Sustainable Aviation Biofuels

UNICAMP

Development of Database Management System (DBMS) for Sustainable Aviation Biofuels in Brazil

Second Research Cycle

Preliminary version of the final report

The DBMS and Results of a Case Study

Authors: Arnaldo Walter (Coordinator), Joaquim E. A. Seabra, Jansle Vieira Rocha, Desirèe Dalmane, Nathália Vieira, Marjorie Guarengui
Faculty of Mechanical Engineering (FEM)
Faculty of Agricultural Engineering (FEAGRI)

February/2020

SUMMARY

THE CONTEXT

Greenhouse gas (GHG) emissions associated with the international civil aviation sector account for about 1.3% of global CO_2eq emissions (estimate for 2015), but this share tends to increase notably as the world becomes more connected. According to ICAO (International Civil Aviation Organization), if no action is taken these emissions could triple in 2045 compared to the expected results for 2020 (reaching 1,600 million tonnesCO_2eq - MtCO_2eq by the end of the period). Aiming to reduce the impact of civil aviation on climate change, in 2010 the ICAO Assembly adopted two aspirational goals: (i) to improve energy efficiency by 2% per year until 2050, and (ii) to achieve carbon neutral growth from 2020 onwards (i.e. absolute GHG emissions must not increase 2020 onwards). In this sense, ICAO estimates that the international aviation sector would have to offset about 2.5 GtCO_2 (billion tonnes) of emissions between 2021 and 2035.

In order to address the increase of GHG emissions from international aviation, in 2016 the ICAO Assembly adopted a global market-based measure scheme, called Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA will be implemented in three phases, being voluntary the participation[1] of States in the first two phases (the pilot one from 2021 through 2023, and the first phase from 2024 through 2026). The participation from 2027 through 2035 will be mandatory for the States which have an individual share higher than 0.5% on the global 2018 RTK (Revenue Tonne-Kilometres)[2][3]. In practice, all aircraft operators that operate international flights between two States in which both (i.e. origin and destination)[4] participate in CORSIA will be required to comply with the compensation requirements defined in the Scheme.

The CORSIA approach is based on comparing the total CO_2 emissions from 2021 onwards against a baseline level, which is defined as the average of CO_2 emissions from international aviation for the years 2019 and 2020. Emissions that exceed the baseline level represent the sector's offsetting requirements for a given year (ICAO, 2019a).

By 2035, it will be acceptable for an aeroplane operator to offset its GHG emissions through carbon credits that would attest to mitigation actions outside the aviation sector (for example, planting and maintaining forests, investing in renewable energy sources that replace fossil sources). Alternatively, an aeroplane operator can reduce its offsetting requirements by the use of CORSIA Eligible Fuels (CEFs), which shall come from fuel producers that are certified by a

[1] As of July 2019, 81 States have declared themselves voluntary to participate in CORSIA; Brazil is not among them.

[2] RTK is an indicator of transport intensity. It indicates the relative importance of a State, or an aeroplane operator, on the aviation.

[3] Or also the States that contributed to a cumulative share of 90% on global 2018 RTK (735,574 tonnes-kilometres). In practice, Brazil and other 35 States are in this list (Brazilian share was 0.78% in 2018). In addition, States can also be involved with CORSIA on voluntary basis.

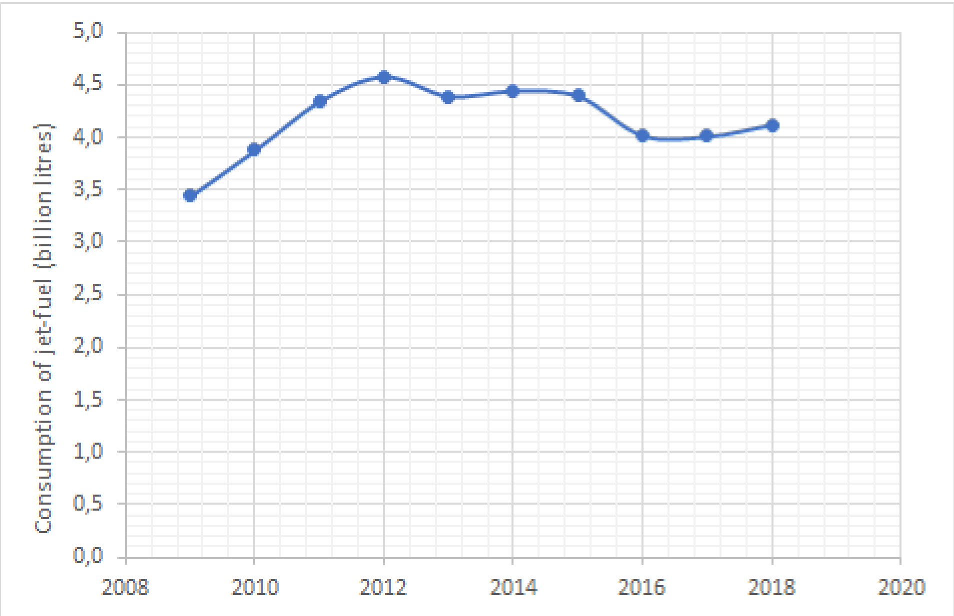
[4] For example, a flight departing from Brazil to Portugal, as both countries are in the list of 35 countries.

Sustainability Certification Scheme (SCS). From 2036 onwards, all requirements must be accomplished by eligible fuels (ICAO, 2019b).

CORSIA eligible fuels include Sustainable Aviation Fuels (SAF) and Lower Carbon Aviation Fuels (LCAF)[5]. For the time being, what would be required for CEFs – from a sustainability point of view – has only be defined for SAFs. And it is understood that in mid- to long-run effective reduction on GHG emissions due to civil aviation can only be achieved with SAFs.

Brazil has significant potential for the production of SAFs (here, also called bio-jet fuels), either due to the country's existing know-how, due to the tradition and relevance in the production and consumption of biofuels, and due to the appropriate conditions, which include land availability, the climate and the rainfall regime (Cortez, 2014). The production of bio-jet fuels could both aim the national aeroplane operators and exports.

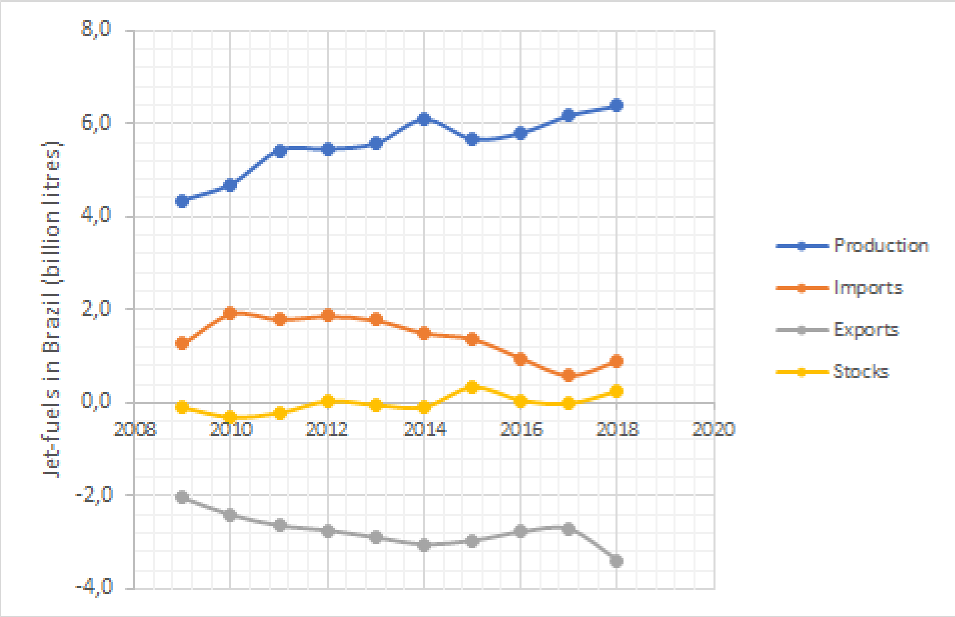
On average, the production of jet-fuels in Brazil raised at 2.57% per year in the period 2000-2019, but this growth was higher until 2014, when a deep economic crisis started in the country (3.52% per year, from 2000 to 2014) (ANP, 2020). Historically, in recent years, the national consumption of jet-fuels has been below of the production; Figure 1 shows the evolution of the consumption from 2009 to 2018 and it can be seen that since 2013 it has been between 4 and 4.5 billion litres. The production in 2018 was estimated at 6.36 billion litres, and it was 6.01 billion litres in 2019 (ANP, 2020). Figure 2 shows the evolution of production, trade and stocks in the same period.



Source: MME-EPE (2019)

Figure 1: The evolution of jet-fuel consumption (in billion litres) in Brazil, in the 2009-2018 period

[5] SAF would be produced from renewable biomass sources or residues (e.g. wood, vegetable oils, sugarcane, animal fats), while LCAF would be produced from fossil energy sources, but with significant reduction in comparison to conventional jet-fuel.



Source: MME-EPE (2019)

Figure 2: Production, trade and stocks of jet-fuel (in billion litres) in Brazil, in the 2009-2018 period

From Figure 2, it seems there is an effort for reducing imports and, possibly due to the constraints on consumption, increase the exports of jet-fuel. On average, the production has increased despite the almost stable consumption in the last years 5-6 years.

Since 2017 the University of Campinas (Unicamp) and Boeing Research and Technology - Brazil (BR&TB), as part of the Boeing Company (Boeing), have collaborative efforts with the aim of building a Data Management System (DBMS) that contains structured information related to selected feedstocks, such as suitability, yields, costs, required and existing infrastructure, for the sustainable production of bio-jet fuels, in Brazil. More specifically, the scope is to create an electronic platform that will provide easy access to relevant information/data related to promising feedstock and specific supply-chains in Brazil; the concept of regional hubs has been explored within the assessments and data gathering. The feedstocks that have been dealt in this project are: sugarcane, soybean, corn, eucalyptus, palm oil, macauba (macaw) palm (*Acrocomia aculeata*), animal fats and steelwork gases.

The agreement Boeing-Unicamp is set in the context of the JRC (Joint Research Centre for Sustainable Aviation Biofuels) between Boeing and Embraer that has as one of its goals to fund research projects and participate in other aviation biofuels related activities.

This project has been developed in two cycles: the first one from April 2017 to June 2018, and the second since December 2018.

This is the preliminary version of the final report of the second research cycle. As explained and detailed in the next section, there is a delay in comparison to the schedule agreed by Boeing and Unicamp, and the project will be completed in early May 2020.

THE PROJECT: AIMS AND DEVELOPMENT

As mentioned in the previous section, the aim is to create a Database Management System (DBMS) that will provide easy access to information and data related to feedstocks of interest for the production of SAFs in Brazil[6], as well as their supply chains. The DBMS can be used as an aid tool for potential investors in SAF production, as well as public policy makers, in addition to the JRC itself when developing research scenarios based on technical, economic and environmental feasibility.

In the first development cycle, a DBMS version was created with data from four biomasses (eucalyptus, cellulosic residues from sugarcane, macauba and halophytes). In the second research cycle the scope has been enlarged with soybean, corn, palm oil, steelwork gases and animal fats. It is also part of the scope of the second cycle the creation of functionalities in the DBMS that allow the analysis of situations of interest, which are referred to in this proposal as "case studies"; four studies will be developed until the end of the project.

It was predicted that the project would be developed in 12 months, starting in December 2018, with two additional months to set corrections and fine adjustments in the DBMS. This means that the project should be completed by the end of February 2020. For the reasons explained below, there is a delay of 2-3 months and all results will be completed in early May 2020.

The project development was organized in 13 activities, and for the time being nine of them were finished. Table 1 shows the proposed schedule of the project. The green marks indicate the activities that have been finished by February 2020. Activities 12 and 13 (final report and the deliverance of the final computational solution) are the two last, and will be finished by April-May 2020. Activities 9 and 11 are related with case studies (related of AtJ and HEFA pathways), and the research team decided to postpone them in order to develop the ultimate solution using the DBMS; both will be finished by March-April 2020. Activities 4 and 6 are also related to case studies (FT-eucalyptus and HEFA-macauba pathways) and previous versions were delivered, but the final version will be presented at the moment it will be possible to use the DBMS with all functions implemented. In this text it is presented an almost-final version of the case study related with FT (eucalyptus) pathway.

[6] Not the whole country is considered a priority, or adequate, for the production of SAFs. For instance, because of the controversy associated with sustainability, the entire legal Amazon, or much of it, and the Pantanal were excluded of the assessment.

Table 1: Proposed project's schedule

Activities/Months	OK	1	2	3	4	5	6	7	8	9	10	11	12
Activity 1 - Proposal and definition of the computational solution													
Activity 2 - Inclusion in the DBMS of detailed information on topography and land use in all relevant states													
Activity 3 - Inclusion in the DBMS of detailed soil type information in all relevant states.													
Activity 4 - Comparative study of the production of SAF by the FT pathway from eucalyptus (Case Study 1)													
Activity 5 - Inclusion in the DBMS of information on steelwork gases and bovine tallow.													
Activity 6 - Case study on the production of SAF by the HEFA pathway, from macauba (Case Study 2)													
Activity 7 - Procedures for classifying areas considering the fulfilment of several criteria													
Activity 8 - Inclusion in the DBMS of information on soy, corn and palm.													
Activity 9 - Evaluation of the production of SAF by pathway AtJ (Case Study 3)													
Activity 10 - Procedures for selecting areas considering the fulfilment of several criteria.													
Activity 11 - Evaluation of SAF production by the HEFA pathway, from soybean (Case Study 4)													
Activity 12 - Final Project Report													
Activity 13 - Delivery of the computational solution in open and off-line WEB platform													

The computational development of the DBMS has been carried out by a service provider (GeoMeridium[7]), since the team of researchers at Unicamp does not have people with this specific knowledge. The project also has a part-time consultant to assist the research team in monitoring the main activities under the responsibility of the service provider.

As the University of Campinas is a public organization, hiring a company requires observing specific procedures, although the project funds are not public, by origin. This is the main reason for the delays previously mentioned, as it was not possible to have the service provider effectively working before April 2019, despite the fact it was planned to have activities developed since January 2019. A second reason is related to difficulties in replacing a computer specialist who left the service provider in November 2019, and this restriction was only overcome in February 2020. A third reason is related to the computational difficulties faced during the development of the project, most related to the effort required to reduce the processing time on a platform that must be available online. The difficulties related to this have been overcome, but, for now, they have not been completely resolved.

The aim to finish the project in early May 2020 is a realistic. To minimize risks, Unicamp's research team was also reinforced.

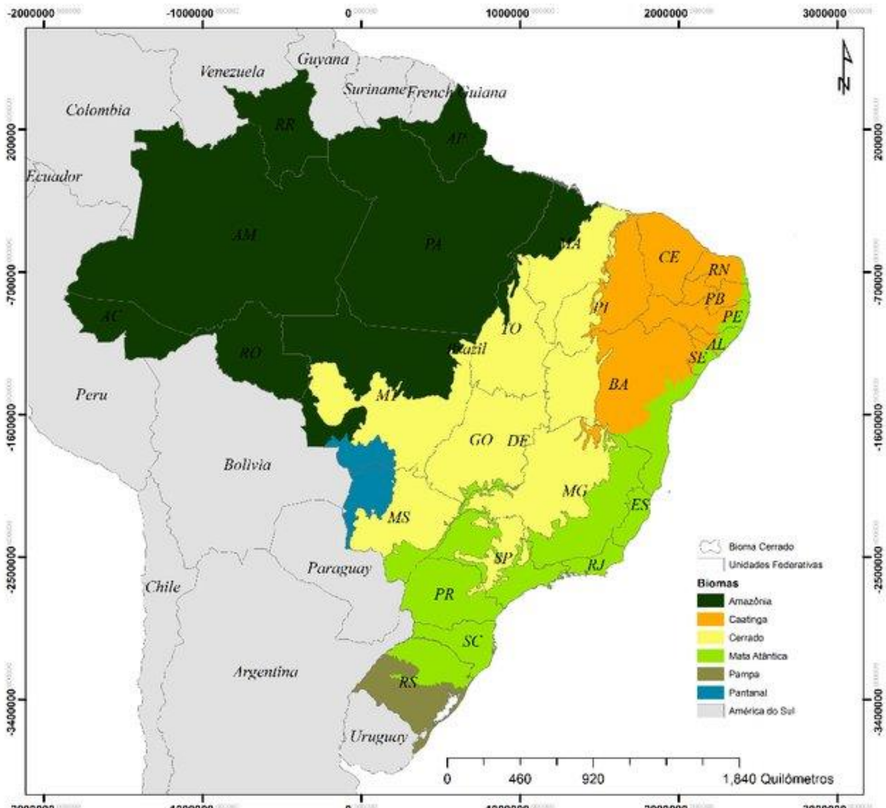
[7] A small company based in Campinas, state of São Paulo, Brazil. The project budget does not allow the hiring of large companies with experience in geoprocessing.

THE DBMS

Geographic scope

The eligibility of SAFs will require fulfilment of specific sustainability conditions (i.e. sustainability criteria). In this sense, it does not make sense to consider its production in sensitive biomes such as the Amazon (except in very specific regions, where sustainable palm production is justifiable) and the Pantanal. On the other hand, since agricultural expansion in Brazil occurs mainly in the Cerrado, it is justifiable to prioritize cultivation in regions within this biome. Figure 3 is a map showing the location of the six existing biomes in Brazil.

Thus, for the bulk of crops considered in this project, the 12 states that have been considered are the following: Rio Grande do Sul [RS], Santa Catarina [SC] and Paraná [PR] (in the South region), São Paulo [SP] and Minas Gerais [MG] (in the Southeast region), Mato Grosso do Sul [MS], Mato Grosso [MT] and Goiás [GO] (and also the Federal District [DF]) (in the Center-West region), Maranhão [MA], Tocantins [TO], Piauí [PI] and Bahia [BA] (the so-called MATOPIBA region). The state of Pará [PA], in the North region, has been considered only in the case of palm oil, as the potential there is the highest in Brazil. Depending on the location of steel plants and slaughterhouses (because of the availability of steelwork gases and animal fats), other states have been also considered.



Source: IBGE (2004)

Figure 3: The six biomes in Brazil and all 27 national states

Feedstocks considered

The feedstocks considered dealt are sugarcane (for ethanol production and also because of the availability of its residues – bagasse and straw), soybean, corn (for ethanol production, and also as oil source), eucalyptus, palm oil, macauba, steelwork gases and animal fats.

Certified pathways and status of bio-jet fuels production

Conventional aviation turbine fuel consists of refined hydrocarbons derived from fossil sources including crude oil, natural gas liquid condensates, heavy oil, shale oil, and oil sands. There is no standard formula for jet fuels because composition depends on the feedstock from which it is refined. Kerosene-type jet fuels consist of hundreds of different components raging between eight and 16 carbons, being n-paraffins, iso-paraffins, cycloparaffins and aromatics the major components (Chuck, 2016).

The rigorous safety standards and procedures adopted by the commercial aviation industry imposes stringent quality requirements for the fuel used to power aircrafts. ASTM D1655 is the most widely used standard to define the kerosene-type fuel specification for aviation turbine fuels, which presents the specifications for Jet A-1 fuel. Due to the strict quality control and economic concerns, the introduction of alternative fuels must follow the “drop-in” concept. This means the alternative fuel must be interchangeable and compatible with the conventional jet fuel when blended so that no adaptations are needed for the aircraft/engine fuel system nor the fuel distribution network (ICAO, 2018).

Complementary to its general ASTM D1655, in 2009 ASTM introduced a standard for alternative drop-in aviation fuels, ASTM D7566, related to the specification for aviation turbine fuel containing synthetized hydrocarbons. Every time a new process is certified, this standard is amended, incorporating a new annex (ASTM, 2020).

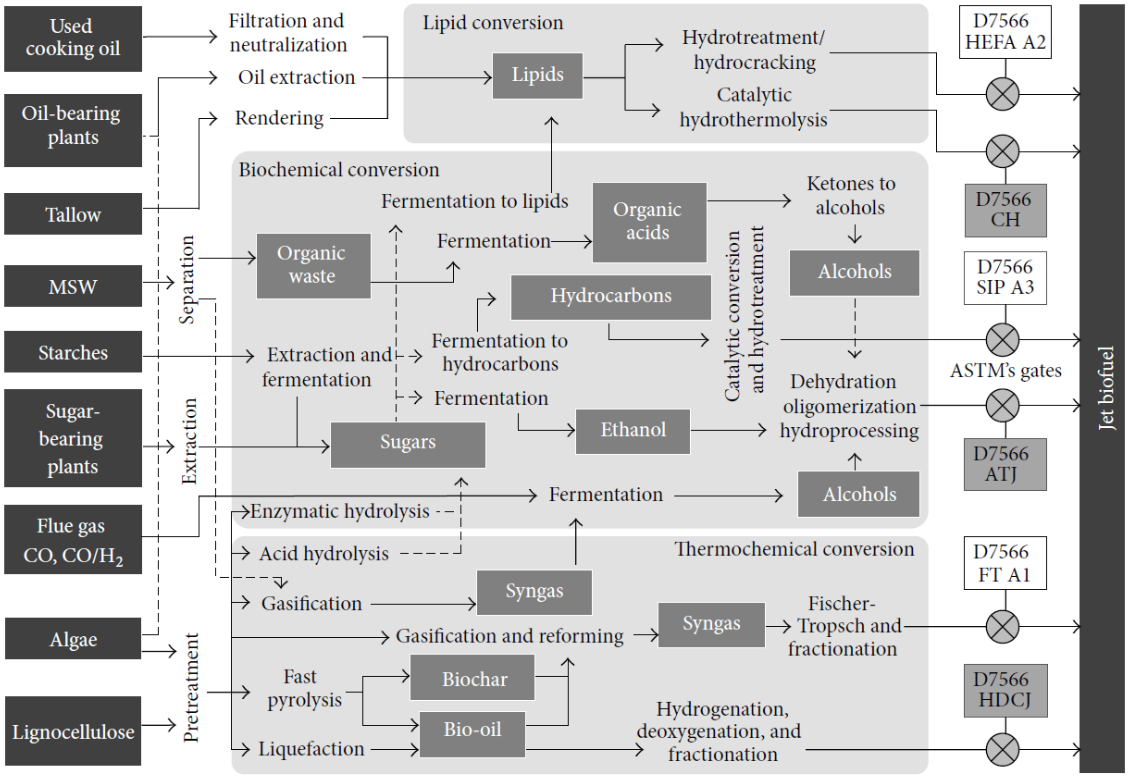
As of January 2020, there were seven conversion processes approved for aviation fuels production under the standards ASTM D7566 and ASTM 1655, which specify blending limits for these fuels (Table 2). The first certified conversion process was announced in 2009, the FT-SPK – derived from coal, natural gas or biomass –, which has a current restriction blend of 50%. In 2011, HEFA-SPK was approved, followed by HFS-SIP, ATJ-SPK and CHJ. FT-SPK with increased aromatic content (FT-SPK/A) has been also certified. Even though the certification allows for a blending with conventional Jet A or Jet A-1 fuel up to 50%, the higher aromatic content may be a route to 100% alternative jet fuel (ICAO, 2018).

