Life cycle analysis of macauba palm cultivation: a promising crop for biofuel production

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Abstract

The 450 Scenario, which limits the increase in global average temperature to 2 ºC, makes it necessary to take steps towards a low-carbon economy. Since the energy sector is a major contribution to anthropogenic greenhouse gas (GHG) emissions, the production of biofuels can play a key role in strategies aimed at climate change mitigation. In this regard, the oil derived from macauba palm (*Acrocomia aculeata*), mainly constituted of saturated organic chains, has been claimed to hold promise for the production of liquid fuels. The high potential yield, diversity of co-products and various positive features of this emerging energy crop make it an interesting option both from a social and an environmental point of view. Nonetheless, a full environmental evaluation is still missing. In the study presented herein, the impacts produced in its plantation, cultivation and harvesting phases and the associated cumulative energy demand have been determined using a life cycle analysis methodology, in addition to shedding some light on its GHG intensity relative to the other energy crops it can displace. Excluding land use changes and biogenic CO_2 fixed by the crop, it was concluded that to produce one ton of macauba fruit in Brazil, the system would absorb 1810.21 MJ, with GHG emissions of 158.69 kg CO_2eq in the 20-year timeframe, and of 140.04 kg CO_2eq in the 100-year timeframe (comparable to those of African oil palm). Damage to human health, ecosystem quality, and resources would add up to 16 $Pt{\cdot}t^{-1}$ according to Eco-indicator 99 methodology. In order to account for the uncertainty derived from improvement and domestication programs, which should affect current production levels, a sensitivity analysis for different productivities was performed. In all analyses, fertilization was found to be responsible for ca. 90% of the impacts, and hence special attention should be paid to the development of alternative fertilizer management schemes.

Keywords: *Acrocomia aculeata*; bioenergy; Brazil; life cycle assessment (LCA); macauba; sustainability.

1. INTRODUCTION

The increase in the energy needs for the development of our world opens the door to new sources of energy that can be used as biofuels. In this regard, the Intergovernmental Panel on Climate Change (IPPC) has stressed that bioenergy can play a key role in the mitigation of climate change, but has also highlighted the need to take into consideration the sustainability of practices and the efficiency of technologies. Thus, there is a need for crops with low emissions throughout their life cycle, compatible with land sustainable management, with a low water footprint, etc.

Amongst the emerging agroforestry crops with a high energy potential, macauba palm (*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.) has been claimed to hold particular promise (Berton et al., 2013; Coimbra and Jorge, 2012; Montoya et al., 2016). It can be dedicated to the direct mitigation of climate change, due to its ability to contribute to the production of biomass of high energetic power, through esterification, and therefore of bioenergy.

Macauba palm presents an interesting productivity that places it among the main agro-energy crops: 25 t fruit·ha^{-1}·yr^{-1} with a high oil content (50-75%), that is, 6200 kg of oil·ha^{-1}·yr^{-1}, comparable to the productions obtained from African oil palm (*Elaeis guineensis* Jacq.) (Cargnin et al., 2008; César et al., 2015; Ciconini et al., 2013; Pires et al., 2013). Given the good prospects for its genetic improvement and domestication, current production is expected to rise above 6500 kg oil·ha^{-1}·yr^{-1}, provided that in recent studies the figures for extracted oil have already exceeded this amount for scenarios of 400 plants·ha^{-1}, surpassing even African oil palm in terms of liters of biodiesel·ha^{-1} (Colombo et al., 2017; Luis and Scherwinski-Pereira, 2017; Vianna et al., 2017).

This palm has similar characteristics to those of other forestry or agricultural residues widely used in the production of biofuels, and is already acclimated to subtropical climates because it is native to Brazil (Cardoso et al., 2017; César et al., 2015). Such adaptation of macauba to a high-range of hydrothermal stressors facilitates the extension of its cultivation and exploitation to marginal lands with grassland coverings and its implantation in slopes. Further, it is suitable for the regeneration of burned land without plant cover (Motoike and Kuki, 2009).

Macauba palm can open up a wide range of possibilities upon combination with livestock activity, with associated savings in fertilizers and the elimination of herbicides throughout the life cycle of the crop (Araújo et al., 2017; Delucchi, 2010). By-products generated after the extraction of the oil are susceptible of use as animal feed (Ali et al., 2017a; Ali et al., 2017b; Costa Júnior et al., 2015; Henrique Bernardes Pereira et al., 2013), and the endocarp of the fruits can be employed for vegetal carbon production (Bhering, 2009; Ministério do Desenvolvimento Agrário, 2014), as a biosorbent for heavy metals removal in wastewater (Altino et al., 2017; Vieira et al., 2012), or for biokerosene production (Cardoso et al., 2017; Zelt, 2018). Finally, other alternative uses would be related to the potential applications of the bioactive compounds present in its oil and in some other plant by-products (Dario et al., 2018; Lescano et al., 2014; Oliveira et al., 2016; Shahidi and de Camargo, 2016; Souza et al., 2017a).

Amongst the positive characteristics of this crop, one may also count its potential for poverty reduction and local economic development, acting as a source of employment, contributing to rural development and to population fixation (Lopes et al., 2013).

