



Research, part of a Special Feature on [Local, Social, and Environmental Impacts of Biofuels](#)

Implications of Biodiesel-Induced Land-Use Changes for CO₂ Emissions: Case Studies in Tropical America, Africa, and Southeast Asia

Wouter M. J. Achten^{1,2} and *Louis V. Verchot*²

ABSTRACT. Biofuels are receiving growing negative attention. Direct and/or indirect land-use changes that result from their cultivation can cause emissions due to carbon losses in soils and biomass and could negate any eventual greenhouse gas (GHG) reduction benefit. This paper evaluates the implications of land-use change emission on the climate-change mitigation potential of different biofuel production systems in 12 case studies in six countries. We calculated carbon debts created by conversion of different land-use types, ranging from annual cropland to primary forest. We evaluated case studies using three different biofuel crops: oil palm, *Jatropha*, and soybean. The time needed for each biofuel production system to pay back its carbon debt was calculated based on a life-cycle assessment of the GHG reduction potentials of the system. Carbon debts range from 39 to 1743.7 Mg CO₂ ha⁻¹. The oil palm case studies created the largest carbon debts (472.8–1743.7 t CO₂ ha⁻¹) because most of the area expansion came at the expense of dense tropical forest. The highest debt was associated with plantation on peatland. For all cases evaluated, only soybean in Guarantã do Norte and Alta Floresta, Brazil needed less than one human generation (30 years) to repay the initial carbon debt. Highest repayment times were found for *Jatropha* (76–310 years) and oil palm (59–220 years) case studies. Oil palm established in peatlands had the greatest repayment times (206–220 years). High repayment times for *Jatropha* resulted from the combined effects of land-cover change and low CO₂ emission reduction rate. These outcomes raise serious questions about the sustainability of biofuel production. The carbon implications of conversion of (semi-)natural systems with medium to high biomass indicate that, in order to generate climate benefits, cultivation of biofuel feedstocks should be restricted to areas that already have low carbon content.

Key Words: *carbon; carbon debt; greenhouse gas; life-cycle assessment; repayment time*

INTRODUCTION

Biofuels are receiving a lot of attention in the public, private, and scientific domains. Seen as an opportunity to reduce both fossil-fuel dependency and greenhouse gas (GHG) emissions, the use of liquid biofuels—such as biodiesel and bioethanol—as an alternative for transportation fuel is expanding (Verrastro and Ladislaw 2007, Hedegaard et al. 2008). Based on these geopolitical and environmental reasons, national and international policies to promote the cultivation and production of biofuels are proliferating. For example, the EU directive on biofuels, which entered into force in May 2003, requires national measures to be taken by 15 member countries in order to replace 5.75% of all transport fossil fuels with biofuels by 2010 (Council 2003, Ryan et al. 2006).

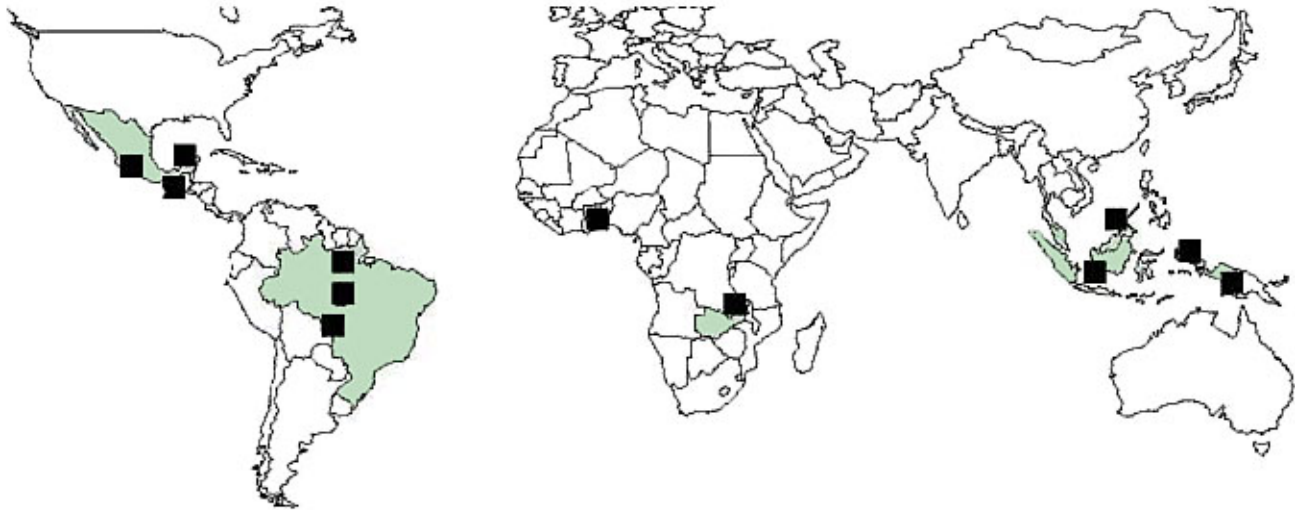
Numerous life-cycle assessments confirm that biofuel systems have the potential to reduce GHG emissions and fossil energy consumption. Oil palm biodiesel has been calculated to reduce GHG emissions (calculated in equivalents – CO₂-eq) by 38–79.5% compared with fossil fuels (Zah et al. 2007, Wicke et al. 2008, Pleanjai and Gheewala 2009, Pleanjai et al. 2009, Yee et al. 2009, Achten et al. 2010f). Estimates suggest that biodiesel from *Jatropha* can reduce emissions from 49% to 72% (Prueksakorn and Gheewala 2008, Ndong et al. 2009, Ou et al. 2009, Achten et al. 2010b). Soybean-based biofuels have an estimated emissions reduction potential of 57% to 74% (Huo et al. 2009).

Despite this climate mitigation potential, biofuels have received growing negative attention as well. As an additional source of competition for land, biofuels can trigger land-use change (LUC), which can result in unwanted social and environmental effects, such as loss of natural vegetation, loss of biodiversity, labor competition, reduced food security (from the displacement of agricultural crops and other land uses, biofuels-induced food price increases, labor competition, and other direct and indirect effects), and overexploitation of water resources (Stephens et al. 2001, UN-Energy 2007, Food and Agriculture Organisation (FAO) 2008, Mitchell 2008, Keeney 2009). The LUC also triggers changes in carbon stocks in biomass and soils. These carbon-stock changes are often not taken into account in life-cycle assessments and can attain proportions that can negate the life-cycle GHG reduction potential of the biofuel production system (Fargione et al. 2008, Searchinger et al. 2008, Lapola et al. 2010). Such initial carbon-stock changes caused by land-cover transformation have been dubbed by Fargione et al. (2008) as the “carbon debt” of the new system.

This paper aims to evaluate the implications of LUCs for the climate-change mitigation potential of different biofuels crops in different settings in Asia, Africa, and Latin America. As can be seen from the other articles in this special issue, the LUCs in these case studies range from conversion of annual cropland to conversion of primary peatland forest. We analyze

¹Department Earth and Environmental Sciences, K.U.Leuven, ²Centre for International Forestry Research (CIFOR)

Fig. 1. Overview map indicating the location of the 12 cases evaluated in six countries.



biofuels produced from (a) oil palm in Malaysia and Indonesia, (b) *Jatropha* in Ghana, Zambia, and Mexico, and (c) soybean in Brazil. Both direct as well as indirect LUC effects on soil and biomass carbon stock are considered. For our analysis, direct LUC refers to that carried out for the production of biofuels. Indirect LUC refers to displacement of current land-use systems by biofuels that results in LUC in new areas (Searchinger et al. 2008). For example, if the development of a biofuel plantation results in the displacement of agricultural land formerly dedicated to cereal crops, and the farmers in the area respond by intensifying cereal production on lands already dedicated to that type of production, there is no indirect LUC. However, if the farmers make up for the shortfall in cereals by bringing previously uncultivated land into production, this would be considered indirect LUC.

The time needed for the biofuel system to pay back its carbon debt (the so-called “repayment time”) is calculated based on life-cycle GHG reduction potentials of the biofuel production system. By including indirect LUC, we take Fargione et al.’s (2008) analysis a step further, similar to what was done by Searchinger et al. (2008) and Lapola et al. (2010). However, this paper is the first to our knowledge that uses specific case studies with LUC data for the calculation of carbon debts caused by biodiesel production. This means that this paper reports on climate-change implications of real-world biodiesel expansion that is happening in the field. This approach allows us to probe the sensitivity of the final repayment time to quite variable case-specific factors, such as location, local LUC practices, displaced land-use types, and biofuel performance.

METHODS

Carbon debt of LUCs and repayment times are calculated following the methodology described by Fargione et al.

(2008). The methodology consists of four steps: (a) determining the amount of carbon lost from biomass and soil stocks due to a particular LUC in each case study area, (b) determining an allocation of this carbon debt to the different products and by-products of the biofuel system (e.g., palm kernel oil, glycerin, soy meal, *Jatropha* press cake), (c) determining the annual CO₂ reduction rate from substituting biofuels for fossil fuels, and (d) calculating the repayment time of the carbon debt based on the annualized rate of emissions reductions.

Case Studies

Although more detailed site descriptions are available in the other contributions to this special issue, a short overview is given here. The spatial distribution of case study sites is illustrated in Fig. 1.

Oil palm

Four oil palm cases are evaluated, three located in Indonesia and one in Malaysia. Two of the Indonesian cases are located in Papua: (i) Keerom and Manokwari Districts in the east (established in 1982) and (ii) Boven Digoel District in central Papua (established in 1998). The third case is located in Kubu Raya District in West Kalimantan (established in 1994). The Papua case studies are located in lowland tropical rainforests on mineral soils, whereas the concession in West Kalimantan lies in a peatland (K. Obidzinski, R. Andriani, H. Komarudin, A. Andrianto *unpublished manuscript*). The Malaysian case is located in Beluran District (Sabah) (established in mid 1980s and replanted during 2007–2009) and evaluates the impact of two estates situated 105 km east of Sandakan on mineral soils (Dayang Norwana et al. *in press*).

Jatropha

The impact of *Jatropha* biodiesel production was evaluated for five cases in Ghana (1), Zambia (1), and Mexico (3). The Ghanaian case study is a commercial-scale *Jatropha* plantation started in 2008 in the forest to savanna transition zone in Pru District, Brong Ahafo Region (Schoneveld et al. 2011). In Zambia, the impact of *Jatropha* outgrowers connected to a private company is evaluated (activities were initiated in 2004). Based on the presence of outgrower clusters, Chinsali and Mungwi Districts in the Northern Province were selected for analysis (German et al. 2011). The Mexican cases, established in 2007, evaluate smallholder systems in Chiapas and Michoacan states and a commercial production operation in Yucatan (Skutsch et al. 2011).

Soybean

The impact of soybean-based biodiesel production is evaluated in three sites in Brazil. Two sites are located in Mato Grosso, one in the Cerrado ecoregion near Sorriso, where soybean is cultivated since the 1980s, and the other in the zone of transition to dense forest near Guarantã do Norte and Alta Floresta, where soybean is currently not very prevalent. In this case, an anticipated future LUC is evaluated. The third site is in the Amazon ecoregion near Santarém, where soybean has been promoted since 2005–2006 (Lima et al. 2011).