Table 2: Conversion processes approved by ASTM International

	Annex	Conversion process	Abbreviation	Possible feedstocks	Blending ratio by volume	Commercialization proposals
ASTM D7566	1	Fischer-Tropsch Hydro-processed synthesized paraffinic kerosene	FT-SPK	Coal, natural gas, biomass	50%	Fulcrum Bioenergy, Red Rock Biofuels, SG Preston, Kaidi, Sasol, Shell, Syntroleum
	2	Synthesized paraffinic kerosene produced from hydro-processed esters and fatty acids	HEFA-SPK	Bio-oils, animal fat, recycled oils	50%	World Energy, Honeywell UOP, Neste Oil, Dynamic Fuels, EERC
	3	Synthesized iso-paraffins produced from hydro-processed fermented sugars	SIP-HFS	Biomass used for sugar production	10%	Amyris, Total
	4	Synthesized kerosene with aromatics derived by alkylation of light aromatics from nonpetroleum sources	SPK/A	Coal, natural gas, biomass	50%	Sasol
	5	Alcohol-to-jet synthetic paraffinic kerosene	ATJ-SPK	Biomass from ethanol or iso-butanol production	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy
	6	Synthesized kerosene from hydrothermal conversion of fatty acid esters and fatty acids	CHJ	Bio-oils, animal fat, recycled oils	50%	ARA
ASTM D1655	Annex	Co-processing		Fats, oils, and greases (FOG) from petroleum refining	5%	

Source: adapted from ICAO (2018) and ASTM (2020)

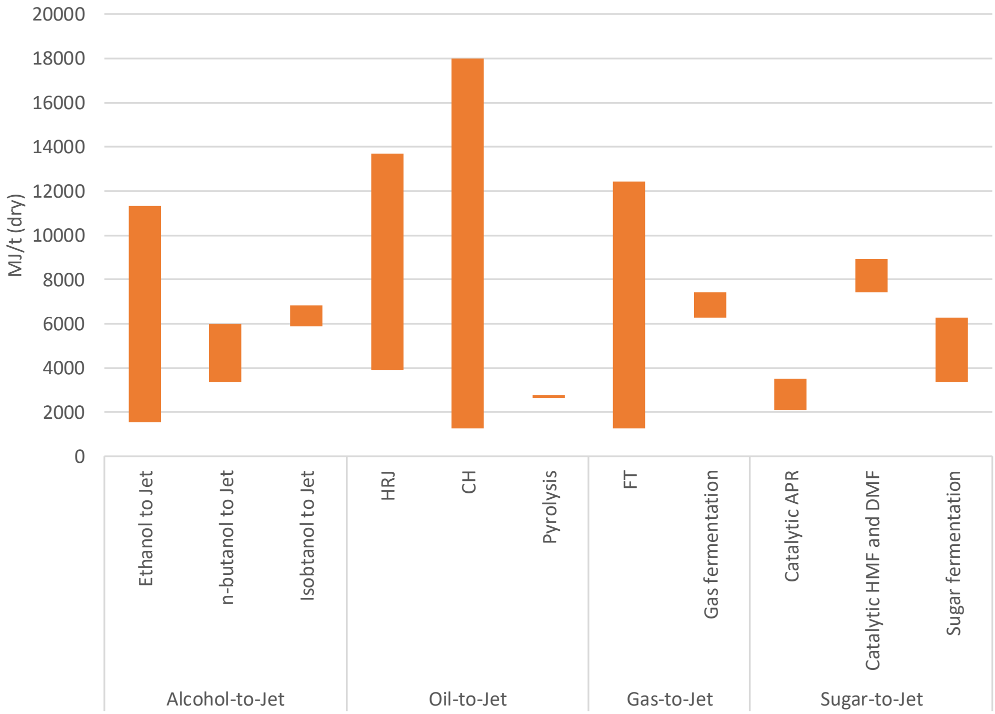
As illustrated in Figure 4, the technologies that convert biomass-based materials into alternative jet fuels depend strongly on the type of feedstock. Oil-based feedstocks are converted into bio-jet fuels through hydro-processing technologies, including hydrotreating, deoxygenation, and isomerization/hydrocracking. Processes such as catalytic hydrothermolysis (CH) have also been developed to treat triglyceride-based oils. Solid-based feedstocks are converted into biomass-derived intermediate through gasification, into alcohols through biochemical or thermochemical processes, into sugars through biochemical processes, and into bio-oils through pyrolysis processes. Syngas, alcohols, sugars and bio-oils can be further upgraded to bio-jet fuel via a variety of synthesis, fermentative, or catalytic processes (Wang and Tao, 2016).



Source: Cortez et al. (2015)

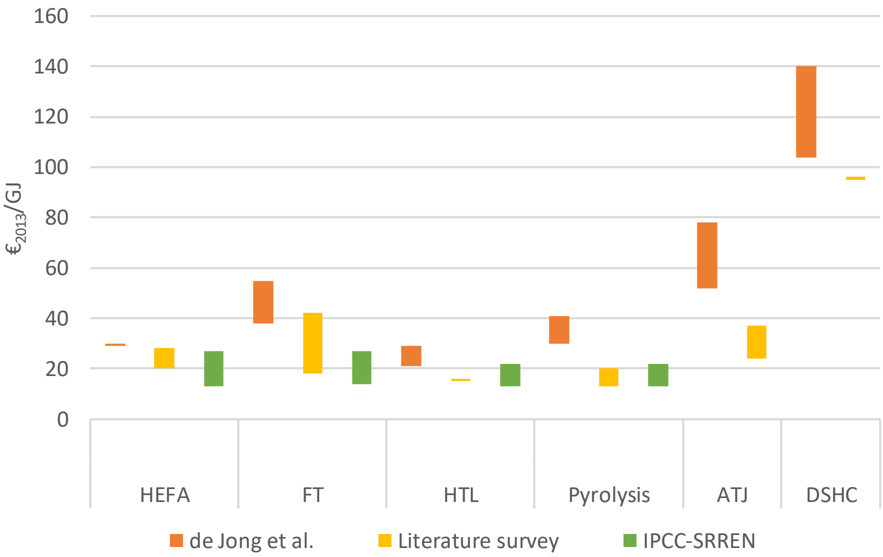
Figure 4: ASTM approved pathways for the production of alternative jet fuels

Jet fuel yields are intrinsically sensitive to the feedstock, conversion technology and process configuration. As depicted in Figure 5, final jet fuel yields reported in the literature vary over a wide range, even for the same conversion technology. When it comes to cost estimation, uncertainties are even higher – given the early development stages of most technologies –, although practically all studies project production costs well above the ranges for fossil kerosene. But cost reductions are expected over time as technology evolves. De Jong et al. (2015), for example, estimate a reduction of the minimum selling price from almost 70 €/GJ (greenfield, pioneer plant) to less than 40 €/GJ (n^{th} plant) for FT jet fuel produced from forest residues.



Source: elaborated based on Wang et al. (2016)

Figure 5: Final jet fuel yield estimations for different routes.



Source: elaborated based on de Jong et al. (2015)

Figure 6: Cost range estimates of bio-jet fuels.

In the present study the focus of the analysis is on pathways that combine the ASTM approved routes with the main feedstocks available in Brazil:

- FT-SPK from eucalyptus;
- HEFA-SPK from soybean oil, palm oil, macaw (macauba) oil and tallow;
- SIP-HFS from sugarcane;
- ATJ-SPK from sugarcane ethanol and steel off-gas.

This document reports the exercise developed for the FT-SPK from eucalyptus for two plant integration strategies: co-locating and greenfield (de Jong et al., 2015). Multiple gasification technologies exist to convert the biomass to syngas and further processing to Fischer-Tropsch (FT) liquids. One option is the indirect-gasification with tar reforming, in which the endothermic gasification process is indirectly-heated by the circulation of hot olivine and the material in the gasifier is fluidized by steam. Alternatively, in a high-temperature (slagging) gasification process, the dried biomass is pressurized and converted into raw synthesis gas during gasification at temperatures around 1300°C in the presence of high purity oxygen and steam (Wang and Tao, 2016).

For the present case study we adopted a directly heated, oxygen-blown, pressurized, fluidized bed gasifier, using the same assumptions as in de Jong et al. (2015), which in turn were based on Zhu et al. (2011) (Figure 7). The FT process modeled in Zhu et al. (2011) was originally target at FT Diesel (naphtha as co-product) and assumes a tubular fixed bed FT reactor with cobalt catalyst in the tubes. Synthesis gas is assumed to make a once through pass through the FT reactor, with a CO conversion efficiency of 70%. In this process design, after cooling the FT products are separated into light, medium and heavy fractions, that are sent to the fuel gas system, the hydrotreater and the hydrocracker, respectively. Hydrocracked and hydrotreated FT products are combined and cooled. Non-condensable components are recovered for use as fuel gas, while condensed components are further separated using distillation columns. Steam is raised at different pressures from process heat release and combustion of off-gas streams. Saturated steam is used to heat process streams, fluidize the gasifier bed and to feed gasification and reformer/water gas shift reactions. Superheated steam is sent to a turbine to generate power in a steam cycle, which is able to produce excess power.

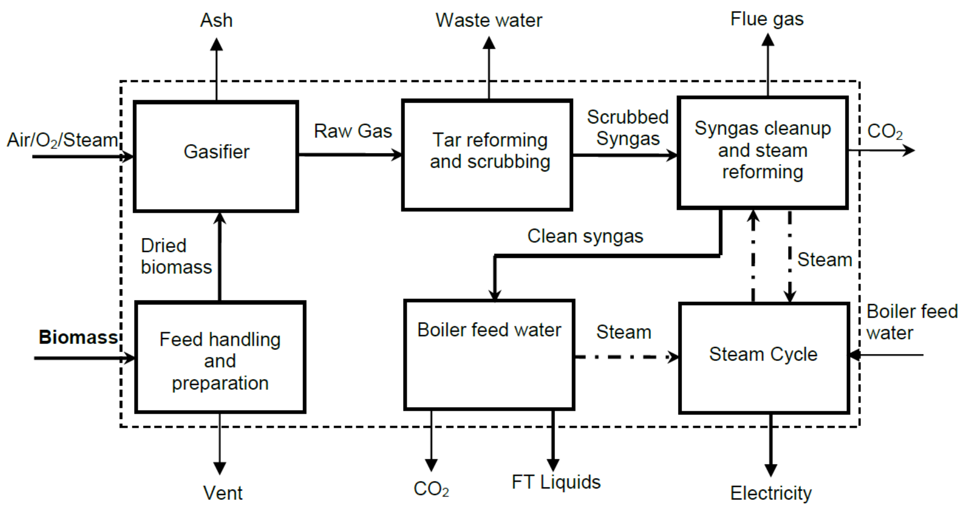


Figure 7: Biomass-to-FT Liquids block diagram modeled in Zhu et al. (2011)

The performance parameters assumed here for the FT process were the same adopted in de Jong et al. (2015) and are summarized in Appendix D. Scaling factors were used to estimate capital investment for different plant scales. In all cases, the feedstock cost was calculated as described hereafter.

Among the companies listed in Table 2 as involved with the route FT-SPK, the web page of Fulcrum Bioenergy (http://fulcrum-bioenergy.com/) states that it has technology for the production of liquid biofuels (bio-jet fuels among them) based on the biomass gasification + FT synthesis, producing from 37.9 to 227.1 million litres per year, from municipal solid waste. Fulcrum states that the process has been demonstrated and the process is certified for commercial operation; it has been reviewed by many companies, including BP and United Airlines. In the webpage with information dated from 2019, it is mentioned that the first plant (Sierra Biofuels Plant) is located in Storey County, Nevada, United States, with capacity of producing 41.6 million litres of biocrude per year (biocrude would be synthetized by other company to produce liquid bio-fuels).

In the web page of Red Rock Biofuels (https://www.redrockbio.com/) it is mentioned that the company (founded in 2011) is able to produce bio-jet fuels through the FT-SPK route, using forest and sawmill residues. The construction of the pioneer plant in Lakeview, Oregon, United States, started in July 2018 and it is predicted that operation can start in 2020. The production could reach 57.16 million litres of liquid biofuels (bio-jet, diesel and naphtha) from 136 thousand tons of waste woody biomass.

In a recent web seminar by IEA Bioenergy (January 2020) it was mentioned that the unit by Fulcrum Bioenergy is under construction and that it would be operational by the end of 2020. As for Red Rock Biofuels plant, what has been said is that the company states the operation could start in 2020, but the information is not fully confirmed.

In the same web seminar[8] it was recalled that the previous attempts related with large scale biomass gasification mostly failed because of economic reasons. On the other hand, there was a boom of small scale gasification facilities in Europe in the last five years, mostly for combined heat and power (CHP), and about 1,500 plants are in operation. However, in a comparison small versus large scale gasification, the challenges are different.

The concept behind the DBMS

The architecture of the DBMS allows the recovery and compilation of geographic data from the combination of attributes in the WebGIS application. Figure 8 illustrates the architecture that has been developed.

[8] Information can be accessed through www.ieabioenergy.com. In the context of the IEA Bioenergy Agreement, the Task 33 deals with biomass gasification.

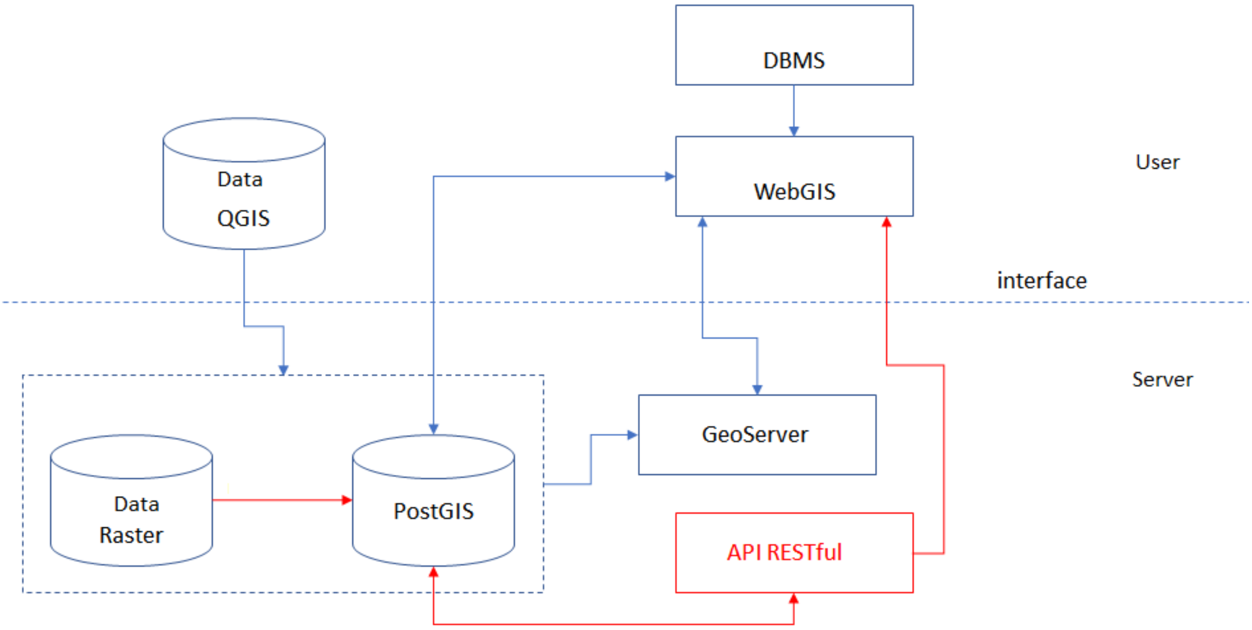


Figure 8: The proposed architecture of the DBMS

Some selected data have been incorporated into the DBMS in raster format (e.g. slop), through mechanisms provided by PostGIS Raster (2019). In the WebGIS application the selection of (multiple) attributes will be available from interface panels. From the combination of the attributes, the areas will be directly selected from the raster tables stored in the database through a RESTful API (2019), which will be responsible for managing and querying spatial data.

The combination of spatial data can be accomplished by stacking them in a data cube, as shown in Figure 9. In the cube, as in a raster image, each layer is represented by a band. Information from land use and land mapping, for example, can be transformed into raster images and overlaid in several layers. Likewise, information obtained from orbital sensors can also integrate this same cube.

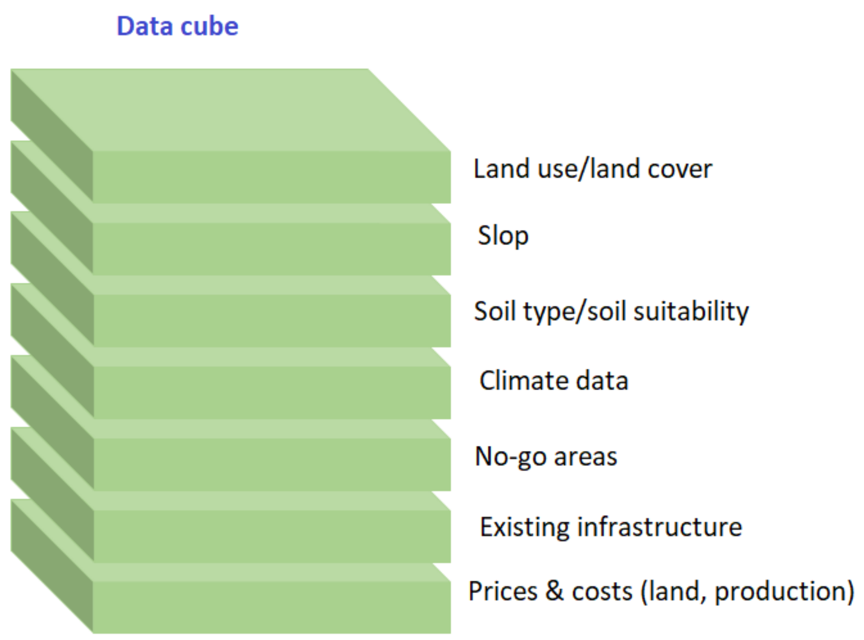


Figure 9: Scheme of a data cube, with relevant parameters listed in right side

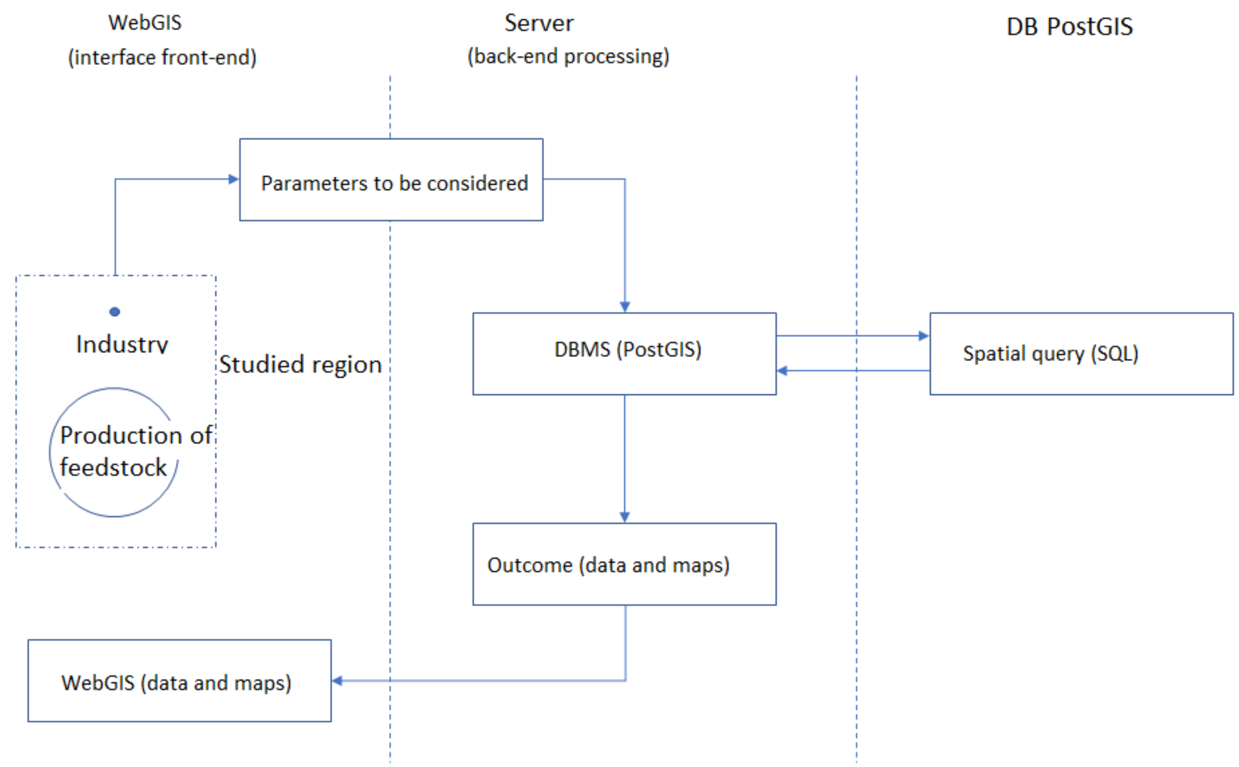


Figure 10: Data flow involved in the consultation and data processing

In the data stack illustrated in Figure 9, the values for each band can be obtained by selecting geographic coordinates represented by a pixel or a set of pixels. In PostGIS these values can be retrieved using SQL queries.

