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

Case study: FT-SPK pathway / eucalyptus

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Executive summary

- The case studies were developed with the aim of illustrating the use of the information available in the database to evaluate the potential of SAF production in Brazil. It is not possible to draw definitive conclusions based on the results obtained, but an effort has been made to make the studies as comprehensive as possible.
- The case study reported here addresses the production of SAF through the FT-SPK route, from self-dedicated eucalyptus plantations. Two cases were explored, the first being a co-locating unit next to REVAP (an oil refinery located in São José dos Campos, SP), and the second a greenfield unit, in Espigão, near Presidente Prudente (SP). The two municipalities are in Southeast, Brazil. Both co-locating (the REVAP case) and greenfield plants (the Espigão one) were considered.
- The estimated MSP varies between 952-1896 €.t^{-1} of SAF (or from 22.2 to 44.3 €.GJ^{-1}), depending on the scale of the industrial plant. The economic results are for the n^{th} plant, considering costs and industrial yields, but the feedstock costs are representative of what can be achieved in the short term. The results were compared with those available in the literature and are consistent.
- Based on the premises considered in this case study, production of SAF from the FT-SPK route, in Brazil, has a good chance of being effectively considered sustainable aviation fuel. However, despite the assumption that new eucalyptus forests would displace pasturelands, because of the potential effects of indirect land use change (ILUC), avoided GHG emissions would have to be estimated specifically. For some of other relevant aspects of sustainability, the case study was developed taking into account hypotheses that minimize potential risks.

Summary

- About the pathway;
- About eucalyptus;
- Eucalyptus in Brazil;
- Methodology;
- Eucalyptus suitability (procedure, results and validation);
- Eucalyptus yields;
- Eucalyptus production costs;
- Case studies;
- Results, analysis & comparisons;
- The risks of extensive monoculture;
- Possible distortions due to aggregate information;
- Eligibility under CORSIA;
- Conclusions;
- References;
- Supplementary Material.

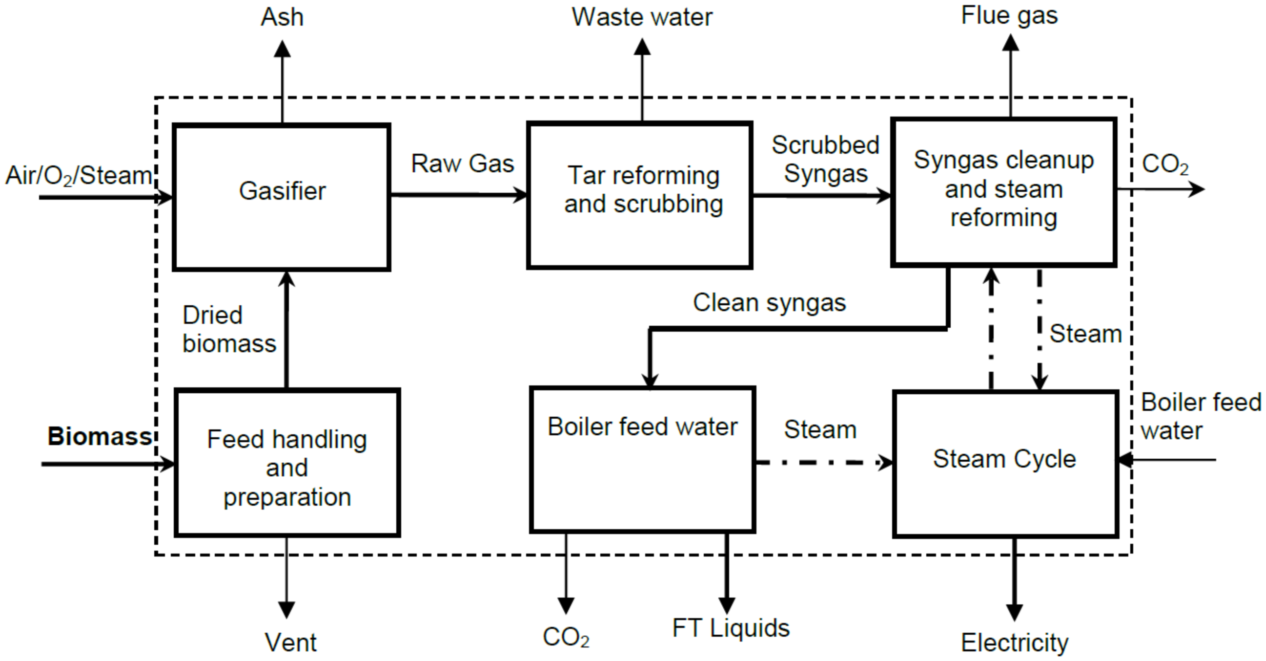
About the pathway (1)

- The route FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene) was the first certified conversion process (ASTM D7566). It was certified in 2009.
- Multiple gasification technologies exist to convert the biomass to syngas and further processing to 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 assumed 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). See Supplementary Material for additional information.

Conversion processes approved by ASTM International

Conversion process	Abbreviation	Possible feedstocks	Blending ratio by volume	Commercialization proposals
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

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



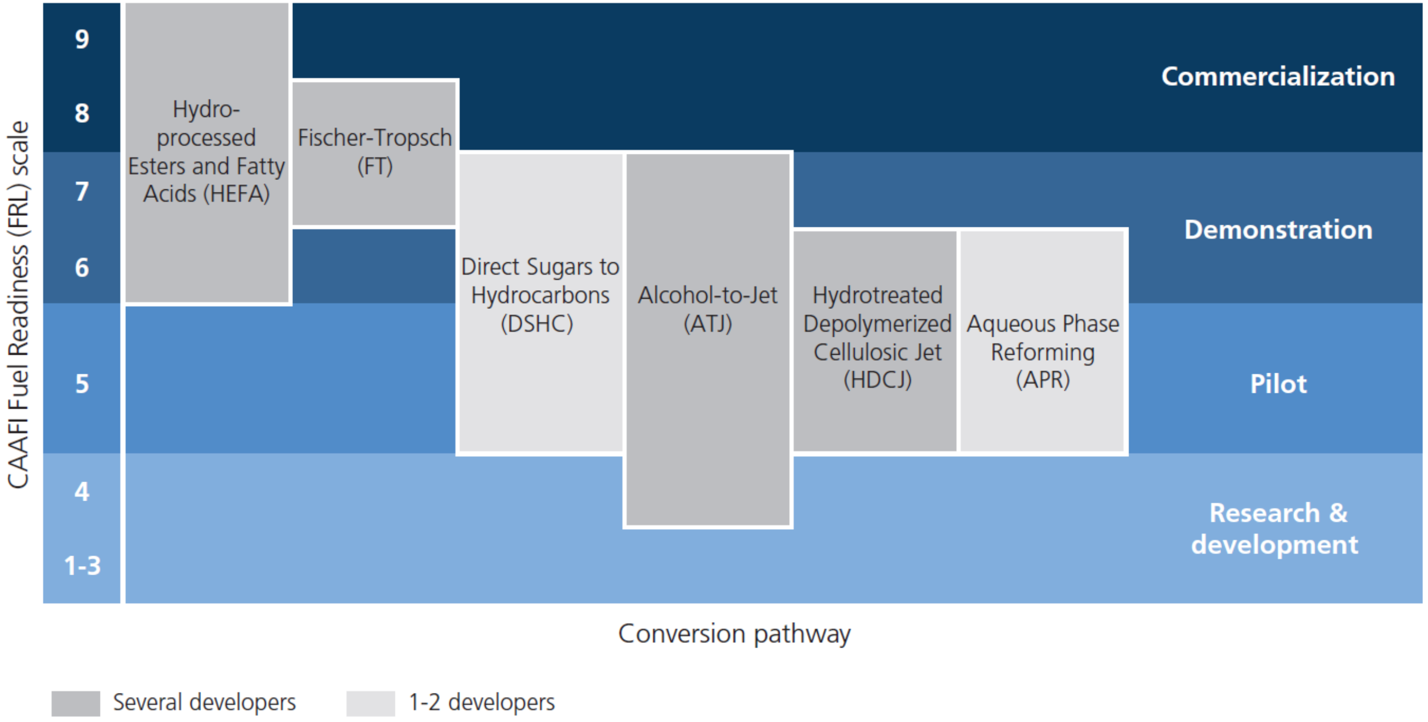
Source: Zhu et al. (2011)

About the pathway (2)

- Among the companies involved with the route FT-SPK (see table in the previous slide), 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 (municipal solid waste – MSW) gasification + FT synthesis, producing from 37.9 to 227.1 million litres per year. Fulcrum states that the process has been demonstrated and 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 could start in 2021. The production could reach 57.16 million litres of liquid biofuels (i.e. bio-jet, diesel and naphtha) from 136 thousand tonnes of waste woody biomass. It is stated that Shell will buy the SAF production.
- In a web seminar by IEA Bioenergy (in January 2020) (www.ieabionergy.com) it was mentioned that the unit by Fulcrum Bioenergy is under construction and that it could 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.
- In the same web seminar 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.

About the pathway (3)

- The figure, extracted from de Jong et al. (2017) is a representation of CAAFI's (Commercial Aviation Alternative Fuels Initiative) Fuel Readiness Level Scale (FRL). It is based on NASA's Technology Readiness Level (TRL) scale and is intended to provide a classification to describe the progress of a conversion pathway towards commercialization. Key milestones include proof of concept (FRL 3), scaling from laboratory to pilot (FRL 5), certification by the American Society for Testing and Materials (ASTM) (FRL 7), and full scale plant operational (FRL 9). This figure is not exhaustive, as more pathways have being considered for the production of SAF.



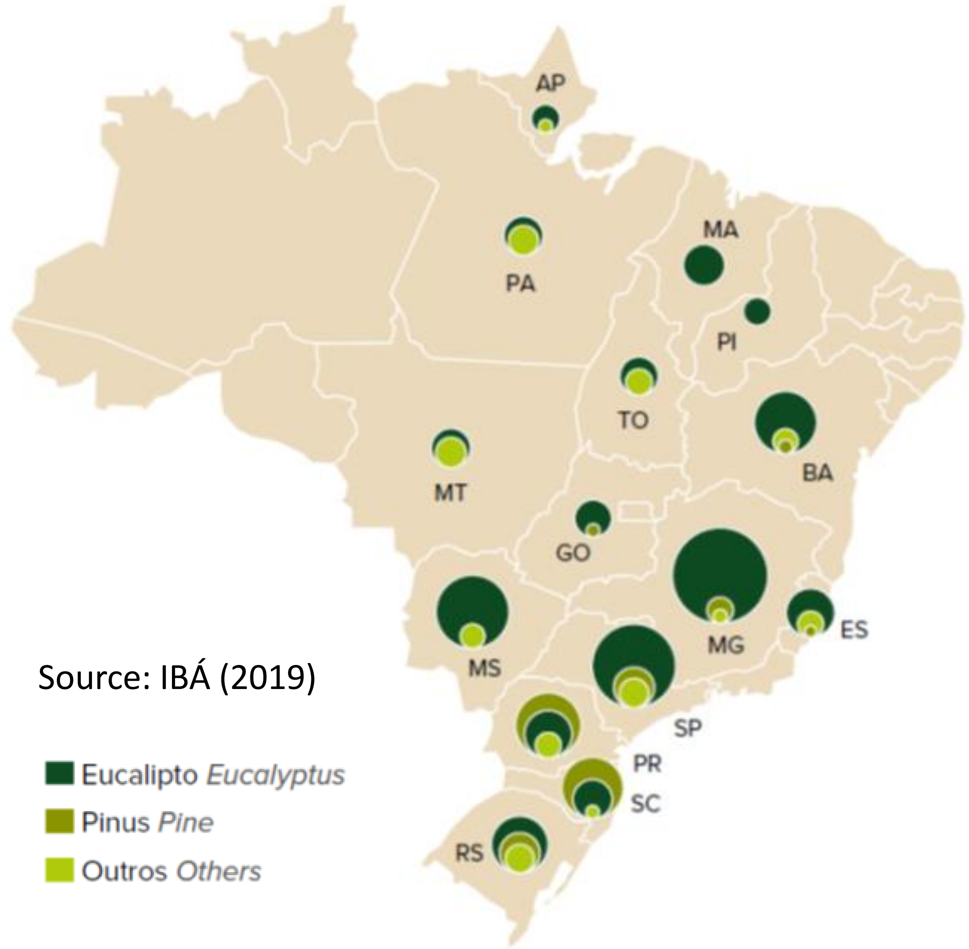
- Similar analysis is provided by Prussi et al. (2019). For the route FT-SPK, the authors present the Readiness Technology Level (RTL) at 6-8, as defined by the EU HORIZON Work Programme 2016-2017 (2019), and the FRL at 6-7, defined as mentioned above.
- The authors say that it is debatable the maturity level of the FT-SPK pathway as, according to them, there it is not yet fully commercial production.

About eucalyptus (1)

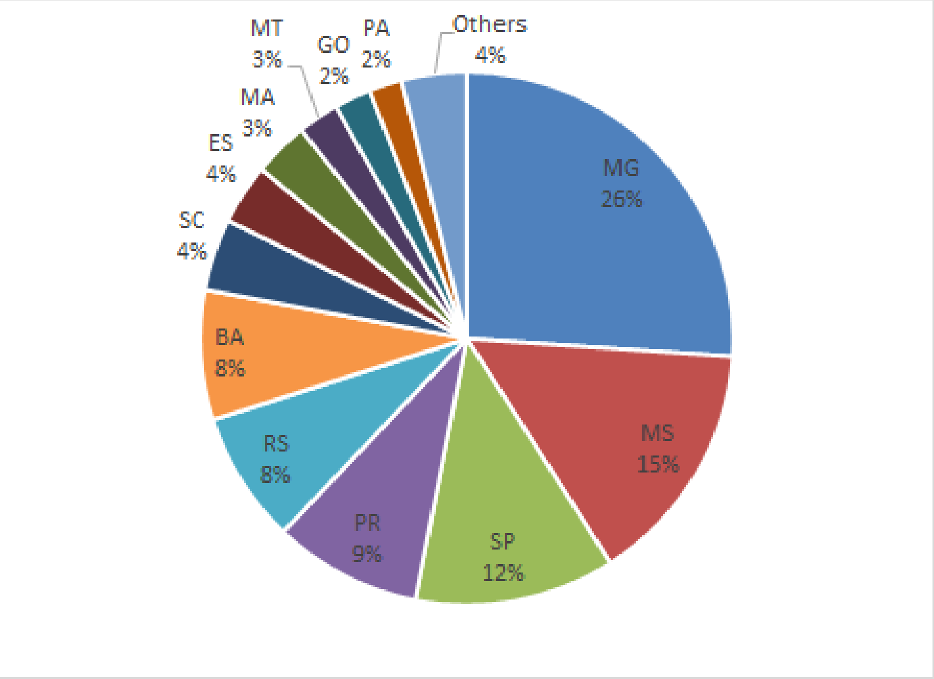

An eucalyptus plantation in Brazil. Source: Veracel/Brazil

- Eucalyptus is a forest specie of the broadleaf group, exotic to Brazil. The genus includes more than 700 species (more than 800, according to Flores et al. 2016), almost all originating in Australia (ESALQ, 2003).
- Eucalyptus was inserted in Brazilian forestry approximately one century ago. It has been used for different purposes.
- 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. In Brazil there is extensive knowhow about these three species.
- 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%) (IBÁ, 2018).

Eucalyptus in Brazil



Source: IBÁ (2019)



- The map shows the states and regions of Brazil where there are the largest areas of planted forests (in 2018).
- The diagram shows the distribution of eucalyptus plantation in different states, also in 2018. The planted area of eucalyptus in Minas Gerais (MG) was 1.97 million hectares.

- In 2018, the total area of trees planted in Brazil summed-up 9.9 million hectares, 75% of which with eucalyptus plantations (7.54 million hectares). These planted areas are located mainly in the Southeast and South regions, but the recent expansion is towards the Centre-West (e.g. Mato Grosso do Sul - MS) and the Northeast (Maranhão – MA – and Bahia – BA) (IBÁ, 2019, IBGE, 2019).
- The Brazilian planted tree sector is recognized worldwide for the high productivity of its areas (e.g. m^3.hectare^{-1}.year^{-1}); in 2018 the average productivity of eucalyptus was estimated at 36 m^3.ha^{-1}.

Methodology: general procedure

Assessing biomass availability → Estimating transportation costs → Defining supply curves at the industrial sites → Estimating SAF production and its costs → Analysis of the results

Scheme indicating the main activities in the process of evaluating the potential and economic viability of SAF, using the platform database.

Methodology: …assessing biomass availability

Assessing biomass availability → Estimating transportation costs → Defining supply curves at the industrial sites → Estimating SAF production and its costs → Analysis of the results

- Suitability of eucalyptus;
- Areas available and where production is desirable;
- Potential yields based on literature review;
- Estimated production costs.

Biomass available due to self dedicated production

Methodology … assessing supply curves at the industrial sites

SAFmaps

Assessing biomass availability → Estimating transportation costs → Defining supply curves at the industrial sites → Estimating bio-jet fuel production and its costs → Analysis of the results

Eucalyptus wood would be transported from the field to pre-defined industrial sites, by truck

→

Supply curves of eucalyptus are set in each industrial site, considering different SAF production capacities

Methodology … assessing costs and analysis of the results

Assessing biomass availability → Estimating transportation costs → Defining supply curves at the industrial sites → Estimating SAF production and its costs → Analysis of the results

Technical parameters and cost figures have been taken from the literature; costs were corrected to estimate values in 2018 (even for the n^{th} plant)

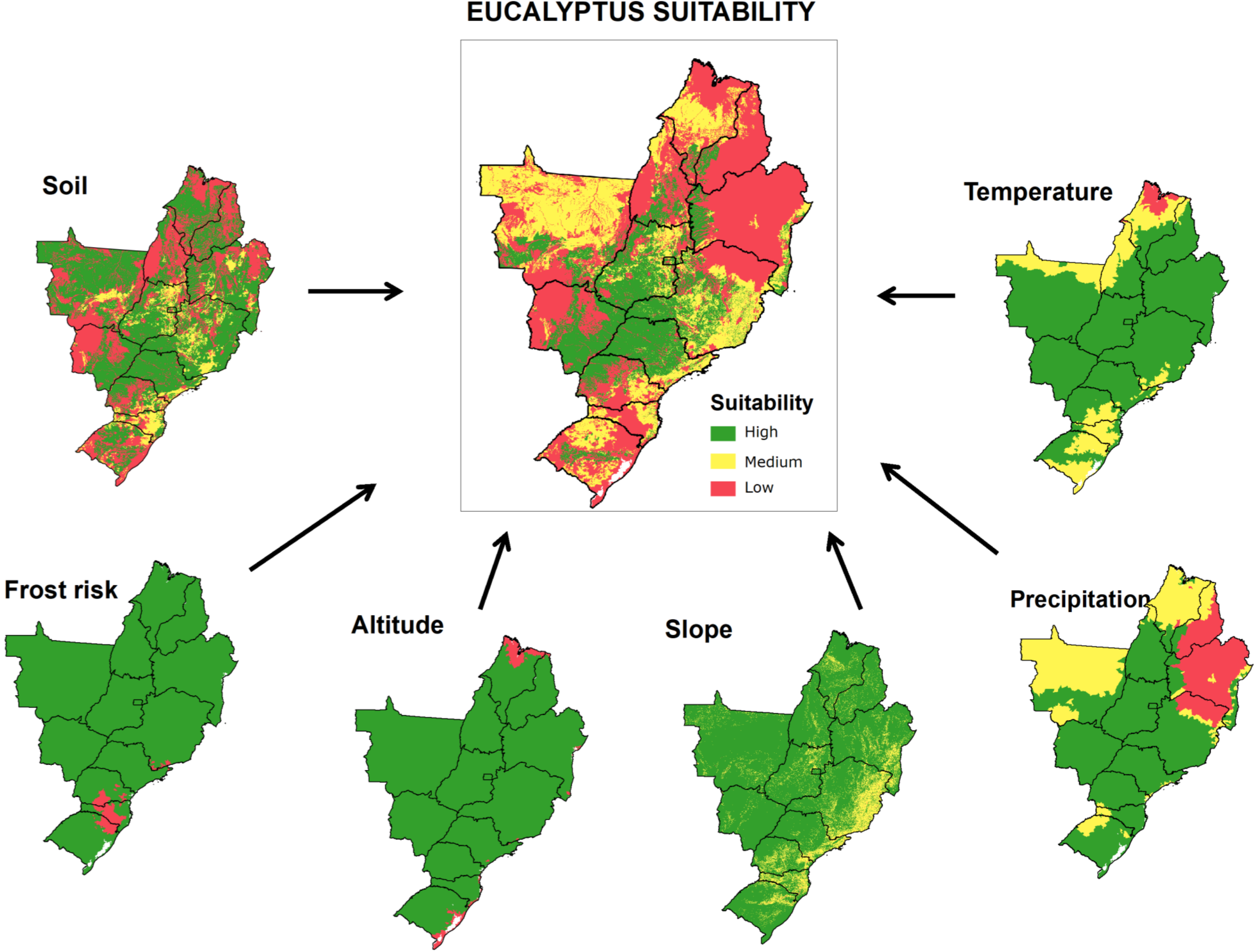
→

Analysis of the results, comparing with those presented in the literature and also with actual fossil kerosene prices, considering cost reduction opportunities and trends, etc.

