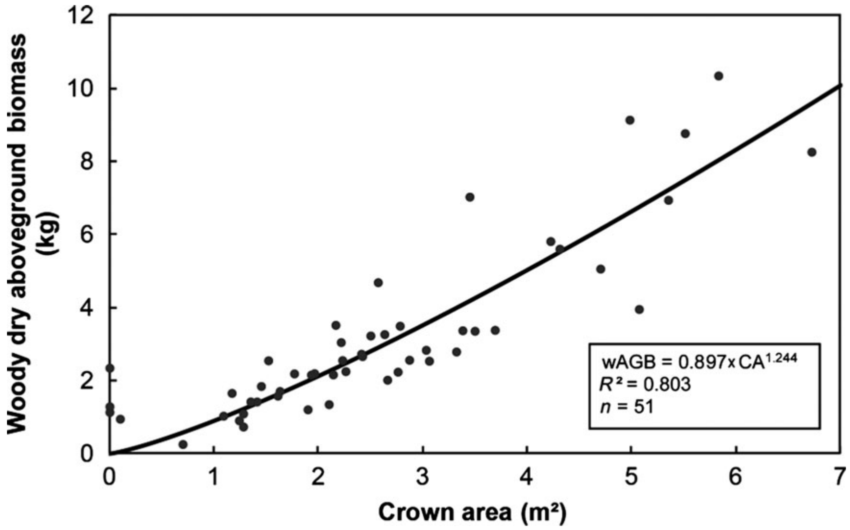

Fig. 3 Allometric relation for woody dry aboveground biomass of individual Jatropha trees based on their crown area.

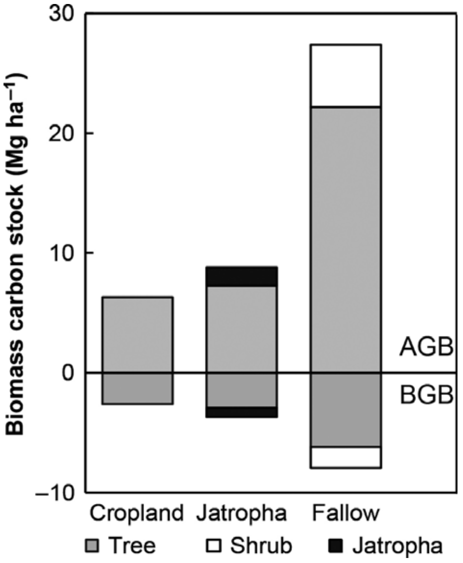

Fig. 4 Partitioning of total biomass carbon stock between aboveground and belowground biomass (AGB and BGB, respectively) and between the different vegetation elements for each land use type. BGB is read below the *x*-axis and AGB above it. The stacked bars represent the vegetation elements: trees, shrubs, and Jatropha.

Spatial variability is largest in fallow and lowest in Jatropha fields, but none of these differences are statistically significant. In all LUs, the within-field CV varies widely between the different fields, making it difficult to estimate the number of samples needed for an accurate estimation of SOC stock in a particular LU. The variability between different fields is the largest source of variation, exceeding the local within-field variability by a factor 2–3.

Total C stock, C debt, and C repayment time

Total C stock differs significantly between fallow land and cultivated land, that is, cropland and Jatropha (Fig. 7a). The same trends were found for the two ecoregions (Table 3), which are therefore displayed together. In cropland and Jatropha fields, most C is stored in the soil, while in fallow land biomass is the dominant C pool. By subtracting the current C stock in Jatropha plantations (at year 4) from the C stock in another LU, the so-called remaining C debt is calculated, that is, the fraction of the initial C debt (C debt at year 0 of the plantation's life cycle) that has not yet been compensated by C sequestration in the Jatropha plantation during the past 4 years (Fig. 7b). On average, this remaining C debt amounts to 32.4 and −3.1 Mg C ha^{-1} for the conversion of fallow land and cropland, respectively, the latter being not significantly different from zero. Based on the nonsignificant differences in SOC between cropland and Jatropha on the one hand and between the two sampling locations within Jatropha fields on the other hand, it can be assumed that SOC sequestration in a timeframe of 4 years is negligible, and consequently, the initial C debt can be approximated by the sum of the remaining C debt and the C stock in Jatropha biomass after 4 years. This results in an average initial C debt of 34.7 Mg C ha^{-1} for fallow land. As can be seen from Fig. 7a, this carbon debt can be mainly attributed to biomass removal prior to planting Jatropha (on average 73% of the total carbon debt is caused by the difference in biomass C content). It should be noted that standard errors of total C stocks are large, resulting in a large variability of C debts (Fig. 7b). For both LUCs under study, the C debt varies