Through the WebGIS application, panels will be made available where the attributes of some previously determined spatial layers can be selected. From the combination of these attributes the parameters needed to perform the query in the database will be compiled and sent to the server responsible for processing the data. In addition to the combined attributes, the selected point or region of interest will also be sent. On the server, the data will be processed and the query will be carried out in the database. At the end, a response will be sent to the WebGIS application containing the recovered data and the maps to be plotted. Figure 10 illustrates the data flow involved in this process.

The WebGIS application responsible for interacting with the user is called the front-end. On the server side the application is called a back-end; it is responsible for data processing, bank consultation and response generation, characteristics inherent to a RESTful API.

Data sources

Some data sources used in DBMS are described below.

- Soil map of Brazil (Embrapa maps, scaled 1: 5,000,000) in vector format (shapefile), with the associated tables, allowing fusion with data available in better spatial resolution for the locations where the information exists (e.g. soil map of the IAC, for São Paulo state);

- Land cover and land use map by MapBiomas (Observatório do Clima), for 2018, has been used; the map is available in vector format (shapefile), with associated tables. Different classes of land use can be identified;

- Slope class map (derived from DEM), in vector format (shapefile). DEM is the Digital Elevation Model (DEM) from Brazil, available in matrix format (raster) and with spatial resolution of at least 30 meters (NASA SRTM or ASTER DEM);

- The declivity data were obtained by the “Shuttle Radar Topography Mission (SRTM)” elevation data, in a spatial resolution of 30m, provided by Topodata database (www.dsr.inpe.br/topodata);

- Climate database provided by Alvares et al. (2013). The information available includes the Köppen’s climate, average temperatures and rainfall in a typical meteorological year, on monthly basis, for all Brazilian municipalities;

- Municipal digital grid (IBGE) in vector format (shapefile), with associated tables for socio-economic themes (Demographic Census base) and municipal agricultural production (SIDRA/PAM base);

- Information for national parks, Environmental Protection Areas - APAs, indigenous reserves, quilombola areas, etc. No-go areas are polygons referring to the Conservation Units obtained from the vector file available on the Ministry of the Environment's website, for 2012. The mapping scale varies from 1: 5,000 to 1: 100,000.

REQUIRED INFORMATION FOR ASSESSING A PATHWAY

Introduction

In this section it is reported the required information for assessing a pathway, using the current version of the DBMS; what is described is based on the case study reported in the next chapter, related with the pathway FT-SPK.

Choices: pathway, feedstock and industrial plants

When the aim is the assessment of specific routes, the user must start the use of DBMS by selecting the pathway and the feedstock. The alternatives available were mentioned in the sub-section “Certified pathways and the status of bio-jet fuels production”, and are one more listed in Table 3.

The second action is to choose between co-locating and greenfield plants. Co-locating units are those in which there is an interest in sharing existing industrial utilities and infrastructure, including aviation fuel distribution. A possible justification would also be the need for hydrogen supply, when the gas is necessary in the production process. On the other hand, greenfield units are those in which all facilities must be built, once the production unit is stand-alone. As it will be further discussed, the investments and the costs of greenfield units tend to be higher.

In the case of FT-SPK, the only option available in the DBMS is eucalyptus.

Table 3: Pathways and feedstocks – alternatives available at the DBMS

Pathway	Feedstock
FT-SPK	Eucalyptus
HEFA-SPK	Soybean
	Palm oil
	Macauba oil
	Tallow
SIP-HFS	Sugarcane
ATJ-SPK	Sugarcane ethanol
	Steel off-gas

In the study case presented at this moment, the user can choose the capacity of the industrial unit among the values presented in Table 4. The capacities were defined for the time being for assure the consistency of the results, but larger capacities could be defined in the future. The capacities are defined in tonnes of FT liquid fuels to be produced per day, being the production of bio-jet fuels equivalent to 16% of the total liquids production. 340 and 500 t/day are capacities mentioned in the de Jong et al. (2015), that is the main reference for the economic analysis. On the other hand, 135 t/day is more representative of the pioneer projects, and 1,000 t/day was defined to explore scale effects. The annual production is based on the hypothesis of operating with a 90% annual capacity factor.

Table 4: Pathways and feedstocks – alternatives available at the DBMS

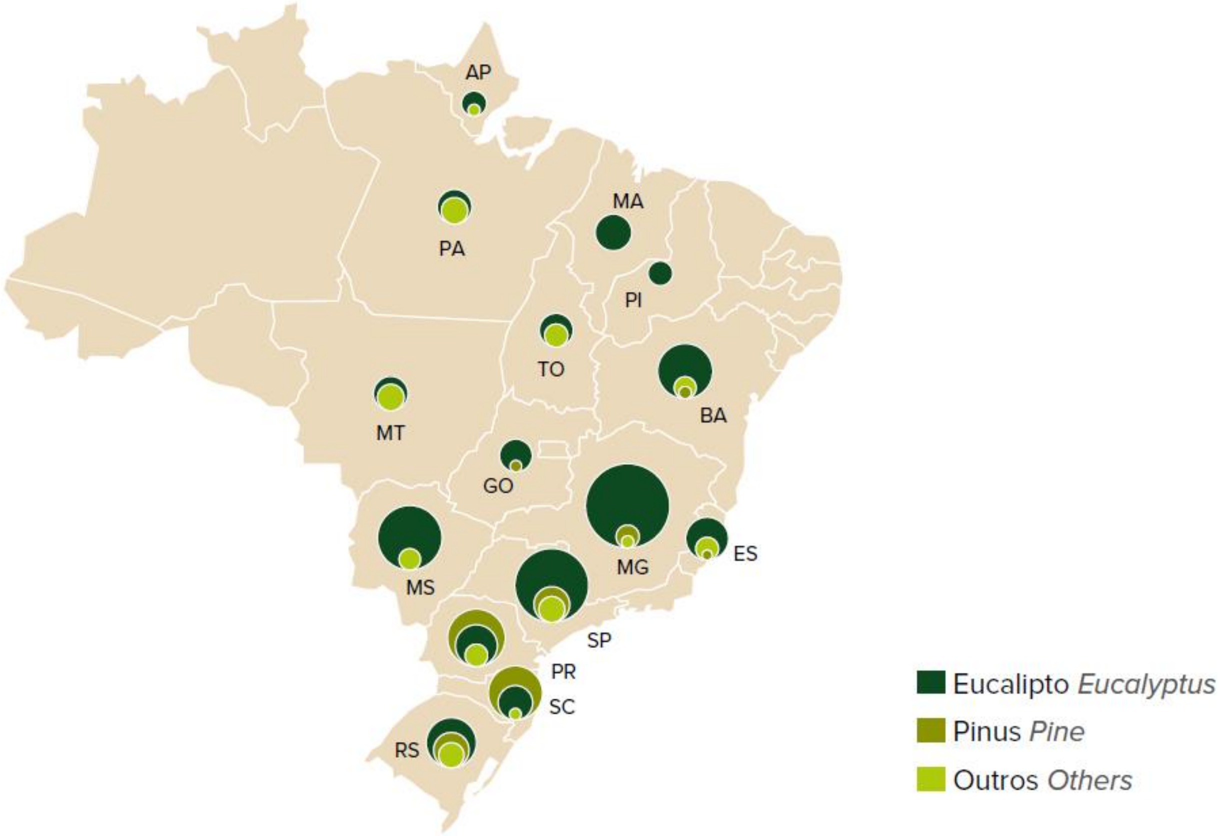
Industrial capacities		Industrial production of bio-jet fuels		
t/day of FT liquids	t/day of bio-jet	t/year of bio-jet	m^3/year of bio-jet	TJ/year of bio-jet
135	21.6	7,096	8,881	304
340	54.4	17,870	22,366	765
500	80.0	26,280	32,891	1,125
1,000	160.0	52,560	65,782	2,250

Eucalyptus

Eucalyptus is a forest specie of the broadleaf group, exotic to Brazil, belonging to the genus Eucalyptus. The genus includes more than 700 species (more than 800, according to Flores et al. 2016), almost all originating in Australia, with only a small number in neighbouring territories, such as New Guinea and Indonesia, in addition to one species in the northern Philippines (ESALQ, 2003).

Eucalyptus was inserted in Brazilian forestry approximately one century ago. For the pulp and paper industry, the large-scale use of eucalyptus began in the late 1950s and, over the years, has consolidated itself as the main raw material for the production of short fibre pulp. The largest share of eucalyptus consumption in Brazil is for pulp production (46%), with consumption also important as firewood (about 30%) and charcoal production (around 14%); these shares are for 2017 (IBÁ, 2018).

The Brazilian planted tree sector is recognized worldwide for the high productivity of its areas (i.e. annual volume of wood produced per unit area). The average productivity of eucalyptus was estimated at 36 m^3/ha per year in 2018. In the same year, the total area of trees planted in Brazil summed-up almost 10 million hectares (9.9 million hectares), 75% of which were eucalyptus plantations (7.54 million hectares). The planted areas are mostly located in the Southeast and South regions (Figure 3), but for eucalyptus there is expansion towards the Centre-West (e.g. Mato Grosso do Sul) and Northeast (Maranhão and Bahia) (IBÁ, 2019, IBGE, 2019). As an illustration, Figure 11 shows the states and regions in Brazil where there are the largest areas of planted forests (as for 2018).



Source: IBÁ (2019)

Figure 11: Planted forests in Brazil, in 2018; as reference, the planted area of eucalyptus in Minas Gerais (MG) was almost 2 million hectares

In this study, in order to characterize suitability, productivity and costs, the species *Eucalyptus grandis*, *Eucalyptus urophylla* and *Eucalyptus cloeziana* were considered. The first two are among the most used species in the pulp industry, while the third is indicated for energy use. The extent and quality of information available in the literature was also considered relevant in the decision.

Crop suitability

The adequacy of the cultivation of the feedstock is crucial information to assess the potential and to the following steps, which aim to estimate how much and at what cost biomass may be available for production of bio-jet fuels.

Details of the procedure adopted for estimating the suitability for eucalyptus is presented in Appendix A. It was developed based on the literature and resulted from the studies conducted since the first research cycle. In synthesis, suitability depends on the climatic parameters (e.g. atmospheric temperatures, rainfall, frost risk), geographic parameters (i.e. altitude, due to the risk of fungus propagation, in addition to the risk of frost and low temperatures), soil adequacy, and slope (because of the cost of harvesting).

As can be seen in Figure 12, frost risk and altitude impose constraints in a small extent, while soil adequacy is a restrictive parameter in many regions. Inadequacy of rainfall regime clearly imposes restriction to commercial production of eucalyptus in Northeast.

Figure 13 shows the final result of suitability for the twelve states assessed. The existence of a site in an area classified as "restrict" for the production of eucalyptus does not mean that a commercial activity would be impossible there. First, because the results are deeply impacted by soil classification (see Figure 12) and the resolution of the soil map (for the whole country) is not too high (1:5,000,000). Second, the feasibility of eucalyptus production depends on the production costs (see information in the following sub-sections), and also on the final purpose. For example, if the land is not expensive, eucalyptus production may be viable if the end use is for firewood or for charcoal production. In this sense, the results presented here are conservative,

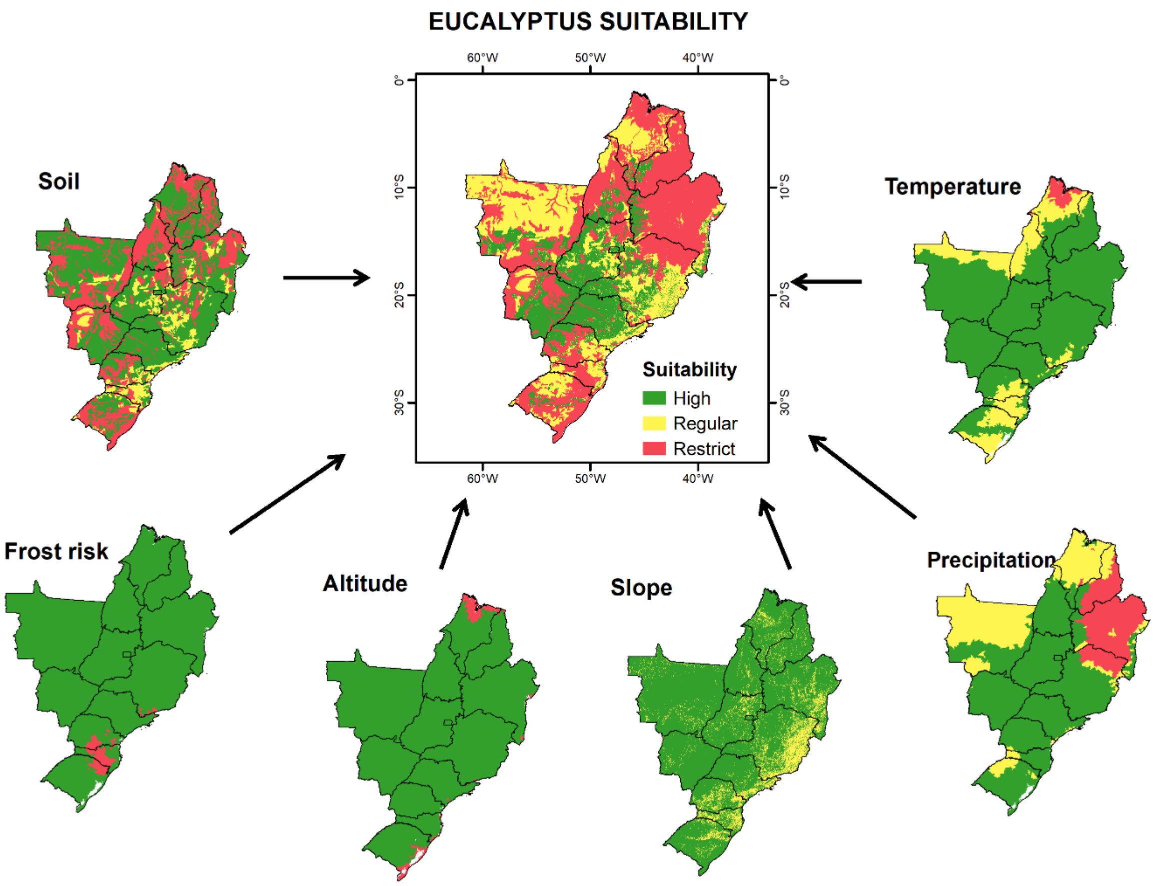


Figure 12: The concept of adequacy for eucalyptus planting, based on the combination of six attributes

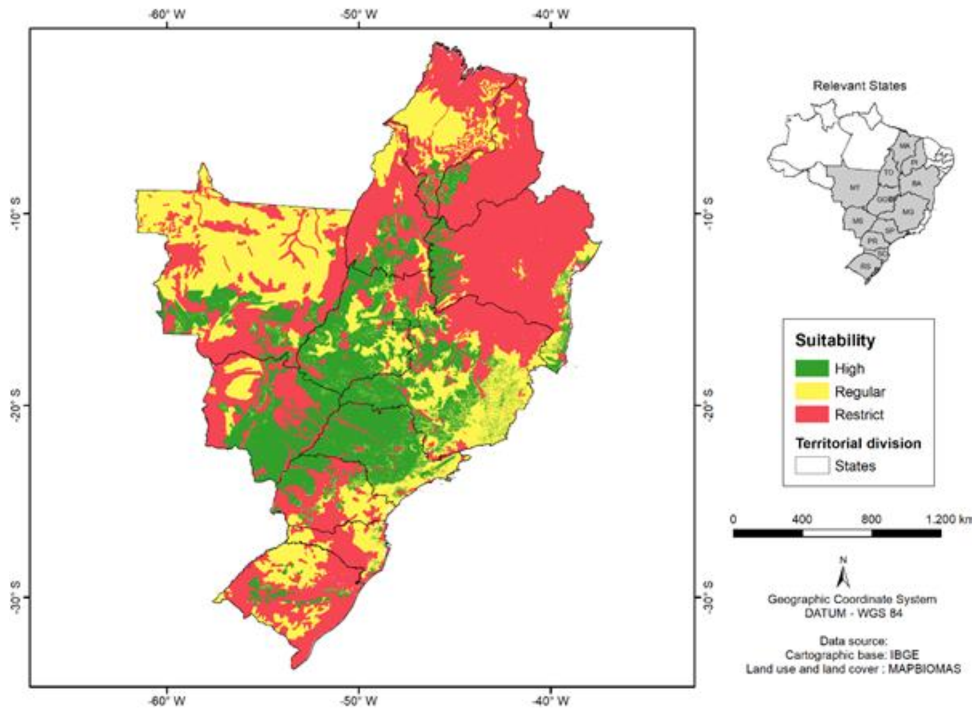


Figure 13: Suitability for eucalyptus production with high yields, in twelve Brazilian states

In the study case presented here, it was defined that eucalyptus for bio-jet production would be planted only over grasslands. Thus, the solution for suitability was merged with the land use map for 2018, resulting the map presented in Figure 14. Clearly, the areas with high suitability for eucalyptus in grassland areas in 2018 is constrained to some regions; it can be highlighted the west of São Paulo state, east of Mato Grosso do Sul, south of Goiás, and Triângulo Mineiro region.

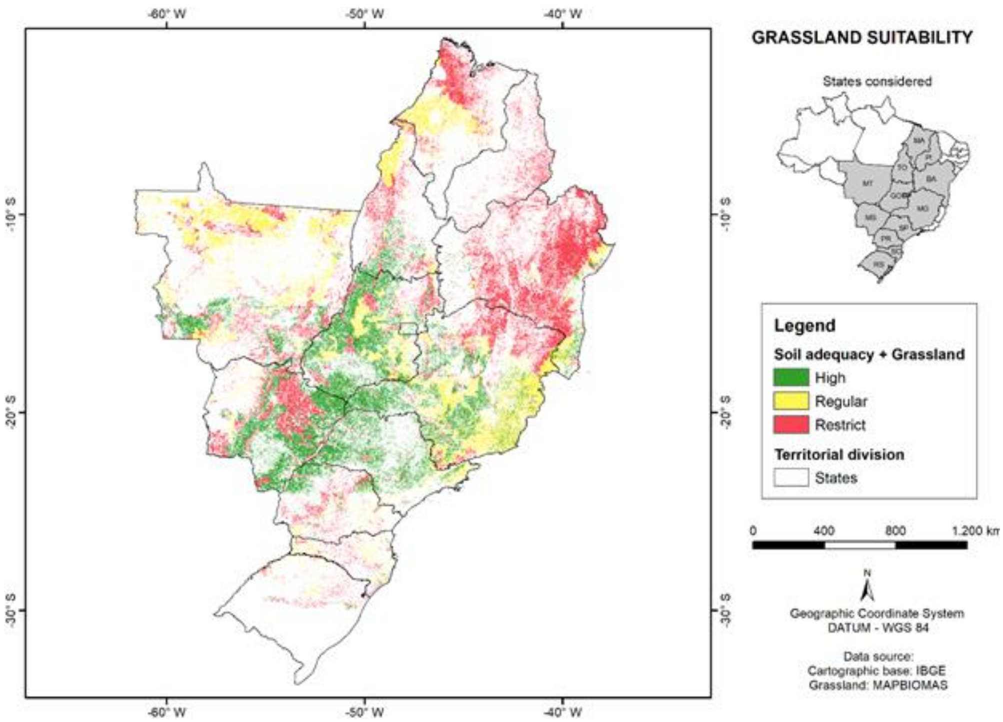


Figure 14: Estimated suitability for eucalyptus production in grassland areas (in 2018), in twelve Brazilian states

The merging procedure that leads to the solution presented in Figure 14 can be done in the DBMS, but for the time being it is time consuming. The research team is working to solve this problem. At this moment the solution is upload the database and the maps related with pre-defined cases.

Estimates of productivity

The second crucial step is estimating the productivity of feedstock production. For eucalyptus, this was done based on statistic model developed in the first research cycle, which is presented in Appendix B.

For this, the main reference is a study by Guimarães and Sans (no date), in the context of a project developed by EMBRAPA, with results of yields based on a procedure for modelling eucalyptus growth. Two technological scenarios were considered: one that corresponds to the adoption of the usual techniques by the pulp industry (that results in higher productivity) and another that corresponds to the practices of small forest producers (that results in lower productivity). Here only the highest productivity results were taken, which are expressed in the useful volume of the tree after seven years growth. The three species considered are three species of eucalyptus *E. grandis, urophylla, and cloeziana*.

