BIO-JET FUELS PRODUCTION FROM MACAW OIL PALM IN BRAZIL: AN ASSESSMENT BASED ON A COMPREHENSIVE DATABASE OF FEEDSTOCKS

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ABSTRACT: A comprehensive geospatial database of feedstocks has been built and used to assess the potential of biofuel production for aviation in Brazil. The information available on the WebGIS platform, called SAFmaps, corresponds to eight feedstocks that can be used in three certified production routes. The dataset allows defining areas suitable for cultivation, estimating yields and potential costs. Restrictions on the selection of areas may be imposed, excluding, for example, areas covered by natural vegetation, preserved areas, areas intended for food production and regions where there could potentially be socioeconomic problems. In addition, users can combine agricultural information with available infrastructure data (for example, paved roads, railways, pipelines, existing conversion units, etc.). This paper reports a case study in which the HEFA-SPK route was considered, based on macaw palm oil (macauba). Ten different locations were evaluated in the Brazilian Southeast and Centre-West regions. Supply curves were used to define the most suitable supply alternative sites at three oil refineries (two in the Southeast and the third in the Northeast), alongside which industrial units could be installed. In most favorable cases, the minimum selling prices (MSP) of bio-jet fuels were estimated in the range of 16.0 to 19.6 €.GJ^{-1} (685 to 840 Euro.t^{-1}). A sensitivity analysis was performed to estimate impacts on variations in oil yield, which is the most uncertain parameter, and the conclusion is that important gains can be achieved. Although there is still not much knowledge about macaw palm production on a commercial scale, the results indicate the potential feasibility of producing sustainable aviation fuels in the medium to long term.
Keywords: biofuel; database; energy crops; geographical information system; vegetable oil.

1 INTRODUCTION

The civil aviation sector has set ambitious targets for reducing its greenhouse gas (GHG) emissions up to mid of this century. Both ICAO – International Civil Aviation Organization –, a special agency of United Nations, as IATA – International Air Transport Association, which congregates the airlines – mention that GHG emissions must be reduced by 50%, in 2050, regarding the estimated emissions of 2005 [1][2].

It is estimated that in 2018 aviation contributed with 2.4% of global CO_2 emissions, while the overall contribution is even higher due to induced aircraft contrails and other emissions [3]. Prior to COVID-19, ICAO [1] estimated that by 2045 the fuel consumption by the international civil aviation could be 2.2 to 3.1 times higher than the one in 2015, depending on the scenarios.

One of the options for reducing GHG emissions is the use of fuels with a lower carbon footprint, partially displacing conventional petroleum-based JET A-1 fuel. These alternative fuels will be classified as Sustainable Aviation Fuels (SAF) if they meet the supply chain sustainability criteria, defined by ICAO CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) [4]. Despite significant uncertainties in forecasting SAF's contribution in the future, a study by one of the ICAO task groups indicates that up to 2.6% of fuel consumption in 2025 could consist of SAF, and eventually 100% in 2050. In this optimistic scenario, SAF would contribute to a 63% reduction in CO_2 emissions [1].

The interest on producing SAF has motivated a set of studies aiming to estimate the potential of various producing routes, based on different feedstocks. In the Brazilian context, some references are [5][6]]7][8]. In this sense, a research group developed during about three years a database with relevant information on the most promising biomasses for SAF production in Brazil; the activities were developed in the context of a project funded by the Boeing Company, in partnership with EMBRAER, and the resultant information is publically available through the SAFmaps platform (www.safmaps.com).

This paper reports the platform itself and, by way of illustration, the results of one of the case studies developed in order to show how the information can be used to identify areas suitable for the production of biomass aiming to evaluate the feasibility of SAF production. The reported case study deals with the self-dedicated production of macaw palm (macauba) and the use of its oil for the production of SAF based on the HEFA-SPK route.

The paper is organized as follows. After this introduction, the second section presents general information about the SAFmaps, macaw palm and the initiatives for its commercial production in Brazil. The third section presents the premises of the reported case study, while the fourth section presents its main results. The fifth section is dedicated to the discussion of the results and, finally, the sixth section reports the conclusions.

2 GENERAL INFORMATION

2.1 The SAFmaps

SAFmaps is a platform that contains information about the most promising feedstocks for the production of SAF in Brazil. The geospatial database was built aiming to provide information on suitability, potential yields (under current practices) and production costs for six agricultural and silvicultural crops (eucalyptus, soybean, palm, macaw palm, sugarcane and corn). These parameters were estimated for the twelve Brazilian states which have the largest potential for these crops (state of Para, the 13th, was included only in the case of palm oil). For beef tallow and steel off-gases, the basic information is the availability of these feedstocks in 2018. All data are explicitly georeferenced.

This information on feedstocks can be combined with data on existing infrastructure (for example, roads, railways, pipelines, airports, oil refineries, ethanol distilleries, vegetable oil extraction units, etc.) and with parameters that can be used to define production restrictions (for example, protected areas, sensitive biomes, municipalities where recently there have been reports of violations on land use and water use rights, etc.).

Aiming to illustrate how the information available can be used, seven case studies were performed, supposing SAF production based on the routes FT-SPK (using eucalyptus), HEFA-SPK (based on soybean oil, palm oil, macaw palm oil and also combining these three vegetable oils with beef tallow) and ATJ-SPK (from ethanol produced from sugarcane and corn, plus based on ethanol produced from steel-off gases). The results of the case study based on the use of macaw palm oil are described here.

From the platform, the user can download maps, most of the database and the reports of the case studies.

2.2 Macaw palm

Macaw palm is the feedstock considered in the case study reported here, based on the HEFA-SPK route. In Brazil, macaw palm is usually known as macauba [9]. Its most common scientific name is *Acrocomia aculeata* (Jacq.) Lodd. ex Mart [10] (it is a palm tree of the genus *Acrocomia*). Its natural occurrence is in semi-deciduous forests or savannas, as well as in anthropized areas, such as in areas occupied by pastures [11]. Records of naturally occurring macauba in dry areas, from Mexico to northern Argentina, are mentioned in [12].

In Brazil, macaw palm naturally occurs mainly in Cerrado. There are naturally occurring records of macauba in the Northeast region (e.g., Bahia, Piauí and Maranhão), Centre-West region (Goiás, Mato Grosso do Sul and Mato Grosso) and in the Southeast (e.g., Minas Gerais, São Paulo and Rio de Janeiro), besides Tocantins (in the North region) [13]. Based on the literature (see subsection 3.2), Figure 1 shows the location of the sites found; it can be seen that most of these sites are in the Cerrado biome.

According to [13], there are few species studies and doubts about taxonomic classification. But there are indications of high genetic diversity and natural populations with large phenotypic variability.

Popular uses of macauba include direct use as food, in the preparation of condiments, in lighting (use of oil), medicinal use of pulp and fruit oil, in feeding animals, as mosquito repellent, and in the manufacture of soaps [12]. More recently, due to the high oil productivity, it has been evaluated as a raw material for the production of biodiesel and bio-jet fuels [9].

