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Greenhouse Gas Emissions and Land Use Change from *Jatropha Curcas*-Based Jet Fuel in Brazil

ROBERT E. BAILIS* AND
JENNIFER E. BAKA
*Yale School of Forestry and Environmental Studies,
195 Prospect St New Haven. Connecticut 06517, United States*

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This analysis presents a comparison of life-cycle GHG emissions from synthetic paraffinic kerosene (SPK) produced as jet fuel substitute from *jatropha curcas* feedstock cultivated in Brazil against a reference scenario of conventional jet fuel. Life cycle inventory data are derived from surveys of actual Jatropha growers and processors. Results indicate that a baseline scenario, which assumes a medium yield of 4 tons of dry fruit per hectare under drip irrigation with existing logistical conditions using energy-based coproduct allocation methodology, and assumes a 20-year plantation lifetime with no direct land use change (dLUC), results in the emissions of 40 kg CO_2e per GJ of fuel produced, a 55% reduction relative to conventional jet fuel. However, dLUC based on observations of land-use transitions leads to widely varying changes in carbon stocks ranging from losses in excess of 50 tons of carbon per hectare when Jatropha is planted in native *cerrado* woodlands to gains of 10−15 tons of carbon per hectare when Jatropha is planted in former agro-pastoral land. Thus, aggregate emissions vary from a low of 13 kg CO_2e per GJ when Jatropha is planted in former agro-pastoral lands, an 85% decrease from the reference scenario, to 141 kg CO_2e per GJ when Jatropha is planted in *cerrado* woodlands, a 60% increase over the reference scenario. Additional sensitivities are also explored, including changes in yield, exclusion of irrigation, shortened supply chains, and alternative allocation methodologies.

I. Introduction

This paper presents a life-cycle assessment of synthetic paraffinic kerosene (SPK) derived from *jatropha curcas* feedstock (hereafter referred to as Jatropha) based on growing conditions in Brazil. SPK is a drop-in substitute for jet fuel that can be produced from vegetable oil (*1, 2*). Direct combustion of jet fuel for commercial aviation is responsible for roughly 2% of global CO_2 emissions (*3*). Additional forcing associated with aviation increases the net impact from 3 to as much as 6% of anthropogenic forcing (ref *4*, cited in ref *5*). Further, aviation is among the fastest growing transportation sectors, with annual growth rates of 5% projected for the coming decade (*5*). The International Air Transport Association (IATA), which represents the majority of the world's commercial airlines, has pledged "carbon neutral growth" beginning in 2020 and further defined an "aspirational goal" of 50% CO_2 emissions reductions from 2005 levels by 2050 (*6*). To meet these goals, airlines may rely on several options: improving technical and operational efficiency, fleet turnover, and retrofits, as well as biofuels (*7*). Biofuels are among the largest contributors to the industry's planned emission reductions, with IATA hoping to achieve a 6% blend by 2020 (*6*).

Commercial airlines have conducted a series of test flights with blends of biobased and conventional jet fuel (CJF) from several feedstocks including Jatropha (*8, 9*). The industry estimates that jet fuels derived from biomass can reduce CO_2 emissions by 80% relative to CJF (*6, 7*). Thus, a 6% blend could reduce emissions by approximately 5% relative to the CJF baseline. However, actual emissions reductions achieved by substituting CJF with SPK depend on specific production practices, as well as coproduct utilization, allocation methodologies, and land use change. For Jatropha, an 80% reduction is achievable only under certain circumstances: for eaxmple, if there is net carbon sequestration from land use change or under certain allocation methodologies. However, if land use change (LUC) leads to net emissions, then reductions will be smaller and, if initial stocks of carbon are high, may lead to net increases in emissions, as others have shown in the case of ground transportation (*10, 11*).

We focus on production in Brazil because the country's position as a major biofuel and commercial agricultural exporter makes it a potential site of large-scale Jatropha production (*12*). At the time of this research, the country had roughly 40 000 ha of Jatropha under cultivation in a mix of large plantations and small-scale plots (*13*). In addition, there has been a major push by EMBRAPA, the federal agricultural research and support organization, to develop the crop (*14*). Prior investigations into Jatropha's life-cycle have focused on conditions in Asia, leaving production conditions elsewhere, particularly Latin America, largely unexplored. Further, while biofuels for ground transportation have received a good deal of attention from researchers, relatively little research about biofuels for aviation has been published.

Native to Central America, but spread by early colonial expansion, Jatropha is now common across tropical and subtropical regions (*15*). This dispersion, along with the plant's ability to survive in harsh conditions, have led many to cite Jatropha's potential not only as a biofuel feedstock, but also as a tool to help alleviate rural poverty across developing regions by providing additional income to farmers (*16*). By 2008, Jatropha projects had been established in over 50 countries across Asia, Africa, and Latin America totaling over one million ha (*12*).

However, investment appears to have outpaced research to find optimal varieties and identify best agronomic practices (*15, 17*). Claims of the plant's ability to thrive in marginal areas with very few inputs have proven to be overoptimistic (*9, 15*). Inputs such as fertilizer, agro-chemicals, and in some cases, irrigation, have been utilized by Jatropha growers trying to make their investments economically viable. However, each input affects the crop's environmental performance by adding to life-cycle energy and material requirements.

A. LUC in Biofuel LCAs. LUC has emerged as a critical issue in biofuel LCA. Current analyses typically divide LUC into direct (dLUC) and indirect land use change (iLUC), a distinction that falls in line with boundary-setting in LCA. Direct land use change (dLUC) constitutes changes occurring within the system boundary: for example, the replacement of natural vegetation with biofuel crops. If biofuel crop cultivation incurs an upfront loss of carbon as a result of changing land cover, it creates a "carbon debt" (*10*). This

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* Corresponding author e-mail: robert.bailis@yale.edu; phone: +1 203 432 5412; fax: +1 203 436 9158.

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debt is repaid over time as biofuel is used to substitute fossil fuel (assuming that other aspects of the life cycle lead to a net decrease in emissions). The degree to which the debt is repaid, and whether or not the activity ever "profits", depends on the magnitude and duration of emission reductions.

Indirect land use change (iLUC) occurs outside the system boundaries, but is attributable to activities occurring inside those boundaries. For example, if biofuels displace other crops and reduce supplies in the near term, this leads to increased prices that provide motivation for producers in other areas to make up for the shortfall. If the shortfall is addressed by expansion of cultivation into previously uncultivated areas, such conversions would be considered iLUC. If the newly opened land experiences a net loss of ecosystem carbon as a result of crop cultivation, this would negate some of the benefits of activities taking place within the system boundary (*18, 19*). This analysis focuses on dLUC, which we account for by cataloging prior land use among Brazilian Jatropha growers and using default emission factors for LUC published in the IPCC's "Good Practice Guidelines for National Greenhouse Gas Inventories" (*20*) to estimate long-term dLUC arising from Jatropha cultivation. Nevertheless, we acknowledge that iLUC may also be relevant in certain production systems and we provide a detailed discussion of iLUC in the context of Brazilian Jatropha in the Supporting Information (SI).

II. Research Methods

A. LCA Goal and Scope. The goal of this analysis is to evaluate the changes in GHG emissions associated with the substitution of conventional jet fuel (CJF) with SPK derived from Jatropha. The scope of the analysis is "well-to-wake" and includes direct land use change (dLUC). We define the functional unit as a unit of fuel energy (1 GJ) so that GHG emissions are expressed as kilograms of CO_2-equivalent per GJ fuel ($kgCO_2e/GJ$). By convention, CO_2e is calculated for non-CO_2 GHGs using 100-year global warming potentials (*21*). Jatropha are produced and the oil extracted in Brazil. Oil is exported to the U.S. for processing into SPK. A range of scenarios for feedstock production is examined. In addition, this study used a 20-year project lifetime, as was done in several other LCAs of Jatropha (*22–24*). A 30-year time frame is explored in the sensitivity analysis.

B. Life Cycle Inventory (LCI). The processes and materials in the inventory were divided into life cycle stages: raw material acquisition; raw material transport; production; product transport; and final use. Key assumptions used to estimate inventories in each life cycle stage are discussed below with full details given in the SI.

1. Raw Material Acquisition. This stage consists of land preparation, including dLUC as well as tillage, sowing, crop management, seed harvesting, and oil extraction. In Brazil, crude Jatropha oil (CJO) has been partially refined prior to export, which is are included in this phase. Extraction yields coproducts like seed husks and seedcake, which are also accounted for. Key assumptions are discussed in more detail below.

Yields: commercial Jatropha production is new to Brazil. None of the plantations surveyed are fully mature and yields have yet to reach peak levels. A range of yields has been reported in the literature (*25, 26*). To examine a range of possible outcomes, a base case was defined as four tons of dry seed per hectare, which matches well to calculated potential yields in Brazilian agro-ecological conditions (*27*). Sensitivity was tested with base yield increased and decreased by 50% (2 and 6 tons/ha).

Land use change: dLUC processes are described by actual changes in land use reported by Brazilian growers. Prior land uses include managed, natural and abandoned pasture, annual crops, and natural *cerrado* vegetation, which may consist of a continuum of grasslands "with scant arboreal component to near open forest" (*28*). Table 1 describes the prior land use among Brazilian Jatropha growers surveyed or visited during the data collection phase of this research. Pasture is the most prevalent prior land use and includes a mix of managed, natural, and degraded areas. Managed pasture is tilled, fertilized, and planted primarily with non-native annual grass (*29*). Natural pasture consists of grazing land covered by minimally managed (often perennial) native grasses. Degraded pasture includes both managed and natural pasture characterized by reduced herbaceous cover, bare patches, and, in some cases, the invasion of native plants (*30*). Also, some growers cleared native vegetation, whereas others displaced food crops. Carbon stocks for each prior land use were estimated using IPCC default values (see ref *20* and the SI).

TABLE 1. Prior Land Use among Brazilian Jatropha Producers Visited during This Research

prior land use	no. of growers	total area (ha)[a]
pasture[b]	6	6400
food crop production[c]	3	120
natural vegetation[d]	2	200

[a] Land area is approximate. [b] Pasture includes managed grazing areas, natural grasslands and degraded pasture (see text for full explanation). [c] This includes 2 medium-scale growers and 58 small farmers who were contracted to provide seeds to two of the larger growers surveyed for this project. In total, growers reported 14 different food crops displaced by Jatropha: the most common crops displaced were manioc (cassava), maize, beans, and banana. [d] Conversion of natural vegetation was found in Northern Minas Gerais in a transition zone between Cerrado and Caatinga biomes. Prior vegetation consisted mainly of drought-deciduous shrubs including varieties of *Combretum*, *Mimosa*, *Manihot*, and *Casearia* species.

Irrigation: several growers report using different forms of irrigation, including drip, spray, and microspray. Drip irrigation was included as part of the base case analysis. The sensitivity of net emissions to nonirrigated production is explored below.

Lime application: soils in Brazil are highly acidic and agricultural lime (limestone ($CaCO_3$) or dolomite $CaMg(CO_3)_2$) is often applied to reduce soil pH. Survey results indicate that Jatropha growers apply an average of 2 tons/ha of limestone. Limestone application is associated with impacts from production and transport as well as emissions resulting from its breakdown in the soil. In solution, carbonates can form bicarbonate (HCO_3^-), which evolves into CO_2 and water. Emissions from the latter are based on IPCC default emission factor of 120 gC per kg lime (*20*).

Fertilizer: fertilizer application in Brazilian Jatropha plantations varies widely. Data linking seed or oil yield to specific levels of inputs are unavailable. Rather than build a model based on one grower's practices or a weighted average of all responses, this analysis follows the approach taken by several other Jatropha LCAs and assumes fertilizer is applied at a rate that replaces nutrients lost though the annual harvest of seeds (*24, 31*). Lower application rates would lead to the loss of macro-nutrients from the soil and higher applications would lead to excessive nutrient runoff. Impacts from fertilizer use include the production and transport of each compound. In addition, urea, Brazil's most common nitrogenous fertilizer (*32*) results in N_2O and CO_2 emissions as it breaks down in the soil (*20*). The quantity of fertilizer needed to replenish lost nutrients is described in the SI.

Oil extraction and refining: oil can be extracted from Jatropha seeds through a number of methods. Techniques

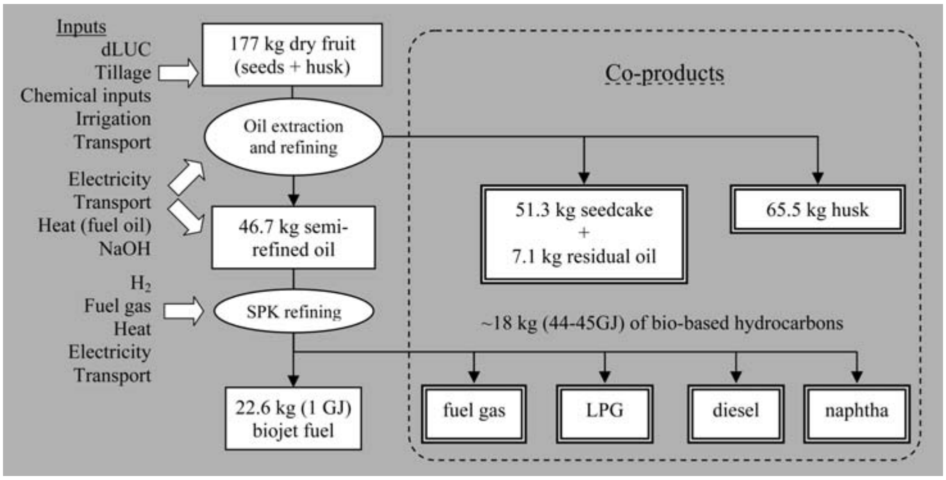

FIGURE 1. Coproducts from production of 1 GJ (22.6 kg) of Jatropha-based SPK.

range from simple mechanical ram or screw presses using human power or small motors (*16*) to solvent-based methods (*33*). Existing LCAs have modeled both small-scale mechanical presses and large-scale solvent-based extraction (*22, 24, 31*).