Table 3 Average and standard deviation (within brackets) of Jatropha carbon stocks, total biomass carbon stocks, soil organic carbon stocks (SOC; 0–30 cm depth) and total carbon stocks grouped per ecoregion and land use. Significant differences between land uses per ecoregion are indicated using differing superscript letters

Ecoregion	Land use	Number of fields	Jatropha C (Mg ha^{-1})	Total biomass C (Mg ha^{-1})	SOC (Mg ha^{-1})	Total C (Mg ha^{-1})
Koulikoro	Cropland	9	–	7.97^{a} (7.73)	17.12^{a} (5.08)	25.09^{a} (10.92)
	Jatropha	9	2.68 (1.57)	11.26^{a} (7.65)	17.04^{a} (5.90)	28.30^{a} (12.67)
	Fallow	7	–	44.75^{b} (41.37)	28.08^{a} (16.06)	72.83^{b} (44.15)
Garalo	Cropland	9	–	9.74^{a} (6.28)	14.66^{a} (6.49)	24.40^{a} (10.93)
	Jatropha	9	2.01 (1.25)	13.70^{a} (9.41)	13.77^{a} (6.91)	27.47^{a} (15.02)
	Fallow	8	–	27.00^{b} (12.92)	20.61^{a} (10.23)	47.61^{b} (14.39)

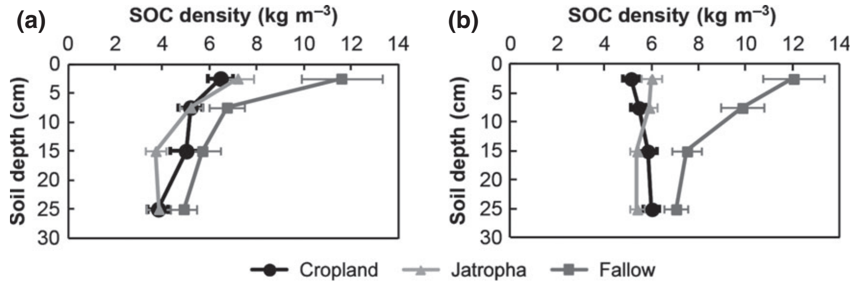

Fig. 5 Relation of soil organic carbon density with soil depth in cropland, Jatropha, and fallow for the Garalo (a) and Koulikoro (b) ecoregions. The error bars represent standard error of the mean.

from highly positive to highly negative, depending on the local situation. All extreme cases (outliers in Fig. 7b) can be explained by large differences in the presence of mature trees between the LUs.

The remaining C debt after 4 years of Jatropha cultivation can be further compensated through substitution of fossil fuels by the produced biodiesel. For this case study, an average biofuel C repayment rate of 0.09 Mg C ha^{-1} yr^{-1} was estimated based on Almeida *et al.* (2014), assuming a seed yield of 0.6 Mg ha^{-1} yr^{-1} (based on local observations). Hence, it would take on average 349 years of Jatropha cultivation and biodiesel production to repay the C debt created after fallow conversion. The calculated repayment time varies between 0 and 1278 years, depending on the C debt. Instead of energy production, Jatropha oil can be diverted to the cosmetic industry or small-scale soap production (Contran *et al.*, 2013), a very attractive practice to smallholders for its simplicity and profitability. Based on the LCA model of Almeida *et al.* (2014), the ratio of materials stated in Contran *et al.* (2013) and assuming that the reaction is heated with fuel wood, the global warming potential (GWP) of Jatropha-based soap production in Koulikoro would amount to 1.2 kg CO_2 eq kg^{-1} soap. The GWP of soaps present in ecoinvent v3 database (The Swiss Centre for Life Cycle Inventories, Switzerland) is on average 5.6 kg CO_2 eq kg^{-1} soap. Hence, with soap production, the average C debt here reported would be repaid within 256 years (range: 0–938 years, depending on C debt).

