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Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: a field study

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Abstract

In recent years, liquid biofuels for transport have benefited from significant political support due to their potential role in curbing climate change and reducing our dependence on fossil fuels. They may also participate to rural development by providing new markets for agricultural production. However, the growth of energy crops has raised concerns due to their high consumption of conventional fuels, fertilisers and pesticides, their impacts on ecosystems and their competition for arable land with food crops. Low-input species such as *Jatropha curcas*, a perennial, inedible crop well adapted to semi-arid regions, has received much interest as a new alternative for biofuel production, minimizing adverse effects on the environment and food supply. Here, we used life-cycle assessment to quantify the benefits of *Jatropha curcas* biofuel production in West Africa in terms of greenhouse gas emissions and fossil energy use, compared to fossil diesel fuel and other biofuels. Biodiesel from *Jatropha curcas* has a much higher performance than current biofuels, relative to oil-derived diesel fuels. Under West Africa conditions, *Jatropha curcas* biodiesel allows a 72% saving in greenhouse gas emissions compared to conventional diesel fuel, and its energy yield (the ratio of biodiesel energy output to fossil energy input) is 4.7. *Jatropha curcas* production studied is eco-compatible for the impacts under consideration and fits into the context of sustainable development.

1   Introduction

Sustainable energy production and supply are strategic objectives for developed as well as developing countries. The energy sector plays a crucial role in attaining the United Nations Millennium Development Goals (Short 2002), and the sustainability of modern economics is based in part on the capacity of countries to ensure their energy supplies (IEA 2008). This is especially true for the transport sector, which consumes 30% of the world energy production, 99% of which is petrol-based (EIA 2007). Transport contributes 21% of global greenhouse gas (GHG) emissions (Watson *et al*. 1996). As a consequence of this heavy reliance on fossil fuels, world oil reserves are undergoing depletion at an unprecedented rate, resulting in a similar increase in atmospheric GHG concentrations. The recent oil crises and growing public awareness of the global energy issue have prompted the consideration of alternative, renewable sources of energy. This explains the vogue for liquid biofuels and the ambitious incorporation targets set by a number of countries (Fulton *et al*. 2004; Kojima & Johnson 2005). Current biofuels are actually based on traditional food crops such as maize, rapeseed or sunflower. A wide range of energy and GHG budgets has been reported for them, although they are generally favourable compared with conventional fossil fuels like gasoline and diesel (Hill *et al*. 2006). However, these types of feedstock raise concerns because their cultivation are fuel-, fertilizer- and pesticide-intensive, with significant impacts on ecosystems. More recently, their role as competitors to food use and thus in the increase in food prices has been pinpointed (Sourie *et al*. 2005; von Braun 2007). The use of *Jatropha curcas* (Jatropha), an inedible crop able to adapt to marginal soils and semi-arid climates, appears a promising alternative for the production of biodiesel in tropical and subtropical regions. Native to Central America, Jatropha is a small tree in the *Euphorbiaceae* family now found in all the tropical and sub-tropical zones (30°N ; 35°S) (Jongschaap *et al*. 2007). It produces inedible seeds containing between 28 and 38% oil (Kaushik *et al*. 2007), which may be transformed into Jatropha methyl ester (JME), a good quality biodiesel (Vaitilingom *et al*. 1997). Although Jatropha grows naturally in Africa, its cultivation on an industrial scale is a recent venture for which little reliable scientific data exists either for management or environmental assessment. At present, the main agro-environmental impact studies on this in Africa are largely qualitative, and concern the East African countries such as Kenya (Achten *et al*. 2007) and Tanzania (Eijck & Romijn 2007). More quantitative studies based on the life cycle assessment (LCA) methodology have recently been published to evaluate the GHG and energy balance of Jatropha oil or

biodiesel compared to conventional fossil diesel, in India (Reinhardt *et al.* 2007) and Thailand (Prueksakorn & Gheewala 2008), but their results may not be extrapolated to West Africa due to important differences in pedo-climatic and growing conditions.

Here, we set out to evaluate the environmental impacts of biodiesel from Jatropha in West Africa, compared to conventional fuel or other biofuel types, in terms of GHG emissions and use of non-renewable resources. We applied the LCA methodology to an actual field situation, using detailed data from a Jatropha experimental agronomic research station in Mali, observations of Jatropha smallholder farming on Ivory Coast, and literature data.

2   Materials and methods

2.1   *Historical background of Jatropha*

Jatropha, a native of Central America (USDA 2000), was introduced in the Cape Verde islands by Portuguese sailors in the 16th century, then into Guinea Bissau from where it spread across Africa and Asia (Heller 1996). Its natural habitat is arid and semi-arid zones (Makkar *et al.* 1997), but it is also found in damp tropical regions such as Guatemala (where annual rainfall may exceed 4000 mm), North Vietnam and Thailand.

Jatropha grows as a bush of up to six metres high, with a life span of up to fifty years (Henning *et al.* 2007). It belongs to the *Euphorbiaceae* family, which reproduces sexually or vegetatively (cuttings, micropropagation) and produces dark brown fruits. The fruit contains seeds that make up 53% to 62% of its dry weight (Cuhna Da Silveira 1934). When pressed, the seeds produce an oil that is traditionally used for soap making, and cake that is returned to the fields as organic fertilizers. Neither the Jatropha oil nor the cake are edible due to the toxic and anti-nutritional substances they contain such as phorbol esters (Gübitz *et al.* 1999) and curcine, which is a strong purgative (Chachage 2003). The phorbols themselves do not induce tumors but promote tumor growth following exposure to a subcarcinogenic dose of a carcinogen. They can thus be designated as cocarcinogens (Goel *et al.* 2007).

The first tests of using Jatropha oil as a fuel date from the beginning of world war II. Interest was rekindled by the two oil crises, prompting CIRAD to launch a programme for using vegetable oils in engines, in particular Jatropha oil (Vaitilingom 1997).

Jatropha is also often used in the tropics as an animal repelling hedge plant and also against erosion (Heller 1996). In Madagasar, a program financed by KfW (Banking German group) and the Ministry of Agriculture and Fish is currently testing the potential of Jatropha plantations in 5 sites to prevent soil erosion and fires.

In recent years, Jatropha has also been promoted to reduce the dependence on fossil fuels in Africa. In Western Africa, the Senegal government launched an ambitious program on Jatropha production (with a 321 000 ha target). In 2004, Mali set up a national program for the conversion of Jatropha to energy, and an electrification project based on Jatropha oil is currently under examination. In Burkina Faso, several Jatropha plantations for biofuel production were set up supported by the national union for the promotion of Jatropha. In Kenya, the Kenya Biodiesel Association was created in 2008 to promote the production of JME in the country and a regulation was proposed to allow a 3% blending of biodiesel in conventional diesel fuel (Kalua 2008).

