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Research, part of a Special Feature on Local, Social, and Environmental Impacts of Biofuels

Implications of Biodiesel-Induced Land-Use Changes for CO_2 Emissions: Case Studies in Tropical America, Africa, and Southeast Asia

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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 $C0_2$ ha^{-1}. The oil palm case studies created the largest carbon debts (472.8–1743.7 t $C0_2$ 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 CO_2 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 – CO_2-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

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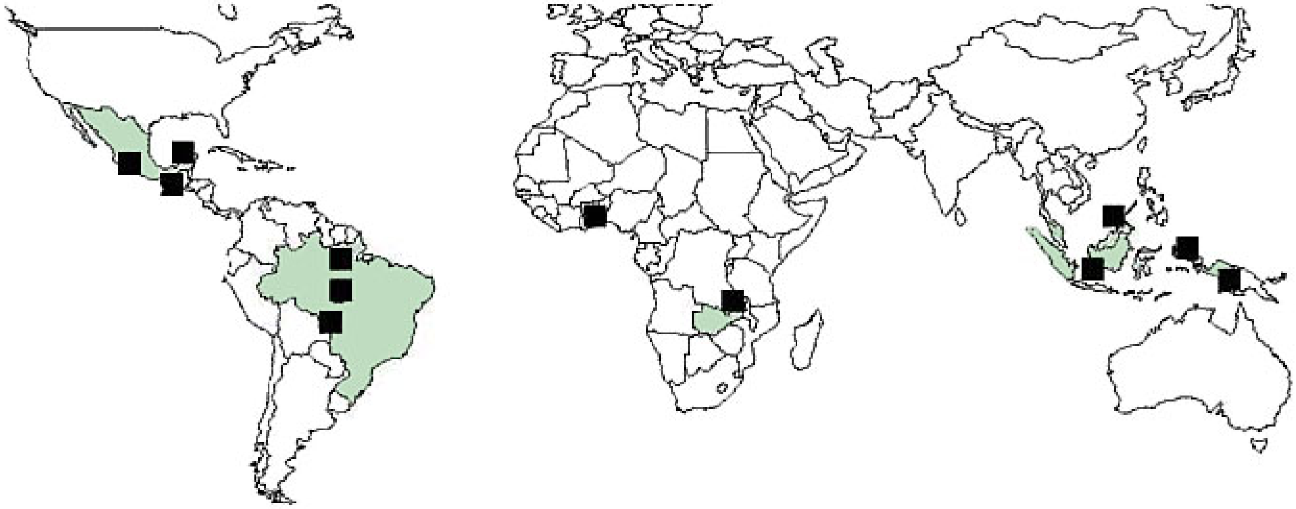
Fig. 1. Overview map indicating the location of the 12 cases evaluated in six countries.



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 CO_2 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 Kalimanatan (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 Intergovermental 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
Oil Palm				
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[†]
Jatropha				
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%	
Michocan, Mexico	25%	Secondary forest	0%	
	25%	Fallow land[‡]	N.A.	Secondary forest[†]
	50%	Permanent cropland (annuals)	N.A.	Secondary forest[†]
Chiapas, Mexico	5%	Secondary forest	0%	
	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%	
Soybean				
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 CO_2-eq

		dLUC ha^{-1}	iLUC ha^{-1}		Total ha^{-1}
Case study		Mg CO_2	Scenario	Mg CO_2	Mg CO_2
Oil Palm					
Beluran District, Malaysia		698.8		0.0	698.8
Prafi,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
Jatropha					
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
Soybean					
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 CO_2 reduction rates of Jatropha biodiesel (after allocation). Because of the yield variability in Jatropha, CO_2 reduction rates were calculated for expected, conservative, and optimistic yields based on a regression analysis of data points linking yield with CO_2 reduction rates available in Achten (2010).

For soybean and oil palm, analyses of CO_2 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 CO_2 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):

Carbon debt [Mg CO_2 ha^{-1}] × Allocation [%] / CO_2 reduction rate [Mg CO_2 ha^{-1} 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 CO_2 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 CO_2 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 CO_2-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 CO_2-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.

