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

Case study: ATJ pathway / ethanol from sugarcane and corn

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Executive summary

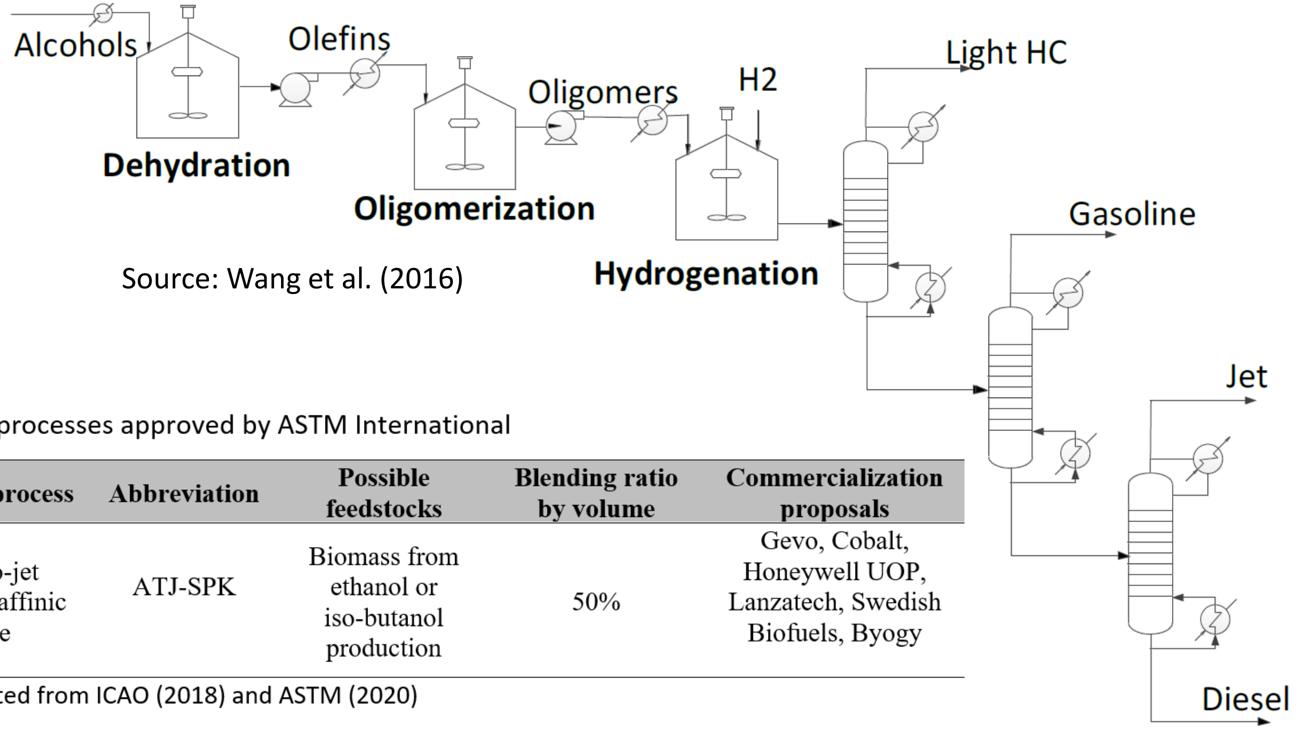
- In this project the case studies were developed with the aim of illustrating the use of the information available in the platform database to evaluate the potential of SAF (sustainable aviation fuel) production in Brazil. It is not possible to draw definitive conclusions based on the results obtained, 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 ATJ-SPK route, considering ethanol production from sugarcane and sugarcane plus corn. It was considered three variants: the use of ethanol produced in 2018 in some specific mills, the possibility of enlarging ethanol production (e.g. due to improving sugarcane yields), and new units of ethanol production, based on sugarcane and corn. In all cases it was considered SAF production at REPLAN, an oil refinery located in Paulínia, São Paulo state. In most of the cases it was explored the possibility of transporting ethanol through a pipeline or by railway.
- The estimated minimum selling price (MSP) varies between 855-1293 €.t^{-1} of SAF (or from 20 to 29 €.GJ^{-1}), depending on the hypotheses of setting value to ethanol. In the lowest value case it was considered self-dedicated production of the feedstock and ethanol, and in the highest one it was considered market prices (in 2018).
- Based on the premises considered in this case study, production of SAF from the ATJ-SPK route, in Brazil, has a good chance of being effectively considered sustainable aviation fuel. Avoided GHG emissions were estimated at 63% in the case of production from sugar cane ethanol, but avoided emissions would have to be estimated specifically for the case of ethanol production from sugarcane and corn. For the other sustainability aspects, the case study was developed taking into account that the potential risks would be minimized as much as possible.

Summary

- About the pathway;
- About ethanol production in Brazil;
- Sugarcane & corn in Brazil;
- Database of ethanol producing units;
- Cases studied;
- Methodology;
- Sugarcane – background information: suitability, yields and costs;
- Corn – background information: suitability, yields and costs;
- Results, analysis & comparisons;
- Conclusions;
- References;
- Supplementary Material.