Land-Use and Carbon-Stock Change

We estimated direct land-use change (dLUC) through farmer, household, and stakeholder interviews (implemented in 2009 in Ghana, Zambia, and Mexico) and through spatial analyses of remote-sensing data (for the Malaysian case: land-cover maps of 1970 and 2007; for the Manokwari, Indonesia case: Landsat images of 1972–1982, 1989–1991, and 2006; for the West Kalimantan, Indonesia case: Landsat images of 1989, 2001, and 2009; and Boven Digoel, Indonesia: Landsat images of 1990, 2002, and 2008). In Brazil, we based dLUC estimates on qualitative stakeholder interviews. Details on these surveys and analyses can be found in the country case studies in this issue (Dayang Norwana et al. *in press*, German et al. 2011, Lima et al. 2011, Schoneveld et al. 2011, Skutsch et al. 2011, K. Obidzinski, R. Andriani, H. Komarudin, A. Andrianto *unpublished manuscript*). Indirect LUC (iLUC) was quantified through household interviews in the Zambia and Ghana cases. In Indonesia, Mexico, and Brazil, this was not possible either because case-study analysis focused on industrial-scale production systems (where household surveys would not be an effective means to generate such data) or interview respondents were unable to recall LUC sequences with sufficient accuracy. In these cases, calculations were based on iLUC scenarios where iLUC factors were selected as defined by Fritsche et al. (2010a, b) based on an expected average annual biofuel yield increase of 1% over the next 25 years. We assume no iLUC when conversion was from forest or other lands not used in agricultural production systems. For

the West Kalimantan case in Indonesia, the Michoacan and Chiapas cases in Mexico, and the Guarantã do Norte, Alta Floresta, and Santarém cases in Brazil, iLUC carbon debts were calculated for low, medium, and high iLUC corresponding to 25% (iLUC_{Low}), 50% (iLUC_{Medium}), and 75% (iLUC_{Max}) of the area of biofuel expansion occurring on land converted from permanent or shifting agricultural systems, respectively (Fritsche et al. 2010a). In addition, this represents the same range as the net displacement factors of different corn ethanol studies summarized by Plevin et al. (2010) and the iLUC values used for soybean and oil palm (48%–49%) in Overmars et al. (2011). Furthermore, the iLUC estimates from the Ghanaian and Zambian cases (29% and 52%, respectively) (German et al. 2011, Schoneveld et al. 2011) also fall within these ranges. Using these figures, we captured the range of likely carbon debts and repayment times. For the cases where these iLUC scenarios were applied, it was assumed that the displaced agriculture or pasture would trigger conversion of the same land-cover type as that which was subject to dLUC. The exception to this was the Guarantã do Norte and Alta Floresta case study in Brazil where the iLUC triggered due to the conversion of pasture was assumed to occur in Cerrado (Table 1).

The calculation of carbon-stock changes from dLUC and iLUC was done by using either carbon-stock data from field measurements (e.g., Mexico) or region-specific carbon values for a particular ecosystem as reported in the literature. Carbon-stock changes due to conversion of cropland were calculated by using the ENCOFOR carbon accounting model developed to facilitate analysis of carbon sequestration in Clean Development Mechanism projects (Verchot et al. 2007). Model inputs were collected from field measurements, literature review, and expert knowledge. Soil carbon changes for the different LUCs are based on region-specific values reported in the literature or calculated based on Tier 1 estimates from the Intergovernmental Panel on Climate Change (IPCC) National Greenhouse Gas Accounting Guidelines (IPCC 2006).

The carbon-stock estimates for the standing biomass of the biofuel feedstock crop were derived from the literature (see Appendices 1–6). To calculate the carbon debt associated with dLUC, these estimates were subtracted from the carbon stock of the original land cover. *Jatropha* growth and productivity are known to be highly variable and dependent on climatic conditions (Achten et al. 2008, 2010d, Trabucco et al. 2010). Thus, the carbon accounting for these case studies was done with three scenarios: for productivity, we work with a best estimate or expected yield (E) for each site based on the global *Jatropha* yield map made by Trabucco et al. (2010), a conservative estimate (C) using yield figures that are 500 kg dry seed ha⁻¹ yr⁻¹ below the best estimate, and an optimistic estimate (O) using yield values that are 500 kg dry seed ha⁻¹ yr⁻¹ greater than the best estimate (E). The carbon-stock values

Table 1. Area converted to biofuel and the direct (dLUC) and indirect land-use change (iLUC) thus triggered

Case Study	dLUC	Type of conversion	iLUC	Type of conversion
<i>Oil Palm</i>				
Beluran District, Malaysia	100%	Lowland tropical rainforest	0%	
Prafi, Manokwari, Indonesia	48%	Lowland tropical primary rainforest	0%	
	43%	Lowland tropical secondary rainforest		
	9%	Agricultural land	N.A.	Lowland tropical primary rainforest [†]
Kubu Raya, West Kalimantan, Indonesia	84%	Tropical peatland forest	0%	
	4%	Swamp	0%	
	12%	Agricultural land	N.A.	Tropical peatland forest [†]
Boven Digoel District, Papua, Indonesia	96%	Lowland tropical primary rainforest	0%	
	2%	Tropical peatland forest	0%	
	1%	Swamp	0%	
	0.5%	Agricultural land	N.A.	Lowland tropical primary rainforest [†]
<i>Jatropha</i>				
Pru, Brong Ahafo, Ghana	46%	Mix of open and closed woodland	0%	
	23%	Permanent cropland (10% yam, 13% other crops)	29%	Fallow land
	31%	Fallow land (naturally regenerating woodland)	0%	
Yucatan, Mexico	100%	Secondary woodland	0%	
	25%	Secondary forest	0%	
Michocan, Mexico	25%	Fallow land [‡]	N.A.	Secondary forest [†]
	50%	Permanent cropland (annuals)	N.A.	Secondary forest [†]
	5%	Secondary forest	0%	
Chiapas, Mexico	29%	Pasture	N.A.	Secondary forest [†]
	66%	Agricultural land (annual cropping)	N.A.	Secondary forest [†]
Chinsali & Mungwi, Zambia	24%	Mature miombo woodland	0%	
	61%	Permanent cropland (annuals)	34%	Miombo woodland
			19%	Fallow land [†]
	15%	Fallow land [†]	0%	
<i>Soybean</i>				
Sorriso, Brazil	50%	Cerrado forest	0%	
	50%	Pasture	N.A.	Cerrado forest
Guarantã do Norte & Alta Floresta, Brazil	100%	Degraded pasture	N.A.	Cerrado forest [†]
Santarém, Brazil	92%	Permanent cropland	N.A.	Amazon rainforest [†]
	8%	Amazon rainforest	0%	

N.A.: not assessed

[†] iLUC_{Max}=75%; iLUC_{Medium}=50%; iLUC_{Low}=25%; [‡] fallow: 8–11 years old

for *Jatropha* are also linked to conservative, estimated, and optimistic *Jatropha* seed yield values (see below). An overview of the different carbon-stock changes and the values used are shown in Appendices 1–6.

Allocation to Bioenergy and Annual CO₂ Reduction Rate of the Biodiesel System

Although the LUCs and related carbon-stock changes considered here are caused by the cultivation of biofuel

feedstocks, the total carbon-stock change should not be fully allocated to the final biodiesel product only (Fargione et al. 2008). Biodiesel production systems generally yield byproducts, and if these byproducts have a productive or economic value (e.g., fertilizer for on-farm use or for sale), a portion of the carbon-stock change should be allocated to these as well. In life-cycle assessment, this allocation of environmental impacts among different products and byproducts can be based on ratios of energy content, mass, or

Table 2. Carbon debt due to direct (dLUC) and indirect land-use change (iLUC) expressed in terms of both carbon and CO₂-eq

Case study		dLUC ha ⁻¹		iLUC ha ⁻¹		Total ha ⁻¹	
		Mg CO ₂	Scenario	Mg CO ₂	Mg CO ₂		
<i>Oil Palm</i>							
Beluran District, Malaysia		698.8		0.0		698.8	
Prati, Manokwari, Indonesia		456.4	25%	15.4		472.8	
			50%	30.8		487.2	
			75%	46.2		502.6	
Kubu Raya, West Kalimantan, Indonesia		1578.9	25%	54.9		1633.8	
			50%	109.8		1688.7	
			75%	164.7		1743.7	
Boven Digoel District, Papua, Indonesia		710.9	25%	0.8		711.6	
			50%	1.6		712.4	
			75%	2.3		713.2	
<i>Jatropha</i>							
Pru, Brong Ahafo, Ghana	C	246.8		11.4		258.2	
	E	239.8		11.0		250.7	
	O	232.7		10.5		243.2	
Yucatan, Mexico	C	190.1		0.0		190.1	
	E	184.5		0.0		184.5	
	O	178.9		0.0		178.9	
Michoacan, Mexico	C	144.2	25%	113.6		257.8	
			50%	227.2		371.4	
			75%	340.8		485.0	
	E	140.0	25%	112.3		252.3	
			50%	224.7		364.6	
			75%	337.0		477.0	
	O	135.7	25%	111.1		246.8	
			50%	222.2		357.9	
			75%	333.2		469.0	
Chiapas, Mexico	C	23.5	25%	199.5		223.1	
			50%	399.1		422.6	
			75%	472.6		496.1	
	E	18.3	25%	197.9		216.3	
			50%	395.9		414.2	
			75%	468.8		487.2	
O	13.2	25%	196.4		209.5		
		50%	392.7		405.9		
		75%	465.0		478.2		
Chinsali & Mungwi, Zambia	C	32.3		26.7		59	
	E	24.7		24.5		49	
	O	17.1		22.4		39	
<i>Soybean</i>							
Sorriso, Brazil		134.5		0.0		134.0	
Guarantã do Norte & Alta Floresta, Brazil		23.5	25%	33.6		57.1	
			50%	67.2		90.7	
			75%	100.9		124.3	
Santarém, Brazil		55.3	25%	159.1		214.4	
			50%	345.9		401.2	
			75%	518.8		574.1	

25%, 50% and 75% represent the low, medium and max iLUC scenarios

C: conservative; E: estimated; O: optimistic

economic value (Jensen et al. 1997). It is preferable to avoid allocation by using system-boundary expansion, in which similar products are substituted for the byproducts in the reference system (Jensen et al. 1997); however, this is not always possible.

For the *Jatropha* cases, the allocation to production system byproducts was avoided by system-boundary expansion in the life-cycle GHG emission reduction calculation. This is because a generic life-cycle assessment is available for *Jatropha* biodiesel (Achten 2010, Almeida et al. 2011). In Achten (2010), the sensitivity of the life-cycle GHG emission reduction to the *Jatropha* seed yield was analyzed for different regions in Tanzania. In the Ghanaian and Zambian case study, *Jatropha* is often intercropped with food crops (e.g., maize, groundnut, beans, sweet potato) during the first few years. This means that, in addition to the byproducts, any LUC also results in the production of other crops to which a part of the carbon change must be allocated. To estimate this allocation, we assume that (1) *Jatropha* is expected to offset decreased income of the food crop, (2) increasing competition makes intercropping economically unviable from year 4, and (3) the food-crop yield will be 100% in the first year, 50% in the second year, and 25% in the third year due to the increasing competition with *Jatropha*. Over a rotation period of 20 years, these yields represent 1.75/20 or 8.75% of the total economic production. This results in an allocation of 91.25% of the LUC emissions to *Jatropha* biodiesel in these case studies.

Based on a global *Jatropha* seed-yield map produced by Trabucco et al. (2010) and based on the scale of production (smallholder vs. industrial-scale plantations), we estimated yields for each case study. We used these values in combination with the generic *Jatropha* life-cycle assessment, which included sensitivity to yield (Achten 2010), to calculate the annual CO₂ reduction rates of *Jatropha* biodiesel (after allocation). Because of the yield variability in *Jatropha*, CO₂ reduction rates were calculated for expected, conservative, and optimistic yields based on a regression analysis of data points linking yield with CO₂ reduction rates available in Achten (2010).

For soybean and oil palm, analyses of CO₂ reduction rates using system-boundary expansion are not available. Therefore, for these feedstocks, we used the ratio of economic values to allocate carbon emissions. The annual CO₂ reduction rates and economic values to calculate allocation ratios were extracted from the literature. In terms of allocation, soybean production adds an extra complication. As a seasonal crop, soybean provides the farmer the opportunity to plant a second crop each year (Skutsch et al. 2011). For appropriate attribution of GHG emissions, this second crop should be considered as a byproduct of the LUC and part of the carbon loss due to LUC should be allocated to it. In Brazil, this second crop is generally maize (Lima et al. 2011). For this analysis,

it was assumed that most of the soybean cultivators cultivate a second crop and that this crop is maize. The allocation was based on average production figures of soybean and maize in Brazil (USDA 2010) and global commodity prices (WorldBank 2010).

