Biofuel from *Jatropha Curcas*: environmental sustainability and option value

Marcello Basili
DEPFID, University of Siena, Italy

Fulvio Fontini*
DSE, University of Padua, Italy

Abstract

The paper considers the use of a non-edible plant, *Jatropha curcas* (JC), for the production of biofuel as a substitute for traditional fossil fuel. The whole production chain is analyzed; energy and environmental balances are reported. The investment value in biofuel from JC is also studied, and both its intrinsic and option values are calculated. A reference case is evaluated, namely, the cultivation of JC as s substitution for conventional fuel in a specific less developed country, Kenya, that lies in the tropical region where JC grows. The investment is modelled as a perpetual investment call option. It is shown that the Net Present Value is positive for a vast range of discount factors and investment costs, while the option value depends crucially on the parameters of the model. Finally, the case of a relinquishment requirement for the specific land-use is also evaluated by modeling the corresponding American call option value; it is shown that a land-use release requirement does not change the optimal investment strategy.

*Corresponding Author. Address: DSE, University of Padua. Via del Sano 33, I-35123 Padova, Italy. E-mail: fulvio.fontini@unipd.it. We thank Chiara d'Alpaos, Luca Di Corato, Michele Moretto, Giuseppe Stellin, Alessandro Ragazzoni and Sergio Vergalli for their comments. University of Padua Research Grant n. CPDA077752/07 is gratefully acknowledged.

1 Introduction.

In July 2008, oil prices rose to more than $147 a barrel as the peak of persistently high prices that were not tied to the shortage of oil, embargo, local wars, worries about terrorism or cutting in supply but to the fast-growing demand of developing countries such as China and India. The energy demand boom increased concerns about carbon emissions and climate change and put forth biofuels as an alternative to burning fossil fuels, since biofuels were perceived greehouse gas (GHG) neutral in their lifecycle: crops fix carbon from the atmosphere during cultivation, and when they are burned as biofuels, the carbon released balances the carbon fixed during the growth.[1] In these circumstances, the U.S. Congress mandated a fivefold increase in the use of biofuels,[2] and similar policies were introduced in Europe where the EU set the goal of having 10% of transportation fuel made from biofuels by 2020. Diversion of grain and corn to produce ethanol and a more general substitution of alimentary plantation by the more efficient biofuel crops, guided from subsidies and tax exemptions,[3] not only induced higher food prices but also enlarged deforestation in Brazil and Southeast Asia, due to sugarcan and palm oil cultivation, respectively.

Recent studies by the World Bank (World Bank, 2008) showed that a large part of the food price increase was produced by the soaring biofuel supply, even if rising prices were observed not only for diverted cultivation such as corn and soy but also for other edible substitute cultivations such as rice and wheat that are never used as biofuels. For many countries, rising global food prices contribute to high food inflation that, for regions where households spend more than 75% of their income on food, undermines the

[1] The lifecycle GHG savings compared to fossil fuels have been estimated from 13% for corn ethanol to 90% in the case of sugarcane ethanol (World Watch Institute, 2007).

[2] Ethanol, extracted from carbohydrates, and biodiesel, extracted from oilseeds, can be blended with existing petroleum fuels for use in unmodified internal combustion engines, in blend of up to 10% or 20%, respectively.

[3] The US biofuel subsidies are expected to total more than $92 billion for the 2006–12 period; as a result, "the average cost to displace petroleum energy during the 2006–12 period is estimated at $12–17 per GJ for corn ethanol; $16–25 per GJ for biodiesel; and up to $19 per GJ for a hypothetical cellulosic case in which existing subsidies are assumed to produce the lower impact cellulosic product. This translates into a public subsidy of $1.40–1.70 per gallon gasoline equivalent and $2 to $2.35 per gallon diesel equivalent—a sizeable percentage of the fuels' retail value" (Koplow, 2007, p. 54).

progress in reducing poverty of the last 10 years.[4]

In Fargione et al. (2008) and Searchinger et al. (2008) it is calculated that conversion of wild lands increases GHGs "by releasing 17 to 420 times more CO_2 than the annual greenhouse gas reductions that these biofuels would provide by displacing fossil fuels" (Fargione et al., 2008, p. 1235), and the diversion of croplands for biodiesel productions creates a biofuel carbon debt, since "instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years" (Searchinger et al., 2008, p. 1238). Oxfam (2008) estimates that diversion of rapeseed and other edible oils to the European biofuel program is overly expensive, and "emission resulting from land-use change in the palm-oil sector may have reached between 3.1 and 4.6 billion tonnes of CO_2 - 46 to 68 times the annual saving the EU hopes to be achieving by then from biofuels" (Oxfam, 2008, p. 2).

The credit crunch and financial crisis induced by the subprime crisis and Ponzi schemes have been hit the energy industry, plunging oil prices by 1/2, i.e., around \$70 a barrel. The downturn in the global economy and high variable oil price forecasts, from \$40 to \$80 a barrel in 2009, have been also inducing a global rethinking about investment in renewable energy, looming on first generation of biofuels derived from diverted commercial feedstock and agricultural crops: ethanol from sugarcane, corn, sugar beets, maize, and wheat and biodiesel from palm, soybean, and rapeseed.