Eucalyptus suitability (1)

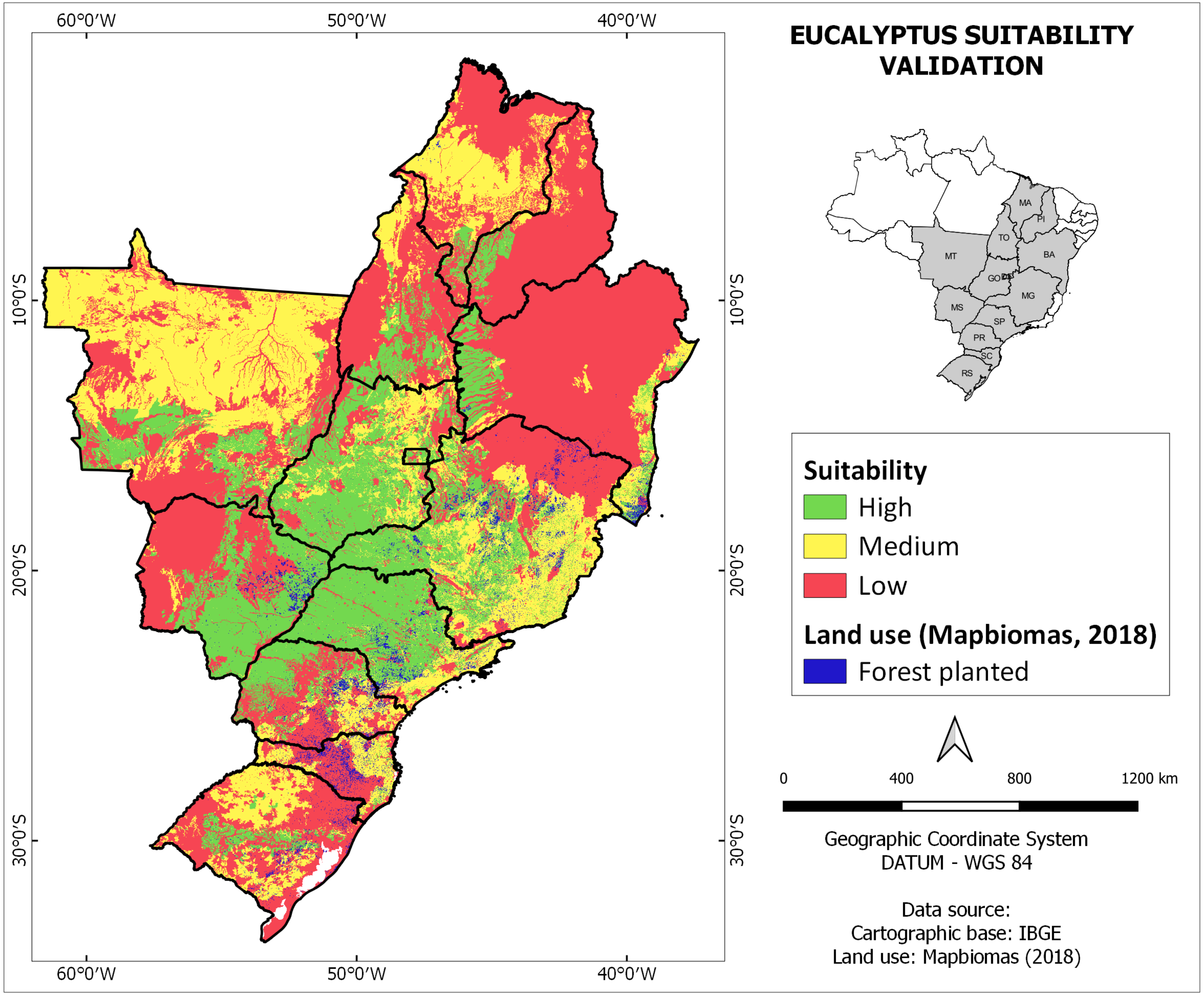
- The suitability of a feedstock is a crucial information in assessing its potential. The ultimate goal is to estimate how much biomass, and at what cost, would be available at a specific location.
- The procedure adopted for estimating the suitability of eucalyptus is based in a study by EMBRAPA, focused on producing eucalyptus in state of Minas Gerais (Alvares et al., 2013). Details of the procedure are presented in Supplementary Material.
- In synthesis, suitability depends on the climatic parameters (e.g. atmospheric temperatures, rainfall, frost risk), geographic parameters (i.e. site altitude, due to the risk of fungus propagation, in addition to the frost risk), soil suitability, and slope (because of the cost of harvesting).
- Here, a site classified as “low suitability” 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 and the resolution of the soil map (here, 1: 250.000 is the resolution). Second, the feasibility of eucalyptus production depends on the production costs (see information in the following slides), and also on the final purpose. For example, even with relative low yields, if the land is not expensive, eucalyptus production can be viable if the end use is for firewood or charcoal production. In this sense, the suitability results presented here are conservative.

Suitability (2)



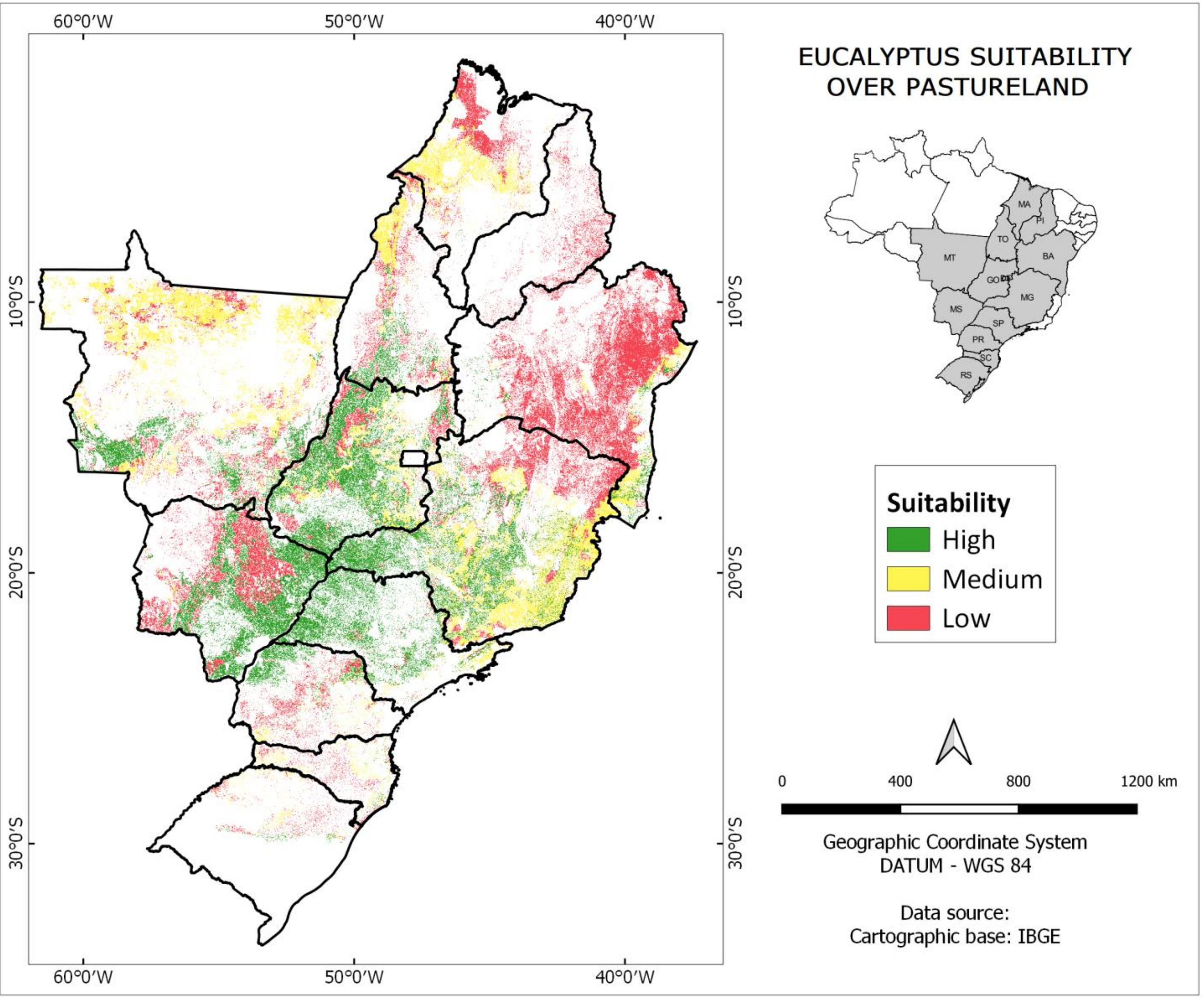
- As can be seen in the figure, the risk of frost and altitude impose restrictions to a small extent, while soil suitability is a restrictive parameter in many regions.
- The inadequacy of the rainfall regime clearly could impose restrictions on commercial eucalyptus production in the Northeast (for example, in BA and PI) and northern Minas Gerais.

Suitability (3)



- The results obtained with the adopted procedure were compared with the maps presented by Flores et al. (2016), for the species *E. grandis*, *E. urophylla* and *E. cloeziana*, and also with the agroecological maps presented by EMBRAPA for Paraná and Rio Grande do Sul (Higa and Wrege, 2010). In general, the conclusion is that the main trends were accurately captured.
- In addition, to be more precise, the resulting suitability map for eucalyptus was combined with MapBiomas's map of silviculture records (planted forests; including eucalyptus) for 2018 (blue dots on the map; as mentioned, eucalyptus is mainly planted in MG, MS and SP).

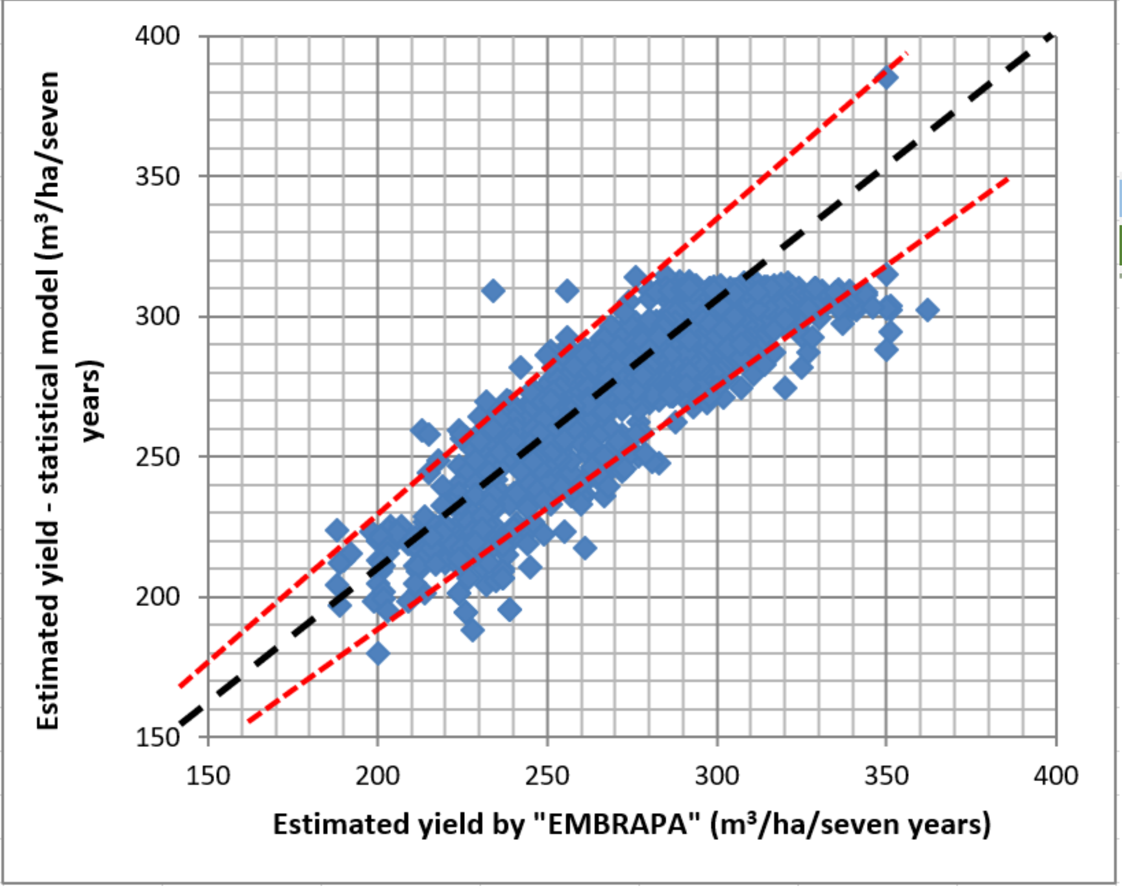
Suitability (4)



- The classification for suitability was developed in association with predicted yields (see following slides), in a way that a high suitability area would have a potential yield higher than 280 $m^3.ha^{-1}$ in a seven-year cycle, i.e. 40 $m^3.ha^{-1}.year^{-1}$, as long as the best technology is applied (a "marginal" area would have yields between 210 and 280 $m^3.ha^{-1}$ in a seven-year cycle).
- The figure shows the predicted results of suitability over pasturelands (in 2018). It was assumed that eucalyptus for SAF production would be planted only over grasslands.
- Clearly, areas with high suitability for eucalyptus in pasture areas in 2018 are mainly restricted to some regions: the west of the state of São Paulo, east of Mato Grosso do Sul, south of Goiás and the Triângulo Mineiro region stand out.

Eucalyptus yields (1)

- The second crucial step is estimating the productivity of feedstock production. For eucalyptus, this was done based on a statistic model developed, which is presented at Supplementary Material.
- For setting the model 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 of 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 producers (that results in lower yields). Here only the highest productivity results were taken, which are expressed in the volume of the tree after seven years growth. The three species considered are *E. grandis, E. urophylla,* and *E. cloeziana*.
- The final explanatory variables – and their coefficients – of the model adjusted are presented in Supplementary Material. The yields depend on the soil suitability for eucalyptus, represented by dummy variables that set differences among “high”, “medium” and “low” yields. The statistic model was applied for the twelve Brazilian states considered in this project. The results were compared with average and best yields of eucalyptus in Brazil, in recent years.

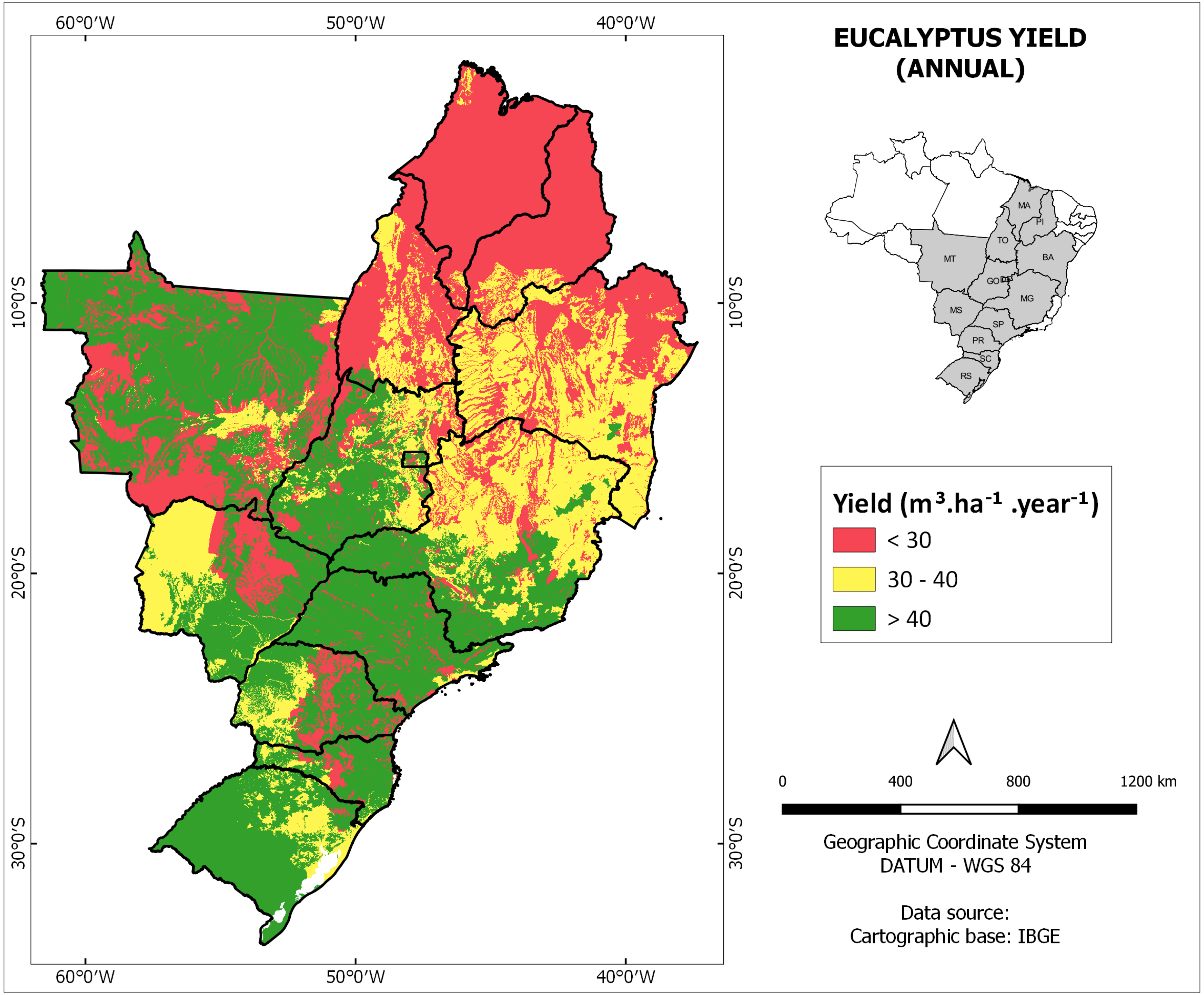


Eucalyptus yields (2)

Yields (m³.ha⁻¹.year⁻¹)	Highest[1]	Medium[1]	Lowest[1]	Actual results[2]
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	

[1] Average model results in each range
[2] Results presented by IBÁ (2019), for Brazil.

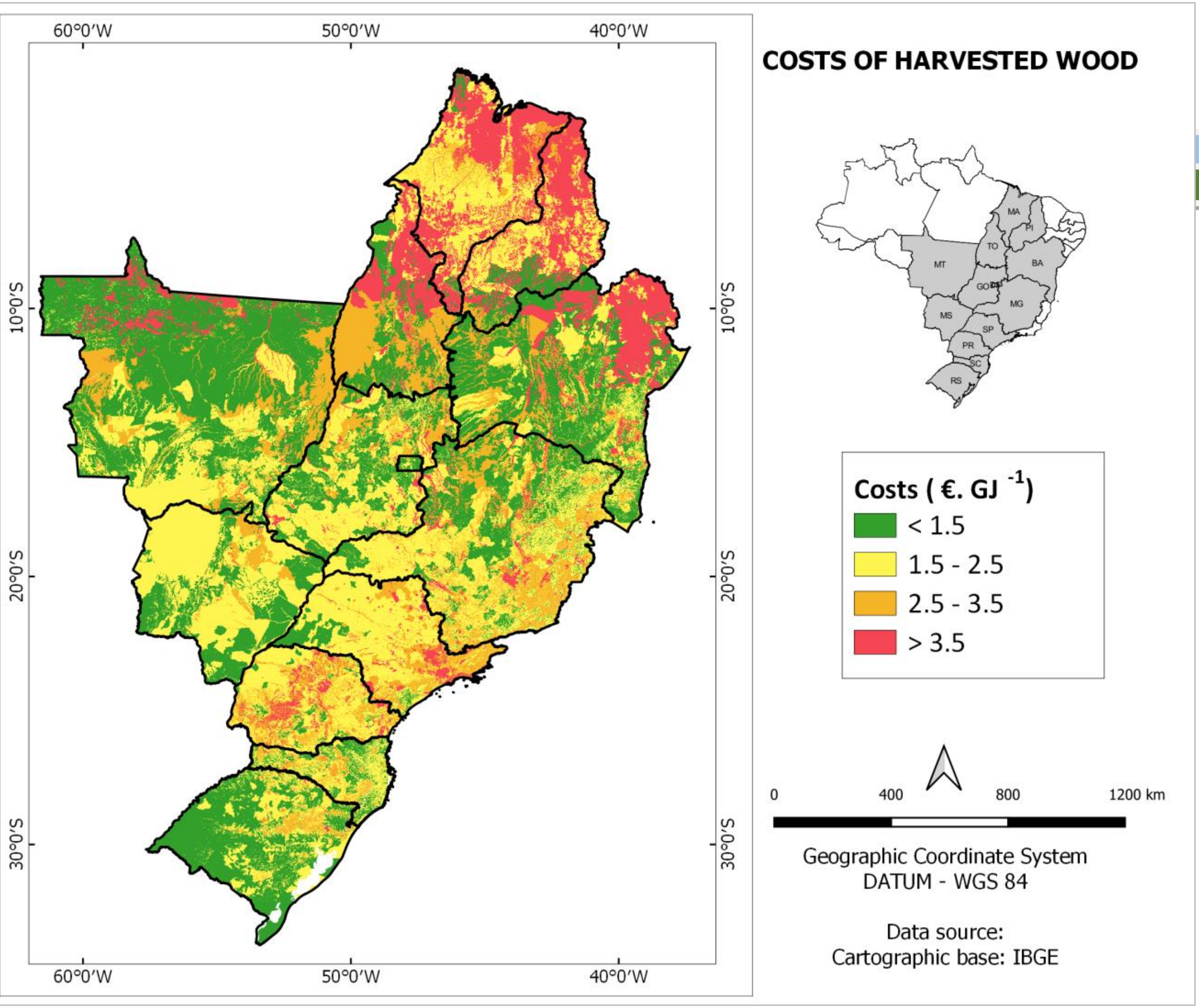
- Figure shows the distribution of the estimated yields for Minas Gerais versus the results presented in the reference publication (in $m^3.ha^{-1}$, in a seven-year cycle). It can be seen that in a few cases (municipalities) the errors are beyond a 15% margin (above or below).
- The multiple correlation procedure resulted in a function with the following explanatory variables: annual precipitation, water deficit, IDP (a parameter that indicates rainfall regularity) and annual atmospheric temperatures (average, minimum and maximum values). Dummy variables in the model differentiate the areas in terms of soil suitability (see Supplementary Material).
- For the twelve states, some statistics related to the set of results are shown in the table; actual results correspond to the national production, as presented by IBÁ (2019). The same comparative analysis was made with the data available in the IBGE database (IBGE, 2019), and in this case the results show that the model is suitable for all states, except Maranhão.