Oil can be produced from the mesocarp (pulp) or from the almonds (seeds). Due to the higher quality, oil from the almonds (i.e., from the endosperm) is used in the pharmaceutical and on the cosmetic industry, while the oil from the pulp can be used for producing fuels (biodiesel or bio-jet fuels) [12]. It was recorded a small commercial production of the macaw fruit in 2017 (133 tonnes) [14].

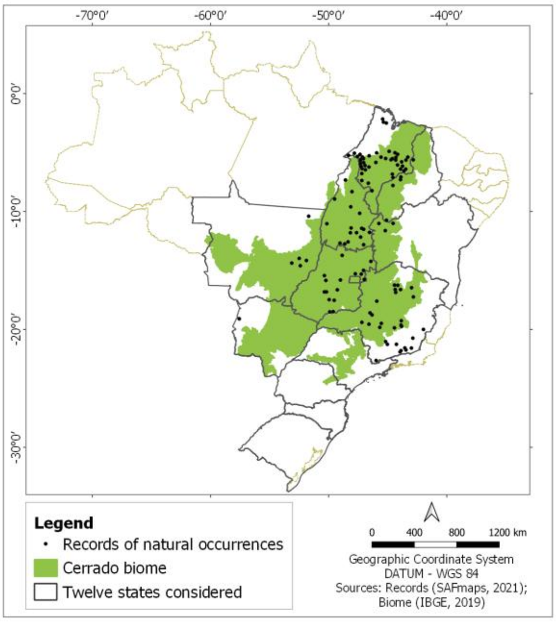

Figure 1: Location of natural occurrences of macaw palm in Brazil, according to the literature

2.3 Developments in Brazil

Embrapa is a public research company linked to the Brazilian Ministry of Agriculture, Livestock and Supply. Embrapa's vision is related with the understanding that macauba could supply food for humans and animals, solid and liquid biofuels and, in addition, assists in the recovery of degraded areas. It is also an important drive the understanding that it can be produced in small scale, in the context of family farmers. Three projects related with macauba have been mentioned [15]. The first one, dated 2014, aimed to create agroforestry models for integrated production of energy and food in the Northeast of Brazil. In 2017, a project created a centre of excellence in genetic improvement and biotechnology for the production of bioenergy. Experimental macauba fields were installed in the municipalities of Parnaíba (PI) and Barbalha (CE) for the study of production systems. The third project, started in 2019, deals with cultivation in areas of family farmers that will serve as a demonstration, dissemination and source of data for the improvement of technologies for the commercial production of macauba.

In [12] it is mentioned that there was three initiatives for the commercial production of macauba. At the time, Entaban Brasil was starting production in an area of 600 hectares, while Soleá Brasil had 1,000 hectares planted, with the expectation of reaching 5,000 hectares in 2022. The third initiative was from the Inocas project, which then planted 2,000 hectares in Patos de Minas, MG. According to the authors, the production could be destined to the production of biodiesel or, in the future, bio-jet fuels.

The Entaban Ecoenergéticas do Brasil is a company of the Spanish group Entaban. The project is in Lima Duarte, Minas Gerais. It started with the planting of 1.5 million macauba seedlings in a nursery, in partnership with the Federal University of Viçosa (UFV). Researchers developed the plant's germination technique in the laboratory. The declared aim is the production of biodiesel.

Soleá Brasil Óleos Vegetais Ltda is planting macauba in João Pinheiro, Minas Gerais. On the company's website [16] it is stated that the objective is the production of special oils, and bio-jet fuels are not mentioned.

In the case of Inocas, the company's website [17] mentions the goal of producing bio-jet fuels and also the partnership with Lufthansa. European funding and the participation of universities (including Leuphana University in Lüneburg, Germany) are cited.

3 CASE STUDY ASSUMPTIONS

3.1 General information

The case studies carried out in the context of SAFmaps correspond to studies of pre-feasibility of SAF production in Brazil. As a priority, they were developed with the objective of illustrating the use of the information available in the platform's database. Despite the effort to make the studies as comprehensive as possible, it is not possible to draw definitive conclusions based on the results obtained.

In the reported case, the production of SAF would be through the HEFA-SPK route, considering macaw palm oil as feedstock. The self-dedicated production of macaw palm oil was assessed in ten different sites and it was considered the possible production of SAF in three oil refineries: two in Southeast Brazil – REVAP and REGAP – Refinaria Henrique Lage (in São José dos Campos – SP) and Refinaria Gabriel Passos (in Betim – MG), respectively, and one in Northeast – RNEST – Refinaria Abreu e Lima (in Suape – PE). The choice of these ten locations is detailed below and was based on the identification of the most suitable locations for cultivation, the estimated yields and production costs. In order to explore scale effects, five different industrial capacities of SAF production were considered.

At the database, the information available for the feedstocks includes maps of suitability, yields and costs. These maps are available for the twelve Brazilian states where the potential and conditions of production (for example, considering the existing infrastructure) are more adequate.

3.2 About macaw palm suitability

As there is still insufficient knowledge about macauba, well-established information on its edaphoclimatic suitability is not available. In this sense, the procedure used here is based on parameters of the sites where the natural occurrence of the macaw palm is verified. The simple logic is that it would be possible to make commercial production feasible in places similar to those for observing natural occurrences.

Thus, climatic parameters were compiled for the municipalities indicated in the literature [18][19][20]. Values from 45 municipalities were used to characterize suitable areas. These municipalities were considered because they have the most reliable information. Values from other 39 municipalities were used to define a broader range, and thus the parameters of suitable and marginal areas were defined. By difference, municipalities were considered suitable and marginal from the suitability point of view. Sites with values that are outside the range were considered unsuitable for macauba production. Suitability requires simultaneous matching of all criteria (i.e., rainfall, air temperature, altitude, etc.). It was assumed that cultivation would take place without irrigation.

Table I shows the parameters and the range of values used to classify municipalities as suitable or marginal for cropping macauba in commercial basis. IRD – Index of Rainfall Distribution – is a parameter defined in the context of the project; IRD = 1.0 would represent an absolutely even rainfall distribution along the year. Temperatures (T) in Table I correspond to the annual averages, both for minimum temperatures as well as for absolute averages.

Table I: Parameters used to classify sites according suitability for macaw palm

Parameters	Unit	Suitable	Suitable + marginal
Rainfall	$mm.y^{-1}$	874-2,052	826-2,381
Hydric deficit	mm	19-409	1.8-695
Hydric deficit	months	4-8	2-8
IRD		< 0.083	< 0.1041
T minimum	°C	13.6-23.5	12.8-29.7
T average	°C	17.3-25.6	16.6-27.8
Altitude	m	62-1,069	24-1,204
Frost risk	%	< 5.6	< 8.9

Soil quality was also considered to define suitability and the same classification used for other crops (in the context of the project) was applied; some references used are [21][22]. Considering the aim of enabling a certain degree of mechanization, the slope of the terrain was also taken into account (<13%).

Defining suitability, annual precipitation and soil were the most restrictive parameters, while the frost risk and altitude had a small impact on the final results.

The resulting suitability map is shown in Figure 2, over which the sites with records of natural occurrence of macauba were plotted. Due to the less permissive criteria adopted, some of these records are in regions classified as “medium suitability” for commercial production. And due to the resolution of the soil map (1:250,000), some records seem to be plotted in areas classified as "low suitability".