In Brazil, solvent-based extraction is common in the soy processing industry, but has yet to be applied in the Jatropha industry. There is a single large-scale facility using mechanical oil presses. Heat derived from heavy fuel oil (HFO) is applied to enhance yields and oil is refined with lye (NaOH) to lower acidity and remove gums. Major inputs required and outputs produced for every kilogram of semirefined oil are given in the SI.

2. *Raw Material Transport.* This phase includes transport of raw material to the point at which it is processed into jet fuel. Currently, seeds are transported by road from farms around the country to the one pressing facility, where the oil is extracted and partially refined. The average distance between growers and the pressing facility in southern Minas Gerais is ∼1400 km (weighted average by planted area). The refined oil is transported again by road, ∼700km to the port of Santos in São Paulo State. From there, it is taken by ocean freight ∼15 000 km to a refinery in the western U.S. An alternate scenario was examined in which the industry's logistics have been improved so that oil extraction facilities are located within 200 km radius of each large-scale producer and distances to the port are also reduced.

3. *Liquid Fuel Production.* This phase accounts for the materials and processes required to make SPK from refined Jatropha oil. Oil is processed with hydrogen, steam, and electricity (*2, 34*), coproducing numerous biobased hydrocarbons. Example values for material inputs and processes for SPK production were provided by UOP (*34*) and incorporated into SimaPro. As with petroleum refining, there is some flexibility to vary the split between SPK and coproducts. The major source of impacts at this stage is the hydrogen that is used to process refined Jatropha oil into SPK. Hydrogen is presumed to be derived from steam reformation of methane, as described by Skone and Gerdes (*35*). For energy-based allocation, calorific values of coproducts were taken from GREET (*36*). Similarly, for system expansion, emissions avoided by using coproducts rather than existing products were also taken from GREET.

4. *Product Transport and Refueling.* This phase accounts for transport of fuel from the refinery to the aircraft. To date, SPK has only been used in test flights and distribution infrastructure does not exist. However, if it is going to be used at a scale envisioned by the industry, it is likely that it will be distributed via a similar infrastructure as current jet fuel. Thus, for this stage we assume emissions are identical to the emissions from the distribution of an energetically equivalent quantity of jet fuel, as estimated by ref *35*.

5. *Aircraft Operation.* This phase accounts for combustion of the liquid fuel in the aircraft's engines. This study assumes emissions per unit energy from SPK production are identical to the emissions from CJF (*35*). Thus, net combustion emissions from SPK are slightly smaller than CJF because SPK has a slightly higher calorific value (*1*).

C. Life Cycle Inventory of CJF. Comprehensive life cycle inventory data for CJF was taken from Skone and Gerdes (*35*), who estimate life cycle emissions for jet fuel are 88.1 kg CO2e/GJ (see the SI for a breakdown by life-cycle stage).

D. Coproduct Allocation. There are numerous methods to attribute life cycle impacts among coproducts (*37*) and each leads to different outcomes, particularly when relative economic and physical values differ. For example, work soy-based biodiesel shows a wide variation in impacts attributable to soy oil and related coproducts depending on allocation methodology (ref *38*, cited in ref *39*).

Jatropha-SPK has numerous coproducts. As Figure 1 shows, oil extraction yields husks, and seed cake with potential applications as fertilizer or heat or power production (*16*). Further, although the seedcake cannot currently be used for livestock feed due to its toxicity, there are research efforts underway to either detoxify the seedcake or breed nontoxic varieties of the plant (for a review of efforts, see ref *15*). If successful, this would open an additional pathway for coproducts.

In addition, the biobased hydrocarbons coproduced with SPK include naphtha, diesel, LPG, and a mix of lighter gaseous compounds similar to LPG and natural gas (*34*). Each of these may be used as fuels or as inputs in industrial processes.

Allocation based on energy content of each coproduct is presented as a base case. This is the methodology adopted by the European Community in its current Renewable Energy Directive (*40*). Other methods, including mass-based allocation and system expansion, which explicitly accounts for the displacement of existing products by coproducts of SPK production, are also presented. Market-based allocation is not presented because, as a novel crop, Jatropha's coproducts are difficult to assign prices and division of impacts based on this method would be speculative. Table 2 shows the mass fraction and energy content used to allocate life-cycle impacts as well as the products assumed to be displaced under system expansion.

III. Results and Discussion

Under the base case scenario (medium yield, 20-year plantation lifetime, and coproduct allocation based on

TABLE 2. Basis for Energy and Mass Allocation and System Expansion Product Displacements

	oil extraction			SPK refining	
	CJO[a]	seedcake (inc. 6% CJO)	husks	SPK	other biobased hydrocarbons[b]
energy content (GJ/ton)	39.6	26.8	19	44.3	44−45[c]
percent of total energy	43%	31%	25%	54%	46%
mass fraction	1	1.1	1.2	1	0.78
percent of total mass	30%	33%	37%	56%	44%
system expansion - scenario 1		fertilizer	fertilizer		equivalent fossil-based hydrocarbons
system expansion - scenario 2		HFO[d]	HFO[d]		

[a] CJO, crude (unrefined) jatropha oil. [b] Includes naphtha, diesel, and lighter gaseous fractions similar to LPG and natural gas as shown in Figure 1. [c] Value varies depending on exact composition of coproducts. [d] HFO, heavy fuel oil.

calorific value, with no dLUC), we estimate that SPK derived from Jatropha under current conditions emits 40 kg CO_2e/GJ, a savings of 55% relative to CJF. Raw Material Acquisition is the most polluting phase of SPK lifecycle, contributing roughly 43% of total emissions in the base case scenario. Emissions in that phase result primarily from the production and transport of lime and fertilizers as well as emissions of CO_2 and N_2O that result when these compounds are applied to the soil (18% of the total). Additional emissions arise from irrigation (4%). Transportation of both seeds and refined oil over long distances contributes 26% to total emissions. Finally, SPK refining contributes 27% of the total, with the bulk of these emissions arising from hydrogen production. A breakdown of emission sources in the base case, as well as each sensitivity analysis is provided in the SI.

A. Sensitivities and Uncertainties. The 55% reduction observed under the base-case scenario is contingent on many assumptions about yield, lifetime, logistics, and irrigation. Results are also sensitive to the choice of allocation methodology as well as dLUC resulting from changes in land cover. The sensitivities are examined below.

1. Yield. Results under energy allocation with no dLUC are relatively insensitive to yield: 50% yield reduction results in net emissions of 42 kg CO_2e/GJ, which is a 52% reduction relative to CJF; 50% increase in yield results in net emissions of 39 kg CO_2e/GJ, a 56% reduction relative to CJF. This low sensitivity arises because we assume yields are linked to fertilizer inputs: lower yields have fewer inputs, and higher yields have more inputs, leaving overall emissions per GJ of fuel produced relatively unaffected. However, if dLUC is non-negligible, the sensitivity of net emissions to yield increases because lower (higher) yield requires more (less) land per GJ fuel. This is discussed in more detail below.

2. Plantation Lifetime. Increasing the time frame of the analysis from 20 to 30 years reduces emissions in all yield scenarios because the additional time allows more substitution of CJF with SPK, which reduces the effect of any one-time emissions associated with the establishment of the plantation such as tilling, lime application, and installation of irrigation infrastructure. Net emissions are 37 kg CO_2e/GJ over a 30 year plantation lifetime, a 7% decrease relative to net emissions with a 20-year plantation lifetime (and a 58% reduction relative to CJF).

3. Irrigation. Roughly 50% of the projects surveyed in a global study conducted in 2008 report using some form of irrigation (*12*). A similar fraction of growers surveyed in Brazil irrigate in the early stages of plantation establishment and on an as-needed basis during the dry season. The base case in this analysis included drip irrigation, and accounts for installation of polyethylene tubing as well as the electric power required to pump water (details are available in the SI). However, some growers do not use irrigation, thus the analysis was repeated without those inputs, holding other parameters fixed. Without irrigation, net emissions decrease 4% relative to production with irrigation, to 38 kg CO_2e/GJ, which is a 57% decrease in emissions relative to CJF.

4. Logistics. Brazil is a large country with long supply chains. Averaging among Brazilian firms surveyed for this analysis and accounting for the movement of inputs as well as outputs, the production of one GJ of SPK and its delivery to a distribution point in the U.S. requires over 500 ton-kilometers (tkm) of ocean freight and 140 tkm of road transport. This is considerably larger than road, rail, and sea transport requirements for an energetically equivalent quantity of CJF refined in the U.S. or EU (*41*). In total, transport of seeds and oil contribute 26% to total emissions in the base case. However, the current situation is not likely to persist as the industry matures. In order to model improved logistics, a sensitivity analysis was conducted in which road transport requirements are reduced by roughly 80% by siting extraction facilities closer to both production zones and to ports for export. Under this scenario, net emissions drop to 33 kg CO_2e/GJ, a 62% reduction relative to CJF. A similar reduction could be achieved by maintaining current distances between production, processing, and ports, but switching from road to rail transport (*41*). Brazil is currently building a rail line linking the center to the north of the country, passing through some of the potential Jatropha zones, which could impact the emissions associated with transport from those areas (*42*).

5. Allocation Methodology. Mass-based allocation attributes more emissions to coproducts than energy-based allocation, so that if mass-based allocation is used, the net emissions attributable to SPK decrease under all scenarios. In the base case, net emissions with mass-allocation decrease to 33 kg CO_2e/GJ, 17% fewer lower than energy-based allocation under the same assumptions and a 62% reduction relative to CJF.

System expansion was also explored to understand the implications of different allocation methodologies. There are multiple coproducts from the SPK life-cycle: seedcake and husks from oil extraction and biobased hydrocarbons from the conversion of refined Jatropha oil into SPK. Three pathways are explored for husk and seedcake. One possibility is that no market develops and the material is not used. The second possibility is that the materials are used as fertilizers that displace commercial fertilizer. Based on nutrient contents of seedcake and husk reported in the literature (*9, 25*, also see the SI), this is equivalent to 14 kg of 30-30-20 (NPK) fertilizer.

The third possibility is that seedcake and husk are pressed into solid briquettes and used as boiler fuel. These briquettes could substitute heavy fuel oil (HFO) to supply heat for industrial applications, including the extraction of Jatropha oil in the one large-scale facility currently operating in Brazil. Specifications of this process are given in the SI.

In addition, the coproducts of SPK refining, which consist of several bioderived hydrocarbons (shown in Figure 1), can

TABLE 3. Emissions (kg CO_2e/GJ) for Product Stages Showing Each Allocation Method Assuming Medium Yields, No dLUC, and 20-Year Plantation Lifetime

	fossil-based jet fuel	energy-based allocation	mass-based allocation	system expansion		
				seedcake and husk unused	seedcake and husk used as fertilizer	seedcake and husk used as boiler fuel
raw material acquisition	6	17	12	76	76	76
raw material transport	1	10	9	29	29	29
liquid fuel refining	6	11	11	11	12	11
final product transport	1	1	1	1	1	1
coproduct credit for seedcake and husk				0	−23	−196
coproduct credit for biobased hydrocarbons[a]				−55	−55	−55
combustion[b]	74	1	1	1	1	1
total emissions[c]	88	40	33	63	40	−134
reductions relative to CJF		55%	66%	29%	55%	252%

[a] Credits are derived from avoided lifecycle emissions including final combustion of each coproduct shown in Figure 1. [b] Combustion emissions for SPK show non-CO_2 emissions only (based on (*35*)). CO_2 emissions are assumed to be canceled by seed growth. [c] Totals may not add up exactly due to rounding errors.

displace equivalent volumes of fossil-based hydrocarbon fuels (see the SI for details). The results of each system expansion scenario using the base case assumption of medium yields with no dLUC are shown in Table 3. Energy and mass-based allocation are included for comparison.

Under system expansion, if seedcake and husks are not utilized, emissions increase to 63 kg CO2e/GJ, which is 58% higher than energy-based allocation, but still represents a 29% reduction relative to CJF. If seedcake and husk are used as fertilizer, net emissions are identical to emissions under the base case (40 kg CO2e/GJ; 55% reduction from CJF). However, if seedcake and husk are used as boiler fuel, emission reductions increase as a result of a large credit from displaced HFO. The resulting emission reductions are larger than the combined emissions from other product stages, rendering the life-cycle for Jatropha SPK GHG-negative (−134 kg CO_2e/GJ, a 252% reduction relative to CJF). This outcome has been observed in other LCAs in which system expansion incorporates coproducts that displace carbon-intensive fossil fuels (see (*2*) and some of the alternate scenarios reported in (*43*)). However, in both system expansion examples, the full GHG reductions from product displacement are only realized if the fuel or fertilizer are fully replaced by the Jatropha seedcake and husk. As this has not yet been observed in reality, the results should be interpreted with caution.

6. *Land Use Change*. The most common prior land use observed among Brazilian Jatropha growers is pasture for grazing cattle. Pasture includes intensively managed pasture, natural pasture, and degraded pasture. Each classification may have different stocks of carbon and result in different dLUC impacts. In addition, Brazilian growers have also replaced small areas of annual crops and native vegetation with Jatropha. Each transition is explored below.

Managed pasture is usually planted with annual grasses and has relatively low stocks of carbon. Annual crops have similar stocks of carbon as managed pasture (see the SI and ref *20*). Converting either type of land to Jatropha cultivation likely results in a net increase in carbon stocks. Natural pasture, consisting primarily of perennial grasses (*29*), may be modeled as natural grasslands, which generally hold larger stocks of carbon than managed pasture or annual crops, particularly belowground biomass (*20*). If these lands are converted to Jatropha, there may be a net loss of carbon. Finally, if native vegetation consists of shrubland, which was observed during fieldwork, or forest, which has not yet been observed (but are included for comparison), conversion to Jatropha results in a large carbon debt, which negates the benefits of fossil fuel replacement over the 20−30 year project lifetimes examined in this study.