Eucalyptus yields (3)

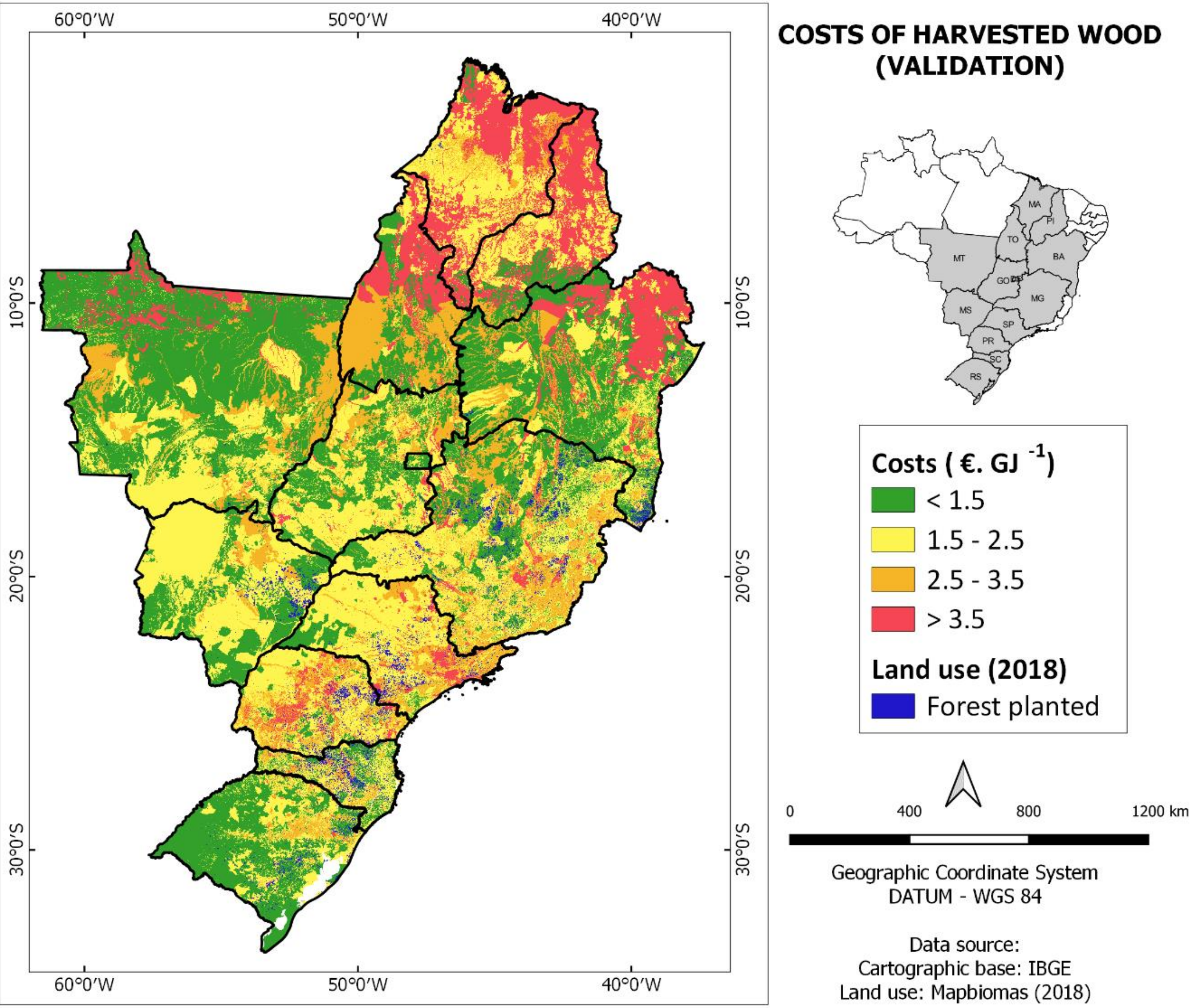
- The figure shows the resulting map of predicted yields of eucalyptus in twelve states. The yields are presented in m^3 of wood, after harvesting (i.e., wood with high humidity).
- The function was applied in combination with the soil suitability map, exploring the various dummies that result in three levels of yields.
- The areas with expected high or intermediate yields match well with the places where eucalyptus was planted to a great extent in 2018 (according to MapBiomas).
- However, comparing maps, it can be seen that the one for yields does not match exactly with the one for suitability (see, for instance, the mismatch in BA, SC and RS). This is mainly due to variations in yields and the intervals defined in the corresponding map.

Estimating wood costs (1)



- The third crucial step is estimating 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 itself 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.
- Figure shows the map of estimated wood costs at the forest, after cutting trees.

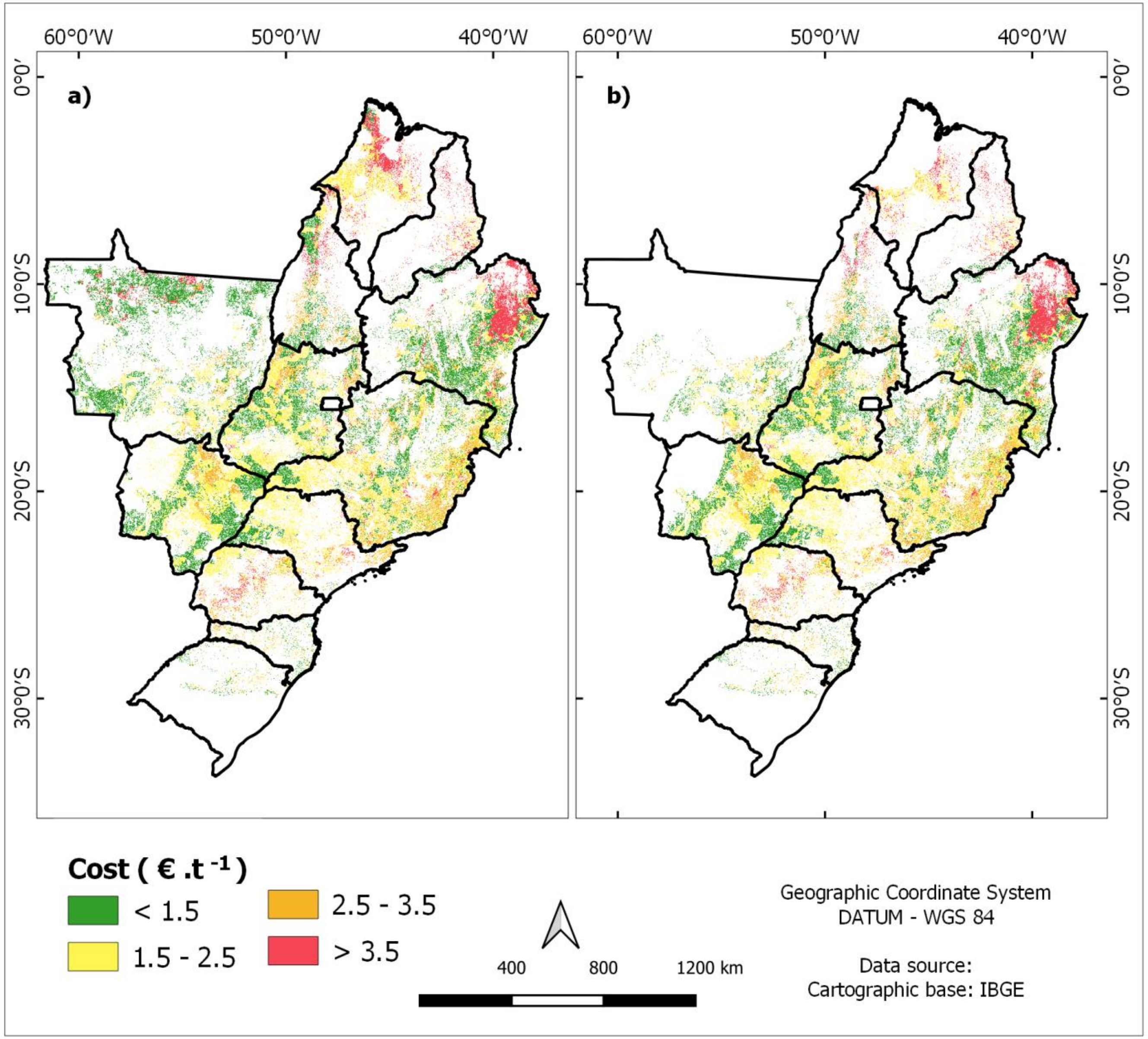
Estimating wood costs (2)



The figure is the map of estimated harvested wood cost, combined with the sites (blue dots) where there was larger silviculture activity in 2018 (not only eucalyptus production).

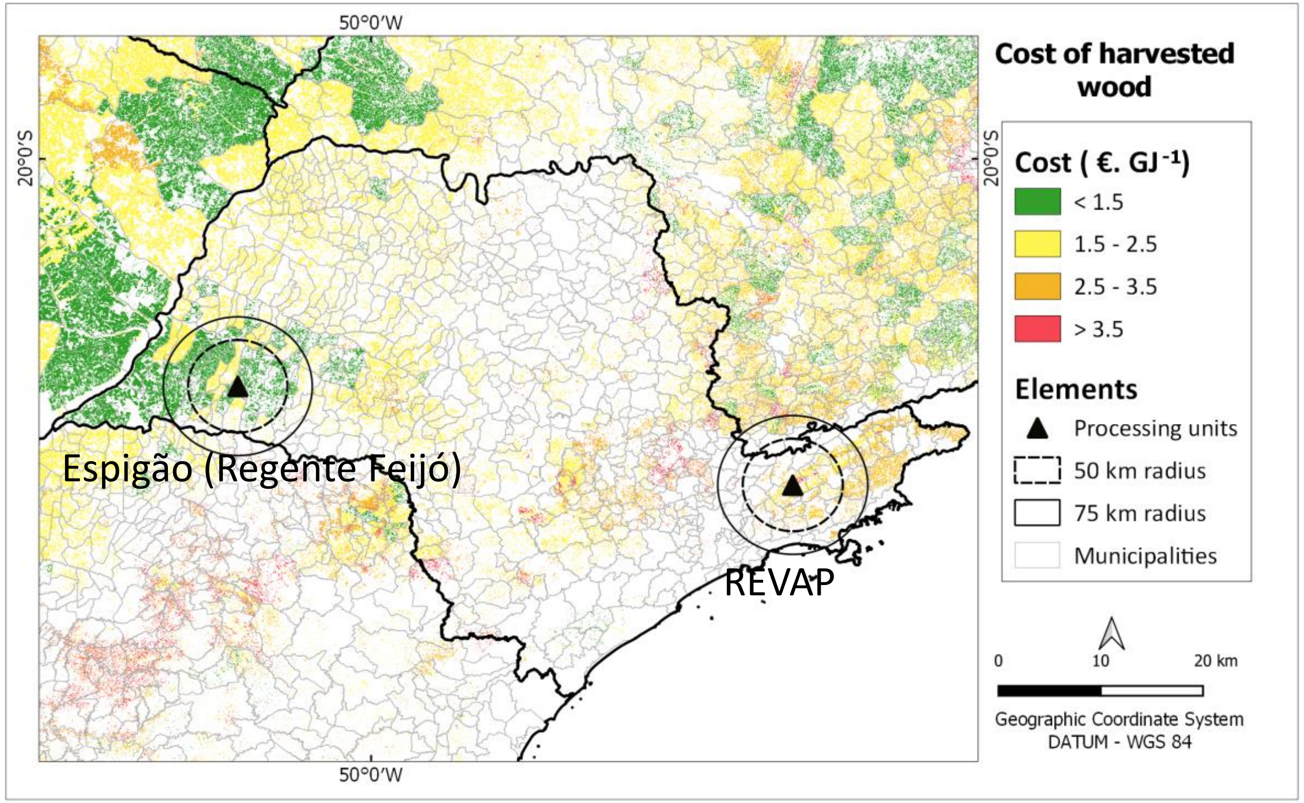
- Details of the procedure and the main assumptions for estimating costs are presented as Supplementary Material.
- The so-called costs of implementing the forest correspond to the investment in preparing the land, planting the seedlings and all maintenance costs until the moment of cutting. These costs were estimated based on the literature and here the median of the collected values was used (8,306 R$.ha^{-1} in 2016, being the minimum value in the data set 6,362 R$.ha^{-1} and the maximum value 9,406 R$.ha^{-1}). These values were corrected to 2018 using the price index for the Brazilian pulp and paper industry (INCAF; 416.1 in 2016 and 466.1 in 2018) (Pöyry, 2019.); then the resulting cost of the forest would be 9.304 R$(2018).ha^{-1}. This cost is further translated to the wood produced considering the local yield.

Estimating wood costs (3)



- The figure shows the map of wood costs at the forest, after cutting trees, in areas that are priority for planted forests (i.e. over pasturelands and after exclusion of sensitive areas). In the case of figure b) the Amazon and Pantanal biomes have been completely excluded, and this represents the most conservative solution. The results shown in this figure were those used in detailing the case study.
- Cutting costs are an additional portion and have been taken from IEMA (2017). There is a significant difference between flat areas and areas with sharp declivity. Original costs were 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, respectively.
- Details are presented as Supplementary Material.

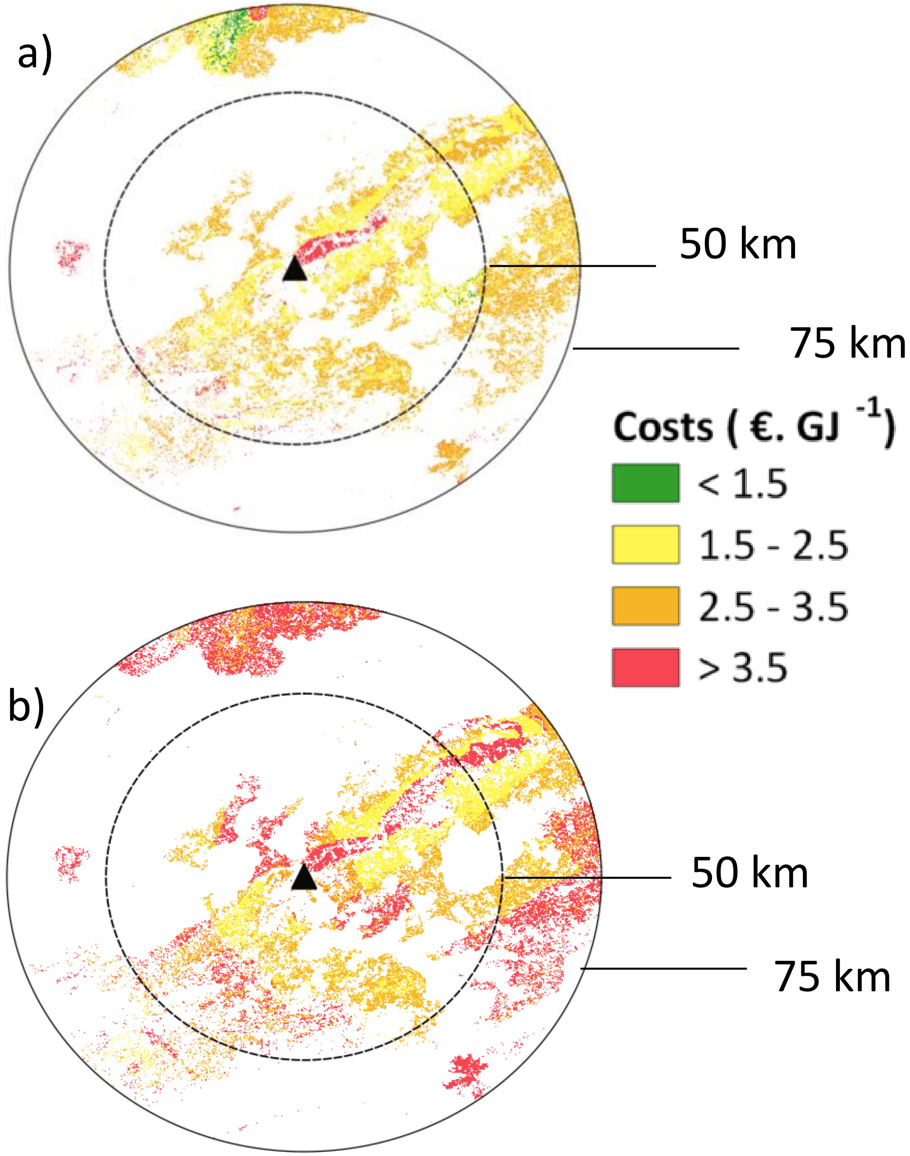
Case studies (1)



- The case study is concerned with the pathway FT-SPK, based on eucalyptus. Both co-locating (at REVAP) and greenfield units (at Espigão) have been considered. Both industrial units would be at state of São Paulo (Southeast Brazil).

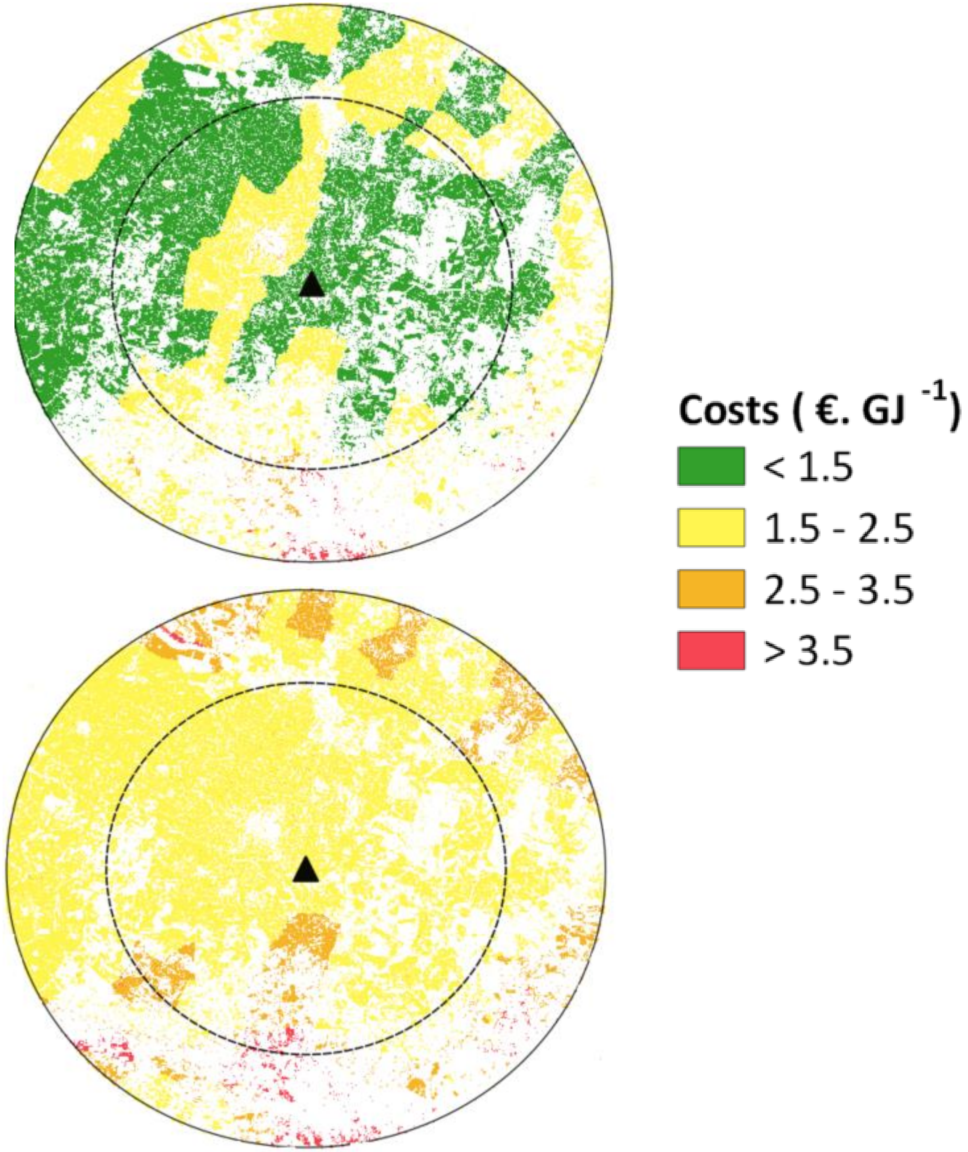
- In one case it was considered a co-locating industry beside the Henrique Lage oil refinery (REVAP), located in São José dos Campos. REVAP is the largest producer of jet-fuels in Brazil, covering, on average (in the last 10 years), 33.4% of the national production. There is a duct that allows the transport 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. 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 SAF production in Espigão, the fuel would be transported by trucks or by train to an oil refinery or to large airports.