The final explanatory variables – and their coefficients – of the statistic model adjusted for the results presented by Guimarães and Sans (no date) is presented in Appendix B. The yields depend on the soil suitability for eucalyptus, represented by dummy variables that set differences among "apt", "inapt" and "marginal" areas. The statistic model was applied for the twelve Brazilian states, supposing that all soils in Brazil would be "apt", "inapt" and "marginal". The results were compared with average and best yields of eucalyptus in Brazil, in recent years. The discussions are presented in Appendix B.

The database of estimated yields was then merged with the database with soil classification, resulting the map that is presented in Figure 15. The yields are presented in m^3 of wood, after harvesting (i.e., with high humidity), per hectare and per year. Comparing the maps presented in Figure 13 and 15 it is clear that depending on specific climatic conditions, medium to high yields could be achieved in areas not classified as with high suitability.

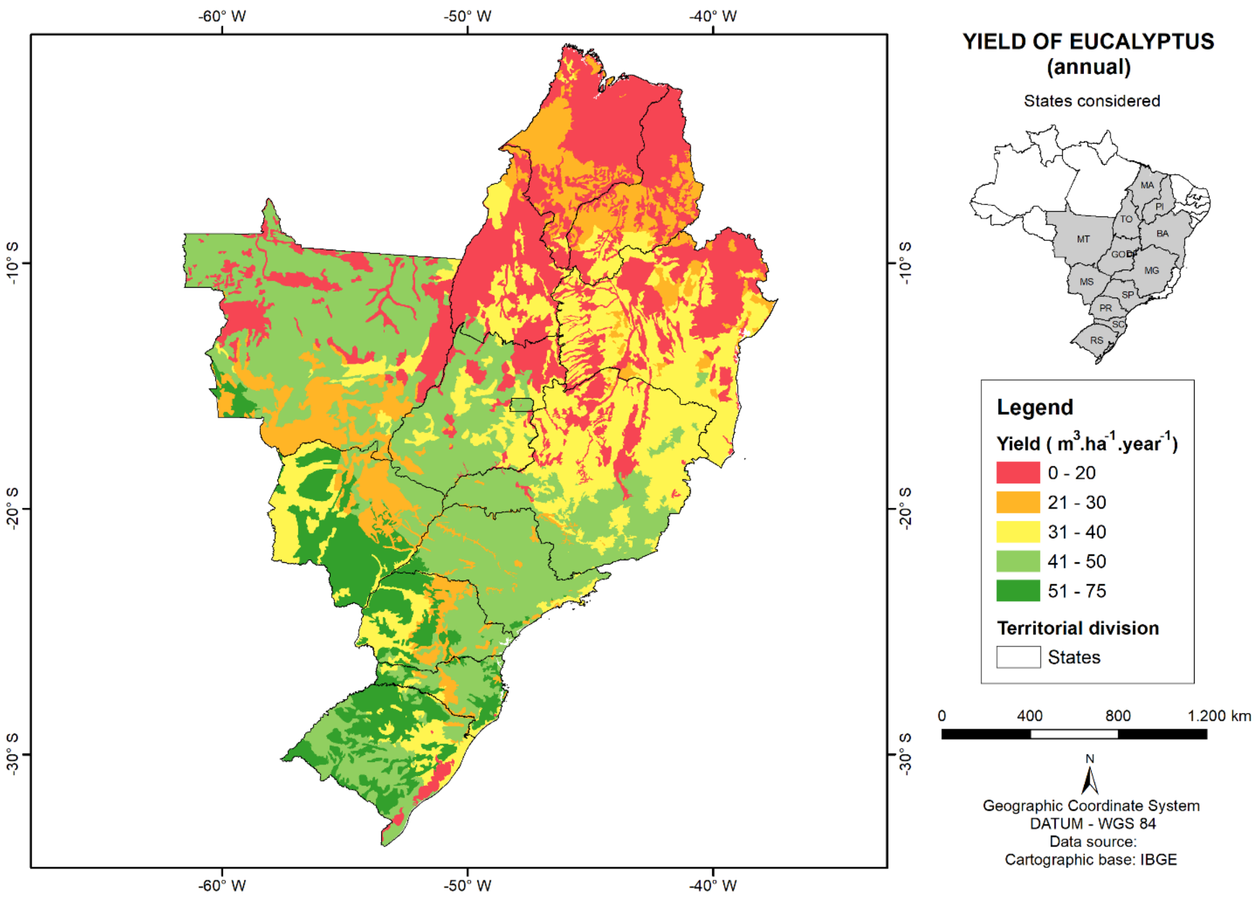


Figure 15: Estimated eucalyptus yields in twelve Brazilian states

Estimating wood costs

The third crucial step is estimating the production costs of wood and the costs of the wood delivered at the mill site. Here a synthesis of the adopted procedure is presented, and details are presented in Appendix C.

Wood costs at the industry have two components: the costs of wood itself at the forest, after cutting the trees, and the cost of transporting the wood to the industry. On the other hand, the cost of wood has three components: the costs of the forest (i.e. preparing the field, planting and keeping the forest), the cost related to the opportunity cost of land, and the cost of harvesting, that depends on the slope of the terrain. The procedure was defined during the first research cycle, and it was improved at this moment. Costs were corrected in order to reflect them in 2018, and a database with land prices was created.

Applying the procedure, it is first calculated the cost of wood before cutting the trees, per m^3, which depends of the local yield, and then this cost is combined with the cost of harvesting, considering the slope at the site. For doing this, it is necessary to merge data of local costs with the declivity data. Them, the cost of the wood, after cutting, at the forest site, is available for each site (pixel).

Figure 16 shows the final map of wood costs, after cutting trees, at the forest. The map is for the twelve states assessed in this project.

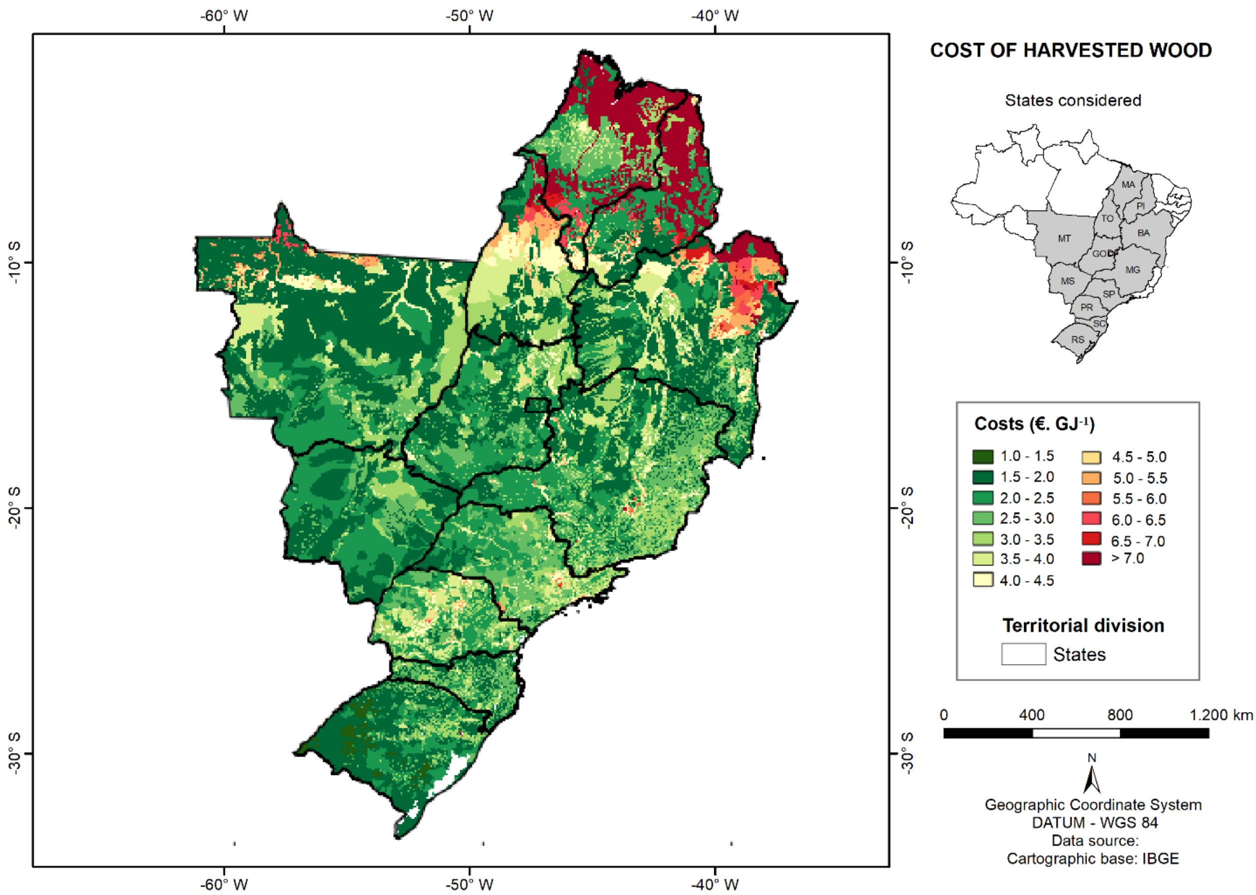


Figure 16: Estimated wood costs at the forest, after cutting trees, in twelve Brazilian states

The next step, and a challenge so far, is related to the cost of transporting wood from the forest site to the industrial site. During pilot tests, inverting the objective, the attempt to calculate the distance from one point (pixel) to all points (pixels) surrounding the destination, for different radii, proved to be computationally impossible, as the processing time was very long. While the ideal solution is not found, what is being done is to fix the destinations and pre-calculate the distance from the various points of origin within pre-established radii. This was done in the case study reported here.

In the two sites considered in the case study further reported, the cost due to transport represent between 21-24% to 37-40% of the costs of wood at the mill site.

No-go areas

No-go areas are sites that cannot be used for producing the feedstock. In this project, at the beginning, no-go areas were defined as the Amazon and the Pantanal regions, which were simply excluded in the assessment of feedstock suitability, yields, etc. In all twelve states (thirteen states, including Pará, which was considered only in the case of palm oil as feedstock), no-go areas are also the sites of national parks, Environmental Protection Areas, indigenous reserves, etc.

The information about these areas are available in electronic maps and the adopted procedure is to exclude from the assessed areas all sites that are inside no-go areas. In the study case further reported, the exclusion of no-go areas will be shown.

Figure 17 shows the map of no-go areas that correspond to Environmental Protection Areas and reserves.

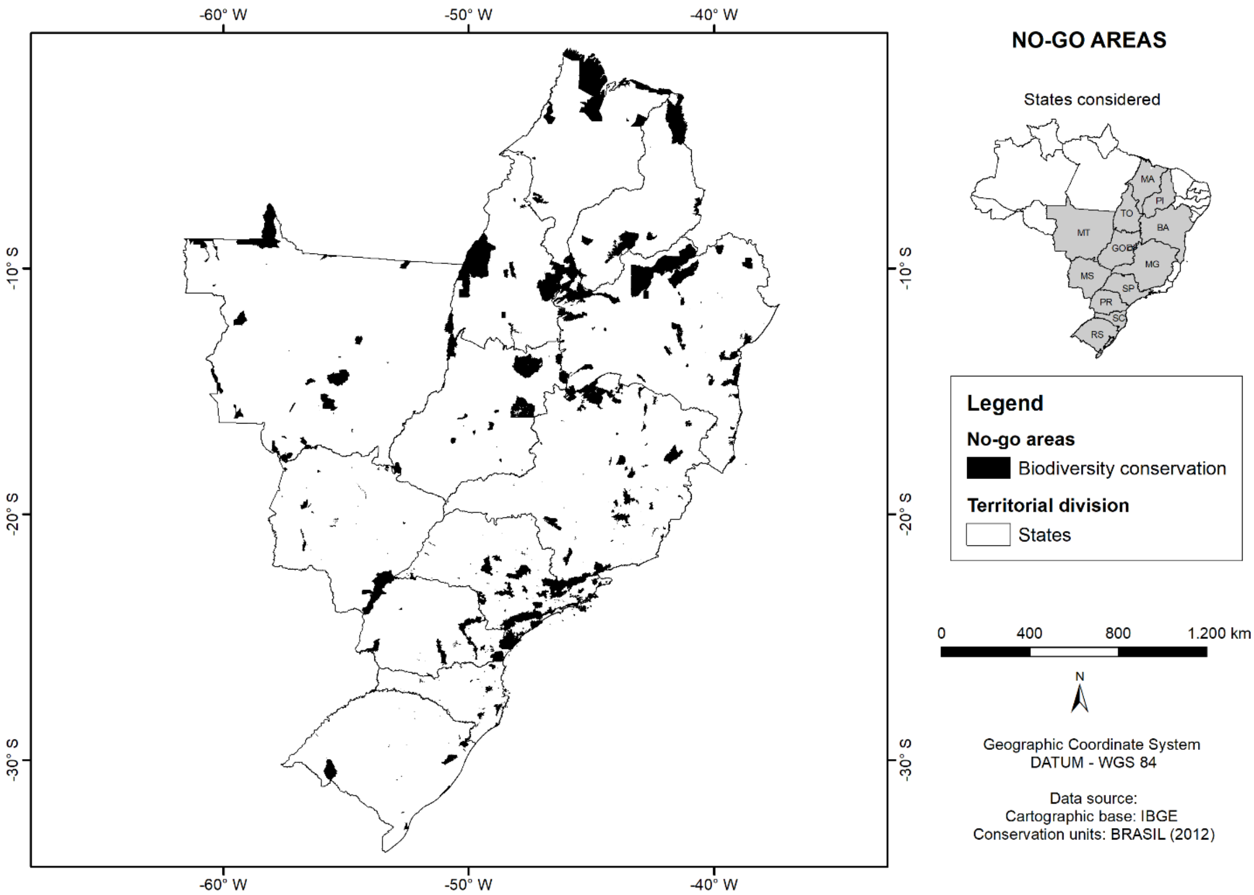


Figure 17: Map showing the location of reserves and Environmental Protection Areas in the twelve states assessed.

Figure 18 shows the map of wood cost at the forest, after cutting trees, combined with the information of pasturelands (in 2018), once it has been considered priority to have planted forests only on pasturelands, and also combined with the information of no-go areas, for preserving reserves and areas of high conservation value.

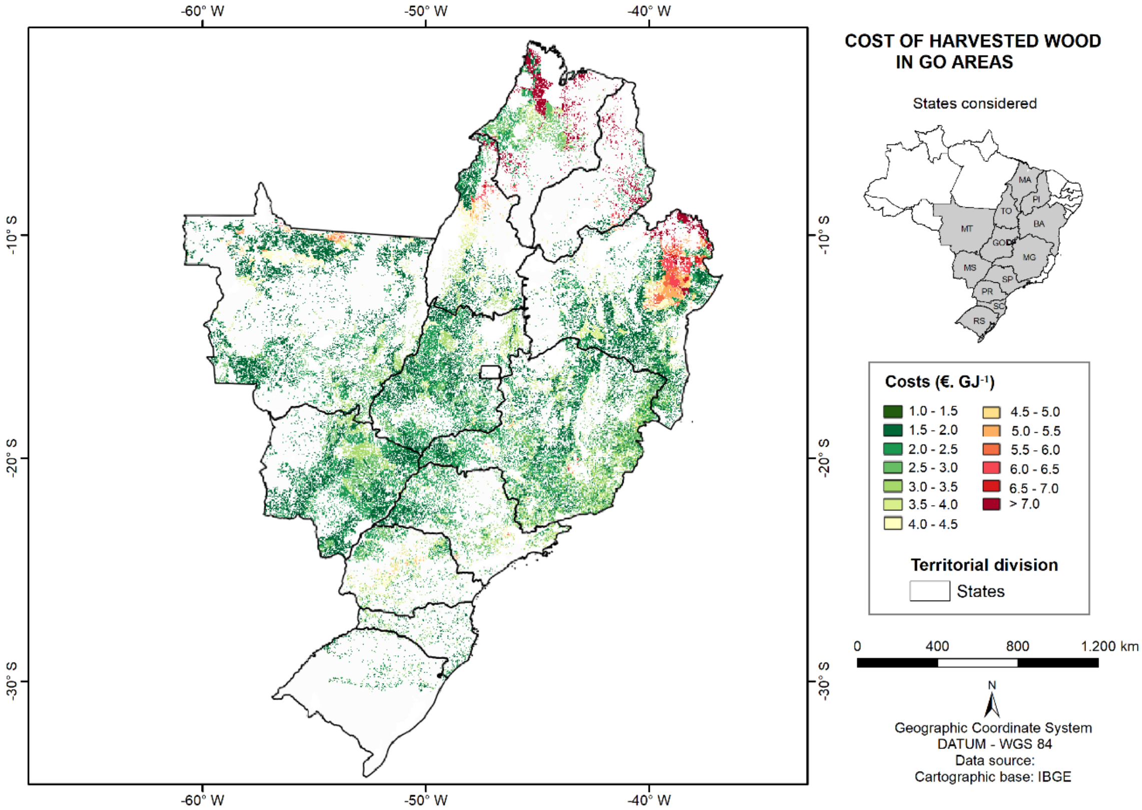


Figure 18: Map of wood costs at the forest, after cutting trees, in areas that are priority for planted forests (i.e. in pasturelands and excluding no-go areas)

It has been seen that with the criteria mentioned above there are few remaining areas in the south region, but a lot in Centre-West region and in Minas Gerais.

A CASE STUDY: FT-SPK PATHWAY BASED ON EUCALYPTUS

Introduction

In this section it is reported a case study developed with the use of the current version of the DBMS (it is not the final version). The case study is concerned with the pathway FT-SPK, based on eucalyptus, with feedstock production and industrial conversion in Southeast Brazil. Both co-locating and greenfield projects have been considered.

Two preliminary versions for the FT-SPK route were previously performed, the first one by the end of the first research cycle and the second at the beginning of the second cycle. Both were developed using the previous version of the DBMS. In the first study it was considered the production in a co-locating industrial plant, beside the REGAP oil refinery, in Betim, Minas Gerais. In the second study it was considered two co-locating units, both in São Paulo state, being one beside the REVAP oil refinery, in São José dos Campos, and the second beside the International Paper pulp mill, at Mogi Guaçú.

The description that follows aims at illustrate how the DBMS could be used for assessing the potential of bio-jet fuels production in Brazil. Due to the yet existing constraints in the DBMS, the case study was simplified in its scope. The restrictions and the way in which they are planned to be resolved are mentioned in the final chapter.

The two case studies

The first case is the final version of the assessment done for the co-locating industrial unit that could be built beside the Henrique Lage oil refinery (REVAP), located in São José dos Campos, state of São Paulo, Brazil. The first reason for choosing this site is because REVAP is the largest producer of jet-fuel in Brazil, covering, on average, in the last ten years, 33.4% of the national production. The second reason is that there is a duct that allows the transport of jet-fuel straight from the refinery to the main international airport in Brazil (the Cumbica airport, in Guarulhos, São Paulo).

The second case corresponds to a greenfield industrial plant that would be built in Regente Feijó, in the district of Espigão, in the west of the state of São Paulo. The first reason is because the map of costs shows that eucalyptus can be produced at low cost within a radius of 150-200 from the hypothetical industrial site. This is due to a set of reasons, including edaphoclimatic conditions, topography and land prices. A second reason is because the industrial site would be close to Presidente Prudente, a medium size municipality, with good infra-structure (e.g. hospitals, schools), including a regional airport. In the case of production in Espigão, the bio-jet fuel would be transported by trucks or by train to an oil refinery or to large airports.

Once the location of the two industrial sites were set, the area around these sites for assessing the potential production of eucalyptus was defined as a circle with 200 km radius. Ideally, the procedure should be accepting the production outside a circle. However, as the processing time is still very long, to make the calculation faster the 200 km circle was defined, and the distances from the various municipalities to the industrial units were pre-calculated. Thus, the costs of wood placed in each industrial unit were calculated, from more than 300 municipalities in each case.

Figure 19 illustrates the location of the two industrial sites (REVAP in the centre of the circle on the right side, and Espigão in the centre of the circle on the left side). The figure also shows the estimated costs of wood delivered to the two industrial sites; green areas indicate where production would be cheaper. Inside the circles, the areas marked in white are no-go areas due to constraints related to declivity, urban areas, or areas that correspond to Environmental Protection Areas and reserves.

