

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 °C, 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

28 have been determined using a life cycle analysis methodology, in addition to shedding some
29 light on its GHG intensity relative to the other energy crops it can displace. Excluding land use
30 changes and biogenic CO₂ fixed by the crop, it was concluded that to produce one ton of
31 macauba fruit in Brazil, the system would absorb 1810.21 MJ, with GHG emissions of 158.69
32 kg CO₂eq in the 20-year timeframe, and of 140.04 kg CO₂eq in the 100-year timeframe
33 (comparable to those of African oil palm). Damage to human health, ecosystem quality, and
34 resources would add up to 16 Pt·t⁻¹ according to Eco-indicator 99 methodology. In order to
35 account for the uncertainty derived from improvement and domestication programs, which
36 should affect current production levels, a sensitivity analysis for different productivities was
37 performed. In all analyses, fertilization was found to be responsible for ca. 90% of the impacts,
38 and hence special attention should be paid to the development of alternative fertilizer
39 management schemes.

40
41 **Keywords:** *Acrocomia aculeata*; bioenergy; Brazil; life cycle assessment (LCA); macauba;
42 sustainability.

44 1. INTRODUCTION

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

52 Amongst the emerging agroforestry crops with a high energy potential, macauba palm
53 (*Acrocomia aculeata* (Jacq.) Lodd. ex Mart.) has been claimed to hold particular promise
54 (Berton et al., 2013; Coimbra and Jorge, 2012; Montoya et al., 2016). It can be dedicated to the

55 direct mitigation of climate change, due to its ability to contribute to the production of biomass
56 of high energetic power, through esterification, and therefore of bioenergy.

57 Macauba palm presents an interesting productivity that places it among the main agro-energy
58 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,
59 comparable to the productions obtained from African oil palm (*Elaeis guineensis* Jacq.)
60 (Cargnin et al., 2008; César et al., 2015; Ciconini et al., 2013; Pires et al., 2013). Given the good
61 prospects for its genetic improvement and domestication, current production is expected to rise
62 above 6500 kg oil·ha⁻¹·yr⁻¹, provided that in recent studies the figures for extracted oil have
63 already exceeded this amount for scenarios of 400 plants·ha⁻¹, surpassing even African oil palm
64 in terms of liters of biodiesel·ha⁻¹ (Colombo et al., 2017; Luis and Scherwinski-Pereira, 2017;
65 Vianna et al., 2017).

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

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

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

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

98

99 **2. MATERIALS AND METHODS**

100 **2.1. *Life cycle analysis methodology***

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

110 crop as a product system) throughout the agricultural operations necessary to produce it, to
111 harvest it and to transport it to the industry of extraction and process.

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

115

116 **2.2. Goal and scope**

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

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

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

^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).

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

132

133 **2.3. Indicators**

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

144 *2.3.1. Cumulative energy demand*

145 As regards the quantitative estimation of the total energy demand in the life cycle of the
146 system, CED v.1.09 provides a measure of the primary energy demand of the product, that is,
147 the energy content of energy carriers that have not yet been subjected to any conversions, while
148 taking losses due to transformation and transport fully into account. The necessary energy per
149 functional unit is expressed in MJ, and normalization is not part of this method.

150 Characterization factors are divided in 5 impact categories: non-renewable, fossil; non-
151 renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; and renewable,
152 water (Frischknecht et al., 2007; Weidema et al., 2013).

153 *2.3.2. IPCC 2013 methodology*

154 The IPCC 2013 method is the successor of the IPCC 2007 method and has been developed
155 on the basis of the Climate Change 2013 report (IPCC, 2014). This method evaluates the factors
156 that affect climate change with a timeframe of 20 and 100 years, using CO₂eq units. However,
157 the characterization factors do not include the indirect NO₂ formation of nitrogen emissions; do

158 not take into account the radiative forcing from NO_x, water, sulfate, etc. emissions in the lower
159 stratosphere or in the upper troposphere; do not take into consideration the range of indirect
160 effects proposed by the IPCC; and do not include the formation of CO₂ by CO emissions. The
161 methodology used in this study corresponded to version 1.02 (March 2016) for the 20-year
162 timeframe and to version 1.09 (August 2014) for the 100-year timeframe.