Repayment Rates

Repayment rates linked to dLUC, iLUC, and total LUC carbon debts were calculated following Fargione et al. (2008):

$$\text{Carbon debt [Mg CO}_2 \text{ ha}^{-1}] \times \text{Allocation [\%]} / \text{CO}_2 \text{ reduction rate [Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}]$$

For the *Jatropha* cases, repayment times are calculated for conservative, expected and optimistic biomass carbon stock and seed yield values, because *Jatropha* yields are highly variable, and CO₂ reduction rates of *Jatropha* biodiesel highly sensitive to the yield (Achten 2010)

For the sake of comparability and for projecting the likely future effects of biofuel expansion, the case studies were analyzed as if they had been established for exclusive production of oil for biodiesel. It is important to note that this does not always reflect the current reality. About 90% of global palm oil production is used for the manufacture of edible and other commercial products different from biofuels (Edem 2002). Carbon debts or carbon losses related to the oil produced for food or other markets (e.g., cosmetics) cannot be converted to repayment times, as these products have no CO₂ emissions reduction potential.

RESULTS

Carbon-Stock Changes Due to Land-Use Change

Table 1 shows the dLUC and iLUC per ha attributable to a biofuel feedstock for each case study. The carbon debt connected to the dLUC and iLUC are shown in Table 2.

The largest dLUC carbon debts were created in the oil palm case studies, in particular those resulting from the conversion of peatland forest in West Kalimantan, Indonesia. Carbon debts were smaller for oil palm on mineral soils, but still among the highest in our case studies because plantation expansion occurred through the conversion of dense tropical forests. dLUC carbon debts created by *Jatropha* and soybean were significantly lower. The *Jatropha* cases resulted in an average dLUC carbon debt of 33.0 Mg C ha⁻¹ (121.5 Mg CO₂-eq ha⁻¹) based on “estimated” values, whereas the soybean cases triggered an average dLUC carbon debt of 19.4 Mg C ha⁻¹ (71.2 Mg CO₂-eq ha⁻¹).

The iLUC carbon debts shown in Table 2 are quite variable, in part due to large differences in dLUC of agricultural land. For example, shares of agricultural land contributing to dLUC were as low as 0.5 % in Boven Digoel and as high as 61% in Zambia or 100% for pasture in Guarantã do Norte and Alta Floresta (Table 1). A second reason for the high variability

was the differences in carbon content of forests lost through iLUC (e.g., Miombo vs. tropical peatland forest) (Table 1). In the case studies where we were able to directly measure iLUC, emissions tended to be lower than estimates based on iLUC scenarios. For cases where iLUC was not quantified in the field, the different scenarios resulted in very different estimates—as might be expected with the large variation in iLUC factors.

The total LUC shows similar trends as the dLUC carbon debt, with the oil palm cases creating the biggest overall carbon debt, and the Jatropha and soybean cases triggering significantly lower total carbon debts. We calculated averages and standard deviations for total carbon debt results with estimated values and $iLUC_{\text{Medium}} = 50\%$ to show the relative difference among different oil crops. These calculations suggest that among our case studies, oil palm creates an average carbon debt of $883.05 (\pm 511.0) \text{ Mg CO}_2 \text{ ha}^{-1}$, Jatropha causes an average total carbon debt of $252.5 (\pm 145.5) \text{ Mg CO}_2 \text{ ha}^{-1}$, and soybean an average debt of $208.7 (\pm 167.9) \text{ Mg CO}_2 \text{ ha}^{-1}$.

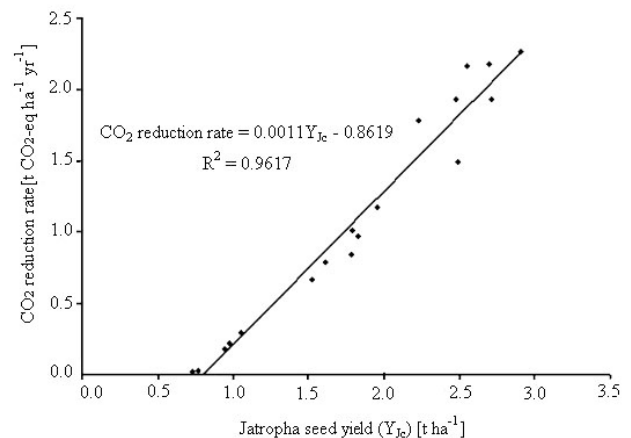
Allocation of Debt to Bioenergy and Annual CO₂ Reduction Rate of the Biodiesel Systems

Based on the economic values of the byproducts of palm oil biodiesel, Fargione et al. (2008) have determined that 87% of the carbon debt should be allocated to biodiesel, and the remaining debt should be allocated to the palm kernel oil and cake. For soybean, there is a first allocation step to the second crop in the rotation (in this case, maize). Average production rates in Brazil and world prices for maize (2.79 t ha^{-1} , $162.7 \text{ US\$ t}^{-1}$) and soybean (3.99 t ha^{-1} , $417 \text{ US\$ t}^{-1}$) (USDA 2010, WorldBank 2010) result in a 64% allocation of carbon debt to soybean. The second step was to allocate the portion of the carbon debt to soybean oil. Using an estimated oil content of 18% (Lima et al. 2011) and the price difference between soybean oil and soybean meal, 42% of the remaining carbon debt may be allocated to the soy biodiesel. Thus, 26.9% of the carbon debt created by the whole production system may be attributable to soy-based biodiesel. For Jatropha, the allocation is incorporated in the CO₂ reduction rate values, as these are calculated with a generic life-cycle assessment avoiding allocation by system-boundary expansion (Almeida et al. 2011, Achten 2010).

For oil palm biodiesel, we calculated different life-cycle CO₂ emissions reduction rates for Malaysia and Indonesia (Table 3) due to the yield difference between the two countries. For Jatropha, estimated seed yields were used to calculate CO₂ emissions reduction rates based on a linear relationship over a broad range of yields (Fig. 2, Table 3). This relationship indicates that a yield of at least $783 \text{ kg ha}^{-1} \text{ yr}^{-1}$ is required to achieve CO₂ emissions reductions. This is because basic operational CO₂ emissions (e.g., from transport, fertilizer, oil extraction, transesterification) exceed the emission reduction

potential of Jatropha at yields below this level. Therefore, as the result for the Zambia case study with the conservative yield estimate shows, under some circumstances, biofuel systems can create a permanent emission source. The life-cycle CO₂ emissions reduction rate for the soybean system was found to be $0.87 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Table 3).

Fig. 2. Regression analysis of the life-cycle CO₂ reduction rate in function of Jatropha seed yields (based on Achten (2010)).



In general, the results show that oil palm cases represent the highest CO₂ emissions reduction rates, eight to nine times higher than soybean system CO₂ emissions reduction rates. The Jatropha cases, based on variable yields, represent CO₂ emission reduction rates ranging from 0.24 to $2.99 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$.

Repayment Time

In Table 4, the repayment times are shown for the different case studies. dLUC carbon debts show a repayment time between 7 and 199 years for pasture to soybean (in Brazil) and peatland forest to oil palm (Indonesia), respectively. In contrast to the dLUC carbon-debt values, the dLUC repayment times are similar for oil palm and Jatropha because of the differences in carbon stocks in the original ecosystem. Repayment times are significantly lower for the soybean cases in Mato Grosso. The dLUC repayment times of the Jatropha cases show big differences among the conservative, expected, and optimistic biomass carbon-stock and seed-yield values. For the case studies with conservative values, repayment times range from 30 to 183 years, and carbon debts would never be repaid in the conservative Zambia case. In this case, cultivating Jatropha with these yields results in sustained carbon emissions. For the case studies using optimistic values, repayment times vary between 7 and 72 years. In case optimistic seed yields can be attained, carbon debts from dLUC in Chiapas and Zambia could be repaid within one

Table 3. Percentage of carbon debt to be allocated to the biodiesels, yield figures used to calculate the CO₂ reduction rates and the CO₂ reduction rates of the biodiesel for each case study

Case study		Allocation [%]	Yield [Mg dry seed ha ⁻¹ yr ⁻¹]	CO ₂ reduction rate [Mg CO ₂ ha ⁻¹ yr ⁻¹]	Sources
<i>Oil Palm</i>					
Beluran District, Malaysia		87		7.69	[6-8]
Prafi, Manokwari, Indonesia		87		6.90	[1, 6-9]
Kubu Raya, West Kalimantan, Indonesia		87		6.90	[1, 6-9]
Boven Digoel District, Papua, Indonesia		87		6.90	[1, 6-9]
<i>Jatropha</i>					
Pru, Brong Ahafo, Ghana	C	91.25	2500	1.89	[10]
	E	91.25	3000	2.44	[5, 10]
	O	91.25	3500	2.99	[10]
Yucatan, Mexico	C	91.25	2500	1.89	[10]
	E	91.25	3000	2.44	[5, 10]
	O	91.25	3500	2.99	[10]
Michocan, Mexico	C	91.25	1500	0.79	[10]
	E	91.25	2000	1.34	[5, 10]
	O	91.25	2500	1.89	[10]
Chiapas, Mexico	C	91.25	1500	0.79	[10]
	E	91.25	2000	1.34	[5, 10]
	O	91.25	2500	1.89	[10]
Chinsali & Mungwi, Zambia	C	91.25	500	-0.32	[10]
	E	91.25	1000	0.24	[5, 10]
	O	91.25	1500	0.79	[10]
<i>Soybean</i>					
Sorriso, Brazil		27.0		0.87	[1,2,4]
Guarantã do Norte & Alta Floresta, Brazil		27.0		0.87	[1,2,4]
Santarém, Brazil		27.0		0.87	[1,2,4]

Sources: [1] (Fargione et al. 2008); [2] (USDA 2010); [3] (World Bank 2010); [4] (Lima et al. 2011); [5] (Trabucco et al. 2010); [6] (Yee et al. 2009), [7] (Wood and Corley 1991), [8] (Yusoff and Hansen 2007), [9] (Pleanjai et al. 2009), [10] (Achten 2010)

C: conservative; E: estimated; O: optimistic

Jatropha rotation (20 years). When estimated yield and biomass values are attained, the Chiapas case is the only one that can achieve a net CO₂ reduction within the first rotation, whereas the Ghana, Michocan, Mexico, and Zambia cases need almost five rotations (>3 human generations) and the Yucatan case, four rotations (2.5 human generations). Skutsch et al. (2011) calculated considerably lower repayment rates for *Jatropha* production systems in the Yucatan (2–14 years). However, their analyses were based on carbon debts created only by loss of aboveground biomass and did not include belowground biomass carbon or soil carbon, as was done in this study. Furthermore, the discrepancy with Skutsch et al. (2011) can be explained by differences in the estimated *Jatropha* yield (6.8–20 t seed ha⁻¹ yr⁻¹ compared with 2.5–3.5 t seed ha⁻¹ yr⁻¹ in this study). For the oil palm case studies, one to seven rotations (and one to about seven human generations) are necessary to repay the dLUC carbon debt.

Repayment times for iLUC were generally low for the oil palm cases and varied from very low to very high for both *Jatropha* and soybean cases. As expected, low repayment times were associated with systems that had high yields and low levels of iLUC. Interestingly, iLUC repayment times can greatly exceed dLUC repayment times in cases where iLUC results in conversion of the intact native ecosystem (e.g., tropical peatland forest in Kalimantan, Indonesia or Cerrado woodland in Sorriso, Brazil). There is a possibility that iLUC could displace activities to degraded or marginal lands, but these lands are rarely productive enough to be worth the effort required to bring them into production.