However, regardless of aforementioned advantages, no system should be considered *a priori* as acceptable or optimal without having studied all the involved aspects that generate emissions of GHGs. The goal of this study has been to evaluate if this agroforestry crop can help mitigate some of the great challenges that climate change entails for the future of the planet, and if its introduction can be deemed as a strategy of adaptation to climate change and a maneuver aimed at the de-carbonization of the environment in a short-term time horizon. To do so, the study presented herein aims to assess the emissions produced by macauba palm plantation, cultivation and harvesting in Minas Gerais, Brazil. By using a life cycle analysis (LCA) methodology, the direct and indirect impacts that affect the ecosphere (Singh et al., 2013) have been estimated, a sensitivity analysis has been performed, and a semi-quantitative comparison with other energy crops has been conducted, paying particular attention to African oil palm. Possible adaptation and mitigation strategies are outlined.

2. MATERIALS AND METHODS

2.1. *Life cycle analysis methodology*

A LCA methodology was chosen to study the potential impact on the environment per ton of macauba fruit produced (and transported to an oil extraction factory 40 km far from the plantation). Inflows (resources) and environmental outflows (emissions), were studied according to ISO 14040: 2006 (Environmental management - Life cycle assessment - Principles and framework), selecting an attributional LCA (ALCA) methodology (Plevin et al., 2014; Recchia, 2011) to faithfully represent the environmental burden needed to produce our functional unit. This approach focuses on the physical flows with environmental relevance to and from a life cycle and its subsystems, tracking the energy and material used throughout the supply chain of the crop studied, including all flows of the agroforestry crop (understanding the crop as a product system) throughout the agricultural operations necessary to produce it, to harvest it and to transport it to the industry of extraction and process.

The ALCA model was preferred over the consequential LCA (CLCA) because the latter is oriented to the description of how these flows are affected by the economic or policy context, and thus would be more oriented to decision making.

2.2. *Goal and scope*

The objective of this study was to assess the macauba palm product system by systematically evaluating the environmental impacts per ton of macauba fruit –assuming a production of 900 $t \cdot ha^{-1}$ in 30 years–, including the generation of pre-seedlings, seedlings, field preparation, planting, cultivation, harvesting and transport of fruits to the gate of industry were they will be transformed into biodiesel. The industrial phase was excluded from the analysis because of the lack of a well-established and representative biodiesel production procedure for this crop[a].

Consequently, the study included the input/output flows of raw materials, as well as energy and human and animal labor. All required services (inputs, such as the transport involved to provide fertilizers to the crop) and all emissions to the environment were evaluated at the inventory stage (European Commission et al., 2010).

The ALCA "cradle to farm gate" analysis can be regarded as an "upstream" approach from the oil extraction industry that gives added value to the macauba. Chronologically, it encompasses all inventory phases that occur before "gate to gate" impacts can occur, prior to the

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[a] It is worth noting that at present there is no consensus on any of the manufacturing stages. For instance, different approaches have been proposed for the oil extraction: using compressed propane (Trentini et al., 2017b); using *n*-hexane, ethyl acetate and isopropanol at low pressure (Trentini et al., 2016); by Soxhlet method with ethanol, hexane and ethyl ether (Lescano et al., 2015); using ethanol and isopropanol (Trentini et al., 2017a); etc. Moreover, different storage conditions and treatments would also need to be assessed, as they influence oil quality (Evaristo et al., 2016b). Further, there is not an agreement either on which would be the best method for conversion to biodiesel (viz., supercritical method, enzyme hydroesterification, alkaline transesterification by homogeneous catalysis with microwave irradiation, cold-flow esterification and transesterification using different alcohols, etc.) (Pereira et al., 2016; Silva et al., 2016; Souza et al., 2016).

entry of the harvested raw material –with high calorific value– to the processing industry (biodiesel production).

2.3. *Indicators*

Depending on the goal and scope of the study, one or more impact categories may be included in the life-cycle impact assessment (LCIA). While global warming potential (GWP) and energy consumption are often included in bioenergy system LCAs, a full environmental evaluation should consider other categories related to impacts to soil, water, air, human health, and ecosystems (Cherubini and Strømman, 2011; Muench and Guenther, 2013). Thus, to determine the environmental burden generated by the product system, relevant impacts were evaluated through three different indicators, estimating in a quantitative manner: (*i*) the primary energy demand (with Cumulative energy demand (CED) v.1.09 method); (*iii*) the GHGs emissions (with IPPC 2013 methodology); and (*ii*) the damage in terms of emissions, land use and resource depletion (with Eco-indicator 99 methodology).

2.3.1. *Cumulative energy demand*

As regards the quantitative estimation of the total energy demand in the life cycle of the system, CED v.1.09 provides a measure of the primary energy demand of the product, that is, the energy content of energy carriers that have not yet been subjected to any conversions, while taking losses due to transformation and transport fully into account. The necessary energy per functional unit is expressed in MJ, and normalization is not part of this method. Characterization factors are divided in 5 impact categories: non-renewable, fossil; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; and renewable, water (Frischknecht et al., 2007; Weidema et al., 2013).