163 2.3.3. *Eco-indicator 99 methodology*

164 Eco-indicator 99 (EI-99) is a damage-oriented methodology for calculating the impacts on
165 three main categories (endpoints): damage to human health, expressed in DALY ("disability
166 adjusted life years") units; damage to ecosystem quality, measured in PDF·m²·yr, where PDF
167 stands for "potentially disappeared fraction"; and damage to resources, measured in MJ of
168 surplus energy. As regards the weighting model, in this study the *egalitarian* archetype was
169 chosen, which has a very long term perspective and that takes into account all possible effects.
170 The aggregated LCA results are expressed in points (Pt) per unit of analyzed material/process.

171

172 2.4. *Functional unit and system boundaries*

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

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

181

[FIGURE 1]

182 The use of the macauba crop was assumed to be the extraction of oil for biofuel production,
183 either in its purest state or as a base for mixing with other hydrocarbons. The production or use
184 of by-products was not taken into consideration in the system (see section 2.10, in which all
185 items excluded from the analysis are detailed), which was limited only to the primary

186 production of the functional unit. Further, any interaction of aforementioned functional unit
187 with other products or systems that are not part of this study, such as economic interactions or
188 interactions with other non-evaluated technical systems, was discarded (since they cannot be
189 taken into account in an ALCA methodology). Intending to include all these interrelations
190 would surely alter the output of the results object of the study.

191

192 **2.5. Assumptions**

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

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

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

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

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

225 The fertilization treatments discussed in previous paragraph was deemed as optimal to
226 maximize fruit production in the agrometeorological conditions of the area of study. The
227 objective was to provide plants with the necessary macro- and microelements to complete their
228 vegetative cycle, obtaining a favorable development and an excellent productivity, without
229 introducing factors that could alter the potential of biomass per unit of area (Machado et al.,
230 2015).

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

239 The expected macauba production was estimated by sampling 100 wild (non-cultivated)
240 macauba plants in the surroundings of the plantation considered in this paper. The number of
241 fruit bunches was counted, resulting in an average of 2.39 bunches per plant, with a standard

242 deviation of 1.37 and a median of 2. For these same 100 wild macauba plants, fruits were
243 weighed, obtaining an average of 24.52 kg of fruit per bunch with a standard deviation of 8.27
244 and a median of 24.58 kg per bunch. Thus, considering 461 macauba palm trees arranged in a
245 5×5 m frame equilateral triangle distribution (i.e., 21.65 m² per macauba palm tree), with an
246 average of 2.39 bunches per palm tree and an average weight of 24.52 kg of fruit per bunch, a
247 total production per hectare of 900 t over the 30 years of cultivation would result. This would be
248 in good agreement with the results reported by Lopes and Steidle Neto (2011).

249 A propos of the use of the land, it was supposed that it was not modified (see section 2.10),
250 conserving the silvopastoral exploitation system (i.e., the destruction of forest or the change of
251 land use were not contemplated in the study). To include the effect of indirect land use change
252 effects (ILUC) on GHGs, a CLCA would be needed (McManus and Taylor, 2015; Plevin et al.,
253 2014; Rajagopal, 2014), which is beyond the scope of this work.

254

255 **2.6. Data and data quality**

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

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

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

267 The integrity used in this study was higher than 97% (percentage of measured or estimated
268 flow). The remaining 3% would not be representative and would have no significant impact on

269 the study as a whole. No phase or stage that was expected to modify either the conclusions or
270 objectives of the study was excluded.