Detailed dLUC emissions from each transition are shown in the SI. Figure 2 shows the impact of each dLUC scenario for medium yield trees using energy-based coproduct allocation with 20-year lifetime. If prior land use was characterized by relatively low stocks of carbon, such as cropland, pasture, or dry-zone grassland, then there is net sequestration that adds to the emission reductions achieved by replacing CJF. However, if initial stocks of carbon were high, as in moist grassland or shrubland, then there is a net release of carbon from dLUC. In the case of moist-zone grasslands, there is a loss of ~8 tC/ha from conversion to Jatropha, which adds ~16 kg CO_2 per GJ of fuel produced and cuts the emission reduction from 55% to 36%. Shrublands lose over 50 tC/ha when converted to Jatropha. If this is allocated by energy content among coproducts, it adds ~100 kg CO_2 per GJ to the net emissions of Jatropha SPK and completely negates the benefit of fuel substitution, resulting in a 59% *increase* in emissions. Other prior land use categories (not shown in Figure 2), such as dry-zone and moist-zone forest, result in emission increases that are 3−4 times larger than emissions from CJF.

Interactions between yield and dLUC are also critical. Shifting from the base case assumption of 4 tons seed per ha to the lower yield scenario doubles the land requirements. If the prior land use was characterized by low carbon stocks, which are increased by Jatropha cultivation, then low yielding trees requiring more area for each GJ of SPK, lead to *more carbon sequestered* per GJ fuel produced. The opposite is true for high-yielding trees. On the other hand, if the prior land use was characterized by high carbon stocks, which decrease when Jatropha is grown, then low yielding trees lead to fewer emission reductions per GJ fuel produced. Again, higher yielding trees have the opposite effect.

Thus, using energy-based allocation and a 20-year plantation lifetime, we estimate that Jatropha planted on former agricultural land leads to a net GHG reduction of 91% relative to CJF under low yields, 83% under medium yields, and 81% under high yields. In contrast, Jatropha planted on shrublands leads to a net GHG *increase* of 193% if yields are low, 59% if yields are medium, and only 14% if yields are high. Additional details are given in the SI.

This analysis demonstrates that, under many plausible scenarios, replacing CJF with SPK derived from Jatropha produced in Brazil leads to a net reduction of GHG emissions. However, the exact emission reductions

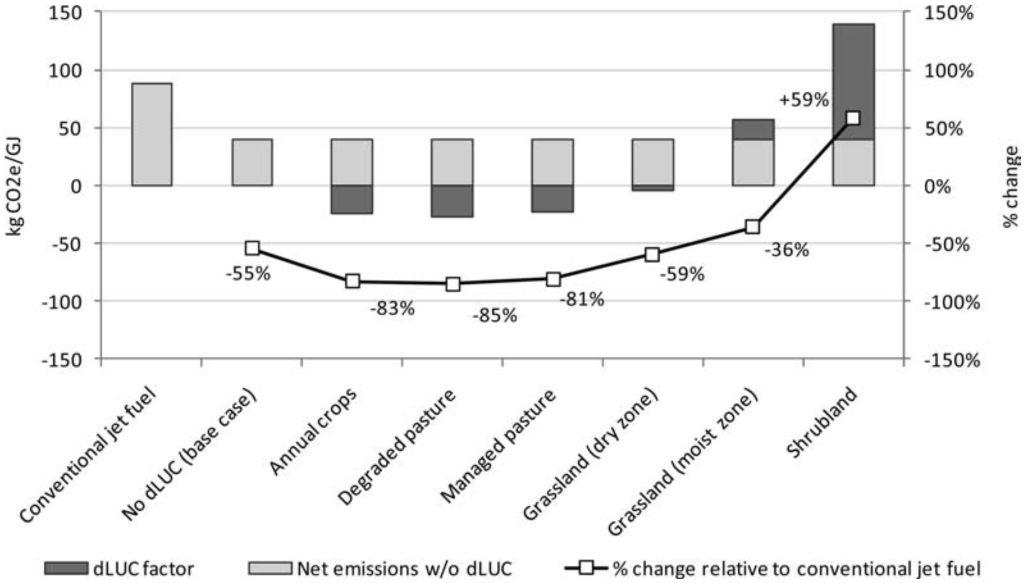

FIGURE 2. Impacts on emission reductions for the base case when dLUC scenarios are included in the assessment (negative values indicate emission reductions).

achieved depend on several factors that vary from producer to producer. The industry is relatively young and growers have yet to arrive at a set of "best practices", thus many key determinants of emissions such as fertilizer application rates, transportation distances, use of irrigation, and yields are in flux. Additional variation is introduced by alternative uses of coproducts and different methodologies used to assign impacts to them.

Moreover, dLUC raises numerous issues. First, the accuracy of the IPCC default factors is questionable. Land management practices vary a great deal in ways that can substantially change terrestrial stocks of carbon. Some plots are scraped bare of existing vegetation or burned prior to tilling and planting, while others may be planted with seedlings in small hand-dug holes, allowing some natural vegetation and soil to remain intact. Moreover, much of the land targeted for Jatropha production is considered "marginal", but this label carries many different meanings ranging from fallow cropland and degraded pasture to native shrublands and grasslands (*44*). Thus, dLUC resulting from the establishment of a Jatropha plantation can lead to a wide range of changes in terrestrial carbon. To obtain deeper understanding of dLUC linked to Brazilian Jatropha production, this study also took empirical measurements of biomass and soil carbon in field conditions. However, plantations are still young and it is too early to observe significant changes in either. These sites will monitored in coming years and long-term results will be reported in the future.

Thus, until better empirical data emerges, we rely on default values to estimate dLUC. With these defaults, we find several cases in which positive dLUC augments emission reductions achieved by replacing CJF with SPK. However, we also find that some Brazilian Jatropha growers are planting in ways that lead to negative changes in carbon stocks. This has also been observed in other Jatropha plantations (for example, our observations in South India, which are currently in preparation for publication, as well as in Tanzania as reported by (*45*)). Moreover, Jatropha plantations have uncertain lifetimes. As with other forestry activities, changes in terrestrial carbon from dLUC are likely to be temporary. Under the UNFCCC's Clean Development Mechanism, carbon sequestered in forestry activities are treated differently than emission reductions achieved through fuel substitution. The latter are considered permanent reductions while the former are defined as temporary (*46, 47*). The dLUC portion of biofuels should be treated in a similar manner; however, additional research is required to quantify the exact implications that this would have on the net change in GHG emissions achieved by replacing CJF with SPK.

Second, land use in Brazil is dynamic. In *cerrado* regions, where the bulk of Brazil's Jatropha cultivation occurs, shifts from natural vegetation to cropland and/or pasture since the 1970s have been followed, in many instances, by degradation and abandonment (*48, 49*). Research has shown that abandoned agro-pastoral land in *cerrado* zones can revert to natural vegetation. For example, Jepson (*49*) notes that 50% of the land that was converted to other uses in a 3900 km^2 area of Eastern Matto Grosso between 1986 and 1999 began to revert to secondary vegetation after abandonment. Thus, it is unclear whether dLUC assessments of Brazil's abandoned pastureland should be based on current carbon stocks, which are relatively low, or whether that land should be considered as "recovering *cerrado*", with dLUC calculations based on carbon levels that would be attained in the absence of Jatropha or other cultivation. This alternative assessment would explicitly recognize that there is a "carbon opportunity cost" of growing Jatropha, or other biofuels, on degraded agro-pastoral land. Better understanding of land cover trajectories is required in order to enumerate the full implications of promoting Jatropha or other biofuel production on abandoned agro-pastoral land.

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Supporting Information Available

Detailed descriptions of research methodologies, data sources, and sensitivity analyses as well as a discussion of potential conflict of interest. This material is available free of charge via the Internet at http://pubs.acs.org.

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Supplemental Information

Greenhouse Gas Emissions and Land Use Change from Jatropha Curcas-Based Jet Fuel in Brazil

Robert E Bailis*

Jennifer E Baka

Yale School of Forestry and Environmental Studies

195 Prospect St

New Haven. CT 06517

* Corresponding Author

Email: robert.bailis@yale.edu

Phone: +1 203 432 5412

Fax: +1 203 436 9158

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Conflict of Interest

This research was conducted with financial support from The Boeing Corporation acting as a member of the Sustainable Aviation Fuel Users Group (SAFUG). The support was provided to the corresponding author through Yale University's Office of Grant and Contract Financial Administration as "sponsored research" and subject to the same oversight as all sponsored research projects. Under the research agreement between the university on behalf of the corresponding author and the research sponsor, the researchers were granted full publication rights with no editorial inputs permitted from the sponsoring organization. While it is true that SAFUG has a vested interest in the outcome of this research, neither Boeing nor any other SAFUG members had influence over the research process or the content of this article.

I. Goal and scope

The goal and scope, choice of functional unit (FU), system boundaries, geographic specificity, and impact assessment methodology are described in Table S1.

Table S1: Specifications for Jatropha biojet LCA

Goal	To evaluate the changes in GHG emissions associated with the substitution of Jatropha-based bio-jet fuel relative to conventional kerosene-based jet fuel
Scope	The LCA is a "well-to-wake" analysis including land use change. It includes a range of realistic scenarios for feedstock production and refined oil production in Brazil, which is exported to the US for final processing into SPK and consumed in US aircraft.
Functional Unit	1 GJ of fuel
System boundaries	System boundaries include the land preparation for cultivation of seeds to fuel combustion. Following convention set by prior biofuel LCAs, infrastructure and labor are not considered.
Temporal specificity	The analysis assumes a 20-year time horizon, such that sources and sinks of GHG emissions are evaluated based on 20 years of Jatropha production. A 30-year timeline is also considered.
Impact assessment	IPCC 2007 Global Warming Potentials (100-year time-frame) including non-CO_2 GHG emissions and direct land use change (dLUC).

II. Results of prior studies

To date, a number of Jatropha Life Cycle Assessments (LCA) have been conducted. Most studies examine Jatropha as a feedstock for either ground transport or electricity production (*1-7*). One study also considered aviation fuel (*8, 9*). Five studies conducted to date report sufficient data to be comparable to each other and to the results of this work. Estimates of emissions in these studies range from 28 kgCO_2/GJ to 79 kgCO2/GJ with emission reductions from 11%-68% relative to the reference scenario used in each study. The jet fuel study reports base-case emissions of 42 kgCO_2/GJ (*9*), but does not consider LUC. There is a broader discussion of these results in the supporting information available online.

III. Sources of data

Data for this LCA was obtained through a combination of site visits, interviews and surveys of Jatropha growers and processors in Brazil. Between January and July 2009, the research team visited or surveyed a total of eight medium and large-scale Jatropha growers in several regions of Brazil in order to build a comprehensive life cycle inventory. The team also surveyed 50 small-scale family farmers who provide seeds to two of the large-scale growers (see supporting information for specific details).

Data on seed crushing, oil extraction, and refining was gathered from Fusermann Bioenergia in Minas Gerais, which was the only large-scale oil extraction facility processing Jatropha oil in Brazil when field work was underway. Data on SPK production from refined Jatropha oil was provided by Universal Oil Products (UOP) (*10*). More information about each life cycle life cycle stage is given below.

IV. Life-cycle Inventory (LCI)

Typically, life cycle inventories account for product disposal and/or recycling, but in this case the product and co-products are either fuels or fertilizers and are consumed during use. Once basic data was compiled, the material flows and processes associated with each life cycle stage were modeled using SimaPro (Version 7.1). When sufficient data were available from Brazilian sources, material and processes were based on local conditions. This included several essential inputs such as urea, phosphate fertilizers, and electric power. Other aspects of production, such as road transport and agricultural lime, could not be modeled after Brazilian conditions due to lack of data, so inventories were based on European conditions (*11*). Data was collected from Brazilian Jatropha growers. Growers approached for surveys are listed in Table S2.

Table S2: Jatropha producers in Brazil approached for data to LCA survey

Grower	Location [a]	Current area (ha)	Production model	Prior land use	Other comments
Saudibras	Caseara – TO	> 3000	Hybrid	Managed pasture	Did not respond to LCA survey. Some data was obtained during a site visit.
Bioauto	Nova Mutum - MT	1200	Hybrid	Pasture	Did not respond to LCA survey. Some data was obtained during a site visit.
Fusermann	Barbacena - MG	1500	Hybrid	Pasture, food crops, and native vegetation	Did not respond to LCA survey. Some data was obtained during a site visit. Other data obtained from farmers contracted to supply seeds to the company. Also provided detailed data about oil expelling process.
Agrima	São Luis - MA	42	Plantation	NA [b]	Responded to survey. The company hopes to expand to 2,000 ha within 5 years.
Biojan	Janauba - MG	54	Plantation	Food crops (irrigated banana)	Responded to survey. One of the oldest managed plantations in Brazil, with trees dating back to 2005. The plantation is now managed entirely for seed production.
Pétroleo Verde	Bela Vista de Goiás - GO	8	Hybrid	Natural pasture	Responded to survey. The company also has ~100 contract farmers cultivating an average of 1 ha each.
Sada Bioenergia	Jaiba – MG	187	Hybrid	Natural vegetation	Responded to survey. The company has 106 contract farmers cultivating an average of 2.1 ha each.
Rio Pardo Bioenergia	Ribas do Rio Pardo - MS	1200	Plantation	NA [b]	Responded to survey. The company hopes to expand to 40,000 ha within 5 years.

[a] Brazilian states: TO - Tocantins, MT - Mato Grosso, MA - Maranhão, MG - Minas Gerais, GO - Goiãs, MS - Mato Grosso do Sul.

[b] These growers prefer their individual data confidential. This and other inputs were used to define industry averages.

Numerous assumptions were needed to complete the life-cycle inventory. These are discussed in this section and detailed in Table S19.

A. Raw Material Acquisition

For this LCA, raw material is presumed to be crude, semi-refined, or refined vegetable oil. Thus, this phase entails land preparation, planting and managing trees, harvesting seeds, and expelling oil.

1. Land preparation

may involve grading as well as tilling or harrowing the soil prior to establishing the plantation. It may also involve excavation for irrigation channels, although that was not the case in Brazil. In addition, in Brazil, acidic soils are common, thus land preparation usually entails the application of agricultural lime (four out of five surveyed growers applied lime and, of these, 3 growers applied ~2 tons per hectare, while one applied one ton per ha).[1] This analysis used 2 tons per ha as a baseline practice.