Considering the total repayment time needed to compensate both dLUC and iLUC, the soybean biodiesel cases established in degraded pasture show the shortest repayment times (18–38 years) because of the relatively low carbon stock in the pre-conversion vegetation. The soybean case studies show shorter

Table 4. Repayment times [years] for direct (dLUC), indirect (iLUC), and total land-use change

Case Study	Repayment time [year]											
	dLUC			iLUC			Total					
<i>Oil Palm</i>												
Beluran District, Malaysia	76			0			76					
Prafi, Manokwari, Indonesia	58			25%			2					
				50%			4					
				75%			6					
Kubu Raya, West Kalimantan, Indonesia	199			25%			7					
				50%			14					
				75%			21					
Boven Digoel District, Papua, Indonesia	84			25%			0					
				50%			1					
				75%			1					
<i>Jatropha*</i>												
Pru, Brong Ahafo, Ghana	C	E	O		C	E	O	C	E	O		
Yucatan, Mexico	129	90	71		6	4	3	135	94	71		
Michocan, Mexico	183			25%			144			84		
				50%			288			168		
				75%			432			252		
Chiapas, Mexico	30			25%			253			148		
	14			50%			506			296		
	7			75%			600			350		
Chinsali & Mungwi, Zambia	∞	95	20		∞	94	26	∞	188	46		
<i>Soybean</i>												
Sorriso, Brazil	41			0			41					
Guarantã do Norte & Alta Floresta, Brazil	7			25%			10			18		
				50%			21			28		
				75%			31			38		
Santarém, Brazil	16			25%			47			64		
				50%			103			120		
				75%			155			171		

25%, 50% and 75% represent the low, medium and high iLUC scenarios

* next to iLUC scenarios, repayment times of Jatropha biodiesel are also calculated based on C: conservative; E: estimated; O: optimistic yield estimations

repayment times in general compared to the other production systems, except when iLUC involves loss of Amazonian forest—as is the case with Santarém, Brazil. Together with these soybean cases, the oil palm cases in Malaysia, Manokwari, and Papua, Indonesia, the optimistic Jatropha scenarios in Ghana and Zambia, and the estimated and optimistic Jatropha cases in Yucatan, Mexico can repay the carbon debt in a period of less than 100 years (four oil palm rotations, five Jatropha rotations). The other cases show repayment times greater than 100 years, and as high as 629 years for the conservative iLUC_{Max} Jatropha scenario in Chiapas, Mexico.

The results show that the Jatropha case study scenarios in Zambia, Michoacan, and Chiapas have repayment times on the same order of magnitude as oil palm in peatland forests. Although there are considerable differences in carbon debts

between these cases, the low CO₂ emissions reduction rate attained by Jatropha compared with oil palm even out this difference. The low CO₂ emission reduction rates of soybean-based biodiesel are compensated by the low allocation percentage of the carbon debt resulting from the other byproducts from the system.

DISCUSSION

The results of this study show that the nature of LUC associated with the expansion of biofuel production systems can have considerable implications for the climate-mitigation potential of biofuels. In all 12 biofuel case studies, in six different counties, based on three different feedstocks, significant carbon debts were created in relation to the CO₂ emissions reduction rate of the respective biodiesel production systems,

resulting in high repayment times. Although each of the biodiesel systems studied here has a climate-change mitigation effect, the LUC triggered by plantation establishment for these systems creates a debt that takes between 18 and 629 years to repay. This means that it takes anywhere between 18 to 629 years before a net CO₂ emissions reduction can be achieved. Of all these case studies, only the soybean systems in Guarantã do Norte and Alta Floresta achieved such net CO₂ emission reductions within one human generation (30 years), and only in cases where this triggers only low to medium iLUC. In the case of maximal (75%) iLUC, it takes slightly more than a human generation to repay the debt.

Due to low yields and the resulting low CO₂ emissions reduction rates (Achten 2010), the *Jatropha* cases exhibit long repayment times for carbon-stock losses, even when these losses seem to be small compared with the LUC induced by the other case studies (comparing, for example, Zambia and Malaysia). Repayment times for all *Jatropha* smallholder systems with “estimated” yields, therefore, exceed the repayment times for oil palm, even where the latter is established in tropical peatland forests. On average, the smallholder-based *Jatropha* case studies showed lower dLUC carbon debts, higher iLUC carbon debts and lower CO₂ emissions reduction rates—resulting in longer repayment times for these systems. Smallholders were observed to convert more land under agricultural use compared with large-scale plantation operations. Furthermore, they achieved lower yields and biomass production than large-scale initiatives. A further complication for these systems is that field observations in Zambia suggest that *Jatropha* seeds yield less oil at the moment of extraction because of inappropriate post-harvest treatments. Seeds are often left to dry for long periods after harvesting before they are sent for oil extraction. Issues such as these are not accounted for in the present analysis, so the repayment times calculated for smallholders may be underestimated.

The performance of *Jatropha* biodiesel production systems may be enhanced by proper agronomic research into the crop (Achten et al. 2010b). At the moment, *Jatropha* is considered to be a wild or semi-domesticated crop, at best (Achten et al. 2010a, Achten et al. 2010c). Evening out yields, selecting high-yielding growing stock, and developing proper varieties could improve the productivity of these systems and allow for the proper integration of *Jatropha* into agricultural systems where production makes both economic and ecological sense (Achten et al. 2010e).

This study covered three biofuel feedstocks that are inherently different from each other. Oil palm and *Jatropha* are perennial plants, whereas soybean is an annual crop. *Jatropha*, due to its toxicity, is almost exclusively promoted for the energetic use of its oil, whereas oil palm and soybean are cultivated more often for other oil and meal uses than for energy. Although

the case studies are very different, operating in different climates and landscapes, with different scales of operation, input levels, and biofuel feedstocks, the allocation procedures applied in this study allow us to compare these different case studies on an equal footing. Allocation of carbon debts to a second crop in the case of soybean and an intercrop in the case of *Jatropha* reduces the rotational differences between feedstocks. Allocation among the byproducts produced during the processing of the biodiesel helps address the effects of the different uses linked to the different feedstocks. By using an annual CO₂ emissions reduction rate per hectare, we integrate the differences in feedstock yield linked to scale of operation and input levels. By following the standard calculation procedure provided by Fargione et al. (2008), results are also comparable with values produced in other studies following the same method.

For oil palm established on non-peatland, published carbon-debt repayment times range from 30 to 120 years (Fargione et al. 2008, Gibbs et al. 2008, Wicke et al. 2008). The results obtained in this study (59–85 years) fit within this range, and the upper limit coincides closely with the results of Fargione et al. (2008) (86 years). For oil palm in peatlands, differences in the literature are large, which is mainly due to the differences in the time span over which peat emissions are accounted. Considering periods of 50 years or more, which corresponds to two rotations, several authors have calculated repayment times to be between 423 and 918 years (Fargione et al. 2008, Gibbs et al. 2008). A study accounting for emissions over 25 years (one rotation), as we did here, found that 169 years are needed to repay the initial carbon debt created by oil palm for biodiesel production in northern Borneo, Malaysia (Wicke et al. 2008), which is a similar order of magnitude to our range of 199 to 220 years.

For the soybean case studies, the results (repayment times of 18 to 171 years) correspond well with results of previous studies suggesting repayment times between 35 and 319 years (Fargione et al. 2008, Lapola et al. 2010). Our results fall at the lower end of the ranges published in the literature because we included allocation of carbon debts to a second crop associated with soybean cultivation. Furthermore, our soybean case studies suggest less deforestation for this oil crop than that suggested by Fargione et al. (2008), in which 100% deforestation rates are considered. In the soybean cases evaluated in this study, expansion of the area cultivated at least partially displaces land uses and covers other than forest (Table 1). The soybean cases give repayment times ranging from 7 to 41 years caused by dLUC, whereas iLUC results in repayment times of 0–155 years (total 18–172). The repayment time caused by dLUC calculated by Lapola et al. (2010) (35 years) corresponds to the range presented here. However, their repayment time calculated for iLUC is considerably higher (211 years). This is because Lapola et al. (2010) model that 100% of the area converted to soybean

(dLUC) will lead to iLUC, which is different from the approach used in this paper (iLUC scenarios: 25%, 50%, 75%).

Jatropha carbon debts and repayment times have been calculated for cases in Tanzania (Achten 2010, Romijn 2011). According to these studies, the conversion of degraded lands in Miombo woodland regions imply a period of 9 to 19 years to repay the carbon debt (Achten 2010), whereas conversion of mature Miombo woodland would require 33 years (Romijn 2011). These results are much lower than the results obtained for the case studies in this paper, and in particular lower than the *Zambian case study*—also in a Miombo woodland. The main reasons for this difference are: (1) the lower carbon content of the degraded systems, (2) the higher yields used for the respective Tanzanian regions in Achten (2010), and (3) the higher CO₂ emission reduction rate used in Romijn (2011). The latter two differences are based on the high yield variability known for *Jatropha* (Achten et al. 2008), which was the main reason for reporting results based on different levels of *Jatropha* yield and biomass production rates. Although this makes the range of repayment times quite wide, it gives comprehensive insight into the sensitivity of results to yield—with important implications for smallholder systems (for which yield-enhancing support services should be considered a fundamental pre-condition to expansion). Results for *Jatropha* are especially interesting for the Ghanaian and Mexican case studies, for which no comparisons are available in the literature. In these cases, repayment times are higher than the *Zambian* and *Tanzanian* cases because the land uses converted in these cases contain higher carbon stocks than the *Miombo* system.

Carbon debts are calculated based on the best available data. The dLUCs in the different case studies were observed with different techniques: quantitative household surveys, remote sensing, and qualitative interviews. These differences might introduce inconsistencies in the analyses. To calculate the carbon debts created by these LUCs, literature data were collected. Although these data might be less accurate than direct measurements, the use of literature data is well established (see Fargione et al. 2008, Lapola et al. 2010). In this study, attention was paid to use region-specific carbon content data of the different land-use types in each case study.

Due to measurement restrictions, it was necessary to use scenarios rather than actual figures for iLUC and to assume indirect conversion of the most natural land-cover type available in the case-study regions, yielding variable results. The quantification of iLUC in these cases is uncertain (Plevin et al. 2010) and raises methodological challenges. However, it is clear from this and other studies (e.g., Lapola et al. 2010) that iLUC is an important issue that can greatly increase the repayment time of a biofuel system and postpone the net carbon-saving benefits of biofuels for long periods (i.e.,

several generations) (Gibbs et al. 2008, Searchinger et al. 2008, Lapola et al. 2010, Plevin et al. 2010). Although such postponement cannot a priori be considered permanent, one has to acknowledge the practical challenges to keep a certain biofuel system in place for several generations in order to repay the carbon debt. During such repayment times demographic, economic, policy, technological, and/or other developments might have triggered new LUCs, leaving behind the previous biofuel system with a non-repaid, and thus permanent, carbon debt. Therefore, it is important for research to focus on a better understanding of iLUC, so that realistic carbon debts and payback times may be generated.

It cannot be denied that introduction of new biofuel feedstocks (e.g., *Jatropha*) and use of already cultivated vegetable oils for biofuels (e.g., oil palm and soybean) will increase the existing pressures on natural ecosystems (Fitzherbert et al. 2008). The analysis presented in this paper has shown that the increased pressure, both direct and indirect, can have considerable implications on GHG emissions from natural ecosystems. But importantly, this study shows that there is great variation of the biofuel-driven LUC emissions depending on the location of farms, even in relatively close locations as is the case for *Sorriso* and *Guarantã do Norte* and *Alta Floresta*, both in *Mato Grosso*, *Brazil*. The LUC cases studied in this paper show that any benefits from converting natural ecosystems to biofuel production will require between 20 years and six centuries to begin to accrue.

CONCLUSION

Carbon debts and repayment times are quantified for 12 biofuel case studies in six countries based on three different feedstocks. Carbon debts from these cases are high, postponing net GHG reductions from biofuels by more than a human generation (except for one soybean case). In light of the classical *Brundtland* definition of sustainable development, this outcome poses concerns about the sustainable development of these biofuel cases. The highest repayment times are triggered by the *Jatropha* cases and by the oil palm cases established in peatlands.

Due to high dLUC carbon implications following the conversion of (semi-)natural ecosystems with medium to high carbon content, and to indirect land-use changes following conversion of agricultural or pasture land, the potential of biofuels to contribute to climate-change mitigation is questioned. The results of this study indicate that to produce positive climate-mitigation benefits, biofuel feedstock cultivation should be restricted to areas that have low carbon content ($< 30 \times$ potential annual CO₂ emission reduction rate), such as permanent cropland and pasture, and to land not currently under agricultural production systems (e.g., abandoned cropland, degraded land) in order to prevent iLUC. In the current reality, these restrictions would leave only a small potential window for sustainable biofuel production

aimed at reducing CO₂ emissions given the limited availability and/or productivity of these land uses.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a response, follow [this link](#). To read responses already accepted, follow [this link](#).