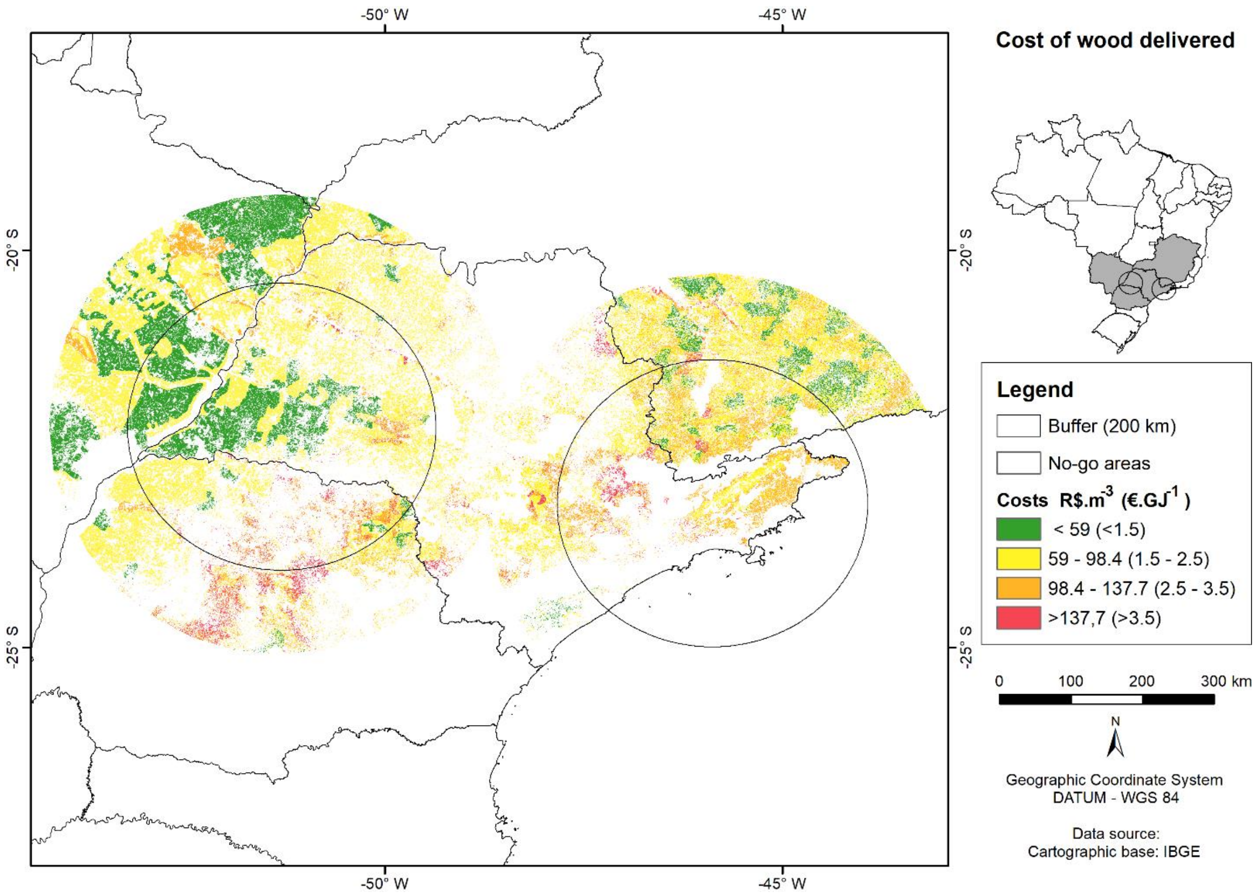


Figure 19: The proposed location of the industrial sites, and the circles indicating where eucalyptus would be produced.

Industrial parameters

The industrial parameters are based on de Jong et al. (2015), for the FT-SPK route. The user of DBMS should define at the beginning the industrial capacity, that will be indicate at the platform as the mass production of bio-jet fuels per day, in tonnes. The four options available and the correspondent parameters are listed in Table 4.

Table 15 summarizes the parameters considered through the calculations, and Table 16 presents the factors used to calculate the production of co-products.

Table 15: Industrial parameters and parameters considered in the calculations

Parameter	Value	Unit/Comment
Annual capacity factor	90%	
Number of days in the year	365	
Output/Input (mass basis)	0.17	t/t (FT liquid/dry wood)
Bio-jet fuel/FT liquids (mass basis)	0.16	t/t (Bio-jet fuel/FT liquids)
Bio-jet fuel density	0.799	kg/m3
Bio-jet fuel LHV	42.8	MJ/kg
Wood after harvesting – humidity index	104%	
Wood after harvesting – density	0.985	t/m^3
Wood at the industry – density	0.774	t/m^3
Wood LHV (dry)	18.07	MJ/kg

Table 16: Parameters used to calculate the production of co-products

Co-product	Factor	Unit
Diesel oil	0,62	t/t (diesel/FT liquids)
Naphtha	0,24	t/t (naphtha/FT liquids)
Surplus electricity	0.015	MWh/GJ of input

Industrial costs

The estimate of the costs of bio-jet fuel production from eucalyptus, through the FT-SPK route, is also based on Jong et al. (2015). The authors have considered the production from forest residues, supposing an industrial unit able to produce 340 tonnes of FT liquids per day. The case that corresponds to n-th plant is the one reflected in this report, and both co-locating and greenfield production are assessed.

Based on the information presented by de Jong et al. (2015) a model was developed, and it allows the calculation of the minimum selling price (MSP) of bio-jet fuel for the four industrial capacities (see Table 4). Details of the procedure and the main results are presented in Appendix D. As all other cost factors are defined, the information that is required to estimate the MSP of bio-jet fuel in a given plant is the cost of eucalyptus at the industrial site. The propose is to estimate the supply curve.

The supply curves of eucalyptus and results for a 50 km radius

Defining the eucalyptus supply curve at the industrial unit requires a combination of eucalyptus cost data (at the factory) and productivity data. For now, the intention is to carry out the study pixel by pixel, but this is time consuming. In this sense, what is presented here are the results for a 50 km radius, and not for a 200 km one. It took many hours to complete the procedure for the smaller circle (about 2 hours with a self-dedicated computer, with an estimate of 32 hours for a 200 km radius), and the team is still working to find a computational solution that allows for more ambitious assessments.

Figure 20 shows the distribution of eucalyptus costs after cutting trees, around REVAP. Areas without information correspond to those in which production is not possible (for example, urban areas or no-go areas due to environmental restrictions). On the other hand, Figure 21 shows the geographic distribution of cost of wood delivered to the industrial site.

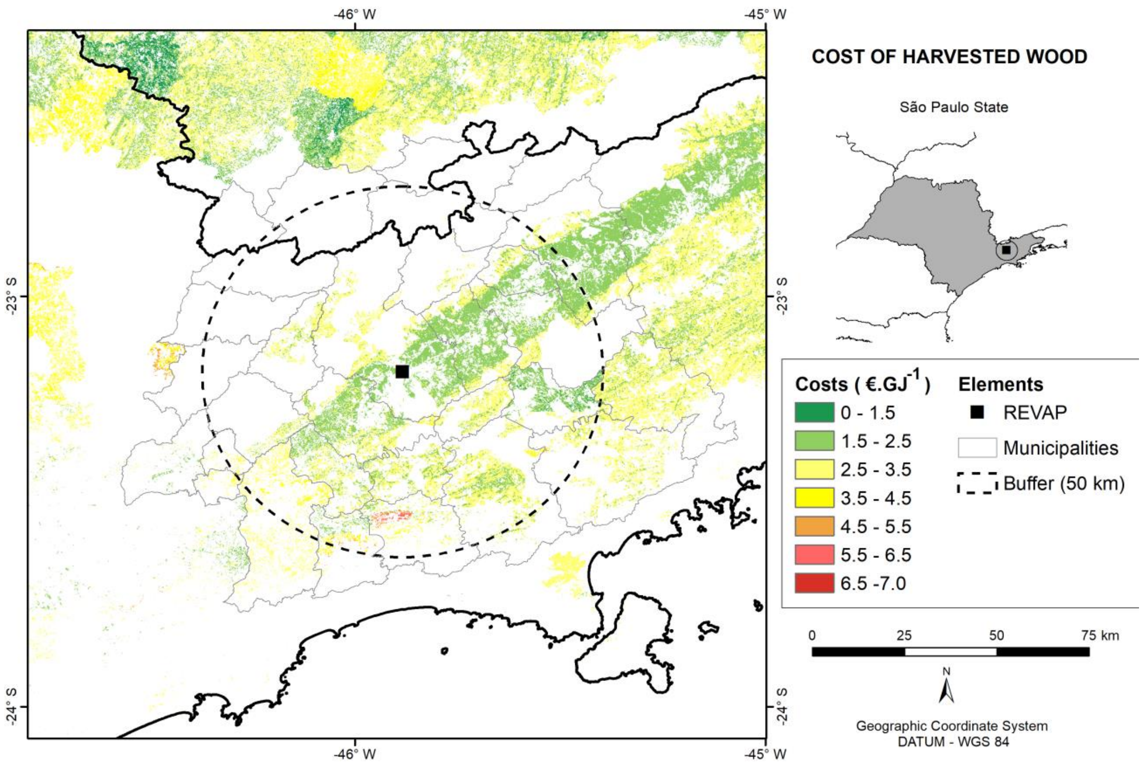


Figure 20: Wood costs of eucalyptus just after cutting trees, around REVAP, and within a radius of 50 km

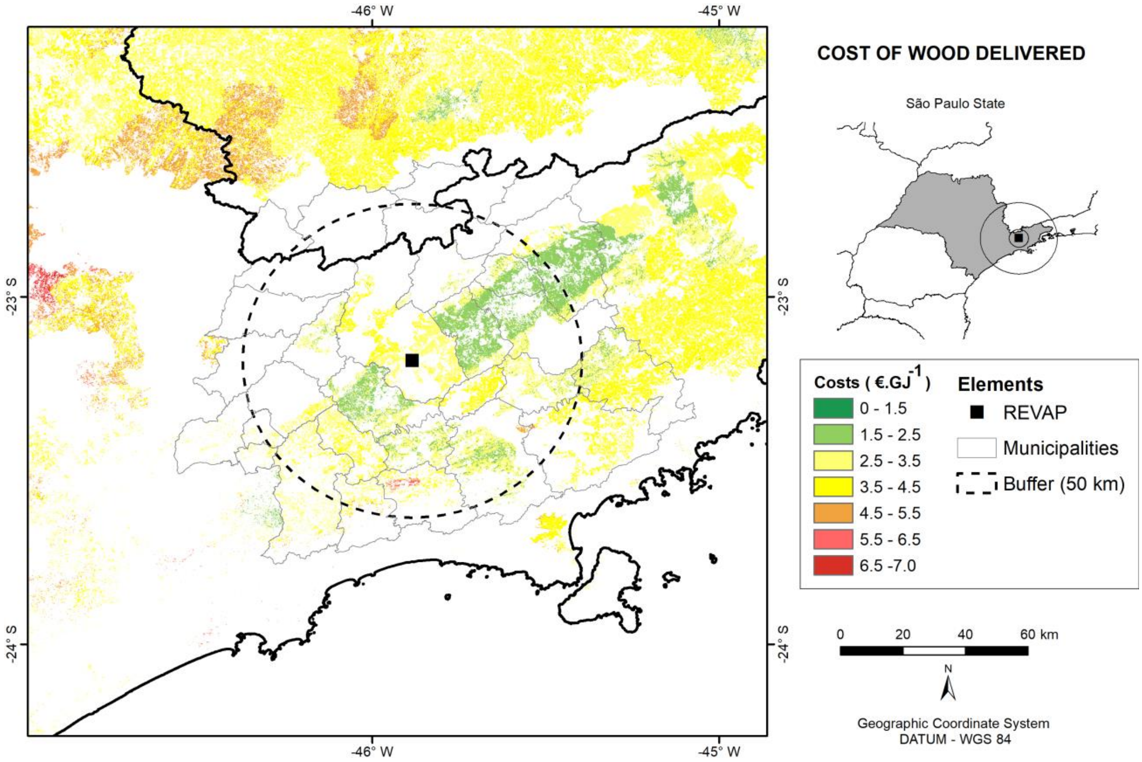


Figure 21: Origin of wood and costs of eucalyptus delivered to REVAP, around the industrial area and within a radius of 50 km

Figures 22 and 23 show similar information for the Espigão case (district of Regente Feijó), in the extreme west of the state of São Paulo.

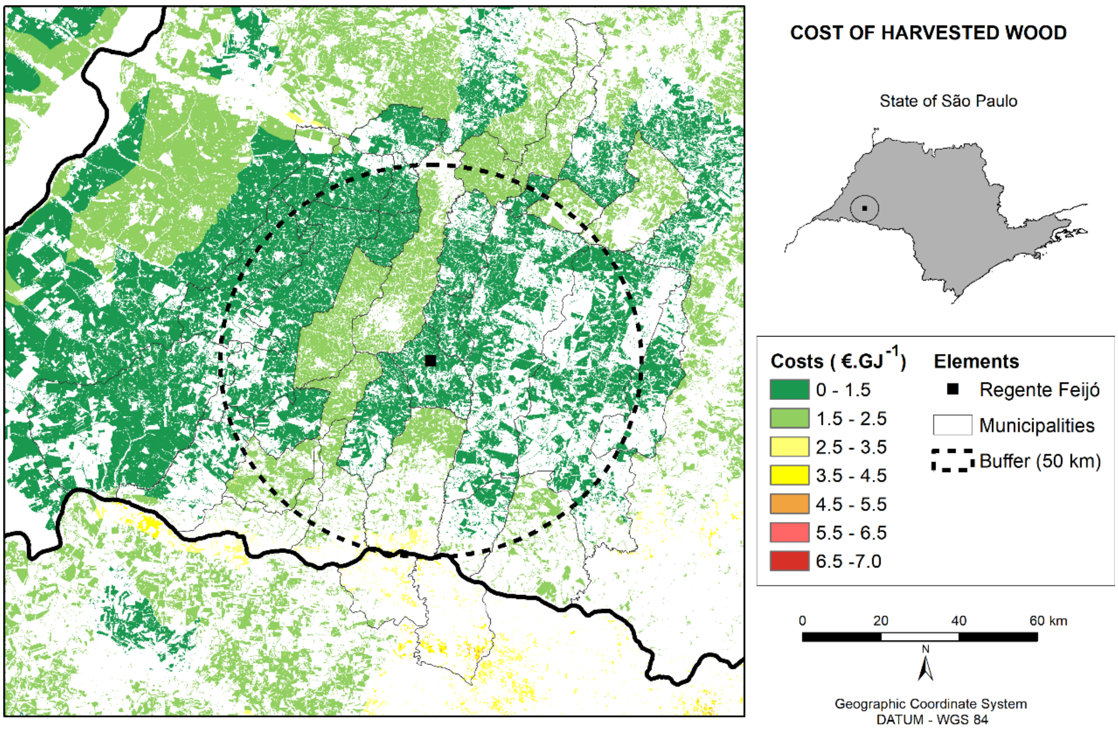


Figure 22: Wood costs of eucalyptus just after cutting trees, around Espigão, and withing a radius of 50 km

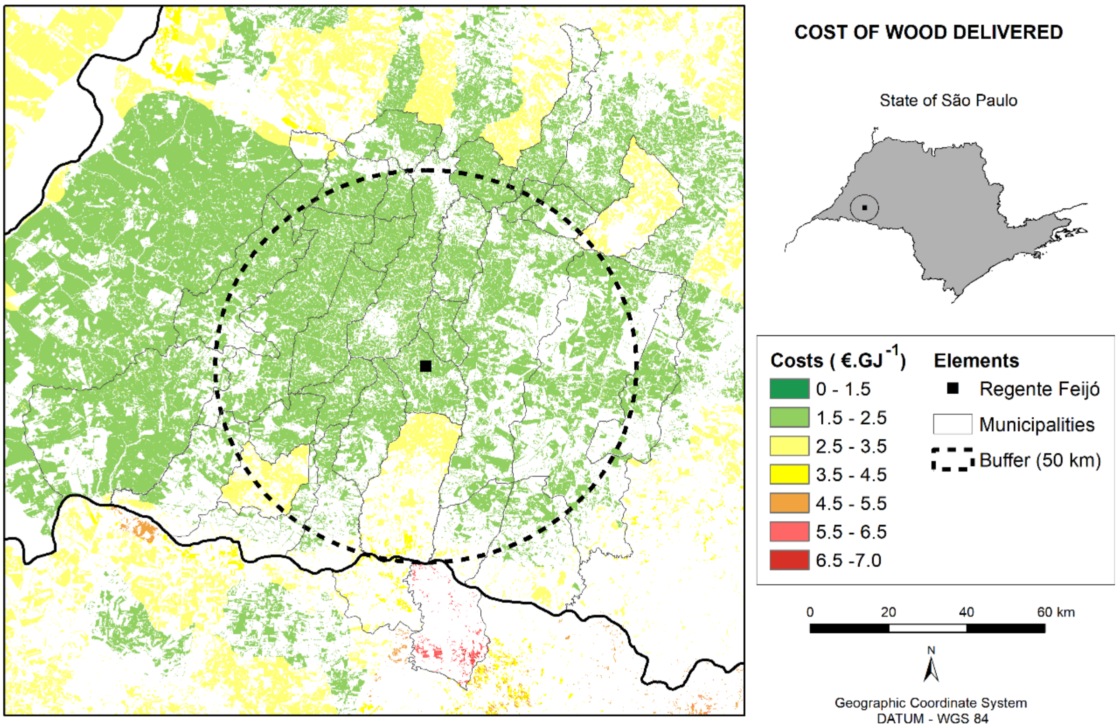


Figure 23: Origin of wood and costs of eucalyptus delivered to REVAP, around the industrial area and within a radius of 50 km

Figure 24 shows the wood supply curves in areas that correspond to a circle with radius 50 km, around REVAP and Espigão. There are clear differences between the two curves. Both regarding the maximum annual production capacities (supposing all sites available would be used for this purpose) and costs.

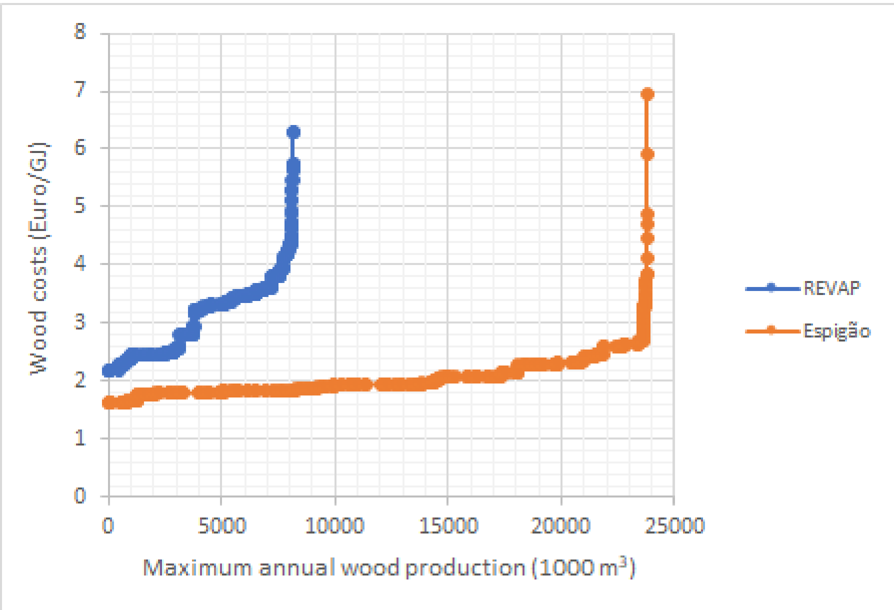


Figure 24: Wood supply curve at REVAP and Espigão (cost at the industrial site)

Table 16 summarises information of wood requirement associated to the four industrial capacities considered in this report.

Table 16: Wood requirement for the four industrial capacities considered

Bio-jet fuel (t/day)	FT liquids (t/day)	Dry wood (t/day)	Wet wood (t/day)[1]	Wet wood (m^3/day)[1]	Wet wood (1,000 m^3/year)[1]	Wet wood (1,000 m^3/cycle)[1]
21.6	135	794	1,617	1,641	539	3,773
54.4	340	2,000	4,072	4,132	1,357	9,502
80.0	500	2,941	5,988	6,077	1,996	13,974
160.0	1,000	5,882	11,976	12,154	3,992	27,947

[1] As available at the forest, after cutting trees

Taking the production of 54.4 t of jet-fuel per day as example, both for the co-locating plant (REVAP) and greenfield plant (Espigão), the minimum wood requirement would be 9,502 thousand m^3 of wet wood per cycle of seven years, demand that corresponds a certain area (due to the yields in the region). Comparing Figures 22 and 23, it is clear that the potential supply in both cases is much higher than that.

However, in practice, the actual required area is greater than the one which theoretically is necessary to supply 9,502 thousand m3 of wet wood along a seven-year cycle, because it is not possible to plant 100% of the area. First, it is necessary to take into account the restrictions imposed by the Forest Code, and in at least 20% of each area the natural vegetation must be maintained. Second, it is necessary to have an area available for infrastructure (roads, buildings, etc.). Thus, here it is estimated that the required area should be 30% larger, that would result in an area able to produce 12,353 thousand m^3 of wet wood along a seven-year cycle.

Figure 24 shows the wood supply curve in the case of a co-locating plant, with capacity of producing 54.4 t/day of bio-jet fuel, located at REVAP. Figure 25 shows a similar curve for the greenfield unit located in Espigão. The weighted average cost of wood (at the industrial site) would be 90 R$/$m^3$, and the maximum would 94.6 R$/$m^3$ in the REVAP case, while in the Espigão case the average would be 65 R$/$m^3$ and the maximum 68.4 R$/$m^3$.