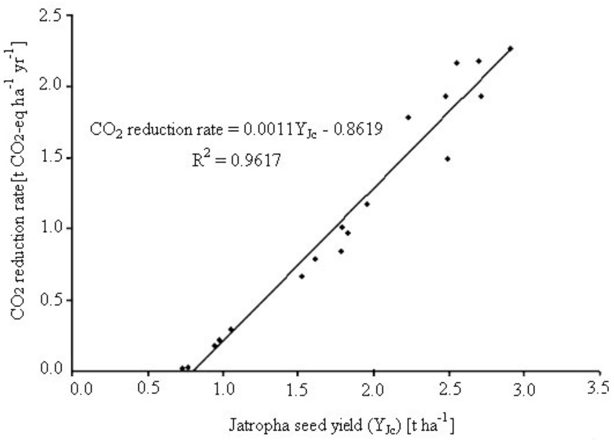
The total LUC shows similar trends as the dLUC carbon debt, with the oil palm cases creating the biggest overall carbon debt, and the Jatropha and soybean cases triggering significantly lower total carbon debts. We calculated averages and standard deviations for total carbon debt results with estimated values and $iLUC_{Medium}$ = 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 (±511.0) Mg CO_2 ha^{-1}, Jatropha causes an average total carbon debt of 252.5 (±145.5) Mg CO_2 ha^{-1}, and soybean an average debt of 208.7 (±167.9) Mg CO_2 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 to 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 US\$ t^{-1}) and soybean (3.99 t ha^{-1}, 417 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 CO_2 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 CO_2 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 CO_2 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 kg ha^{-1} yr^{-1} is required to achieve CO_2 emissions reductions. This is because basic operational CO_2 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 CO_2 emissions reduction rate for the soybean system was found to be 0.87 Mg CO_2 ha^{-1} yr^{-1} (Table 3).

Fig. 2. Regression analysis of the life-cycle CO_2 reduction rate in function of Jatropha seed yields (based on Achten (2010)).



In general, the results show that oil palm cases represent the highest CO_2 emissions reduction rates, eight to nine times higher than soybean system CO_2 emissions reduction rates. The Jatropha cases, based on variable yields, represent CO_2 emission reduction rates ranging from 0.24 to 2.99 Mg CO_2 ha^{-1} 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 CO_2 reduction rates and the CO_2 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 CO2 ha^{-1} yr^{-1}]	Sources
Oil Palm					
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]
Jatropha					
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]
Soybean					
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 CO_2 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		
Oil Palm										
Beluran District, Malaysia	76				0			76		
Prafi, Manokwari, Indonesia	58			25%	2			59		
				50%	4			61		
				75%	6			63		
Kubu Raya, West Kalimantan, Indonesia	199			25%	7			206		
				50%	14			213		
				75%	21			220		
Boven Digoel District, Papua, Indonesia	84			25%	0			85		
				50%	1			85		
				75%	1			85		
*Jatropha**	C	E	O		C	E	O	C	E	O
Pru, Brong Ahafo, Ghana	129	90	71		6	4	3	135	94	71
Yucatan, Mexico	101	76	60		0	0	0	101	76	60
Michocan, Mexico	183	105	72	25%	144	84	59	327	189	131
				50%	288	168	118	471	273	190
				75%	432	252	176	615	356	248
Chiapas, Mexico	30	14	7	25%	253	148	111	283	162	111
				50%	506	296	208	536	310	215
				75%	600	350	246	629	364	253
Chinsali & Mungwi, Zambia	∞	95	20		∞	94	26	∞	188	46
Soybean										
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 CO_2 emissions reduction rate attained by Jatropha compared with oil palm even out this difference. The low CO_2 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 CO_2 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 CO_2 emissions reduction can be achieved. Of all these case studies, only the soybean systems in Guarantã do Norte and Alta Floresta achieved such net CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 × potential annual CO_2 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 CO_2 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.