2.3.2. *IPCC 2013 methodology*

The IPCC 2013 method is the successor of the IPCC 2007 method and has been developed on the basis of the Climate Change 2013 report (IPCC, 2014). This method evaluates the factors that affect climate change with a timeframe of 20 and 100 years, using CO_2eq units. However, the characterization factors do not include the indirect NO_2 formation of nitrogen emissions; do not take into account the radiative forcing from NO_x, water, sulfate, etc. emissions in the lower stratosphere or in the upper troposphere; do not take into consideration the range of indirect effects proposed by the IPCC; and do not include the formation of CO_2 by CO emissions. The methodology used in this study corresponded to version 1.02 (March 2016) for the 20-year timeframe and to version 1.09 (August 2014) for the 100-year timeframe.

2.3.3. *Eco-indicator 99 methodology*

Eco-indicator 99 (EI-99) is a damage-oriented methodology for calculating the impacts on three main categories (endpoints): damage to human health, expressed in DALY ("disability adjusted life years") units; damage to ecosystem quality, measured in PDF·m^2·yr, where PDF stands for "potentially disappeared fraction"; and damage to resources, measured in MJ of surplus energy. As regards the weighting model, in this study the *egalitarian* archetype was chosen, which has a very long term perspective and that takes into account all possible effects. The aggregated LCA results are expressed in points (Pt) per unit of analyzed material/process.

2.4. *Functional unit and system boundaries*

In the study presented herein, the functional unit was a metric ton of macauba with 36% humidity.

The system boundaries are depicted in Figure 1. They included the production of pre-seedlings (nursery), seedlings, preparation of the land, planting, cultivation, harvesting and transport to the extractive industry located 40 km apart from the plantation. The transportation of the necessary machinery to carry out the planting, the transportation of the fertilizers and agrochemical products, and -in general- all the inflows and outflows of each of the two systems (technological and natural) that integrate the ecosphere were also taken into consideration.

[FIGURE 1]

The use of the macauba crop was assumed to be the extraction of oil for biofuel production, either in its purest state or as a base for mixing with other hydrocarbons. The production or use of by-products was not taken into consideration in the system (see section 2.10, in which all items excluded from the analysis are detailed), which was limited only to the primary production of the functional unit. Further, any interaction of aforementioned functional unit with other products or systems that are not part of this study, such as economic interactions or interactions with other non-evaluated technical systems, was discarded (since they cannot be taken into account in an ALCA methodology). Intending to include all these interrelations would surely alter the output of the results object of the study.

2.5. *Assumptions*

It should be clarified that, in relation to the spatiotemporal location of the study, it was conducted with data referring to Minas Gerais, Brazil in 2017, which that cannot be directly extrapolated to other regions (Chiaramonti and Recchia, 2010; Ossés de Eicker et al., 2010). For the extrapolation of crop LCA, the use of Modular EXtrapolation of Agricultural LCA (MEXALCA) method would be the preferred approach, as it does not discard processes nor jeopardize the understanding of the production system upon derivation of LCIA results for a crop in a specific (target) country using the LCIA data of the same crop in another (original) country (Roches et al., 2010).

A plantation of macauba palm with an extension of 30 hectares, 40 km far from a medium-sized city of about 15,000 inhabitants (Mirabella, State of Minas Gerais, Brazil) and 70 km far from a large city of 360,000 inhabitants (Montes Claros, State of Minas Gerais, Brazil) is proposed.

The selected area for the plantation is in the Minas Gerais (Brazil) region, near 16°29'54.90" S, 44°4'12.43" W geographical coordinates, at an altitude of 818 m above sea level. This region is part of a neotropical savannah that includes parts of Brazilian federal states and extends from the Equator to the Tropic of Capricorn, and is representative of the potential growing areas for this agroforestry crop (Falasca et al., 2016). According to Köppen classification, the *Cerrado* biome exhibits a typical Aw climate (humid tropical savannah) with a distinct dry season between May and September. The average annual precipitation is 1200 mm.

Since in this area there are no commercial plantations older than seven years, both consumption and production have had to be estimated beyond the 8th year.

The total amounts of inputs/machinery/human labor per hectare of macauba palm plantation is summarized in Table S1. The transport of raw materials/machinery was assumed to be carried out from different centers/cities: for the production of macauba pre-seedlings, 366 km; for the production of macauba seedlings and their transportation to the plantation, 366 km; for the heavy machinery rented for the land preparation and planting operations: 70 km; for the purchase of machinery (tractors and agricultural machinery) for agroforestry tasks, 40 km; for the acquisition of fertilizers (6:30:6, 20:5:20, 10:10:10 nitrate, phosphorus, potassium, with boron, zinc, copper, urea, lime and KCl microelements), 70 km; and for the acquisition of agrochemicals (herbicides and insecticides, in particular thermicides and formicides), 70 km. Transportation media have been restricted to those currently existing in Brazil, employing a maximum payload of 20 t.

The fertilization treatments discussed in previous paragraph was deemed as optimal to maximize fruit production in the agrometeorological conditions of the area of study. The objective was to provide plants with the necessary macro- and microelements to complete their vegetative cycle, obtaining a favorable development and an excellent productivity, without introducing factors that could alter the potential of biomass per unit of area (Machado et al., 2015).

The extraction, esterification or final disposal of the residues generated by the crop in its industrial phase were not included, and no recovery, reuse, recycling or use of by-products that can be obtained from the waste generated from the macauba plantation were considered (see section 2.10). For instance, the agricultural by-product obtained from the exploitation of the palm trees referred to as "*tusa*" (empty palm bunch, rachis of the macauba), which is a lignocellulosic material that contains 60-65% moisture and 1-3% vegetable oil, was not taken into consideration. The phase of use of the biofuel generated after the industrial extraction phase was not considered either.