By contrast, the high volatility of barrel price and biofuels from first-generation plants and large estimated carbon debts of land conversion could represent an opportunity for implementing production from non-food crops (second generation) for biofuels, such as algae and *Jatropha*. The latter, in particular, appears to be suitable for cultivation in marginal and idle lands that do not cause additional pressure on agricultural land and global shift in agricultural production. The EU biofuels target for 2020 of 10%

[4] "The rising trend in international food prices continued, and even accelerated, in 2008. U.S. wheat export prices rose from \$375 t^{-1} in January to \$440 t^{-1} in March, and Thai rice export prices increased from \$365 t^{-1} to \$562 t^{-1} . This came on top of a 181 percent increase in global wheat prices over the 36 months leading up to February 2008, and a 83 percent increase in overall global food prices over the same period. [...]. Increased biofuel production has contributed to the rise in food prices [...]. Only a relatively small share of the increase in food production prices (around 15%) is due directly to higher energy and fertilizer cost. The observed increase in food prices is not a temporary phenomenon, but likely to persist in the medium term" (World Bank, 2008, p. 1).

from biofuels by energy could determine a gross land requirement of 22-31.5 million hectare, and some 37% of the estimated land requirement comes from export diversion or diversion of domestic use. Nonetheless, a large part of energy from biofuels, namely, 22-54%, would be derived from imports that would determine an indirect land-use change of approximately 4.7-10 million hectares outside the EU (Dehue and Hettinga, 2008).

To Summarize, second-generation plants for biodiesel do not induce land-use change, since they grow in degraded lands, do not compete for food production, are non-food feedstock, and disentangle the puzzle related to undervalued emissions of N_2O (from three to five times) from nitrogen-based fertilizers that definitively reverse GHG emission saving worsening global warming,[5] since by-products of oil extraction (i.e., seed-cake) produce organic fertilizer through composting. Finally, cultivation of second-generation plants could represent an opportunity for poor countries to benefit from the growing demand for biofuels: assuming an oil price of \$65 a barrel, *Jatropha* shows a marginal return of \$2 per day and a gross marginal return of \$1200 per ha in India (Wiggin et al., 2008).

In 2005, the Indian Ministry of Petroleum and Natural Gas launched a biodiesel purchase policy at \$0.56 l, but the estimated production cost of biodiesel from *Jatropha* ranged between \$0.67 and 0.89 l (Press Trust of India Limited, 2006). *Jatropha* could be used to produce a barrel of fuel for around \$43, less than \$45 of sugarcane-based ethanol and \$83 of corn-based ethanol (Barta, 2007). Finally, a recent study on the life cycle cost of *Jatropha* biodiesel production in Thailand shows a cost with and without environmental externality of \$0.5 l^{-1} and \$0.42 l^{-1}, respectively, that is derived from agricultural process (63%), production process (25%), and environmental cost (12%) (Sampattagul et al., 2007).

2 *Jatropha Curcas*

Jatropha curcas (JC) induces GHG abatement directly by substituting fossil fuel, through extracted oil from the seeds, and indirectly by fixing carbon stocks in soil and plant biomass, two of the most important biologically active carbon stores.

[5] N_2O is a by-product of fixed nitrogen application in agriculture; it is a “greenhouse gas” with a 100-yr average global warming potential (GWP), 296 times larger than an equal mass of CO_2 (Prather et al., 2001).

JC (genus *Euphorbiaceae*) is one of the main non-edible oil-yielding species that can be used for biodiesel production in several countries (India, Tanzania, Madagascar, Cambodia, Guinea, etc.). JC is a perennial drought-resistant plant (bush or small tree) native to South and Central America, first classified by Karl von Linne in 1793, and its genus contains 170 species. *Jatropha* is a toxic plant due to the presence of toxic phorbol esters (a non toxic variety exists in Mexico) and grows in all tropical and subtropical regions well adapted to extreme environmental conditions. *Jatropha* grows in drier regions with rainfall of 500-600 $mm\ yr^{-1}$ (250 mm in special condition such as Cape Verde Island). *Jatropha* can survive long drought periods of 7 or 8 months, depending on air humidity, and withstands light frost.

JC is well adapted to growing on marginal and degraded lands, as a fence or protection hedge of cultivated lands from animals and erosion. JC is a valuable multi-purpose crop to alleviate soil degradation, desertification and deforestation. A recent study on impact of cultivation of *Jatropha* on the structural stability and carbon-nitrogen content of degraded Indian entisol reports that "cultivation of *Jatropha curcas* resulted in 11% average increase in mean weight diameter of the soil and 2% increase in soil macro-aggregate turnover. Cultivation of Jatropha curcas with nitrogen and phosphorus- or without any-amendment improved macro-aggregate stability from 6-30% [...]. For nitrogen, *Jatropha* without amendment demonstrated superiority in soil nitrogen concentrations than in the natural vegetation with 33% increase in nitrogen concentrations at both whole soil level and at fine particulate organic matter fraction [...]. Soil structure recovery under cultivation of *Jatropha curcas* implies a sustainable improvement in the surface integrity of these soils, which will ensure more water infiltration rather than runoff and erosion" (Ogunwole et al., 2008, p. 250).