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[1] The lime used in agricultural applications to increase the pH of acidic soils is typically pulverized limestone (calcium carbonate -- $CaCO_3$) and is sometimes referred to as ‘agricultural lime’. This is distinct from other compounds also that are also referred to simply as lime such as ‘quicklime’ or ‘slaked lime’. The latter consist of

Lime results in CO2 emissions as it dissolves and releases bicarbonate, which evolves into CO_2 and water. The IPCC's Tier 1 emission factor for CO2 released by the application of agricultural lime is 0.12 tons of carbon per ton of agricultural lime (*12*). Thus, over a 20-year period, applying two tons of lime per hectare prior to the establishment of the plantation, contributes 1.3 – 3.9 kg CO2e/GJ. The range depends on the total yield over the 20-year period. As it is applied in large physical quantities, lime transportation is potentially a significant contributor GHG emissions from land preparation. Lime is produced domestically, primarily in Minas Gerais (*13*). Thus, the transport distance averages roughly 1000 km from the growers listed in Table S2. Table S3 provides a summary of these and other key distances.

Table S3: Road distances between growers surveyed for this analysis and Brazil's main Jatropha oil expeller (Fusermann in Barbacena – MG) [a]

Company	Location	km	Area (ha)
Sada	Jaiba - MG	789	187
Biojan	Janauba - MG	719	54
Pétroleo Verde	Bela Vista de Goiás - GO	983	8
Agrima	Sao Luis - MA	2,671	42
Saudibras	Caseara - TO	1,803	3,200
Bioauto	Nova Mutum - MT	1,951	1,150
RioPardo	Ribas de Rio Pardo - MS	1,230	1,200
Fusermann	Barbacena - MG	150	1,080
Weighted average distance to current oil expeller [b]		1,439	
Distance between seed production and oil extraction in optimized scenario		200	
Distance from current oil expeller to Brazil's principle seaport at Santos – SP [c]		597	
Distance from Santos port to UOP facility on West Coast of US		15,000	
Distance from extraction and port (e.g. São Luis – MA) in optimized scenario		50	
Distance from port in São Luis – MA to UOP facility on West Coast of US		12,000	

[a] Road distances were estimated using Google Earth. Ocean distances were estimated using an online port-distance calculator (http://www.portworld.com/map/).

[b] Weighting is based on planted area of each grower

[c] Other seaports may be used for Jatropha export; however, Santos, located in the state of São Paulo, is Brazil's largest port. To dtae, this has been the only port used for exporting oil.

2. Direct land use change (dLUC)

This is an important component of land preparation. As outlined in the main text, Brazilian Jatropha producers have converted land from a range of prior uses including pasture, food crops, and natural vegetation, which may include grassland, shrubland, or forest. This analysis relies on IPCC default values to estimate the impacts of land use change. Carbon stocks exist in multiple

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calcium oxide or hydroxide produced by heating limestone. The process is both energy and carbon intensive. The lime used to increase pH in Brazilian soils is agricultural lime ($CaCO_3$).

pools: above-ground, below-ground, dead organic matter (DOM), and soil. Values for initial carbon stocks within each pool and for each type of land cover are given in Table S4 along with the source of data and any assumptions that were made.

Table S4: Carbon stocks in tons of dry matter per hectare based on estimates of above-ground (AG) biomass, below-ground (BG) biomass, dead-organic matter (DOM), and soil.

Land type		AG biomass	BG biomass	DOM	Soil	Total	Comments and sources
Brazil	Forest (moist zone)	300	111	13	65	489	AG biomass - (*12*) table 4.7; BG biomass - (*12*) table 4.4; DOM - (*12*) table 2.2; Soil - (*12*) table 2.3
	Forest (dry zone)	210	59	28	38	335	
	Shrubland	80	32	2	38	152	
	Grassland (moist zone)	6.2	10	0	65	81	AG biomass - (*12*) table 6.2; BG biomass - (*12*) table 6.1; Litter - assume zero for Tier 1 assessment; Soil - (*12*) table 2.3
	Grassland (dry zone)	2.3	6	0	38	47	
	Managed pasture	6.2	2	0	38	46	AG biomass - (*12*) table 6.2; BG biomass - IPCC offers no default for pasture – we assume 30% of AG, which is common for annual crops (*14, 15*); Litter – assume zero; Soil - (*12*) table 2.3
	Degraded pasture	3.1	1	0	38	42	AG biomass - IPCC offers no default for degraded pasture. We assume 50% of non-degraded value; BG biomass - same; Litter - zero; Soil - (*12*) table 2.3
	Annual crops	4.7	1	0	38	44	AG biomass - (*12*) table 6.2; BG biomass - NGGIP offers no default for crops – we assume 30% of AG, which is common for annual crops (*14, 15*); DOM - zero; Soil - (*12*) table 2.3

The analysis also required an estimate of carbon stocks in Jatropha plantations. Lacking any mature plantations, the best option was to estimate the mass of AG and BG biomass along with DOM and soil carbon. Details are provided in Table S5.

Table S5: Carbon stocks (tons of carbon per hectare) in Jatropha plantations based on estimates of carbon content in above-ground (AG) biomass, below-ground (BG) biomass, dead-organic matter (DOM), and soil.

Land type	AG biomass	BG biomass	DOM	Soil [a]	Total	Comments and sources
Jatropha (high yield)	14	6	0	varies	49-85	AG-biomass assumes trees reach 25, 20, or 15 kg per full grown tree dry matter for high, medium, or low yield respectively by year 5 and trees are 50% carbon. Trees are spaced 2 x 4 (1250 plants per ha). BG biomass is based on root to shoot ratios measured by Reinhardt and colleagues (*16*); DOM is assumed to be zero.
Jatropha (med yield)	11	5	0	Varies	45-81	
Jatropha (low yield)	8	3	0	varies	40-76	

[a] Soil carbon depends on prior land use. If prior use was natural vegetation, we assume that 25% is lost as a result of the disturbance induced by planting seeds (growers till the soil multiple times). If land was intensively managed prior to Jatropha cultivation, we assume no change. This follows Searchinger and colleagues (*17*), who assume 25% loss in soil carbon under land use change from native vegetation to biofuel plantations. However, this assumption may be inappropriate for Jatropha, which may be tilled multiple times prior to establishment, but is not tilled every year like annual food crops that Searchinger and colleagues were modeling. Reduced tillage relative to annual crops may cause less loss of soil carbon in Jatropha plantations.

When land is shifted from one of the uses in Table S4 to Jatropha cultivation, the change in carbon stock is given by the sum of differences in each pool: AG, BG, DOM, and soil. These form a matrix defined by prior land use and Jatropha yield, as shown in Table S6. Note, the entries in the table show total changes in carbon per unit area and are not allocated among SPK or various co-products.

Table S6: dLUC estimates (tons of carbon per ha) in Brazil based on changes in carbon stocks given in the previous tables. Positive values indicate net gains in carbon; negative values indicate net losses.

Brazil	Forest (moist zone)	Forest (dry zone)	Shrub-land (dry zone)	Grassland (moist zone)	Grassland (dry zone)	Pasture	Degraded pasture [a]	Annual crops
Jatropha (high yield)	-215	-152	-48	-4	6	16	18	17
Jatropha (med yield)	-219	-156	-52	-8	2	12	14	13
Jatropha (low yield)	-223	-160	-56	-12	-2	8	10	9

[a] Degraded pasture is not included as a category in IPCC default values. We assume it has 50% of the carbon stocks found in managed pasture.

3. Planting and managing trees

This includes sowing seeds, pruning branches (common practice to increase fruit production), weeding plots around the trees, and harvesting fruits. All material and energy inputs such as fertilizers, pesticides, herbicides, and irrigation are also accounted for in this stage. Bulk materials such as fertilizers involve lengthy transportation and this too was accounted for.

With few exceptions, seeds or seedlings are planted manually.[2] As seedlings grow, the trees may be pruned several times. In Brazil, two of the firms surveyed prune annually for the first several years, two firms do not, and one firm failed to specify. Those that do prune leave the waste in the field as green manure.

All Brazilian growers that were surveyed weed their plots. Two growers rely solely on manual weeding while three rely on a mix of manual weeding, mowing, and chemical herbicides. Two cite the use of glyphosate, which is more commonly known by its commercial name “Roundup”. The small quantity applied carried little impact form a GHG perspective, but may be a cause for concern with respect to other environmental impacts. This is discussed in more detail below.

Fertilizer: surveys of Brazilian Jatropha growers indicate that most growers rely on mineral fertilizer applications for at least the first few years of plantation establishment.

4. Fertilizer

In Brazil, there are no ‘best practices” and fertilizer application varies widely. There are no reliable data that links seed or oil yield to specific levels of nutrient applications. Rather than build a model based on one grower’s practices or some weighted average of all responses, this analysis follows the approach taken by several other Jatropha LCAs by assuming fertilizer inputs

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[2] We encountered just one grower, Saudibras, that uses mechanized planting.

are set at the theoretical application rate that would be needed to replace nutrients lost though the annual harvest of seeds (*4, 6*). This informs us of the impact of the “sustainable” application of fertilizers. Lower application would lead to the mining of macro-nutrients from the soil and higher applications would likely lead to nutrient run-off. Fertilizer applications necessary to replenish the nutrients lost when fruit is harvested are shown in Table S7.

Table S7: Fertilizer requirements based on the nutrient content of harvested fruits (based on *4*)

	N	**P as P_2O_5**	**K as K_2O**
Percent of nutrient in harvested fruit (%)	2.1	0.84	2.3
Application in kg/ha-yr			
Low yield scenario (2 t seed per ha-yr)	42	17	47
Medium yield scenario (4 t seed per ha-yr)	84	34	94
High yield scenario (6 t seed per ha-yr)	126	51	141

These applications are assumed to continue annually to replenish the nutrients removed by continually harvesting fruits. The specific sources of fertilizer used by Jatropha growers are not known. Brazil is not self-sufficient in fertilizer so there are considerable imports of both N- and P-fertilizers. In addition N- and P-fertilizers come from multiple sources and are applied in different forms.

For this analysis, N-fertilizer is assumed to be applied as urea, which is the most common N-fertilizer currently used in Brazil. It is both produced domestically and imported. The ratio of domestic production to imports is roughly 1.5:1 (*18*). Imported urea comes primarily from China and Ukraine (*19*). P_2O_5 is assumed to be used as a mix of single- and triple-super phosphate (SSP and TSP), which are consumed in a 60:40 proportion and together constitute a majority of Brazil’s net phosphate consumption (*18*). SSP is produced domestically in plants distributed around the center-south of the country.[3] All of Brazil’s TSP is produced in similar locations. Imported TSP comes from a mix of locations.[4] Lastly, K-fertilizer is almost entirely imported as Potassium chloride (muriate of potash) (*18*) with imports sourced from Canada (33%), Russia (39%), Israel (12%), and Germany (15%).

Fortunately basic LCI data exists for several of the major fertilizers produced in Brazil (*20-22*). These data were used to model the fraction of domestic fertilizer production. LCI data for imported fertilizers was not available in a country-specific form so generic European data were used (Ecoinvent, 2009). Transportation for imports was assumed to be by a combination of sea freight and road transport. Domestic production was all transported by road. Additional details are given in Table S19.

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[3] Over three fourths of Brazil’s SSP production is concentrated in 6 plants distributed in 4 states in the south/southeast of the country: Rio Grande do Sul, Goiás, Minas Gerais, and São Paulo.

[4] Importing countries are Morocco (30%), China (30%), and Russia (40%) (*19*).

5. Irrigation

Like fertilizer applications, Brazilian Jatropha growers report a range of irrigation practices. Their practices are outlined below in Table S8. Irrigation is used because it reduces mortality of young plants and will likely boost overall yields. However, irrigation is also associated with higher energy use and GHG emissions because of both the energy and the infrastructure (channels, pipes, etc) required to bring water to the plants. Moreover, there is some disagreement over the actual benefits of irrigation.

Table S8: Irrigation practices among Jatropha growers surveyed for this study

Grower	Irrigation (type)	Comments
Agrima	?	Provided no data about irrigation
Rio Pardo	?	Provided no data about irrigation
Biojan	Yes (mixed drip and micro-spray)	Biojan only applies water as needed. 90 ha of Jatropha is under drip irrigation (*gotamento*) and 1 ha is under micro-spray (*micro-aspersão*) irrigation.
Pétroleo Verde	Yes (spray)	Pétroleo Verde applies irrigation about 2 hours per day, but the volume of water was not disclosed and the duration for which water is applied was not clear from their survey response. They did not respond to requests for clarification.
Sada	Yes (drip)	Sada applies 3 drips per plant (1.6 l/hr from each drip). This is applied from Oct-June for ~ 4 hours per day (a total of about 19 liters per plant per day)

Thus, with the current state of knowledge, the additional energy/GHG costs are difficult to incorporate into a life-cycle model because there are few studies that quantify the relationship between irrigation and increased yield. As a consequence of this variation in observed practices and uncertainty of the benefits of irrigation, we conduct a sensitivity analysis by including/excluding irrigation, but we do not attempt to link yields to the presence or absence of irrigation.

6. Other chemical inputs

In addition to fertilizer and herbicide many growers use other chemical inputs to manage pests and diseases in their Jatropha plantations. Common pests and diseases vary regionally (*23*).

Only one Brazilian grower, Sada, provided detailed data about their chemical inputs. They apply *dimethoate*, an organophosphate that requires careful handling and has been banned in certain applications,[5] and *abamectin*, a nematicide.

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[5] Dimethoate has been banned in aerial spraying applications in Australia. In the US, the American Bird Conservancy has recently petitioned the US EPA to similarly ban crop imports out of concern for the effects on birds, honey bees, and livestock (*24*).

Treatments are applied in low volumes that have no measurable impact on net energy or GHG balances. However, like the application of herbicides mentioned above, they are important to document in the LCI because they may have impacts on other important environmental impacts.

7. Harvesting

Harvesting *seeds* involves primarily manual labor. While there are currently very few inputs of note for this stage of Raw Material Acquisition, it is relevant for two reasons. First, this is the point at which seed yields become apparent. Yields are a critical factor in the overall GHG balance and are discussed further below. Second, there is currently a great deal of interest in developing a mechanized harvester. If successful, this innovation will both reduce labor requirements and introduce additional emissions into the Jatropha life cycle (*25*).