ACKNOWLEDGMENTS

This paper has been produced with the financial assistance of the European Union, under a project entitled, "Bioenergy, sustainability and trade-offs: can we avoid deforestation while promoting bioenergy?" The objective of the project is to contribute to sustainable bioenergy development that benefits local people in developing countries, minimizes negative impacts on local environments and rural livelihoods, and contributes to global climate change mitigation. The project is managed by Center for International Forestry Research and implemented in collaboration with the Council on Scientific and Industrial Research (South Africa), Joanneum Research (Austria), the Universidad Autónoma de México, and the Stockholm Environment Institute. The views expressed herein can in no way be taken to reflect the official opinion of the European Union. The country teams of the different case studies are gratefully acknowledged. Discussions with George Schoneveld, Margaret Skutsch, Krustof Obidzinshi, Rubeta Andriani, Heru Komarudin, and Agus Andrianto are greatly appreciated. A special thanks goes to Laura German for the in-depth discussions and constructive comments, suggestions, and edits on the manuscript. The authors thank the two anonymous reviewers for their constructive comments, suggestions, and edits.

LITERATURE CITED

- Achten, W. M. J. 2010. *Sustainability evaluation of biodiesel from Jatropha curcas* L.—A life cycle oriented study. Dissertation. Katholieke Universiteit Leuven, Leuven, Belgium.
- Achten, W. M. J., F. K. Akinnifesi, W. H. Maes, A. Trabucco, R. Aerts, E. Mathijs, B. Reubens, V. P. Singh, L. Verchot, and B. Muys. 2010a. *Jatropha* integrated agroforestry systems—biodiesel pathways toward sustainable rural development. Pages 85–102 in C. Ponterio and C. Ferrá, editors. *Jatropha curcas as a premier biofuel: cost, growing and management*. Nova Science Publishers, Hauppauge, New York, USA.
- Achten, W. M. J., J. Almeida, V. Fobelets, E. Bolle, E. Mathijs, V. P. Singh, D. N. Tiwari, L. Verchot, and B. Muys. 2010b. Life cycle assessment of *Jatropha* biodiesel for transportation in rural India. *Applied Energy* 87:3652–3660. <http://dx.doi.org/10.1016/j.apenergy.2010.07.003>
- Achten, W. M. J., W. H. Maes, R. Aerts, L. Verchot, A. Trabucco, E. Mathijs, V. P. Singh, and B. Muys. 2010c. *Jatropha*: from global hype to local opportunity. *Journal of Arid Environments* 74:164–165. <http://dx.doi.org/10.1016/j.jaridenv.2009.08.010>
- Achten, W. M. J., W. H. Maes, B. Reubens, E. Mathijs, V. P. Singh, L. Verchot, and B. Muys. 2010d. Biomass production and allocation in *Jatropha curcas* L. seedlings under different levels of drought stress. *Biomass and Bioenergy* 34:667–676. <http://dx.doi.org/10.1016/j.biombioe.2010.01.010>
- Achten, W. M. J., L. R. Nielsen, R. Aerts, A. G. Lengkeek, E. D. Kjaer, A. Trabucco, J. K. Hansen, W. H. Maes, L. Graudal, F. K. Akinnifesi, and B. Muys. 2010e. Towards domestication of *Jatropha curcas*. *Biofuels* 1:91–107. <http://dx.doi.org/10.4155/bfs.09.4>
- Achten, W. M. J., P. Vandenbemt, J. Almeida, E. Mathijs, and B. Muys. 2010f. Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon. *Environmental Science and Technology* 44:4809–4815. <http://dx.doi.org/10.1021/es100067p>
- Achten, W. M. J., L. Verchot, Y. J. Franken, E. Mathijs, V. P. Singh, R. Aerts, and B. Muys. 2008. *Jatropha* bio-diesel production and use. *Biomass and Bioenergy* 32:1063–1084. <http://dx.doi.org/10.1016/j.biombioe.2008.03.003>
- Almeida, J., W. M. J. Achten, M. P. Duarte, B. Mendes, and B. Muys. 2011. Benchmarking the environmental performance of the *Jatropha* biodiesel system through a generic life cycle assessment. *Environmental Science and Technology* 45:5447–5453. <http://dx.doi.org/10.1021/es200257m>
- Council, E. P. A. 2003. *On the promotion of the use of biofuels or other renewable fuels for transport (Directive 2003/30/EC)*. European Parliament and Council.
- Dayang Norwana, A.A.B., R. Kunjappan, M. Chin, G. Schoneveld, L. Potter and R. Andriani (*in press*) The local impacts of oil palm in Sabah, Malaysia: Lessons for an incipient biofuel sector. CIFOR Working Paper. Bogor, Indonesia: Center for International Forestry Research.
- Edem, D. O. 2002. Palm oil: Biochemical, physiological, nutritional, hematological and toxicological aspects: a review. *Plant Foods for Human Nutrition* 57:319–341. <http://dx.doi.org/10.1023/A:1021828132707>
- Food and Agriculture Organisation (FAO). 2008. *The state of food and agriculture—biofuels: prospects, risks and opportunities*. FAO, Rome, Italy.
- Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235–1238. <http://dx.doi.org/10.1126/science.1152747>
- Fitzherbert, E. B., M. J. Struebig, A. Morel, F. Danielsen, C. A. Brühl, P. F. Donald, and B. Phalan. 2008. How will oil palm expansion affect biodiversity? *Trends in Ecology and*

- Evolution* 23:538–545. <http://dx.doi.org/10.1016/j.tree.2008.06.012>
- Fritsche, U. R., K. Henneberg, and K. Hünecke. 2010a. *The “iLUC Factor” as a means to hedge risks of GHG emissions from indirect land use change*. Öko-Insitut, Darmstadt, Germany.
- Fritsche, U. R., R. E. H. Sims, and A. Monti. 2010b. Direct and indirect land-use competition issues for energy crops and their sustainable production—an overview. *Biofuels, Bioproducts and Biorefining* 4:692–704. <http://dx.doi.org/10.1002/bbb.258>
- German, L., G. C. Schoneveld, and D. Gumbo. 2011. The local social and environmental impacts of smallholder-based biofuel investments in Zambia. *Ecology and Society* 16(4): 12. <http://dx.doi.org/10.5751/ES-04280-160412>
- Gibbs, H. K., M. Johnston, J. A. Foley, T. Holloway, C. Monfreda, N. Ramankutty, and D. Zaks. 2008. Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology. *Environmental Research Letters* 3:034001. <http://dx.doi.org/10.1088/1748-9326/3/3/034001>
- Hedegaard, K., K. A. Thyø, and H. Wenzel. 2008. Life cycle assessment of an advanced bioethanol technology in the perspective of constrained biomass availability. *Environmental Science and Technology* 42:7992–7999. <http://dx.doi.org/10.1021/es800358d>
- Huo, H., M. Wang, C. Bloyd, and V. Putsche. 2009. Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environmental Science and Technology* 43:750–756. <http://dx.doi.org/10.1021/es8011436>
- Intergovernmental Panel on Climate Change (IPCC). 2006. *Guidelines for national greenhouse gas inventories*. IPCC, Geneva, Switzerland.
- Jensen, A. A., L. Hoffman, B. T. Moller, A. Schmidt, K. Christiansen, J. Elkington, and F. van Dijk. 1997. *Life cycle assessment. a guide to approaches, experiences and information sources*. European Environment Agency, Copenhagen, Denmark. [http://dx.doi.org/10.1016/S0360-1323\(96\)00052-2](http://dx.doi.org/10.1016/S0360-1323(96)00052-2)
- Keeney, R. 2009. The indirect land use impacts of United States biofuel policies: the importance of acreage, yield, and bilateral trade responses. *American Journal of Agricultural Economics* 91:895.
- Lapola, D. M., R. Schaldach, J. Alcamo, A. Bondeau, J. Kock, C. Koelking, and J. A. Priess. 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America* 107:3388–3393. <http://dx.doi.org/10.1073/pnas.0907318107>
- Lima, M., M. Skutsch, and G. de Medeiros Costa. 2011. Deforestation and the social impacts of soy for biodiesel: perspectives of farmers in the south Brazilian Amazon. *Ecology and Society* 16(4): 04. <http://dx.doi.org/10.5751/ES-04366-160404>
- Mitchell, D. 2008. *A note on rising food prices*. The World Bank, Washington, D.C., USA. <http://dx.doi.org/10.1596/1813-9450-4682>
- Ndong, R., M. Montrejaud-Vignoles, O. Saint Girons, B. Gabrielle, R. Pirot, M. Domergue, and C. Sablayrolles. 2009. Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: a field study. *Global Change Biology Bioenergy* 1:197–210. <http://dx.doi.org/10.1111/j.1757-1707.2009.01014.x>
- Ou, X. M., X. C. Zhang, S. Y. Chang, and Q. F. Guo. 2009. Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) People’s Republic of China. *Applied Energy* 86:S197–S208. <http://dx.doi.org/10.1016/j.apenergy.2009.04.045>
- Overmars, K. P., E. Stehfest, J. P. M. Ros, and A. Gerdien Prins. 2011. Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data. *Environmental Science and Policy* 14:248–257. <http://dx.doi.org/10.1016/j.envsci.2010.12.012>
- Pleanjai, S., and S. H. Gheewala. 2009. Full chain energy analysis of biodiesel production from palm oil in Thailand. *Applied Energy* 86:S209–S214. <http://dx.doi.org/10.1016/j.apenergy.2009.05.013>
- Pleanjai, S., S. H. Gheewala, and S. Gariavait. 2009. Greenhouse gas emissions from the production and use of palm methyl ester in Thailand. *International Journal of Global Warming* 1:418–431. <http://dx.doi.org/10.1504/IJGW.2009.029213>
- Plevin, R. J., M. O’Hare, A. D. Jones, M. S. Torn, and H. K. Gibbs. 2010. Greenhouse gas emissions from biofuels’ indirect land use change are uncertain but may be much greater than previously estimated. *Environmental Science and Technology* 44:8015–8021. <http://dx.doi.org/10.1021/es101946t>
- Prueksakorn, K., and S. H. Gheewala. 2008. Full chain energy analysis of biodiesel from *Jatropha curcas* L. in Thailand. *Environmental Science and Technology* 42:3388–3393. <http://dx.doi.org/10.1021/es7022237>
- Romijn, H. A. 2011. Land clearing and greenhouse gas emissions from *Jatropha* biofuels on African miombo woodlands. *Energy Policy* 39:5751–5762.
- Ryan, L., F. Convery, and S. Ferreira. 2006. Stimulating the use of biofuels in the European Union: implications for climate change policy. *Energy Policy* 34:3184–3194. <http://dx.doi.org/10.1016/j.enpol.2005.06.010>

- Schoneveld, G. C., L. A. German, and E. Nutakor. 2011. Land-based investments for rural development? A grounded analysis of the local impacts of biofuel feedstock plantations in Ghana. *Ecology and Society* 16(4): 10. <http://dx.doi.org/10.5751/ES-04424-160410>
- Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Heyes, and T. H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* **319**:1238–1240. <http://dx.doi.org/10.1126/science.1151861>
- Skutsch, M., E. de los Rios, S. Solis, E. Riegelhaupt, D. Hinojosa, S. Gerfert, Y. Gao, and O. Masera. 2011. Jatropha in Mexico: environmental and social impacts of an incipient biofuel program. *Ecology and Society* 16(4): 11. <http://dx.doi.org/10.5751/ES-04448-160411>
- Stephens, W., T. Hess, and J. Knox. 2001. *Review of the effects of energy crops on hydrology*. Ministry of Agriculture, Fisheries and Food, London, UK.
- Trabucco, A., W. M. J. Achten, C. Bowe, R. Aerts, J. van Orshoven, and B. Muys. 2010. Global mapping of *Jatropha curcas* yield based on response of fitness to present and future climate. *Global Change Biology Bioenergy* **2**:139–151.
- UN-Energy. 2007. *Sustainable bioenergy: a framework for decision makers*. United Nations, New York, New York, USA.
- USDA. 2010. *Foreign agricultural service*. Washington, D. C., USA.
- Verchot, L. V., R. Zomer, O. van Straaten, and B. Muys. 2007. Implications of country-level decisions on the specification of crown cover in the definition of forests and land area eligible for afforestation and reforestation activities in the CDM. *Climatic Change* **81**:415–430. <http://dx.doi.org/10.1007/s10584-006-9111-9>
- Verraastro, F., and S. Ladislav. 2007. Providing energy security in an interdependent world. *The Washington Quarterly* **30**:95–104. <http://dx.doi.org/10.1162/wash.2007.30.4.95>
- Wicke, B., V. Dornburg, M. Junginger, and A. Faaij. 2008. Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass and Bioenergy* **32**:1322–1337. <http://dx.doi.org/10.1016/j.biombioe.2008.04.001>
- World Bank. 2010. *Commodity price data*. World Bank, Washington, D.C., USA.
- Yee, K. F., K. T. Tan, A. Z. Abdullah, and K. T. Lee. 2009. Life cycle assessment of palm biodiesel: revealing facts and benefits for sustainability. *Applied Energy* **86**:S189–S196. <http://dx.doi.org/10.1016/j.apenergy.2009.04.014>
- Zah, R., H. BÖni, M. Gauch, R. Hirschier, M. Lehmann, and P. Wäger. 2007. *Life cycle assessment of energy products: environmental assessment of biofuels*. EMPA, Sankt Gallen, Switzerland.