About the pathway (1)

- The conversion routes based on biogenic alcohols are referred as “Alcohol-to-Jet”-processes (ATJ).
- ATJ fuel can be produced from alcohols such as methanol, ethanol, butanol and long-chain fatty alcohols (Wang et al, 2016).
- A scheme of the process is presented in the beside figure. The main steps are alcohol dehydration, oligomerization, and hydrogenation.
- The necessity of high-purity ethanol is uncertain, but here it was only considered the use of anhydrous ethanol.
- The route ATJ-SPK (Synthetic Paraffinic Kerosene) was approved by ASTM D7566 in 2011.



Source: Wang et al. (2016)

Conversion processes approved by ASTM International

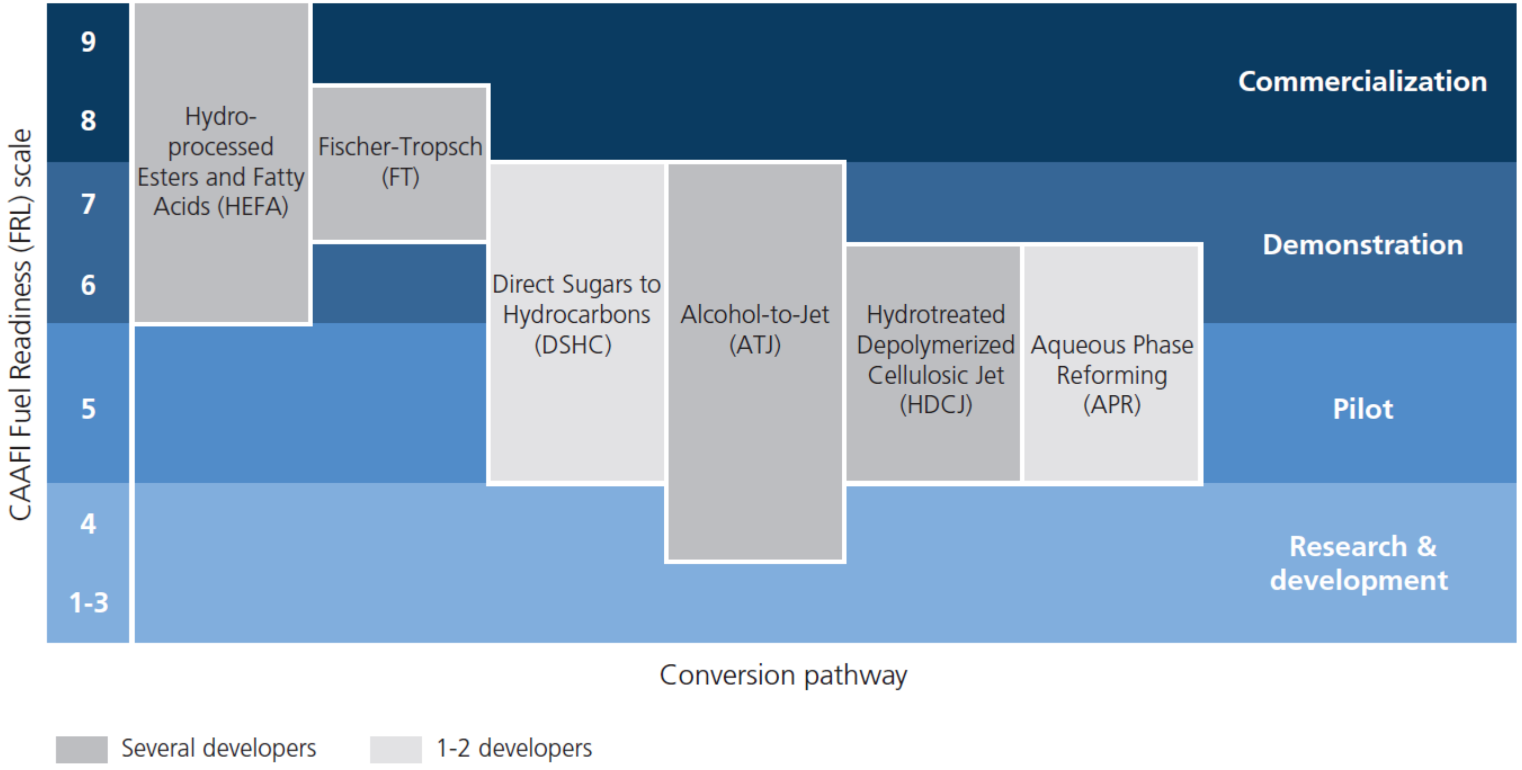
Conversion process	Abbreviation	Possible feedstocks	Blending ratio by volume	Commercialization proposals
Alcohol-to-jet synthetic paraffinic kerosene	ATJ-SPK	Biomass from ethanol or iso-butanol production	50%	Gevo, Cobalt, Honeywell UOP, Lanzatech, Swedish Biofuels, Byogy

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

- Some companies that are investing in the route ATJ-SPK (from different feedstocks for ethanol production) are listed in the table above. Prussi et al. (2019) states that ATJ-SPK has been supplied for commercial flights, and highlight the experience by GEVO (2019).