Jatropha is a low-growing tree that can live up to 50 years. *Jatropha* grows up to 5-7 meters and produces from 100 $kg\ ha^{-1}\ yr^{-1}$ to more than 10 $t\ ha^{-1}\ yr^{-1}$. Crucially it is not self-propagating and infesting plant but has to be planted. The number of *Jatropha* trees per hectare of planting ranges from 1600 to 2200; wider spacing is reported to give a larger yield of fruit. The oil content of *Jatropha* seeds ranges from 30 to 50% by weight, whereas in kernel the oil content ranges from 45 to 60%. The amount of oil produced from seeds and kernels is contingent upon the method of extraction. The by-product of oil extraction from the seeds and kernels is called seedcake, and when oil is extracted as a cottage industry, the resulting cake is said to still contain approximately 11% oil. There exist two main extraction oil methods: mechanical and chemical; the latter produces seedcake with much lower oil content. The fatty acid composition of Jatropha oil consists of oleic acid (43.1%), linoleic acid (34.3%), stearic acid (6.9%), palmitic acid (4.2%) and other acids (1.4%). One major obstacle in using vegetable oils was their high viscosity, which causes clogging of fuel lines, filters and injectors. Therefore, vegetable oils could not be used directly in diesel engines at room temperatures. Conversion of vegetable oil to biodiesel is predominantly done using a base catalyzed transesterification process. This chemical reaction is catalyzed by a strong base, and involves filtered fat or oil reacting with an alcohol (usually methanol) to form crude methyl ester biodiesel and crude glycerol. The crude biodiesel can be further refined by washing with mildly acidic water, which will remove soap residues. The resulting biodiesel has a viscosity comparable to that of normal diesel.

Nevertheless, unrefined *Jatropha* oil has been applied in certain types of diesel engines, such as Lister-type engines, that are commonly used in developing countries to run small-scale flourmills or electric generators (the so-called Multifunctional Platform For Village Power - PTFM), or in modified diesel engines, where modifications were applied to the injection system parts such as fuel lines, filters and pumps.[6] It is worth to note that the only engine especially developed for successful use of virgin vegetable oil is the Elsbett-Engine.[7] Crucially in 2006, the Bosch-Siemens Home Appliances Group (BSH) publicly launched the second-generation protos cooking stove, which burns oil that had been mechanically filtered and required no refining. Today, protos cooking stove, supported by a plant oil supply chain, could

[6]Interestingly enough, in December 2008 an Air New Zealand 747-400's Rolls-Royce RB211 engines were powered by a biofuel blend of 50:50 *Jatropha,* that has a solidification point at -37°C, and Jet A1 fuel. Air New Zealand was the first to use *Jatropha* seed oil and was followed by Continental Airlines and Japan Airlines that tested a blend of 50:50 Jatropha-algae-camelina derived biofuel and traditional Jet A1 fuel in Boeing commercial airplanes. In mid 2009 a coalition headed by Boeing released a full report on the test flights that induce the International Standard Board to approve and certify plant-derived biofuels as jet A1 fuel. The Federal Aviation Administration (FAA) estimates a bio-derived synthetic paraffinic kerosene (Bio-Spk) demand of 660 million of barrels in 2015.

[7]Elsbett Diesel Technology - Elsbett Engine defines a basket of specific engine components that makes it possible to achieve the optimum thermal and mechanical conditions required for combustion of natural vegetable oils. Elsbett Diesel Technology is a cheap technology able to adapt a standard engine to virgin vegetable fuel, and the company's latest developments are conversion kits for agricultural machinery ($\$1200-5200$), industrial engines ($\$1400-3000$), cars ($\$950-1600$), vans ($\$2000-3000$), and tracks ($\$3400-4200$) (www.elsbett.com).

be a good alternative for more than 2.5 billion people that prepare food on traditional three-stone fireplaces fuelled by firewood or charcoal and the emissions of which have very high concentrations of carcinogenic substances (according to WHO, more than 1.6 million people die annually from indoor air pollution).

3 Energy balance and environmental balance of fuel from JC

The properties of JC biofuel are similar to biodiesel obtained from biomass with conventional fatty acid compositions, such as canola, linseed and sunflower, even if the oil content of JC is higher than those reported for other vegetal oils, such as soybean. It is well known that the crude *jatropha* oil has high acid values that could lead to difficulties in fuel production. The most effective technique for reducing fuel viscosity is the chemical conversion of the oil in fatty esters that removes glycerine, indeed transesterification. As a consequence, the energy balance and the environmental balance depend on the choice of producing vegetable oil or biodiesel (methyl ester).

A large body of literature exists that analyzes each step of JC cultivation, oil extraction and use (Achten et al., 2008; Becker and Makkar, 2008; Kaushik et al., 2007). To evaluate the whole sustainability of the JC biodiesel as an alternative to fossil fuels, we describe in the subsequent two subsections the energy balance and environmental balance based on the life-cycle assessment (LCA).

3.1 Oil and biodiesel characterization.

Transesterified JC oil or biodiesel is more efficient than pure JC oil, and even if transesterification is an energy-consuming process, it not only produces a larger percentage of oil from seeds but also permits an energetic use of end-products and by-products. As a result, even in the case of transesterified JC oil, the Net Energy Balance is positive almost everywhere (Prueksakorn and Gheewala, 2006); indeed, if none of the by-products are used, "the energy balance will be only slightly positive (886 MJ input for 1,000 MJ JME output) or even negative. On the other hand, if all by-products (including wood and fruit husks) would be used efficiently this total input of 886 MJ

results in a total output of 17,235MJ, resulting in a allocated energy input of 160 MJ per 1,000 MJ JME" (Achten et al., 2008, p. 1077).