APPENDIX 1 - Malaysia

Table A1.1. Carbon debt calculation of Malaysia case

		estimates					references	
Carbon debt due to conversion of lowland tropical rainforest								
Aboveground carbon stock loss	197.5 Mg C ha ⁻¹	268	254.5	201.25	157	178	126	(Yamakura et al. 1986, Hoshizahi et al. 2004, Imai et al. 2009, Miettinen and Liew 2009, Niiyama et al. 2010)
-19% forest products	37.5 Mg C ha ⁻¹							(IPCC 2006)
subtotal	159.9 Mg C ha⁻¹							
Belowground carbon stock loss								
biomass	47.8 Mg C ha ⁻¹	13%	21%	26%	23.50%	37%		(Houghton and Hackler 2001)
		47.95	[Mg C ha ⁻¹]					(Niiyama et al. 2010)
soil	18.2 Mg C ha ⁻¹							(IPCC 2006)
subtotal	66.0 Mg C ha⁻¹							
Carbon stocked in oil palm plantation	35.8 Mg C ha ⁻¹	36	35.5	31.5	40			(Germer and Sauerborn 2008, Murdiyarso et al. 2010, Pereira de Souza et al. 2010)
Total carbon debt	190.2 Mg C ha⁻¹							
	698.8 Mg CO₂ ha⁻¹							

LITERATURE CITED

- Germer, J. and J. Sauerborn. 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. *Environment, Development and Sustainability* 10:697-716.
- Hoshizahi, K., K. Niiyama, K. Kimura, T. Yamashita, Y. Bekku, T. Okuda, E. S. Quah, and N. Supardi. 2004. Temporal and spatial variation of forest biomass in relation to stand dynamics in a mature, lowland tropical rainforest, Malaysia. *Ecological Research* 19:357-363.
- Houghton, R. A. and J. L. Hackler. 2001. *Carbon flux to the atmosphere from land-use changes: 1850-1990*. No. 5054, U.S. Department of Energy.
- Imai, N., H. Samejima, A. Langner, R. C. Ong, S. Kita, J. Titin, A. Y. C. Chung, P. Lagan, Y. F. Lee, and K. Kitayama. 2009. Co-benefits of sustainable forest management in biodiversity conservation and carbon sequestration. *Plos One* 4:e8267.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Miettinen, J. and S. C. Liew. 2009. Estimation of biomass distribution in Peninsular Malaysia and in the islands of Sumatra, Java and Borneo based on multi-resolution remote sensing land cover analysis. *Mitigation and Adaptation Strategies for Global Change* 14:357-373.
- Murdiyarso, D., K. Hergoualc'h, and L. V. Verchot. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America* 107:19655-19660.
- Niiyama, K., T. Kajimoto, Y. Masuura, T. Yamashita, N. Matsuo, Y. Yashiro, A. Ripin, A. R. Kassim, and N. S. Noor. 2010. Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. *Journal of Tropical Ecology* 26:271-284.
- Pereira de Souza, S., S. Pacca, M. Turra de Avila, and J. L. B. Borges. 2010. Greenhouse gas emissions and energy balance of palm oil biofuel. *Renewable Energy* 35:2552-2561.
- Yamakura, T., A. Hagihara, and S. O. Sukardjo, H. 1986. Aboveground biomass of tropical rain forest stands in Indonesian Borneo. *Plant Ecology* 68:71-82.

APPENDIX 2 - Indonesia

Table A2.1. Carbon debt calculation of the Manokwari, Indonesia case

		estimates					references
Carbon debt due to conversion of primary lowland tropical rainforest							
Aboveground carbon stock loss	193.3 Mg C ha ⁻¹	236	269.7	160.9	120.8	179	Fox et al. 2010; Bryan et al. 2010; Fargione et al. 2008
-19% forest products	36.7 Mg C ha ⁻¹						Fargione et al. 2008
subtotal	156.6 Mg C ha⁻¹						
Belowground carbon stock loss							
biomass	46.6 Mg C ha ⁻¹	13%	21%	26%	23.5%	37%	Fargione et al. 2008
soil	18.2 Mg C ha ⁻¹						IPCC 2006
subtotal	64.8 Mg C ha⁻¹						
Carbon stocked in oil palm plantation	35.8 Mg C ha⁻¹	36	31.5	40			Pereira de Souza et al. 2010; Murdiyarto et al. 2010; Germer & Sauerborn 2008; Fargione et al. 2008
Total carbon debt	185.5 Mg C ha⁻¹ 681.7 Mg CO₂ ha⁻¹						
Carbon debt due to conversion of secondary lowland tropical rainforest							
Aboveground carbon stock loss	99.2 Mg C ha ⁻¹	99.2					Fox et al. 2010; Bryan et al. 2010; Fargione et al. 2008
- 19% forest products	18.8 Mg C ha ⁻¹						Fargione et al. 2008
subtotal	80.4						
Belowground carbon stock loss							
biomass	23.9 Mg C ha ⁻¹	13%	21%	26%	23.5%	37%	Fargione et al. 2008
soil	18.2 Mg C ha ⁻¹						IPCC 2006
subtotal	42.1 Mg C ha⁻¹						

Table A2.1. continued Carbon debt calculation of the Manokwari, Indonesia case

		estimates			references
Carbon stocked in oil palm plantation	35.8 Mg C ha-1	36	31.5	40	Pereira de Souza et al. 2010; Murdiyarso et al. 2010; Germer & Sauerborn 2008; Fargione et al. 2008
Total carbon debt	86.6 Mg C ha-1 318.4 Mg CO2 ha-1				
Carbon debt due to conversion of agricultural land					
Total carbon debt					
	biomass	-16.4	Mg C ha-1		ENCOFOR tool
	soil C (20 yr)	-10.2	Mg C ha-1		IPCC 2006
Total carbon debt	-26.6 Mg C ha-1 -97.9 Mg CO2 ha-1				

Table A2.2. Carbon debt calculation of the Kubu Raya, West Kalimantan, Indonesia case

Carbon debt due to conversion of peat swamp forest										
		estimates					references			
Aboveground carbon stock loss	163.0	Mg C ha ⁻¹	179.2	130	179.7					Brealey et al. 2004; Miettinen & Liew 2009; Murdiyarso et al. 2010
- 19% forest products	31.0	Mg C ha ⁻¹								Fargione et al. 2008
subtotal	132.0	Mg C ha⁻¹								
Belowground carbon stock loss										
biomass	39.3	Mg C ha ⁻¹	13%	21%	26%	23.5%	37%			Fargione et al. 2008
emission from peat (25 years)	362.6	Mg C ha ⁻¹	10.8	16.2	19.9	14.8	10.0	15.4		Murdiyarso et al. 2010; Hergoualc'h & Verchot 2011; Fargione et al. 2008
subtotal	401.8	Mg C ha⁻¹								
Carbon stocked in oil palm plantation	35.8	Mg C ha⁻¹	36	31.5	40					Pereira de Souza et al. 2010; Murdiyarso et al. 2010; Germer & Sauerborn 2008; Fargione et al. 2008
Total carbon debt	498.0	Mg C ha⁻¹								
	1830.2	Mg CO₂ ha⁻¹								
Carbon debt due to conversion of peat swamp										
emission from peat (25 years)	362.6	Mg C ha ⁻¹	10.8	16.2	19.9	14.8	10.0	15.4		Murdiyarso et al. 2010; Hergoualc'h & Verchot 2011; Fargione et al. 2008
Total carbon debt	362.6	Mg C ha⁻¹								
	1332.5	Mg CO₂ ha⁻¹								
Carbon debt due to conversion of agricultural land										
Total carbon debt										
biomass	-16.4	Mg C ha ⁻¹								ENCOFOR tool
soil C (20 yr)	-10.2	Mg C ha ⁻¹								IPCC 2006

Table A2.2. continued Carbon debt calculation of the Kubu Raya, West Kalimantan, Indonesia case

Total carbon debt	-26.6 Mg C ha⁻¹
	-97.9 Mg CO₂ ha⁻¹

Table A2.3. Carbon debt calculation of the Boven Digoel, Papua, Indonesia case

Carbon debt due to conversion of primary lowland tropical rainforest Papua, Indonesia

		estimates						references
Aboveground carbon stock loss	193.3 Mg C ha ⁻¹	236	269.7	160.9	120.8	179	Fox et al. 2010; Bryan et al. 2010; Fargione et al. 2008 Fargione et al. 2008	
-19% forest products	36.7 Mg C ha ⁻¹							
subtotal	156.6 Mg C ha⁻¹							
Belowground carbon stock loss							Fargione et al. 2008 IPCC 2006	
biomass	46.6 Mg C ha ⁻¹	13%	21%	26%	23.5%	37%		
soil	18.2 Mg C ha ⁻¹							
subtotal	64.8 Mg C ha⁻¹							
Carbon stocked in oil palm plantation	35.8 Mg C ha⁻¹	36	31.5	40			Pereira de Souza et al. 2010; Murdiyarso et al. 2010; Germer & Sauerborn 2008; Fargione et al. 2008	
Total carbon debt	185.5 Mg C ha⁻¹ 681.7 Mg CO₂ ha⁻¹							
Carbon debt due to conversion of peat swamp forest								
Aboveground carbon stock loss	163.0 Mg C ha ⁻¹	179.2	130	179.7			Brealey et al. 2004; Miettinen & Liew 2009; Murdiyarso et al. 2010 Fargione et al. 2008	
- 19% forest products	31.0 Mg C ha ⁻¹							
subtotal	132.0 Mg C ha⁻¹							
Belowground carbon stock loss							Fargione et al. 2008 Murdiyarso et al. 2010; Hergoualc'h & Verchot 2011; Fargione et al. 2008	
biomass	39.3 Mg C ha ⁻¹	13%	21%	26%	23.5%	37%		
emission from peat (25 years)	362.6 Mg C ha ⁻¹	10.8	16.2	19.9	14.8	10.0 15.4		
subtotal	401.8 Mg C ha⁻¹							

Table A2.3. continued Carbon debt calculation of the Boven Digoel, Papua, Indonesia case

		estimates					references		
Carbon stocked in oil palm plantation	35.8 Mg C ha-1		36	31.5	40				Pereira de Souza et al. 2010; Murdiyarso et al. 2010; Germer & Sauerborn 2008; Fargione et al. 2008
Total carbon debt	498.0 Mg C ha-1 1830.2 Mg CO2 ha-1								
Carbon debt due to conversion of peat swamp									
emission from peat (25 years)	362.6 Mg C ha-1		10.8	16.2	19.9	14.8	10.0	15.4	Murdiyarso et al. 2010; Hergoualc'h & Verchot 2011; Fargione et al. 2008
Total carbon debt	362.6 Mg C ha-1 1332.5 Mg CO2 ha-1								
Carbon debt due to conversion of agricultural land									
Total carbon debt		biomass	-16.4 Mg C ha-1						ENCOFOR tool
		soil C (20 yr)	-10.2 Mg C ha-1						IPCC 2006
Total carbon debt	-26.6 Mg C ha-1 -97.9 Mg CO2 ha-1								