Discussion

Biomass carbon in Jatropha plantations

Allometric relations based on stem diameter are most frequently used in the literature to estimate the aboveground biomass of Jatropha (Ghezehei *et al.*, 2009; Achten *et al.*, 2010c; Firdaus & Husni, 2012; Hellings *et al.*, 2012; Bayen *et al.*, 2015). However, due to the specific tree architecture of Jatropha, that is, branching close to the soil surface, stem diameter is often difficult to measure. In this study, crown area was found to be the best alternative to predict wAGB. The use of this predictor variable should, however, be restricted to cases where there is no pruning and canopy closure is not yet reached, as these factors highly influence crown dimensions. This shows that the allometric relation to be used for Jatropha biomass estimation should be both location and management specific. The potential sources of error mentioned above can be partly avoided in future allometric relations using both stem and crown diameter simultaneously.

The average root-to-shoot ratio observed in this study (0.48) is higher compared to the value of 0.32 reported by Hellings *et al.* (2012) in similar climatic conditions

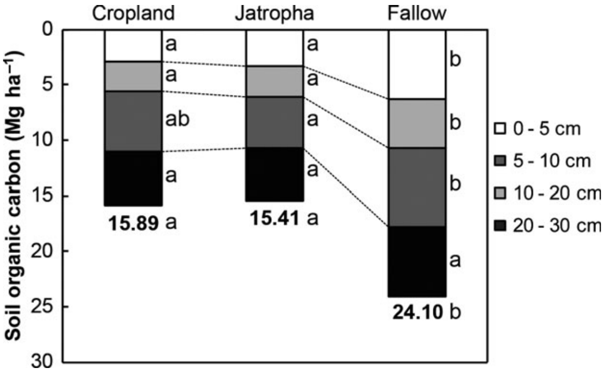

Fig. 6 Average differences in soil organic carbon stocks between the three land uses for each soil layer. Significant differences between land uses are indicated for each soil layer using letters: a soil layer marked with 'a' differs significantly from the same layer in another land use marked with 'b', but not from 'a' or 'ab'; bold numbers represent the total soil carbon stock.

(Northern Tanzania), but agrees well with the value of 0.51 found by Torres *et al.* (2011) for a humid climate in Brazil, both for a similar plant age. Hence, caution should be exercised when using any of these values as a default root-to-shoot ratio for Jatropha in future studies, as this plant characteristic is not only affected by climate, but also by local soil conditions (cf. Table 2: largest root biomass found in stone-free, coarse-textured soils). As most manual measurements of BGB were conducted in plantations on gravel soils, the average root-to-shoot ratio was likely to be underestimated.

Woody biomass stocks for 4-year-old Jatropha plantations found in this study (on average 5.04 Mg ha^{-1}) agree well with the average value of 3.9 Mg ha^{-1} reported by a study under similar environmental conditions in Burkina Faso (Bayen *et al.*, 2015), but are at the lower end of the range between 9 and 28 Mg ha^{-1} given in the literature for various other locations and planting densities (Reinhardt *et al.*, 2007; Firdaus *et al.*, 2010;

Table 4 Coefficient of variation (CV) of soil organic carbon stocks within and between fields

		Within field CV (%)					
	Land use	Mean	Standard deviation	Number of fields	Minimum	Maximum	Between field CV (%)
Koulikoro	Cropland	12.13	13.51	9	0.87	44.06	29.67
	Jatropha	10.27	6.36	9	0.82	19.41	34.60
	Fallow	21.40	12.97	7	8.75	43.20	53.46
Garalo	Cropland	22.59	17.17	9	3.54	62.74	44.27
	Jatropha	16.63	13.77	9	1.54	38.72	50.18
	Fallow	25.76	20.79	8	4.54	62.09	50.08