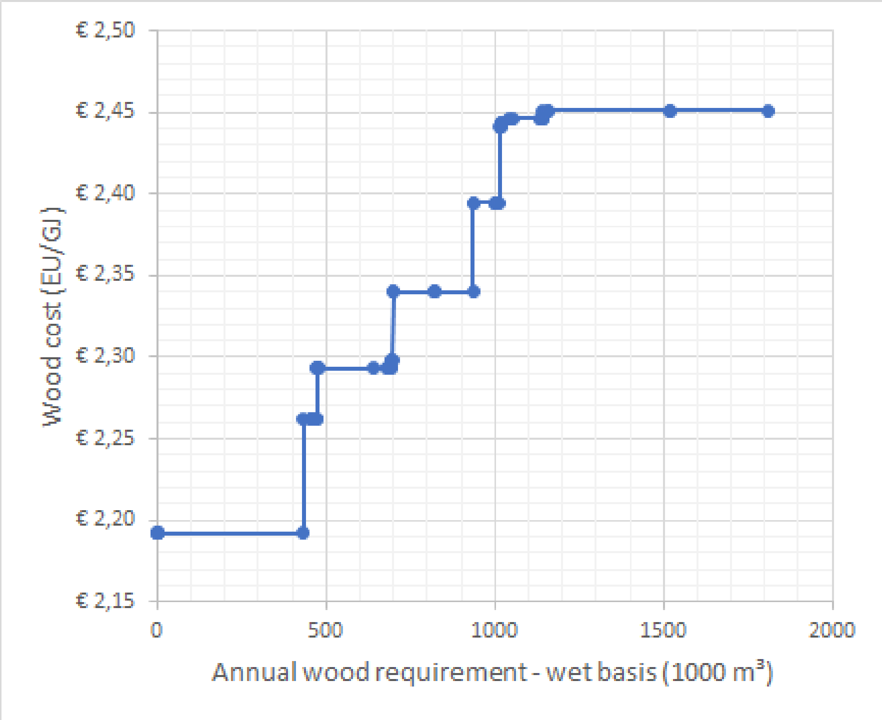


Figure 24: Wood supply curve at REVAP (co-locating plant; 54.4 t/day of bio-jet fuel) (cost at the industrial site) for assuring the supply along a seven-year cycle

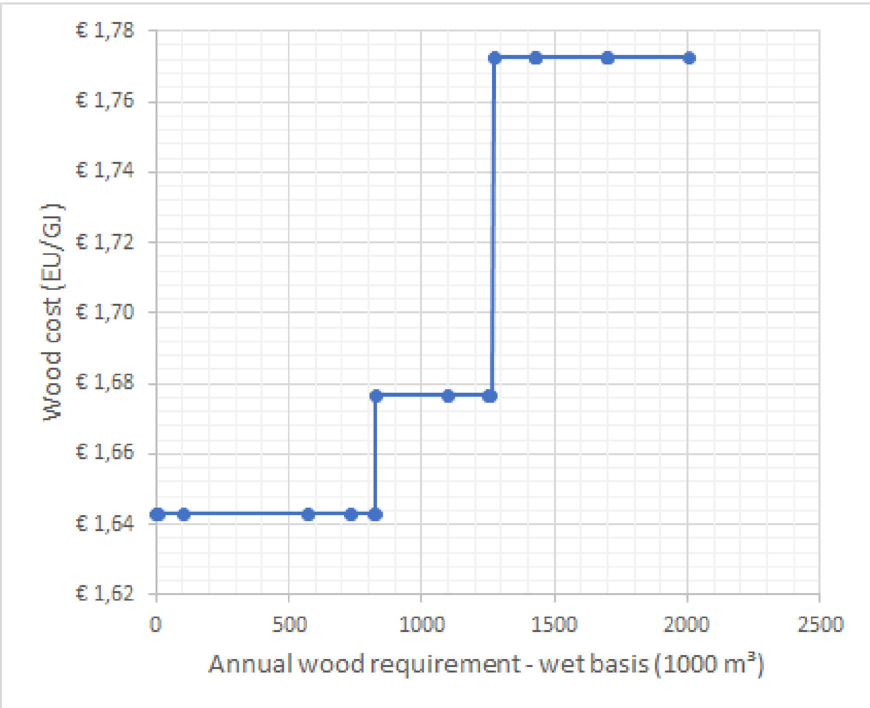


Figure 25: Wood supply curve at Espigão (co-locating plant; 54.4 t/day of bio-jet fuel) (cost at the industrial site) for assuring the supply along a seven-year cycle

For an industrial unit able to produce 54.4 t/day of bio-jet fuel, the average weighted cost of wood at REVAP (co-locating plant) would be 2.34 Euro/GJ, while in the Espigão case (greenfield plant) the average weighted cost would be 1.70 Euro/GJ.

For the costs of wood presented above, and using the procedure described in Appendix D, it is estimate that the MSP of bio-jet fuel would 1,354 Euro/t, or 32 Euro/GJ, in the case of the co-locating plant beside REVAP, and 1,363 Euro/t, or 32 Euro/GJ, in the case of the greenfield unit in Espigão. The lower cost of the feedstock in Espigão balances the higher CAPEX and OPEX of the greenfield plant.

Due to the lower costs of the feedstock, the MSP in both cases assessed here are substantially lower (15-20%) than the MSP estimate by de Jong et al. (2015) for a n^{th} plant of the same capacity: 1,636 Euro/t and 1,727 Euro/t for the co-locating and the greenfield plants, respectively.

For the four industrial capacities assessed in this report, Table 17 summarizes the main results, supposing in all cases that the feedstock would be produced around the industrial site, within a circle with 50 km radius. As the results suggest that the greenfield solution could have advantages for larger capacities, it is added the case of producing 140 t/day of bio-jet fuels, and its results are also presented in the same table.

Table 17: Summary of results for the production of bio-jet fuels in co-locating and greenfield plants, with feedstock produced within a 50 km radius around the industrial plant

Co-locating cases					
Bio-jet fuel production (t/day)	21.6	54.4	80.0	160.0	240.0
Share of Brazilian consumption in 2018	0.22%	0.54%	0.80%	1.60%	2.40%
Average weighted MSP (Euro/t bio-jet fuel)	1.839	1.354	1.202	1.015	950
Average weighted MSP (Euro/GJ bio-jet fuel)	43	32	28	24	22
Greenfield cases					
Average weighted MSP (Euro/t bio-jet fuel)	1.896	1.363	1.196	956	846
Average weighted MSP (Euro/GJ bio-jet fuel)	44	32	28	22	20

It can be seen that considering the MSP at the industry gate, assuming that the supply would be constrained to a 50 radius around the industrial plant, the greenfield case becomes clearly advantageous because of the lower weighted cost of biomass (1.79 Euro/GJ in the greenfield case – industrial site at Espigão, and 3.00 Euro/GJ in the co-locating case – industrial site at REVAP). In the REVAP case the required biomass would be close to the maximum capacity of production, while in the Espigão case it would be possible to enlarge the industrial capacity even more.

Comparing supply curves for 50 and 75 km radii

It was developed a second supply curve of eucalyptus in both regions (around REVAP and Espigão), considering circles with radius 75 km. Figure 26 shows the comparison of both supply curves (buffers of 50km and 75 km) for the REVAP case.

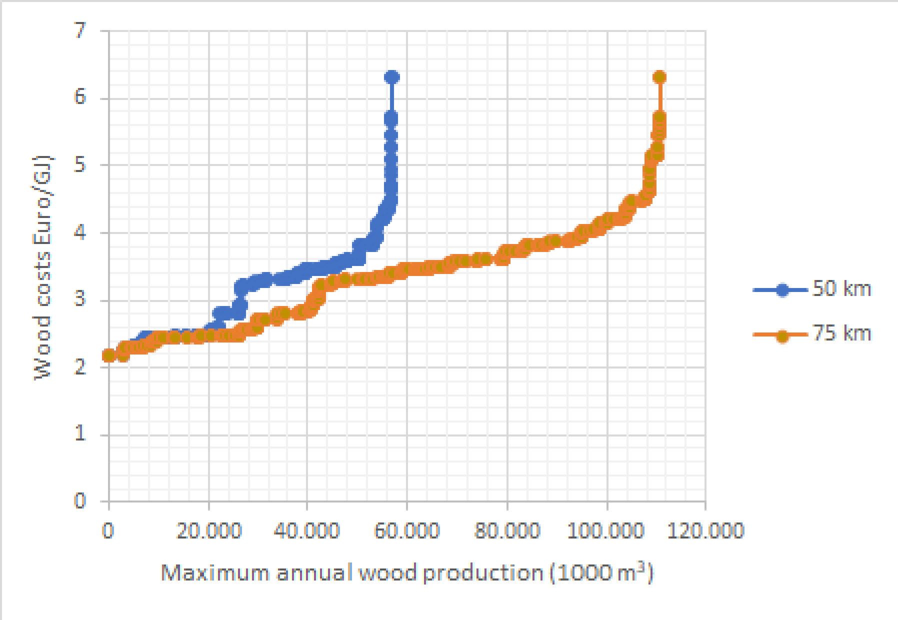


Figure 26: Comparison of the wood supply curves at REVAP (co-locating plant) (cost at the industrial site) for buffers of 50 and 75 km (circles taking the industrial site as centre)

It can be seen that by expanding the buffer area 2.25 times, the potential production of wood almost doubles. Up to a potential supply of around 20 million m^3 of wood per year, there are no substantial differences between the two curves. The significant difference is that the potential supply considerably increases between 3 and 4 Euro / GJ. Since the case study presented (for 54.4 t/day of bio-jet fuels) requires much less wood than 20 million m^3 per year, there will be no significant differences in the MSP results presented.

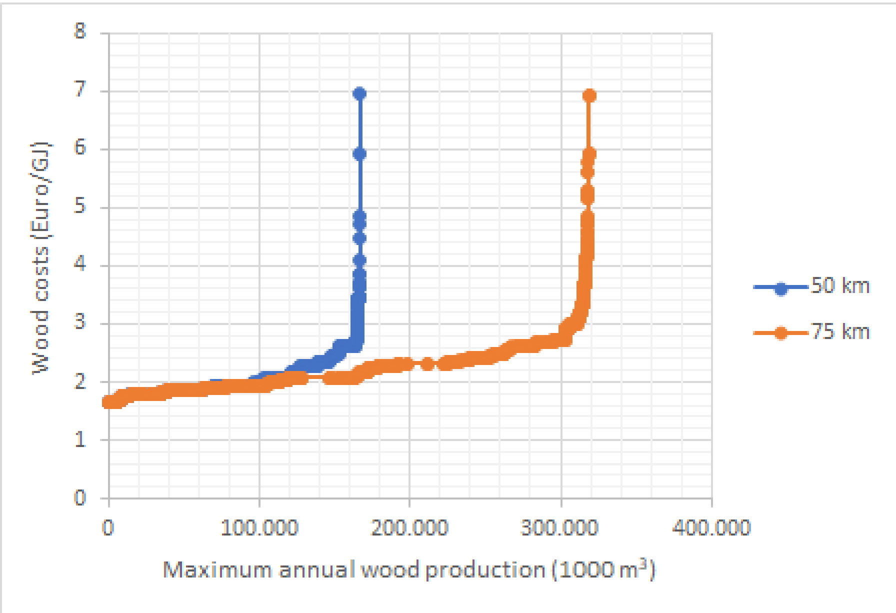


Figure 27: Comparison of the wood supply curves at Espigão (greenfield plant) (cost at the industrial site) for buffers of 50 and 75 km (circles taking the industrial site as centre)

Figure 27 shows the same comparison (50 km and 75 km) for the Espigão case and the conclusions are similar to those for REVAP, as the supply curves are almost the same in both cases. In synthesis, the results previously presented are the same considering the supply within a radius of 50 km or 75 km.

Comments about the procedure and the results of the case study

The procedure developed and applied in the FT-SPK case study, considering industrial co-location and greenfield facilities, leads to a theoretical potential and to a practically minimum MSP for the bio-jet fuels production. The results of the MSP are impacted by the cost of wood supply and, only based on the supply curves presented above, the best locations were selected. Thus, it would be necessary to go further and, first, identify where these places are and, second, evaluate the impacts related to a different selection of supplying sites.

Considering the supply curves in each buffer (REVAP and Espigão), four clusters in each case were identified among the solutions of lower wood cost at the industrial site. The location of these clusters is presented in Figure 28, for the REVAP case, and in Figure 29 for the Espigão case.

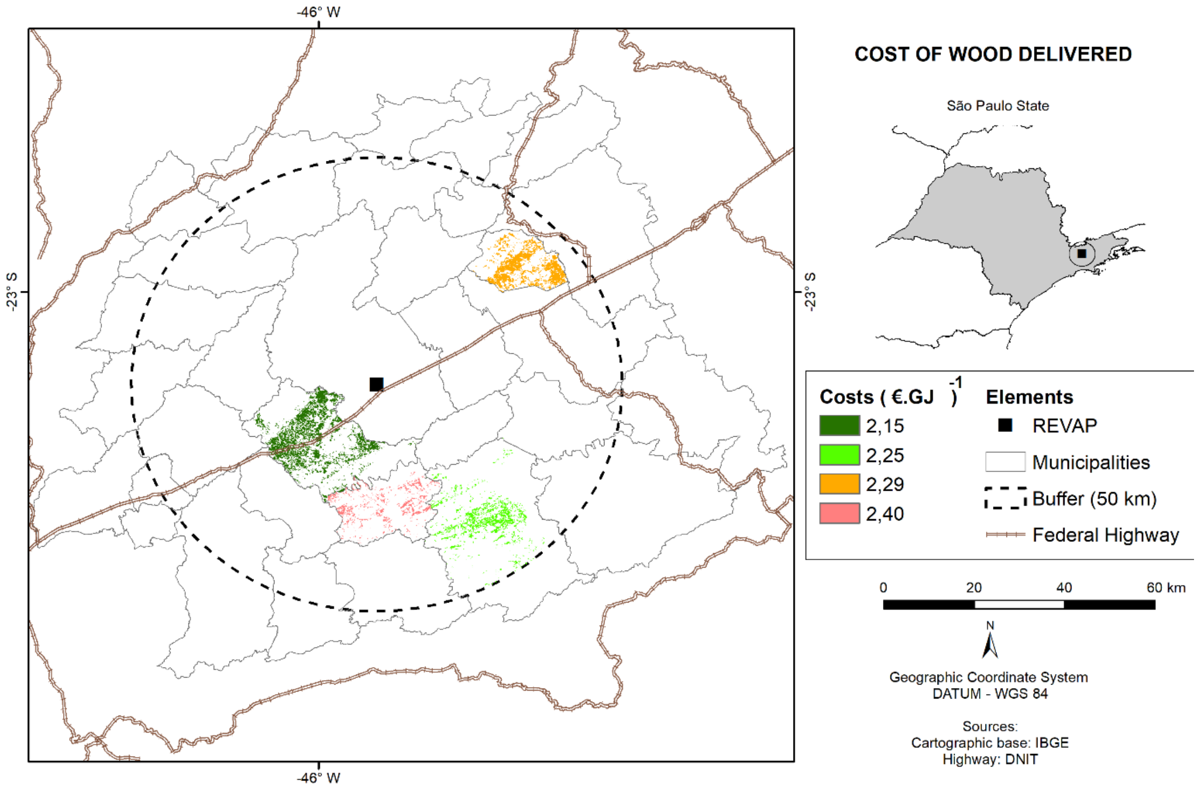


Figure 28: Location of four clusters of potential wood production among those of lower costs, within the circle of radius 50 km – REVAP case

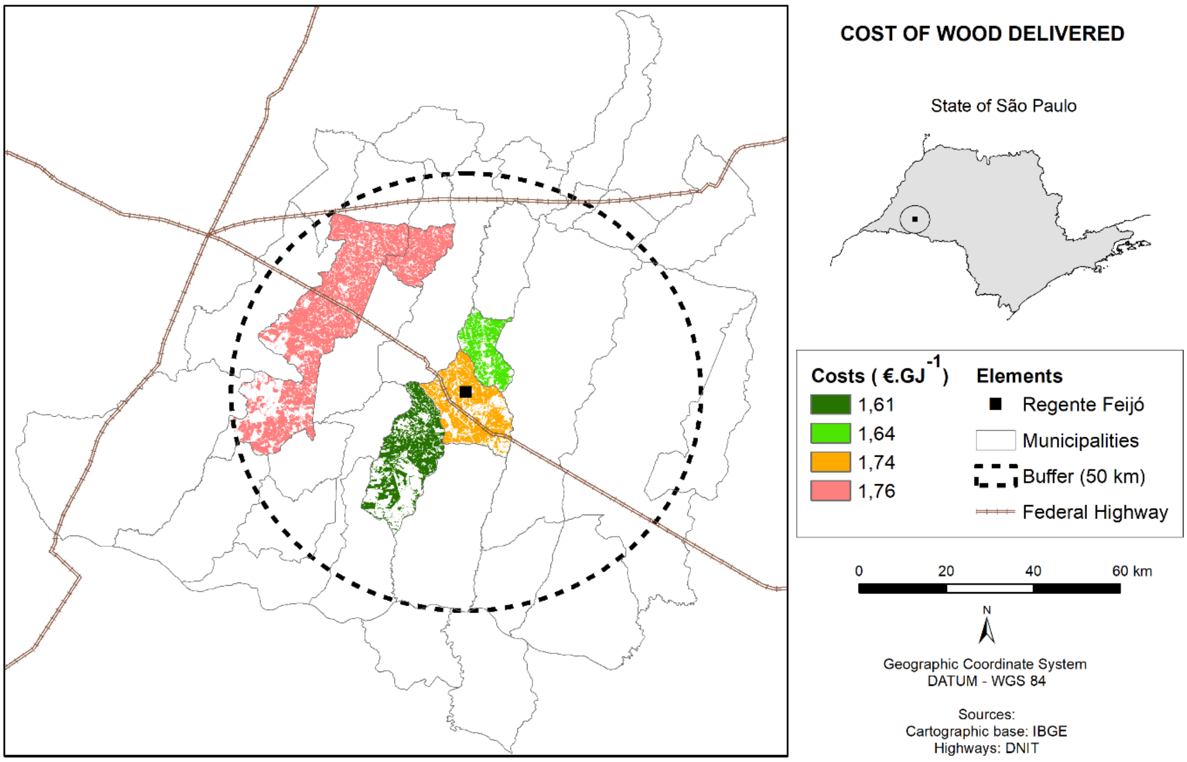


Figure 29: Location of four clusters of potential wood production among those of lower costs, within the circle of radius 50 km – Espigão case

Observing Figures 28 and 29, it calls attention that there would be the risk of very large areas with monocultures related to eucalyptus production. First, this could be a risk to the effective sustainability and/or this could be heavily criticized. Second, such very large homogeneous areas could not be in accordance with the local regulation/legislation. In this sense, it would be necessary to adopted a "ceiling" factor.

Second aspect, and this is mainly related to clusters that correspond to 2.25 and 2.40 Euro / GJ in the REVAP case, many areas seem to be dispersed and this can impose economic restrictions. The consequence is that, in practice, the potential would be reduced and the costs increased.

A third aspect is related to the procedure adopted to estimate the costs of wood production. A database with average land prices was used in 2018, but it is reasonable to assume that the price of land close to the Presidente Dutra highway (again in the REVAP case), for example, would be higher (or even much higher) than the average. Related to this aspect, the first necessary action is to carry out a sensitivity analysis and, if necessary, a further effort to improve the database on land prices.

A final comment related to the case study presented in this report, and also to the industrial production capacities considered, is that the supply curves indicate that the potential for low-cost wood production is large compared to the requirements. Thus, the main economic results would not be impacted if some restrictions were imposed (for example, limiting the production area in the municipalities).

FINAL REMARKS

The project is not yet completed and what is presented here is a preliminary report, aiming to clarify the current status (approximately 75 days before its end). There is a delay of about 2 to 3 months, but considering its scope, it will be possible to complete the project as planned.

This reported is based on eucalyptus and on the route FT-SPK. To address all other raw materials, the required stages are not exactly the reproduction of what is presented here, but, from a methodological point of view, there are no major differences. In addition, for many feedstocks (e.g. sugarcane, soybean, macauba) the activities that correspond to assessing suitability, estimating yields and costs are ready or almost ready. Another important aspect is that, for other feedstocks, the number of potential production sites tends to be smaller, and this can facilitate computational solutions.

Indeed, what has been a challenge for the research group is to find computational solutions to speed up processing, especially for online situations. The research team has studied different options and discussed alternatives with experts. Once these appropriate solutions were implemented, it would be possible to be more ambitious in the definition of case studies.

Unfortunately, due to excessive processing time (for issues like estimating road distances and for selecting the best sites, i.e. pixels), the current version of the DBMS is static, i.e. the case studies were pre-established and all necessary data and maps have been uploaded into the platform. However, as the aim is to make DBMS an effective interactive platform, it will be enhanced.

In addition, the appearance of the current version of DBMS is inadequate. In fact, and for now, the research team has not prioritized this issue. The company that was hired (GeoMeridium) has a web designer capable of improving the solutions used so far.

APPENDIX A

Suitability for eucalyptus

Along the country, the areas must be classified according to their suitability for the production of the different feedstocks considered in the project (e.g. sugarcane, corn, palm oil). Here, the procedure adopted for eucalyptus is described.

A study by EMBRAPA, focused on producing eucalyptus in Minas Gerais state, was used as reference (Alvares et al. 2013). The available documents include a spreadsheet with estimates of wood production over a seven-year cycle (from planting to cutting trees), considering (1) the technology normally applied by the pulp and paper industry (higher yields) and (2) the one used by ordinary investors (lower yields). The results are site specific and are impacted by soil suitability. The reference study was developed taking into account three of the most used species of eucalyptus in Brazil: *E. grandis*, *E. urophylla* and *E. cloeziana*.

For the lowest technological level, the results for Minas Gerais have an average yield of 16.462 m^3/ha/year (± 4.361), while for the highest yield the average is 35.336 m^3/ha/year (± 9,433)[9]. In the report it is mentioned that the minimum productivity that justifies the commercial operation is 15 and 25 m^3/ha/year, respectively for lower and higher yields (Guimarães & Sans, no date). The average yield of eucalyptus in Brazil, in 2018, was estimated at 36 m^3/ha/year (IBÁ, 2019). The procedure described here and adopted at DBMS is based on the hypothesis that eucalyptus – as feedstock for sustainable aviation bio-fuels – would be produced with the best technology available.