Transesterification is the biggest energy-consuming process, but fertilization also has high negative impact on energy balance. Crucially, the negative impact on the energy balance of these two factors can be marginalized. The use of transesterification could be by-passed, in the case of virgin oil production for domestic use, in modified engines and cooking stoves, and energy savings could be obtained from the substitution of chemical fertilizers with JC seedcake, that pure or in nutrient-enriched compost by lignocellulolytic fungi could be used as natural fertilizer (Sharma et al., 2009).[8]

3.2 GHG balance

For a long time, plants have been considered renewable energy sources and vegetable oil production proposed as a possible alternative to reduce GHGs: "a range of studies has shown that where feedstock is produced without land-use change (either direct or indirect) most biofuels achieve net GHG savings. Current biodiesel technologies generally achieve a $40 - 50\%$ saving compared to that of conventional diesel. The range of savings from current bio-ethanol technologies is much wider, from 20% to 80% depending upon: feedstock, rates of fertilizer application; type of other energy source (coal, gas or biomass); heat and power source (simple boiler, CHP or advanced turbine) and the specific use of co-products" (Gallagher, 2008, p. 22).

Recent evidence (Searchinger et al., 2008; Crutzen et al., 2008) has challenged this conclusion and introduced doubts about the net effect on GHGs emission when land-use change and chemical fertilizers are considered in the production of first-generation biofuels.[9]

On the contrary, JC appears to be an ideal feedstock since JC can grow on marginal land, and recent studies (Tobin and Fulford, 2005; Prueksakorn and Gheewala, 2006) showed a positive LCA in the production of JC biodiesel

[8] Prueksakorn and Gheewala (2006) find that energy consumption (input) of transesterification and fertilization is 353 MJ and 198 MJ, respectively.

[9] Crutzen et al. (2008) show that "the yield of N_2O-N from fixed nitrogen application in agro-biofuel production can be in the range of 3–5%, 3–5 times larger than assumed in current life cycle analyses, with great importance for climate....the replacement of fossil fuels by biofuels may not bring the intended climate cooling due to the accompanying emissions of N_2O". (Crutzen et al., 2008, p. 393).

with respect to fossil diesel.[10] Considering that transesterification and fertilization are responsible for 23% and 30% of GHG emissions in JC biodiesel use, this positive GHG balance could be improved to produce virgin oil and use seedcake for organic manure.[11]

Even if more than 90% of the total life-cycle GHG emissions are caused by the end-use, land-use change can modify the LCA of JC. Carbon storage depends on site quality, nature of land-use, choice of species and crop management; larger biomass is more efficient in carbon storage because of a better utilization of space, so the potential carbon sequestration is $300-400$ $t\ ha^{-1}$ yr^{-1} in rainforest, $90-150$ $t\ ha^{-1}\ yr^{-1}$ in agro-forestry and $7-20t\ ha^{-1}$ yr^{-1} in shrub and marginal lands (Moura-Costa, 1996). *Jatropha* carbon sequestration is highly variable depending on biomass production. A 5000-*ha* JC plantation in the desert near Luxor (Egypt), installed in 2003 and irrigated with sewage water, shows that $1,600$ plants ha^{-1} (spacing 2.5x2.5 *m*) produce about 80 $t\ ha^{-1}\ yr^{-1}$ of biomass: since JC plants are shrubs higher than 2 meters it is possible to assume[12] a storage $5.5-20$ $t\ ha^{-1}\ yr^{-1}$. Therefore the existence of an induced carbon debt due to land-use change is at least questionable if marginal land or semi-arid lands are considered.

[10] LCA of GHG emissions for the production of 1000 MJ JC biodiesel are 56.7 and 16.5 kg CO_2 equivalent, respectively, with respect to the 246.1 kg CO_2 equivalent for fossil diesel.

[11] From the second year of plantation, JC seedcake can be used instead of chemical fertilizers: 1.0 kg of seedcake is equivalent to 0.15 kg of N:P:K (40:20:10) chemical fertilizer (Openshaw, 2000).

[12] In Kenya, where the carbon stock of native vegetation (*Tarchonanthus camphoratus*) is 59 $t\ ha^{-1}\ yr^{-1}$ (29 soil and 30 plant) if "native vegetation is replaced by grain cultivation and charcoal is produced in a traditional earthmound kiln, one ton of charcoal results in the release of over 2.7 t over its entire life-cycle....If natural vegetation is replaced by fast growing exotic species like Eucalyptus grandis, the increase in biomass that results acts as a sink of carbon, such that after 50 years of coppice management, roughly 0.8 t are sequestered for every ton of charcoal produced" (Bailis, 2005, p. 303). Crucially *Eucalyptus grandis* has a biomass production of 39-83 $t\ ha^{-1}\ yr^{-1}$ very similar to JC so it is possible to assume an analogous carbon storage.