Nevertheless, the industrial production of Jatropha is fairly recent: to date, almost 900 000 ha have been established:765 000 ha in Asia, 120 000 ha in Africa and 20 000 ha in Latin America (Renner 2008). The projected development of Jatropha production is 5 million ha for 2010 and 13 million ha for 2015 (Renner 2008).

2.2   Biodiesel production from Jatropha in Ivory Coast

We focused our analysis on a Jatropha biodiesel chain in Ivory Coast, a West African country with high potential for Jatropha production. We combined data from actual smallholder plantations in Ivory Coast and from both smallholder and experimental plantations in neighbouring Mali, in the absence of such detailed data for Ivory Coast. The Mali Jatropha plantations were established in 2006, 2007 and 2008 by a local farmers' association and the agronomic experiments by the Centre de coopération Internationale en Recherche Agronomique pour le Développement (CIRAD) –*(Centre for International Cooperation on Developmental Agronomic Research)* and the AgroGeneration company. The Ivory Coast Jatropha smallholder plantations date from 2007 and 2008.

Ivory Coast extends from the Atlantic Ocean in the south to Ghana in the east, Burkina Faso and Mali in the north, and Guinea and Liberia in the west. In terms of climate and vegetation, there are two distinct zones. South of the 8th parallel, a sub-equatorial zone with high temperatures and humidity, above 2 000 mm of annual rainfall, and four seasons, all favouring high forest growth rates. In the

north of the country, there is a two-season tropical climate, savannahs with less and less trees, and average annual rainfall of about 1 000 mm. The rainy season lasts from around June to October. In Mali, the experimental station is located in "Teriya Bugu", where the annual rainfall averaged 748 mm between 2000 and 2007.

The production of Jatropha in Ivory Coast only started recently and there is no real organised structure at present. However, there are large plantation developments especially in the Ferkessédougou-Korogho zone where 1500 ha were planted in 2007, and at least 2000 more in 2008. These plantations, replacing former cotton fields, were established by smallholders grouping together in cooperatives. The abandonment of cotton growing positions Jatropha as a substitute for this crop, and explains its potential interest to local farmers. The structure of the first Jatropha plantations is in some ways similar to West African smallholder cotton cultivation.

This current, rudimentary development forms the basis for this study to evaluate the agro-environmental impact of the production of Jatropha-based biofuels. It may be considered as a model from which the probable development of Jatropha may be scaled-up, as follows. The agricultural production takes place 560 km north of Abidjan in the Ferkessédougou-Korogho zone, and it follows the semi-intensive cotton-growing model in which local farmers are grouped in supervised cooperatives. The latter provide agricultural inputs in the form of credit on the season's harvest, each smallholder, farming between one and ten ha of Jatropha. Following harvest and dehusking, the seeds are sun-dried prior to truck transport to Ferkessédougou where they are cold pressed. This pressing close to the production area is justified because adequate facilities already exist there and are under-utilized due to the cotton crisis. Secondly, there is a significant great potential for local use of the Jatropha oil, in particular as fuel for stationary engines. The crude vegetable oil (CVO) is taken by railway to the seaport of Abidjan and shipped to France where it is transesterified into Jatropha methyl ester (JME). Transesterification is a chemical reaction between a mole of a triglyceride and three moles of methyl alcohol to form a mole of glycerol and three moles of fatty acids methylic ester (biodiesel).

This model is based on transesterification in France because at the time of writing, the industrial capacities in the Ivory Coast and West Africa are very limited. In addition, the tax laws and regulations covering use of biofuels are still not clearly defined in West Africa whereas in Europe the market is the

incentive, clear and structured. Later, when the legal framework has been set up, the biodiesel can be produced and used by the local market.

2.3   Management of Jatropha

The management data were obtained from the "Teriya Bugu" experimental station in Mali. Two 5-ha experimental fields were selected with contrasting soil conditions. The first site (13°13.42 N 5°29.5 W) has been cultivated for 30 years, while the second site (13° 12.974 N 5° 30.045 W) is on marginal land that had not been cultivated for the past 50 years. Each site comprised two blocks with 24 trial plots (24 m x 24 m in size), and all agronomic treatments were duplicated. Since the management of Jatropha has not been optimized yet, four influential parameters were varied and tested: variety, fertilizer rate, plantation density, and plant size.

Jatropha seedlings were assumed to be grown in trough nurseries, which are more adapted to local conditions and more accessible to farmers than those based on pots. The nursery troughs were 10 m by 1 m in size and 0.2m in depth, and contained 1000 plants. Since the plantation density i the field is 1111 plants ha^{-1}, 1222 nursery plants are needed per ha because there is a 10% loss after transplantation. The substrate a mixture of 70% topsoil, 30% sand, and a ternary fertiliser (N-P-K: 16-26-12). The average water requirements are 0.2 l plant^{-1} d^{-1} for the 45 days in the nursery. The seeds are coated and soaked in fungicide before sowing, and may be sprayed with insecticide in case of attack during the nursery period.

Before digging the holes, the ground is cleared and staked out. A plantation density of 1111 plants ha^{-1} was found optimal for the pedo-climatic conditions of the Ferkessédougou-Korogho zone, which influences the growth and architecture of the plants. The holes are dug during the dry season which means that transplantation can take place right at the beginning of the rainy season (Table 1). Ternary fertiliser is applied into the holes during the planting out to avoid rapid leaching of the nutrients with the rain, and the plants are pruned for the first time 7 to 8 months after planting. Ternary fertiliser is applied during the first three years (Table 2), with the following rates: 100 kg ha^{-1} in the first year, 150 kg ha^{-1} in the second year, and 200 kg ha^{-1} in the third. In the fourth year, 248 kg ha^{-1} of ternary fertiliser and 201 kg ha^{-1} of ammonitrate are applied. These inputs compensate the estimated removal of NPK nutrients in fruits (Achten *et al*, 2008). From the fifth year on, Jatropha oilcake (3.75% N; 0.9% P_2O_6; 1.1% K_2O, (Gosh *et al*. 2007) is applied as an organic fertiliser. This sequence allows to

maintain soil fertility while improving the level of soil organic matter. Thus, from the 4th year on, the quantities of mineral elements supplied via the pulp, shells and oilcake returns are equivalent to those taken up by the plants. The plants are sprayed with two chemical insecticides (carbofuran and lambda cyhalothrine) and one fungicide (copper oxychloride) each year between June and September. Weeding is done in wintertime, mechanically between the rows and manually between plants on the same row. There is no harvesting for the first three years because the plants are heavily pruned to achieve an optimal architecture for seed production.