The expected macauba production was estimated by sampling 100 wild (non-cultivated) macauba plants in the surroundings of the plantation considered in this paper. The number of fruit bunches was counted, resulting in an average of 2.39 bunches per plant, with a standard deviation of 1.37 and a median of 2. For these same 100 wild macauba plants, fruits were weighed, obtaining an average of 24.52 kg of fruit per bunch with a standard deviation of 8.27 and a median of 24.58 kg per bunch. Thus, considering 461 macauba palm trees arranged in a 5×5 m frame equilateral triangle distribution (i.e., 21.65 m^2 per macauba palm tree), with an average of 2.39 bunches per palm tree and an average weight of 24.52 kg of fruit per bunch, a total production per hectare of 900 t over the 30 years of cultivation would result. This would be in good agreement with the results reported by Lopes and Steidle Neto (2011).

A propos of the use of the land, it was supposed that it was not modified (see section 2.10), conserving the silvopastoral exploitation system (i.e., the destruction of forest or the change of land use were not contemplated in the study). To include the effect of indirect land use change effects (ILUC) on GHGs, a CLCA would be needed (McManus and Taylor, 2015; Plevin et al., 2014; Rajagopal, 2014), which is beyond the scope of this work.

2.6. *Data and data quality*

The data used in the LCA corresponded to current and real agricultural production processes that use cultivation methods, raw materials, phytosanitary products, fertilizers (NPK) and machinery for African oil palm production.

Both the machinery used and the means of transport corresponded to the geographical area where the study was carried out (Minas Gerais, Brazil) and to agricultural processes, machinery and conditions that are currently in force. Existing technologies were used for the materials, products and agroforestry area that came into play, appropriate for a limited geographic area as well as for a defined spatiotemporal window (less than three years from the obtaining of the data to the preparation of this study).

These data satisfied all the requirements to define the chosen functional unit and ensured that the study was within the defined system limits.

The integrity used in this study was higher than 97% (percentage of measured or estimated flow). The remaining 3% would not be representative and would have no significant impact on the study as a whole. No phase or stage that was expected to modify either the conclusions or objectives of the study was excluded.

2.7. *Life cycle inventory*

The life cycle inventory (LCI) was carried out with the following databases (with data updated as of June 2017 and that corresponded to the year 2017): Ecoinvent 3.4, Agri-footprint, EL CD, Industry data 2.0, LCA food DK, EU & DK Input Output Database, Methods (based on existing ESU database in Swiss IO Database), Swiss Input Output Database, USA Input Output Database, US Database System Expansion and USLCI.

2.8. *Allocation*

The allocation of the inflows/outflows of the different products was carried out by means of a “physical allocation” with data on the energy used and from the mass/quantity and hourly distribution of each one of the tasks of each of the processes considered throughout the entire cultivation process. All the stages and sub-stages leading to the functional unit result were taken into account.

2.9. *Reproducibility, coherence and representativeness*

The LCA of the functional unit under study can be deemed as reproducible by culture methods that can be produced with the same inputs and outputs into the environment taken into account in this study. All the necessary data are available and complete in this work, so that it can be repeated in an experimental manner. The data used in this LCA study are technically and scientifically valid and are in accordance with the reality of the country where it is geographically located. The data handled in this study (*viz*. processes, flows, materials, tillage, labor and energy required) are representative of current cultivation processes, geographically referred to Minas Gerais, Brazil and with a space-time window of three years, to ensure an optimal representativeness of each of the handled parameters.

2.10. *Further clarifications to the study*

Explicit consideration shall be given to the possible limitations of the conclusions due to parts of the product system that were excluded from the analysis. The following points were intentionally not taken into consideration in this study:

- The effects of soil transformation from pasture/woodland into agroforestry land. As noted above, the current use of the land is conserved, not generating deforestation of virgin jungle or lands with a current silvicultural use.
- The impact on biodiversity due to land use transformation.
- The externalities created by the cultivation of the macauba, such as by-products susceptible to employment in animal feed, charcoal generation, etc.
- The use of by-products from pruning/harvesting in animal feed or other use.
- The CO_2 emitted by the burning of by-products of the macauba plantation.
- The biogenic CO_2 fixed by the crop in the plant mass created by the plantation.
- NH_3, N_2O, N_2 and NO emitted by the plantation to the atmosphere.
- The burning of residues during land preparation, their destruction or the originated CO_2.
- The coverage of the land with other crops associated with the macauba during the initial stages of growth, until it enters into production.
- The emissions produced by the pruning waste deposited in the soil, biomass in decomposition.
- The percolation of fertilizers, N and K, from the soil of the plantation.
- The contamination with heavy metals (Hg, As, Cr, Se, Ni, Mo, etc.) by percolation resulting from the use of fertilizers.
- The emissions produced when using pesticides in the plantation.
- The emissions derived from land cover in the plantation, decomposing biomass.
- The recycling of polyethylene from the bags of macauba seedlings.

- The recycling / reuse of fertilizer containers (sacks), insecticides / phytosanitary / formicidal / insecticide containers at a packaging of plant protection products waste collection point.
- The recycling of seedling containers and polystyrene trays.
- The empty return and the average load of the means of transport in the material transport system.
- The necessary infrastructures for the implementation, handling and transport of the products.
- The elimination of the plantation once it reaches the end of its production period (after 30 years).