4 The value of the investment in JC for the production of biofuel.

4.1 Investing in JC in Kenya

We calculate the value of the investment in JC focusing on a case study that can provide useful hints for the development of JC exploitation for biofuel production in a subsaharian LDC, where JC oil can be used without trans-esterification as a substitute for energy production either for domestic use or in specific places where conventional-oil generators are used. Kenya is taken as a reference country since it lies within the JC production belt[13] of sub-Saharan Africa, one of the poorest regions in the World with the worst health status and the minimum energy consumption per capita.[14] The investment in JC can be beneficial not only by direct substitution of fossil diesel in power generators but also for substitution of primary energy sources still largely used. Indeed, even if production and consumption of vegetable oil are increasing (in Kenya doubled since 2001 up to more than $700,000t$ in 2009),[15] firewood and charcoal are widely used for energy requirements of households and small firms. Firewood and charcoal have deep negative impacts on social and environmental conditions in sub-Saharan Africa. In Kenya every day the equivalent of over forty thousand tonnes of wood is consumed in the form of charcoal and the total amount of wood used for charcoal production and directly as firewood is 1–1.5 t per capita in a year (Ministry of Energy, Kenya, 2002). It has been recently pointed out that "the net GHG emissions from residential energy use in sub-Saharan Africa in 2000 were 79 million tonnes of carbon (MtC) (61% from wood, 35% from charcoal, 3% from kerosene and 1% from LPG). In the absence of systematic changes in fuel-use patterns and in production and harvesting techniques (BAU scenario), cumulative emissions between 2000 and 2050 will be an estimated 6.7 GtC" (Bailis et al., 2005, p. 101). This large biomass consumption for energy production is unsubstainable not only because it produces deforestation, land-use change and GHGs emissions, but also because the consumption has negative effects on human health by inducing severe diseases associated with household fuel

[13] It is the belt delimited by the Tropics of Cancer and Capricorn.

[14] Kenya's Human Development Index is 0.521, which gives the country a rank of 148^{th} out of 177 countries (UNDP, 2008),

[15] Source: GAIN (2009).

use "mortality from lower respiratory infections (LRIs, mainly pneumonia) among children and chronic obstructive pulmonary disease (COPD) among adult women. In 2000, there were 690,000 LRI deaths among children and 53,000 COPD deaths among adult females. Without systematic changes in urban and rural fuel-use patterns, household biomass use will result in an estimated 8.1 million LRI deaths among young children and 1.7 million COPD deaths of adult women between 2000 and 2030" (Bailis et al., 2005, p. 102). Given this scenario it is desirable a gradual transition to different form of energy production. The large amount of new cultivation of JC in Kenya induces the consideration of *Jatropha* as an alternative source for local energy production. As a reference study, we consider a case study that is tailored on an existing venue.[16] We assume that JC is planted on 80 ha of land, with an average production of 4 $t\ ha^{-1}$ of seeds; each ton of seeds contains 35% of oil, that is extracted (with an oil press) at 75%.[17] This yields 263 $kg\ ha^{-1}$ of oil ; Assuming a specific weight equals to 0.918, an average yearly production of $91,670$ l of oil from JC is obtained from 80 ha of land.

4.2 The value of the investment: the model

The value of the investment in the production of oil from JC can be calculated by evaluating the Net Present Value (NPV) and the option premium value, i.e., the waiting value that arises whenever the investment decision has an embedded opportunity cost due to the riskiness of the decision process. An irreversible investment opportunity is indeed equivalent to a financial perpetual call option on a stock, where the investment expenditure is the exercise price and the project value, which is the expected payoff from investing, is

[16] The example is tailored over The Sands at Chale, a tourist resort located on a 1.2 km long and 0.8 km wide private coral island with a mangrove forest 1 km from the mainland and 10 km south of Diani (Kenya). Energy is obtained by generator that also provides energy for desalted sea water used in the resort (1000 $l\ \ h^{-1}$). On the island there is also a well used for irrigation. The total fuel consumption (generator and cooking) is assessed at 250-300 l a day for 300 days a year. We assume a consumption of 90,000 l of fuel a year by the resort. The Diani region experiences a constant high temperature, 21°-33°C, and humidity associated with equatorial latitudes. The average annual rainfall in the coastal region is over 1,000 mm, and the distribution of rainfall follows the inter-tropical rain-belt, from April to May (long rains), and a secondary less copious raining period, between October and November (short rains). As a consequence, the Diani region has ideal characteristics for *Jatropha* plantations.

[17] Similar figures are reported in Achten et al. (2008) and in Becker and Makkar (2008).

the underlying asset (Dixit and Pindyck, 1994). In JC cultivation, the output of the investment is the oil that can be used as a substitute for diesel (a perfect substitute in case of transesterification). Irreversibility is justified by the sunk cost of the investment in the JC cultivation, which has no edible usage and can be planted in marginal lands and by the technical investment needed for the use of JC oil (by adaptation of existing engines or by transesterification). The development decision is represented as a sequential process (with or without an end-time) in which the available choice is either to invest in JC at once or wait for additional information. The investment risk is due to the volatility of the savings, and depends on the specific time path of the diesel price. At each point in time, the investor can either exert the option, invest in the JC, or wait for the next period, paying the opportunity cost due to the fuel consumption that has to be bought for energy needs. When the investment is undertaken, the option to wait and see is lost forever. At time $t = 0$, the expected present value of the investment is

$$NPV = E[\int_0^T (\tilde{\pi}_t e^{-rt} - K)dt] = (\frac{\pi_0}{r-\alpha})[1 - e^{-(r-\alpha)T}] - K = V - K \quad (1)$$