In the literature, yield data are highly variable for Jatropha. They may be as low as 2 to 3 tons of dry seeds ha^{-1} in the semi-arid zones and marginal lands (Tewari 2007, Heller 1996), and reach 5 tons of dry seeds ha^{-1} in good soil with an annual rainfall from 900 to 1200 mm (Tewari 2007, Francis *et al.* 2005, Foidl *et al.* 1996). In Mali, Henning (1995) reported yields of 3 tons ha^{-1} with a 1020 mm annual rainfall. In Paraguay, yields average 4 tons ha^{-1} a 1370 mm annual rainfall (Achten *et al.* 2008). Jongschaap *et al.* (2007) estimate a potential yield between 1.5 and 7.8 tons ha^{-1}. In this study, we assumed yields equivalent to those reported in Nicaragua where the rainfall and planting density are similar to Ferkessédougou-Korogho (1200 mm, 1111 plants ha^{-1}). The yields recorded on experimental fields in Nicaragua range between 3.5 and 5.0 tons ha^{-1} after the establishment phase (Achten *et al.* 2008). Thus, we assumed a medium yield of 4 tons dry seeds ha^{-1} tons here.

Harvesting takes place from mid-July to mid-November, and we assumed each worker to pick an average of 83 kg of dry fruits (or 50 kg of dry seeds) per day. This rate varies strongly according to the density and yields of plantations. A value of 3 kg of grain fresh matter per hour was reported on Jatropha hedges Tanzania (Henning 1992). For a plantation, the same author estimates an output of 2 kg dry seeds per hour (Henning 2008, pers. comm.),while the Biomasa project in Nicaragua reports outputs of 18 kg fruit dry matter per hour for the 'best pickers' (Sucher 1999). Our estimate is thus in the mid-range of the above values.

2.4   Life cycle assessment

LCA is an environmental analysis methodology, as defined by a set of ISO norms (ISO 14040 to 14044, 2006). It studies the potential environmental impacts throughout the product life cycle, from the extraction of raw materials to the production, end use and disposal or recycling of the product. It may be used to calculate range of environmental impact categories, among which GHG emissions and

their contribution to global warming, altogether with the use of non-renewable resources (such as fossil hydrocarbons).

It comprises four steps:

- The definition of the objectives and scope of the study,
- The life-cycle inventory,
- The characterization of impacts,
- The interpretation.

2.5 Goal and scope, system boundaries

The main objective of this LCA is to compare the greenhouse gas emissions and non-renewable energy consumption of the Jatropha biodiesel with those of conventional diesel fuel. The LCA results will also allow the environmental impacts of this biodiesel production to be further improved.

The function of the system is thus to supply biodiesel to road vehicles. As a consequence, the functional unit of the LCA (quantifying the unit function fulfilled by biodiesel) is the 1 MJ of JME or conventional gasoline lower heating value.

System boundaries include all the processes necessary to deliver the system's function (Jolliet et al. 2005). For this LCA, we used the « well to tank » scheme, i.e. from agricultural production to biodiesel storage. Thus, the combustion of the end-product in the vehicle is not included in our analysis. However, an estimation of GHG emissions assuming a complete combustion of the fuels, based on their carbon content is included. Only pure biodiesel is considered here. Although the study does not take into account CO_2 fixation during plant growth (through photosynthesis), it is compensated for by assuming that the CO_2 released from the combustion of biodiesel does not contribute to the greenhouse effect.

In terms of system boundaries, land use change (LUC) is presently one of the major problems in the assessment of energy crops. It may be direct (replacing a forest by farmland for biofuels) or indirect (when an energy crop displaces a food crop which in turn displaces a grassland or a forest). The results of these land-use changes is a rapid and strong oxidation of soil organic carbon, causing the GHG emissions balance of the bioenergy chain to become negative several decades (Fargione *et al.* 2008). Conversely, the production of energy crops on marginal soils or soils with low organic matter content can favour carbon sequestration and significantly improve the biofuels' environmental balance (Reinhardt *et al.* 2007). This LUC approach is only recent and has still not been taken into account in

the main LCA's for biofuels (IFEU 2006). Although the impact of LUC has not been specifically evaluated in this LCA, because the Jatropha plantations studied have been made on old cotton fields (annual plants), it is probable that there has been a large quantity of carbon stocked in the soil and in the above-ground parts of the Jatropha (Ogunwole *et al*. 2008) as the plant grew. This carbon stocking in Jatropha croplands will be greater than that of a cotton crop, and taking it into account would further improve its environmental balance. The carbon content of above- and below-ground parts of cotton crops may be estimated as follows: the overall accumulation of C in above-ground parts totals 1400 kg C ha-1 yr-1, of which 630 kg C ha-1 yr-1 in stems (for grain cotton) and 140 kg C ha-1 yr-1 in roots (unpublished data from Cretenet M, CIRAD). Only the roots are returned to the soil, since cotton is managed as an annual crop to reduce the potential of disease and pest transmission from one growing season to the next (Martin *et al*. 1997). Cotton stalks are harvested or, most often, burnt. Hence, the soil C input rate from cotton crops is limited to 140 kg C ha-1 yr-1 from their roots.

In contrast, soils under Jatropha were reported to accumulate 3 140 kg C ha-1 over the first 3.5 years of plantation (Reinhardt 2007), corresponding to an average of sequestration rate of 900 kg C ha-1 yr-1. This additional sink was not considered in our baseline LCA, but its potential effect is dealt with in the discussion section.

Several scenarios have been envisaged for this LCA. The baseline (reference) scenario corresponds to the above-described chain, and the yield of Jatropha was set at 4 tonnes of dry seeds ha^{-1}.The method of energetic allocation was used for the following coproducts: glycerin and free fatty acids (FFA).

In Scenario A, the yields were varied between 3 tons and 5 tons dry seeds ha-1.

Scenario B involved a truck transport of the oil from Ferkessédougou to the seaport of Abidjan, while scenario C took the energy needs of the farm labour into account.

The latter allowed the adaptation of LCA to the context of Africa, where farming is more labour-intensive and involves far less machinery than in developed countries. The energy needs for labour was approximated by their daily total food intake and, even if the farmer has others activity. The energy intake was set at 2300 kcal, the mean average for adults in sub-Saharan Africa (World Bank 2003). Energy use for the transportation of farmers to the plantations was disregarded, since it involves mostly walking. In scenario D, pure Jatropha oil was directly used in stationary engines.

2.6   Life cycle inventory

This part consists of quantifying the various input/output flows of energy, matter or contaminants through the system, as sketched out on the process tree system (Figure 1).

2.6.1

This inventory was based on the agricultural data obtained from the Jatropha experiments in Mali, supplemented with field data from Jatropha plantations in the Ivory Coast, and literature sources (see Appendix 1).