2.11. *Software*

Simapro v.8.2.0.0 software (PRé Sustainability, Amersfoort, The Netherlands) was used in this study.

3. RESULTS

3.1. *Cumulative energy demand methodology*

As regards the quantitative estimation of the total energy demand in the life cycle of the system, the obtained result for the case of study was 1810.21 MJ per ton of macauba fruit, broken down into three main activities according to the following Sankey diagram (Figure 2*a*).

[FIGURE 2]

The energy embedded in the system would thus mostly correspond to the cultivation stage (90.93%), followed by the harvest (6.98%) and the tree planting (2.09%). Attention should be paid to the fact that 89.41% of the energy required in the cultivation stage would be invested in activities related to the fertilization of the plantation.

3.2. *IPCC 2013 methodology*

In relation to the climate change factors of IPCC with a timeframe of 20 years, the results are shown in Figure 2*b*. The set of activities aimed at the maintenance and conservation of the plantation would represent 92.87% of the total CO_2 emissions per ton of fruit obtained. It is worth noting that out of those 147.38 kg $CO_2eq\cdot t^{-1}$ of fruit associated to the cultivation stage, fertilizers would be responsible for 90.85% of the GWP.

The results for the 100-year timeframe are summarized in Table 1. In this case, the total GWP would add up to 140.04 kg CO_2eq per ton of macauba fruit. The cultivation stage would involve 92.4% of the total emissions and, out of those 129.37 kg $CO_2eq\cdot t^{-1}$, fertilizers would account for 89.5% of the GWP.

[TABLE 1]

3.3. *Eco-indicator 99 methodology*

As concerns the impacts on air, water, soil, land use, land occupation, soil conversion, MJ for material extraction, MJ of energy extracted, MJ of energy used, etc. created by the system, they are summarized for the three main categories in Figure 3. It follows that the activity that has the greatest damage to human health, to the quality of the ecosystem and to resources is the cultivation stage, accounting for 92.1%, 88.4% and 89.4% of the total endpoints, respectively. On the other hand, the initial plantation (which encompasses the pre-cuttings, cuttings (saplings), open streets, land preparation and planting saplings operations) represented less than 2% of the damage in all the three categories.

[FIGURE 3]

A breakdown of the damage for all the impact categories is depicted in Figure 4. One may observe that most of the impact associated to macauba cultivation corresponded to the respiratory inorganics category (ca. 40%), i.e., respiratory health risks resulting from winter smog caused by emissions of dust, sulphur and nitrogen oxides to air. Fossil fuels depletion accounted for ca. 29% of the damage, followed by carcinogens (toxicological risk and potential impacts of carcinogenic chemicals released into the air, water, soil, and agricultural soil), which represented ca. 15% of the total damage, and by climate change (with ca. 9% of the total damage). The fossil fuel score can be ascribed to the amounts of fossil fuels used in the agrochemicals production, in crop-related operations involving machinery (tilling) and in transportation (both inside the plantation and from the plantation to the oil extraction factory), which would also be responsible for the scores in respiratory inorganics and climate change. The use of phytosanitary products and fertilizers would in turn be the main cause for carcinogens.

[FIGURE 4]

If one focuses only on the cultivation stage, which –as noted above– would be responsible for most of the damage, the impact throughout the 30 years of cultivation for several of the operations is shown in Figure 5. The fertilizers used (viz. urea, phosphate fertilizer y potassium fertilizer) would be responsible for 88% to 93.5% of the total impacts generated, depending on the category, while the impact associated with lime, pyrethroid, glyphosate, 2,4-dichlorophenoxyacetic acid, weed-killers, insecticides, formicides, mowing, transportation, etc. would account for the ca. 10% remaining damage. This is line with other studies for other energy crops (Ndong et al., 2009; Rodrigues et al., 2014; Siregar et al., 2015).

[FIGURE 5]

3.4. *Sensitivity analysis*

A sensitivity analysis was conducted by changing the productivity of the macauba crop per hectare, provided that the ongoing domestication and breeding programs of this species for oil yield –which have revealed specimens with a potential to produce as much as 10 t oil·ha^{-1}·y^{-1} (Galembeck and Abreu Filho, 2017)– would represent an importance source of uncertainty that could affect results and conclusions (Castro et al., 2017; Simiqueli et al., 2018). The inputs for pre-cuttings, cuttings, the plantation and the cultivation were kept fixed, while those associated with the harvest stage were modified (as a consequence of the differences in the transport of the fruits inside the plantation and from the plantation to the oil extraction factory). Results are summarized in Figure 6.

As regards the CED, it would change from 1721.22 MJ·t^{-1} for a productivity of 800 t·ha^{-1} to 1449.33 MJ·t^{-1} for a productivity of 1000 t·ha^{-1} (ca. 34 MJ/25 t of fruit on average). Thus, increasing the crop productivity from 800 to 825 t·ha^{-1} would decrease the CED by 2.90%, while by increasing the productivity from 975 to 1000 t·ha^{-1} a 2.35% reduction would be attained.