Case studies (2): costs around REVAP



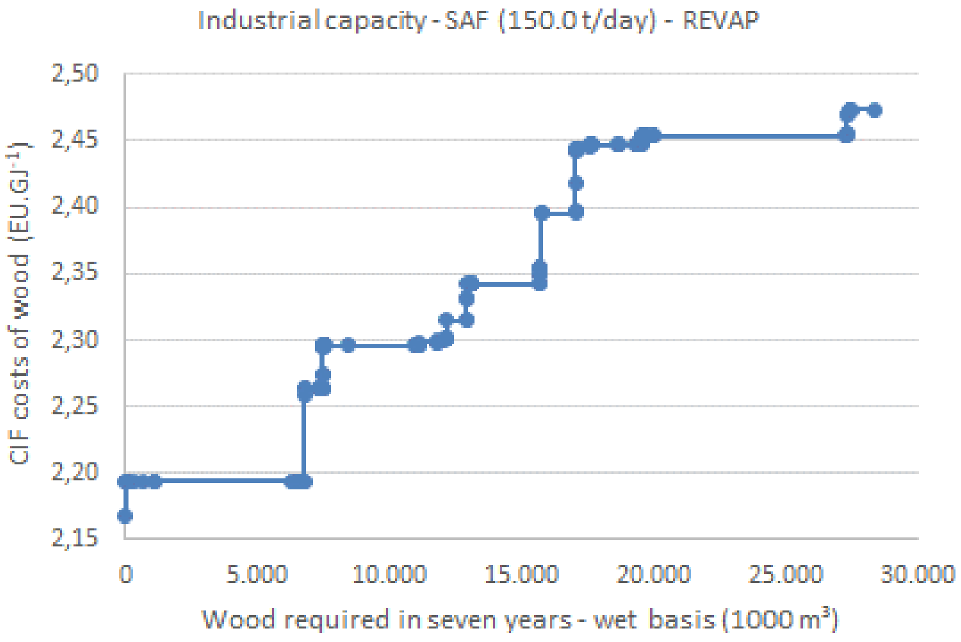
- Once the location of the two industrial sites was defined, to assess the potential of eucalyptus production the area surrounding these sites was considered within circles with 50 and 75 km radius.
- Defining the eucalyptus supply curve at the industrial unit requires a combination of eucalyptus cost data (wood harvested, plus transportation costs) and yield estimates.
- Transport costs were estimated from the center of each eucalyptus production cluster to the industrial site, assuming that transport would be by truck.
- The upper figure shows the spatial distribution of the costs due to the hypothetical production of eucalyptus around REVAP (costs just after cutting trees), within the two circles. At the bottom the figure shows the spatial distribution of wood costs at REVAP, including the transport cost from each cluster to the industrial plant.
- Areas not marked correspond to those which were not pasturelands in 2018.

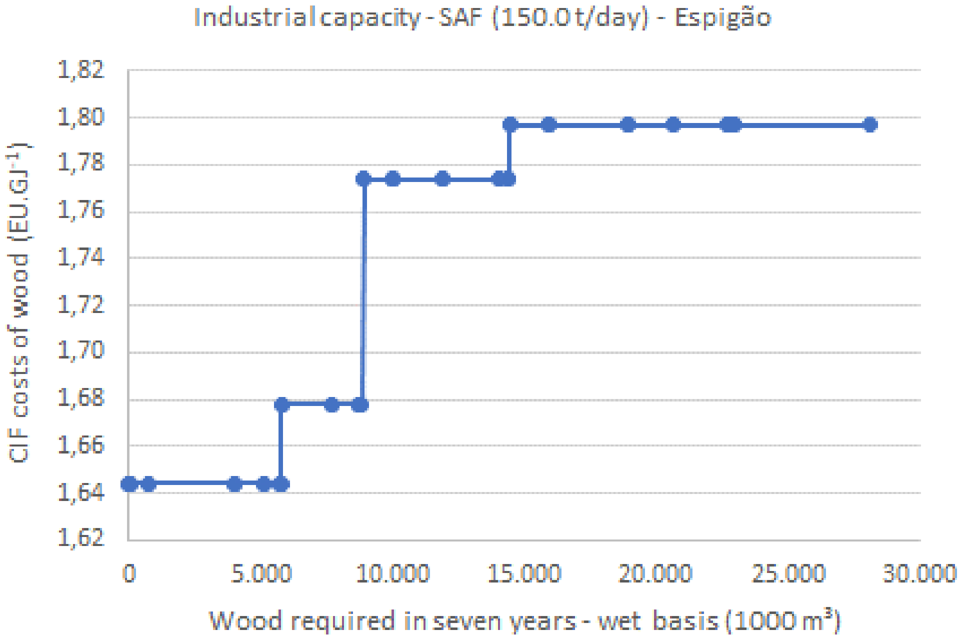
Case studies (3): costs around Espigão



- Similar results are presented for the areas where it would be possible to produce eucalyptus within the circles with radius of 50 km and 75 km around Espigão, on the west bank of the state of São Paulo.
- The upper figure shows the spatial distribution of the costs (just after cutting trees), while at the bottom the figure shows the spatial distribution of CIF wood costs, including the transport cost from each cluster to the industrial site, at Espigão.
- For the Espigão and the REVAP cases, the cost due to transport represents between 21-24% to 37-40% of the costs of wood at the mill site, respectively. This is due to the fact that the humidity is still high, although it was assumed that, after cutting, the wood would be left in the field for two months (in order to reduce humidity).

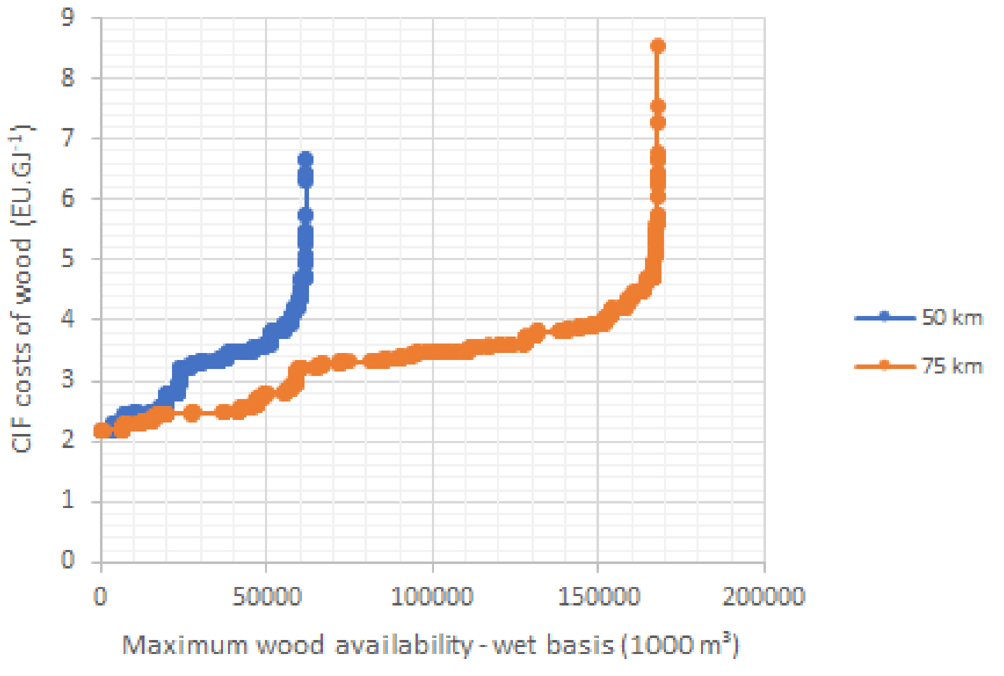
Results (1)

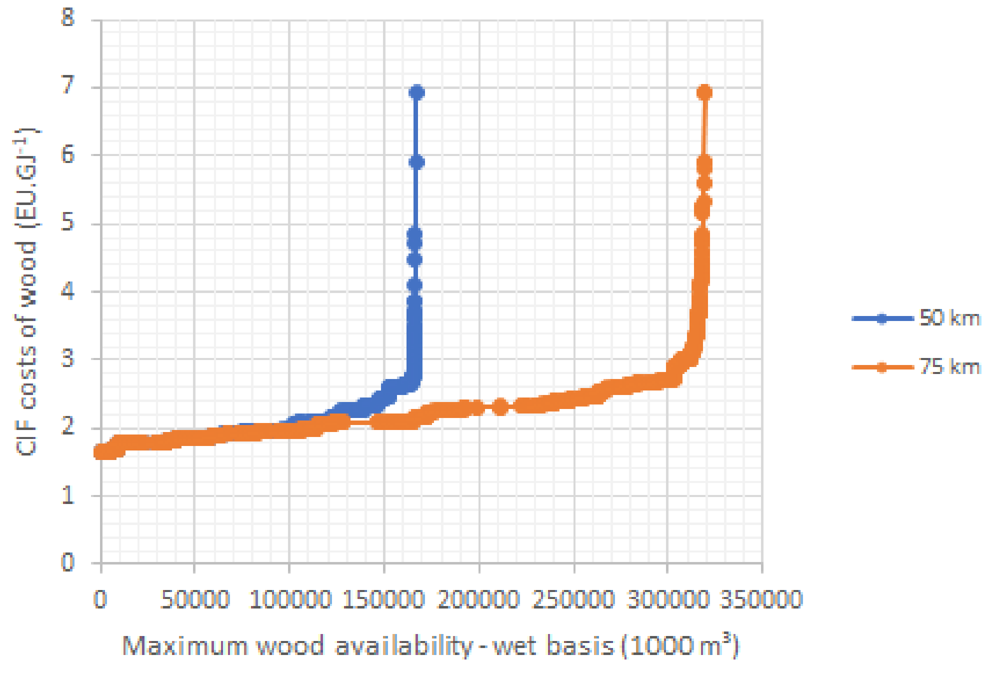




- Taking the production of 150 t.day^{-1} of SAF as example (the largest capacity considered here), the minimum wood requirement would be almost 28 million m^3 of wet wood per cycle of seven years, demand that corresponds a certain area (due to the yields in each region).
- The differences in CIF wood costs in industrial units, comparing the cases of REVAP and Espigão, are explained by the greater availability of areas for the production of eucalyptus in Espigão and, associated to this point, by the shorter distances to the industry. In addition, the lower costs of standing wood are due to a number of factors, including yields, topography (which impacts harvesting costs) and land prices.
- The average CIF wood price at Espigão would be 1.73 ± 0.07 €.GJ^{-1}, while at REVAP it would be 2.35 ± 0.09 €.GJ^{-1}.

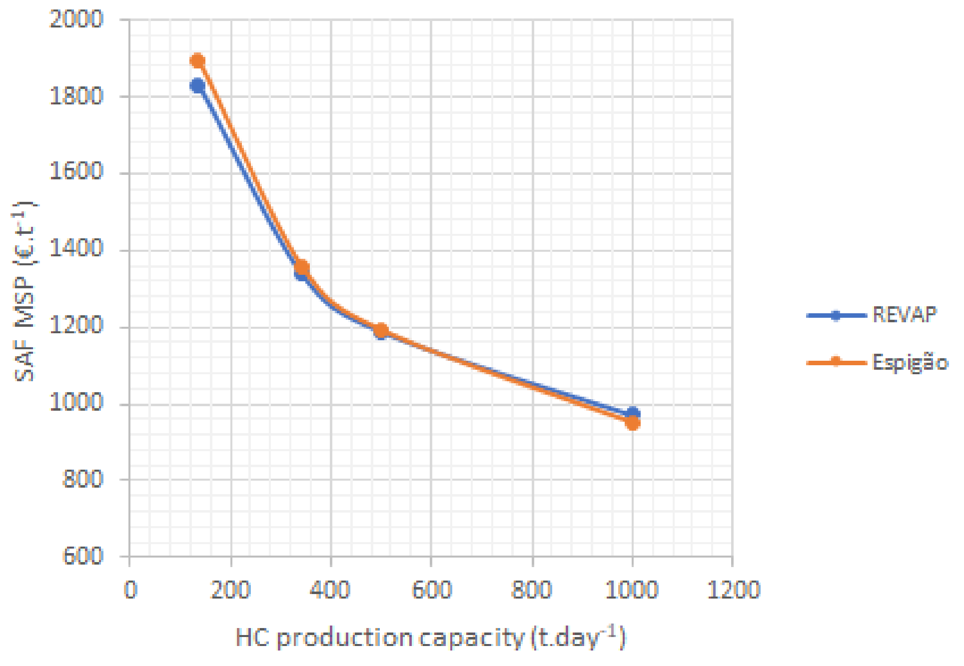
Results (2)

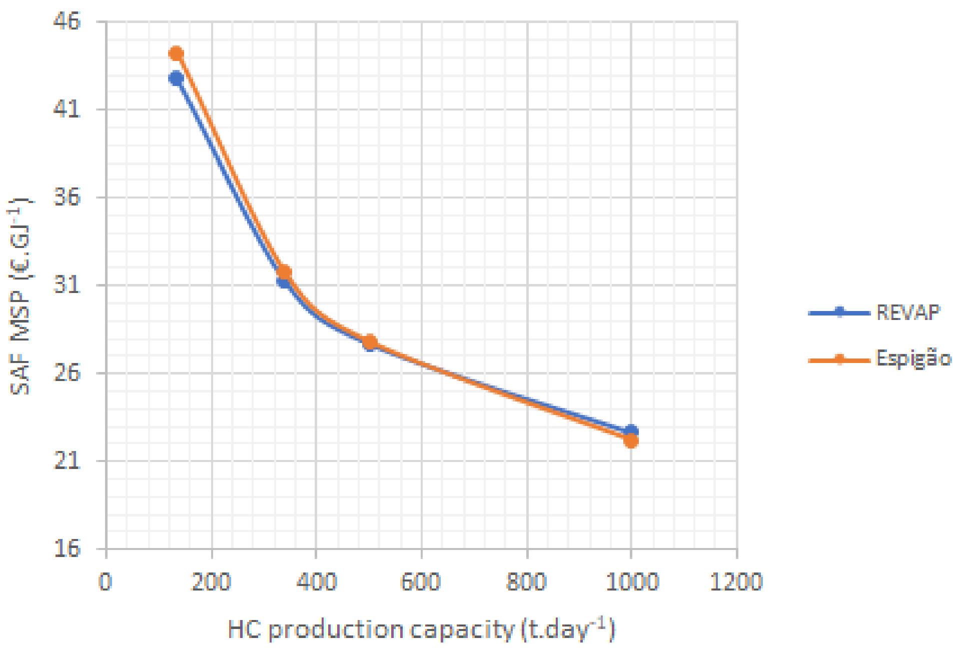




- Considering the areas of influence with lower or larger radius, the upper figure shows the maximum supply curve for eucalyptus wood in REVAP, while the second shows the maximum supply curve in Espigão.
- The curve for the REVAP case suggests that there is a relatively small amount of wood available at low cost within the 50 km circle. Considering the largest industrial capacity assumed here, the average CIF costs would be 13% higher if the supply was limited to 50 km, compared to the wider supply option (i.e. the circle with a radius of 75 km).
- This is not the case around Espigão and it can be concluded that the capacity of SAF production could be either larger than 150 t.day^{-1}, or more plants could be close each other.

Results (3)



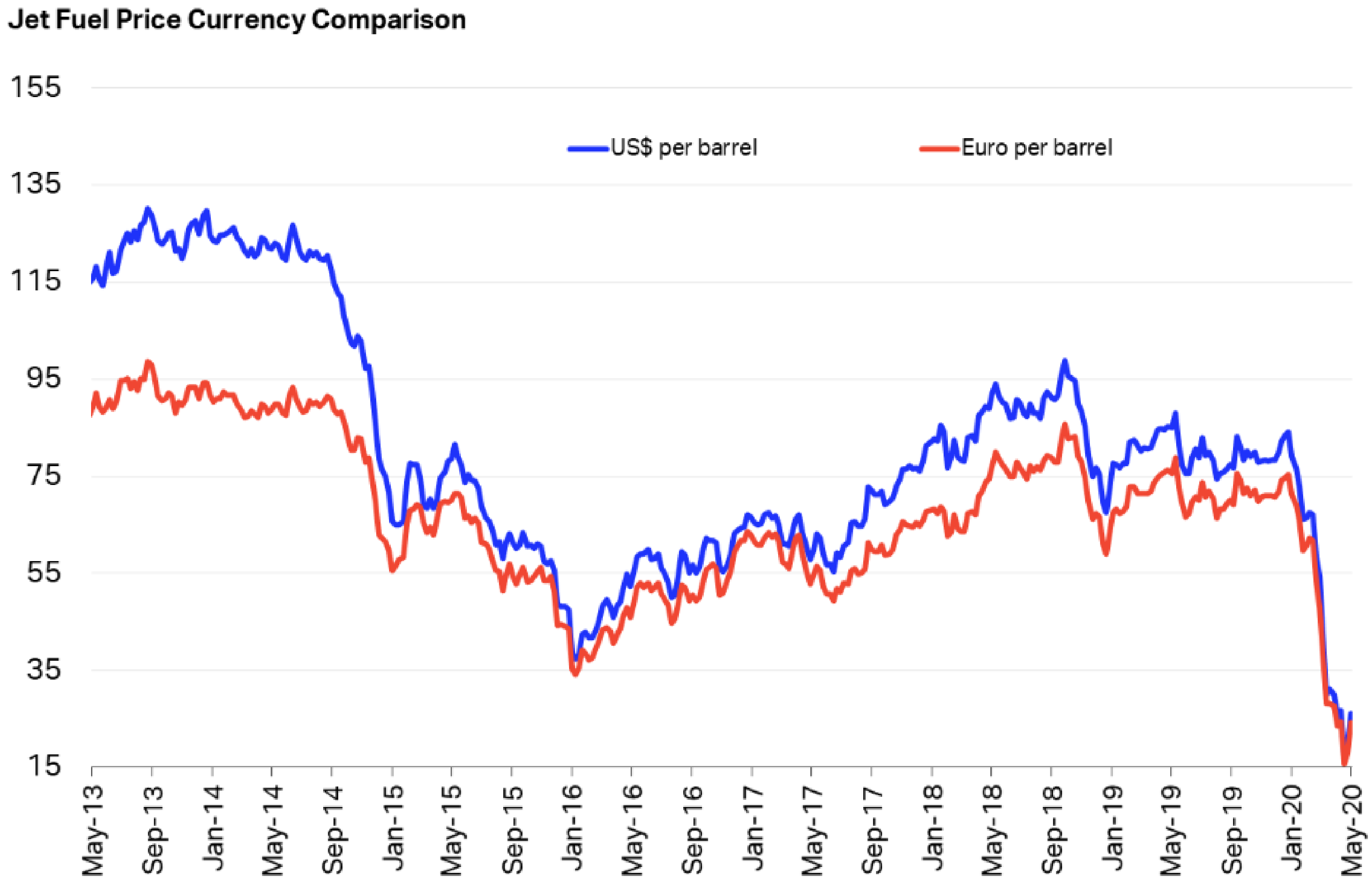


- The estimated minimum selling prices (MSP) of SAF based on FT-SPK route using eucalyptus, for the two sites here considered, are presented in the beside figures. The upper figure shows the results on mass basis, and the second figure present results on energy basis.
- The hypotheses and the procedure used for estimating the MSP are presented as Supplementary Material. It is based on de Jong et al. (2015).
- For the same industrial capacity, the CAPEX and OPEX are slightly higher for the greenfield case (here, the Espigão unit) and this explains the higher MSP for the production in Espigão compared to REVAP, for small units. However, as the wood is cheaper around Espigão, for larger industrial capacities there is an advantage for producing there compared to the production at REVAP.
- The results indicate a clear impact of scale effects, once CAPEX and OPEX are determinant in both cases.