271

272 **2.7. Life cycle inventory**

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

278

279 **2.8. Allocation**

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

285

286 **2.9. Reproducibility, coherence and representativeness**

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

296

297 **2.10. Further clarifications to the study**

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

- 301 – The effects of soil transformation from pasture/woodland into agroforestry land. As
302 noted above, the current use of the land is conserved, not generating deforestation of
303 virgin jungle or lands with a current silvicultural use.
- 304 – The impact on biodiversity due to land use transformation.
- 305 – The externalities created by the cultivation of the macauba, such as by-products
306 susceptible to employment in animal feed, charcoal generation, etc.
- 307 – The use of by-products from pruning/harvesting in animal feed or other use.
- 308 – The CO₂ emitted by the burning of by-products of the macauba plantation.
- 309 – The biogenic CO₂ fixed by the crop in the plant mass created by the plantation.
- 310 – NH₃, N₂O, N₂ and NO emitted by the plantation to the atmosphere.
- 311 – The burning of residues during land preparation, their destruction or the originated CO₂.
- 312 – The coverage of the land with other crops associated with the macauba during the initial
313 stages of growth, until it enters into production.
- 314 – The emissions produced by the pruning waste deposited in the soil, biomass in
315 decomposition.
- 316 – The percolation of fertilizers, N and K, from the soil of the plantation.
- 317 – The contamination with heavy metals (Hg, As, Cr, Se, Ni, Mo, etc.) by percolation
318 resulting from the use of fertilizers.
- 319 – The emissions produced when using pesticides in the plantation.
- 320 – The emissions derived from land cover in the plantation, decomposing biomass.
- 321 – The recycling of polyethylene from the bags of macauba seedlings.

- 322 – The recycling / reuse of fertilizer containers (sacks), insecticides / phytosanitary /
323 formicidal / insecticide containers at a packaging of plant protection products waste
324 collection point.
- 325 – The recycling of seedling containers and polystyrene trays.
- 326 – The empty return and the average load of the means of transport in the material
327 transport system.
- 328 – The necessary infrastructures for the implementation, handling and transport of the
329 products.
- 330 – The elimination of the plantation once it reaches the end of its production period (after
331 30 years).

332

333 **2.11. Software**

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

336

337 **3. RESULTS**

338 **3.1. Cumulative energy demand methodology**

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

342

[FIGURE 2]

343 The energy embedded in the system would thus mostly correspond to the cultivation stage
344 (90.93%), followed by the harvest (6.98%) and the tree planting (2.09%). Attention should be
345 paid to the fact that 89.41% of the energy required in the cultivation stage would be invested in
346 activities related to the fertilization of the plantation.

347

348 **3.2. IPCC 2013 methodology**

349 In relation to the climate change factors of IPCC with a timeframe of 20 years, the results are
350 shown in Figure 2b. The set of activities aimed at the maintenance and conservation of the
351 plantation would represent 92.87% of the total CO₂ emissions per ton of fruit obtained. It is
352 worth noting that out of those 147.38 kg CO₂eq·t⁻¹ of fruit associated to the cultivation stage,
353 fertilizers would be responsible for 90.85% of the GWP.

354 The results for the 100-year timeframe are summarized in Table 1. In this case, the total
355 GWP would add up to 140.04 kg CO₂eq per ton of macauba fruit. The cultivation stage would
356 involve 92.4% of the total emissions and, out of those 129.37 kg CO₂eq·t⁻¹, fertilizers would
357 account for 89.5% of the GWP.

358 [TABLE 1]

359

360 **3.3. Eco-indicator 99 methodology**

361 As concerns the impacts on air, water, soil, land use, land occupation, soil conversion, MJ
362 for material extraction, MJ of energy extracted, MJ of energy used, etc. created by the system,
363 they are summarized for the three main categories in Figure 3. It follows that the activity that
364 has the greatest damage to human health, to the quality of the ecosystem and to resources is the
365 cultivation stage, accounting for 92.1%, 88.4% and 89.4% of the total endpoints, respectively.
366 On the other hand, the initial plantation (which encompasses the pre-cuttings, cuttings
367 (saplings), open streets, land preparation and planting saplings operations) represented less than
368 2% of the damage in all the three categories.