3.3 Estimated yields

The adopted procedure is based on information available in the literature, and the literature mostly reports yields of non-commercial plantations. In this sense, the results presented here can be considered conservative. Again, production without irrigation was assumed.

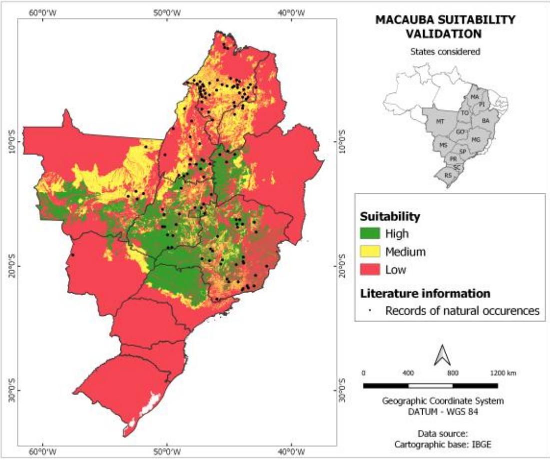

Figure 2: Resulting suitability map for macaw palm, and location of naturally occurring sites, according to the literature

The adopted procedure allows to estimate the oil yields, but the yield of the production of fresh fruits (FF) is the relevant parameter for the estimation of the agricultural costs. Thus, oil yields and fresh fruit yields were correlated with assumptions of realistic oil extraction factors.

The actual oil yield per unit area is a function of many factors, such as the age of the trees, the density of trees per hectare, the weight of fresh fruits produced and the oil content in the pulp. Here it was assumed that plant density varies from 350 to 400 plants per hectare.

IAC [23] mentions that a typical total oil yield is about 6.2 $t.ha^{-1}.year^{-1}$ in the mature phase, being 80% oil from the pulp. In some texts it is not clear whether the mentioned yield corresponds to the total production of oil (both from the pulp and the seeds) or only to the pulp oil.

The macauba cycle has three stages: implantation (until the end of the fourth year after planting), the growth period (from year 5 to 9) and, finally, the mature phase, from year 10 to 30. There is no oil production in the first four years and oil yields grow during the fifth to ninth years, being almost stable since then.

Here, the estimate of the average yield of macaw palm oil (only oil from pulp) is based on 14 registers obtained from five sources [10][11][12][24][25]; yields vary from 2.3 to 6.7 t of $oil.ha^{-1}.year^{-1}$, with an average of 4.08 $t.ha^{-1}.year^{-1}$. It was assumed that all these registers are for the mature phase.

Figure 3 shows the correlation(s) obtained between maximum yiels – and also minimum ones – and average values (based on nine registers, obtained from three sources) [10][24][25]. It was assumed that the oil yield during macauba's mature phase (year 10 to 30) in the regions with medium suitability would be 4.08 t of $oil.ha^{-1}.year^{-1}$. Based on the correlations, the yields for the regions with high and low suitability would be, respectively, 5.92 $t.ha^{-1}.year^{-1}$ and 2.24 $t.ha^{-1}.year^{-1}$.

Considering that the producing cycle is from year 5 to 30, and that yields are lower in the years 5 to 9, the assumed average yields in the whole producing cycle (26 years) are: for high suitability areas, 5.43 $t.ha^{-1}.year^{-1}$, 3.74 for the areas with medium suitability and 2.06 $t.ha^{-1}.year^{-1}$ for the areas with low suitability.

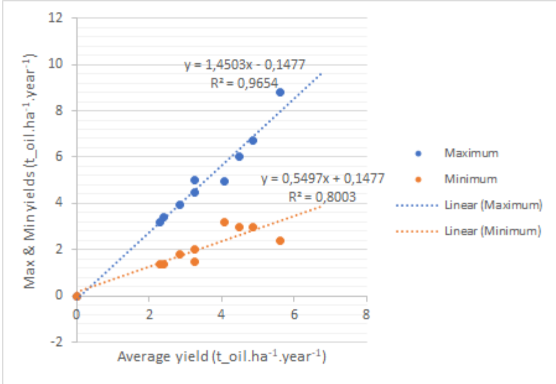

Figure 3: Correlation between maximum (and minimum) yields of oil production and average figures, based on information available in the literature

These values can be compared with the estimates presented by [12], which vary from 2.5 to 5.0 $t.ha^{-1}.year^{-1}$, and with the estimates done from data presented by [26] (5.2 $t.ha^{-1}.year^{-1}$, for the whole sample of fruits, and 8.1 $t.ha^{-1}.year^{-1}$, for the best fruits).

With these results of oil yields, the average production of fresh fruits over the cycle was estimated to vary from 12.3 $t.ha^{-1}.year^{-1}$ in the case of low productivity to 25.3 $t.ha^{-1}.year^{-1}$ in the case of high productivity (19.4 $t.ha^{-1}.year^{-1}$ in the intermediate case). This estimate is based on the assumption that the oil content ranges from 16.8% to 21.5%.

Since oil yields were defined in association with the suitability for macauba production, its map (not shown here, but available at www.safmaps.com) is closely related to the suitability map, shown in Figure 2.

3.4 Predicted agricultural costs

Agricultural costs were estimated based on information presented by [26] and the results were compared with estimates by [27]. Costs were estimated in R$ (2018) per tonne of fresh fruits produced per year (on average terms, considering the producing cycle).

The estimated costs include the opportunity cost of land, all procedures before planting, manual and mechanized operations, necessary inputs, maintenance and harvesting. They are impacted by fresh fruits yield and oil content. The results of the aggregated analysis, at a municipality level, show that the costs vary from 175 $R\$.t^{-1}$ of fresh fruits to 1,360 $R\$.t^{-1}$ per year (average 230 ± 53 $R\$.t^{-1}.year^{-1}$). In a more detailed analysis, done for the ten sites that were chosen as case studies (see information below), the costs vary from 178 $R\$.t^{-1}$ of fresh fruits to 357 $R\$.t^{-1}$ per year (average 238 ± 33 $R\$.t^{-1}.year^{-1}$).

The shares of land opportunity cost and transportation of fruits to the extraction plant vary case by case. In the adopted procedure, the calculation was done for each pixel. Land prices (for land used as pastures in 2018) were taken from the database available at the platform, which was built from different sources of information (for additional information, see https://data.mendeley.com/datasets/czrwfbd7ct). The impact of land opportunity costs on the estimated cost of fresh fruit production is small where conditions are economically adequate, but very high where conditions are inadequate: disregarding the land value, production costs at the municipal level vary from 174 $R\$.t^{-1}.year^{-1}$ of fresh fruit to 213 R$.t^{-1}.year^{-1} (average 191 ± 16 R$.t^{-1}.year^{-1}).

3.5 Areas excluded

For the selection of producer sites, some areas were excluded and some hypotheses were made. First, areas belonging to the Amazon and Pantanal biomes (assumed as sensitive sites for cultivation) within the states considered in the project were excluded. Second, all areas that would have some legal restriction, such as reserves (e.g. environmental reserves and indigenous lands), preserved areas, and areas of Afro-Brazilian settlements (quilombola communities) were also excluded. Third, areas covered by natural vegetation in January 2008 were excluded as a very conservative approach to defining compliance with Principle 2 of CORSIA's sustainability rules [28]. Fourth, it was considered that self-dedicated production of macaw palm would only occur by displacing pastures, and for that a land cover map of 2018 was used [29].