where $T = 40$ is the duration of the investment; r is the discount factor; $\tilde{\pi}_t$ is the net value of the underlying asset: $\tilde{\pi}_t = (\tilde{p}_t - c)q$, i.e., the price minus the average cost of each liter of JC oil times the overall production; V is the expected discounted cash flow; $\tilde{p}_t$ is a log-normal stochastic variable whose time path evolves according to the following geometric Brownian motion $dp_t/p_t = \alpha dt + \sigma dz$, where z is a Wiener process; π_0 is the initial value of $\tilde{\pi}_t$, being p_0 the initial value of $\tilde{p}_t$, so that $E[\pi_t] = \pi_0 e^{\alpha t} = (p_0 - c)qe^{\alpha t}$;[18] and K is the strike price of the option, which encompasses the cost of land. Since JC can be planted on marginal land, we do not need to consider the opportunity cost of alternative land-use. Moreover, the marginality of the land allows us to assume, at first glance, that it has null cost. However, the cultivation of JC is increasing in countries in the *Jatropha* belt. It make sense to use land for cultivation that has a positive cost, and this assumption is captured by a sensitive analysis on the strike price of the option, i.e., the investment cost.

4.3 The value of the investment: the data

[18] Throughout the paper, we assume that $\tilde{p}_t - c \geq 0 \; \forall \; t$. Both the economics rationale of JC as a substitute of diesel and the analysis of the time series of oil compared with JC cultivation costs justify the assumption.

The price of the underlying asset for the investment in JC oil is assumed to be the average diesel price in Kenya, because of the perfect substitutability between diesel and JC oil guaranteed by the technical adjustment in the existing generator (or purchase of a specific generator).[19] The drift and variance parameters of the price equation of motion need to be estimated. Due to insufficient data about the fuel price in Kenya to estimate the price directly, the Crude Oil-Africa FOB Bonny Light times series[20] is used as a proxy, which seems to be adequate given the high correlation ($\rho = 0.94$) between a short Kenya fuel price time-series[21] and the oil one. The assumption of non-stationarity in the oil price is coherent with previous results in literature about oil time-series with short-range observations[22] (Dixit and Pindyck, 1994; Krichene, 2006).[23] The estimated drift is $\alpha = 0.053$; s.d. is $\sigma = 0.532$. Assuming that the (unknown) Kenyan fuel time series is distributed according to a geometric Brownian motion, it is sufficient to take just one observation (the latest available) for the diesel price to deduce its time path. In our case,[24] $p_0 = \$0.9$ (all prices are expressed in US dollars using the June 2009 exchange rate). The estimate of costs is extremely variable, depending on the characteristics of the soil, the climate, the specific country and so on. For our calculation, we consider average figures of data existing in the literature (Chen et al., 2008; Henning, 2003).[25] The average cost of JC oil refers to labor costs, assumed at 120 man-days ha^{-1} for harvesting and pruning, maintenance and irrigation (including JC seed processing), with an average daily wage of \$2, which yields an average cost per liter (c) that equals \$0.209, thus $\pi_0 = \$63.343$. The cost of investment derives from

[19] Another assumption might be transesterifying JC oil and obtaining a substitute for diesel without adapting the power generator.

[20] Daily, starting 7/6/82, deflated.

[21] Average yearly price, inc. taxes, from 1991 to 2009. See that the Kenya fuel price time-series cannot be used to estimate the equation of motion due to the limited number of observations.

[22] Longer oil time series (hundred years) are distributed according to mean-reverting processes (see, for instance, Dixit and Pindyck, 1994, p. 77). However, such a time-horizon would be outside the time-scale of the investment in JC.

[23] Recent contribution have considered more complex non-stationary processes with Skewness and Kurtosis, such as the Jump Diffusion one in (Kirkene, 2006). However, for our purposes, it is sufficient to obtain estimates for a simple non-stationary process, such as the Brownian motion Equation in the text.

[24] June 2009, Source: Kenya National Bureau of Statistics.

[25] We assume that oil from renewable sources, such as JC, will not be taxed throughout the whole period, as it at present (GAIN, 2009).

the purchasing cost of land, if any, plus the cost of acquiring seeds or small plants, fertilizer for the first two years, site preparation (tillage, alignment and stalking, digging and planting) as well as the cost of machinery needed for extracting JC oil. The cost also includes the opportunity cost of the two-years time-to-maturity of the investment and the adaptation cost for the generator. JC oil extraction and filtering at a small scale can be realized by modified oil presses used for other oil crops (both manual press such as Bielenberg Ram press or motor pressing). Three Sayari electric presses[26] are assumed, with a capacity of 120 t of seeds each, a lifetime of 17 years and a cost (including maintenance and two workers per each press) of $4,000 each, for a total investment of $36,000. Encompassing the cost of plants[27] (1,600 plants ha^{-1} with a unit price of $0.1) and site preparation (85 man-days ha^{-1})[28] in the total cost as well as the engine adaptation cost, we define a basic (reference) level for investment cost of $65,000.[29] This scenario supposes that JC is planted on marginal land that has zero value. Positive values for land are captured by positive multiples of the basic level (three, six and nine times higher).

It is worth noting that the estimated cost of JC virgin oil per barrel amounts to $36, excluding transesterification costs.[30] This is compatible with the estimation reported in the previous Sections.[31]

In Paddock et al. (1988) an estimation of the payout rate of the option (δ) for the case of investment in undeveloped oil leases is provided. Applying the same methodology, we can calculate the payout rate of the JC plantation. Indeed, it equals the (yearly) percentage gain of each unit of production (liter of JC oil). Let us denote by $\hat{\delta}$ the theoretical value of the δ of the option that can be calculated based on the estimate of our case study. We

[26] See http://www.jatropha.de/tanzania/index.html.