The GHG emission and extraction factors (for non-renewable resources) were taken from the Ecoinvent database (Frischknecht *et al*. 2007), by selecting the unit process closest to our conditions in terms of geographical validity. Emission factors are coefficients converting unit inputs (eg, 1 kg of fertilizer N) into life-cycle GHG emissions incurred by the use of this input, while extraction factors express the fossil energy use of the same unit input.

2.7   Evaluation of environmental impacts

Here, we focused on the GHG emissions (CO_2, CH_4, N_2O) and the use of non-renewable resources, corresponding to the climate change and energy consumption impact categories. Other types of environmental impacts exist for LCA's (such as eutrophication and acidification), but they are beyond the scope of this study.

The emissions of CO_2, CH_4 and N_2O were converted to CO_2 equivalents using the 100-year global warming potentials (GWP) from the latest IPCC assessment report (Foster *et al*. 2007): the GWP of CH_4 and N_2O were 25 and 298, respectively. Energy consumption is given in MJ of non-renewable energy.

In addition to their average values, the Ecoinvent database provides minimum and maximum values for emission factors, making it possible to assess the resulting uncertainty on life-cycle GHG emissions. This is not the case for the extraction factors, for which only average values are available. For inputs, alternative scenarios were set up to estimate the sensitivity of the results relative to their settings.

3   Results

3.1   Energy and GHG balance

Biofuel production requires direct (electricity, fuels, natural gas) and indirect (manufacturing of agricultural inputs, methanol…) energy consumption.   Figure 2 shows the amounts of energy consumed at the level of each elementary process for the production of 1 MJ of JME. The energy expense is 0.21 MJ, which translates as an energy yield of 4.7. Thus, for each MJ of fossil fuel consumed to produce JME, 4.7 MJ of JME energy content are produced.

The actual Jatropha cultivation phase only represents 12% of total energy consumption (Figure 2) and uses less energy than the transport steps (of seeds, oilcake and unrefined Jatropha oil), with a   15% share. The transesterification process is the main energy consumer, requiring 61% of the life-cycle energy needs.

The breakdown of GHG emissions across the various elementary processes was as follows: Jatropha cultivation accounted for 52% of the overall emissions, while the shares of the transesterification and final combustion steps were 17% and 16%, respectively (Figure 3).

Large shares (93%) of the emissions occuring during the agricultural step are due to fertilisers. In spite of the sparing use of pesticides, the latter are responsible for 2.4% of the total GHG emissions and almost 6.8% of the energy consumption. This relatively high share of energy consumption by pesticides, is in part down to the high amount of energy necessary to manufacture them. The transesterification is the most energy demanding stage with more than 61% of the total consumption, and this is because of the large volume of methanol (Figure 5) used in the process (1130 kg of CVO and 112 kg of methanol are required to produce one tonne of JME). Besides methanol, transesterification requires phosphoric acid (0.8 kg), sulphuric acid (0.5 kg), caustic soda (18 kg), water (154 kg), natural gas (968 MJ) and electricity (22 kWh) to produce 1 ton of JME. Co-products are issued during transestérification process: glycerin (70 kg per ton of JME) and FFA, 77.2 kg per ton of JME). These two co-products can be promoted by combustion in hot water tank.

The stages which emit the highest amounts of GHG's are not the most energy demanding and the converse is also true, thus it is necessary to optimise both the fertiliser use and the transesterification in order to reduce the energy consumption and the GHG emissions of the production.

Transport accounts for 15% of the total energy consumption linked to JME production, of which 53% comes from the transport of the Jatropha oil by boat from the port of Abidjan to France (6528 km), and

22% comes from the initial journey by rail from Ferkessédougou to Abidjan (564 km). This intercontinental oil transport is slightly unfavourable on the overall energy balance sheet and GHG of the biodiesel. Indeed, local transformation of the oil into JME would achieve an energy yield of 5.2 compared to 4.7 for the reference scenario, i.e. an improvement of more than 10%, reducing at the same time the GHG emissions by 2% over the corresponding reference value.

Overall, the production and combustion of a MJ of JME emits 23.5 gCO_2eq, whereas the corresponding emissions of 1 MJ of conventional diesel fuel emit 83.8 gCO_2eq (EC 2008). Thus, the production of this Jatropha biodiesel under our conditions allows a 72% reduction in GHG emissions compared to conventional diesel fuel.

3.2 Alternative scenarios

Various scenarios with alternative sets of parameters were implemented to test the robustness of our LCA results to our baseline hypotheses. In scenario A, the Jatropha yields were varied between 3 and 5 tons dry seed ha^{-1}. The lower yield bound increased GHG emissions by 17% and energy consumption by 4%, whereas the higher yield reduced the GHG emissions and the energy consumption by 10% and 2%, respectively (Table 3, Figure 4). These results may be explained by the fact that the energy consumptions and GHG emissions for growing Jatropha do not vary with seed yield (Jatropha management is fixed irrespective of final yield). As the final quantity of JME produced per ha of Jatropha plantation is directly correlated to the seed yield, the energy balance and GHG emissions of JME improve as the yield increases.

In the reference scenario, Jatropha oil is transported by freight train over 564 km from Ferkessédougou to Abidjan. Using trucks instead increased the GHG emissions and energy needs by 8% and 14%, respectively. This increase is mainly due to the lower load capacity of trucks compared to freight trains, resulting in higher GHG emissions and energy consumption per tonne.kilometre transportered.

Unlike European energy crops, the Jatropha production model studied is not motorised, and uses a large labour force. Very few LCA's take into account this labour force (Hill *et al.* 2006). Here, we assessed its impact by including the daily energy ration of workers in our system. The labour force increased the energy consumption needed to produce one MJ of JME by 29%, which is significant.

Lastly, pure vegetable oil from Jatropha may be directly sold on local markets and used as fuel for motor-driven pumps and mills, and rural electrification. Such a direct usage reduced the GHG emissions by 45% and the energy consumption by 82% relative to the reference scenario. The fact that energy and GHG reductions do not follow the same pattern is due to the fact that these indicators are driven by two distinct subsystems (Figure 1): the upstream cultivation step predominates the GHG emissions on the one hand, and the downstream industrial transformation (especially the transesterification process) determines energy consumption. Direct use of the oil does not change the GHG emissions from Jatropha cultivation, but reduces to a large extent energy consumption because the transesterification step is unnecessary.

Across the various scenarios, the energy yield varied from 3.7 to 26.4, and the percentage reduction in GHG emissions compared to conventional diesels from 67% to 84%.

4.   Discussion

4.1 Sensitiviy of LCA to system parameters

The yield hypotheses had a significant impact on the GHG and energy balances of Jatropha biodiesel. An increase of 1 ton seeds ha-1 resulted in a 10% reduction in fossil energy use compared to the baseline value of 4 tons ha-1. It thus appears critical to pursue field experiments and extension to obtain realistic, large-scale estimates of Jatropha yields.