Analysis of the results (1)

- The MSP results of this study are in the range 952-1896 €.t^{-1} of SAF, depending on the industrial capacity scale, or 22.2 to 44.3 €.GJ^{-1}. These results can be compared with the MSP presented by de Jong et al. (2015), which are in the 38-55 €.GJ^{-1} range considering the use of forest residues or wheat straw as feedstock (feedstock CIF cost 4.8 €.GJ^{-1} or 10.6 €.GJ^{-1} , respectively). The results by de Jong et al. (2015) are also quoted by Bosch et al. (2017), with the MSP presented in the range 1700-2600 €.t^{-1} of SAF.
- Bann et al. (2017) also present the estimate MSP of SAF production (in fact, a basket of middle distillates) through the FT-SPK route based on municipal solid waste (MSW) in a case that the feedstock is not charged. The authors did Monte Carlo simulations and considered different hypotheses; the median of the MSP was estimated at 1.15 \$.L^{-1}, varying from 0.95 to 1.39 \$.L^{-1} in a range of 95% probability (i.e. varying from about 1,019 to 1,491 €.t^{-1}, with median on 1,233 €.t^{-1}).

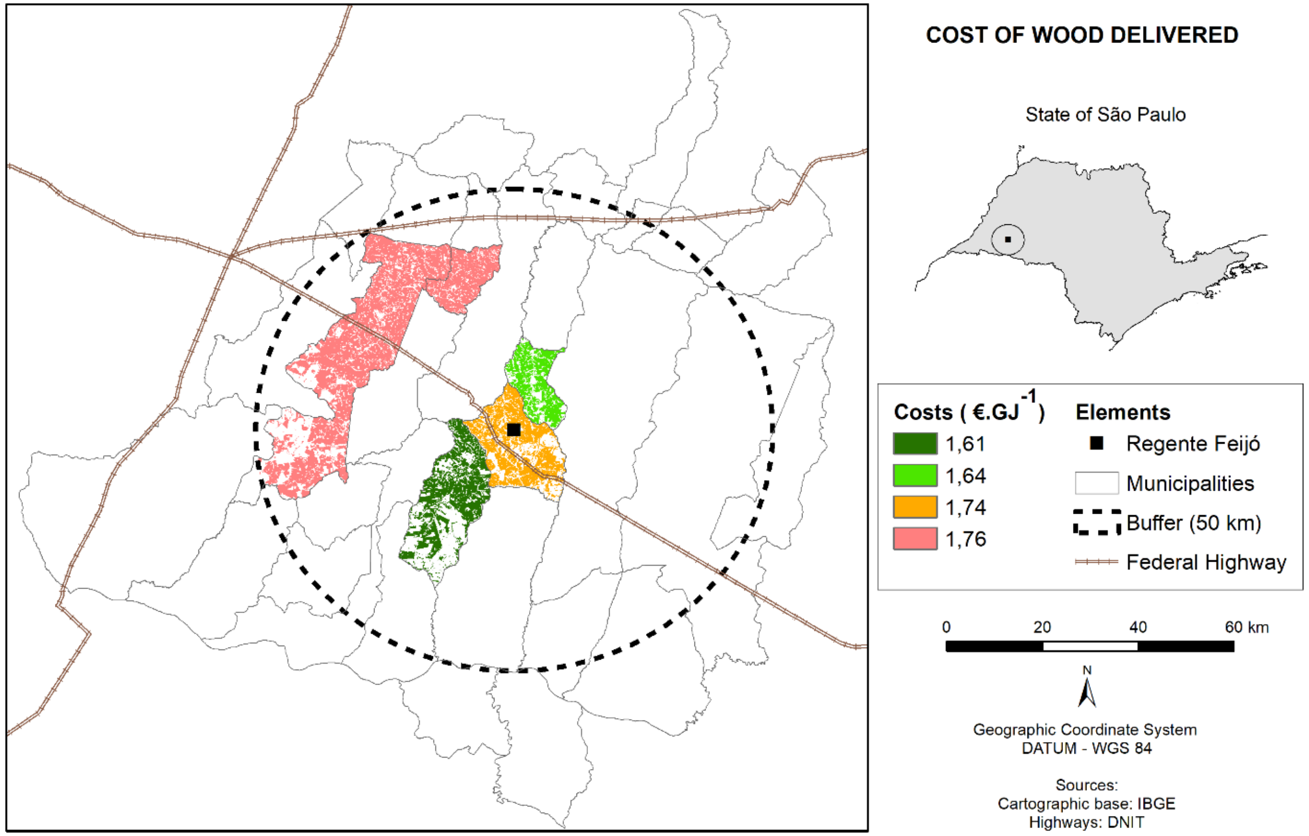
Analysis of the results (2)



Source: Platts, Datastream https://www.iata.org/en/publications/economics/fuel-monitor

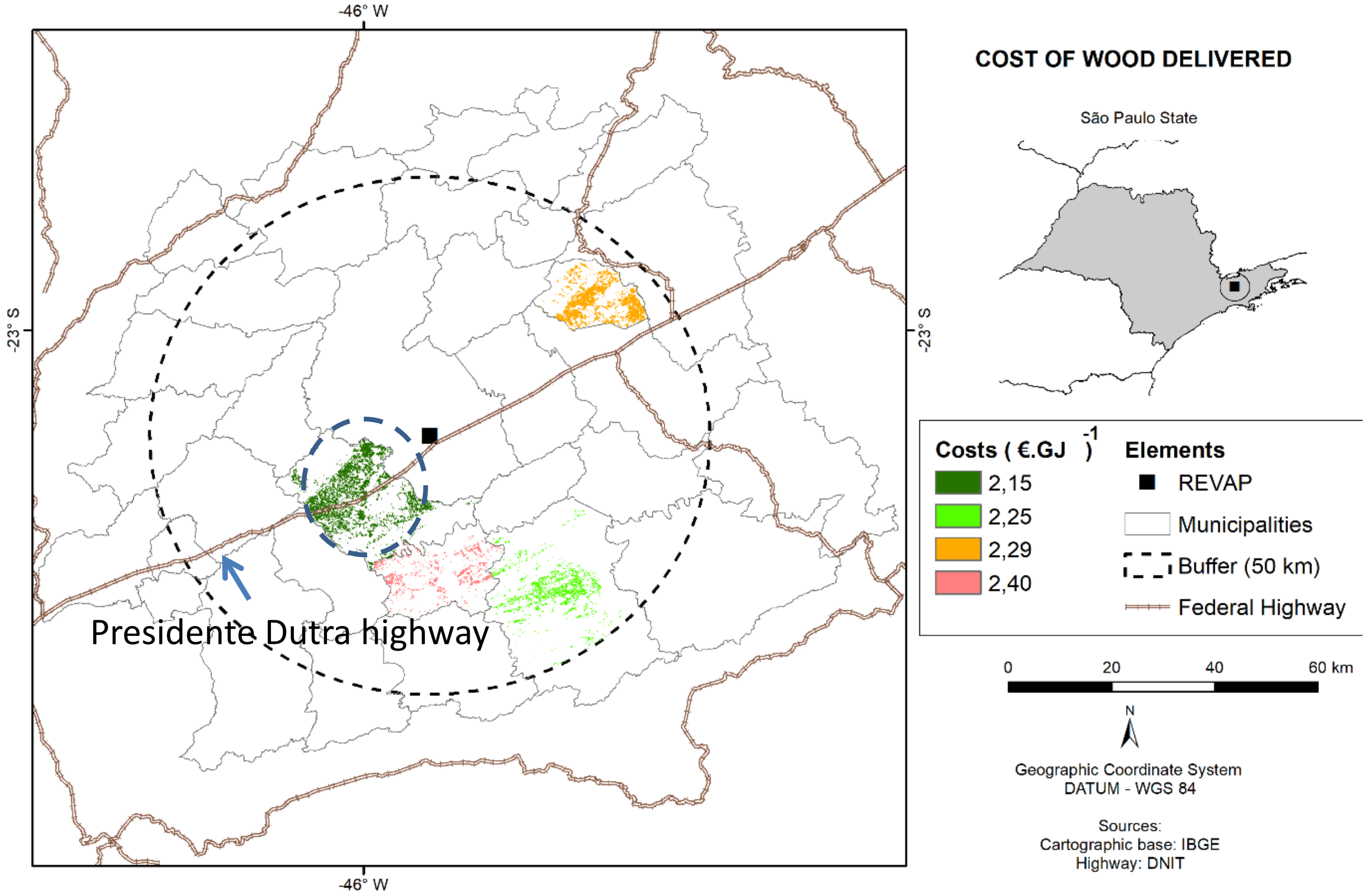
- For the MSP of SAF in the range 952-1896 €.t^{-1} (estimated here) the break-even price of jet-fuel would be 144-286 \$.barrel^{-1}.
- For the lower MSP values in the range, the estimated break-even jet fuel prices were reached in 2013-2014. Jet fuel market prices is extremely correlated with international oil prices (see Supplementary Material).
- The Platts Global Index indicates that the jet fuel index price in Latin America is about 12% higher than the global figure. In Europe it is about 6% lower, and in North America about 8% higher.

The risks of extensive monoculture



- Considering the supply curves in each case (areas around Espigão and REVAP), four clusters (related to costs) were selected for analysis among the lowest cost solutions at the industry site.
- For the circle with a radius of 50 km, the location of these clusters is shown in the figure for the Espigão case.
- Looking at the figure, it is worth noting that there would be a risk of areas with extensive monoculture related to eucalyptus production. This could be a risk to the effective sustainability and such a solution could be heavily criticized. One of the necessary actions would be to keep areas with native vegetation, with at some extent impacting the supply curve. These impacts could be minor in the case of Espigão, as there is a large potential availability of low-cost wood.
- Still related to the maintenance of certain extensions of area with natural vegetation, an additional aspect is the enforcement of the Forest Code.

Possible distortions due to aggregate information



- The figure shows the four clusters around REVAP, selected for analysis.
- An additional comment concerns the procedure used to estimate the costs of wood production. It was used a database with the average land prices in each municipality (here, used as pastures), but it is reasonable to assume that the land price close to the Presidente Dutra highway, for example, would be higher than the assumed average values.
- Thus, it would be necessary to refine the analysis once the main areas for wood production are identified. This is the case of the area with the lowest potential cost of wood, close to the highway, highlighted in the figure.

Eligibility under CORSIA

- Eligible fuels in the context of CORSIA include Sustainable Aviation Fuels (SAF) (from biomass) and Lower Carbon Aviation Fuels (LCAF) (from fossil energy sources). The production of both must be certified from the point of view of sustainability. For SAF, in the CORSIA pilot phase, only two principles must be accomplished (see Supplementary Material): 1) they should generate lower carbon emissions on a life cycle basis, and 2) should not be made from biomass obtained from land with high carbon stocks.
- Here, compliance with Principle 2 is guaranteed by the fact that wood production would occur by displacing pastures, in areas that were not converted after January 1, 2008.
- To comply with Principle 1, the SAF could not emit more than 90% of 89 gCO2eq.MJ^{-1} over its life cycle, which is the assumed footprint of fossil fuel for aviation. The producer can either use the Default Life Cycle Emissions Values, published by ICAO or, alternatively, assess the carbon footprint of its own production. The route FT-SPK from eucalyptus (produced in Brazil) has not been studied so far, and its Default Value is not available. Among the Default Values available, the closest route is for the use of poplar (a short-rotation woody crop) as feedstock, produced in US. For FT-SPK, the Core LCA values for different feedstocks vary from 5.2 to 12.2 $gCO_2eq.MJ^{-1}$, for MSW and poplar, respectively, and it can be supposed that this value would not be much different in case of eucalyptus. However, the ILUC (Indirect Land Use Change) component could be controversial in case of eucalyptus displacing pasturelands, and must be evaluated carefully. In the published CORSIA's default life cycle emissions values the ILUC component varies from 7.3 to 11.3 $gCO_2eq.MJ^{-1}$ for sugarcane in Brazil (for different routes), and is 27.0 $gCO_2eq.MJ^{-1}$ for soy oil (HEFA-SPK) (CORSIA, 2019).

Conclusions

- The reported case study addresses the production of SAF through the FT-SPK route, from self-dedicated eucalyptus plantations. Two cases were explored, the first being a co-locating unit next to REVAP (in São José dos Campos, SP), and the second a greenfield unit, in Espigão, near Presidente Prudente (SP).
- The CAPEX and OPEX of a co-locating unit would be lower, but in the cases evaluated here wood is more expensive near REVAP than near Espigão. As a consequence, the estimated minimum sales prices (MSP) of the SAF are almost equal, with a slight advantage for production in Espigão (greenfield unit) in the case of larger industrial capacities.
- The estimated MSP varies between 952-1896 €.t^{-1} of SAF (or 22.2 to 44.3 €.GJ^{-1}), depending on the scale of the industrial plant. These results are inferior to those reported in the literature in the cases in which the feedstock considered are residues, but with associated cost, and tend to be greater in comparison with the cases in which biomass does not have cost (e.g. in case of MSW).
- Based on the premises assumed in this case study, production has a good chance of being effectively considered sustainable aviation fuel. However, avoided GHG emissions would have to be estimated specifically for the case of eucalyptus wood production in Brazil. For the other aspects of sustainability, the case study was developed taking into account hypotheses that minimize potential risks.

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

Case study: FT-SPK pathway / eucalyptus

Supplementary Material

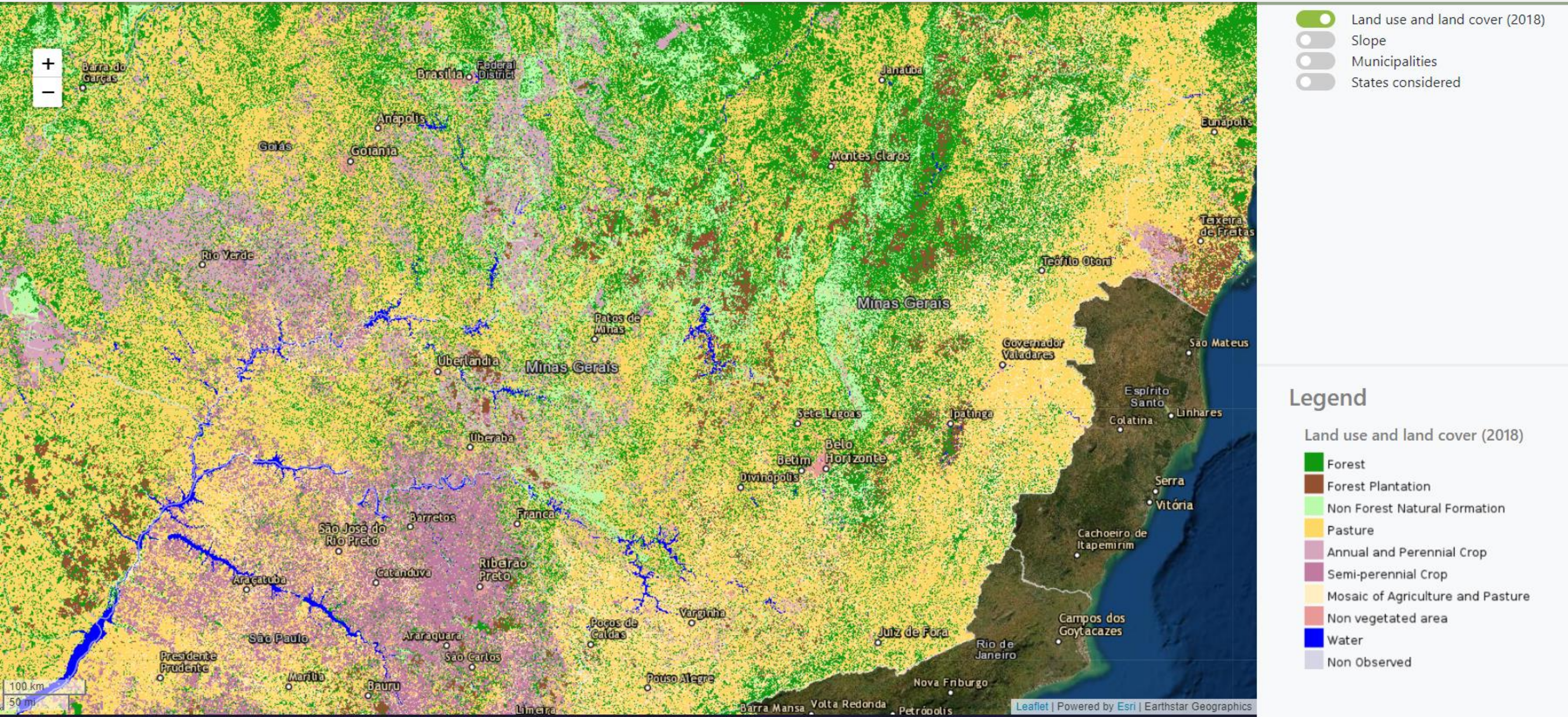
List of Contents

- Land use and land cover;
- Sensitive areas;
- Reported violations to land use and water use rights;
- Suitability of eucalyptus (procedure and results);
- Estimating yields;
- Estimating wood costs: land prices, standing wood, harvesting and transport;
- Industrial parameters;
- Industrial costs;
- Generalized results;
- Jet-fuel prices;
- About CORSIA and eligible fuels.

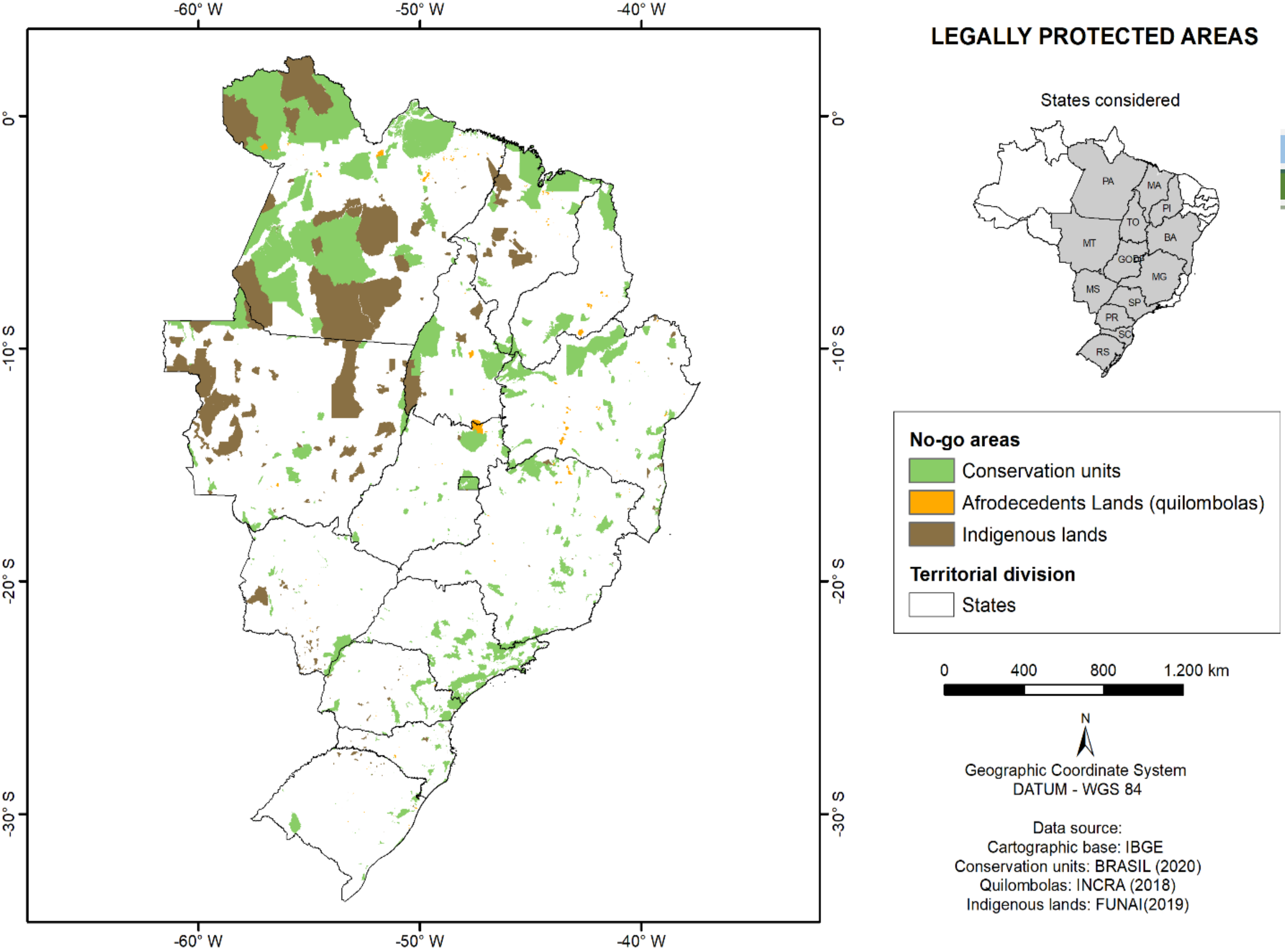
Land use and land cover in 2018

- Figure shows the land use & land cover map available at the database and used in this study.
- Information of land use and land cover available at the database corresponds to 2018. The source is MapBiomas.
- The next slide shows a zoom-in image for São Paulo, Minas Gerais and Goiás.