LITERATURE CITED

- Brearley, F. Q., S. Prajadinata, P. S. Kidd, J. Proctor, and Suriantata. 2004. Structure and floristics of an old secondary rain forest in Central Kalimantan, Indonesia, and a comparison with adjacent primary forest. *Forest Ecology and Management* 195:385-397.
- Bryan, J., P. Shearman, J. Ash, and J. B. Kirkpatrick. 2010. Estimating rainforest biomass stocks and carbon loss from deforestation and degradation in Papua New Guinea 1972-2002: best estimates, uncertainties and research needs. *Journal of Environmental Management* 91:995-1001.
- Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235-1238.
- Fox, J. C., C. K. Yosi, P. Nimiago, F. Oavika, J. N. Pokana, K. Lavong, and R. J. Keenan. 2010. Assessment of aboveground carbon in primary and selectively harvested tropical forest in Papua New Guinea. *Biotropica* 42:410-419.
- Germer, J. and J. Sauerborn. 2008. Estimation of the impact of oil palm plantation establishment on greenhouse gas balance. *Environment, Development and Sustainability* 10:697-716.
- Hergoualc'h, K. and L. V. Verchot. 2011. Stocks and fluxes of carbon associated with land-use change in Southeast Asian tropical peatlands: a review. *Global Biogeochemical Cycles* in press.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Miettinen, J. and S. C. Liew. 2009. Estimation of biomass distribution in Peninsular Malaysia and in the islands of Sumatra, Java and Borneo based on multi-resolution remote sensing land cover analysis. *Mitigation and Adaptation Strategies for Global Change* 14:357-373.
- Murdiyarto, D., K. Hergoualc'h, and L. V. Verchot. 2010. Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Sciences of the United States of America* 107:19655-19660.
- Pereira de Souza, S., S. Pacca, M. Turra de Avila, and J. L. B. Borges. 2010. Greenhouse gas emissions and energy balance of palm oil biofuel. *Renewable Energy* 35:2552-2561.

APPENDIX 3 - Ghana

Table A3.1. Carbon debt calculation of Ghana case

Carbon debt due to conversion of open to closed forest in Ghana			estimates		references
Loss of biomass carbon stock					
Aboveground + belowground carbon stock loss		Mg C ha ⁻¹	240	92.6	(Tan et al. 2009)
aboveground		Mg C ha ⁻¹	136	30	(Houghton and Hackler 2001)
belowground biomass			21.6%		(Fargione et al. 2008)
-9% forest products or trees left (50 years)			9%		(Fargione et al. 2008)
subtotal	121.6	Mg C ha⁻¹			
Loss of soil carbon stock					
carbon stock		Mg C ha ⁻¹	30.2	20.9	(Tan et al. 2009)
carbon loss			38.8%		(IPCC 2006)
subtotal	9.9	Mg C ha⁻¹			
Carbon stocked in oil Jatropha plantation					
aboveground	8.4	Mg C ha ⁻¹			(Achten 2010)
belowground	2.5	Mg C ha ⁻¹	30%		(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹			
Conservative (2500 kg/ha.yr)	9.1				
Estimation (3000 kg/ha.yr)	10.9				
Optimistic (3500 kg/ha.yr)	12.7				
Total carbon debt		Mg C ha⁻¹	C	E	O
			122.4	120.6	118.8
		Mg CO₂ ha⁻¹	449.8	443.1	436.4

Table A3.1. continued Carbon debt calculation of Ghana case

Carbon debt due to conversion of fallow land			estimates			references
Loss of biomass carbon stock	46.8	Mg C ha ⁻¹				(Tan et al. 2009)
subtotal	46.8	Mg C ha⁻¹				
Loss of soil carbon stock						
carbon stock	21.4	Mg C ha ⁻¹				(Tan et al. 2009)
carbon loss			38.8%			(IPCC 2006)
subtotal	8.3	Mg C ha⁻¹				
Carbon stocked in oil Jatropha plantation						
aboveground	8.4	Mg C ha ⁻¹				(Achten 2010)
belowground	2.5	Mg C ha ⁻¹	30%			(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹				
Conservative (2500 kg/ha.yr)	9.1					
Estimation (3000 kg/ha.yr)	10.9					
Optimistic (3500 kg/ha.yr)	12.7					
Total carbon debt		Mg C ha ⁻¹	C	E	O	
		Mg CO₂ ha⁻¹	46.0	44.2	42.4	
			169.0	162.4	155.7	
<hr/>						
Carbon debt due to conversion of agricultural land						
Total carbon debt			C	E	O	
biomass	-13.4	Mg C ha ⁻¹	-11.1	-13.4	-15.6	ENCOFOR tool
soil C (20 yr)	-3.7	Mg C ha ⁻¹				(IPCC 2006)
Total carbon debt	-17.0	Mg C ha⁻¹	-14.8	-17.0	-19.3	
	-62.6	Mg CO₂ ha⁻¹	-54.4	-62.6	-70.7	

LITERATURE CITED

- Achten, W. M. J. 2010. *Sustainability evaluation of biodiesel from Jatropha curcas L. - A life cycle oriented study*. Ph.D dissertation. Katholieke Universiteit Leuven, Leuven, Belgium.
- Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235-1238.
- Houghton, R. A. and J. L. Hackler. 2001. *Carbon flux to the atmosphere from land-use changes: 1850-1990*. No. 5054, U.S. Department of Energy.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Reubens, B., W. M. J. Achten, W. H. Maes, F. Danjon, R. Aerts, J. Poesen, and B. Muys. 2010. More than biofuel Jatropha curcas roots, symmetry and soil erosion control. *Journal of Arid Environments* 75:201-205.
- Tan, Z., L. L. Tieszen, E. Tachie-Obeng, S. Liu, and A. M. Dieye. 2009. Historical and simulated ecosystem carbon dynamics in Ghana: land use, management, and climate. *Biogeosciences* 6:45-58.

APPENDIX 4 – Mexico

Table A4.1. Carbon debt calculation of Yucatan, Mexico case

Carbon debt due to conversion of secondary forest

			estimates			references
Aboveground carbon stock loss	30	Mg C ha⁻¹				(Skutsch et al. 2011)
Belowground carbon stock loss						
biomass	6	Mg C ha ⁻¹	20%			(Achard et al. 2004)
soil	23.3	Mg C ha ⁻¹				(IPCC 2006)
subtotal	29.3	Mg C ha⁻¹				
Carbon stocked in oil Jatropha plantation						
aboveground	7	Mg C ha ⁻¹				(Skutsch et al. 2011)
belowground	2.1	Mg C ha ⁻¹	30%			(Achten 2010, Reubens et al. 2010)
subtotal	9.1	Mg C ha⁻¹				
Conservative (2500 kg/ha.yr)	7.6					
Estimation (3000 kg/ha.yr)	9.1					
Optimistic (3500 kg/ha.yr)	10.6					
Total carbon debt		Mg C ha⁻¹	C	E	O	
		Mg CO₂ ha⁻¹	51.7	50.2	48.7	
			190.1	184.5	178.9	

Table A4.2. Carbon debt calculation of Michoacan, Mexico case

Carbon debt due to conversion of secondary forest			estimates			references
Aboveground carbon stock loss	115.7	Mg C ha⁻¹				(Ordóñez et al. 2008)
Belowground carbon stock loss						
biomass	29.5	Mg C ha ⁻¹	25%	26%		(Ordóñez et al. 2008)
soil	25.1	Mg C ha ⁻¹	101.3	pine-oak forest		(Ordóñez et al. 2008)
			76.2	plantation		(Ordóñez et al. 2008)
subtotal	54.6	Mg C ha⁻¹				
Carbon stocked in oil Jatropha plantation						
aboveground	8.4	Mg C ha ⁻¹				(Achten 2010)
belowground	2.5	Mg C ha ⁻¹	30%			(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹				
Conservative (1500 kg/ha.yr)	5.5					
Estimation (2000 kg/ha.yr)	7.3					
Optimistic (2500 kg/ha.yr)	9.1					
Total carbon debt		Mg C ha⁻¹	C	E	O	
		Mg CO₂ ha⁻¹	164.8	163.0	161.2	
			605.8	599.1	592.4	
<hr/>						
Carbon debt due to conversion of shifting cultivation						
assumption: shifting cultivation takes rotations of 10 years						
Total carbon debt			C	E	O	
biomass	0.6	Mg C ha ⁻¹	0.3	0.4	0.5	ENCOFOR tool
soil C (20 yr)	7.9	Mg C ha ⁻¹				
Total carbon debt		Mg C ha⁻¹	8.2	8.3	8.4	
		Mg CO₂ ha⁻¹	30.0	30.4	30.8	

Table A4.2. continued Carbon debt calculation of Michoacan, Mexico case

Carbon debt due to conversion of agricultural land

			estimates			references
			C	E	O	
Total carbon debt						ENCOFOR tool
biomass	-8.7	Mg C ha ⁻¹	-4.4	-5.8	-7.3	
soil C (20 yr)	-3.7	Mg C ha ⁻¹				
Total carbon debt		Mg C ha⁻¹	-8.0	-9.5	-10.9	
		Mg CO₂ ha⁻¹	-29.5	-34.8	-40.1	

Table A4.3. Carbon debt calculation of Chiapas, Mexico case

Carbon debt due to conversion of forest

			estimates			references
Loss of biomass carbon stock						
Aboveground	170.0	Mg C ha ⁻¹		200	140	(Houghton and Hackler 2001, Mendoza-Vega et al. 2003)
Belowground	30.2	Mg C ha ⁻¹				(Mendoza-Vega et al. 2003)
subtotal	200.2	Mg C ha⁻¹				
Loss of soil carbon stock						
carbon stock	71	Mg C ha ⁻¹				(Mendoza-Vega et al. 2003)
carbon loss				38.8%		(IPCC 2006)
subtotal	27.5	Mg C ha⁻¹				
Carbon stocked in oil Jatropha plantation						
aboveground	8.4	Mg C ha ⁻¹				(Skutsch et al. 2011)
belowground	2.5	Mg C ha ⁻¹		30%		(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹				
Conservative (1500 kg/ha.yr)	5.5					
Estimation (2000 kg/ha.yr)	7.3					
Optimistic (2500 kg/ha.yr)	9.1					
Total carbon debt	216.8	Mg C ha⁻¹	222.3	220.5	218.6	
	796.8	Mg CO₂ ha⁻¹	816.8	810.2	803.5	

Table A4.3. Continued Carbon debt calculation of Chiapas, Mexico case

Carbon debt due to conversion of pasture						references
Pasture holds 10t C/ha (Houghton & Hackler 2001)						
Total carbon debt			C	E	O	
biomass	-7.5	Mg C ha ⁻¹	-3.8	-5.0	-6.3	ENCOFOR tool (IPCC 2006)
soil C (20 yr)	9.1	Mg C ha ⁻¹				
Total carbon debt		Mg C ha⁻¹	5.3	4.1	2.8	
		Mg CO₂ ha⁻¹	19.5	14.9	10.3	
Carbon debt due to conversion of agricultural land						
Total carbon debt			C	E	O	
biomass	-8.7	Mg C ha ⁻¹	-4.4	-5.8	-7.3	ENCOFOR tool (IPCC 2006)
soil C (20 yr)	-5.6	Mg C ha ⁻¹				
Total carbon debt		Mg C ha⁻¹	-9.9	-11.4	-12.8	
		Mg CO₂ ha⁻¹	-36.6	-41.9	-47.2	

LITERATURE CITED

- Achard, F., H. D. Eva, P. Mayaux, H.-J. Stibig, and A. Belward. 2004. Improved estimates of net carbon emission from land cover change in the tropic for the 1990s. *Global Biogeochemical Cycles* 18:GB2008.
- Achten, W. M. J. 2010. *Sustainability evaluation of biodiesel from Jatropha curcas L. - A life cycle oriented study*. Ph.D dissertation. Katholieke Universiteit Leuven, Leuven, Belgium.
- Houghton, R. A. and J. L. Hackler. 2001. *Carbon flux to the atmosphere from land-use changes: 1850-1990*. No. 5054, U.S. Department of Energy.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Mendoza-Vega, J., E. Karlton, and M. Olsson. 2003. Estimations of amounts of soil organic carbon and fine root carbon in land use and land cover classes, and soil types of Chiapas highlands, Mexico. *Forest Ecology and Management* 177:191-206.
- Ordóñez, J. A. B., B. H. J. de Jong, F. García-Oliva, F. L. Aviña, J. V. Pérez, G. Guerrero, R. Martínez, and O. Masera. 2008. Carbon content in vegetation, litter, and soil under 10 different land-use and land-cover classes in the Central Highland of Michoacan, Mexico. *Forest Ecology and Management* 255:2074-2084.
- Reubens, B., W. M. J. Achten, W. H. Maes, F. Danjon, R. Aerts, J. Poesen, and B. Muys. 2010. More than biofuel Jatropha curcas roots, symmetry and soil erosion control. *Journal of Arid Environments* 75:201-205.
- Skutsch, M., E. de los Rios, S. Solis, E. Riegelhaupt, D. Hinojosa, S. Gerfert, Y. Gao, and O. Masera. 2011. Jatropha in Mexico - A grounded assessment of environmental and social impacts of a biofuel programme. *Ecology & Society* submitted.