Transporting Jatropha by truck instead of freight train had a similar impact as Jatropha yield, and It highlights the benefits of using existing, high-efficiency infrastructures.

Unlike energy crops in northern countries, Jatropha production in Ferkessédougou is not motorized, and requires substantial manpower. This has a large potential for creating value and employment for the local populations. Taking this labour force into account in an LCA study is rather unusual, however, because of its importance in the production of Jatropha, we estimated its effect using a worker's average daily ration. Including the labour force had a very significant impact, since it reduced the energy yield by 27% (Table 3).

The end-use of Jatropha oil had the most impacts on its overall energy and GHG intensities. Local use as fuel for fueling pumps, millls or small-scale power production increased the energy yield from 4.7 to

26.4 compared to the baseling JME end-use, and increased GHG savings (compared to conventional diesel) from 72 to 85%. Given that 92% of the population in sub-Saharan Africa do not have yet access to electricity (Davidson *et al*. 2006), and that human energy remains the only energy source available in certain rural areas, locally use of Jatropha oil may help providing an access to basic energy services. However, technically, the direct use of CVO as a fuel requires a modification or adaptation of the engines.

Regarding land-use change impacts, we assumed that Jatropha was grown on former cotton fields and that it was neutral in terms of soil organic carbon content (SOC). As shown in section 2.4, Jatropha may sequester about 750 kg C ha^{-1} yr^{-1} compared to cotton crops, which is significant in terms of SOC dynamics. Taking into account this additional soil C sink made possible by growing Jatropha would dramatically reduce the life-cycle GHG emissions and actually turn this pathway into a net sink of GHG (of 2270 kg CO_2 eq ha^{-1} or 44 g CO_2 eq MJ^{-1} JME). These results illustrate the robust opportunities and the high potential of Jatropha to attract carbon credits from the Clean Development Mechanism market (Achten et al. 2008) especially in Sub-Saharan Africa. In the context of the CDM, that region's current share in the project pipeline is only 1.4 percent—only 53 out of 3902 projects—or nine times smaller than its global share in GHG emissions, including emissions from land use and land-use change (De Gouvello *et al*. 2008).

4.2 Comparison with other LCAs and biofuels

Comparing the LCA results of biofuels is delicate because specific characteristics may vary widely across studies, such as feedstock type, production region, cropping systems used and crop yields, transport distances and energy sources. Some of these factors always exert a major effect on LCA results, together with LCA hypotheses (system boundaries and functional unit) (Farrell *et al*. 2006).

Our results for Jatropha biodiesel may be compared to LCA studies carried out in India (Reinhardt *et al*. 2007) and Thailand (Prueksakorn & Gheewala 2008). The former focused on JME production in the Bhavnagar region of India, and is characterized by saline and eroded, marginal soils. The term marginal soils is used to characterize zones with pedo-climatic conditions unsuitable for conventional crops (in particular for food production). This study uses system expansion for all co-products, and the Jatropha production is motorized and requires irrigation for the first three years. This implies a high

consumption of fuel and irrigation water. (Reinhardt *et al*. 2007), and results in a much lower performance. The energy yield was only 1.8, compared to 4.7 in our baseline scenario, and the GHG savings compared to fossil diesel were only marginal (11%), ie 6 times lower than our baseline (Table 4).

Although it is proven that Jatropha grows on marginal soils (Spaan *et al.* 2004), the commercial viability of oil production on these soils is still unproven (Francis *et al*. 2005). The comparison of two types of large scale Jatropha productions (for biofuels) clearly shows that such a project on marginal soils generally translates into, on the one hand an increase in production costs linked to investments for irrigation and ground preparation, and on the other, lower seed yields (and oil yields). These drawbacks translate not only into lower energy yields and less reduction in GHG percentages but also lower economic profitability.

For Jatropha grown on regular soil across 20 provinces in Thailand, Prueksakorn and Gheewala (2008) report higher energy yields, ranging from 1.93 to 11.98 with an average value of 6.03. This is similar to our results in terms of range and average (4.7), although the plantations were much more machinery-and input-intensive. However, their results were very sensitive to the end-use of co-products.

Lastly, the performance of Jatropha was far superior to current, temperate first-generation biofuels, whose energy GHG savings compared to fossil equivalents typically vary from 20% to 50% (Quirrin *et al*. 2006).

4.3 Barriers to Jatropha development

Our results evidenced the significant benefits provided by Jatropha in West Africa regarding energy and GHG savings. However, further development of this species for bioenergy purposes raise a range of technical and non-technical barriers, as underlined by Openshaw (2000).

First, the fact that Jatropha is not edible cannot imply that it dose not compete with food crops since it may compete for land, unless if grown on marginal land unsuitable for food crops. In our case, Jatropha was considered here as an alternative to cotton crops, whose value has considerably dropped in the last few years. Because these crops are no longer profitable, many cotton growers have abandoned them and may be interested in alternative crops, among which Jatropha may be a good candidate. There is thus no direct competition with food crops as such, since Jatropha would displace a non-food crop and provide an opportunity for diversification and complementary incomes.

Still, direct land-use changes may occur should the price of cotton go up again and stimulate the growth of cotton crops, which would make it necessary to find new arable land for Jatropha. This would dramatically affect the GHG balance of Jatropha oil, in the same way (but opposite) as the inclusion of C sequestration rate compared to cotton crops.

The interest of West African farmers, in particular smallholders, will be utlimately determined by the profits they may expect from Jatropha. However, the yields are still quite uncertain, and farmers might be reluctant to grow Jatropha if it does not meet their expectations (Foidl *et al.* 1997). If Jatropha was to be developed in commercial plantation, as was envisaged here, its management should be further investigated and optimized, in particular regarding the concerne raised by Openshaw (2000) on the nutrient exports by the plants.

The harvest of Jatropha is labor-intensive, so farmers will have to be flexible and optimize their work schedule to accomodate Jatropha in their farm organization. The production of biodiesel also requires specific technical skills, in particular for the storage and drying of seeds which are crucial steps to obtain a vegetable oil of sufficient grade for esterification. Another critical characteristic of Jatropha is that its oil is not edible, and the long-term side effects of skin contact with the phorbol esters contained in the grains have not been fully investigated yet (Üllenberg 2007).

Some co-benefits of Jatropha have been proven, such as protection against soil erosion (Openshaw, 2000). However, the commonly-held view that the toxicity of Jatropha prevents damages by insects, but it is simply not proven. Jatropha itself may be attacked by such pests (Grimm *et al.* 1997), which lowers its yield and may incur additional pesticide costs. Jatropha is also a host plant for the cassava virus.