3.6 Choice of production sites

The rationale is that the oil extraction nits would be located in selected municipalities and the area of influence for planting macaw was defined by a circle with 50 km radius, with centre in the municipality.

Aiming to explore different situations, in total ten municipalities were chosen for the case study. The first obvious criterion is where the estimated cost of production would be low. The second criterion was to explore the places where pilot projects are known to exist (this is the case of some municipalities in the state of Minas Gerais). The third aspect taken into account was the existing infrastructure, also considering road and rail access. And the fourth main aspect considered was the distance to the three selected oil refineries, where SAF production would take place.

The sites were chosen in three states: Minas Gerais, Goiás and Tocantins. The municipalities chosen in Minas Gerais were: Lima Duarte, Dores do Indaiá, João Pinheiro, Mirabela and Campina Verde. In the first four there are initiatives for commercial production of macauba. Campina Verde was chosen because it is the centre of an area with potentially low producing costs.

In Goiás state, the chosen municipalities were Itarumã (in the South), Goiás in the central part, and Porangatu (in the North). In Tocantis the municipalities chosen were Figueirópolis and Taipas do Tocantins (located in Southeast).

Figure 4 shows the location of the five municipalities in Minas Gerais, while Figure 5 shows the location of the other five sites in Goiás and Tocantins. In both figures the sites were plotted on the map of estimated costs of fresh fruit production and, in this sense, it is clear the criterion for choosing areas with lower potential costs, except – at some extent – in the case of the two sites to the south of Tocantins. These two locations were chosen exactly with the objective of evaluating the viability of less suitable areas, and also distant to where the production of SAF would occur.

3.7 SAF industrial units

SAF production at oil refineries was considered because the HEFA-SPK route requires a substantial supply of hydrogen, which is available at these industrial sites. In addition, oil refineries also have infrastructure for storing and transporting fuels to airports.

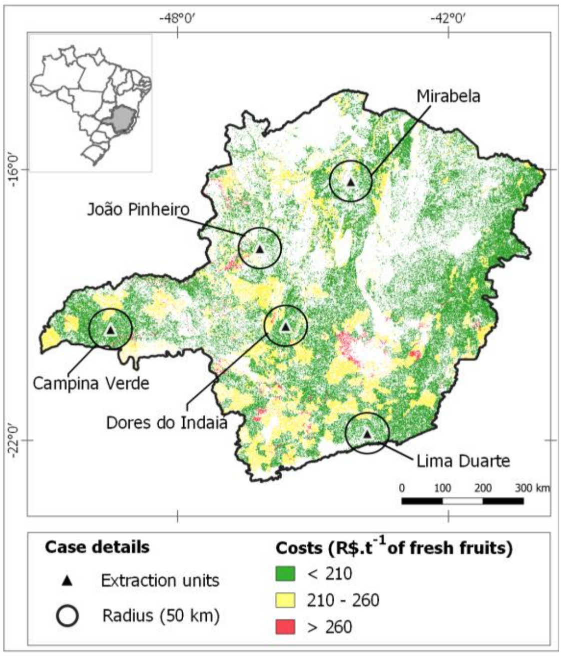

Figure 4: The five sites chosen in state of Minas Gerais. In white, areas not considered for macaw production

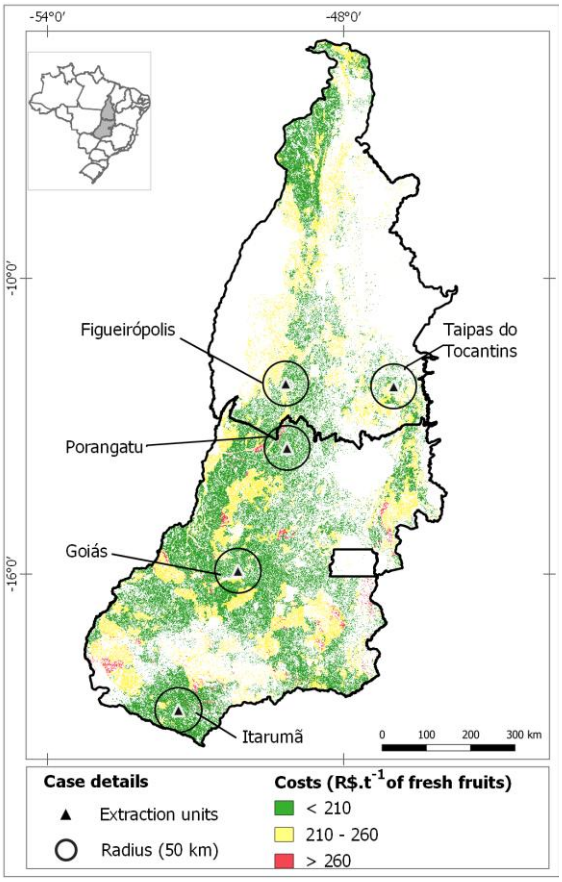

Figure 5: The five sites chosen in states of Goiás and Tocantins. In white, areas not considered for macaw production

Three industrial units for SAF production were considered. First, at REVAP, in São José dos Campos (SP), which is the largest producer of JET A-1 in Brazil, and is connected through a pipeline with the most important international airport in Brazil – Cumbica. Second, at REGAP, in Betim (MG), a city close to Belo Horizonte. The reason is that this refinery is the closest to some potential producing areas of macaw palm. And, finally, at RNEST, located nearby Recife (PE), in Northeast Brazil. This a relatively new refinery and the aim was to identify the feasibility of producing bio-jet fuels in less developed regions.

The main reference for the industrial units is de Jong et al. [30], since it is based on a comprehensive review of performance factors and costs for different pathways. The process that was taken as reference by the authors is the one developed by Nestè, a Finish company, and the technology is commercial. In the reference case, the production of bio-jet fuels (SAF) would be equal to 300 $t.day^{-1}$. SAF is one of the hydrocarbons that can be produced. Here, industrial capacities were scaled-down in order to identify the supply limits of specific production sites. The industrial units would operate all over the year with a 90% capacity factor.

Table II presents information on the industrial capacities considered, i.e. the products and an estimative of how much the SAF production would represent in relation to the Brazilian consumption of jet fuel in 2018 [31].

Table II: Parameters of the five industrial capacities considered

Production ($t.day^{-1}$)					
SAF	20	51	75	150	300
Diesel oil	108	271	399	798	1597
Propane	7	17	25	49	98
Naphtha	3	7	11	21	42
LPG	3	6	9	19	38
Share of JET A-1 consumption in 2018 (%)					
	0.11	0.28	0.41	0.82	1.63
Requirement of macaw palm oil ($t.day^{-1}$)					
	169	425	625	1250	2500

Based on de Jong et al. [30], the total adjusted investment cost would be € 662.1 million (2018) for the reference plant. This would correspond to the n^{th} plant and to this value a location factor of 1.14 was applied [32] to take into account, more realistically, the costs in Brazil. The scale fator assumed was 0.6. A annual discount rate of 8% was considered in all cases.