Yield and spacing: as with other aspects of the Jatropha life-cycle, it is too soon for the industry to provide accurate yield data for mature trees. However, seed yields are critical determinants of the crop's GHG balance. This research collected several data points from Brazilian growers. Spacing is also an important determinant of life cycle impacts. A wide range of spacing is currently used by Brazilian growers. Data are shown in Table S9 below. Several survey respondents chose not to answer the survey questions about yield. Others had trees too immature to produce any seed.

Table S9: Yields of seed (tons per hectare) reported in young plantations in Brazil

Grower	Year 1	Year 2	Year 3	Spacing (m)	Comments
Biojan	0.3	1	2	2x3, 3.5x2, and 2x6	These represent the majority of growers plots, but he also has small areas of other spacing. He expects yields of ~4 t/ha from year 4 onwards
Contract farmer for Sada [a]	1.1	NA	NA	2.5x4	Expects 4-5 t/ha in second year
Test plot in Pernambuco	3.2	3.6	NA	NA	Plots used drip irrigation (cited in *26*)
Saudibras [b]	NA	1.5	NA	2x3	Expects yields to reach 5-6 t/ha by maturity

[a] This small-scale grower was visited during a site visit to Sada Bioenergia.

[b] This grower did not respond to our survey, but we gathered data during a preliminary site visit.

In order to model a 20-year production run, a range of reasonable yields was explored. We defined low, medium and high-yield scenarios in which annual seed production reached 2, 4, and 6 tons per ha respectively. Assuming that full yields are not achieved until the fourth year, these scenarios produce 35.6, 71.3, and 107 t of seed per hectare over the 20-year project cycle. By extending the plantation lifetime to 30-years, cumulative production is boosted roughly 50% under each yield scenario. Total seed production under each yield scenarios for both the 20-year and 30-year timeframe are shown in Table S10.

Table S10: cumulative seed yield (in tons) under each yield scenario for both 20 and 30-year plantation lifetime

	Low yield (tons)	Medium yield (tons)	High yield (tons)
20-year	36	71	107
30-year	56	111	167

Oil extraction

Oil can be extracted from Jatropha seeds through a number of methods. Techniques range from simple mechanical ram or screw presses that use human power or small motors to squeeze the oil from the seeds (*23*) to sophisticated capital-intensive methods that dissolve the oil in a non-polar solvent (usually hexane) (*27*). Existing LCAs have modeled both small-scale mechanical pressing (*4*) and large-scale solvent-based extraction (*6*): one study compares numerous extraction methods (*1*).

Mechanical extraction is less capital intensive and can typically extract 0.25 kg oil per kg seed (70-75% extraction efficiency). Solvent-based extraction is more efficient, achieving 0.30 kg oil per kg seed or higher (90%-95% extraction efficiency). However, solvent-based extraction requires higher capital investment and technical know-how and is only suitable for large-scale industrial processes (*6, 27*). In Brazil, solvent-based extraction is common in the soy processing industry, but it is not yet used in the Jatropha industry. Currently, the industry relies primarily on a single facility (Fusermann) for extraction. This facility uses mechanical extraction, but applies heat to enhance yields and follows oil pressing by a semi-refining process that uses lye (sodium hydroxide - NaOH) to lower the oil's acidity.[6] Major inputs required and outputs produced for every kilogram of semi-refined oil are given in Table S11.

Seed oil content

Oil content of Jatropha seeds has shown some variation. However, magnitude of observed variation is relatively small in comparison to variation in seed yield. For example, Achten and colleagues provide a statistical breakdown of the fraction of Jatropha seeds comprised of kernel and husk, in which the kernel constitutes 63.1% ± 4% (mean ± s.d.) based on 21 samples (*28*). They also provide a breakdown of seed kernel composition in which seeds comprise 54.6% ± 5% crude fats (oil) by mass (mean ± s.d.) based on 38 samples. Taking the product of the means and using standard error propagation, we conclude that the oil content is 34% ± 6% (mean ± s.d.), which is a fairly narrow range relative to the range of reported seed yield. Thus, we use the mean value reported by Achten and colleagues (*28*) and do not choose to test sensitivity to this parameter because evidence suggests that uncertainty is small relative to uncertainty in seed yield.

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[6] Acidity is a measure of the free fatty acid (FFA) content in the oil. High FFA content can cause the oil to degrade over time. FFAs build up after the ripening of the fruit or during storage of the pressed crude oil in poor storage conditions (e.g. contact with fresh air or elevated temperatures) (*23*).

Table S11: Inputs and outputs from oil expressing and semi-refining (*29*)

	Quantity per kg semi-refined oil	Comment
Inputs (units)		
Seeds (kg)	3.79	Assumes a pressing efficiency of ~86%, which yields 0.30 kg oil per kg seed. This is followed an additional 12% volume loss as a result of the semi-refining process [a]
Transport (tkm)	Base case - 5.68 Optimized case - 0.76	In the base case, seeds are brought an average of 1439 km.[b] In the optimized logistics scenario, we assume seeds are produced within 200 km of the expelling facility so that transport distance decreases by 86%.
Water (liters)	0.24	
NaOH (kg)	0.012	NaOH is produced domestically. However, Brazilian LCI data for NaOH was not available so we use data from Europe (Ecoinvent, 2007).
Electricity (kWh)	0.38	This is derived from the total capacity of all electric motors involved in both expelling and refining oil, assuming that the motors run at 80% capacity when they process 1 ton of oil per hour.
Fuel oil (kg)	0.015	Fuel oil is burned to produce, steam which is used both in the expelling and refining process. The fuel used is locally called BPF, which is the equivalent of heavy/residual fuel oil. LCI data for BPF is lacking, therefore generic European data for heavy fuel oil was used (Ecoinvent, 2007)
Outputs (units)		
Gums (kg)	0.137	Quantity of gum produced depends on the initial acid content of the oil
Waste water (liters)	0.24	Contaminated with gum
Jatropha seed cake (kg)	1.39	Seedcake includes 12% oil by mass
Jatropha seed husk (kg)	1.40	Seed husk is removed by decorticators on-site
Semi-refined oil (kg)	1.00	

[a] Volume loss during the semi-refining process depends on the acidity of the oil. Higher acidity causes more volume loss

[b] This is a weighted average of the major producers surveyed.

8. Co-Products

The expelling process produces co-products in the form of seed husk and seedcake. Currently, in Brazil, little is done with these co-products. However, in different production areas, such as India and Tanzania, they are used as fuel and/or fertilizer (*23*). As the Brazilian industry matures, it is very likely the co-products of Jatropha oil extraction will be put to similar uses. Jatropha seedcake contains numerous macro-nutrients, which makes it a potentially useful fertilizer.[7] The husks have a lower nutrient content, but can also be used for this purpose.

Alternatively, both husks and seedcake may be burned directly in the form of pellets or briquettes. Seedcake may also be used as a feedstock for methane production through anaerobic digestion (*23*). Table S12 shows the physical characteristics of both cake and husks including the macro-nutrient content and calorific value. As a fuel, these co-products could be put to a number of end-uses. Solid fuel briquettes could displace other solid or liquid fuels in either household cooking applications or for the production of industrial process heat. Biogas derived from anaerobic digestion could also be used for direct heating, as well as generating shaft power or electricity.

Table S12: Macro-nutrient contents of seedcake and husk based on mid-reanges of the values reported in (*28, 30, citing multiple sources*)

	Seedcake	Husks	Total
Mass fraction of dry fruit (%)	29 %	37 %	66 %
Quantity produced per GJ SPK output (kg)	58 kg	66 kg	124 kg
Macro-nutrient content [a]			
N	5.5 %	0.4 %	3.5 kg (as N)
P	2.6 %	0.03 %	3.4 kg (as P_2O_5)
K	1.4 %	0.9 %	2.2 kg (as K_2O)

[a] In the far right column, P and K follow standard convention for labeling commercial fertilizer and are reported as P2O5 and K2O equivalents where %P2O5 = %P ÷ 0.436 and %K2O = %K ÷ 0.83.

For the Brazilian LCA, we examine three possible scenarios for seedcake and husks. First, we examine a situation in which the material is simply discarded as waste, second, we examine the use of the material as fertilizer, and third, we examine the use of the material as fuel for industrial heating where it displaces fuel oil.

In the fertilizer scenario, we assume that the seedcake displaces an equivalent quantity of nutrients in commercial fertilizer: domestically produced urea and SSP, and imported potash. As

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[7] van Eijck notes that seedcake with high oil content, such as that derived from mechanical cold-pressing, is not readily usable as fertilizer because it somewhat sticky and creates a dense covering over the soil. She suggests letting it dry in the sun for several days prior to application or storage (personal communication, also see *23, ch. 5*).

was mentioned above, we have chosen system boundary expansion as an allocation methodology to include these avoided products.

Macro-nutrient contents of seedcake and husk are listed in Table S12. For seedcake, these values are 5.5%, 2.6%, and 1.4% (N:P:K respectively). For husks, these values are 0.4%, 0.03%, and 0.9% (N:P:K respectively). Under these assumptions, 1GJ of fuel one ton of seed yields 370 kg of husk and 370 kg of seedcake (including 12% oil), which contains the equivalent of 21.8 kg N, 24.6 kg P2O5, and 8.51 kg K2O.

In the fuel scenario we assume that the seedcake and hulls are used to displace heavy fuel oil in industrial boilers. From our analysis of the current situation in Brazil, this appears to be the most likely near-term application. For example, the extraction and refining process currently used in Brazil to make export-grade Jatropha oil uses 15 kg of heavy fuel oil for every ton of Jatropha oil processed: approximately 641 MJ. Every ton of Jatropha processed produces 1.39 tons of seedcake (12% oil) and 1.40 tons of husk. The combined energy content of these materials is over 60 GJ, which exceeds the heat energy required for processing by nearly a factor of 100. Thus, the extraction facility could, in theory, add a briquetting machine to process seedcake into briquettes, use ~2% of the briquettes to offset their use of fuel oil, and sell the remaining briquettes as industrial heating fuel. Details are given in Table S13

Table S13: Characteristics of seedcake and husk when used as boiler fuel

Calorific value (MJ/kg)	
Seedcake	25
Husk	19
Briquette made from 47% seedcake and 53% husk	22
HFO	40
Energy requirements for briquetting (*31*):	
Electricity (kWh/ton)	60
Heat (MJ/ton)	350
Fraction of seedcake + husk needed to supply heat (assuming 80% boiler efficiency)	2%
Briquettes produced per GJ SPK (kg)	121
HFO displaced per GJ SPK (kg)	69

Using the seedcake as feedstock for biogas appears to have clear advantages over other pathways to energy production because it also yields a high quality fertilizer.[8] This is currently done in at least one project in Tanzania (*23*). However, we did not explore this option in the current analysis because there appears to be little experience with biogas in Brazil.

One final use to which seedcake might be put is as an animal feed. The toxicity of the seedcake presents a barrier to this application. Nevertheless, it has generated a great deal of interest and

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[8] Only seedcake is appropriate for anaerobic digestion because the husk has higher contents of ligno-cellulosic materials, which do not readily decompose in bio-digesters.

there are numerous research programs attempting to either breed a non-toxic variety of seed or detoxify the seedcake produced from regular toxic varieties of the plant (*32, 33*). This route deserves to be explored from a life-cycle perspective as well; however, there is no LCI data available about the detoxification process. Thus, developments in this area should be closely monitored and incorporated as a likely use of co-products if/when the detoxification process becomes viable.[9]

B. Raw Material Transport

There are two components of raw material transportation: seeds from the farm-gate to the oil expelling/refining facility and extracted oil from the facility to the site where it is processed into biojet fuel. The current state of the Brazilian industry, with widely dispersed Jatropha growers and a single large-scale oil extraction facility located far from an international seaport, this stage of the life-cycle makes a relatively large contribution to the net life-cycle GHG impact. Distances between the growers visited and/or surveyed for this analysis and the main processing facility are shown in Table S3.

The mean distance from the growers to the oil expeller is considerably larger than the distance from the expeller to the main seaport. Seed transport takes a heavy toll on GHG emissions because ~70% of the material being transported, is not the primary product. Of course, this impact is buffered under mass-based allocation.

The second component of raw material transport involves bringing the crude or semi-refined Jatropha oil to the biojet refinery. Though there are many biodiesel facilities in Brazil, there are no facilities producing bio-derived jet fuel. This analysis assumes oil is transported to one of UOP's facilities on the west coast of the US via the main seaport in Santos, São Paulo. It travels ~700km by road from the pressing facility to the port and over 15,000 km by ship to the facility in the US.

As the industry matures, we assume that oil extraction facilities will be constructed closer to Jatropha production zones and/or closer to seaports to facilitate export. Therefore we model an "optimized logistics" scenario that assumes plant production is located within 200km of an extraction facility, which itself is located near a major port city.[10] This shortened supply chain was only explored with the "high yield" scenario. Presumably, once the industry matures, growers will also have identified higher yielding varieties. Brazil is also investing in a north-south railway that will link the center with the north of the country (*34*). Rail transport is 65-75%

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[9] In addition, as was shown in **Error! Reference source not found.**, the choice of displaced product has a very large effect on the outcome of any LCA.

[10] We chose the Port of São Luis in the state of Maranhão. However, there are numerous ports in the north and northeast of the country that would yield similar results: e.g. Fortaleza, Recife and Salvador are all considerably closer to the US and EU than Santos.

less greenhouse intensive than road transport on a ton-kilometer basis (*11*).[11] Thus, once this link is complete, GHG emissions due to transport from producers in the center of the country should also decrease considerably. This optimized logistics scenario reduces emissions from road and surface transport by ~80% and 17% respectively. Shifting to rail but maintaining longer distances, which is the only option for growers in the center of the country who intend to export their oil, would lead to a similar decrease in emissions from inland transport.