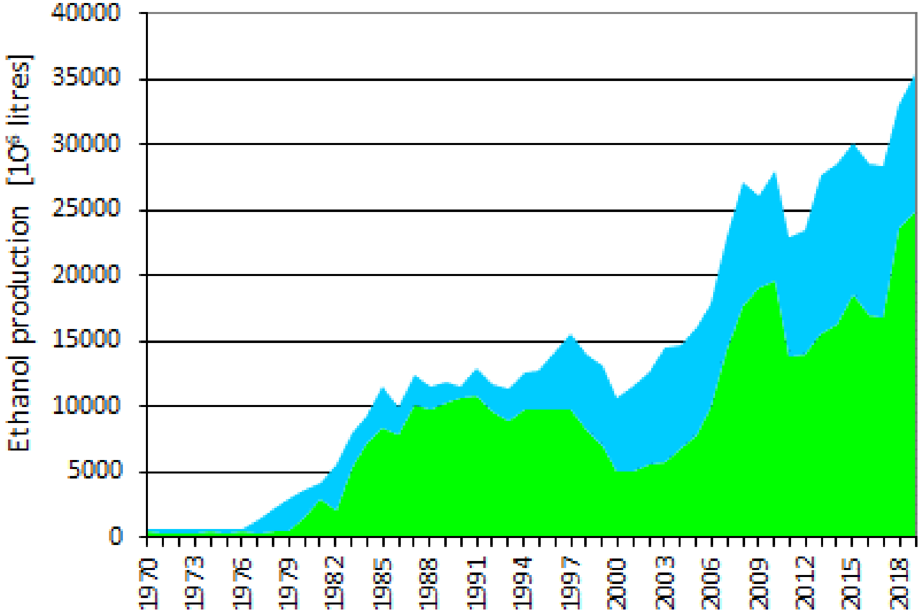
About the pathway (2)

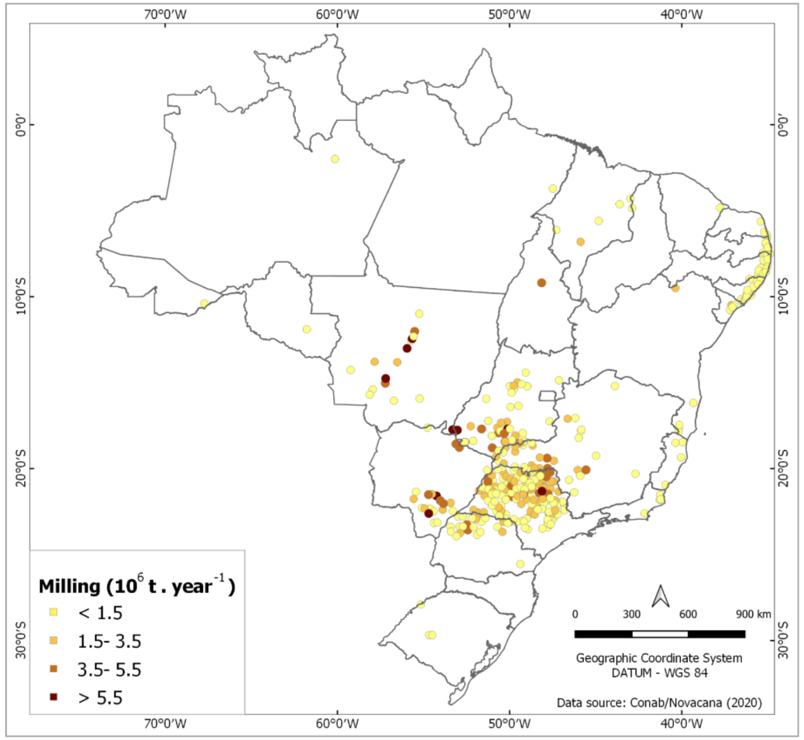
- The figure, extracted from de Jong et al. (2017) is a representation of CAAFI's (Commercial Aviation Alternative Fuels Initiative) Fuel Readiness Level Scale (FRL). It is based on NASA's Technology Readiness Level (TRL) scale and is intended to provide a classification to describe the progress of a 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).