3.8 Oil extraction and transport infrastructure

It was assumed that macaw oil would be extracted in one or more processing units located at the municipality that is the centre of the circle of influence (radius of 50 km). Distances were calculated from each pixel (i.e. macaw production site) to the centre, assuming the trafic of trucks through the existing roads.

For transporting the oil from the extraction unit(s) to the three oil refineries it was assumed, in the base case, that the transport would by trucks.

As is presented in Table III, the road distance of some potential sites of macauba production to the oil refineries is very large.

The impacts of oil transport by trucks on the feasibility of SAF production will be further discussed and, for some of the most promising cases, it was further explored the possibility of transporting oil by train.

Table III: Road distances (km) from potential macauba production sites to the three oil refineries considered

Macauba production at	REVAP	REGAP	RNEST
Dores do Indaiá (MG)	630	234	2,246
João Pinheiro (MG)	937	443	2,064
Lima Duarte (MG)	323	302	2,352
Mirabela (MG)	1,012	577	1,765
Campina Verde (MG)	700	709	2,641
Goiás (GO)	1,143	1,005	2,426
Itarumã (GO)	969	1,052	2,657
Porangatu (GO)	1,401	1,195	2,201
Figueirópolis (TO)	1,563	1,347	2,107
Taipas Tocantins (TO)	1,673	1,351	1,792

Figure 6 illustrates the location of the ten macaw oil production sites, the location of the three refineries and the distribution of existing and under construction railways (in 2018).

3.9 Estimating the minimum selling price of SAF

A vertical supply chain for macaw production to SAF was assumed. Thus, the CIF costs of vegetable oil at the three refineries were estimated based on the various costs along the chain. In this sense, a supply curve was estimated from each of the ten macaw production sites to the oil refineries.

At the industrial site, the revenue from each co-product (based on its market prices) was considered in the SAF's minimum selling price (MSP) estimate. The same hypotheses used by de Jong et al. [30] were assumed, aiming to obtain results comparable to those of the reference. A spreadsheet was developed and validated against the results presented by [30]. Then, the tool was applied in the different cases considered.

4 RESULTS

4.1 First set of results, and decisions taken

In order to identify the restrictions and the best supply options, the first round of results was obtained assuming that each of the ten sites would supply macaw oil independently.

Table IV shows preliminary results, assuming oil transported by trucks. It can be seen that the maximum oil supply from most of sites would not be enough to feed the largest industrial plants. Indeed, comparing the potential oil supply (second column) with the daily requirement of macaw oil for operation throughout the year (see Table II), only Itarumã (GO) would be able to supply the second largest industrial plant on its own.

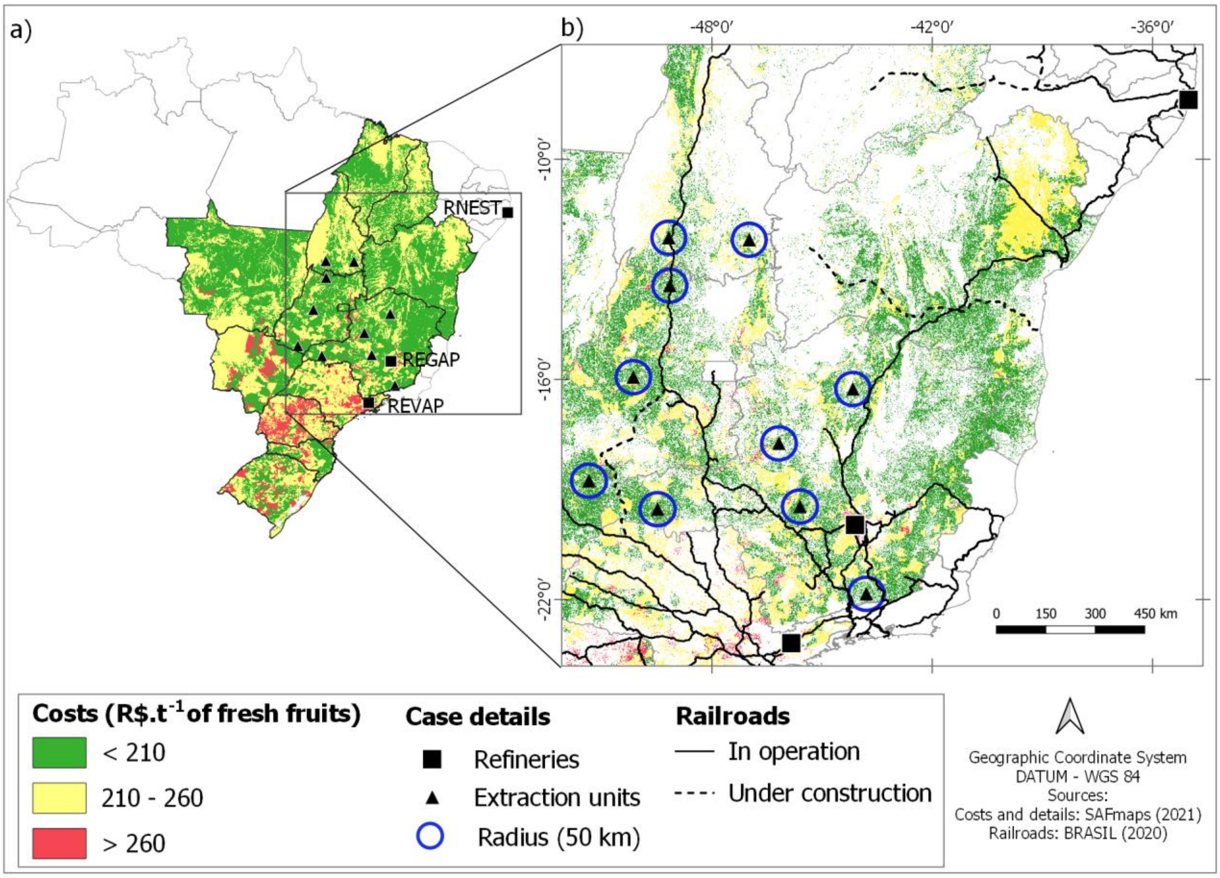

Figure 6: The ten potential sites of macaw oil production, the three refineries considered for SAF production and the nearby railway network

Table IV: Estimated maximum macaw oil supply from each of the ten potential supply sites considered and their CIF costs at the three refineries

Production at	Supply	REVAP	REGAP	RNEST
	$t.day^{-1}$		$€_{2018}.GJ^{-1}$	
Dores Indaiá	641.8	9.95	9.58	10.99
João Pinheiro	259.8	9.92	9.53	10.62
Lima Duarte	162.5	9.20	9.17	10.56
Mirabela	246.8	10.02	9.69	10.50
Campina Verde	1029.1	10.25	10.26	11.44
Goiás	701.7	10.29	10.19	11.05
Itarumã	1565.1	10.40	10.46	11.40
Porangatu	647.3	10.11	9.97	10.58
Figueirópolis	344.7	10.63	10.49	10.94
Taipas	179.4	10.06	9.86	10.13

Thus, the first case chosen to be addressed in detail corresponds to the production of macaw oil at the pole that has Itarumã (GO) as a reference, with SAF production at REVAP. There is a small difference in CIF costs at REVAP compared to REGAP (see Table IV), while REVAP is a more strategic location for SAF production due to the pipeline connection to the largest international airport in Brazil. Thus, in order to assess the economic impact of transporting oil by truck, a version of this case explored transport by train.