C. Liquid fuel production

This stage of the life-cycle involves the production of hydro-processed synthetic paraffinic kerosene (SPK) from semi-refined Jatropha oil. SPK is produced through methods that are already utilized in petroleum refining. The components of the oil treated with hydrogen to remove oxygen, resulting in a mixture of straight-chain, branched-chain, and cyclic hydrocarbons with properties that are similar, though not identical to conventional kerosene-based jet fuel. These properties include near-zero sulfur content, high thermal stability, low lubricity, and near-zero aromatic content (*9, 35*). Hydro-processed SPK can be derived from a range of vegetable oils, including Jatropha, and has been tested in numerous aircraft (*8*).

Hydro-processed SPK has been produced by three refiners: Neste Oil, UOP, and ConocoPhillips (*8*). This report relies on input/output data from UOP's process and it is unclear if other processes are substantially different because they have not made material and energy requirements for their processes public. Material and energy requirements in UOP's hydro-processed SPK are given in the main text.

The co-products from SPK production rival SPK output itself in volume and energy content. As with co-products of crude oil extraction, all co-products of refining are incorporated into the analysis by system expansion. To accomplish this, we assume that production of these bio-based hydrocarbons results in the displacement of fossil-based equivalents. The LCI data that was used is described in Table S19. These data incorporate emissions up to the refinery gate. For allocation by system expansion, we also credit the emissions from the end use of the displaced products in order to capture the full impact of product substitution. To do this, we use emission factors from the GREET model (*36*). Further, we assume that the final combustion of the bio-based co-products does not differ substantially from the fossil fuels they substitute. Thus, the credit from product substitution is based on the GHGs that would have been emitted by each life cycle stage of the analogous fossil fuels prior to their final use: raw material acquisition, raw material transport, liquid fuel production, and product transport/distribution. Emissions of non-CO2 GHGs are assumed to be the same from both the bio-based co-products and the fossil fuels that are replaced.

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[11] These emission factors assume average European conditions. 65% reflects diesel powered freight trains; 75% reflects electric freight trains powered by the average EU mix of power. These data are only roughly indicative of the difference between road and rail freight in Brazil or India.

D. Product transport and fueling

This stage of the life-cycle accounts for the transportation of the fuel from the refiner to the aircraft's fuel tank. Unlike the previous stages, this stage is highly speculative. Currently there are a limited number of facilities producing hydro-processed SPK from Jatropha or any other plant oil. Given the experimental nature of current SPK use, the networks used to distribute SPK for recent test flights are not accurate depictions of future emissions from this stage. For this analysis, we assume that commercial SPK will follow a similar distribution path as is taken for conventional kerosene-based jet fuel. An emission factor for distribution of Jet-A under current US conditions has been estimated by Skone and Gerdes at 0.9 kg CO2e per kg (*37*) . Lacking more detailed information about the future location of production facilities, distribution to US airports, and the likely transport methods that will be used, we will also use this value.

E. Use/Aircraft Operation

This stage involves the combustion of fuel in the aircraft's gas turbine engines. As with product transport and fueling, our estimations of emissions for this stage do not involve empirical data. Data do not exist for emissions from SPK, although this is an area of active research (*8*). For this analysis, we rely on published emission factors for the combustion of conventional kerosene-based jet fuel in modern gas turbine engines (*37*). These are shown in Table S14.

Table S14: GHG Emissions for Kerosene-Based Jet Fuel (*37, Table 7.2 but converted from kg CO2E/MMBtu to kg CO2e/GJ*)

Emissions in kg CO2e/GJ	**Raw material acquisition**	**Raw material transport**	**Liquid fuels production**	**Product transport/ refueling**	**Combustion**	**Total:WTT**	**Total:WTW**
CO2	4.3	1.3	5.5	0.9	73.1	12.0	85.1
CH4 (CO2e)	2.1	0.0	0.2	0.0	0.01	2.3	2.3
N2O (CO2e)	0.0	0.0	0.0	0.0	0.59	0.1	0.7
Total	6.4	1.3	5.7	0.9	73.6	14.4	88.1

Lacking data that is specific to SPK combustion, we assume the same values for SPK. Allen and colleagues (*38*) suggest omitting non-CO2 GHGs from the combustion stage of SPK LCAs because of limited understanding of the actual emissions and their impacts. We include these emissions; however, their inclusion has negligible impact on the outcome of the analysis.

F. Results in detail

Table S15a and b show the results the LCA disaggregated by life-cycle stage for all yield and allocation scenarios assuming 20-year and 30-year plantation lifetimes respectively.

Table S15a: GHG Emissions (kgCO$_2$e/GJ) **for each yield scenario under different allocation methodologies for a 20-year plantation lifetime.**

Emissions (kgCO2e/GJ)	CJF	Energy-based allocation			Mass-based allocation			System expansion - no use of seedcake/husks			System expansion - seedcake/husks as fertilizer			System expansion - seedcake/husks as fuel		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Tree planting and land management (without dLUC)	--	11	9	8	8	6	6	45	36	33	45	36	33	45	36	33
Lime and Urea application	--	8	7	7	5	5	5	32	30	29	32	30	29	32	30	29
Oil extraction and partial refining	6	1.4	1.5	1.6	1	1	1	9	10	10	9	10	10	9	10	10
Co-product credits for seedcake and husk	--							0	0	0	-24	-23	-24	-196	-196	-196
Raw material transport: seeds to expeller	1	6	6	6	4	4	4.1	21	21	21	21	21	21	21	21	21
Raw material transport: Jatropha oil to biorefinery	--	5	5	5	5	5	5	8.1	8.2	8.1	8.1	8.2	8.1	8.1	8.2	8.1
Liquid fuel refining	6	11	11	11	11	11	11	11	11	12	11	12	12	11	11	12
Credits for refining co-products	--							-55	-55	-55	-55	-55	-55	-55	-55	-55
Final product transport	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Combustion	74	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total:WTW (without LUC)	88	42	40	39	35	33	33	74	63	59	50	40	36	-123	-134	-137
Percentage change from CJF	--	-52%	-55%	-56%	-60%	-62%	-63%	-16%	-29%	-33%	-43%	-55%	-59%	-239%	-252%	-256%
Total WTW (with LUC)																
Forest (moist)		905	464	316	646	333	229	3692	1840	1222	3668	1817	1199	3495	1643	1026
Forest (dry zone)		661	342	235	473	247	172	2670	1329	881	2646	1306	858	2473	1132	685
Shrub-land (dry)		259	141	101	188	104	77	983	485	319	959	462	296	786	288	123
Grassland (moist)		88	55	44	68	44	37	269	128	81	245	105	58	72	-69	-115
Grassland (dry)		50	36	31	40	30	28	106	47	27	82	24	4	-91	-150	-169
Pasture		11	17	18	13	17	18	-56	-34	-28	-80	-57	-51	-253	-231	-224
Degraded pasture		3	13	16	8	14	17	-88	-51	-38	-112	-74	-61	-285	-248	-234
Annual crops		7	15	17	10	15	17	-72	-42	-33	-96	-65	-56	-269	-239	-229
Percentage change from CJF (with LUC)																
Forest (moist)		927%	426%	259%	633%	278%	160%	4091%	1988%	1287%	4064%	1962%	1261%	3867%	1764%	1064%
Forest (dry zone)		651%	288%	167%	437%	180%	95%	2931%	1408%	900%	2903%	1382%	874%	2707%	1184%	678%
Shrub-land (dry)		194%	60%	15%	114%	18%	-13%	1015%	450%	262%	988%	424%	236%	792%	227%	39%
Grassland (moist)		0%	-37%	-50%	-23%	-50%	-58%	205%	45%	-8%	178%	19%	-35%	-19%	-178%	-231%
Grassland (dry)		-44%	-59%	-65%	-54%	-66%	-69%	21%	-47%	-70%	-6%	-73%	-96%	-203%	-271%	-292%
Pasture		-87%	-81%	-79%	-85%	-81%	-79%	-163%	-139%	-131%	-191%	-165%	-157%	-387%	-363%	-354%
Degraded pasture		-96%	-85%	-82%	-91%	-84%	-81%	-200%	-157%	-144%	-227%	-184%	-170%	-424%	-381%	-366%
Annual crops		-92%	-83%	-81%	-88%	-83%	-80%	-182%	-148%	-137%	-209%	-174%	-163%	-405%	-372%	-360%

Table S15b: GHG Emissions (kgCO$_2$e/GJ) for each yield scenario under different allocation methodologies for a 30-year plantation lifetime.

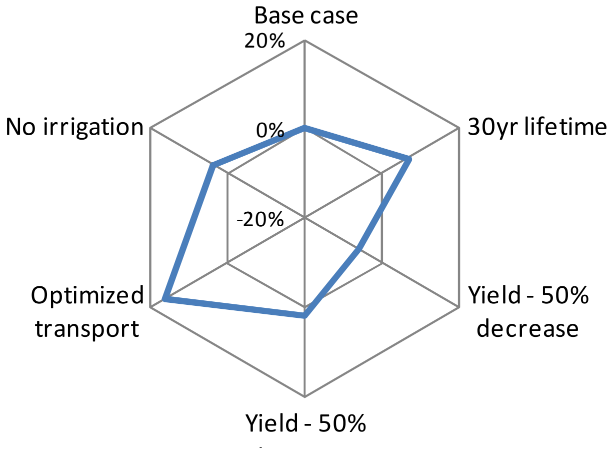
Emissions (kgCO2e/GJ)	CJF	Energy-based allocation			Mass-based allocation			System expansion - no use of seedcake/husks			System expansion - seedcake/husks as fertilizer			System expansion - seedcake/husks as fuel		
		Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Tree planting and land management (without dLUC)	--	10	8	8	7	6	5	43	34	32	43	34	32	43	34	32
Lime and Urea application	--	5	5	5	3.6	3.4	3.3	21	20	20	21	20	20	21	20	20
Oil extraction and partial refining	6	1.4	1.5	1.7	1.05	1.1	1.18	9	9	10	9	9	10	9	9	10
Co-product credits for seedcake and husk	--							0	0	0	-24	-24	-24	-196	-196	-196
Raw material transport: seeds to expeller	1	6	6	6	4	4	4.1	21	21	21	21	21	21	21	21	21
Raw material transport: Jatropha oil to biorefinery	--	4.5	4.5	4.5	4.5	4.5	4.5	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1
Liquid fuel refining	6	10.8	10.8	10.8	10.8	10.8	10.9	13	13	13	13	13	13	13	13	13
Credits for refining co-products	--							-55	-55	-55	-55	-55	-55	-55	-55	-55
Final product transport	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Combustion	74	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total:WTW (without LUC)	88	39	37	37	33	31	31	62	53	50	39	29	26	-134	-144	-147
Percentage change from CJF	--	-55%	-58%	-59%	-63%	-65%	-65%	-29%	-40%	-43%	-56%	-67%	-70%	-252%	-263%	-266%
Total WTW (with LUC)																
Forest (moist)		868	459	324	619	330	234	3537	1824	1253	3514	1800	1229	3341	1627	1056
Forest (dry zone)		625	338	243	448	244	177	2520	1315	914	2497	1291	890	2324	1118	717
Shrub-land (dry)		221	136	108	162	101	81	825	468	349	802	444	325	629	271	152
Grassland (moist)		53	52	52	43	42	42	122	117	115	99	93	91	-74	-80	-82
Grassland (dry)		13	32	39	15	27	32	-47	32	58	-70	8	34	-243	-165	-139
Pasture		-25	13	26	-12	14	23	-207	-48	5	-230	-72	-19	-403	-245	-192
Degraded pasture		-33	9	24	-18	11	22	-239	-64	-6	-262	-88	-30	-435	-261	-203
Annual crops		-29	11	25	-15	13	23	-223	-56	0	-246	-80	-24	-419	-253	-197
Percentage change from CJF (with LUC)																
Forest (moist)		885%	421%	268%	603%	274%	166%	3914%	1970%	1322%	3888%	1943%	1295%	3692%	1746%	1098%
Forest (dry)		610%	284%	176%	408%	177%	101%	2760%	1393%	937%	2734%	1366%	910%	2538%	1170%	714%
Shrub-land (dry)		151%	54%	23%	84%	15%	-8%	836%	431%	296%	810%	404%	269%	614%	207%	72%
Grassland (moist)		-39%	-41%	-41%	-51%	-53%	-52%	39%	32%	30%	13%	5%	3%	-184%	-191%	-193%
Grassland (dry zone)		-85%	-64%	-56%	-83%	-69%	-63%	-154%	-64%	-34%	-180%	-91%	-61%	-376%	-287%	-258%
Pasture		-129%	-85%	-70%	-114%	-84%	-73%	-335%	-154%	-94%	-361%	-182%	-122%	-557%	-378%	-318%
Degraded pasture		-137%	-90%	-73%	-120%	-87%	-76%	-372%	-173%	-107%	-398%	-200%	-134%	-594%	-397%	-330%
Annual crops		-133%	-87%	-72%	-117%	-86%	-74%	-353%	-163%	-100%	-379%	-191%	-128%	-575%	-387%	-324%

G. Details on the sensitivity analyses

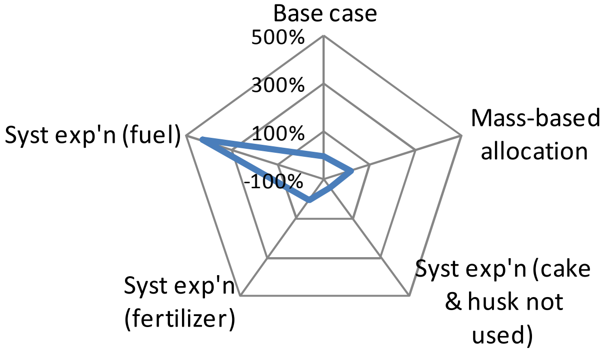
Sensitivity of the results to numerous assumptions concerning plant management and logistics, allocation methodologies, and land use change were explored. These are illustrated in Figure S1 relative to the base scenario, which was defined as energy-based allocation, irrigated plantation, long travel distances, and no dLUC. Within the category of plant management and logistics, shortening supply chains has the largest impact on the base-case outcome. Among alternative allocation methodologies, shifting to mass-based allocation reduces emissions associated with SPK production by 17% while adopting a system expansion approach depends strongly on the materials that each co-product displaces. If seedcake and husks replace nothing and system expansion is only carried out for the bio-based hydrocarbons co-produced during SPK refining, then the result is a 58% increase in emissions relative to the energy-based allocation. If seedcake and husk are used as fertilizer, the outcome is equivalent to energy-based allocation. However, if seedcake and husk are used as boiler fuel, this drives the system carbon-negative, resulting in a 435% improvement in emission reductions relative to the energy-based assessment. Last, dLUC scenarios were examined and show that many plausible shifts in land-use result in carbon storage savings relative to a system in which dLUC is ignored. Degraded pasture shows the largest potential for carbon sequestration. Managed pasture and annual crops show similar results. Grasslands and natural pasture vary depending on the moisture regime, which is a strong determinant of carbon stocks. Moist-zone grasslands with large stocks of carbon may experience a net loss of carbon when converted to Jatropha depending on the quantity of above-ground biomass that accumulates in the plantation. Shrubland conversion leads to the greatest loss among the observed dLUC transitions. Converiosn of dry or moist forest would lead to even higher losses of carbon; but such conversions have not been observed in Brazil at this time.