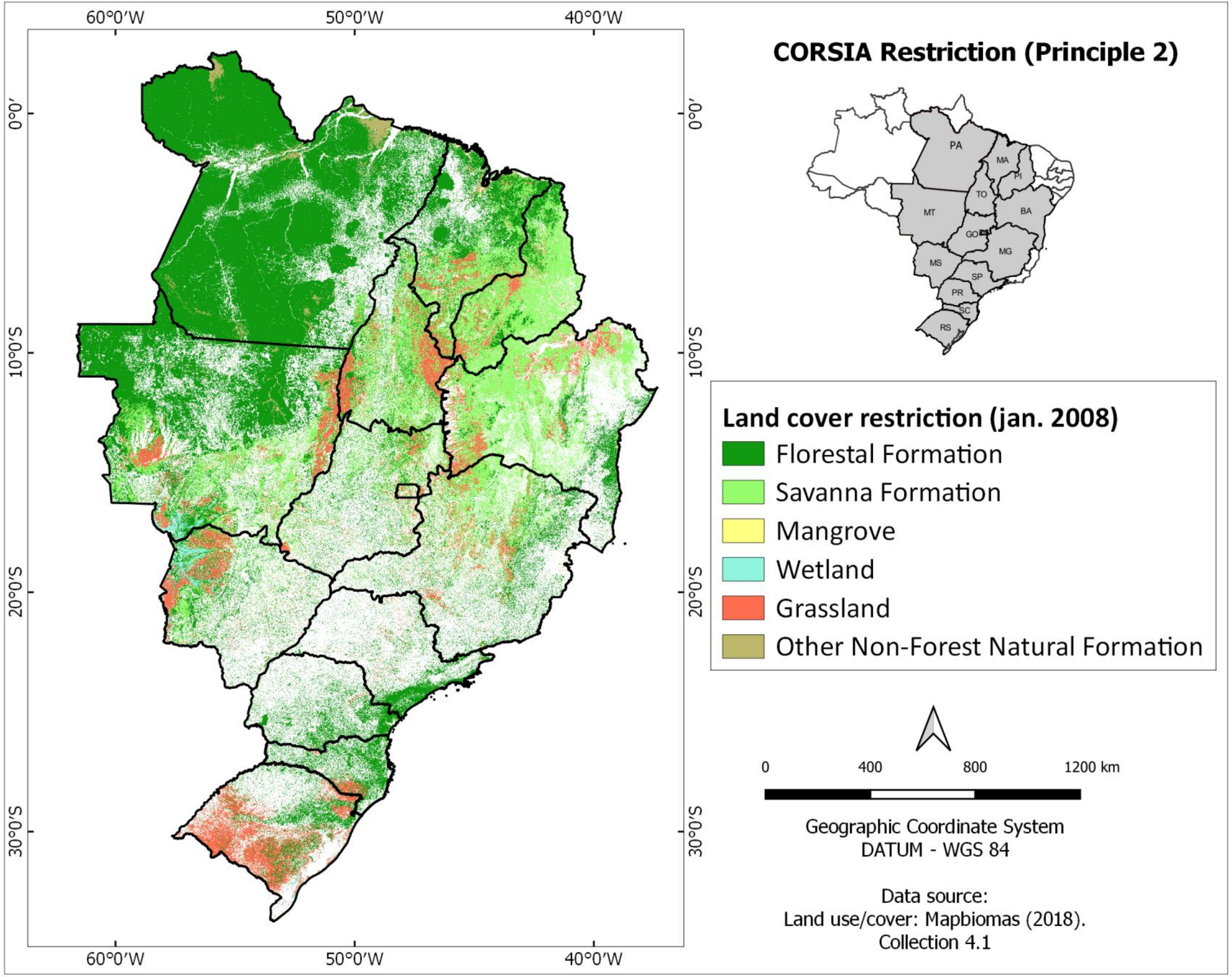
Land use and land cover in 2018 – detailed image for Minas Gerais and Goiás



Sensitive areas (1)

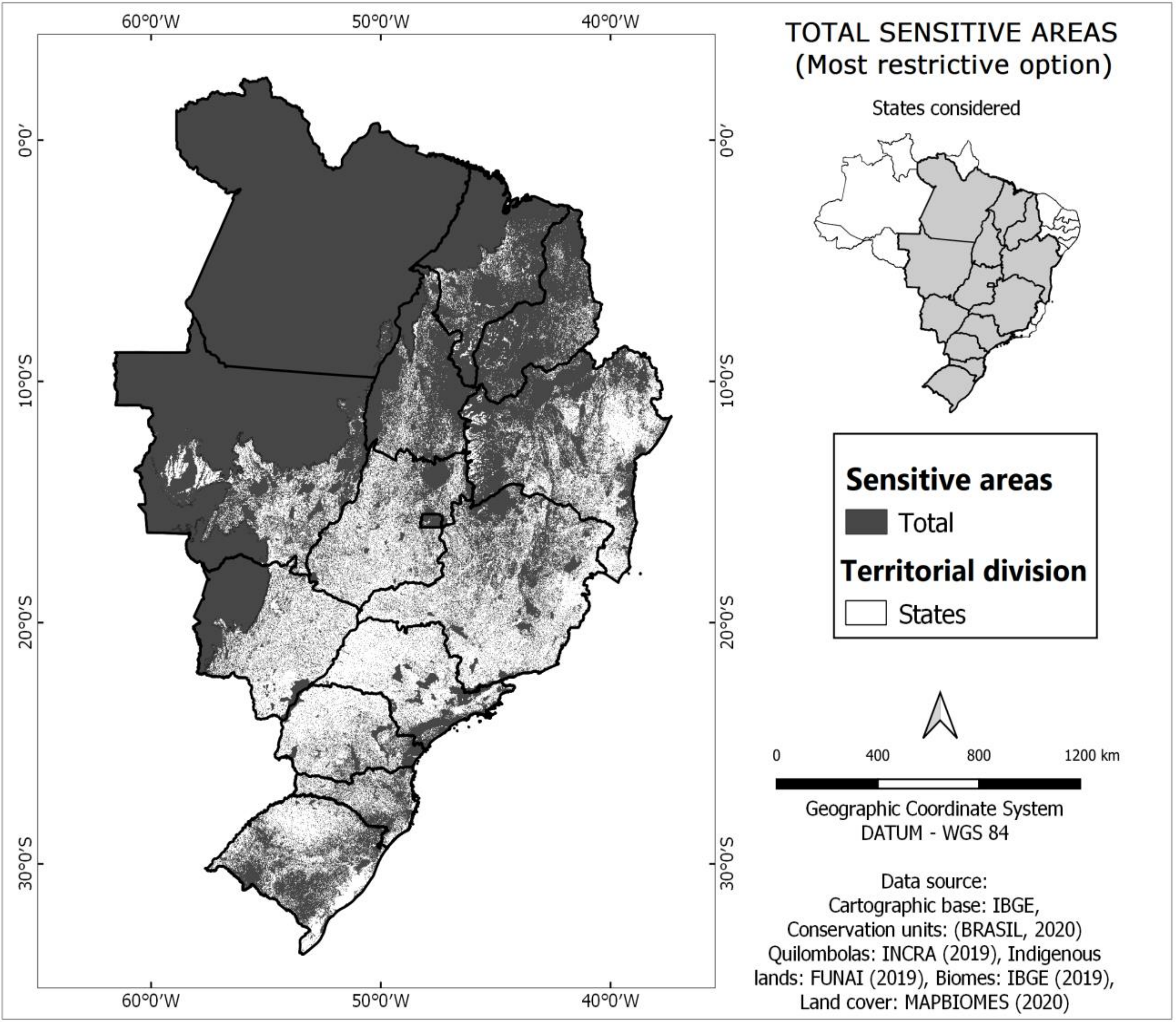


- Feedstock production cannot occur in legally protected areas.
- Legally protected areas include conservation units (for environmental reasons), the land that belongs to Afro-descendants (i.e. quilombola areas, or Afro-Brazilian settlements) and reserves of indigenous peoples.



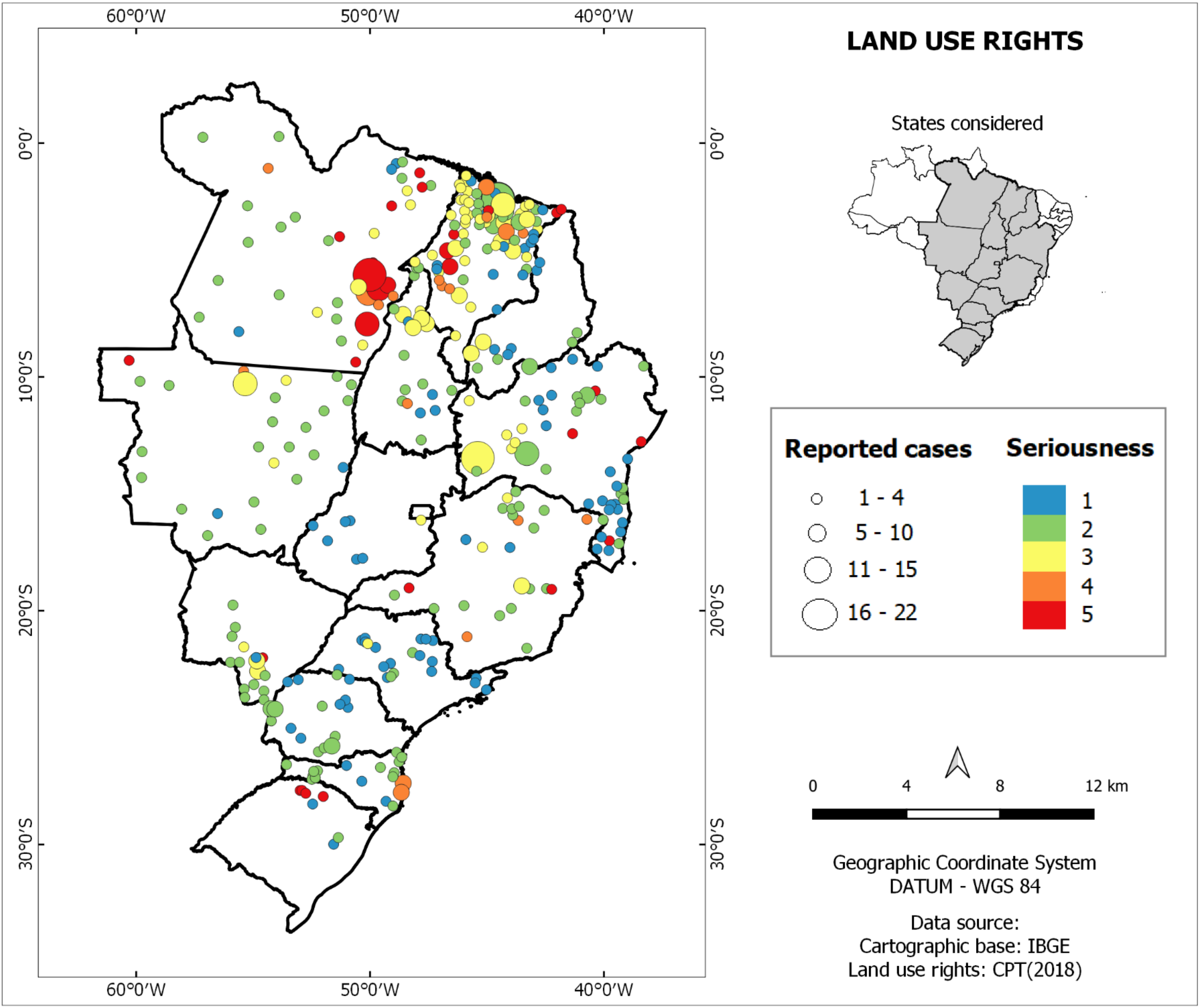
Sensitive areas (2)

- According to CORSIA, SAF cannot be made from feedstocks obtained in certain areas (for example, primary forests, wetlands, etc.) where land was converted after January 1, 2008 (see information about CORSIA).
- In this sense, a map of land uses and land cover by the end of 2007 was used to define - conservatively - areas that should not be used for this purpose.
- The figure shows the areas with natural vegetation in January 2008. Thus, and conservatively, all areas with natural vegetation at that time were excluded.



Sensitive areas (3)

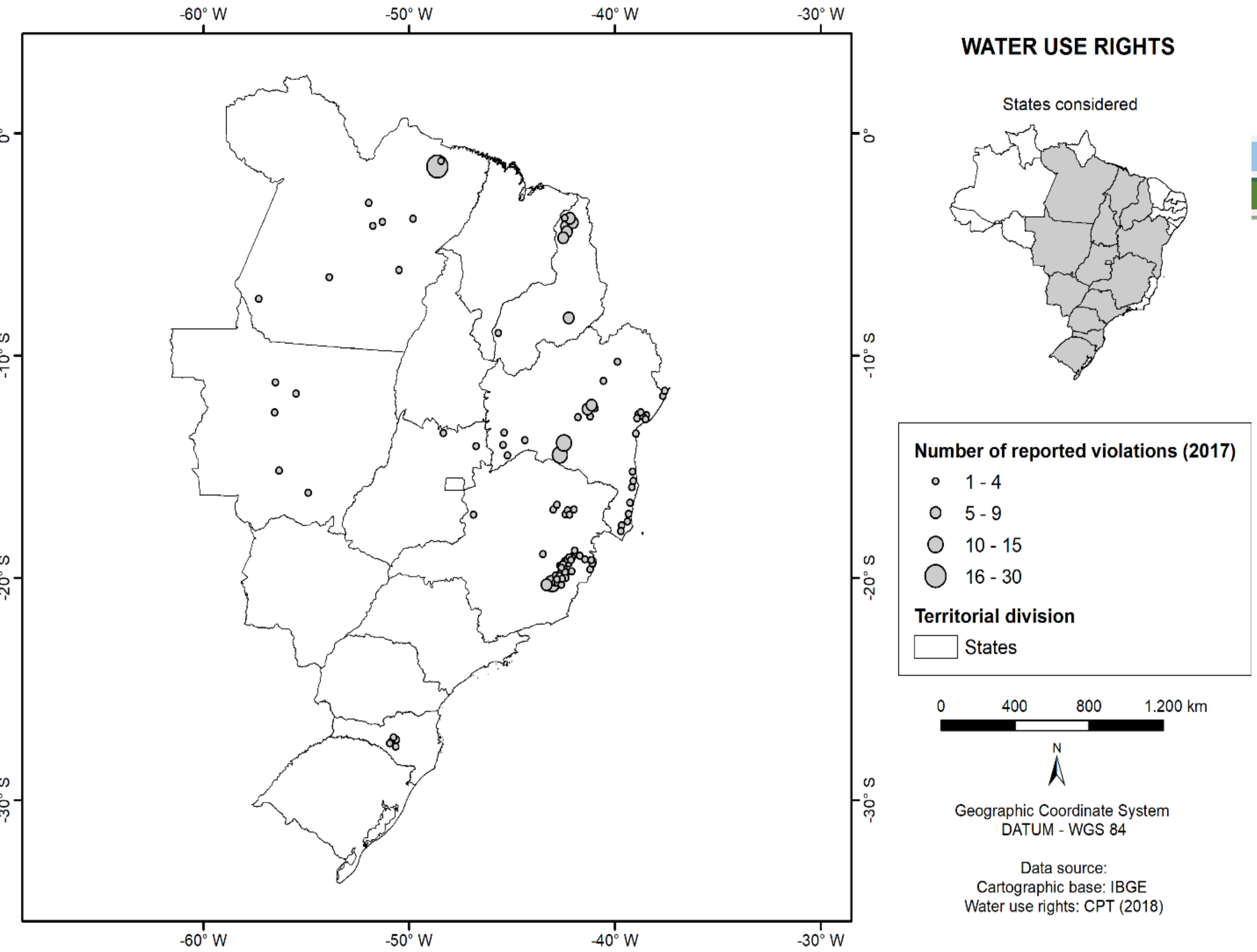
- The figure combines the previous map with areas of the biomes Amazon Forest and Pantanal, which are biodiversity hot-spots.
- In this project, this is the most restrictive option.
- Both maps include, as unusable areas for feedstock production, the lands classified as national parks, areas protected by environmental reasons, indigenous and quilombola areas, etc.



Land use rights

- CPT – Comissão Pastoral da Terra – is an organization linked to the Catholic Church (https://www.cptnacional.org.br/).
- CPT compiles information of reported violations to land use and water use rights.
- The figure shows the locations of reported violations to land use, in the 2016-2018 period.
- Seriousness vary from 1 (e.g. threats) to 5 (e.g. murders); the metric was defined by the authors of this case study. Reported cases is the number of registers in CPT database (in each municipality).

Water use rights

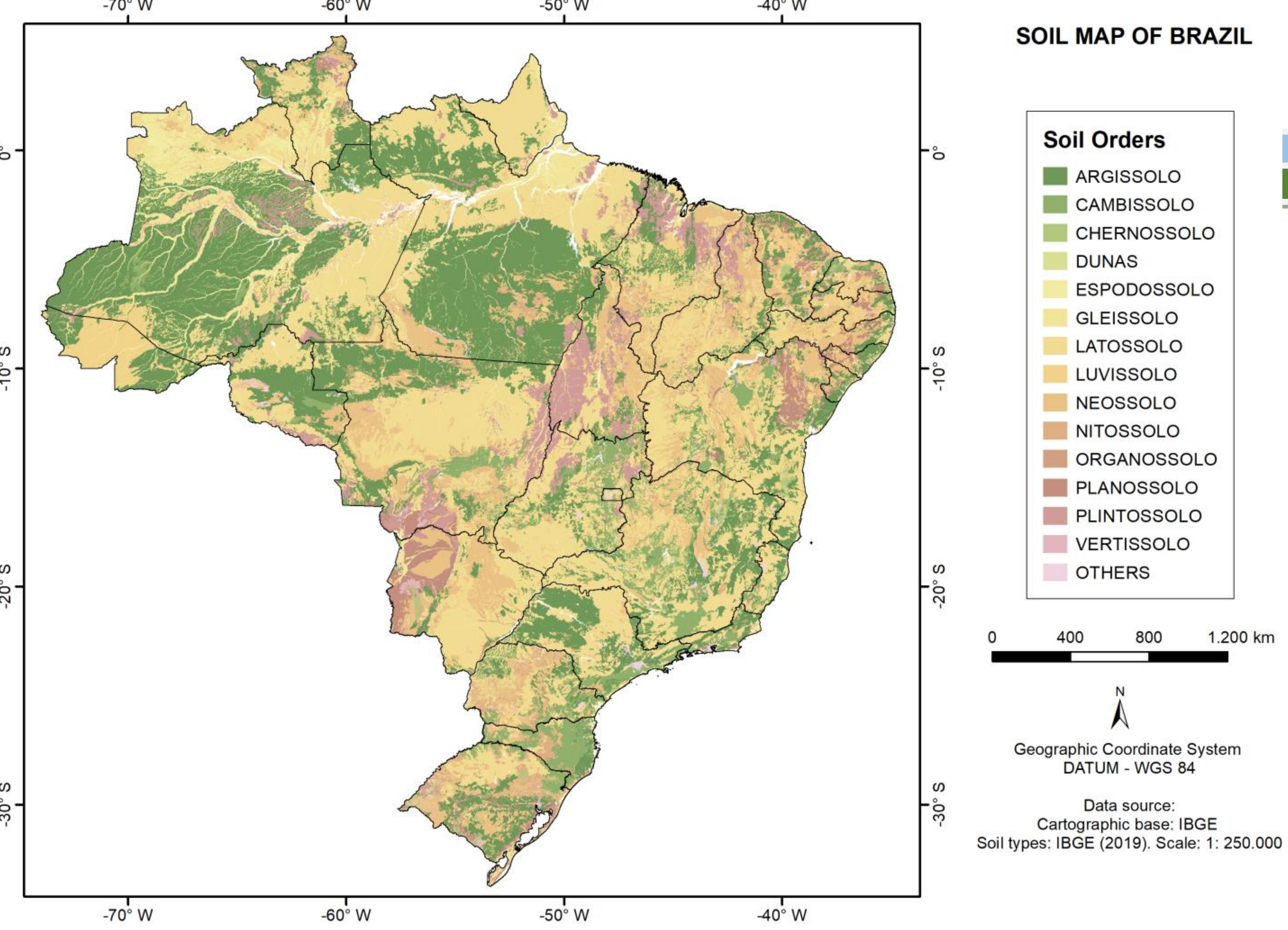


- The distribution of reported violations to water use rights in 2017 is presented in the figure.
- The cases are related to threats, reduced access to water bodies, pollution, destruction of socio-cultural heritage, illegal procedures, etc. Details are available in CPT's database.
- Both for land and water use rights, the reported violations are related to different economic activities.