369 [FIGURE 3]

370 A breakdown of the damage for all the impact categories is depicted in Figure 4. One may
371 observe that most of the impact associated to macauba cultivation corresponded to the
372 respiratory inorganics category (ca. 40%), i.e., respiratory health risks resulting from winter
373 smog caused by emissions of dust, sulphur and nitrogen oxides to air. Fossil fuels depletion
374 accounted for ca. 29% of the damage, followed by carcinogens (toxicological risk and potential
375 impacts of carcinogenic chemicals released into the air, water, soil, and agricultural soil), which
376 represented ca. 15% of the total damage, and by climate change (with ca. 9% of the total

377 damage). The fossil fuel score can be ascribed to the amounts of fossil fuels used in the
378 agrochemicals production, in crop-related operations involving machinery (tilling) and in
379 transportation (both inside the plantation and from the plantation to the oil extraction factory),
380 which would also be responsible for the scores in respiratory inorganics and climate change.
381 The use of phytosanitary products and fertilizers would in turn be the main cause for
382 carcinogens.

383 [FIGURE 4]

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

392 [FIGURE 5]

393

394 **3.4. Sensitivity analysis**

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

404 As regards the CED, it would change from 1721.22 MJ·t⁻¹ for a productivity of 800 t·ha⁻¹ to
405 1449.33 MJ·t⁻¹ for a productivity of 1000 t·ha⁻¹ (ca. 34 MJ/25 t of fruit on average). Thus,
406 increasing the crop productivity from 800 to 825 t·ha⁻¹ would decrease the CED by 2.90%,
407 while by increasing the productivity from 975 to 1000 t·ha⁻¹ a 2.35% reduction would be
408 attained.

409 The GWP values with the IPCC 2013 methodology in the 20-year timeframe would range
410 from 177.48 kg CO₂eq·t⁻¹ to 143.66 kg CO₂eq·t⁻¹ for productivities of 800 t·ha⁻¹ and 1000 t·ha⁻¹,
411 respectively. This would imply that an increase in productivity of 25 t·ha⁻¹ would entail, on
412 average, a reduction of ca. 4.2 kg CO₂eq. As the productivity is increased, the changes are again
413 less marked: increasing the productivity from 800 to 825 t·ha⁻¹ would decrease emissions by
414 2.96%, while increasing the productivity from 975 to 1000 t·ha⁻¹ would decrease emissions by
415 2.4%.

416 If the 100-year timeframe is considered instead, the emissions would range from 156.55 kg
417 CO₂eq to 126.82 kg CO₂eq for productivities of 800 t·ha⁻¹ and 1000 t·ha⁻¹, respectively. In this
418 case, an average decrease of ca. 3.7 kg CO₂eq would be attained upon an increase in
419 productivity of 25 t·ha⁻¹.

420 Apropos of the damage to the environment, estimated with EI-99, it would vary between
421 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).
422 An increase in crop productivity of 25 t·ha⁻¹ would result in an average decrease of around 0.42
423 Pt, with a maximum decrease of 2.84% for the 800 to 825 t·ha⁻¹ productivity improvement and a
424 minimum decrease of 1.92% for the 975 to 1000 t·ha⁻¹ improvement.

425 [FIGURE 6]

426

427 **4. DISCUSSION**

428 **4.1. Comparison with other energy crops**

429 It should be stressed that the scarcity of case studies on LCA of the cultivation stage of
430 energy crops (most studies focus on the actual biofuel production stage (Castanheira and Freire,
431 2016)), together with the differences between studies (in terms of the chosen indicators, the

432 assumptions, the boundaries, the secondary data, data quality, etc.), make it impossible to make
433 direct comparisons (Chiaramonti and Recchia, 2010; Shonnard et al., 2015). Furthermore,
434 although the majority of the studies in the literature have focused on GHG emissions and energy
435 requirements (Shonnard et al., 2015), there is no common agreement in relation to the units (i.e.,
436 results may be expressed per ton of fruit/fresh fruit bunches, per ton of crude oil, per ton of
437 refined oil, per ton of biodiesel, per ha, per MJ, etc.), which further which jeopardizes the
438 comparison between studies^b.