The GWP values with the IPCC 2013 methodology in the 20-year timeframe would range from 177.48 kg CO_2eq·t^{-1} to 143.66 kg CO_2eq·t^{-1} for productivities of 800 t·ha^{-1} and 1000 t·ha^{-1}, respectively. This would imply that an increase in productivity of 25 t·ha^{-1} would entail, on average, a reduction of ca. 4.2 kg CO_2eq. As the productivity is increased, the changes are again less marked: increasing the productivity from 800 to 825 t·ha^{-1} would decrease emissions by 2.96%, while increasing the productivity from 975 to 1000 t·ha^{-1} would decrease emissions by 2.4%.

If the 100-year timeframe is considered instead, the emissions would range from 156.55 kg CO_2eq to 126.82 kg CO_2eq for productivities of 800 t·ha^{-1} and 1000 t·ha^{-1}, respectively. In this case, an average decrease of ca. 3.7 kg CO_2eq would be attained upon an increase in productivity of 25 t·ha^{-1}.

Apropos of the damage to the environment, estimated with EI-99, it would vary between 17.83 Pt·t^{-1} (for a productivity of 800 t·ha^{-1}) and 14.49 Pt·t^{-1} (for a productivity of 1000 t·ha^{-1}). An increase in crop productivity of 25 t·ha^{-1} would result in an average decrease of around 0.42 Pt, with a maximum decrease of 2.84% for the 800 to 825 t·ha^{-1} productivity improvement and a minimum decrease of 1.92% for the 975 to 1000 t·ha^{-1} improvement.

[FIGURE 6]

4. DISCUSSION

4.1. *Comparison with other energy crops*

It should be stressed that the scarcity of case studies on LCA of the cultivation stage of energy crops (most studies focus on the actual biofuel production stage (Castanheira and Freire, 2016)), together with the differences between studies (in terms of the chosen indicators, the assumptions, the boundaries, the secondary data, data quality, etc.), make it impossible to make direct comparisons (Chiaramonti and Recchia, 2010; Shonnard et al., 2015). Furthermore, although the majority of the studies in the literature have focused on GHG emissions and energy requirements (Shonnard et al., 2015), there is no common agreement in relation to the units (i.e., results may be expressed per ton of fruit/fresh fruit bunches, per ton of crude oil, per ton of refined oil, per ton of biodiesel, per ha, per MJ, etc.), which further which jeopardizes the comparison between studies[b].

For instance, the treatment of biogenic carbon may lead to significant differences in LCA results: Rodrigues et al. (2014) studied the GHG balance of crude palm oil from *E. guineensis* for biodiesel production in Brazil and concluded that the system worked as a carbon sink because it fixed approximately 1.1 times more CO_2 than it released: the system could attain a sequestration of 166.42 kg $CO_2eq \cdot t^{-1}$ of crude palm oil or up to 207.96 kg $CO_2eq \cdot t^{-1}$ by partial substitution of synthetic fertilizers by organic ones (a strategy from which the system presented herein could also benefit). However, this negative emissions balance would result from taking into consideration the large quantity of CO_2 captured during the growth of palm trees, whereas in the study presented herein such biogenic CO_2 fixed by the crop in the plant mass created by the plantation was excluded from the analysis, as noted in subsection 2.10. A reduction of approximately 10 $Mg \cdot ha^{-1}$ of CO_2 for each hectare planted with *A. aculeata* may be expected throughout its production cycle (César et al., 2015).

Rivera-Méndez et al. (2017) analyzed the carbon footprint of the production of African oil palm fresh fruit bunches (FFB) in Colombia and estimated the emissions in 118 kg $CO_2eq \cdot t^{-1}$ of fresh fruit bunches, slightly lower (ca. 8.8% lower) than the 129.37 kg $CO_2eq \cdot t^{-1}$ estimated herein for the cultivation stage of macauba.

Silalertruksa et al. (2017) studied the environmental sustainability of African oil palm cultivation in different regions of Thailand. GHG emissions results (estimated using IPCC 2007 GWP100)

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[b] For instance, refined oil and not crude oil should be used for the functional unit, since different crude oils contain different levels of impurities and free fatty acids that are removed in the refinery stage (hence, the crude oils are not substitutable in a one to one ratio) (Schmidt, 2015).

varied over a large range: from 183 kg $CO_2eq·t^{-1}$ FFB in the Northeast and 137 kg $CO_2eq·t^{-1}$ FFB in the North to 94 kg $CO_2eq·t^{-1}$ FFB in the South, depending on the productivity, growers' practices and the transport of raw materials. Stichnothe and Schuchardt (2011), who studied the GWP of African oil palm production in Indonesia and Malaysia, also found GWP100 values (using IPCC 2007 methodology) slightly above 100 kg $CO_2eq·t^{-1}$ FFB for its cultivation (excluding land use change (LUC), since if rainforest or grassland is converted to palm oil plantations in Malaysia or Indonesia, this would cause between 1850 and 425 kg $CO_2eq·t^{-1}$ of FFB). For comparison purposes, the GWP100 (recalculated with IPCC 2007 methodology to allow comparison) for macauba cultivation was 141.54 kg $CO_2eq·t^{-1}$ of fruit, so it would be close to or slightly higher than the average GWP100 for African oil palm.