The second case to be dealt with in detail would be described by the joint production of macaw oil in the four locations where there are pilot projects in the state of Minas Gerais (Dores do Indaiá, João Pinheiro, Lima Duarte and Mirabela). These four sites are among the ones with the lowest estimated production costs. Here, the results of the production of SAF in REVAP are presented, in order to facilitate the comparison between cases.

The third case considers the combined supply of the ten potentially supplier locations to the three possible SAF production locations (REVAP, REGAP and RNEST). In this case, it was assumed the oil would be transported by truck because of the overall constraints of the railway network. In this case, the goal was to identify which sites would be more and less relevant.

4.2 Macaw oil produced at Itarumã, and SAF at REVAP

Figure 7 shows the supply curves of macaw oil at REVAP, with all the production of fresh fruit in the surroundings of Itarumã, and all oil extraction in this municipality. The supply curves correspond to the transport by trucks or by train. In the last case the hypothesis is that oil would be transported by trucks from Itarumã to Cassilândia (MS) (where oil would be shipped), and finally by train to REVAP.

The difference in CIF costs ranges from 3% for the most expensive productions to 6% for the cheapest. For the case that corresponds to the largest volume to be transported throughout the year, the cost of transport by truck represents about 13% of the CIF cost at the industrial site.

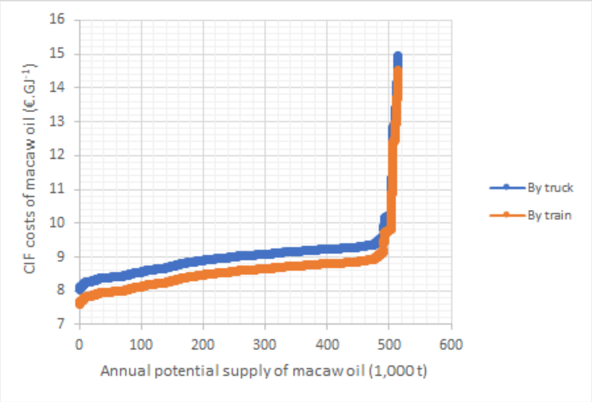

Figure 7: Supply curves of macaw oil from Itarumã (GO) at REVAP, transporting by truck or by train

Figure 8 shows the estimated MSP of SAF produced at REVAP, exclusively using macaw oil extracted at Itarumã.

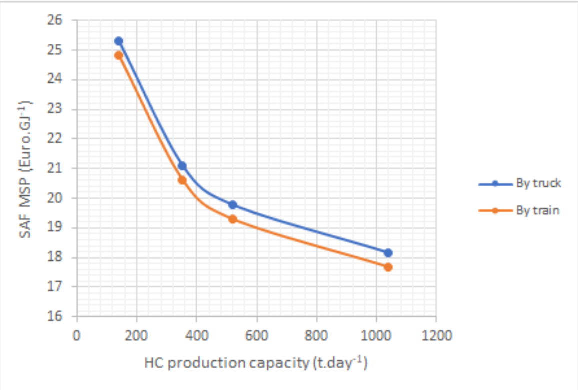

Figure 8: Estimated MSP of SAF produced at REVAP, as function of hydrocarbons (HC) production capacity, with oil transported by truck or by train from Itarumã

The estimated MSP would vary from 18.2 to 25.3 €.GJ^{-1} in case of oil transported by road (777.8-1,082.9 €.t^{-1}), and from 17.7 to 24.8 €.GJ^{-1} in case of oil transported by railway (757.1-1,062.2 €.t^{-1}).

The macaw oil availability in the surroundings of Itarumã would not be enough to assure the annual operation of the largest industrial unit considered here (300 t.day^{-1} of SAF, or 2,075 t.day^{-1} of hydrocarbons), being the largest possible unit half of that.

4.3 Macaw oil produced in Minas Gerais, and SAF at REVAP

This case is related to the hypothesis of macaw palm production in the surroundings of four municipalities in state of Minas Gerais, in which there are pilot projects. In order to easily compare with the results of the previous case, the SAF production was assumed at REVAP. The transport of oil would be by roads.

Figure 9 shows the oil supply curve at REVAP, while Figure 10 shows the estimated MSP of SAF.

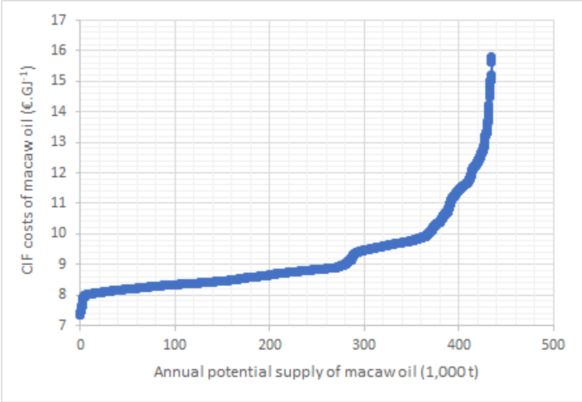

Figure 9: Macaw oil supply curve at REVAP, from four sites in state of Minas Gerais

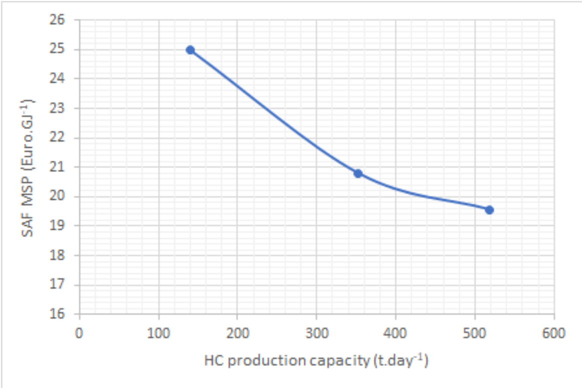

Figure 10: Estimated MSP of SAF produced at REVAP, as function of hydrocarbons (HC) production capacity, with oil supplied from four sites in state of Minas Gerais

Even combining the biomass that could be produced in these four sites, the maximum annual production is constrained to 75 t.day^{-1} of SAF, or 519 t.day^{-1} of hydrocarbons. To feed such industrial unit, the annual requirement of macaw oil would be 247 kt.year^{-1} of macaw oil.

The estimated MSP would vary from 19.6 to 25.0 €.GJ^{-1} (836.8-1,069.4 €.t^{-1}). In comparison with the results of the case previously reported, the effects of the scale are less marked, because with the combination of the supply locations it is possible to take advantage of the production from the lower supply costs.

Table V shows the results of the comparison between the annual production potential and what could be effectively supplied, according to the order of merit defined by the costs. It is noted that a decision based on the simple observation of the costs shown in Table IV would lead to the opposite solution to the one that is more appropriate: Mirabela, which has the highest average costs, would proportionately better exploit its potential, and the opposite would happen with Lima Duarte.