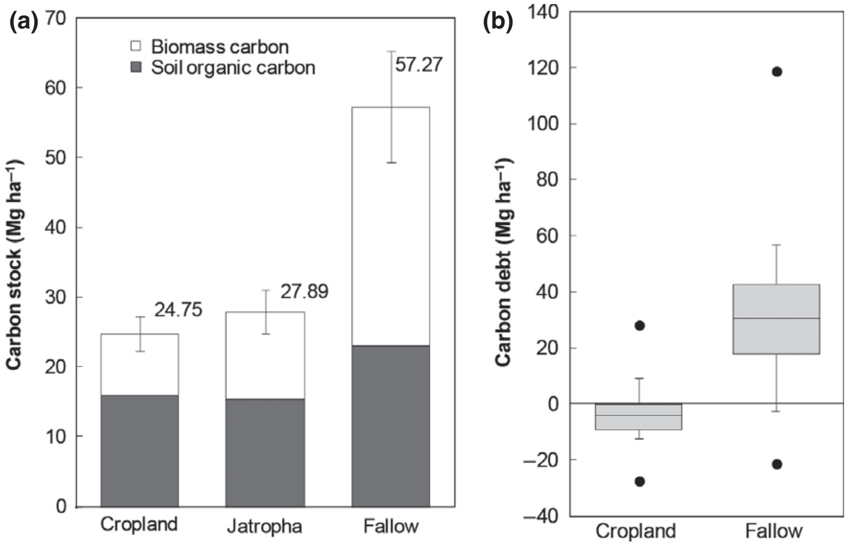

Fig. 7 (a) Average biomass carbon and soil carbon (0–30 cm depth) stocks per land use type. The error bars represent the standard error of the total carbon stocks. (b) Differences in total carbon stocks between Jatropha on the one hand and cropland and fallow on the other hand, or Jatropha carbon debts, presented as boxplots. Large dots represent outliers.

Bailis & McCarty, 2011; Torres *et al*., 2011; Firdaus & Husni, 2012; Wani *et al*., 2012), mainly owing to the relatively low amount of rainfall, poor soil conditions, and lack of management in the sites at hand. It should be noted that plant mortality, although frequently observed (on average 30% in Garalo, mainly due to termite activity – data not shown), was not taken into account in the calculation of Jatropha biomass. Due to this simplification, the biomass results reported here represent the achievable biomass under current management practices and likely overestimate reality. In addition, leaf biomass was not considered in this study due to a lack of data. According to Bayen *et al.* (2015), leaf biomass represents on average 9% of the total AGB in Jatropha plantations.

Soil carbon in Jatropha plantations

The average SOC stock of 15.4 Mg ha^{-1} in the top 30 cm soil profile of Jatropha plantations is lower compared to the value of 28.0 Mg ha^{-1} reported for intensively managed Jatropha plantations in Burkina Faso (0–20 cm). This difference can be due to multiple factors, including climate (Jobbagy & Jackson, 2000), soil (Walker & Desanker, 2004; Takimoto *et al*., 2008), and management (mainly fertilization and tillage). Within our study, soil texture and gravel content explained most of the observed variability in SOC content between the different sites in Koulikoro and Garalo, respectively (Table S2.2, Supporting Information Data S2).

In general, SOC densities found in this study for cropland and fallow (respectively, 16 and 22 Mg ha^{-1}) agree well with the range of 10–30 Mg ha^{-1} reported in similar environmental conditions (Tschakert *et al*., 2004; Woomer *et al*., 2004; Vagen *et al*., 2005; Takimoto *et al*., 2008; Saiz *et al*., 2012; Baumert *et al*., 2014), but are slightly lower than the IPCC default values for a tropical dry climate and low activity clay soils (20 and 35 Mg ha^{-1}, respectively; Eggleston *et al*.,, 2006). The logarithmic relation between SOC and soil depth found in this study is confirmed by Jobbagy & Jackson (2000) and Walker & Desanker (2004) for various ecosystems around the globe.