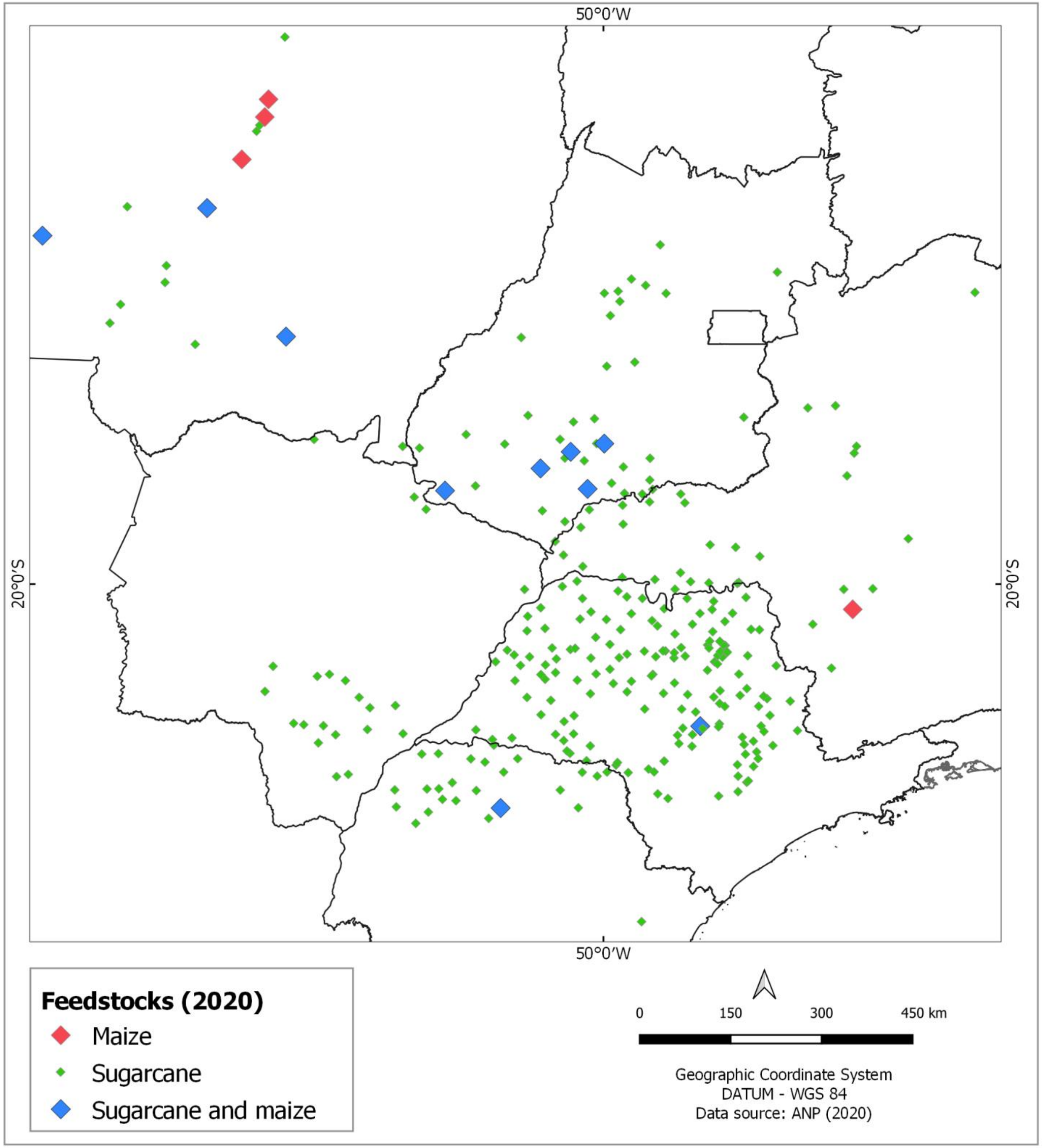
- The figure is not exhaustive, as more pathways have being considered for the production of SAF.
- Similar analysis is provided by Prussi et al. (2019). For the route FT-SPK, the authors present the Readiness Technology Level (RTL) at 6-8, as defined by the EU HORIZON Work Programme 2016-2017 (2019), and the FRL at 6-7, defined as mentioned above.

Ethanol production in Brazil



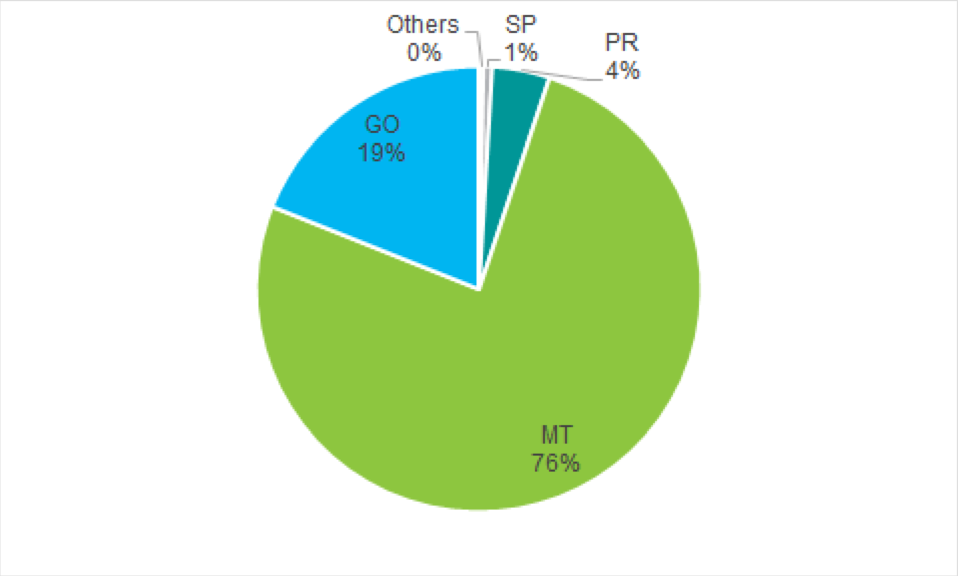


- The upper figure shows the evolution of fuel ethanol production in Brazil from 1970 to 2019. The blue area indicates anhydrous ethanol (blended with gasoline) while green area indicates hydrated ethanol (a competitor of gasoline).
- The two moments of fastest growth of ethanol production were in the 1970s and early 1980s, due the Brazilian Alcohol Program (PROALCOOL), and from 2003 to 2008, with the advent of flex-fuel vehicles.
- Until recently all fuel ethanol was produced from sugarcane, but since recently there is also commercial production from corn. Out of 35.3 billion litres of ethanol produced in 2019, 1.7 GL was produced from corn. The use of corn as feedstock is growing.
- The second figure shows the location of sugarcane mills; the mills were classified according to their installed milling capacity (in million tonnes por year). There is large concentration in Southeast and Northeast, being those in Southeast more efficient, while the newest (and most of the largest) are in the Centre-West.