Figure S1: Sensitivities to variation in assumptions and parameters. Plots show percentage change from base case of 55% GHG reductions by substituting 1GJ of CJF with SPK (energy-based allocation, irrigated plantation, long travel distances, and no dLUC). Positive values are improvements relative to the base case.

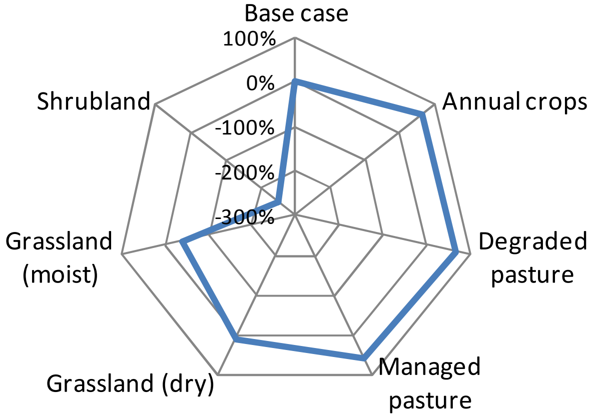
a. Plant management and logistics



b. Allocation methodologies



c. dLUC scenarios



H. Indirect land use change (iLUC)

iLUC is also a potentially important area for which the sensitivity of these results should be tested. Several analyses have examined the ways in which indirect effects can negate the emission reduction benefits of fuel switching (*17, 39, 40*). However, these assessments typically rely on economic models that simulate the impact of increased crop demands on international commodity markets and forecast spatially explicit growth in crop cultivation (see, for example *41, 42*). These are not appropriate to assess iLUC impacts of Jatropha because it is not a traded commodity so there is no indication how global markets will respond to increased demand for Jatropha oilseeds. Nevertheless, there is a chance that Jatropha could displace existing cultivation of other crops. Should this occur in large volumes, iLUC impacts could result.

In reviewing the recent work by Lapola and colleagues cited by Reviewer 1, we note those authors find substantial iLUC impacts occur under a scenario in which Brazil meets its mandated biodiesel blend relying wholly on Jatropha as feedstock between 2003 and 2020. The authors present a net iLUC impact, claiming 81,000 km2 of land will be impacted, releasing ~3.4 Pg CO2e by 2020.

However, they do not convert their estimated impact into an iLUC factor that can be compared to other emissions from the fuel life cycle. To do this, one needs to divide the iLUC emissions by the net fuel-energy produced over the time period in question. We have done this assuming linear growth from zero production in 2003 to production of 4.47 billion liters in 2020 (as noted in Table S5 of the author's report). This yields a total of 38 billion liters of Jatropha biodiesel or 1.27 EJ over a 17 year period. Taking the ratio of emissions to fuel-energy and using the author's allocation factor of 72% for Jatropha gives an iLUC factor of ~2,000 kgCO2e/GJ. For comparison, we also converted the authors' findings for other feedstocks into similar units. These results are shown in Table S16.

Table S16: Parameters needed to assess dLUC and iLUC factors based on the analysis of Lapola and colleagues

	Production (10^9 liters)		Total area affected (1000 km^2)		LUC emissions (Tg CO$_2$e)		Total production (2003-2020)		Allocation factor	dLUC factor (kgCO$_2$e/GJ)	iLUC factor (kgCO$_2$e/GJ)
	2003	2020	dLUC	iLUC	dLUC	iLUC	(10^9 liters)[a]	(MJ)[b]			
Sugarcane	15	50	57	78	396	3829	549	1.2E+13	100%	33.9	328
Soybean	1	4	108	108	878	5173	42	1.4E+12	39%	243.4	1434
Jatropha	0	4	32	81	237	3438	38	1.3E+12	72%	134.9	1956
Sunflower	0	4	73	91	312	4260	38	1.3E+12	82%	202.2	2761
Oil palm	0	4	4	23	54	911	38	1.3E+12	87%	37.1	626

[a] Assuming linear growth in each fuel between 2003 and 2020

[b] Assumes the calorific values of ethanol and biodiesel are 21.3 MJ/liter and 33.3 MJ/liter respectively (*36*).

These results show substantial emissions linked to iLUC from all feedstocks. Indeed, they are orders of magnitude larger than the emissions most analyses find from the non-land-use segments of the lifecycle. However, as with other iLUC analyses, the model that the authors use to derive their results is somewhat of a black box. They present no uncertainties and no sensitivity analyses. In addition, the results are somewhat counter-intuitive. Conventional wisdom about d/iLUC typically conceives of the two concepts as somewhat in opposition: if one is high, the other is typically minimal or zero. This is because if biofuel crops are planted in an area initially covered in natural vegetation with potentially large stocks of carbon, dLUC emissions are high, but no economic activities are displaced so that indirect effects are minimized. On the other hand, if biofuel crops displace other crops, then dLUC impacts are small because minimal losses of carbon result from conversion of one cropping system to another. However, the activity displaced by the shift to biofuels is likely transferred somewhere else, which leads to iLUC and its associated carbon penalty. Of course, this conventional wisdom does not hold if crops are planted on land that has a low initial stock of carbon (low dLUC) and is currently unutilized and likely to remain so in the near future (low iLUC). Such land tends to be of poor quality; of course, one of the motivating factors driving the growth of Jatropha is that it can be planted on such land.

However, Lapola and colleagues' analysis posits that the opposite is true. They find that dLUC from Jatropha is large and iLUC is larger still. For example, they estimate the dLUC factor from Jatropha is ~135 kgCO2e/GJ, which is roughly equal in magnitude to the dLUC we find when Jatropha displaces Brazilian shrubland (our worst-case dLUC scenario). However, to this, Lapola and colleagues add an iLUC factor of 1,956 kgCO2e/GJ. This implies that, in their analysis, the average unit of fuel both directly displaces an area of shrubland and displaces enough economic activity to lead to clearance of dense forest. Each result is individually reasonable, but together the two seem somewhat implausible.

We may raise additional doubts about the plausibility of their results. For example, Lapola and colleagues restrict the area that Jatropha is planted to the arid Northeast region of the country. In contrast, our surveys of current producers find large-scale Jatropha activity spread throughout the country with particularly large plantations present in the center and south of the country (Minas Girais, Matto Gross do Sul, and Tocantins). Further, the most prevalent land type on which Jatropha is currently grown is on former pasture, which is unlikely to have substantial dLUC or iLUC impacts (though, as we acknowledge in the main text, dLUC impacts may be considerable if future biomass regeneration of recovering ecosystems is accounted for).

In order to further gauge the accuracy of Lapola and colleagues' iLUC estimations it is also worth examining other iLUC analyses. To our knowledge theirs is the only attempt to quantify iLUC from Jatropha. However, others have estimated iLUC factors for soybean, sugarcane, and other feedstocks also included in their analysis. Comparing Lapola and colleagues' results for these feedstocks to others reported in the literature gives an indication of the level of agreement in published iLUC analyses (Table S17).

Table S17: Crop-specific iLUC factors reported in the literature (kgCO_2e per GJ-fuel)

	RFS-2[a]			LCFS[b]	Oeko Inst.		Searchinger et al.	Lapola et al.
	Brazil	RoW	Total	Total	Low	High		
Soy biodiesel	5	37	42	42	41	67	NA	1434
Sunflower/Rapeseed [c]	NA	NA	NA	NA	33	67	NA	2761
Corn ethanol	22	10	32	30	NA	NA	111	NA
Sugarcane ethanol	-1	5	4	46	21	42	NA	328
Cellulosic [d]	14	2	16	18	38	77	NA	NA
Brazil Jatropha	NA	NA	NA	NA	NA	NA	NA	1956

[a] From USEPA 2009 Figure 2.4-41

[b] From CARB 2009 Tables VI-3 and 4

[c] The analysis from the Oeko Institute reports an iLUC factor for rapeseed while Lapola and colleagues report both sunflower and rapeseed together.

[d] Cellulosic ethanol under the RFS and LCFS is derived from switchgrass. In the EU analysis it is derived from short-rotation forestry.

As Table S17 demonstrates, the Brazil-specific iLUC factors estimated by Lapola and colleagues are between *eight and eighty times larger* than iLUC factors estimated by other researchers. While the reasons for this are not entirely clear, several factors may contribute. First, the time-horizon in their analysis is shorter than in other analyses. Other iLUC analyses extend for 25-30 years, while Lapola and colleagues' truncate theirs in 2020 after just 17 years. If we extend their analysis to 30 years, production would double but the land area affected would remain fixed, thereby cutting their iLUC factors roughly in half.

Second, Lapola and colleagues' assume terrestrial carbon emissions per unit area of land affected by iLUC are 20-80% larger than estimates in other analyses (shown in Table S18).

Table S18: Average emissions resulting from areas affected by iLUC under each scenario

	iLUC emissions (tCO_2e/ha)	Source
RFS-2	288	(*42*)
LCFS	235	(*41*)
Oeko Inst.	270	(*43*)
Searchinger et al.	351	(*17*)
Lapola et al. [a]		(*44*)
Jatropha	424	
Range for all feedstocks	396-491	

[a] Derived from Figure S2 by dividing iLUC "carbon debt" by iLUC area

Third, the analysis by Lapola and colleagues assumes that the area affected by iLUC due to Jatropha cultivation exceeds the area that is directly brought under cultivation by a factor of 2.5 (see Figure S2 in *44*). Other analyses assume, at worst, a 1:1 relationship; i.e. every hectare of farmland replaced by biofuel production leads to one hectare of iLUC (*45*).

The differences described above offer a partial explanation of the large difference between Lapola and colleagues' estimate of iLUC impacts per unit fuel. However, they leave a large component of the differences unaccounted for. For this reason, we are not confident that the iLUC estimates for Jatropha realistically portray its potential impacts in Brazil and do not offer a quantitative sensitivity analysis at this time.

If other estimates of iLUC are considered, such as those for soy shown in Table S17, the range of possible iLUC factors narrows considerably. Excluding Lapola and colleagues, published estimates for iLUC from soy range from 42 $kgCO_2e$ per GJ-fuel (*42*) to 67 $kgCO_2e$ per GJ-fuel (*43*). If these factors are applied to Jatropha, adjusting for the difference in oil yield between typical soy crops (0.56 t/ha-yr) and Jatropha in our base case scenario (4 tons of seed ≈ 1.4 t/ha-yr), we get a range of 17-27 $kgCO_2e$ per GJ-fuel. Adding this to the base case LCA results with no dLUC, under energy-allocation, which was 40 $kgCO_2e$ per GJ-fuel (see Table S15), shows that net emissions range from 57-67 $kgCO_2e$ per GJ-fuel, which is still a reduction of 24 to 35% relative to the CJF baseline. However, this is likely an overly pessimistic scenario. If Jatropha actually displaced crops, resulting in iLUC similar to iLUC estimates from soy, then it is likely that there would also be net sequestration of carbon from dLUC because, as was discussed in the main text, when annual crops are replaced by a perennial shrub like Jatropha, additional carbon is sequestered *within* the system boundaries. We estimate that this is ~25 $kgCO_2e$ per GJ-fuel under the base case scenario, which would effectively cancel out the iLUC impact. Of course, neither iLUC nor dLUC are permanent, which makes this type of estimation highly uncertain.

Table S19: Assumptions and data sources made for the life-cycle inventories in all stages of the SPK life-cycle

Material or Process	**Comments**
Land preparation	
dLUC	dLUC is assessed based on actually observed transitions based on surveys and site visits. Carbon stocks in prior land use categories (AG, BG, DOM and soil) are based on IPCC default values (*12*). Carbon stocks in Jatropha are estimated by the authors based on extrapolations from destructive sampling of young trees carried out as part of this research. See details in Table S5
Tilling/harrowing	Assumed land was harrowed and/or tilled 4 times prior to planting. Inventory data are based on European conditions (*11*)
Excavation (e.g. for irrigation channels)	None accounted for
Lime	Used Ecoinvent database entry for "crushed, washed limestone" (Swiss production conditions) (*11*). 2 tons per ha are applied prior to planting (based on data from surveys of Jatropha growers)
Lime transport [a]	Lime is assumed to originate in Minas Girais, roughly 600 km from most producers. Transport is via heavy duty truck. LCI data for Brazilian transport were not available so data based on EU conditions were used (16t lorry, EU fleet average in *11*).
Lime application	No LCI data specific to lime application was available so broadcast fertilizer was used in its place (*11*). Units are defined in terms of area treated based on 20 or 30-year yield of seeds.
Emissions from lime application	IPCC's Tier 1 emission factor for CO2 released by the application of agricultural lime is 0.12 tons of carbon per ton of agricultural lime (*12*).
Tree planting and management	
Planting of seeds	Manual planting (no emissions). At least one grower does use mechanized planting.
Irrigation	Several of the growers in Brazil irrigate in the early stages of plantation establishment and on an as-needed basis during the dry season. The base case in this analysis included drip irrigation, and accounts for installation of polyethylene tubing and electric power required to pump water However, some growers do not use irrigation, thus the analysis was repeated without those inputs, holding other parameters fixed. Without irrigation, net emissions decrease 4% relative to production with irrigation, to 38 kg CO2e/GJ, which is a 57% decrease in emissions relative to CJF.
Water	Survey data indicate ~19 liters per plant per day from Oct-June. With 4m x 2m spacing (1250 plants per ha), annual water application is roughly 6400 m^3 per ha.
Polyethylene tubing	4x2 spacing requires ~2600 m of half inch polyethylene tubing per ha. Tubing weighs roughly 60g per linear meter. Thus, 1 ha requires 156 kg of polyethylene. Assuming the tubing has a 10-year lifetime, double this quantity will be needed for 20-year plantation and triple this quantity for a 30 year lifetime. Brazil-specific data for polyethylene production is not available, so generic EU data were used based on (*11*).
Electricity	Electricity requirements for pumping are based on survey responses, which indicated a 30 hp (22.4 kW) pump runs 63 hours/week for ~9 months per year. This totals 273 kWh of annual consumption per ha. The power sector is modeled based on Brazilian conditions in the Ecoinvent database (*11*).