Land-use change impact and carbon sequestration by Jatropha plantations

Unlike C emissions from biomass, which are concentrated on the moment of land clearing, soil C emissions triggered by LUC can continue for multiple years due to the slow process of mineralization. This implies that, as the moment of LUC, two opposite C fluxes are simultaneously occurring in the Jatropha plantations: (i) continuous carbon emission from soil due to LUC and (ii) building up of newly sequestered C in Jatropha woody biomass and soil (through litterfall and root decay). As only total C stocks were measured at year 0 and year 4, there is no way to strictly separate or quantify either of both fluxes (Conteh, 1999). Despite this drawback, some qualitative conclusions can still be made. The C debt created by converting cropland to Jatropha is generally low and is compensated within 4 years of Jatropha cultivation through C sequestration in Jatropha biomass. There is no significant SOC sequestration taking place within the first 4 years after Jatropha establishment, as there are no differences found in SOC content between Jatropha vs. cropland nor between inter-row and within-row locations in Jatropha plantations. This concurs with the findings of Baumert *et al.* (2014) in Burkina Faso, who used a similar paired sites approach on 4-year-old Jatropha plantations, supplemented by ^{13}C isotope measurements. However, multiple monitoring studies have demonstrated the positive effect of Jatropha cultivation on several soil properties, including SOC concentrations (Ogunwole *et al*., 2008; Wani *et al*., 2012; Srivastava *et al*., 2014). In addition, Baumert *et al.* (2014) found a significantly larger SOC stock in 15- to 20-year-old Jatropha living fences compared to surrounding cropland. Converting cropland to Jatropha thus may have a positive effect on SOC in the long term, but further monitoring is required to confirm this trend for our case. Despite the negligible SOC sequestration estimated in our case study, SOC should not be disregarded from future C sequestration assessments of Jatropha. The high share of SOC in the total ecosystem C stock (38–64%, which agrees well with the range of reported values for West African savannah systems, i.e. 30–90%; Tschakert *et al*., 2004; Bationo *et al*., 2007; Takimoto *et al*., 2008) highlights the importance of this C pool and stresses the need for good crop management practices (Lal, 2004) to avoid the loss of SOC during cultivation.

Converting fallow land to Jatropha has a clear negative impact on C stocks, especially biomass. Due to the protection of some tree species, such as *Vitellaria paradoxa* C.F. Gaertner, not all biomass is removed upon LUC. These few mature trees still make up the largest fraction of biomass after 4 years of Jatropha cultivation (Fig. 4), which clearly shows their benefits from a GHG mitigation perspective. In addition to biomass C, on average 8 Mg SOC ha^{-1} (34%) is lost, which is at the lower end of the 20–60% range that is reported in literature for the conversion of natural land to cropland in similar conditions (Elberling *et al*., 2003; Walker & Desanker, 2004; Vagen *et al*., 2005). The calculated total C debt of 34.7 Mg C ha^{-1} is in line with the estimations of Achten *et al.* (2013) for the conversion of scrubland in semi-arid regions (24–28 Mg C ha^{-1}). Although being at the lower end of the wide range found for various biofuel crops in various ecosystems (0–940 Mg C ha^{-1}, Fargione *et al.*, 2008), it still represents a considerable environmental impact, as can be seen from the high repayment times, implying that the production of Jatropha-based biofuel (and soap) on fallow land under current practices in Mali is unsustainable. Rasmussen *et al.* (2012) found similar high repayment times (187–966 years) for a case study in Mozambique.

One could conclude that Jatropha plantations should only be established in degraded ecosystems with low initial biomass and soil C stocks, as is also recommended by, for example, Achten & Verchot (2011) and Romijn (2011). However, the initial C stocks in soil and biomass are not the only factors that should be considered. Oil yields on degraded lands are often low, giving rise to low repayment rates and hence long repayment times. Low yields incentivize farmers to shift Jatropha to more productive lands, containing more C, and thus giving rise to higher C debts. This trend may cause competition with food production and additional indirect LUCs, which again increase the C debt (Achten & Verchot, 2011). Hence, there is a need for more agronomical research aiming at stabilizing and optimizing Jatropha yields on degraded lands (Muys *et al.*, 2014). Still, in regions such as the Sahel, where rainfall is erratic, significant annual yield variations are expected, causing C repayment rates to be highly variable from 1 year to another.

In addition to repayment through substitution of fossil fuels, the remaining C debt at year 4 can also be partially repaid by additional biomass growth in the Jatropha plantations (until the average biomass C stock of a rotation is reached; Achten *et al.*, 2013). This aspect is, however, not included in the calculation of the repayment time and most likely led to a slight overestimation of the latter. Furthermore, the calculation of C debt and associated repayment time neglects the fate of the C stocks in the biomass and soil of Jatropha plantations. While the C sequestered in biomass will be in principle released after the rotation ends, the evolution of SOC is unknown. This is an important factor to the repayment time because a trend of SOC sequestration may speed it up whilst a trend of loss will postpone it. Due to the lack of long-term chronosequences, it is not possible to infer from the data here presented whether there is sequestration or loss of SOC throughout the lifetime of a Jatropha plantation. The literature data are also contradictory in this matter (e.g., Rasmussen *et al.*, 2012; Baumert *et al.*, 2014).