Conclusion

In principle, Jatropha has a significant agronomic, environmental and economic potential. Our LCA based on detailed field study on Jatropha cultivation and transformation in West Africa show that, regardless of the technical variants, biodiesel production based on Jatropha presents higher fossil energy and GHG savings than most current biofuels when it is used as a substitute for conventional diesel fuel. This is still the case when Jatropha oil is transported to Europe for transformation into biodiesel. Thus, Jatropha biodiesel has a strong potential to contribute to climate change mitigation and increased energy independence. The cultivation of Jatropha appeared as a critical stage in the biodiesel life cycle, along with the land-use change pattern. The good performance of Jatropha, compared to previous work on other continents, may be mainly explained by the perennial nature of the crop and by the decentralised, non-motorised and low-input production system. However, this assessment should be completed regarding potential local impacts linked to the cultivation phases (eutrophication, ecotoxicity...), which have not been covered in this LCA.

Finally, in addition to its more favourable environmental impacts, Jatropha cultivation participates in the diversification of agricultural productions in West Africa, and better still, it constitutes a new, interesting production sector for creating jobs and income for the producers. Whatever happens, this new Jatropha production drive must be soundly managed, in order to achieve synergies with the local food crops.

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Tables

Table 1: Cropping system for the Jatropha over the first plantation year

Reference in the text: page 7, line 22

Operations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Ground preparation		→	→									
Making holes			→	→								
Transplanting						→						
Fertiliser application						→	→					
Replacing dead plants							→					
Hand weeding							→	→				
Phytosanitary treatment							→	→	→			

Table 2: Cropping system for the Jatropha from the second plantation year on

Reference in the text: page 7, line 26

Operations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Fertiliser application		→→										
Hand weeding							→→					
Phytosanitary treatment							→→					
Pruning								→→				
Harvesting (from year 4)										→→		

Table 3: Percentage differences between results for alternative scenarios and the reference scenario. The energy yield is the ratio of one MJ of JME to the amount of energy (MJ) consumed to produce it. The relative values of the alternative scenarios are calculated using the following formula: X%= (Value of alternative scenario –Value of reference scenario)/ Value of reference scenario.

MJ/ 10 MJ JME is the quantity of fossil energy consumed to produce 10 MJ of JME

Text: page 13 line 16

	Reference	Yield 3t	Yield 5t	Transport by truck	Labour force	Jatropha oil
gCO_2eq/MJ	24	17%	-10%	8%	0%	-45%
% reduction CO_2eq	72	-7%	4%	-3%	0%	18%
MJ/10 MJ JME	2.11	4%	-2%	14%	29%	-82%
Energy yield	4.7	-4%	2%	-12%	-27%	452%

Table 4: Comparisons between the LCA of Heidelberg IFEU and that of AEDR/AgroGeneration/CIRAD

Reference in the text: page 16, line 3

	Plants/ha	kg N/ha	kg P/ha	kg K/ha	Dry seed yield t/ha	t CVO/ha	t JME /ha	Energy yield	MJ/MJ JME	CO_2geq/MJ JME	% reduction of GHG
AEDR/CIRAD/ AgroGeneration (Jatropha)	1111	108	25	30	4	1.2	1.05	4.7	0.2	23.5	72
IFEU Heidelberg (Jatropha)	1667	48	19	53	1.4	0.4	0.36	1.8	0.6	74.5	11

Figure captions

Figure 1: Process tree system for the production of biodiesel from Jatropha grown by smallholders in Ivory Coast. For each elementary process (centre), the chart shows the inputs (left) and outputs (right), studied in this LCA

Figure 2: Energy consumed (MJ) by an elementary process for the production of one MJ of JME. This figure shows the amounts of energy consumed per elementary process (actual values and relative values).

Figure 3: Contributions of the elementary processes to GHG emissions. Those shown are the GHG emissions (g CO_2 eq actual values and relative values) for each process during the production of one MJ of JME. The error bars correspond to the uncertainty on GHG emissions.

Figure 4: Energy and greenhouse gas balances for the 5 scenarios studied in this LCA. The error bars correspond to the uncertainty on GHG emissions.