If one expresses the results per MJ, in a meta-analysis of over 70 environmental LCA studies of liquid transportation biofuels in the Pan American region, Shonnard et al. (2015) concluded that the GHG emissions (excluding the LUC effect) of African oil palm cultivation were on average 25 g $CO_2eq·MJ^{-1}$. Taking a lower heating value for biodiesel of 37.1 $MJ·kg^{-1}$ (Iriarte et al., 2012), a density of 0.916 $g·cm^{-3}$, and considering that 1 t of macauba fruit yields 200 l of biodiesel (Colombo et al., 2017; del Río et al., 2016; Evaristo et al., 2016a), a GWP value of 23.34 g $CO_2eq·MJ^{-1}$ would result, which again is very similar to that of palm oil biodiesel.

In terms of CED, Harsono et al. (2012) studied the energy balances of *E. guineensis* oil biodiesel in Indonesia and concluded that the total energy input for commercial plantations was 81.82 $GJ·ha^{-1}·yr^{-1}$. Subtracting the industrial phase and the land use change contributions, the energy input would be 45.73 $GJ·ha^{-1}·yr^{-1}$. If one compares it with the values for macauba, (1810.21 $MJ·t^{-1}$ of macauba fruit × 900 $t·ha^{-1}$) / 30 yr = 54.3 $GJ·ha^{-1}·yr^{-1}$, the energy input would be higher for macauba, but its higher biodiesel yield (ca. 200 l $biodiesel·t^{-1}$ fruit for macauba) would compensate for it, in such a way that the total energy input in $GJ·t^{-1}·yr^{-1}$ biodiesel would be very similar: 10.66 for African oil palm *vs*. 10.86 $GJ·t^{-1}·yr^{-1}$ biodiesel for macauba palm.

Apropos of other energy crops, Siregar et al. (2015) studied the LCA of African oil palm and physic nut (*Jatropha curcas* L.) as a feedstock for biodiesel production in Indonesia. They found that the values of 100-year GWP (IPCC 2007) for producing 1 t of biodiesel fuel from

African oil palm and *Jatropha curcas* were 2568.82 and 1733.67 kg CO_2eq, respectively. Upon subtraction of the oil extraction and biodiesel production stages, the impact derived from the planting, cultivation and harvesting stages would add up to 1378.36 and 817.25 kg $CO_2eq\cdot t^{-1}$ biodiesel, respectively. Assuming that the biodiesel yield per ton of macauba fruit is ca. 200 l (0.184 t), and considering that for 1 ton of fruit the GWP was 141.54 kg CO_2eq (recalculated with IPCC 2007 methodology), the GWP100 per ton of macauba-derived biodiesel would be around 769.2 kg CO_2eq, so it would be lower than those of the other two crops. Regarding the energy consumption, it was 25667 $MJ\cdot t^{-1}$ biodiesel for African oil palm and 15872 $MJ\cdot t^{-1}$ biodiesel for *Jatropha curcas*, higher than the 9838.1 $MJ\cdot t^{-1}$ biodiesel for macauba.

In the case of biodiesel derived from castor-bean (*Ricinus communis*) oil, Amouri et al. (2016) reported that GHG emissions during the cultivation stage were 452.38 kg $CO_2eq\cdot t^{-1}$. Assuming that the oil content in castor-seeds is ca. 43%, and taking into consideration its density (0.96 $g\cdot cm^{-3}$), 412.8 l oil per ton of seeds would be obtained, resulting in a GWP of 1.09 kg $CO_2eq\cdot l^{-1}$ biodiesel for *Ricinus communis*. In turn, the GWP emissions for macauba (using Impact 2002+ methodology, to allow a certain degree of comparison) would be noticeably lower (147.38 kg CO_2eq/200 l biodiesel, i.e., ca. 0.74 kg $CO_2eq\cdot l^{-1}$ biodiesel).

Finally, Schmidt (2015) compared the IPCC's GWP100 for several different refined vegetable oils and found that the agricultural stage involved 3016, 976, 718 and 949 kg $CO_2eq\cdot t^{-1}$ of oil for palm oil, rapeseed oil, sunflower oil and peanut oil, respectively. Considering that the estimated GWP100 for macauba (recalculated with IPCC 2007 methodology) was 141.54 kg $CO_2eq\cdot t^{-1}$ of fruit and that 25 t $fruit\cdot ha^{-1}\cdot yr^{-1}$ result in 6200 kg of $oil\cdot ha^{-1}\cdot yr^{-1}$ (0.248 conversion factor), the GWP100 value per ton of oil would be 570.7 kg CO_2eq, lower than those of the four aforementioned oils.

4.2. *Adaptation and mitigation strategies*

As noted by Dislich et al. (2017), strategies are required to improve the capacity for local adaptation to reduce climate impacts and maintain regional stability in oil production. An in-depth analysis of the opportunities offered by macauba palm cultivation to mitigate the share of GWP emissions that directly depend on land use and land management techniques is beyond the scope of this study (for an analysis of bioenergy as a climate mitigation option within a 2 ºC target, the interested reader is referred, for instance, to the recent works by Creutzig et al. (2015); Röder and Thornley (2016); Souza et al. (2017b)). Nonetheless, in view of the LCA results, which show that the impact in all three indicators could mostly be ascribed to NPK fertilization, a brief comment on this matter may be useful.