APPENDIX 5 – Zambia

Table A5.1. Carbon debt calculation of Zambia case

Carbon debt due to conversion of miombo			estimates					references			
Aboveground carbon stock loss	24.0	Mg C ha ⁻¹	19	6.8	9.8	35.4	36.5	14.2	32.5	37.5	(Chidumayo 2002, Chidumayo and Kwbisa 2003, Williams et al. 2008, Romijn 2010)
-9% forest products (50 years)	2.2	Mg C ha ⁻¹									(Romijn 2010)
subtotal	21.8	Mg C ha⁻¹									
Belowground carbon stock loss											
biomass	7.9	Mg C ha ⁻¹	33%								(Romijn 2010)
soil C stock	57.9	Mg C ha ⁻¹									(Williams et al. 2008)
soil C stock loss			33%	23%	42%						(Williams et al. 2008)
biomass and soil C stock	80.0	Mg C ha ⁻¹									(Walker and Desanker 2004)
biomass and soil C stock loss			47%								(Walker and Desanker 2004)
subtotal	29.4	Mg C ha⁻¹									
Carbon stocked in oil Jatropha plantation											
aboveground	8.4	Mg C ha ⁻¹									(Achten 2010)
belowground	2.5	Mg C ha ⁻¹	30%								(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹									
Conservative (500 kg/ha.yr)	1.8										
Estimation (1000 kg/ha.yr)	3.6										
Optimistic (1500 kg/ha.yr)	5.5										
Total carbon debt		Mg C ha⁻¹	C	E	O						
		Mg CO₂ ha⁻¹	49.4	47.6	45.8						
			181.7	175.0	168.3						

Table A5.1. continued Carbon debt calculation of Zambia case**Carbon debt due to conversion of fallow**

			estimates			references
Aboveground carbon stock loss (8-11 years)	6.7	Mg C ha⁻¹	<i>0.7</i>	<i>Mg C ha⁻¹ yr⁻¹</i>		(Williams et al. 2008)
Belowground carbon stock loss biomass + soil (Fallow)	44.9	Mg C ha ⁻¹				(Walker and Desanker 2004)
biomass + soil (Agriculture)	42.4	Mg C ha ⁻¹				(Walker and Desanker 2004)
subtotal (loss)	2.5	Mg C ha⁻¹				
Carbon stocked in oil Jatropha plantation aboveground	8.4	Mg C ha ⁻¹				(Achten 2010)
belowground	2.5	Mg C ha ⁻¹	30%			(Achten 2010, Reubens et al. 2010)
subtotal	10.9	Mg C ha⁻¹				
Conservative (500 kg/ha.yr)	1.8					
Estimation (1000 kg/ha.yr)	3.6					
Optimistic (1500 kg/ha.yr)	5.5					
Total carbon debt		Mg C ha⁻¹	C	E	O	
		Mg CO₂ ha⁻¹	7.3	5.5	3.7	
			26.9	20.2	13.6	

Carbon debt due to conversion of cropland

Total carbon debt			C	E	O	
biomass	-13.4	Mg C ha⁻¹	-2.2	-4.5	-6.7	ENCOFOR tool (IPCC 2006)
soil C (20 yr)	-4.44	Mg C ha⁻¹				
Total carbon debt	-17.8	Mg C ha⁻¹	-6.7	-8.9	-11.1	
		Mg CO₂ ha⁻¹	-24.5	-32.7	-40.9	

LITERATURE CITED

- Achten, W. M. J. 2010. *Sustainability evaluation of biodiesel from Jatropha curcas L. - A life cycle oriented study*. Ph.D dissertation. Katholieke Universiteit Leuven, Leuven, Belgium.
- Chidumayo, E. N. 2002. Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography* 29:1619-1626.
- Chidumayo, E. N. and L. Kwibisa. 2003. Effects of deforestation on grass biomass and soil nutrients in miombo woodland, Zambia. *Agriculture Ecosystems and Environment* 96: 97–105.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Reubens, B., W. M. J. Achten, W. H. Maes, F. Danjon, R. Aerts, J. Poesen, and B. Muys. 2010. More than biofuel Jatropha curcas roots, symmetry and soil erosion control. *Journal of Arid Environments* 75:201-205.
- Romijn, H. A. 2010. Land clearing and greenhouse gas emissions from Jatropha biofuels on Walker, S. M. and P. V. Desanker. 2004. The impact of land use on soil carbon in Miombo Woodlands of Malawi. *Forest Ecology and Management* 203:345-360.
- Williams, M., C. M. Ryan, R. M. Rees, E. Sambane, J. Fernando, and J. Grace. 2008. Carbon sequestration and biodiversity of re-growing miombo woodlands in Mozambique. *Forest Ecology and Management* 254:145-155.

APPENDIX 6 – Brazil

Table A6.1. Carbon debt calculation of Sorriso, Brazil case

Carbon debt due to conversion Cerrado forest

			estimates								references
Aboveground carbon stock loss	14.9	Mg C ha ⁻¹	9.65	9.85	15.9	14.5	6.45	11.55	45.85	5.2	(Barbosa and Fearnside 2005, Fargione et al. 2008)
-9% forest products	2.8	Mg C ha ⁻¹									(Fargione et al. 2008)
subtotal	12.0	Mg C ha⁻¹									
Belowground carbon stock loss											
biomass	3.5	Mg C ha ⁻¹	23.3%	26.5%	20.6%	30.9%	13.8%	24.6%	22.9%		(Fargione et al. 2008)
soil		Mg C ha ⁻¹	74.1	56.8	50.4	32.8	68.0				(Zinn et al. 2002, Corbeels et al. 2006, Maquere et al. 2008)
soil C loss			42%	loss							(IPCC 2006)
soil C loss rate (Cerrado-Agriculture)		Mg C ha ⁻¹ yr ⁻¹	<u>31.1</u>	<u>23.9</u>	<u>21.2</u>	<u>13.8</u>	<u>28.6</u>				(Carvalho et al. 2010)
soil C loss (20 years)			<u>28.8</u>								(IPCC 2006)
subtotal	24.5	Mg C ha⁻¹									
Total carbon debt	36.6	Mg C ha⁻¹									
	134.5	Mg CO₂ ha⁻¹									

Table A6.2. Carbon debt calculation of Guarantã do Norte & Alta Floresta, Brazil case

Carbon debt due to conversion of pasture

			estimates										references
Aboveground carbon stock loss	1.1	Mg C ha ⁻¹	1.94	1.89	1.76	0.68	0.63	0.45	0.41				(da Silva et al. 2004)
Belowground carbon stock loss biomass	4.1	Mg C ha ⁻¹	3.3	4.1	(root:shoot)								(Fargione et al. 2008)
soil stock		Mg C ha ⁻¹	37.46	54.3									(Maia et al. 2009, Carvalho et al. 2010)
soil C loss	1.2		-7.8%	0.2%	9.3%	6.0%	8.4%	5.1%	15.0%	-0.7%	-9.0%	-0.6%	(Fargione et al. 2008)
	5.3	Mg C ha ⁻¹											
Total carbon debt	6.4	Mg C ha⁻¹											
	23.5	Mg CO₂ ha⁻¹											

Table A6.3. Carbon debt calculation of Santarem, Brazil case

Carbon debt due to conversion of Amazonian rainforest

			estimates			references
Aboveground carbon stock loss	129.1	Mg C ha ⁻¹	131.5	141	114.8	(Fearnside et al. 1999, Johnson et al. 2001, Keller et al. 2001)
+dead biomass	13.5	Mg C ha ⁻¹				(Keller et al. 2001)
-14% forest products	18.1	Mg C ha ⁻¹				(Fargione et al. 2008)
subtotal	124.5	Mg C ha⁻¹				
Belowground carbon stock loss biomass	30.5	Mg C ha ⁻¹	29.5	31.5		(Fearnside et al. 1999, Keller et al. 2001)
soil carbon stock	53.5	Mg C ha ⁻¹	27.85	96	41.85	
soil carbon loss	33.2	Mg C ha ⁻¹	62.0%			(IPCC 2006)
subtotal	63.7	Mg C ha⁻¹				
Total carbon debt	188.2	Mg C ha⁻¹				
	691.7	Mg CO₂ ha⁻¹				
Carbon debt due to conversion of agricultural land						
Total carbon debt	0.0	Mg C ha⁻¹				
	0.0	Mg CO₂ ha⁻¹				

LITERATURE CITED

- Barbosa, R. I. and P. M. Fearnside. 2005. Above-ground biomass and the fate of carbon after burning in the savannas of Roraima, Brazilian Amazonia. *Forest Ecology and Management* 216:295-316.
- Carvalho, J. L. N., G. S. Raucci, C. E. P. Cerri, M. Bernoux, B. J. Feigl, F. J. Wruck, and C. C. Cerri. 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. *Soil & Tillage Research* 110:175-186.
- Corbeels, M., E. Scopel, A. Cardoso, M. Bernoux, J.-M. Douzet, and M. S. Neto. 2006. Soil carbon storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. *Global Change Biology* 12:1773-1787.
- da Silva, J. E., D. V. S. Resck, E. J. Corazza, and L. Vivaldi. 2004. Carbon storage in cleyey Oxisol cultivated pastures in the "Cerrado" region, Brazil. *Agriculture Ecosystems and Environment* 103:357-363.
- Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235-1238.
- Fearnside, P. M., P. M. de Alencastro Graça, N. L. Filho, F. J. Alves Rodrigues, and J. M. Robinson. 1999. Tropical forest burning in Brazilian amazonia: measurement of biomass loading, burning efficiency and charcoal formation at Altamira, Pará. *Forest Ecology and Management* 123:65-79.
- IPCC. 2006. *Guidelines for National Greenhouse Gas Inventories*
- Johnson, C. M., C. G. Vieira, D. J. Zarin, J. Frizano, and A. H. Johnson. 2001. Carbon and nutrient storage in primary and secondary forests in eastern Amazonia. *Forest Ecology and Management* 147:245-252.
- Keller, M., M. Palace, and G. Hurtt. 2001. Biomass estimation in the Tapajos National Forest, Brazil examination of sampling and allometric uncertainties. *Forest Ecology and Management* 154:371-382.
- Maia, S. M. F., S. M. Ogle, C. E. P. Cerri, and C. C. Cerri. 2009. Effect of grassland management on soil carbon sequestration in Rondonia and Mato Grosso states, Brazil. *Geoderma* 149:84-91.
- Maquere, V., J. P. Laclau, M. Bernoux, L. Saint-Andre, J. L. M. Gonçalves, C. C. Cerri, M. C. Piccolo, and J. Ranger. 2008. Influence of land use (savanna, pasture, *Eucalyptus* plantations) on soil carbon and nitrogen stocks in Brazil. *European Journal of Soil Science* 59:863-877.
- Zinn, Y. L., D. V. S. Resck, and J. E. da Silva. 2002. Soil organic carbon as affected by afforestation with *Eucalyptus* and *Pinus* in the Cerrado region of Brazil. *Forest Ecology and Management* 166:285-294.