439 For instance, the treatment of biogenic carbon may lead to significant differences in LCA
440 results: Rodrigues et al. (2014) studied the GHG balance of crude palm oil from *E. guineensis*
441 for biodiesel production in Brazil and concluded that the system worked as a carbon sink
442 because it fixed approximately 1.1 times more CO₂ than it released: the system could attain a
443 sequestration of 166.42 kg CO₂eq·t⁻¹ of crude palm oil or up to 207.96 kg CO₂eq·t⁻¹ by partial
444 substitution of synthetic fertilizers by organic ones (a strategy from which the system presented
445 herein could also benefit). However, this negative emissions balance would result from taking
446 into consideration the large quantity of CO₂ captured during the growth of palm trees, whereas
447 in the study presented herein such biogenic CO₂ fixed by the crop in the plant mass created by
448 the plantation was excluded from the analysis, as noted in subsection 2.10. A reduction of
449 approximately 10 Mg·ha⁻¹ of CO₂ for each hectare planted with *A. aculeata* may be expected
450 throughout its production cycle (César et al., 2015).

451 Rivera-Méndez et al. (2017) analyzed the carbon footprint of the production of African oil
452 palm fresh fruit bunches (FFB) in Colombia and estimated the emissions in 118 kg CO₂eq·t⁻¹ of
453 fresh fruit bunches, slightly lower (ca. 8.8% lower) than the 129.37 kg CO₂eq·t⁻¹ estimated
454 herein for the cultivation stage of macauba.

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

^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).

457 varied over a large range: from 183 kg CO₂eq·t⁻¹ FFB in the Northeast and 137 kg CO₂eq·t⁻¹ FFB in
458 the North to 94 kg CO₂eq·t⁻¹ FFB in the South, depending on the productivity, growers' practices
459 and the transport of raw materials. Stichnothe and Schuchardt (2011), who studied the GWP of
460 African oil palm production in Indonesia and Malaysia, also found GWP100 values (using
461 IPCC 2007 methodology) slightly above 100 kg CO₂eq·t⁻¹ FFB for its cultivation (excluding land
462 use change (LUC), since if rainforest or grassland is converted to palm oil plantations in
463 Malaysia or Indonesia, this would cause between 1850 and 425 kg CO₂eq·t⁻¹ of FFB). For
464 comparison purposes, the GWP100 (recalculated with IPCC 2007 methodology to allow
465 comparison) for macauba cultivation was 141.54 kg CO₂eq·t⁻¹ of fruit, so it would be close to or
466 slightly higher than the average GWP100 for African oil palm.

467 If one expresses the results per MJ, in a meta-analysis of over 70 environmental LCA studies of
468 liquid transportation biofuels in the Pan American region, Shonnard et al. (2015) concluded that the
469 GHG emissions (excluding the LUC effect) of African oil palm cultivation were on average 25 g
470 CO₂eq·MJ⁻¹. Taking a lower heating value for biodiesel of 37.1 MJ·kg⁻¹ (Iriarte et al., 2012), a
471 density of 0.916 g·cm⁻³, and considering that 1 t of macauba fruit yields 200 l of biodiesel (Colombo
472 et al., 2017; del Río et al., 2016; Evaristo et al., 2016a), a GWP value of 23.34 g CO₂eq·MJ⁻¹
473 would result, which again is very similar to that of palm oil biodiesel.

474 In terms of CED, Harsono et al. (2012) studied the energy balances of *E. guineensis* oil
475 biodiesel in Indonesia and concluded that the total energy input for commercial plantations was
476 81.82 GJ·ha⁻¹·yr⁻¹. Subtracting the industrial phase and the land use change contributions, the
477 energy input would be 45.73 GJ·ha⁻¹·yr⁻¹. If one compares it with the values for macauba,
478 (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
479 be higher for macauba, but its higher biodiesel yield (ca. 200 l biodiesel·t⁻¹ fruit for macauba)
480 would compensate for it, in such a way that the total energy input in GJ·t⁻¹·yr⁻¹ biodiesel would
481 be very similar: 10.66 for African oil palm vs. 10.86 GJ·t⁻¹·yr⁻¹ biodiesel for macauba palm.