Ethanol production from corn

- The beside figure shows the location of the ethanol producing units in Centre-West and Southeast-South Brazil, according to the feedstock.
- So far, the ethanol production from corn is concentrated in two states (MT and GO), where it is the bulk of corn production as second crop (mostly associated with soy).
- The ethanol production from corn reached 2.7 x 10^9 litres in 2020 (until August), i.e. a 60% growth regarding the previous year.



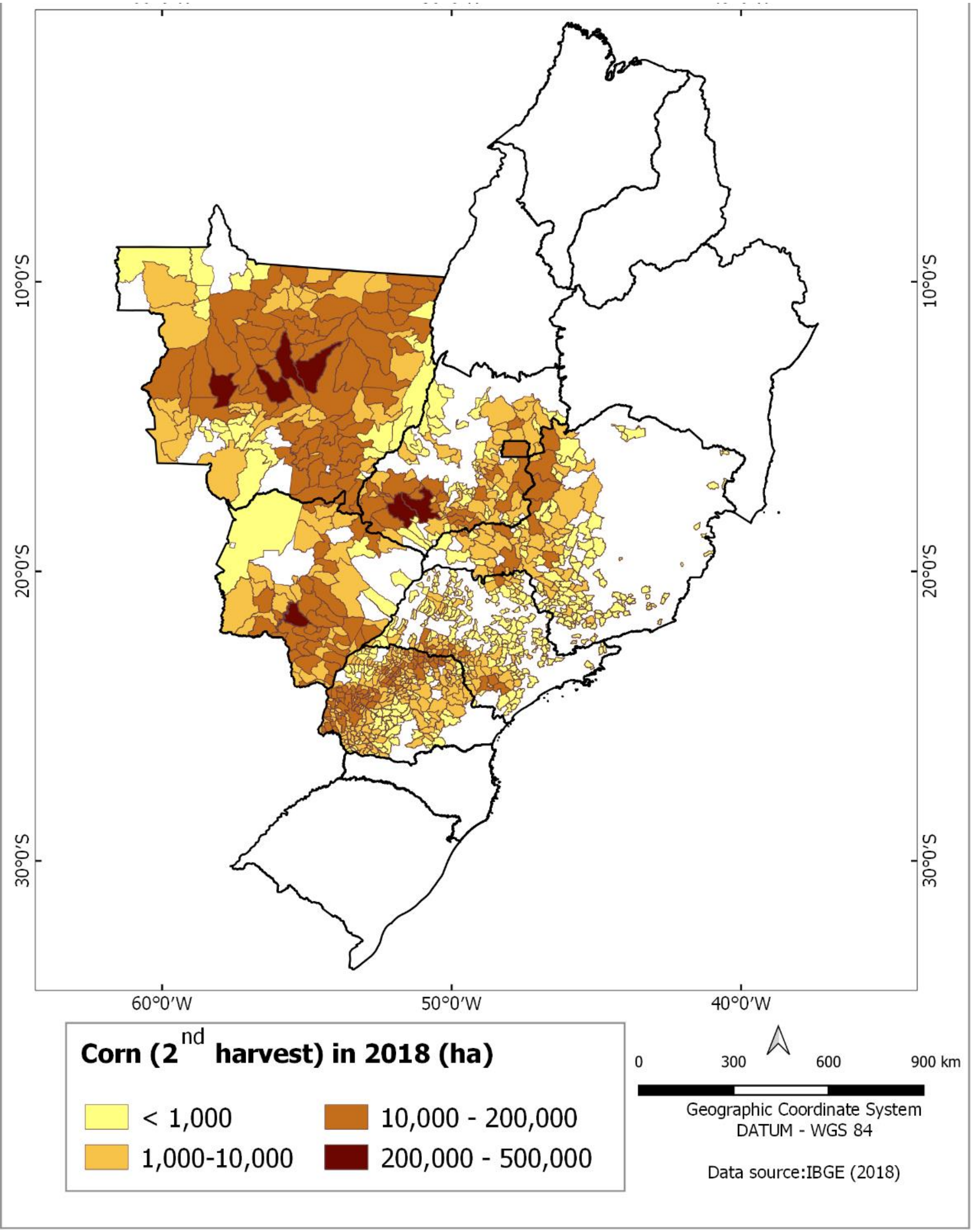
Sugarcane in Brazil

Satellite image of sugarcane fields in countryside São Paulo
Source: Google

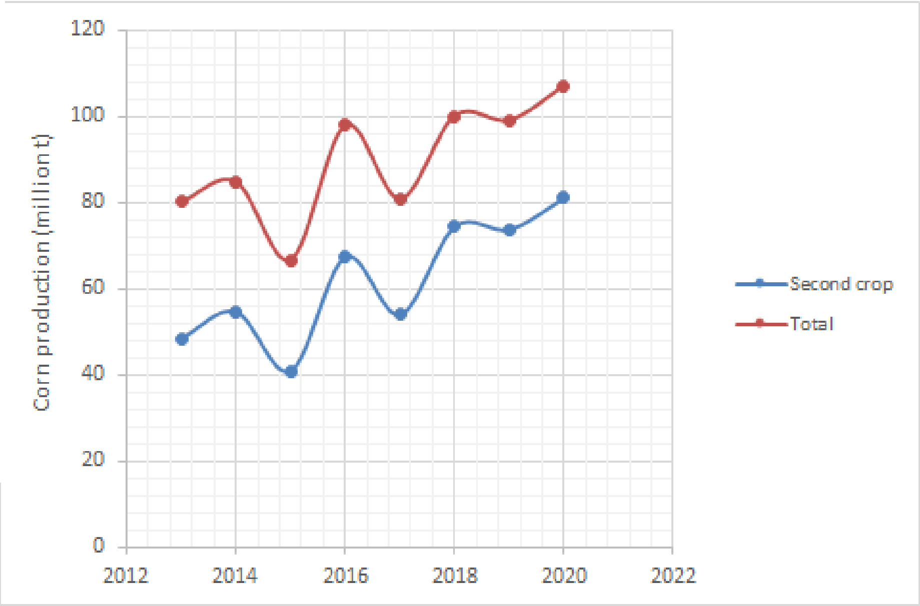
Sugarcane mechanical harvesting
Source: Canaoeste