Adaptive nitrogen and soil health management strategies should be regarded as a must with a view to mitigating and adapting to climate change in the case of macauba cultivation. An overall reduction of N-fertilizer use would lead to a significant reduction of the associated CO_2 emissions from the Haber-Bosch process that produces these fertilizers, from their transportation and application, and would reduce losses of nitrous oxide too, which is by far the largest source of greenhouse gas emissions associated with agriculture. To reduce N_2O emissions from applied N fertilizer, the four main management factors (commonly known as the 4R's) should be implemented: namely, right N application rate; right formulation (fertilizer type; possible replacement by other fertilizers that are equally effective but of less polluting origin or waste that can enter the life cycle of the product mainly by fertilizers of organic origin); right timing of application; and right placement. Best agricultural practices should be established with the help of sensors and an adequate fertilizer plan adapted to the needs of the crop and the expected productions. A reduction of nutrient losses by up to an average of 30 percent may be obtained with such improved management practices, according to the International Fertilizer Association.

The use of technologies such as foliar application; coated soluble granules (to allow controlled release of nutrients in the root zone); urea deep placement (to improve nitrogen recovery); addition of inhibitors (to slow the conversion of urea fertilizer to ammonia and thereby minimize potential ammonia loss to the atmosphere); and fertigation are also amongst the options that would need to be contemplated so as to effectively minimize the negative impacts of fertilizers on the environment. Besides, organic agriculture strategies should be examined, in line with IPCC's Assessment Report, as they offer added benefits (e.g., recycling of crop waste intensifies biological activities of soils, enhances biodiversity as well as nitrogen fixation and improving phosphorous availability by symbiosis; organic farming builds up soil fertility and increases or conserves soil organic matter; it can synchronize supply and demand of nutrients, conserving water and sequestering CO_2 into the soil, etc.). In short, improving soil health, carbon and nitrogen management would provide win-win opportunities, increase profits and decrease environmental losses, as shown, for instance, in the study by Rodrigues et al. (2014) mentioned above.

Finally, attention should be paid to the fact that improvements will be required in the macauba palm nutrients uptake efficiency by breeding for suitable root systems: prolonged root uptake and better remobilization of nutrients are targets for breeding, provided there is sufficient plasticity of these characteristics (Rival, 2017).

5. CONCLUSIONS

A full environmental evaluation, including not only global warming potential and energy consumption, but also other categories related to impacts to soil, water, air, human health, and ecosystems was conducted for *Acrocomia aculeate* planting, cultivation and harvesting, using IPCC 2013, CED and EI-99 methodologies. It was found that the introduction of macauba palm as a candidate for the production of biofuels *a priori* presents environmental benefits as compared to energy crops such as rapeseed, sunflower, castor seed or physic nut. Moreover, the 100-year GWP (ca. 140 kg $CO_2eq \cdot t^{-1}$ of fruit) and CED (1810.21 $MJ \cdot t^{-1}$ of fruit) associated with its cultivation would be comparable to those of *Elaeis guineensis*. Nonetheless, from the LCA it becomes apparent that there is room for improvement in terms of the impacts produced, in particular in relation to fertilizers, which contributed with ca. 90% of the GHG emissions, energy consumed by the crop and damage to all the environmental impact categories. Consequently, future lines of research aimed at the development of alternative fertilizer management schemes, including for instance the replacement of conventional NPK solid fertilizers by foliar fertilizers or compost, should have a remarkable effect on the sustainability of this emerging energy crop.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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TABLES

Table 1. Breakdown of IPCC 2013 results in the 100-year timeframe (in kg $CO_2eq \cdot t^{-1}$ of macauba fruit).

Stages					
Tree planting		Cultivation		Harvest	
Operation	GWP	Operation	GWP	Operation	GWP
Pre-cuttings	0.07	Nitrogen	64.25	Transport, tractor and trailer, agricultural	1.18
Cuttings	0.07	Phosphate	6.68	Transport 16-32 t	6.73
Land-preparation	0.73	Potassium	44.87		
Open streets	0.28	Soil pH raising	1.02		
Plantation	1.61	Pyrethroid	0.66		
		Maintenance	6.13		
		Glyphosate	0.53		
Subtotal GWP	2.76		129.37		7.91
Total GWP = 140.04					

FIGURE CAPTIONS

Figure 1. System limits for the functional unit under study.

Figure 2. (a) Cumulative energy demand (in MJ) to produce one ton of macauba fruit. Subcategories with CED values below 0.01 $MJ \cdot t^{-1}$ fruit have been omitted for clarity reasons. (b) Global warming potential (in kg CO_2eq) per ton of macauba fruit produced in the plantation for the 20-year timeframe.

Figure 3. Damage caused by the system to each of the three main categories according to EI-99 methodology (in $Pt \cdot t^{-1}$ of macauba fruit).

Figure 4. Itemized damage caused by each of the operations to the different impact categories according to EI-99 methodology (in $Pt \cdot t^{-1}$ of macauba fruit).

Figure 5. Itemized damage caused by the operations of the cultivation stage to the different impact categories according to EI-99 methodology (per ton of macauba fruit).

Figure 6. Evolution of global warming potential (*black*, y-axis on the left side of the graph), energy demand (*red*, first y-axis on the right side of the graph) and damage according to EI-99 methodology (*blue*, second (rightmost) y-axis on the right side of the graph) as a function of crop productivity (all values per ton of macauba fruit).