Finally, the repayment of the C debt is based on the assumption that there is 100% substitution of the fossil fuel in question. However, it is not always the case. It can be argued that in Mali the availability of a liquid fuel in a rural setting may instead add to the energy which is already consumed, given that the energy demand is increasing rapidly in this part of the world (CIA, 2014). In this case, the actual repayment time would be even larger compared to the results reported here. Alternatively, Jatropha oil or biodiesel can replace fuel wood or charcoal, which are the most common fuels in the region, particularly in rural areas (Dasappa, 2011). These fuels are obtained with negligible energy input. In case, they are taken from sustainably managed woodland they are fully renewable and truly C neutral. In such case, the repayment would not exist.

Concluding remarks

Unlike many previous repayment time studies, this study is completely based on field data, which means that the analysis takes into account local specificities which can strongly influence the results and are often missed by modeling approaches (in this case: the dominant effect of retaining mature trees on the C debt). Our C stock data can therefore serve as valuable input for local Jatropha biofuel policy (Witcover *et al.*, 2013), Jatropha sustainability and C sequestration assessments (van Eijck *et al.*, 2014) and for estimating benefits from selling Jatropha-based C credits. Despite the large potential of semi-arid ecosystems to sequester SOC, C stock data in these regions remain particularly scarce (Saiz *et al.*, 2012). Our empirical database might therefore be used in a broader sense, for example, for the calibration and validation of local LUC and SOC models (e.g., RothC, DayCent). However, the results presented here cannot be generalized without caution, as C dynamics are known to be highly dependent on environmental characteristics and local management factors (Powers *et al.*, 2011).

The spatially paired site design applied in this study only results in an approximation of the C dynamics under Jatropha. Monitoring studies using a stock change approach with a timespan of more than 5 years should be conducted on Jatropha plantations to further assess its biomass and soil C sequestration potential, as data on plantations older than 5 years are particularly scarce for this biofuel tree (Rasmussen *et al.*, 2012). In addition, there is a need for more detailed studies that quantify the amount of C lost during LUC, for example, using the eddy covariance technique (Zenone *et al.*, 2012). Finally, future studies aiming at assessing the effect of LU on SOC are advised to not only determine total SOC stocks, but also to look at the different fractions of SOC (particulate organic matter (OM) vs. stable OM; fractions of humic acid, fulvic acid, and humin), as this can provide valuable information regarding the quantity of newly sequestered SOC (Guimarães *et al.*, 2013).

The high repayment times associated with the conversion of fallow land corroborate previous concerns regarding the mitigation potential of Jatropha cultivation and biofuel production (e.g., Rasmussen *et al*., 2012; Achten *et al*., 2013). In this paper, we present an empirical dataset to support these claims. It is, however, important to realize that Jatropha cultivation and the associated LUC can have various other environmental, economic and social effects, either positive or negative (Achten & Verchot, 2011). Research has pointed out positive effects on the level of increased erosion control (Reubens *et al*., 2011) and, on the societal side, empowerment of rural communities involved in smallholder projects (van Eijck *et al*., 2014). Negative issues pertain mostly to failure in secure access to food and land as well as economic unviability (Skutch *et al*., 2011; van Eijck *et al*., 2014). Hence, this study should be seen as part of a larger complex story and should be complemented with a more holistic study in which all these other impacts are included.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Field metadata.
Table S1.1. Field metadata, biomass and soil carbon stocks for each field visited. The field ID (first column) is composed of ecoregion (first letter), land use (second letter) and triplet ID.
Figure S1.1. Example pictures of the three land uses in (a) Koulikoro and (b) Garalo.

Data S2. Soil organic carbon - additional results.
Table S2.1. Means and standard deviations (between brackets) of soil organic carbon (SOC) concentrations, SOC densities and soil bulk densities (BD) per depth for different land uses in the two ecoregions (significant differences between land uses are indicated with differing letters).
Table S2.2. Summary of highly significant ($P < 0.01$) correlations between soil organic carbon density (kg m^{-3}) and soil texture, gravel content, pH and bulk density.