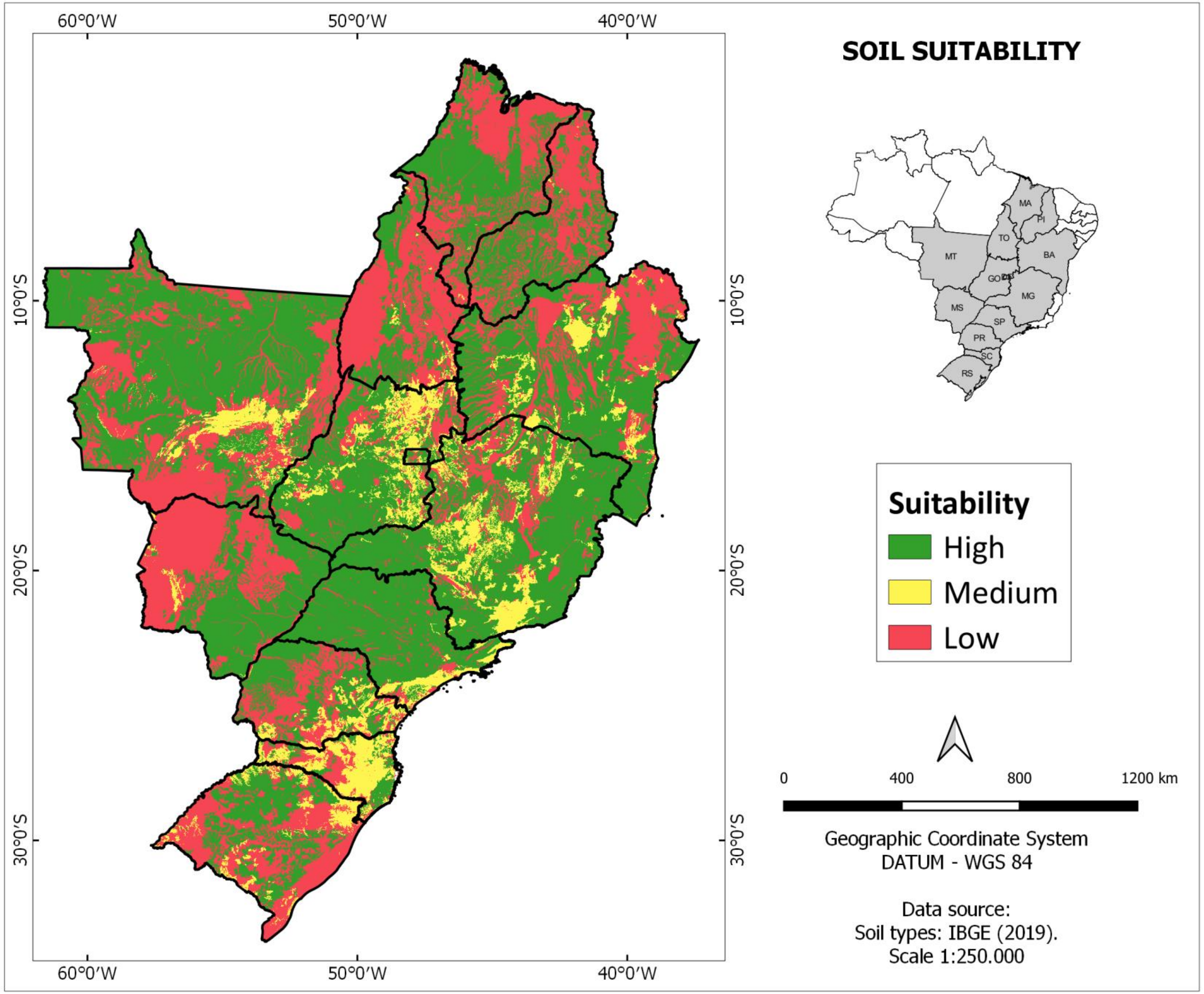
Suitability of eucalyptus

- 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 16.46 $m^3.ha^{-1}.year^{-1}$ (± 4.36), while for the highest yield the average is 35.34 $m^3.ha^{-1}.year^{-1}$ (± 9.43).
- It is mentioned that the minimum productivity that justifies the commercial operation is 15 and 25 $m^3.ha^{-1}.year^{-1}$, respectively for lower and higher yields (Guimarães & Sans, no date). Here, the procedure adopted is based on the hypothesis that eucalyptus would be produced with the best technology available.
- Based on a 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 define the criteria related to precipitation and temperature, and to justify the chosen values and ranges.
- The first validation was against the results presented by Alvares et al. (2013), which are based on modeling plant growth. In a second round, the suitability classification defined here was compared with the results presented by Higa and Wrege (2010) and by Flores et al. (2016).

Soil suitability (1)



- In this project it was used the soil classification presented by IBGE (2019) and the respective georeferenced map (scale 1:250,000).
- Based on the literature, soils were classified according to their suitability for agriculture. The same classification was used for eucalyptus and all other crops assessed in this project.
- As an illustration, the figure shows the map of Brazilian soil classification, elaborated by the authors based on IBGE (2019).
- As an illustration, the table in the next slide presents the classification used according to soils suitability for different crops (the designation of soil types is in Portuguese).



Soil suitability (2)

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

- The resulting soil map used in this project is shown in the figure, for the 12 states considered.

Suitability of eucalyptus – hydric suitability

- Based on Booth and Pryor (1991), two parameters were defined considering the three species took into account in this case study. They are:
- The annual average rainfall, in mm;
- The estimated number of months with water deficit; the deficit was estimated based on the difference between monthly precipitation and potential evapotranspiration (PET) (both in mm). PET was estimated for each municipality and the results included in the database.
- Details of the criteria considered for both parameters and the criteria adopted for classifying areas according to hydric suitability, for eucalyptus, are described in the table.
- A site would be classified as "high" suitability from a hydric point of view when both conditions were matched. When only one condition was matched, the area was classified as "medium", while no conditions matched would mean "low" suitability.

Parameter	Criteria	Comments
Annual rainfall	1,100 > Rainfall > 2,000 mm	Values in this range mean that the local is "high" suitability. The minimum value is presented by Booth and Pryor (1991) for *E. urophylla*, while the maximum one is indicated by the same authors for *E. cloeziana*.
Deficit (# of months)	< 6	The number of months with water deficit must be below 6. Six is the value presented by Booth and 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.

Suitability of eucalyptus – atmospheric temperature

SAFmaps

Parameter	Criteria	Comments
Mean	18°C > T > 27.5°C	To justify the "high" classification, the average annual temperature must be in the range. The range is based on Booth and Pryor (1991) and was defined as a compromise solution, being subsequently adjusted to make the procedure more flexible.
Maximum	< 28°C	The classification as "high" requires an average maximum annual temperature below 28°C. It is a compromise solution taking into account the three different species considered; the limite is higher for *E. cloeziana* and slightly lower for the other two (Booth and Pryor, 1991).
Minimum	> 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 and Pryor (1991) (they present the required absolute minimum) and was adopted to impose some constraint (considering the weather conditions in Brazil).

- Also based on Booth & Pryor (1991), the parameters presented in the table were defined for setting suitability according to the atmospheric temperature. All ranges of temperatures are in °C.
- To be considered "high" suitability it is necessary to fulfil all three conditions presented in the table. With two conditions the classification would be “medium", while with one or no conditions met the classification would be “low”.

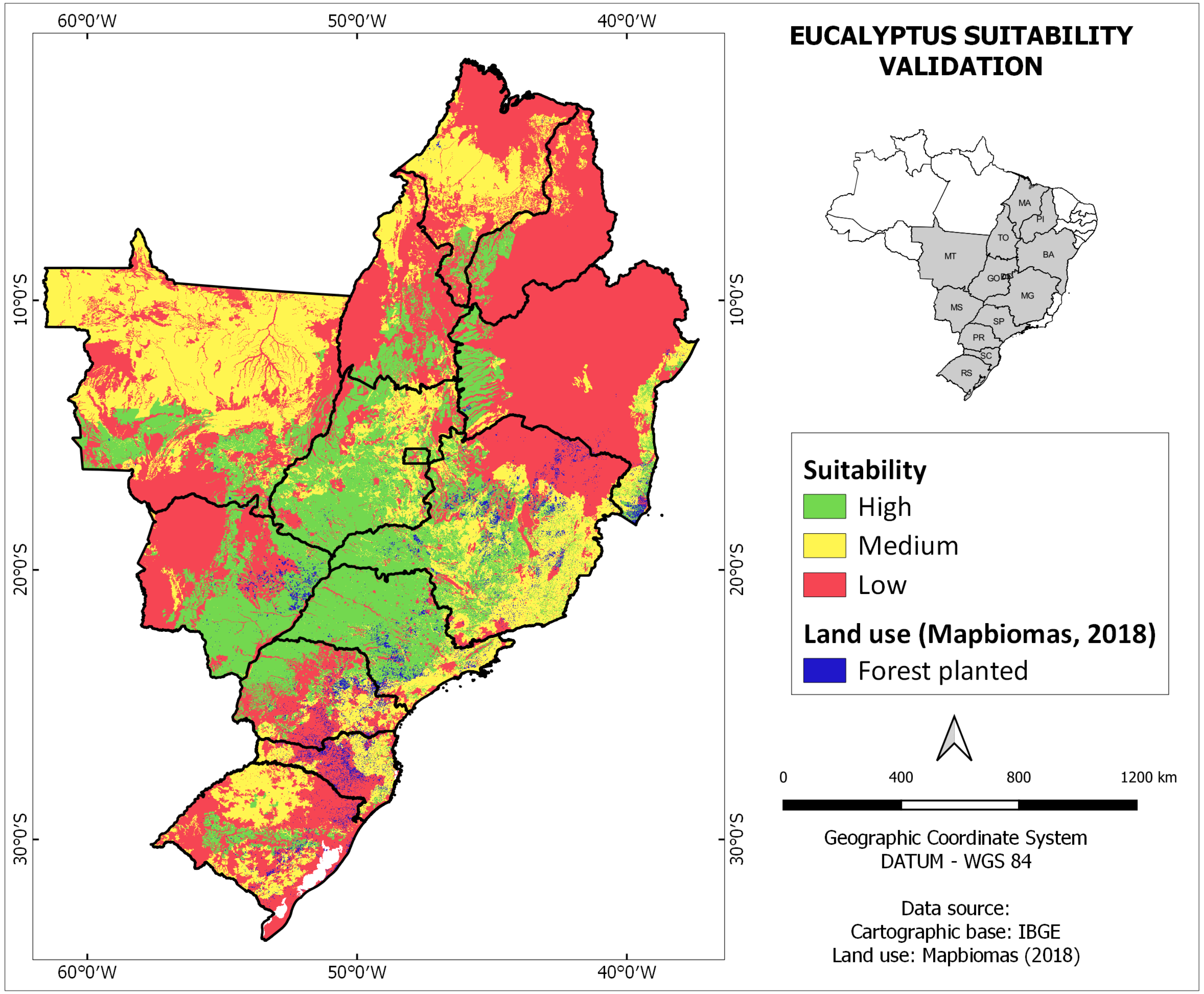
Suitability of eucalyptus – other parameters

- 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]

- In addition, a location would be classified as “high” suitability as long as its altitude is between 50 and 1,500 m above sea level (“low”, 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 altitude value was used for each municipality, when it would be more appropriate to use altimetry curves.

Suitability of eucalyptus – validation



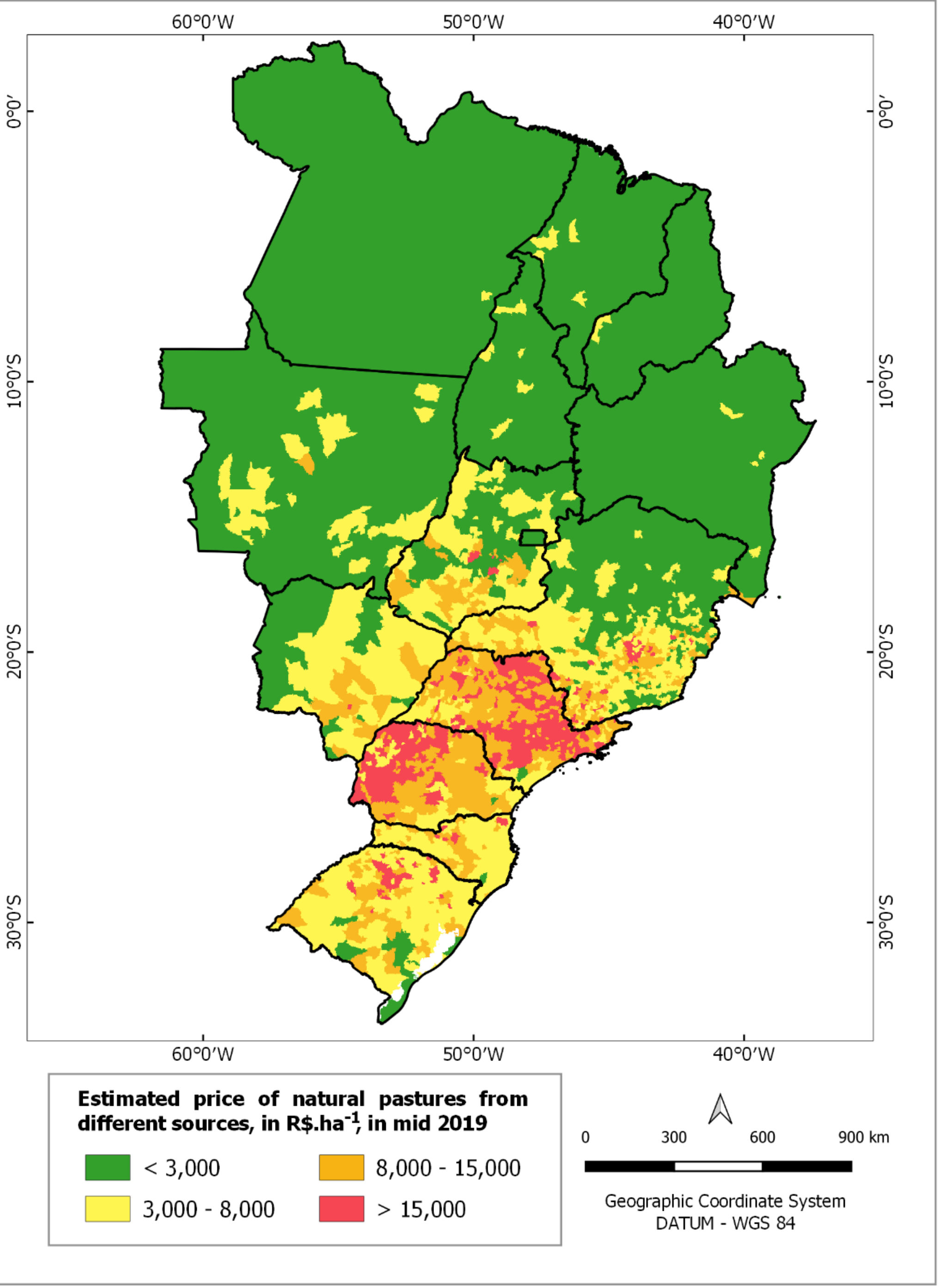
- In order to check the accuracy of the adopted procedure, the results were compared with the maps presented by Flores et al. (2016), for the species *E. grandis*, *E. urophylla* and *E. cloeziana*, and with the agro-ecologic maps presented by EMBRAPA for Paraná and Rio Grande do Sul (Higa and Wrege, 2010). In general, the main trends have been accurately captured. To be more precise, the resulting suitability map for eucalyptus was matched with the map of silviculture registers (planted forests), by MapBiomas, for 2018, as shown in the figure.
- First, it is important to highlight that it is not only eucalyptus plantations that are indicated as blue dots, and other species (e.g. pinus) are more resistance to frost (e.g. see the concentration of blue 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.

Estimating yields

- The table presents the main statistics related with each explanatory variable statistically discernible in the model used for estimating yields.
- All explanatory variables kept in the 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%.
- 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).

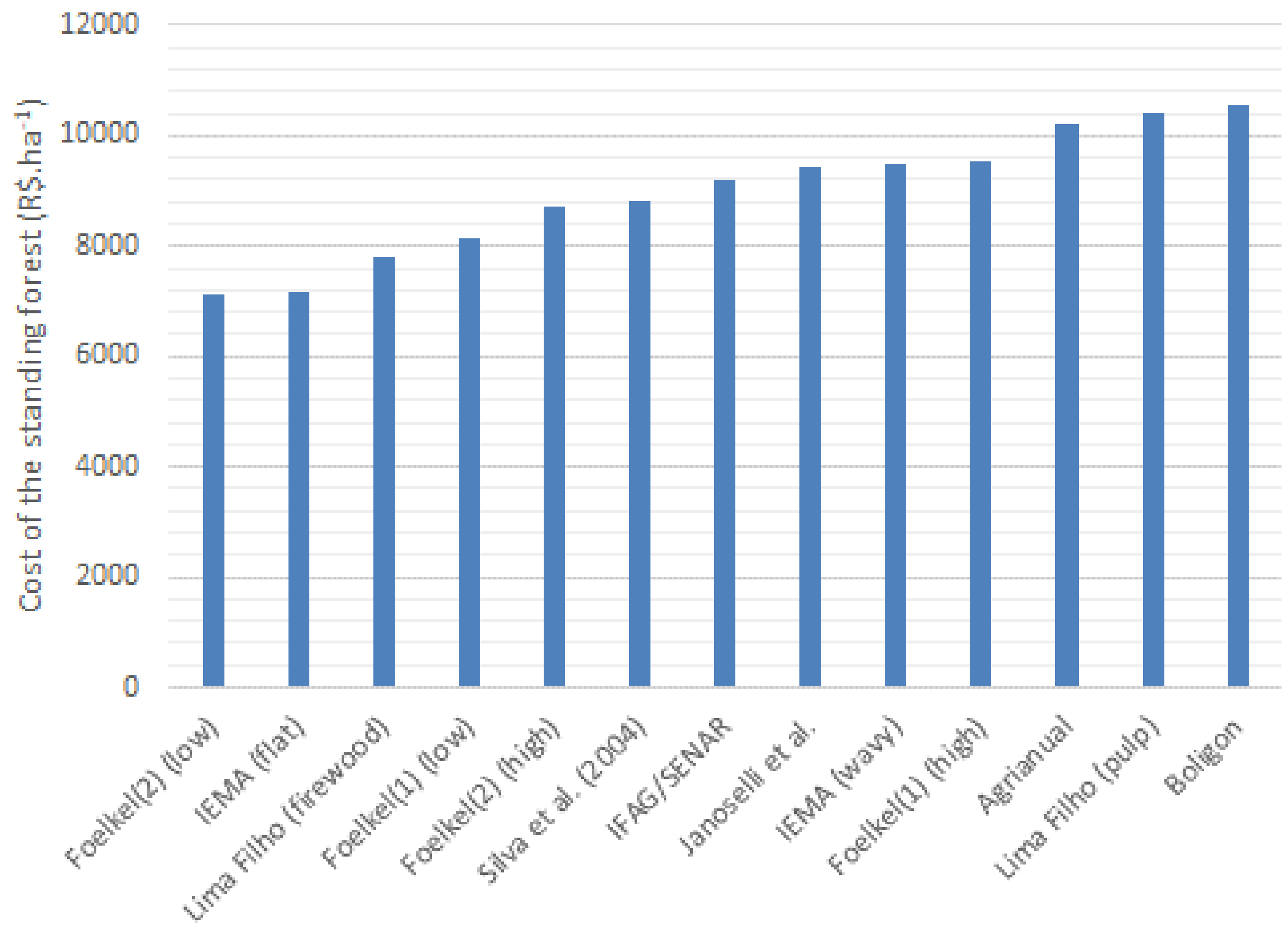
Variable	Coefficients	Standard deviation	Statistics t	P-value
Intersection	-1217.8500	217.8405	-5.5906	2.68E-08
Dummy_soil_high	-18.1288	8.2038	-2.2098	0.02727
Dummy_soil_medium	117.0162	12.7784	9.1573	1.66E-19
Dummy_soil_low	-68.1579	9.7320	-7.0035	3.73E-12
Altitude	0.2268	0.0396	5.7213	1.27E-08
Dummy_rainfall_high	0.0446	0.0048	9.2083	1.06E-19
Dummy-rainfall_medium	-0.0592	0.0086	-6.8665	9.54E-12
Dummy_rainfall_low	-0.0230	0.0064	-3.5661	0.00037
Deficit_water_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

Land prices



- The cost related to leasing land is a component in the procedure for estimating wood costs. The price of land 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 the information is available, (3) for various states, from the Ministry of Economy database, and (4) if necessary, the series was completed with information from INCRA.
- The resulting database was built for six classes of land use, but in this case study only the information for “established pasturelands " was used.
- All prices in the database are in R$ of 2018. For the twelve states assessed in this study, the average price of land in the database is 8,269 R$.hectare^{-1}, but with a high standard deviation (8,903 R$.ha^{-1}).
- The impact of the land price on the cost of wood 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.
- As an illustration, the figure shows the distribution of land prices in 2019, used for livestock (natural pastures).