Based on the literature review, the procedure for assessing suitability for eucalyptus is based on six parameters: soil suitability, slope (because of the cost of harvesting), rainfall, atmospheric temperature, frost risk and altitude. The results presented by Booth & Prior (1991) for the three species mentioned above were used to set the best criteria related to rainfall and temperature, and to justify them. Below it is presented the rationale for the six parameters used. The procedure was applied and the first validation was against the results presented by Alvares et al. (2013), which are based on modelling. In a second round, the classification regarding suitability was compared with the results presented by Higa and Wrege (2010) and by Flores et al. (2016)[10].

The classification was developed in a way that an "apt" area would have a potential productivity higher than 280 m^3/ha in a seven-year cycle, i.e. 40 m^3/ha/year, as long as the best technology is applied. Using this technology, a "marginal" area would have a potential productivity between 210 and 280 m^3/ha in a seven-year cycle (30-40 m^3/ha/year), while an "inapt" area would have a potential productivity lower than 210 m^3/ha in a seven-year cycle.

[9] It is worth mentioning that the average real productivity of eucalyptus production is not high in Minas Gerais, compared to the results of other states.

[10] Respectively, for *E. grandis*, only considering the production in South of Brazil, and for *E. grandis*, *E. urophylla* and *E. cloeziana*., for the whole country.

Soil suitability

In this project it was used the soil classification presented by EMBRAPA (2011) and the respective electronic map available (scale 1:5,000,000). Based on the literature, soils were classified according to their suitability for agriculture. In principle, the same classification was used for eucalyptus and all other crops assessed in this project, but with the possibility of further fine-tuning, i.e. at the moment the final suitability map was available and the results could be compared with the available information. As an illustration, Table A1 presents the classification used according to soils suitability for different crops (the designation of soil types is in Portuguese).

Also as an illustration, Figure A1 shows the image of the soil map published by EMBRAPA in 2011.

Figure A1: Soil map by EMBRAPA (2011)

Table A1: Classification adopted for setting soils suitability for different crops

Soil types	Classification
Argilossolo Amarelo	Apt
Argilossolo Vermelho	Apt
Argilossolo Vermelho-Amarelo	Apt
Latossolo Amarelo	Apt
Latossolo Vermelho	Apt
Latossolo Vermelho-Amarelo	Apt
Latossolo Bruno	Apt
Argilossolo Acinzentado	Apt
Afloramentos de Rochas	Inapt
Alissolo Crômico	Inapt
Dunas	Inapt
Gleissolo Háplico	Inapt
Gleissolo Sálico	Inapt
Gleissolo Tiomórfico	Inapt
Luvissolo Crômico	Inapt
Massa d´Água	Inapt
Neossolo Flúvico	Inapt
Neossolo Litólico	Inapt
Neossolo Quartzarênico	Inapt
Neossolo Regolítico	Inapt
Nitossolo Háplico	Inapt
Nitossolo Vermelho	Inapt
Planossolo Háplico	Inapt
Planossolo Hidromórfico	Inapt
Planossolo Nátrico	Inapt
Plintossolo Háplico	Inapt
Plintossolo Pétrico	Inapt
Vertissolo Cromado	Inapt
Vertissolo Ebânico	Inapt
Vertissolo Hidromórfico	Inapt
Cambissolo Háplico	Marginal
Cambissolo Húmico	Marginal
Chernossolo Argilúvico	Marginal
Chernossolo Ebânico	Marginal
Chernossolo Rêndzico	Marginal
Espodossolo Ferrocárbico	Marginal
Organossolo Mésico	Marginal

The resulting soil map used in this project is shown in Figure A2, for the 12 states analysed in case of eucalyptus. In the legend, high corresponds to “apt”, restrict to “inapt” and regular to “marginal”. An issue to take into account, as further presented in the subsection Validation, is that the scale 1 : 5,000,000 can impose distortions in some cases.

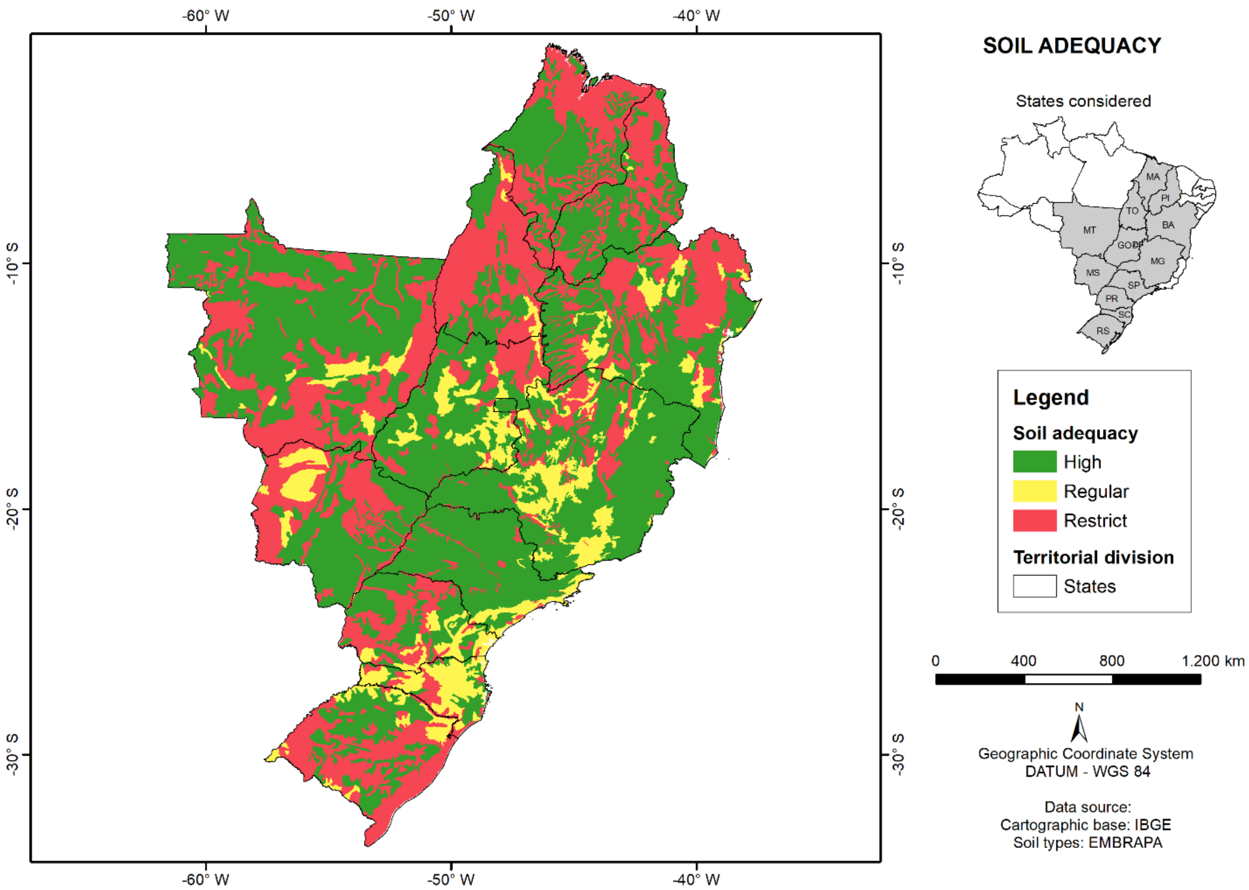


Figure A2: Distribution of soils along Brazil according to their classification to agricultural purposes: green = “apt”, yellow = “with restriction” and red = “inapt”

Hydric suitability

Two parameters were defined, based on Booth & Pryor (1991), considering the three species took into account. They are:

R_annual (annual average rainfall, in mm);

#months_def (estimate of the months with hydric deficit) – the result is based on the difference between monthly precipitation and potential evapotranspiration (PET) (both in mm). The PET was estimate for each municipality and the results were included at the DBMS. Details of the criteria considered for both parameters are described in Table A2.

Table A2: Parameters and criteria adopted for classifying areas according to hydric suitability, for eucalyptus

Parameter	Criteria	Comments
R_annual	1.100 > R_annual > 2.000 mm	Values in this range mean that the local is "apt". The minimum value is presented by Booth & Pryor (1991) for *E. urophylla*, while the maximum one is indicated by the same authors for *E. cloeziana*.
#months_def	< 6	The number of months with hydric deficit must be below 6. Six is the value presented by Booth & Pryor (1991) for *E. urophylla*; for *E. cloeziana* the same authors mention 5, while for *E. grandis* the maximum is 7. Thus, six months is a compromise solution.

A site would be classified as "apt" from a hydric point of view when both conditions were matched. When only one condition was matched, the area was classified as "marginal", while no conditions matched would mean "inapt" site.

Suitability according to atmospheric temperature

Also based on Booth & Pryor (1991), the following parameters were defined for setting suitability according to the atmospheric temperature: T_mean (the average annual temperature, expressed in °C), T_max (the average maximum annual temperature, in °C) and T_min (the average minimum annual temperature, in °C). The criteria adopted, and related comments, are presented in Table A3.

Table A3: Parameters and criteria adopted for classifying areas according to thermal suitability, for eucalyptus

Parameter	Criteria	Comments
T_mean	18°C > T > 27.5°C	The average annual temperature must be in the range to justify the "Apt" classification. The range is based on Booth & Pryor (1991) and was defined as a compromise solution, being subsequently adjusted to make the procedure more flexible.
T_max	< 28°C	The classification as "Apt" requires na average maximum annual temperature below 28°C. It is a compromise solution taking into account the three diffrent species considered; it can be higher for *E. cloeziana* and slightly lower for the other two (Booth & Pryor, 1991). O atendimento da condição corresponde ao valor "1"
T_min	> 8°C	The average minimum annual temperature must be equal or higher than 8°C. The value is higher than the limit presented by Booth e Pryor (1991) (they present the required absolute minimum) and was adopted to impose some constraint (considering the weather conditions in Brazil).

To be considered "apt" it is necessary to fulfil all three conditions presented above. With two conditions the classification would be "marginal", while with one or no conditions met the classification would be "inapt".

Suitability considering frost risk

Some species of eucalyptus are susceptible to frost and the risk must be taken into account. The frost risk was assessed based on the function defined by Higa and Wrege (2010), which is presented below. Numerically, the values can be negative and it was understood that, in these cases, the risk would be zero. It was defined that the threshold is 8%, i.e. that would be the minimum frost risk.

Frost_risk [%] = -35.035 – 1.076 x latitude [degrees] – 0.062 x longitude [degrees] + 0.0139 x altitude [m]

Suitability according to altitude

A location would be classified as "apt" as long as its altitude is between 50 and 1,500 m above sea level (“inapt”, otherwise). The restriction is not only related to the frost risk, but also to the risk of pest proliferation that would be common close to the coast. The interval was adjusted in comparison to the one presented by Garcia et al. (2014) (between 130 and 2,600 meters) after checking the locations where there are large eucalyptus plantations. A second reason is that in the procedure a single value was used for each municipality, when it would be more appropriate to use altimetry curves; this improvement can be made hereafter, despite the fact that there is no significant error with the procedure adopted.

Validation

In order to check the accuracy of the adopted procedure, the results were compared with the maps presented by Flores et al. (2016), for the species *E. grandis*, *E. urophylla* and *E. cloeziana* and with the agro-ecologic maps presented by EMBRAPA for Paraná and Rio Grande do Sul (Higa and Wrege, 2010). In general, the conclusion is that the main trends have been accurately captured. To be more precise, the resulting suitability map for eucalyptus was overload by the map of silviculture registers (planted forests), by MapBiomas, for 2018; the resulting information is presented in Figure A3.

First, it is important to highlight that it is not only eucalyptus plantations that are indicated as black dots in Figure A3, and other species are more resistance to frost (e.g. see the concentration of back dot points in Santa Catarina and Rio Grande do Sul, in Brazilian south). Second, the existing eucalyptus plantations, even in large scale, are for different purposes (e.g. for firewood), and productivity is not exactly the main concern (e.g. some areas in Minas Gerais). Third, and most important, the resolution of the map for soils impose some distortions, and good examples are some areas in Paraná and Mato Grosso do Sul. Soil maps with higher resolution are available for only few Brazilian states and until the end of the project an effort will be done aiming to improve the quality (and spatial resolution) of this information.

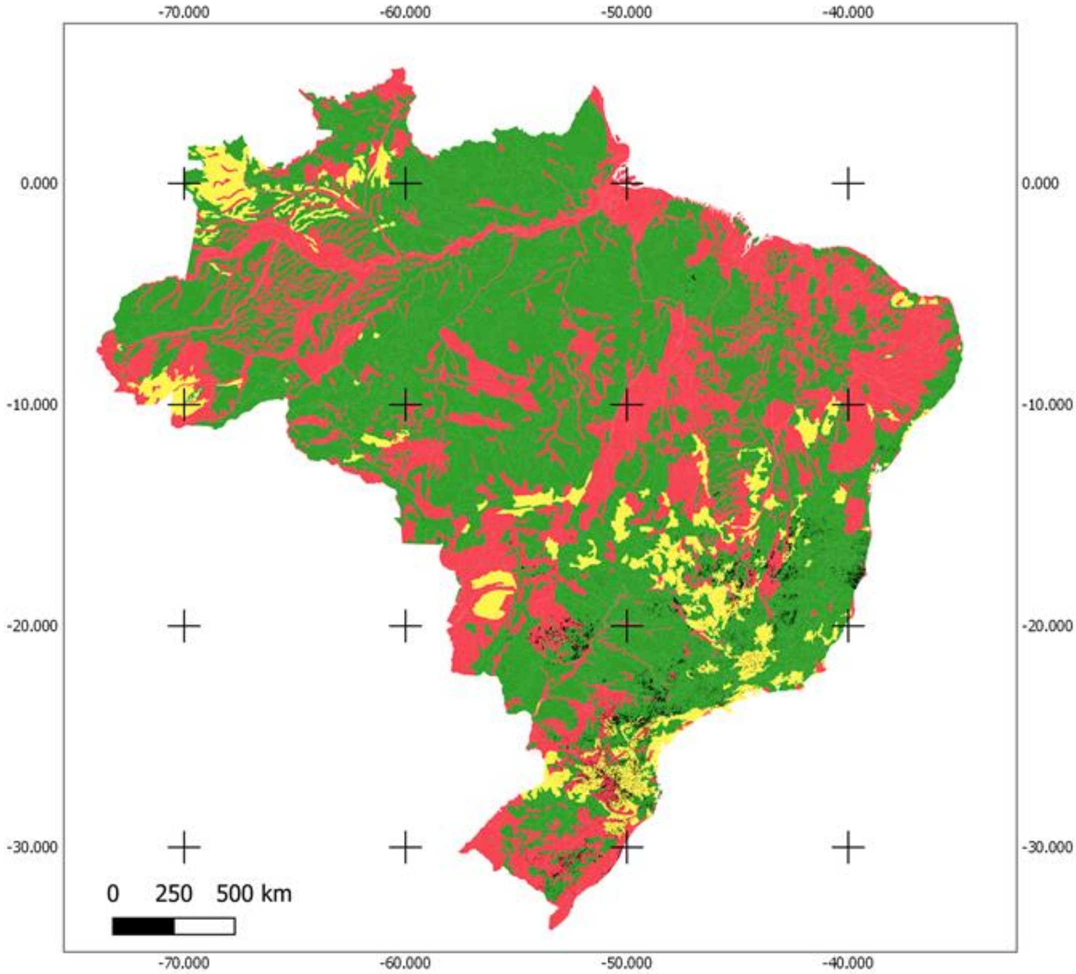


Figure A3: Matching of the suitability map for eucalyptus production, with high yields, and forest planted areas in 2018 (based on MapBiomas)

Finally, as an illustration, Table A4 indicates the number of municipalities in each Brazilian state, among the twelve assessed in this project, able to produce eucalyptus with medium to high yields.

Table A4 Number of municipalities suitable for eucalyptus cropping, with medium to high yields ("apt" and "marginal" classification), in the twelve states assessed

State	Combined results			Rainfall			Temperatures			Frost risk		Altitude	
	Apt	Inapt	Marginal	**Apt**	**Inapt**	**Marginal**	Apt	Inapt	Marginal	**Apt**	**Inapt**	Apt	Inapt
TO	62	5	72	112	0	27	62	5	72	139	0	139	0
MA	3	108	106	18	3	196	36	103	78	135	82	217	0
PI	7	134	82	7	129	87	190	3	30	218	5	223	0
BA	64	305	48	67	292	58	417	0	0	404	13	417	0
MG	605	128	120	706	98	49	752	0	101	850	3	823	30
SP	596	7	42	627	0	18	615	0	30	641	4	641	4
PR	313	35	51	382	0	17	327	0	72	398	1	365	34
SC	69	96	128	216	0	77	160	0	133	265	28	225	34
RS	102	89	305	358	0	138	244	0	252	453	43	450	68
MT	77	0	1	77	0	1	78	0	0	78	0	78	46
MS	65	0	76	67	0	74	116	0	25	141	0	141	0
GO	246	0	0	246	0	0	246	0	0	246	0	246	0
DF	1	0	0	1	0	0	1	0	0	1	0	1	0
Sum	2210	907	1031	2884	522	742	3244	111	793	3969	179	3966	182

APPENDIX B

Estimating yields

Estimating potential yields is a crucial aspect in the DBMS. In some cases the yields have been estimated based on historical data, while in other cases the estimate is based on data obtained with modelling. This is the case of eucalyptus. The procedure is described below.

The reference data are those presented by Guimarães and Sans (no date), in a study developed by EMBRAPA, which are based on a procedure for modelling eucalyptus growth. Unfortunately, it was not possible to use the model in this project. Two technological scenarios were considered: one that corresponds to the adoption of the usual techniques by the pulp industry (and that results in higher productivity) and another that corresponds to the practices of small forest producers (and that results in lower productivity). The highest productivity results were taken, which are expressed in the useful volume of the tree after seven years of growth. The three species considered are three species of eucalyptus *E. grandis, urophylla, and cloeziana*.

The Supplementary Material available includes a spreadsheet with 1,539 estimated productivity results in all 853 municipalities in Minas Gerais and, in most cases, the results were differentiated according to different types of soil.

A statistical model was developed with the aim of correlating potential yields with the variables available in the DBMS and that reflect local climatic conditions. Dummy variables that differentiate the results according to soil suitability were tested. The multiple correlation procedure resulted in a function with the following explanatory variables: annual precipitation, water deficit, IDP (a parameter that indicates rainfall regularity), annual average, minimum and maximum annual atmospheric temperatures. Dummy variables were also kept and they differentiate the areas in terms of soil suitability. All explanatory variables kept in the final model are statistically discernible at least at the 97.8% level. The multiple correlation coefficient, adjusted for degrees of freedom (R^2), is 91.5%.

Figure B1 shows the distribution of the estimated yield for Minas Gerais versus the results presented in the reference publication. It can be seen that in a few cases the errors are beyond the 15% margin (above or below), which was considered an adequate range.

Table B1 presents the main statistics related with the interception and each explanatory variable statistically discernible in the final model.

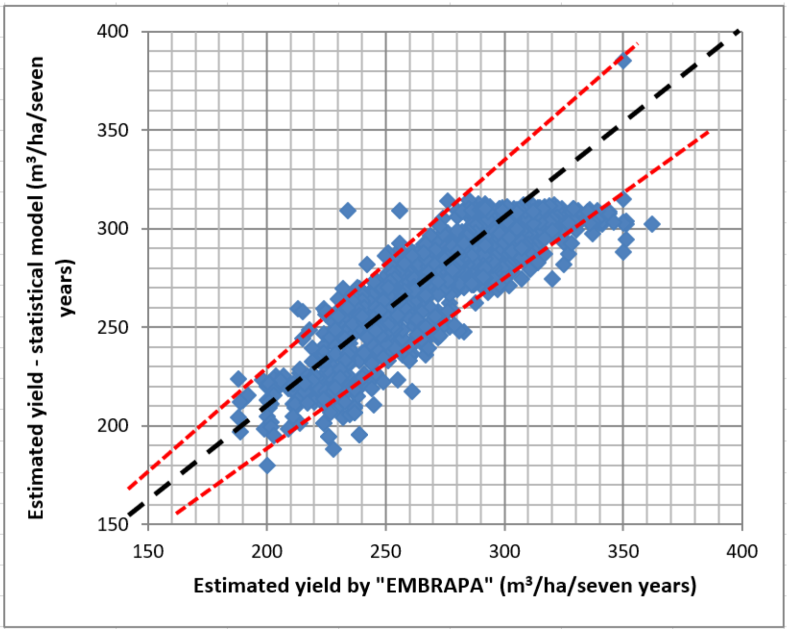


Figure B1: Estimated eucalyptus productivity (in m^3/ha/seven-year cycle) based on a statistical model versus productivity estimated by EMBRAPA (reference), for Minas Gerais.

Table B1: Main statistics related with the interception and each explanatory variable statistically discernible in the final linear model

Variable	Coefficients	Standard deviation	Statistics t	P-value
Intersection	-1217.8500	217.8405	-5.5906	2.68E-08
Dummy_soil_apt	-18.1288	8.2038	-2.2098	0.02727
Dummy_soil_regular	117.0162	12.7784	9.1573	1.66E-19
Dummy_soil_inapt	-68.1579	9.7320	-7.0035	3.73E-12
Altitude	0.2268	0.0396	5.7213	1.27E-08
Dummy_rainfall_apt	0.0446	0.0048	9.2083	1.06E-19
Dummy-rainfall_reg	-0.0592	0.0086	-6.8665	9.54E-12
Dummy_rainfall_inapt	-0.0230	0.0064	-3.5661	0.00037
Deficit_hydric_year	-0.0620	0.0177	-3.4948	0.00049
IDP	-1.1402	0.4992	-2.2839	0.02252
Temperature_mean	82.1738	15.7443	5.2193	2.04E-07
Temperature_year_max	54.0742	13.3928	4.0376	5.67E-05
Temperature_year_min	-93.9434	11.8473	-7.9296	4.21E-15

The adjusted model was then applied to the 12 states considered in the project, aiming to estimate the potential productivity of wood production from planted eucalyptus forests. For the twelve states, some statistics related to the set of results are presented in Table B2; the data for Brazil correspond to average figures presented by IBÁ (2019).