- Sugarcane is a traditional crop in Brazil and its main uses are related to sugar and fuel ethanol production.
- In 2018, according to IBGE (2020) the total harvested area was slightly larger than 10 million hectares, with the production of 746.8 million tonnes (for different uses). Only considering the use of feedstock for sugar and ethanol production, these figures were 8.4 million hectares and 642.7 million tonnes (CONAB, 2020).
- The bulk of the production for sugar and ethanol is in state of São Paulo (more than 50%). The Centre-West region is the new producing area, and state of Goiás is already the second largest producer in the country (almost 12% of the total).
- The sugar and ethanol sector has faced economic problems in the last ten years, and the impacts on some indicators are clear: reduced sugarcane yields, less plants in operation and increased product costs.

Corn in Brazil



- On average, corn production has grown in Brazil in the 2013-2020 period (see figure below). The values for 2020 are estimates. About 75% of the total production in the last three harvests was produced as second crop, i.e. in association with other agricultural culture. Recently, it has been common the corn production in association with soy, mainly in the Centre-West region (70% of the production of corn as second crop).
- The map shows the municipalities with production of corn as second crop.



- As for corn as the main crop, its production is concentrated in the south and southeast regions, contributing with 17% of the total production.
- In general, yields are higher for corn production as the main crop, but costs are also higher.

Database of ethanol producing units

Parameter	Data	Source
Number of registered mills	360	MAPA
Do not operating in 2019-2020	12	MAPA
Able to produce sugar & ethanol	192	MAPA
Only producing ethanol	137	MAPA
Units authorized to produced from cane & corn	10	MAPA
Units authorized to produced only from corn	3	MAPA
Number of registers of milling capacity	352	NovaCana
Milling capacity (tonnes of cane.year^{-1})	750 x 10^6	NovaCana
Largest mill (tonnes of cane.year^{-1})	10.5 x 10^6	NovaCana
Units that produced ethanol in 2019	321	ANP
Ethanol production in 2019 (10^9 litres)	35.8	ANP
Ethanol production capacity (10^9 litres)	70.0	ANP
Units that produced anhydrous in 2019	178	ANP
Anhydrous production in 2019 (10^9 litres)	10.45	ANP

- A database of ethanol producing units was built based on information of different sources (e.g., ANP, MAPA, NovaCana). The information available includes authorized units, classification according products (i.e. ethanol, sugar, or both products), installed milling capacity, installed capacity of ethanol production, effective ethanol production in 2019 and feedstocks used.
- A summary of the information available in the database is presented in the table.
- In 2020, the installed capacity of the units able to produce ethanol from corn (only corn or combined with sugarcane) is only 4% of the total.
- It is estimated that 86% of the installed sugarcane milling capacity was used in 2019.

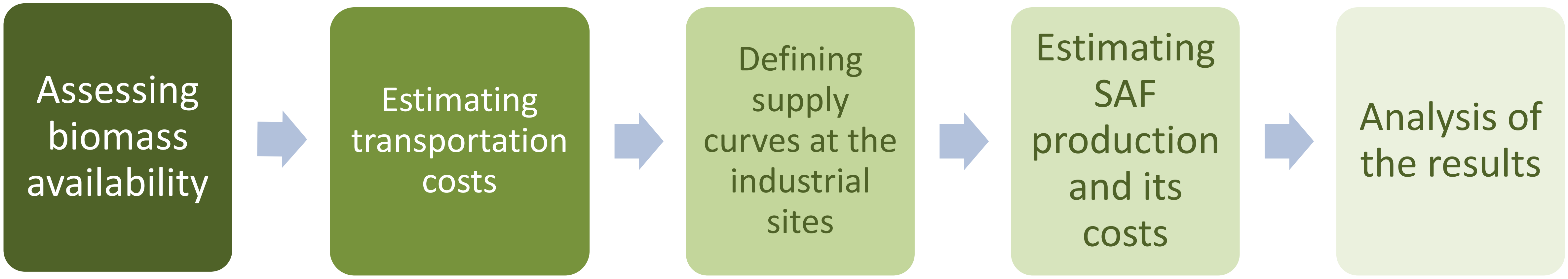
Cases studied (1)

- The case study related to the ATJ route has three variants, in all cases considering the production of SAF from anhydrous ethanol, the industrial unit being located at REPLAN (Refinaria do Planalto), in Paulínia (SP).
- In the first variant, the potential supply of the sugarcane mills that produced anhydrous ethanol in 2019 was assumed. The necessary amount of ethanol would be diverted from its use in the road transport sector, in which it is consumed blended with fossil gasoline.
- In the second variant, it was assumed that the production of anhydrous ethanol could be expanded, assuming that the installed capacity could be used to the maximum. In this case, there would be an effort to increase the supply of cane, making the most of the installed milling capacity, with an increase in agricultural productivity. If necessary, anhydrous production would be prioritized over hydrated production.
- In these two variants, the opportunity costs of anhydrous ethanol (the price paid to ethanol producers in 2018) is the reference.