Estimating wood costs: standing wood



- The figure shows 13 estimates of the cost of implementing and keeping the forest until the moment of harvesting (values in R$ 2018). Costs vary with the technology used and the conditions of the terrain. As mentioned, the median of these values was used in this case study.
- Around Espigão, the estimated costs of standing wood would vary from 27.0 to 27.8 R$.m^{-3} in areas with high or marginal potential yield, and from 29.2 to 32.1 R$.m^{-3} around REVAP, respectively.

Estimating wood costs: harvesting

- Harvesting cost was estimated based on IEMA (2017). Because of the restrictions related to mechanization, and also because of the time required for harvesting, there is a significant difference between flat areas and areas with steep slopes. Original 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 the table), respectively. Thus, in case of flat areas, the cost of cutting can represent about 30% of the cost of harvested wood, or even 65% in case of wavy areas.
- 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 associated costs are presented in the table.

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

Estimating wood costs: transport

- It was assumed that wood transport from the field to the industry would be by truck.
- The distances were estimated from the clusters of wood production to the industry. The distances correspond to the road network available in the database, which was taken from IBGE. Due to the relative inaccuracy of the procedure, a safety factor was applied.
- Once the distance is known, the cost (in R$.$t^{-1}$. km^{-1}) was calculated using the function below, which has been adjusted for different estimates presented by IEMA (2017). The values obtained with this function are equivalent to those presented by Alves et al. (2013), in R$. m^{-3}.km^{-1}, 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.
- Before using the above function, it is necessary to correct the wood density, as it was supposed that wood would be left 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.
- On average, the transport represents about 40% of the CIF wood costs in the cases of wood production with higher yields and in flat areas around Espigão, and 35-37% in the case of REVAP.

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

Industrial parameters (1)

- The assumed industrial parameters are based on de Jong et al. (2015). In the reference 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. Here, four industrial capacities were assessed, being one of them the same considered by de Jong et al. (2015); the other three were: 135, 500 and 1,000 $t.day^{-1}$ of hydrocarbons. 135 $t.day^{-1}$ is roughly equivalent to the predicted capacity of the Red Rock Biofuels plant, which has been built in Lakeview, Oregon, United States.
- The table on the left side summarizes the parameters considered in this case study. The table on the right side presents the factors used to calculate the production of co-products.
- Additional information about the route FT-SPK is presented in the next slide.

Parameter	Value	Unit
Annual capacity factor	90	%
Number of days in the year	365	days
Output/Input (mass basis)	0.17	$t.t^{-1}$ (FT liquid/dry wood)
Bio-jet fuel/FT liquids (mass basis)	0.15	$t.t^{-1}$ (SAF/FT liquids)
Bio-jet fuel density	0.804	$t.m^{-3}$
Bio-jet fuel LHV	42.8	$MJ.kg^{-1}$
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	$MJ.kg^{-1}$

Co-product	Factor	Unit
Diesel oil	0.657	$t.t^{-1}$ (diesel/FT liquids)
Naphtha	0.193	$t.t^{-1}$ (naphtha/FT liquids)
Surplus electricity	0.015	$MWh.GJ^{-1}$ of input

Industrial parameters (2)

- The technology that was considered is based on a directly-heated, fluidized bed gasifier, pressurized, with oxygen injection. The subsequent Fischer-Tropsch (FT) process would allow the conversion of the resulting gas into hydrocarbons. It was assumed that bio-jet fuel (0.15 tonne per tonne of FT liquids), diesel (0.657 $t.t^{-1}$) and naphtha (0.193 $t.t^{-1}$) 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.
- The main reference for the technology is the FT process modeled by Zhu et al. (2011) that originally targeted at FT Diesel (naphtha as co-product); it is assumed 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 surplus power.

Industrial costs (1)

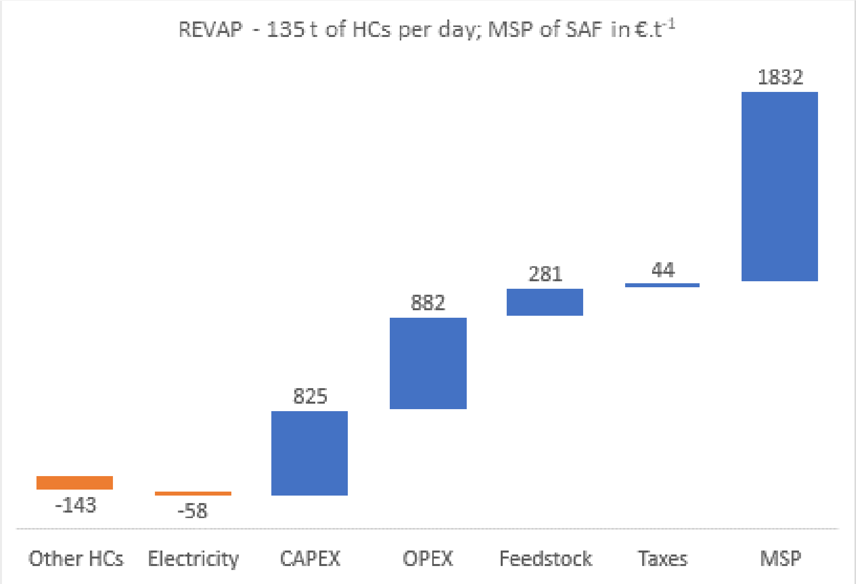
- The capital costs (CAPEX) taken by de Jong et al. (2015) from the literature were analysed and them they defined that the total purchase equipment cost (TPEC) of the n^{th} plant (reflecting learning effects) would be equal to 96 million Euro, resulting 471 million Euro as the total cost investment (TCI). These costs were originally expressed in Euro 2013, and here the Chemical Engineering Plant Cost Index (CEPCI) was used to convert the original 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. First, the CAPEX presented by de Jong et al. (2015) was compared with the values presented by Carvalho (2017), who has considered four industrial capacities for a biomass gasification + FT synthesis plant. 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 presents OPEX costs, and these, in annual basis, were estimated at 10% of the CAPEX. Thus, this percentage was taken as the first reference and then adjusted (a slight increase) in order to have a final result compatible with those presented by Jong et al. (2015).

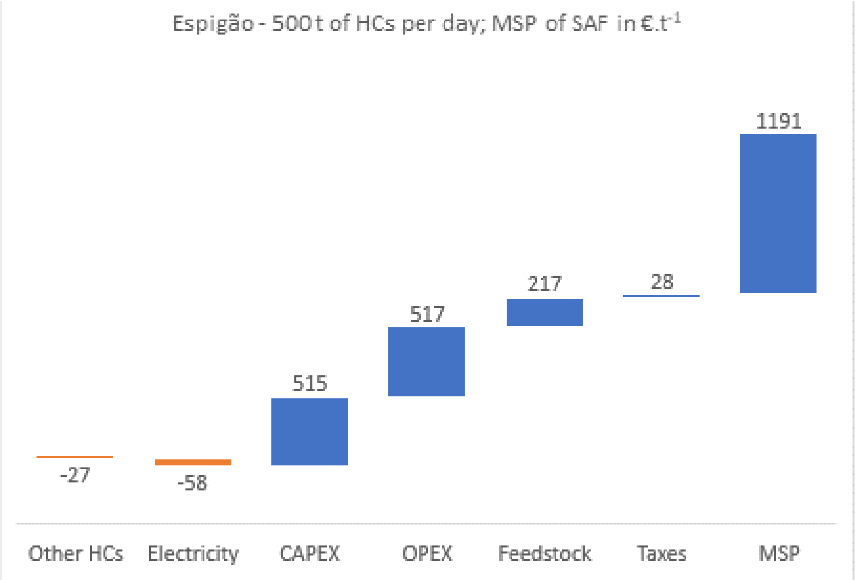
Industrial costs (2)

- 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 the table below.

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%

Industrial costs (3)





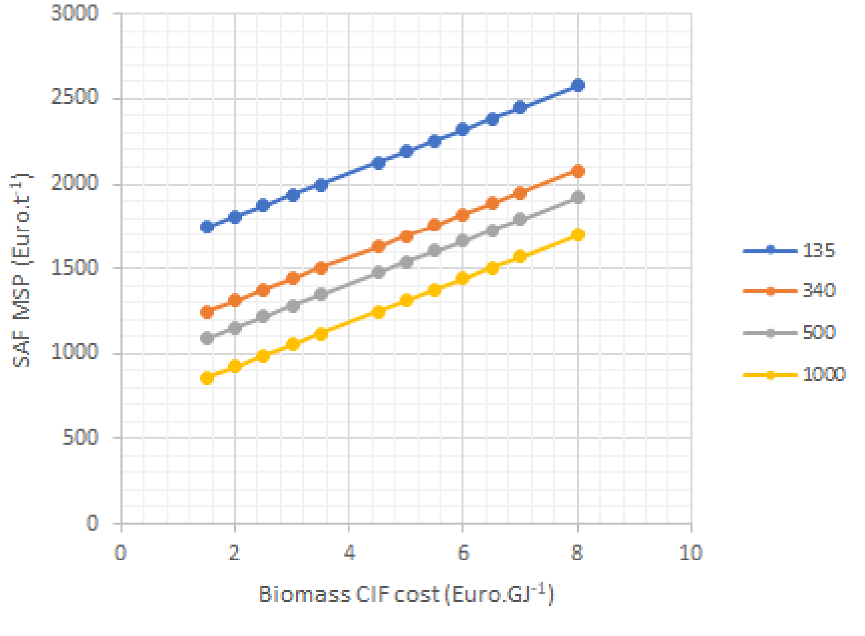
- Coherent to the cases assessed by de Jong et al. (2015), here the MSP of SAF was estimated both for co-locating (e.g. the production in an oil refinery or in a pulp mill) and for greenfield industrial plants. The authors estimate that the MSP would be 4-8% higher for greenfield production than in the case of co-locating plants. Here both the estimates for CAPEX and OPEX were increased by 5.5% in the case of greenfield plants in order to reflect the higher costs.
- Surplus electricity (0.015 $MWh.GJ^{-1}$ of input) could be sold and the revenue was considered in the estimate of the MSP of FT fuels; here, the rate considered was 30 $€.MWh^{-1}$.
- As an illustration, the figures show the components of the MSP of SAFs. In the REVAP case, feedstock represents 15.4% of the MSP, while the feedstock share is 18.2% in the Espigão case (note that these results are for a larger industrial plant).

Synthesis of results

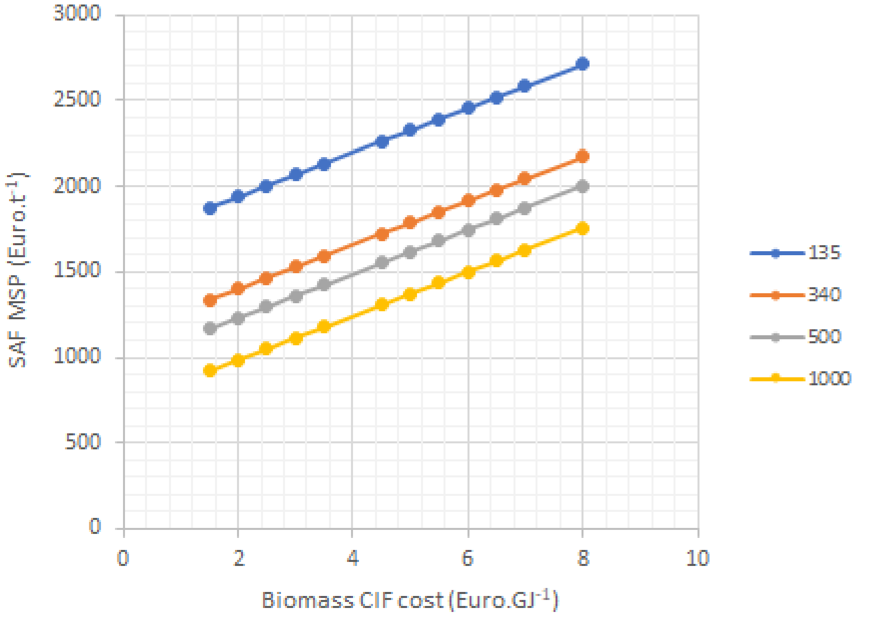
- Industrial capacities are defined in tonnes of FT liquid fuels to be produced per day, being the production of bio-jet fuels (SAF) equivalent to 15% of the total liquids production. 340 and 500 $t.day^{-1}$ are capacities mentioned by de Jong et al. (2015), that is the main reference for the economic analysis. On the other hand, 135 $t.day^{-1}$ is more representative of pioneer projects, and 1,000 $t.day^{-1}$ was here defined to explore scale effects. The annual production is based on the hypothesis of operating with a 90% annual capacity factor.
- Table presents a summary of the results of the two case studies related to the route FT-SPK from eucalyptus.

Industrial capacities		Industrial production of SAF			Production @ REVAP (Co-locating)		Production @ Espigão (Greenfield)	
$t.day^{-1}$ of FT liquids	$t.day^{-1}$ of SAF	$t.year^{-1}$	$m^3.year^{-1}$	$TJ.year^{-1}$	$€.t^{-1}$	$€.GJ^{-1}$	$€.t^{-1}$	$€.GJ^{-1}$
135	20.3	6,652	8,274	285	1,832	42.8	1,896	44.3
340	51.0	16,754	20,838	717	1,340	31.3	1.360	31.8
500	75.0	24,638	30,644	1,054	1,188	27.8	1,192	27.8
1,000	150.0	49,275	61,287	2,109	971	22.7	952	22.2

Generalized results



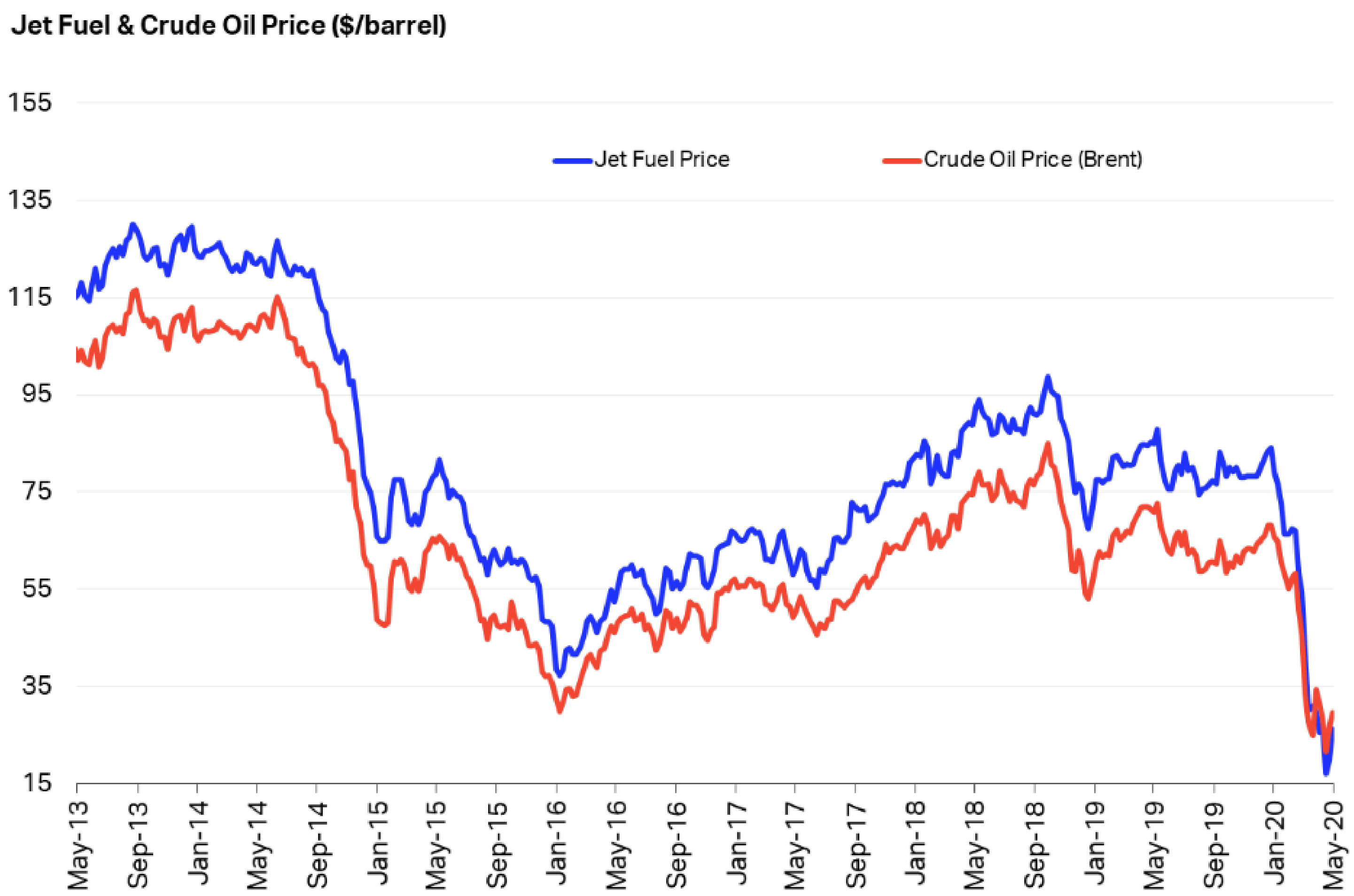
MSP of SAF – FT-SPK route, co-locating plants



MSP of SAF – FT-SPK route, greenfield plants

- Estimates of the MSP of SAF production through the route FT-SPK are presented in the figures, as function of the CIF cost of the feedstock at the industrial plants, and also as function of production of hydrocarbon liquids, in $t.day^{-1}$.
- For the same feedstock cost and for the same industrial capacity, the MSP is higher for the greenfield plants. In the cases illustrated in both figures, the difference varies from 3.2% to 7.7%. The difference is smaller the higher the cost of the feedstock and the greater the industrial capacity.
- It is worth to remember that all industrial parameters (e.g. costs and efficiencies) correspond to estimates for the n^{th} plant, based on de Jong the al. (2015).
- Assuming that the target in the future would be the production of SAF with MSP not exceeding 1,000 $€.t^{-1}$, and assuming that it will be difficult to have feedstock CIF costs below 1.5 $€.GJ^{-1}$, it is clear that a possible solution is to have industrial capacities of approximately or even greater than 1,000 t of hydrocarbon liquids per day.
- Given the advantage of co-locating units, and also considering the convenience of production close to airports, since the availability of cheap wood is less close to these locations, one of the objectives in the decision-making process would be to reduce the cost of transportation from wood to industrial units (for example, by train). This option was not explored in this case study.

Jet fuel prices: historical data and worldwide variations



Source: Platts, Datastream

https://www.iata.org/en/publications/economics/fuel-monitor/

- The figure reinforces the common understanding that aviation fuel prices are strongly correlated to international oil prices.
- Table below shows, as an illustration, the jet fuel average prices in different regions, in May 15, 2020 (the smallest value in many years).

Region	US$.barrel^{-1}	US$.t^{-1}
Global average	30.38	239.84
Asia & Oceania	29.47	232.84
Europe & CIS	28.49	224.50
Middle East	25.72	202.93
Africa	25.72	202.93
North America	32.75	258.73
Latin America	34.13	269.63

CORSIA and eligible fuels

- CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) is a global market-based measure scheme adopted by ICAO Assembly, in 2016, aiming to address the increase of GHG emissions from international aviation.
- 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 according sustainability.
- In the CORSIA pilot phase, the two principles (and their criteria) that must be met are presented in the table.

Theme	Principle	Criteria
1. Greenhouse Gases (GHG)	Principle: CORSIA eligible fuel should generate lower carbon emissions on a life cycle basis.	Criterion 1: CORSIA eligible fuel shall achieve net greenhouse gas emissions reductions of at least 10% compared to the baseline life cycle emissions values for aviation fuel on a life cycle basis.
2. Carbon stock	Principle: CORSIA eligible fuel should not be made from biomass obtained from land with high carbon stock.	Criterion 1: CORSIA eligible fuel shall not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peat lands and/or contributes to degradation of the carbon stock in primary forests, wetlands, or peat lands as these lands all have high carbon stocks.
		Criterion 2: In the event of land use conversion after 1 January 2008, as defined based on IPCC land categories, direct land use change (DLUC) emissions shall be calculated. If DLUC greenhouse gas emissions exceed the default induced land use change (ILUC) value, the DLUC value shall replace the default ILUC value.

Source: ICAO (2019)