Table V: Comparison between the potential supply and what could be effectively used based on the combined supply curve

Production sites	Potential supply ($kt.y^{-1}$)	Effective supply ($kt.y^{-1}$)	Share used (%)
Dores Indaiá	210.8	125.7	59.6
João Pinheiro	85.3	52.1	61.0
Lima Duarte	53.4	15.1	28.4
Mirabela	81.1	54.1	66.7

4.4 Feasibility for the combined supply of macaw oil

Considering all ten potential supply locations, the total amount of macaw oil reaches 1.9 million $tonnes.year^{-1}$. To put into perspective, as the oil requirement of the largest industrial unit considered here (300 $t.day^{-1}$ of SAF) would be 986 $kt.year^{-1}$, the identified potential would be sufficient to supply only two of these units. The purpose of this assessment was to identify the best locations for oil supply to the largest unit and, eventually, where the SAF unit should be located.

Figure 11 shows the combined supply curve of macaw oil at RNEST. The costs were calculated supposing the transport of oil by trucks. The oil costs at RNEST are at least 10% higher than at REVAP. The supply curve at REGAP is quite similar to the curve at REVAP, with costs that are about 1.4-3.4% lower.

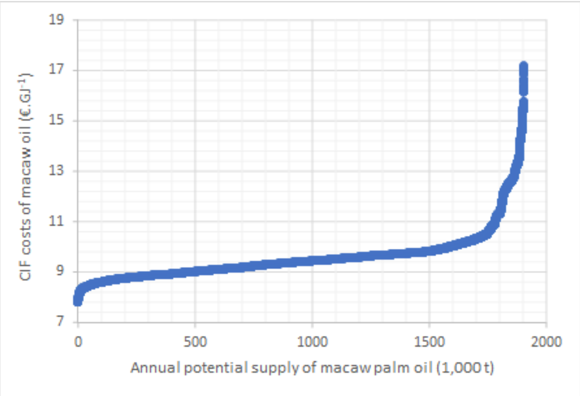

Figure 11: Combined supply curve of macaw oil at RNEST

Figure 12 shows the estimated MSP of SAF produced in the three refineries considered, supposing the combined supply of macaw oil from ten sites. The cheapest production would be at REGAP, but the difference to produce at REVAP is only about 1%. On the other hand, the production at RNEST would result MSP 3.8%-5.9% higher than at REVAP.

The highest MSP are between 24.7-25.9 $€.GJ^{-1}$ (1,057-1,110 $€.t^{-1}$) in case of the smallest industrial capacity, and in the 16.0 to 17.1 $€.GJ^{-1}$ (686-732 $€.t^{-1}$) range for the highest industrial capacity.

As expected, the order of merit between the delivery locations differs from case to case. In the case of the production of SAF at REVAP, Figueirópolis (TO) is not eligible and the productions in Taipas do Tocantins (TO) and Lima Duarte (MG) could be disregarded without significant impact on the economic result. In this case, Campina Verde (MG) and Itarumã (GO) are the most important suppliers, and would cover around 55-60% of the necessary input.

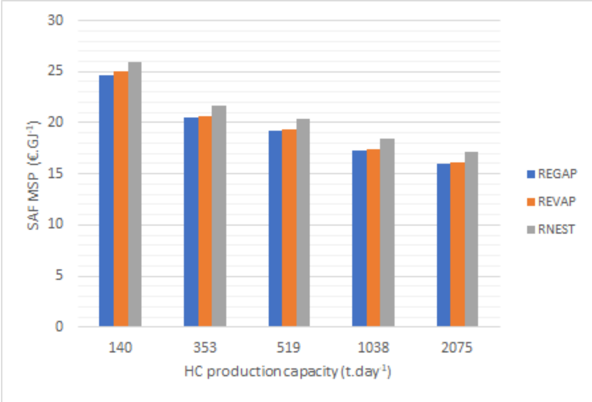

Figure 12: Results of SAF MSP for the combined supply of macaw oil

In the case of production at RNEST, the supplies from Figueirópolis (TO) and Lima Duarte (MG) could be disregarded, with no significant impact on economic results. In this case, the importance of each of the other locations would be more balanced.

It is clear that the best places for the production of macauba with the objective of producing SAF at RNEST would be in the north of Minas Gerais and/or in the south of Bahia (see Figure 6), but these options were not explored in this case study.

5 DISCUSSION

The best economic results obtained in each previously reported case are summarized in Table VI. The best results correspond to the maximum industrial capacity considered (due to the scale effects) or the maximum possible production due to supply restrictions.

Table VI: Results of the best cases of SAF production

SAF production at	Supply sites	Production $kt.year^{-1}$	MSP $€.GJ^{-1}$
REVAP	Itarumã (GO)	49.3	17.7
REVAP	Four sites (MG)	24.6	19.6
REVAP	Seven sites	98.6	16.2
REGAP	Seven sites	98.6	16.0
RNEST	Eight sites	98.6	17.1

These MSP results should be compared to 29 $€.GJ^{-1}$ (1,241 $€.t^{-1}$), which is the figure presented by de Jong et al. [30] considering the production based on HEFA-SPK pathway, from UCO (Used Cooking Oil), in Europe. The use of UCO valued at market prices, and the difficulties in collecting it, explain the differences.

Le Freuve [33] stated that production costs based on HEFA-SPK route recently varied between 770 and 1,750 $€.t^{-1}$ (18 to 40.9 $€.GJ^{-1}$). These values indicate some degree of viability in the short to medium term for the route based on macauba, analyzed here.

Another figure of comparison is the market price of conventional jet fuels. An estimate based on Platts Global Index [34] was 622 $€.t^{-1}$ in May 2018, but it is important to note that these market prices are extremely impacted by oil prices, which are low at that time. For the results reported above, the strict parity of SAF with fossil jet fuel would require an international oil price in the range 100-130 US$.barrel^{-1}.

The MSP results are more impacted by the cost of the feedstock than by the hypotheses of cost of capital and costs of operation and maintenance (O&M). By way of illustration, in the case of the best result that corresponds to the production at REVAP (with the production of macaw oil in the surroundings of Itarumã) the impact of the raw material cost is higher than 50% of the SAF MSP, while the combined impact of capital and O&M costs is around 35%.

As the yield is decisive in the feedstock costs and there are uncertainties in this regard, a sensitivity analysis was carried out. Taken the case of macaw palm production in Itarumã and SAF production at REVAP, the oil yield was varied ±20%, resulting the range of yields in the best case from to 2.47 to 6.52 t.ha^{-1}.year^{-1}, and 1.72-4.53 t.ha^{-1}.year^{-1} in the worst case. The impact on the CIF costs of macaw palm would be about ±17%.

The results of the SAF MSP on the sensitive analysis are shown in Figure 13. The 20% reduction in oil yield would imply an increase of 5.7% to 8.7% in the MSP, while the 20% increase in yield would imply a reduction of 4.9% to 7.7% in the MSP. The impacts are most pronounced for the largest industrial capacities. In the best case, the MSP would be reduced to 16.2 €.GJ^{-1} (to be compared with 17.7 €.GJ^{-1} in the reference case).