Cases studied (2)

- Finally, the third variant considered the production of anhydrous ethanol in new plants. Four producing units were considered (in Prata (MG), Caçú (GO), Paranaíba (MS) and Presidente Venceslau (SP). In one case, the production of ethanol was assumed only from sugarcane, and for the development of the study it was necessary to consider the cost of producing cane and investments in new plants. In the second case, the production of anhydrous from sugar cane and corn was considered as a complementary feedstock (operating with corn after the end of the sugarcane harvest season). As well, new plants were considered and the costs of producing sugarcane and corn were estimated.
- In the three variants it was assumed that the production of anhydrous would be in mills located as close as possible to a pipeline that allows the supply of ethanol to REPLAN. The existing stretch connects Uberaba (MG) to the refinery, with a terminal in Ribeirão Preto (SP), and in the future the pipeline will be extended to the south of Goiás (Itumbiara and Jataí-Quirinópolis).

Methodology: general procedure



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

SAFmaps

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

- Existing production
- Market constraints
- Estimating costs (or opportunity costs)

→ **Ethanol currently available**

- Biomass suitability
- Areas available and where production is desirable
- Potential yields based on modelling
- Estimated production costs

→ **Ethanol to be produced with expansion**

Methodology … assessing supply curves at the industrial sites

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

Anhydrous ethanol would be transported from the mills to REPLAN, combining trucks (to the terminals) and a pipeline (to the refinery) (in some cases, also using railroads)

→

Supply curves were defined, considering different mills that can supply ethanol, and different capacities (in case of new mills)

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)