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

485 African oil palm and *Jatropha curcas* were 2568.82 and 1733.67 kg CO₂eq, respectively. Upon
486 subtraction of the oil extraction and biodiesel production stages, the impact derived from the
487 planting, cultivation and harvesting stages would add up to 1378.36 and 817.25 kg CO₂eq·t⁻¹
488 biodiesel, respectively. Assuming that the biodiesel yield per ton of macauba fruit is ca. 200 l
489 (0.184 t), and considering that for 1 ton of fruit the GWP was 141.54 kg CO₂eq (recalculated with
490 IPCC 2007 methodology), the GWP100 per ton of macauba-derived biodiesel would be around
491 769.2 kg CO₂eq, so it would be lower than those of the other two crops. Regarding the energy
492 consumption, it was 25667 MJ·t⁻¹ biodiesel for African oil palm and 15872 MJ·t⁻¹ biodiesel for
493 *Jatropha curcas*, higher than the 9838.1 MJ·t⁻¹ biodiesel for macauba.

494 In the case of biodiesel derived from castor-bean (*Ricinus communis*) oil, Amouri et al.
495 (2016) reported that GHG emissions during the cultivation stage were 452.38 kg CO₂eq·t⁻¹.
496 Assuming that the oil content in castor-seeds is ca. 43%, and taking into consideration its density
497 (0.96 g·cm⁻³), 412.8 l oil per ton of seeds would be obtained, resulting in a GWP of 1.09 kg CO₂eq·l⁻¹
498 biodiesel for *Ricinus communis*. In turn, the GWP emissions for macauba (using Impact 2002+
499 methodology, to allow a certain degree of comparison) would be noticeably lower (147.38 kg
500 CO₂eq/200 l biodiesel, i.e., ca. 0.74 kg CO₂eq·l⁻¹ biodiesel).

501 Finally, Schmidt (2015) compared the IPCC's GWP100 for several different refined vegetable
502 oils and found that the agricultural stage involved 3016, 976, 718 and 949 kg CO₂eq·t⁻¹ of oil for
503 palm oil, rapeseed oil, sunflower oil and peanut oil, respectively. Considering that the estimated
504 GWP100 for macauba (recalculated with IPCC 2007 methodology) was 141.54 kg CO₂eq·t⁻¹ of fruit
505 and that 25 t fruit·ha⁻¹·yr⁻¹ result in 6200 kg of oil·ha⁻¹·yr⁻¹ (0.248 conversion factor), the GWP100
506 value per ton of oil would be 570.7 kg CO₂eq, lower than those of the four aforementioned oils.

507

508 **4.2. Adaptation and mitigation strategies**

509 As noted by Dislich et al. (2017), strategies are required to improve the capacity for local
510 adaptation to reduce climate impacts and maintain regional stability in oil production. An in-
511 depth analysis of the opportunities offered by macauba palm cultivation to mitigate the share of
512 GWP emissions that directly depend on land use and land management techniques is beyond the

513 scope of this study (for an analysis of bioenergy as a climate mitigation option within a 2 °C
514 target, the interested reader is referred, for instance, to the recent works by Creutzig et al.
515 (2015); Röder and Thornley (2016); Souza et al. (2017b)). Nonetheless, in view of the LCA
516 results, which show that the impact in all three indicators could mostly be ascribed to NPK
517 fertilization, a brief comment on this matter may be useful.

518 Adaptive nitrogen and soil health management strategies should be regarded as a must with a
519 view to mitigating and adapting to climate change in the case of macauba cultivation. An overall
520 reduction of N-fertilizer use would lead to a significant reduction of the associated CO₂
521 emissions from the Haber-Bosch process that produces these fertilizers, from their
522 transportation and application, and would reduce losses of nitrous oxide too, which is by far the
523 largest source of greenhouse gas emissions associated with agriculture. To reduce N₂O
524 emissions from applied N fertilizer, the four main management factors (commonly known as the
525 4R's) should be implemented: namely, right N application rate; right formulation (fertilizer
526 type; possible replacement by other fertilizers that are equally effective but of less polluting
527 origin or waste that can enter the life cycle of the product mainly by fertilizers of organic
528 origin); right timing of application; and right placement. Best agricultural practices should be
529 established with the help of sensors and an adequate fertilizer plan adapted to the needs of the
530 crop and the expected productions. A reduction of nutrient losses by up to an average of 30
531 percent may be obtained with such improved management practices, according to the
532 International Fertilizer Association.