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APPENDIX 1 - Malaysia

Table A1.1. Carbon debt calculation of Malaysia case

Carbon debt due to conversion of lowland tropical rainforest			**estimates**						**references**
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 CO_2 ha^{-1}**							

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APPENDIX 2 - Indonesia

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

Carbon debt due to conversion of primary lowland tropical rainforest								
			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
-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; 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 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 Papau, 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
-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; 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
- 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**							

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**							

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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**					
			C	**E**	**O**	
Total carbon debt		**Mg C ha^{-1}**	**122.4**	**120.6**	**118.8**	
		Mg CO_2 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**					
			C	**E**	**O**	
Total carbon debt		Mg C ha^{-1}	**46.0**	**44.2**	**42.4**	
		Mg CO$_2$ ha^{-1}	**169.0**	**162.4**	**155.7**	
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 CO$_2$ ha^{-1}**	**-54.4**	**-62.6**	**-70.7**	

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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**					
			C	**E**	**O**	
Total carbon debt		**Mg C ha^{-1}**	**51.7**	**50.2**	**48.7**	
		Mg CO_2 ha^{-1}	**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**					
			C	**E**	**O**	
Total carbon debt		**Mg C ha^{-1}**	**164.8**	**163.0**	**161.2**	
		Mg CO$_2$ ha^{-1}	**605.8**	**599.1**	**592.4**	

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 CO$_2$ 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**
Total carbon debt						ENCOFOR tool
			C	**E**	**O**	
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 CO$_2$ 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**					
			C	**E**	**O**	
Total carbon debt	**216.8**	**Mg C ha^{-1}**	**222.3**	**220.5**	**218.6**	
	796.8	**Mg CO$_2$ 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
soil C (20 yr)	9.1	Mg C ha^{-1}				(IPCC 2006)
Total carbon debt		**Mg C ha^{-1}**	**5.3**	**4.1**	**2.8**	
		Mg CO$_2$ 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
soil C (20 yr)	-5.6	Mg C ha^{-1}				(IPCC 2006)
Total carbon debt		**Mg C ha^{-1}**	**-9.9**	**-11.4**	**-12.8**	
		Mg CO$_2$ ha^{-1}	**-36.6**	**-41.9**	**-47.2**	

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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**											
			C	**E**	**O**							
Total carbon debt		**Mg C ha^{-1}**	**49.4**	**47.6**	**45.8**							
		Mg CO_2 ha^{-1}	**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}**		*0.7*	*Mg C ha-1 yr-1*	(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**					
			C	**E**	**O**	
Total carbon debt		**Mg C ha^{-1}**	**7.3**	**5.5**	**3.7**	
		Mg CO_2 ha^{-1}	**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
soil C (20 yr)	**-4.44**	**Mg C ha^{-1}**				(IPCC 2006)
Total carbon debt	**-17.8**	**Mg C ha^{-1}**	**-6.7**	**-8.9**	**-11.1**	
		Mg CO_2 ha^{-1}	**-24.5**	**-32.7**	**-40.9**	

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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)
			42%	loss							(IPCC 2006)
soil C loss			31.1	23.9	21.2	13.8	28.6				
soil C loss rate (Cerrado-Agriculture)		Mg C ha^{-1} yr^{-1}	1.44								(Carvalho et al. 2010)
soil C loss (20 years)			28.8								(IPCC 2006)
subtotal	**24.5**	**Mg C ha^{-1}**									
Total carbon debt	**36.6**	**Mg C ha^{-1}**									
	134.5	**Mg CO_2 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** **23.5**	**Mg C ha^{-1}** **Mg CO$_2$ 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*	*48.48*	
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 CO_2 ha^{-1}**					
Carbon debt due to conversion of agricultural land							
Total carbon debt	**0.0**	**Mg C ha^{-1}**					
	0.0	**Mg CO_2 ha^{-1}**					

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