Table B2: Comparison of predicted yields of eucalyptus production, based on modelling, and actual average results – in m^3 of wood after harvesting, per hectare, per year

Model	Highest	Medium	Lowest	Actual results for Brazil
Average	43.9	38.2	21.1	36.0
Standard deviation	11.9	12.1	10.9	
Maximum value	77.1	74.6	55.8	70.0
Minimum value	9.3	7.0	0.0	

The same comparative analysis that is summarized in Table B2 was done for the twelve states, using data available at the IBGE database (IBGE, 2019) and the results show that the model is adequate for all states, except for Maranhão (the estimate yields would be low in comparison with the estimate actual average results). Most important, modelling results are coherent with the actual practice of large producers in all relevant producing states (e.g. São Paulo, Minas Gerais, Paraná, Rio Grande do Sul, Bahia).

APPENDIX C

Estimating wood costs

Wood costs at the industry have two components: the costs of wood itself at the forest, after cutting the trees, and the cost of transporting the wood to the industry. The cost of wood after cutting has three shares, which are described below.

The so-called costs of implementing the forest correspond to the investment in the preparation of the land, planting of seedlings, and all maintenance costs until the moment of cutting. These costs were estimated based on the literature and were presented in a report during the first research cycle. The estimate used here corresponds to the median of the values obtained from the literature (8,306 R$/ha in 2016, being the minimum value in the data set 6,362 R$/ha and the maximum value 9,406 R$/ha). These values were corrected to 2018 using the price index for the Brazilian pulp and paper industry (INCAF; 416.1 in 2016 and 466.1 in 2018); then the resulting cost of the forest would be 9.304 R$(2018)/ha. This cost is further translated to the wood produced considering the local yield.

The cost related to leasing land is the second share. The price of the land on which planting takes place was taken from four databases: (1) for Minas Gerais, from the EMATER database, which publishes market prices, per hectare, for different municipalities and for different land uses, (2) for all other states, from the AgriAnual database, for locations where there was information, (3) for various states, from the Ministry of Economy database, and (4) if necessary, it was completed with information from the INCRA. The resulting database was built for six classes of land use, but in the case study only the information for "Established Pasturelands " was used. All prices in the database are in R$ of 2018. For the twelve states the average price of land in the database is 8,269 R$/hectare, but with a high standard deviation (8,903 R$/ha).

The impact of the land price on the cost of forest production was estimated by calculating a uniform series, assuming the initial investment as the price per hectare, a period of 21 years (the period of three complete cycles) and a discount rate of 8% per year. The lease cost incurs in each cycle of seven years. Following this procedure, the resulting value is very close to the estimated land lease costs.

The cutting costs is the third share and they were taken from IEMA (2017). There is a significant difference between flat areas and areas with sharp declivity. These costs are presented per cubic meter of wood, for 2016, and were updated for 2018: 12.3 and 51.5 R$/m^3, in flat areas and with a steep slope (“moderate”, according to the information presented in Table C1), respectively.

It was first calculated the cost of wood before cutting the trees, per m^3, which depends of the local yield, and then this cost was combined with the cost of harvesting, considering the slope at the site.

In the project the declivity data were obtained from the “Shuttle Radar Topography Mission (SRTM)” elevation data, in a spatial resolution of 30 meters, provided by Topodata database (www.dsr.inpe.br/topodata). The classes of costs associated are presented in Table C1.

Table C1: Data used for estimating local slope

Declivity classes	Degrees	Description	Associated cost
1	1.35	Flat	Low
2	3.6	Slightly undulating	Low
3	9	Undulating	Low
4	20.25	Strong undulating	Moderate
5	33.75	Mountainous	Moderate
6	> 33.75	Steep	High

Combining the three reported shares, the cost of the wood, after cutting, at the forest site, is available for each site (pixel).

The next step, and a challenge so far, is related to the cost of transporting wood from the forest site to the industrial site. More specifically, the challenge has been the estimate of the distance, by road, to the destination. During pilot tests, inverting the objective, the attempt to calculate the distance from one point (pixel) to all points (pixels) surrounding the destination, for different radii, proved to be computationally impossible, as the processing time was very long. While the ideal solution is not found, what is being done is to fix the destinations and pre-calculate the distance from the various points of origin within pre-established radii. This was done in the case study reported here.

Once the distance is known, the cost (in R $ / t / km) is calculated using the function below, which has been adjusted for different estimates presented in IEMA (2017). The values obtained with this function are equivalent to those presented by Alves et al. (2013), in R $ / m3 / km, for distances between 100 and 140 km, using trucks with a transport capacity of 54 t. The original function, valid for 2016, was updated to 2018 using INCAF.

$$Cost_{transport}\ (R\$/t) = 1.259\ .\ (km)^{-0.294} \tag{1}$$

Before using the above function, it is necessary to correct the density of the wood, as the wood is left for a few weeks in the forest location, in order to lose water and, consequently, reduce the cost of transportation. Here it was considered that the humidity index is reduced to 60% in 60 days.

APPENDIX D

Estimating industrial costs

Estimates of industrial cost are based on the literature. For the time being, the main reference has been de Jong et al. (2015), since it is based on a comprehensive review of performance factors and costs for different pathways. In the case of the FT route, a brief literature review was done trying to update the necessary data, but the only publication with information that was considered relevant was Carvalho (2017). The main hypothesis, the parameters used, the model developed and the results are presented below.

Hypotheses and parameters used

The route that was taken as reference is based on a directly-heated, fluidized bed gasifier, pressurized, with oxygen injection. The subsequent Fischer-Tropsch process would allow the conversion of the resulting gas into hydrocarbons. It was assumed that bio-jet fuel (0.16 tonne per tonne of FT liquids), diesel (0.62 tonne per tonne) and naphtha (0.22 tonne/tonne) would be produced and that it is not necessary to use hydrogen. Based on an extensive literature review, de Jong et al. (2015) defined that in the base case 0.17 tonne of hydrocarbons could be produced from one dry tonne of biomass; the authors considered that forest residues would be used as feedstock. In the study it was considered that the plant would have the capacity of producing 340 tonnes of hydrocarbons per day, operating all over the year with a 90% capacity factor.

The capital costs (CAPEX) taken by the authors from the literature were analysed and them they defined that the total purchase equipment cost (TPEC) of the n^{th} plant (reflecting learning effects) would be equal to 96 million Euro, resulting 471 million Euro as the total cost investment (TCI). These costs were expressed in Euro 2013, and here the Chemical Engineering Plant Cost Index (CEPCI) was used to convert the monetary values to 2018 values (CEPCI = 567.3 in 2013 and 603.1 in 2018).

On the other hand, the operating and maintenance costs (OPEX) were not clearly presented by the authors and an estimate was done in this report. First, the CAPEX presented by de Jong et al. (2015) was compared with the values presented by Carvalho (2017), who has considered four estimates for a biomass gasification + FT synthesis plant (i.e. four different industrial capacities). Carvalho (2017) presents costs in US$ 2014. The capacities in both publications are not equal and a comparison was done after estimating the scaling factor (0.68) associated to the values presented by Carvalho (2017). Using the same scaling factor, and considering the average exchange ratio US$-Euro in 2013-2014, it was verified that the estimate by de Jong et al. (2015) for CAPEX is compatible with the values presented by Carvalho (2017).

Carvalho (2017) clearly presented OPEX costs, and these, in annual basis, were estimated at 10% of the CAPEX. Thus, in a first moment 10% was the percentage used, but the final results were not consistent with those presented by de Jong et al. (2015). As all other values were compatible, it was necessary to increase the estimate of annual OPEX to 11.65% of the CAPEX.

In the study by de Jong et al. (2015) the authors estimated and presented the MSP of the bio-jet fuel, per tonne and per GJ. They used an allocation rule in order to distribute the costs (in fact, to estimate the MSP) among all three FT liquids, and the same procedure was applied here. The same economic hypotheses used in the reference were applied in the model developed in this project, i.e. the same lifetime, discount rate, plant start-up schedule, etc. These hypotheses are summarised in Table C.1.

Table D1: Main economic hypotheses used by de Jong et al. (2015) for estimating the MSP of bio-jet fuels, and also used in this report

Parameter	Value	Unit
Plant lifetime	25	Year
Depreciation period (straight linear method)	10	Year
Debt-to-equity ratio	80:20	
Interest rate on debt	8%	
Rate of principal payments	15	Year
Discount rate	10%	
Corporate tax rate	22%	
Annual capacity factor	90%	
Year	**TCI schedule**	**Plant availability**
-1	30% of fixed capital	0%
0	50% of fixed capital	0%
1	20% of fixed capital	30%
2		70%
3		100%

Coherent to the cases assessed by de Jong et al. (2015), here the MSP of bio-jet fuels were estimated both for co-locating (e.g. the production in an oil refinery or in a pulp mill) and for greenfield industrial plants. The authors estimate that the MSP would be 4-8% higher for greenfield production than in the case of co-locating plants. Here both the estimates CAPEX and OPEX were increased by 5.5% in the case of greenfield plants in order to reflect the higher costs; as presented below, the MSP for greenfield facilities result 3.5%-7.7% higher than for co-locating plants, depending on the industrial capacity and on the biomass cost at the mill site.

It is assumed that electricity could be generated in a BIG-CC (biomass integrated gasifier-combined cycle) cogeneration system in order to supply electricity (and steam) to the industrial plant. Surplus electricity (0.015 MWh/GJ of input) could be sold and the income should be considered in the estimate of the MSP of FT fuels; here, the rate considered was 30 Euro/MWh.

In this report the estimates of MSP were done considering three industrial capacities, in order to assess the scale effects: 340 tonnes of FT fuels per day, as presented by de Jong et al. (2015), 500 tonnes/day, and 135 tonnes/day; the last capacity is roughly equivalent to the predicted capacity of the Red Rock Biofuels plant, which has been built in Lakeview, Oregon, United States (the start-up is predicted to 2020).

The financial-economic model built was first validate to reproduce the results presented by de Jong et al. (2015), considering that the biomass would cost 4.8 Euro/GJ at the industrial site. Then, the adjusted model was used in order to estimate the MSP as function of the biomass cost at the industrial site, for the three industrial capacities, both considering co-locating and greenfield investments. Considering that biomass would cost 4.8 Euro/GJ at the industrial site, the MSP of bio-jet fuel produced in a 340 t/day of FT liquid biofuels (54.4 t of bio-jet fuel per day) would be 1,669 Euro/t (39 Euro/GJ) for the production in a co-locating plant, and 1,762 Euro/t (41.2 Euro/GJ) in a greenfield plant (5.6% higher in the case of greenfield plant). Figures D.1 and D2. show the estimate MSP of co-locating and greenfield plants, respectively, as function of the biomass cost at the industrial site and as function of the industrial capacity.

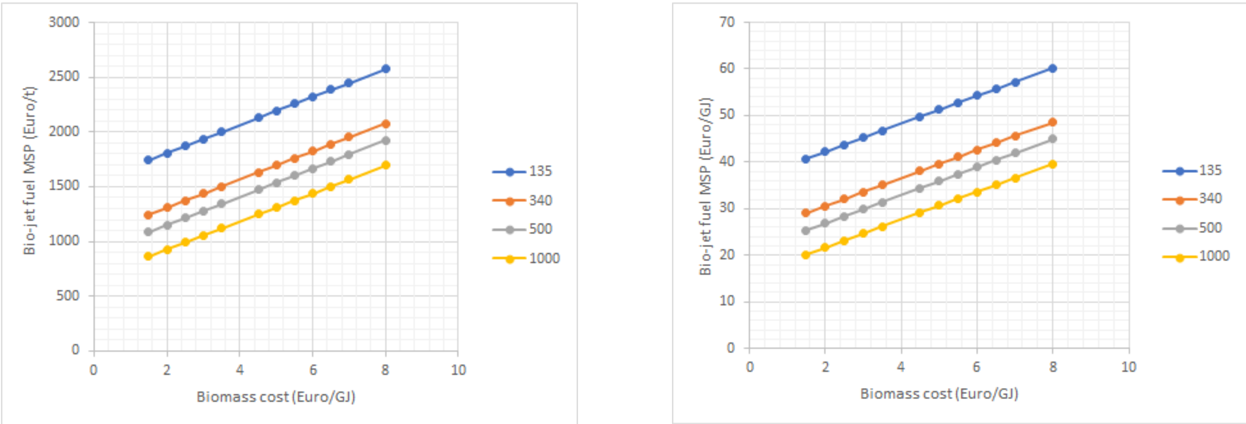


Figure D1: MSP of bio-jet fuels (FT pathway, from planted forests of eucalyptus) as function of biomass costs at the industrial plant and of industrial capacity (t/day of FT biofuels) – co-locating units

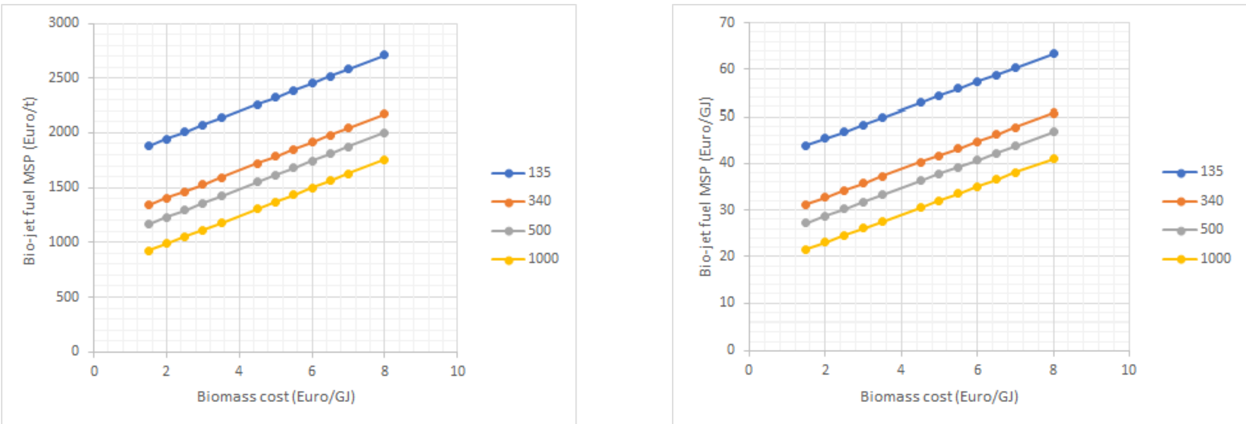


Figure D2: MSP of bio-jet fuels (FT pathway, from planted forests of eucalyptus) as function of biomass costs at the industrial plant and of industrial capacity (t/day of FT biofuels) – greenfield units

Summarizing the model, with the two functions presented below it is possible to estimate the MSP of bio-jet fuels, produced with the route FT-SKP, in case of co-locating industrial units (Equation 2) and of greenfield units (Equation 3). The MSP, estimate in Euro/t, is function of the biomass cost at the industrial site, in Euro/GJ, and of the industrial capacity, in t/day of FT liquids.

$$MSP_{bio\text{-}jet\_co\text{-}locating} = 128.44 \,.\, (\text{Biomass cost}) + 12{,}146.05 \,.\, (\text{Industrial capacity})^{-0.4196} \qquad \text{(Equation 2)}$$

$$MSP_{bio\text{-}jet\_greenfield} = 128.44 \,.\, (\text{Biomass cost}) + 13{,}093.25 \,.\, (\text{Industrial capacity})^{-0.418} \qquad \text{(Equation 3)}$$

REFERENCES

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M.; Sparovek, G., 2013. Köppen's climate classification map for Brazil, Meteorologische Zeitschrift.

API RESTful. O que é API? REST e RESTful? Conheça as definições e diferenças. Disponível em: < https://becode.com.br/o-que-e-api-rest-e-restful/>. Acesso em 15.nov.2019.

ASTM. 2020. Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. ASTM International. https://doi.org/10.1520/D7566-19B

Booth, TH, Pryor, LD. 1991. Climatic requirement of some commercially important eucalypt species. Forest Ecology and Management, 43, p. 47-60.

Brasil. Ministério do Meio Ambiente. 2012. Unidades de Conservação do Brasil. Brasília. Available at <http://mapas.mma.gov.br/i3geo/datadownload.htm>

Chemical Engineering. 2019. Chemical Engineering Price Cost Index. Information available at https://www.chemengonline.com/2019-cepci-updates-january-prelim-and-december-2018-final/

Chuck, C. 2016. Biofuels for aviation: feedstocks, technology and implementation, 1st edition. ed. Elsevier, Cambridge, MA.

Cortez, LAB (editor). 2014. Roadmap for Sustainable Aviation Biofuels for Brazil: a Flightpath to Aviation Biofuels in Brazil. São Paulo: Blucher.

Cortez, LAB, Nigro, FEB, Nogueira, LAH, Nassar, AM, Cantarella, H, Moraes, MAFD., Leal, RLV, Franco, TT, Schuchardt, UF, Baldassin Junior, R. 2015. Perspectives for Sustainable Aviation Biofuels in Brazil. International Journal of Aerospace Engineering, 1–12. https://doi.org/10.1155/2015/264898

de Jong, S, Hoefnagels, R, Faaij, A, Slade, R, Mawhood, R, Junginger, M. 2015. The feasibility of short-term production strategies for renewable jet fuels - a comprehensive techno-economic comparison: The Feasibility of Short-term Production Strategies for Renewable Jet Fuels - A Comprehensive Techno-economic Comparison. Biofuels, Bioprod. Bioref. 9, 778–800. https://doi.org/10.1002/bbb.1613

EMATER – Empresa de Assistência Técnica e Extensão Rural do Estado de Minas Gerais. 2019. Valor da Terra Nua. Informações disponíveis em http://www.emater.mg.gov.br/portal.cgi?flagweb=novosite_pagina_interna&id=19167.

ESALQ. 2003. Botânica de Eucalyptus spp [WWW Document]. TUME - Teste de Uso Múltiplo de Eucalyptus. URL http://www.tume.esalq.usp.br/botanica.htm.

Flores, TB, Alvares, CA, Souza, VA, Stape, JA. 2016. Eucalyptus no Brasil: Zoneamento Climático e Guia para Identificação. Piracicaba: IPEF.

Geocoding - Leaflet Routing Machine. Disponível em: <https://www.liedman.net/leaflet-routing-machine/tutorials/geocoders/>. Acesso em 10.set.2019.

Guimarães, D.P.; Sans, L.M.A. Zoneamento do Potencial Produtivo do Eucalipto em Minas Gerais. Relatório de projeto. Disponível em https://www.macroprograma1.cnptia.embrapa.br/finep/metas-fisicas/meta-fisica-6/relatorios/04%20-%20zoneamento-eucalipto-minas-gerais.doc/view.

Higa, RCV, Wrege, MS. 2010. Zoneamento climático de *Eucalyptus grandis* para a região Sul do Brasil. Colombo: Embrapa Florestas.

Higa, R.C.V. et al. 2010. Zoneamento Climático de Espécies Florestais. Relatório de projeto. Disponível em https://www.macroprograma1.cnptia.embrapa.br/finep/metas-fisicas/meta-fisica-6/relatorios/

IBÁ – Brazilian Tree Industry. 2018. Report Ibá 2018.

IBÁ – Brazilian Tree Industry. 2019. Report Ibá 2019.

IBGE – Instituto Brasileiro de Geografia e Estatística. 2004. Mapas de Biomas e de Vegetação. – Information available at https://ww2.ibge.gov.br/home/presidencia/noticias/21052004biomashtml.shtm

IBGE – Instituto Brasileiro de Geografia e Estatística. 2019. Information available at https://www.ibge.gov.br/estatisticas/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html?=&t=resultados

ICAO – International Civil Aviation Organization. 2018. Sustainable aviation fuels guide, Version 2. ed, Transforming Global Aviation Collection. ICAO, UNDP, GEF.

ICAO – International Civil Aviation Organization. 2019. Information about CORSIA. Available at (https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-FAQs.aspx)

IEMA – Instituto Energia e Meio Ambiente. 2017. Reservatórios Verdes. Apresentação em evento realizado em São Paulo.

INPE – Instituto Nacional de Pesquisas Espaciais. Topodata database. Available at www.dsr.inpe.br/topodata.

Oliveira, AC. 2015. Secagem de toras de eucalipto. PhD Thesis. Federal University of Viçosa.

PostGIS Raster. Chapter 9 – Raster Reference. Disponível em: https://postgis.net/docs/RT_reference.html. Acesso em: 30.out.2019.

Wang, W.-C., Tao, L., 2016. Bio-jet fuel conversion technologies. Renewable and Sustainable Energy Reviews 53, 801–822. https://doi.org/10.1016/j.rser.2015.09.016

Wang, W.-C., Tao, L., Markham, J., Zhang, Y., Tan, E., Batan, L., Warner, E., Biddy, M., 2016. Review of biojet fuel conversion technnologies (Technical Report No. NREL/TP-5100-66291). National Renewable Energy Laboratory, Golden, CO, USA.

Zhu, Y., Rahardjo, S.A.T., Valkenburg, C., Snowden-Swan, L.J., Jones, S.B., Machinal, M.A., 2011. Techno-economic analysis for the thermochemical conversion of biomass to liquid fuels (No. PNNL-19009). Pacific Northwest National Laboratory, Richland, Washington, USA.