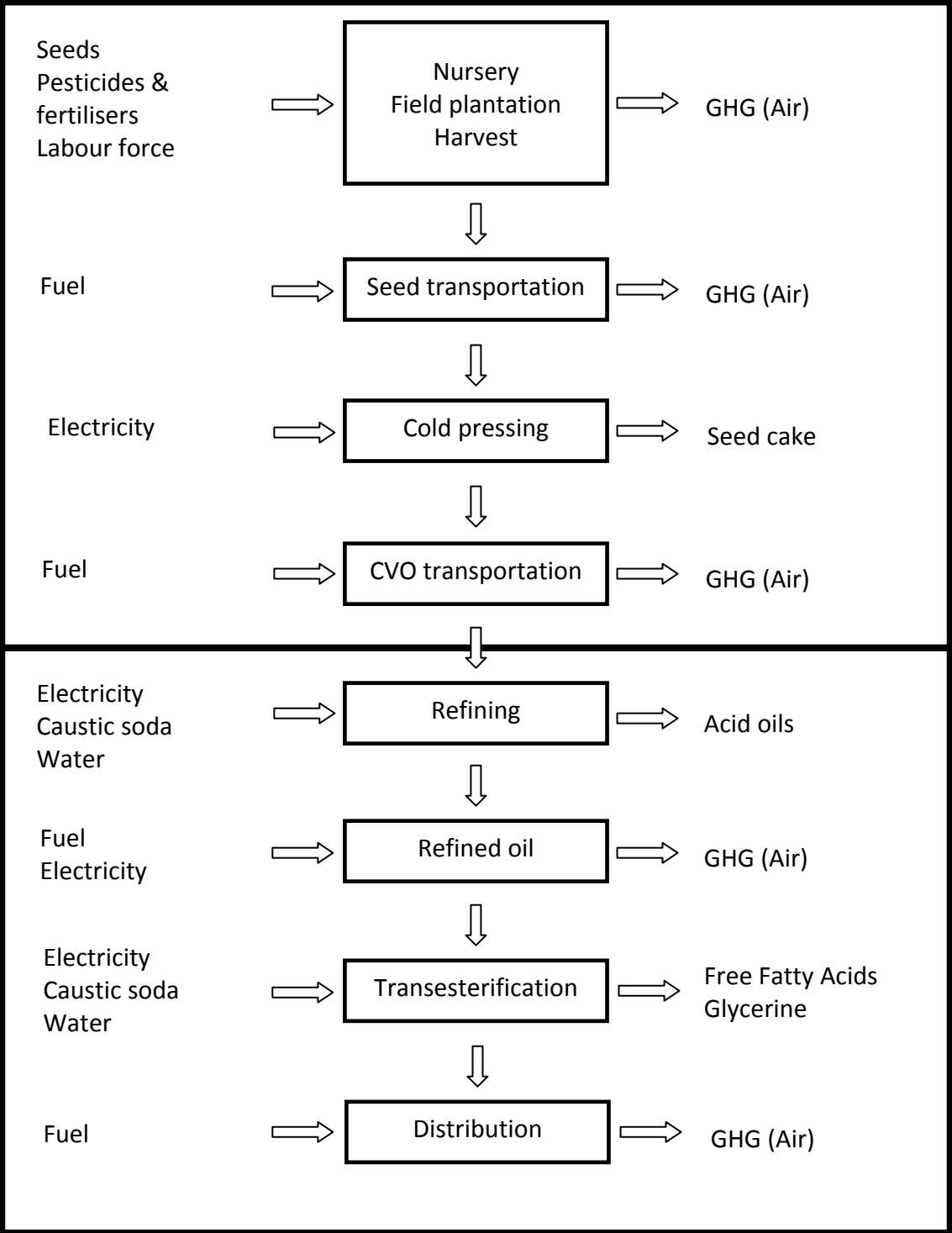Figure 5: GHG emissions and energy consumption linked to fertiliser use, methanol, and pesticides during the production of one MJ of JME
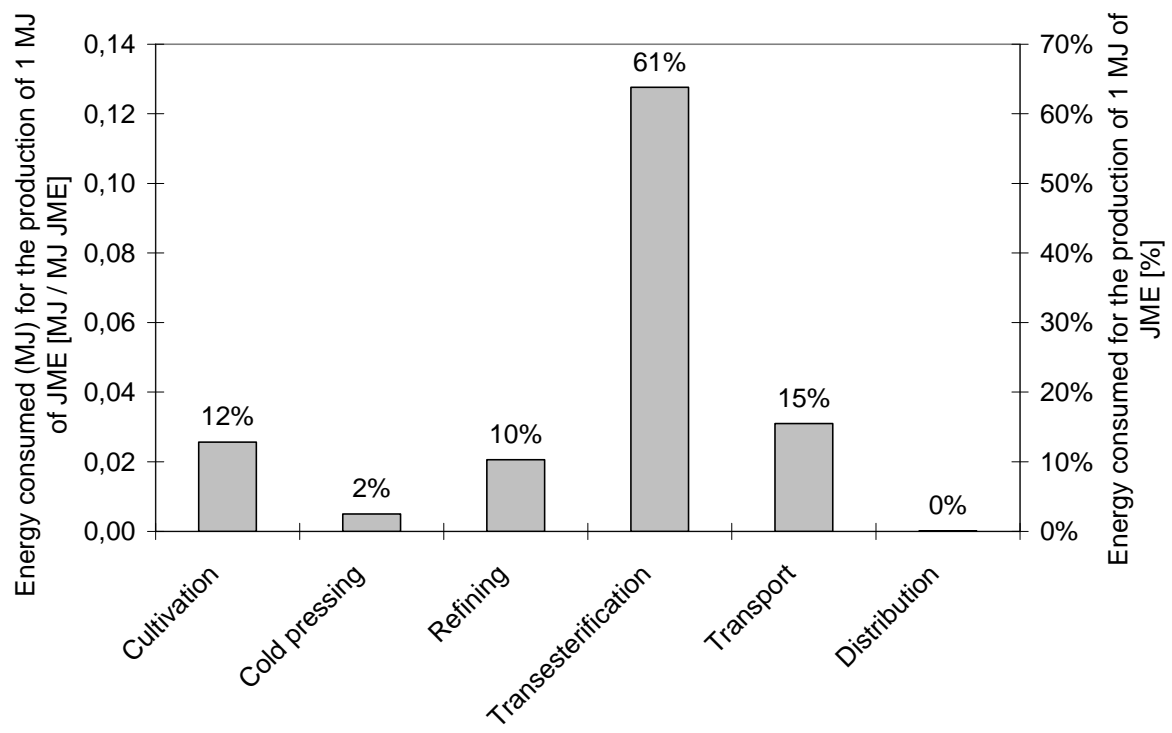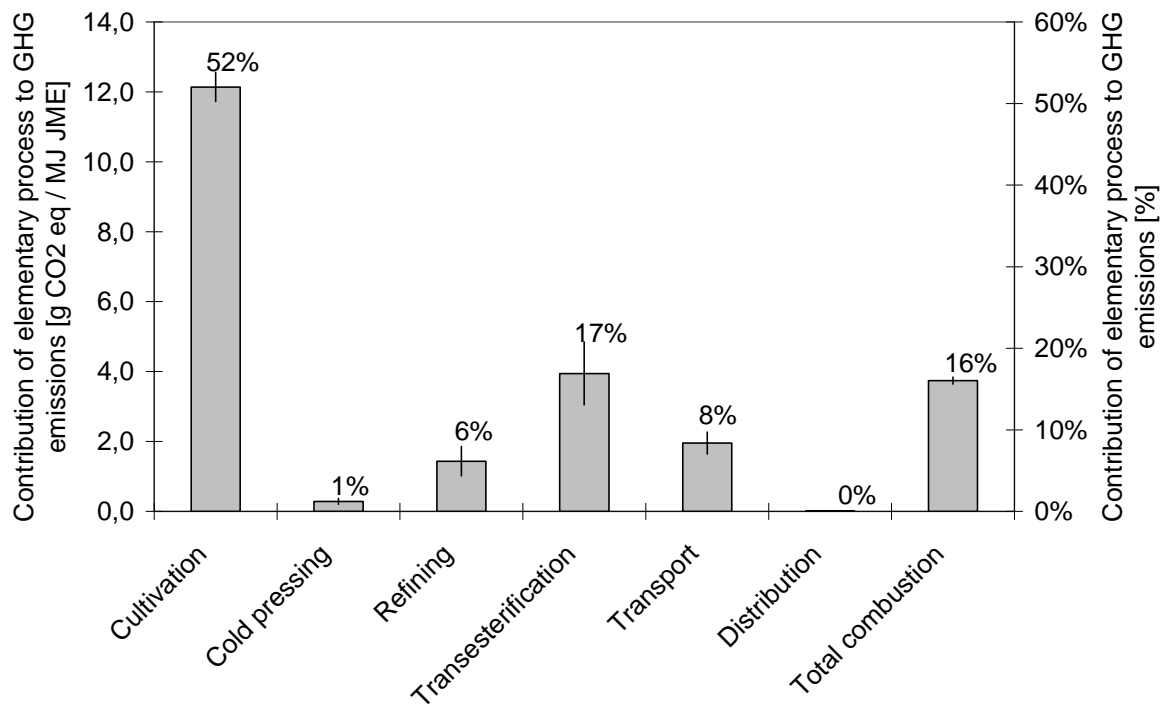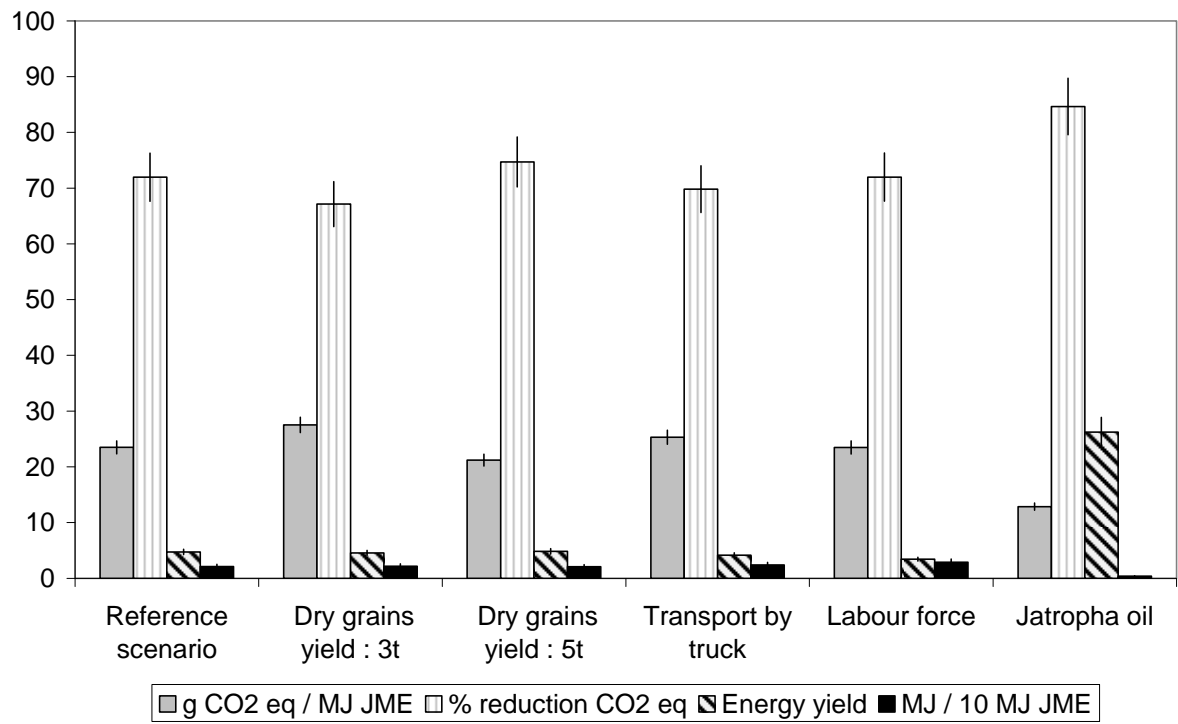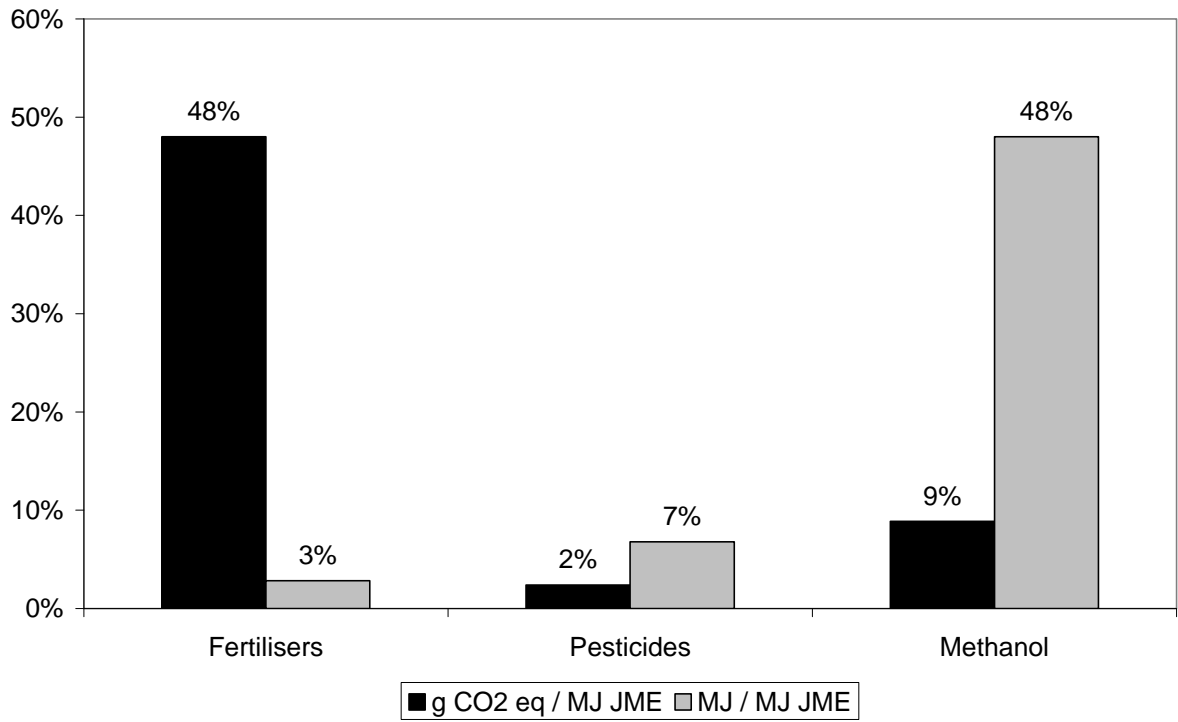
Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Appendix 1: The main sources of data used in the LCA

For chemicals, the emission and extraction factors refer to the pure active substance.

Reference in the text: page 10, line 5

Data	Sources	Dates
Choice of nursery	Mali experiments	2007-2008
Crop field density	Mali experiments Observation in the field, Ivory Coast Bibliographical study	2007-2008 2008 Rijssenbeek *et al.* 2007
Labour force	Mali experiments	2006-2008
Seed yield	Mali experiments Bibliographical study	2006-2008 Reinhardt *et al.* 2007
Fertilisers	Mali experiments	2008
Pesticides	Mali experiments	2008
Definition of technical itineraries for cultivation	Mali experiments Observations in the field, Ivory Coast	2006-2008 2008
Jatropha oil analyses	CIRAD/AgroGeneration	2008
Jatropha cake analyses	CIRAD/AgroGeneration	2008
Industrial data	Factory builders	2008
Emission and extraction factors	Ecoinvent database	Ecoinvent (2006)
Impact factors	IPCC	Foster *et al.* 2007