[27] We use the figures used in most studies. See, for instance, Henning (2003).

[28] Source: Chen et al. (2008).

[29] This figures also includes the cost of storing seeds and seedcakes. We start by setting it equal to null due to the land availability; The increase in K will also account for possible changes of seed storage costs. Notice that the oil storage cost can be considered null since it is assumed that tanks already exist for storage of conventional oil.

[30] Transesterification costs depend on the specific country in which JC is refined. For instance, in India a cost (net of by-product - glycerol) of $0.06 l^{-1} is reported, which leads to a transesterification cost per barrel that equals $9.5.

[31] Notice, however, that in order to use the data reported in the text to calculate the value of the investment to be used in a non-LDC non-JC-belt country an estimate of transportation cost must be provided and the diesel price adapted.

have that $\hat{\delta} = \frac{1}{T}\frac{p-c}{c} = 0.082$. Under the spanning assumption, the risk-adjusted interest rate, which equals the riskless interest rate plus a risk-adjusted premium, should equalize the expected return of the investment, i.e., the payout rate of the option and the expected rate of capital gain of the investment (expected increase of the value of the underlying). The latter, for JC, is given by the estimated drift parameter $\alpha = 0.053$. Therefore, if there were perfectly competitive stock markets and if the no-arbitrage assumption held, the risk-adjusted expected rate of return of the replicating portfolio (reference discount rate) would be $\hat{r} = \hat{\delta} + \alpha = 0.135$. In the paper, however, we do not constrain our analysis to the case of markets' spanning only, and calculate the NPV and the option value for various discount rates (which need not necessarily coincide with the risk-adjusted one for the case of the perfectly competitive market).

4.4 The value of the investment: results

We start by calculating the NPV of the investment, i.e., the intrinsic value of the investment option, for the reference strike-price as well as for its increasing multiples that can be due to a positive, increasing, cost of land, including the cost of fertilization, irrigation, storage, and other costs. See Table 1.

	K=65,000	K=65,000*3	K=65,000*6	K=65,000*9
r=6%	2,157,604	2,027,604	1,832,604	1,637,604
r=10%	1,081,912	951,912	756,912	561,912
r̂=13.5%	680,786	550,786	355,786	160,786
r=15%	576,356	446,356	251,356	56,356

Table 1: NPV for different values of r and K.

The NPV is extremely sensitive to the increase in the discount factor, given the length of the investment, and decreases as the investment cost rises, reaching an extremely low level for the extreme case of unusually high fixed costs.

The option value depends on the optimal investment's threshold, i.e., the critical value V^*above which it is optimal to invest. It is a standard result in real option theory (e.g., see Dixit and Pindyck, 1994) that, for problems similar to the one we are investigating here, the threshold is given by $V^* = \Phi K$, $\Phi = \left(\frac{\beta_1}{\beta_1 - 1}\right)$, where β_1 is the following positive root:[32]

$$\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \left[\left(\frac{\alpha}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}\right]^{\frac{1}{2}} \tag{2}$$

We report in Table 2 the critical values Φ and the expected cash flow V for different values of r, where $r = \delta + \alpha$. To perform the comparative static analysis, we maintain the drift parameter constant (at its estimated value), adjusting δ to compensate for the discount rate. To obtain finite solutions, we constrain the range of admissible discount factor to $r > \alpha$. Table 3 describes the thresholds V^* calculated for different r and K;

	V	Φ
r=6%	2,222,604	29.497
r=10%	1,146,912	5.770
r̂=13.5%	745,786	3.956
r=15%	641,356	3.572

Table 2: Expected cash flow and critical value Φ for diffrent values of r

	K=65,000	K=65,000*3	K=65,000*6	K=65,000*9
r=6%	1,917,295	5,751,884	11,503,768	17,255,652
r=10%	375,037	1,125,110	2,250,220	3,375,330
r̂=13.5%	257,135	771,406	1,542,811	2,314,217
r=15%	232,206	696,619	1,393,239	2,089,858

Table 3: V^* for different values of r and K

The value of the investment opportunity is calculated by solving explicitly the option value function $F(V) = AV^{\beta_1}$, where $A = (V^* - K)/(V^*)^{\beta_1}$, and β_1 is defined in equation 2.[33] This provides the value of the option to invest for $V < V^*$ (when $V \geq V^*$ the option is called immediately and the value of

[32] It is the positive root of the fundamental quadratic equation that solves the second-order differential equation of the optimal investment path $\frac{1}{2}\sigma 2\pi 2F''(\pi) + \alpha\pi F'(\pi) - rF(\pi)$, where $F(\pi)$ solves the maximization problem of Equation 1, s.t. the equation of motion for p_t described in the text.

[33] See Dixit and Pindyck (1994, ch. 5).

investment equals the NPV). The option premium, i.e., the waiting value, is the positive difference between the investment value and the net present value: $\max[F(V) - NPV, 0]$. Finally, a Monte-Carlo simulation is run to obtain the expected first hitting time of each problem, i.e., the expected time at which the investment is undertaken. Figure 1 summarizes the finding. The first entry of the table is the value of the investment, the waiting value is the second entry (between square brackets), while the third entry, in italics, is the expected first hitting time (expected waiting years before the investment is undertaken). Cases for which it is optimal to invest immediately (null waiting value) are highlighted in bold.