533 The use of technologies such as foliar application; coated soluble granules (to allow
534 controlled release of nutrients in the root zone); urea deep placement (to improve nitrogen
535 recovery); addition of inhibitors (to slow the conversion of urea fertilizer to ammonia and
536 thereby minimize potential ammonia loss to the atmosphere); and fertigation are also amongst
537 the options that would need to be contemplated so as to effectively minimize the negative
538 impacts of fertilizers on the environment. Besides, organic agriculture strategies should be
539 examined, in line with IPCC's Assessment Report, as they offer added benefits (e.g., recycling
540 of crop waste intensifies biological activities of soils, enhances biodiversity as well as nitrogen

541 fixation and improving phosphorous availability by symbiosis; organic farming builds up soil
542 fertility and increases or conserves soil organic matter; it can synchronize supply and demand of
543 nutrients, conserving water and sequestering CO₂ into the soil, etc.). In short, improving soil
544 health, carbon and nitrogen management would provide win-win opportunities, increase profits
545 and decrease environmental losses, as shown, for instance, in the study by Rodrigues et al.
546 (2014) mentioned above.

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

551

552 **5. CONCLUSIONS**

553 A full environmental evaluation, including not only global warming potential and energy
554 consumption, but also other categories related to impacts to soil, water, air, human health, and
555 ecosystems was conducted for *Acrocomia aculeate* planting, cultivation and harvesting, using
556 IPCC 2013, CED and EI-99 methodologies. It was found that the introduction of macauba palm
557 as a candidate for the production of biofuels *a priori* presents environmental benefits as
558 compared to energy crops such as rapeseed, sunflower, castor seed or physic nut. Moreover, the
559 100-year GWP (ca. 140 kg CO₂eq·t⁻¹ of fruit) and CED (1810.21 MJ·t⁻¹ of fruit) associated with
560 its cultivation would be comparable to those of *Elaeis guineensis*. Nonetheless, from the LCA it
561 becomes apparent that there is room for improvement in terms of the impacts produced, in
562 particular in relation to fertilizers, which contributed with ca. 90% of the GHG emissions,
563 energy consumed by the crop and damage to all the environmental impact categories.
564 Consequently, future lines of research aimed at the development of alternative fertilizer
565 management schemes, including for instance the replacement of conventional NPK solid
566 fertilizers by foliar fertilizers or compost, should have a remarkable effect on the sustainability
567 of this emerging energy crop.

568

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572

573 **CONFLICTS OF INTEREST**

574 The authors declare no conflict of interest.

575

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800

801 **TABLES**

802

803 **Table 1.** Breakdown of IPCC 2013 results in the 100-year timeframe (in kg CO₂eq·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		

804

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805 **FIGURE CAPTIONS**

806

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

808 **Figure 2.** (a) Cumulative energy demand (in MJ) to produce one ton of macauba fruit.

809 Subcategories with CED values below $0.01 \text{ MJ}\cdot\text{t}^{-1}$ fruit have been omitted for clarity reasons.

810 (b) Global warming potential (in $\text{kg CO}_2\text{eq}$) per ton of macauba fruit produced in the plantation

811 for the 20-year timeframe.

812 **Figure 3.** Damage caused by the system to each of the three main categories according to EI-99

813 methodology (in $\text{Pt}\cdot\text{t}^{-1}$ of macauba fruit).

814 **Figure 4.** Itemized damage caused by each of the operations to the different impact categories

815 according to EI-99 methodology (in $\text{Pt}\cdot\text{t}^{-1}$ of macauba fruit).

816 **Figure 5.** Itemized damage caused by the operations of the cultivation stage to the different

817 impact categories according to EI-99 methodology (per ton of macauba fruit).

818 **Figure 6.** Evolution of global warming potential (*black*, y-axis on the left side of the graph),

819 energy demand (*red*, first y-axis on the right side of the graph) and damage according to EI-99

820 methodology (*blue*, second (rightmost) y-axis on the right side of the graph) as a function of

821 crop productivity (all values per ton of macauba fruit).