Fertilizer	This analysis assumes fertilizer is applied at rates that replace the loss of nutrients due to harvesting seeds over a 20-year period. Exact applications depend on yields. For example, in the low yield scenario: 0.84 t-N/ha (1.91 t urea); 0.34 t/ha P2O5 -- 60% as SSP (0.66 tons) and 40% as TSP (0.40 tons); and 0.94 t/ha K2O (1.49 tons KCl) over a 20 year period. In the medium and high yield scenarios, these quantities are doubled and tripled respectively to reflect the larger offtake. Over a 30-year period, these quantities are increased by a factor of 1.5.
Application	Assumed mechanized application is done annually to apply nutrients as described above based on generic EU conditions (*11*).
N-fertilizer (urea)	Assume 56% is imported and 44% is produced domestically. This mirrors patterns in the most recent data from the FAO (*18*).
Domestic urea production	We built a SIMAPRO module using Brazil-specific data from da Silva and colleagues (*22*).
Imported urea production	Lacking data about production conditions in exporting countries (see immediately below) generic EU conditions were used (based on *11*).
Ocean transport[b]	Imports to Brazil originate in Ukraine (56% - 12,000km by ship) and China (44% - 22,000km by ship) (*19*). Generic ocean freight data were used (*11*).
Road transport [a]	Imports arrive at the port of Santos, which is on average 1300 km by road from the producers. Domestic production of urea takes place at several sites, which are, on average, ~1200 km from producers. LCI data specific to Brazilian transport were not available so generic EU data were used (*11*).
P-fertilizer (SSP and TSP)	60% of P-fert is used in the form of Single-superphosphate (SSP) and 40% is used in the form of Triple-superphosphate (TSP) (*18*). 100% of SSP is produced domestically. TSP production is split: 60% is imported and 40% is made domestically. To replace lost nutrients in the low-yield scenario, growers must apply 0.30 t P205 over 20 years. The assumed 60:40 breakdown between SSP and TSP requires the application of 0.99 t SSP and 0.27 t TSP respectively. Medium and high yield scenarios double and triple these values respectively.
SSP - Domestic production	All SSP is produced domestically. A SimaPro module was created using Brazil-specific LCI data (*20, 21*)
TSP - Domestic production	40% of TSP is produced domestically. A SimaPro module was created using Brazil-specific LCI data (*20, 21*)
TSP - Imported production	Imported TSP was simulated with LCI data based on EU conditions (*11*).
Surface transport of imported TSP [b]	Imports come from Morocco (30% - 7700km), China (30% - 22000km) and Russia (40% - 22000km) (*19*). Generic ocean freight data based on EU conditions were used (*11*)
Road transport of both SSP, imported and domestic TSP [a]	This is the combination of SSP and TSP road transport including both domestic production and imports. Domestic production occurs in the center/south and southeast. We assume both SSP and TSP travel an average distance of 1,200 km from growers. We assume imported TSP arrives at the port of Santos and also travels ~1,300 km to the growing zones. EU road transport LCI data were used (*11*).

K-fertilizer	This analysis assumes all K2O is applied in the form of KCl (muriate of potash) , which constitutes 98% of K-fertilizer imports and 99% of consumption (*18*) . To replace lost potassium in the low-yield scenario, growers must apply 0.83 t K2O equivalent over 20 years (1.32 t KCl). In the medium or high yield scenarios, this quantity doubles or triples accordingly. KCl is imported from Canada (33%), Russia (39%), Israel (12%), and Germany (15%) (*19*).
Imported production	LCI data for KCl extraction specific to each of these producers is not available so generic EU data was used from the Potassium chloride production (as K_2O) was used (*11*).
Surface transport[b]	Imports originate from Canada (33%; 16,000 km), Russia (39%; 12,500 km), Israel (12%; 12,000 km), and Germany (15%; 10,000 km) (*19*). Shipping LCI was based on generic EU conditions (*11*)
Road transport [a]	Surface transport accounted for both rail transport from production sites to ports in producing countries (variable) and road transport from the port at Santos to production zones in Brazil (1,300 km). LCI data specific to transport conditions in exporting countries were not available so generic EU data were used (*11*)
Herbicides	In Brazil, two of the six growers visited use glyphosate ("Roundup") to control weeds. Though the chemical is made in Brazil, LCI data for local production is not available, so general LCI data based on EU production is used (*46*). Based on survey responses, we assume 2.5 liters per hectare, applied 4 times per year, until trees reach three years of age for a total of ~30 liters. The typical product contains 360 g active ingredient per liter [REF] so this rate of application is equivalent to 10.8 kg of glyphosate. This quantity was divided by the total yield over 20 or 30 years to determine the input into the LCA model.
Pesticides	In Brazil, one of the six growers cited the application of dimethoate (an organo-phosphate). Application rates for dimethoate are 0.6 liters per hectare per year for the first two years of the plantation. LCI data was not available for the specific product, so generic LCI data for Organophosphorus-compounds, at regional storehouse under EU conditions were used (*11*).
Other chemical inputs	The same grower also noted use of abamectin, a nematicide. Application rates were very low: only 0.16 l/ha for the first two years. Thus no LCI data were included in the model. Abamectin is derived from soil bacteria and degrades rapidly so its environmental impact is thought to be reatively low if applied at recommended doses (*47*).
Other operations	
Mowing	Some growers mow spaces between rows of Jatropha trees once annually. We model this with LCI data from the Ecoinvent database "Mowing, by rotary mower" which assumes fuel consumption of roughly 5 lites of diesel per ha (*11*).
Harvest	Harvesting is currently done manually. No GHG impact is included for manual labor.
Oil extraction	The current process presses seeds with heat applied. We assume seeds contain 34% oil. Roughly 86% of the oil is extracted, giving a 30% yield by mass. Oil is then refined with NaOH to remove gums and lower the free-fatty acid (FFA) content. Refining leads to a 12% loss of oil volume (assuming initial pressing has 6% FFA content). In total, 3.79 kg of seeds yield 1 kg refined oil (*29*).
Transport to expelling unit [a]	Currently, only one expelling unit is processing Jatropha on a commercial scale. This is located an average of 1400 km from producers (see Table S1). An alternate scenario examines the impact of optimizing logistics by locating oil pressing facilities ~200 km of producers. As with other transportation data, LCI data specific to Brazilian transport were not available so generic EU data were used (*11*).

Electricity input	Based on the interview with Luciano Leme, we account for all electric motors but no other loads (e.g. lighting, electronics, etc). The total capacity of electric motors in the plant is 560 hp (~420 kW). We assume that the motors run at 80% capacity (336 kW) when the press outputs 1 ton of unrefined oil per hour. After semi-refining, 880 kg of oil remain. Thus, the plant's power consumption is ~0.380 kWh per kg semi-refined oil. Electricity is specific to Brazil (84% hydro, 6% gas, 3% diesel, 3% bagasse-fired cogen, and 2% coal with small but growing amounts of wind energy. Emissions factors for each source are taken from (*11*).
Heat input	Heat is derived from heavy fuel oil (HFO). Surveys of the oil extraction facility report 15 liters of consumption per hour, which supplies heat to both extraction and refinfing processes. Emission factors for Brazilian HFO were not available so data for HFO burned in an industrial boiler under EU conditions were used (*11*).
Chemical input	NaOH is used to lower the free fatty acid content in the oil. The plant requires roughly 12 kg per ton of oil processed. LCI data specific to Brazil is not available so EU data was used (*11*).
Co-products of oil extraction	
Energy allocation	Based on calorific value and mass distribution of CJO, seedcake and husk, impacts are allocated such that 43% is attributable to Jatropha oil, 31% to seedcake and 25% to husk (see main text for specific data).
Mass allocation	Based solely on mass distribution of CJO, seedcake and husk, impacts are allocated such that 30% is attributable to Jatropha oil, 33% to seedcake and 37% to husk (see main text for specific data).
System expansion - use as fertilizer	In this scenario, husks and seedcake are used to displace a nutritionally equivalent quantity of commercial fertilizer. We estimate one ton of seed yields 370 kg of husk and 370 kg of seedcake (including 12% oil), which together contain the equivalent of 21.8 kg N, 24.6 kg P_2O_5, and 8.51 kg K_2O. For N and P fertilizer, we assume domestic production of urea and SSP is displaced, with a reduction in emissions according to the LCI data from (*20-22*). As there is little domestic production of K fertilizer, we assume only imports are displaced, with impacts defined as above.
System expansion - use as fuel	In this scenario, husks and seedcake are compressed into briquettes for use in an industrial boiler and are used to displace an energetically equivalent quantity of HFO. We assume 2% of the briquettes produced are consumed to provide heat to the briquetting process and 60 kWh of electricity per ton of briquettes are required to drive the extruder (FAO, 1996). The HFO displaced is the same fuel used in the oil expelling process (see above).
SPK production	**Data were obtained from UOP, the producers of SPK used in recent test flights (*8, 10*). According to the company, 1 kg of Jatropha oil produces 0.48 kg of Jatropha-based SPK. Using a calorific value of 44.3 MJ/kg for SPK (*35*), then 46.7 kg Jatropha oil are required to produce 1 GJ (22.6 kg) of SPK. Production takes place in the US. Therefore, LCI data based on US materials and processes were used when available. Inputs and outputs are described below.**
Transport to of oil to SPK refinery [a,b]	Fuel is transported from the oil expeller by lorry to a port for overseas shipment. In the baseline scenario, road transport is 600 km. In the optimized scenario, we assume the oil expelling unit is located within 50 km of the port. As above, we use generic LCI data for ground transport in the EU (*11*). Shipment from the Brazilian port to the refiner on the West Coast of the US covers 15,000 km. Under the optimized scenario, we assume a closer Brazilan port is used, which reduces ocean transit to ~12,000 km. In each case, generic ocean freight LCI data were used (*11*).
Inputs	1 GJ of Jatropha SPK uses the following inputs, provided by UOP (*10*).

Electricity	Previous work estimated the electricity input for Jatropha-based SPK production ranged from 1.6 to 2.6 kWh/GJ (*9*). While the value provided by UOP lay within this range, it cannot be disclosed exactly due to the proprietary nature of UOP's process. Life cycle impacts are assumed based on emissions from the US power grid (*11*).
Natural Gas	Previous work estimated the natural gas input for Jatropha-based SPK production ranged from 9 to 10 MJ/GJ (*9*). The value provided by UOP for this analysis was considerably higher than this. However, it cannot be disclosed exactly due to the proprietary nature of UOP's process. We use LCI data for the US natural gas infrastructure and assume combustion in an industrial boiler (*48*).
Hydrogen	Previous work estimated the natural gas input for Jatropha-based SPK production ranged from 0.8 to 1.8 kg/GJ (*9*). The value provided by UOP for this analysis was slightly higher than this range. However, it cannot be disclosed exactly due to the proprietary nature of UOP's process. We assume H_2 is produced in a steam methane reformer (SMR). Industry average conditions from the EU were used (*49*), which have net impacts very similar to US hydrogen production via SMR that is commonly used by the petroleum industry in the US (*37*).
Steam	Producing one GJ of Jatropha SPK produces a small quantity of excess low-pressure steam, which is used in other refinery processes (*10*). The specific amount is also confidential. Generic LCI data for steam production in the EU was used to estimate the benefit of this credit (*11*).
Co-products	Data from UOP indicate that in mass terms, one kg of Jatropha-based SPK is co-produced with ~0.8 kg of additional bio-based hydrocarbon fuels. In energy terms, 1 GJ of SPK (22.6 kg fuel) is co-produced with ~0.8 GJ (~18 kg) of bio-based hydrocarbon co-products (*10*). However, as with other data related to SPK production, UOP wishes to maintain confidentiality concerning the specific quantities of each co-product.
Energy allocation	Based on calorific values and mass distribution the co-products impacts were allocated among co-products in this manner: SPK 54%, 46% bio-based hydrocarbon co-products.
Mass allocation	Based solely on mass distribution impacts are allocated among co-products in this manner: SPK 48%, 52% bio-based hydrocarbon co-products.
System expansion - use as fuel	The only scenario explored for co-products of SPK production assumes co-products displace the equivalent fossil fuels in common applications described below.
Naphtha	Naphtha is assumed to displace fossil-based naphtha in the US. No LCI data was available for naphtha production in the US so EU data was used (*11*). To estimate the reductions in emissions in the use-phase, emissions from gasoline (petrol) are used. These are taken from the GREET database (*36*).
Diesel	Bio-based diesel displaces fossil-based diesel in a standard compression ignition engine. LCI data for diesel production in the US was used (*50*). The emission reductions resulting from the substitution in the use-phase , are taken from GREET (*36*).
LPG	Bio-based LPG, displaces fossil-based LPG. LCI data for LPG production is taken from (*48*). The emission reductions resulting from the substitution in the use-phase , are taken from GREET (*36*).
Natural Gas	Bio-based fuel gas (similar to natural gas) displaces fossil-based natural gas. US-based LCI data are used (*50*). To estimate the reductions in emissions by this displacement, we substitute emissions from natural gas from GREET (*36*).

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[a] All road distances were estimated using Google Earth

[b] All shipping distances were estimated with an online shipping distance calculator (http://www.portworld.com/map/).

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