	K=65,000	K=65,000*3	K=65,000*6	K=65,000*9
r=6%	**2,157,604**	2,076,407	2,026,230	1,997,437
	[-]	[48,803]	[193,626]	[359,833]
	-	*15.2*	*24.4*	*28.2*
r=10%	**1,081,912**	**951,912**	822,609	755,245
	[-]	[-]	[65,697]	[199,333]
	-	-	*9.8*	*14.9*
$\hat{r}$=13.5%	**680,786**	550,901	435,244	379,199
	[-]	[115]	[79,458]	[218,413]
	-	*4.7*	*11.0*	*14.6*
r=15%	**576,356**	447,153	341,086	291,123
	[-]	[797]	[89,730]	[234,767]
	-	*5.8*	*11.4*	*16.4*

Table 4: Investment value, waiting value and expected first hitting time for different levels of r and K

The investment is undertaken immediately only if V is higher than the threshold V^*. Crucially, the range of values for which the option is immediately called depends on the level of the interest rate and the strike price. As is standard in option theory, when the implicit dividend parameter $\delta = r - \alpha$ decreases, the threshold value increases. In the real option theory, the parameter δ, the implicit dividend yield of the option, can be interpreted as the opportunity cost of delaying the investment and keeping the option alive (Dixit and Pindyck, 1994, p. 149). As a consequence, when the opportunity cost of keeping the option alive is extremely low the investment is not undertaken even if the NPV is extremely high. Obviously, the strike price lowers the investment value and rises the threshold level. According to our analysis, when land has a null (or extremely low) cost, i.e., $K = 65,000$, the option is exerted immediately, i.e., the investment is undertaken even for high interest rate. On the contrary, a positive cost for land (from three times the other sunk costs onward) induces the investor to wait almost always, except for a limited range of r for which the opportunity cost of waiting is more than compensated by the high present value of the return.

Throughout the paper, it has been assumed that land is free, or it can be acquired, since its opportunity cost included in the strike price. However, cultivating JC might also bear a positive value from the standpoint of the government, for instance, because of the positive environmental externalities. It might be interesting to consider also the (theoretical) case in which a land-use regulation allows the possibility of JC cultivation for a given enterprise up to a certain deadline, at which the land-use right has to be released if the investment has not been undertaken (as it is for oil exploration licenses). This changes the nature of the implicit option embedded into the investment. Indeed, if the marginal land assumption implies that the real option of the investment in JC cultivation is a perpetual one, the relinquishment requirement means that the investment opportunity has to be represented by an American call option. Define as τ the option expiration date (relinquishment requirement). For each level of r and K described in the text, we have analyzed the case of the relinquishment requirement by calculating the value of a sequence of American call options, as $\tau \to 1$, following the Bjerksund and Stensland approximation (Bjerksund and Stensland, 1993), solved numerically through a Monte Carlo simulation.[34] It has been observed that, even if the investment value decreases as the relinquishment time decreases (since the option expires earlier), the investment is never undertaken before the expiration of the option, for all those cases in which it was not undertaken immediately for the perpetual case, i.e., when there was a positive waiting value without relinquishment. In other words, the nature of the option (perpetual or American) does not change the investment decision: the investment is either undertake immediately or postponed, besides any relinquishment requirement. Clearly when $\tau = 0$, the option disappears, since it

[34] We have calculated the option value $c(r, k, \tau)$ for $r \times K \times \tau$, where $r = [0.06; 0.1; 0.135; 0.15]$, $K = [65,000; 195,000; 390,000; 585,000]$, $\tau = [10; 9; 8; 7; 6; 5; 4; 3; 2; 1]$.The results (160 entries) are available from the authors upon request.

is not possible to wait any longer.[35] In this case, the investment is always undertaken, given the positive NPV for all cases considered.

5 Concluding remarks.

JC is a non-edible second-generation biofuel plant that does not conflict with food, since JC grows in wastelands, and increases land productivity as an intercropping or living fence. JC appears to be a serious candidate for bio-energy production on marginal soils in tropical regions and an optimal decentralized renewable source of energy for rural and remote areas where it is impossible to ensure a stable supply of energy. Joined with simple and cheap technological instruments such as protos or other simple plant oil stoves and lister-type diesel engine or Elsbett engine, JC cultivation not only could be a real possibility for the production of fuel for local use but also new income-generating activities related to the commercialization of its by-products: soap, organic fertilizer and exceeding seedcake for gas production through a biogas digester.

In this paper, we show that the value of the investment in JC is positive and can be extremely high; however, it is extremely volatile, depending on the effective cost of the investment (in particular the land and the extraction costs) and the discount factor. When we take into account the option value, i.e., the waiting value that is embedded in the strategic structure of the investment, we can observe that the investment is undertaken immediately when the investment cost is low, i.e., when there is a low or null cost for the land, for a large interval of discount rates. It is worthwhile noticing that the investment calculated values are the minimum ones, the positive revenue associated with the economic exploitation of its by-products is not included.

Finally, JC cultivation might also be beneficial for its indirect effect on the wealth conditions, not only by reducing the GHG emission, but also because of the improvement in household incomes (double dividend) through an increase of employment in agriculture. Our reference case, for instance, would ensure a stable annual income for 27 workers, in one of the poorest regions of the World.

[35] Assuming that the investment opportunity is lost after the deadline; otherwise, it would be back to the perpetual case.

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