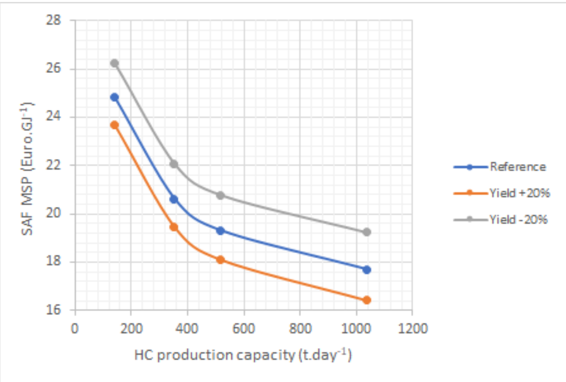

Figure 13: Results of the sensitivity analysis on oil yields/feedstock production in Itarumã, and SAF at REVAP

The economic results presented here are more representative for the medium and long term, as capital and O&M costs are for the nth unit. However, oil production costs, which account for the largest MSP share, are impacted by yields and the assessment made in the base case was conservative. Thus, it is likely that the MSP of SAF in the medium to long term could be below 16 €.GJ^{-1}, or very close to that. Obviously, as there is very little commercial experience for producing macauba, it will be necessary to invest in the development of genetic knowledge, cultural practices and conduct pilot experiences.

As with any bioenergy project, the risk of adverse effects of the monoculture should be carefully analyzed, and it will be no different for large-scale production of macauba. In the case of the evaluation made for the production of the input only in Itarumã (GO), the estimate is that it would be necessary to occupy 54% of the area within the circle that has a radius of 50 km to guarantee the supply of the second largest unit of industrial capacity considered here. The obvious action is to diversify production spatially, which would also be beneficial for reducing economic risks. In this sense, the information available in SAFmaps is of great importance in the decision-making process.

Another important aspect from the point of view of sustainability, and which can be adequately explored in the SAFmaps, is to prioritize production in degraded pasture areas. Thus, as it is an action considered to be low iLUC (induced land use change) risk, the resulting avoided GHG emissions could be higher.

As an illustration, the case of macauba production around Itarumã (GO) is taken again. Figure 14 shows the estimates of the level of degradation of pasturelands in the surroundings of the municipality, by 2018 (based on [29]). Assuming the exclusion of all pasturelands with no degradation, the area available for commercial production of macaw palm would be reduced by 35%.

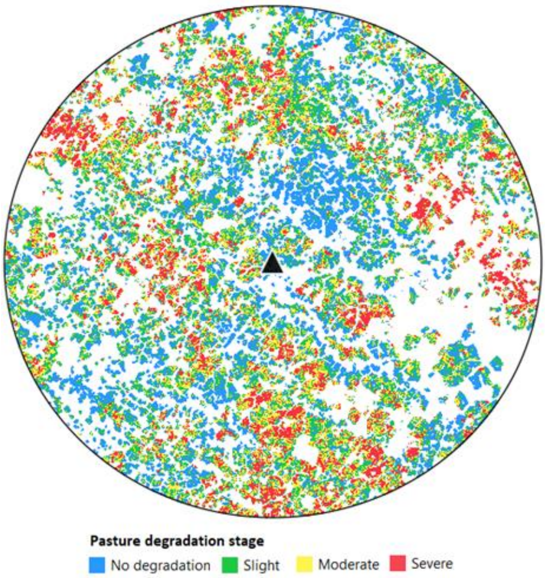

Figure 14: Distribution of the pasturelands in the surroundings of Itarumã (GO), according to the degradation level

The hypothesis assumed is that the soil would be recovered before the beginning of the macauba cycle. The costs would be paid for what would be cropped after the recovery procedure. There would be no impact on productivity or production costs of macauba oil but, on the other hand, the start of its cycle would be delayed.

The consequences of producing only on degraded lands would be a reduction in macaw oil supply, as well as a higher CIF cost due to restricted supply. In the case related to the supply from Itarumã, exclusively, the maximum SAF production would be reduced to 24.6 kt.year^{-1} (instead of 49.3 kt.year^{-1}), with the best MSP close to 19.5 €.GJ^{-1} (to be compared with 17.7 €.GJ^{-1}). Depending on the emission factor that will be obtained with the SAF, the strategy may be economically justified.

The last comment on sustainability is that with the information available in the SAFmaps it is possible to explicitly address several important aspects, which would potentially result in design solutions with lower environmental and social risks.

5 CONCLUSIONS

This paper has a dual purpose. First, to highlight a comprehensive database that has been developed to provide information on eight Brazilian biomasses and on important aspects for their use. The database was originally built to supply information for potential investors interested in the production of bio-jet fuels in Brazil. The database is publically available through www.safmaps.com. The second objective is to report a case study, among the several that were done to validate the database, and that illustrates the information available and how it can be used in the analysis of the feasibility of projects aiming at the production of bio-jet fuels. The reported case study deals with the production of SAF (Sustainable Aviation Fuels) through the HEFA-SPK route, based on macaw palm oil.

Based on suitability data, estimated yields and potential costs (for no-irrigated production), ten sites for the production of macauba were identified. Three industrial sites have been specified, all together with oil refineries (because of the high demand for hydrogen).

Here, the results of three specific studies are reported: the production of macauba in only one location (the one with the greatest potential – Itarumã (GO)), the joint production in four locations in the state of Minas Gerais, in which there are pilot projects for the cultivation of macauba on a commercial basis, and the combined production of all ten considered sites (in this case, evaluating the feasibility of SAF production in the three possible industrial units considered).

The viability of SAF production is based on its estimated minimum selling prices (MSP). The best results show that the MSP would range from 16.0 to 19.6 $Euro.GJ^{-1}$ (685 to 840 $Euro.t^{-1}$). The assessment was made considering that the costs of capital and O&M would be for the n^{th} plant, but the costs of feedstocks could be reduced because the hypothesis for estimating oil yields is somewhat conservative in the base case. In this sense, a sensitive analysis was done on oil yields, showing that it would be possible to reduce 5%-10% the MSP of SAF with an average oil yield 20% larger than it was estimated in the base case.

An important conclusion is that it would be possible to commercially produce SAF from macauba, but first it is necessary to invest in genetic improvement, in agricultural practices and to experiment with large-scale commercial production. Currently, there is limited knowledge about macauba. Obviously, it will take some years before investments in SAF production become a reality, but the message about the potential is important and is it is given here.

On the other hand, the entire potential production of macauba oil in the ten locations evaluated here would be sufficient to produce the equivalent of only about 3% of the Brazilian consumption of JET A-1 in 2018, which indicates the challenge of large-scale substitution of this fossil fuel.

Other important conclusions, as in several bioenergy projects, are that the demand for land can be significant and that it is necessary to conceive the plantations in order to avoid monocultures, and their deleterious effects. Plantations must be dispersed and this represents a challenge due to restrictions on the existing transport infrastructure in Brazil. In this paper, the possibility of transporting oil by rail from the extraction units to the industrial plants was explored.

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8 SAFMAP LOGO AND LINK

The SAFmaps logo is

To access SAFmaps, go to www.safmaps.com
To access information on macaw palm in the context of the project, go to http://dx.doi.org/10.17632/5498jdrm87