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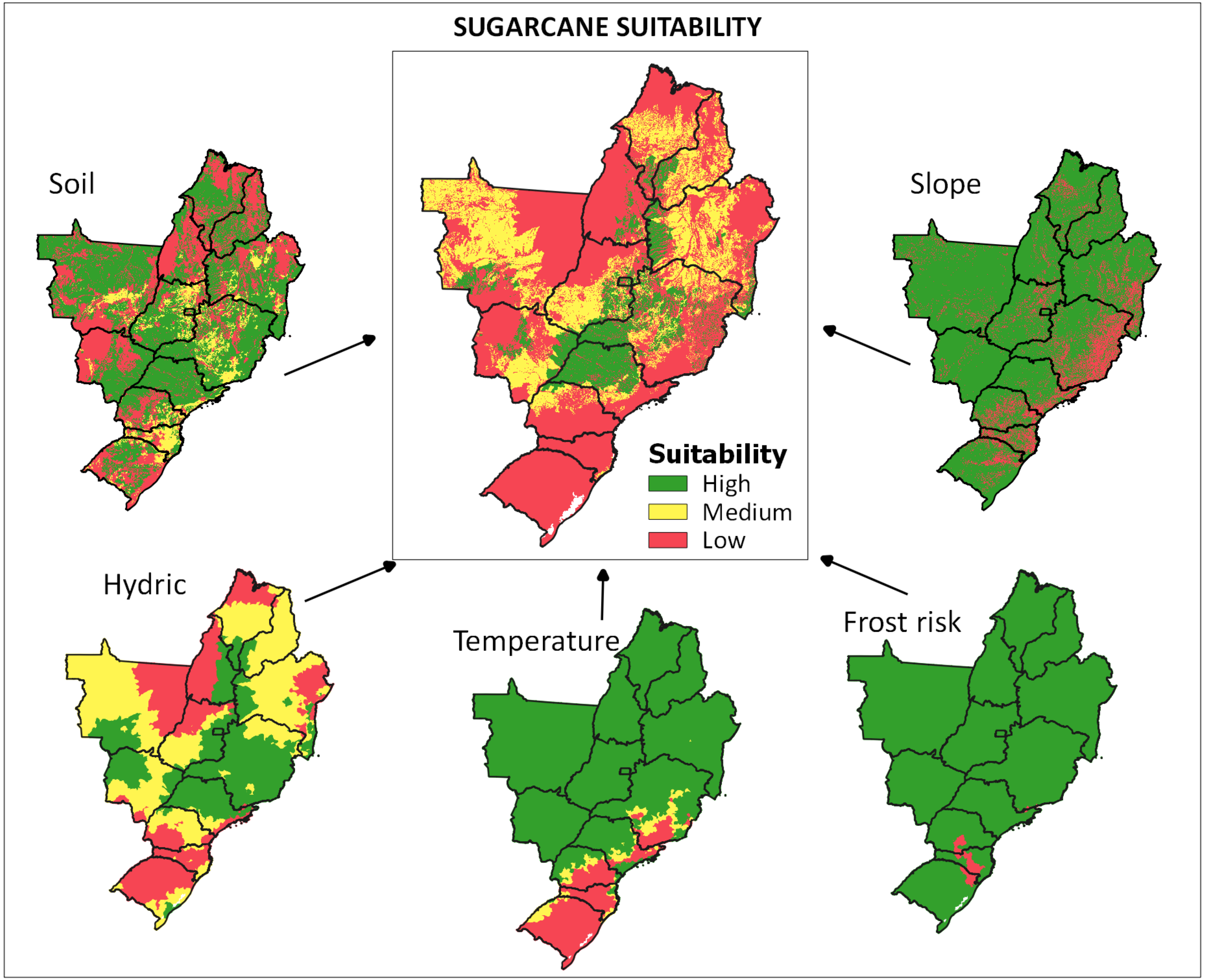
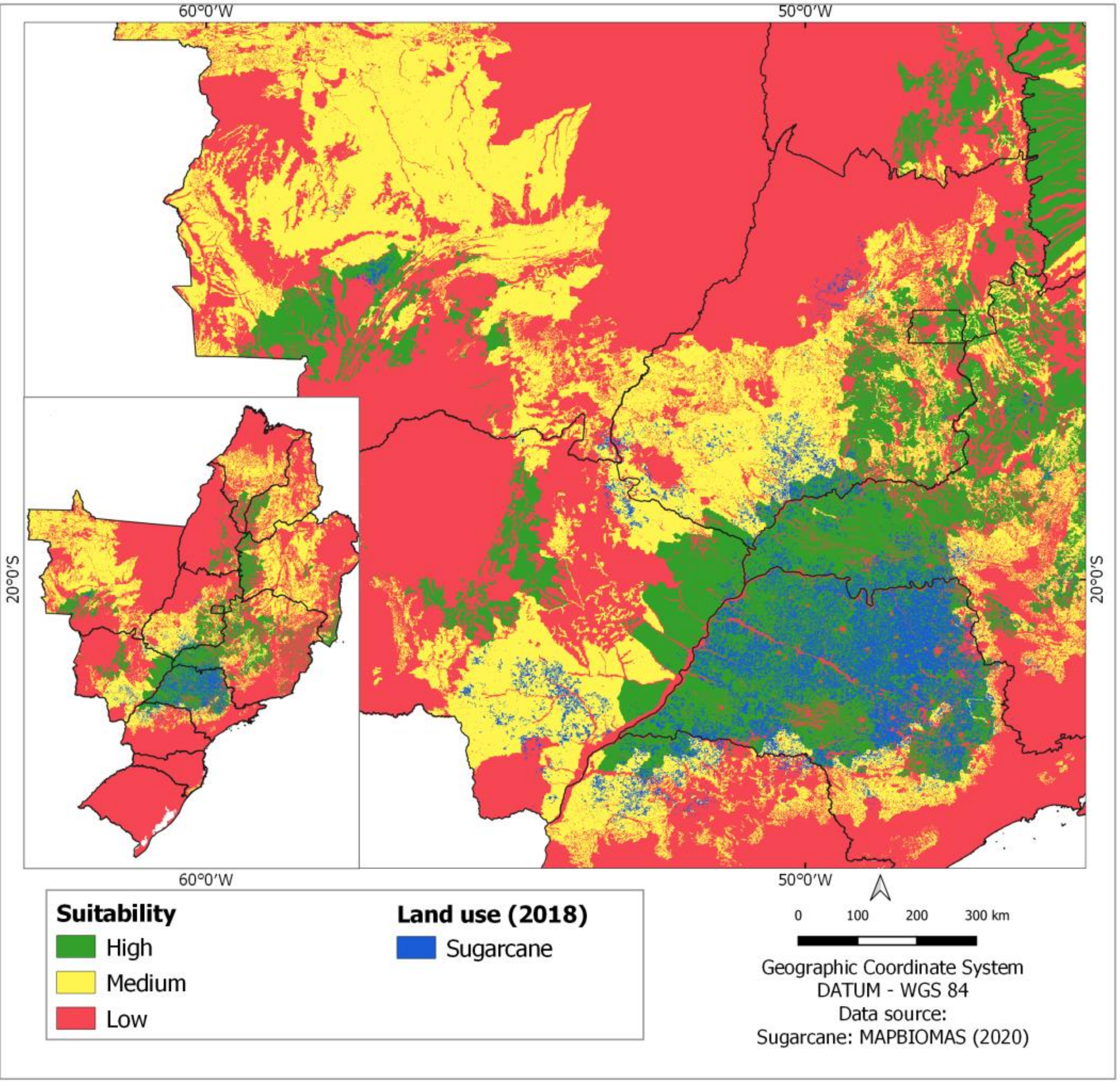
Analysis of the results, comparing with those presented in the literature, considering cost reduction opportunities and trends. Current fossil kerosene prices were also considered.



Sugarcane suitability (1)

- Sugarcane suitability was defined based on combining five parameters, as shown in the figure. Climatic suitability was defined in accordance with the procedure used to set the Agro-Ecologic Zonning of sugarcane (EMBRAPA, 2009).
- The slope restriction is based on the assumption that both the planting and harvesting of sugarcane must be fully mechanized.

Sugarcane suitability (2)



- The areas were classified in three categories (high, medium and low suitability), being high suitability the result of the best results in each sub-set.
- The validation of the sugarcane suitability map was done combining it to the registers of sugarcane cropping in 2018, based on satellite images (MapBiomas).
- It can be seen that the largest areas with sugarcane cropping in 2018 have a good match with the high suitability result.
- The lower resolution of the soil map in some states (for example, GO and PR) results in the apparent classification of some areas as of low suitability, despite the commercial cultivation of cane.

Sugarcane yields in a five-year cycle

	CONAB[1]		IBGE		Model
State	1,000 $t.year^{-1}$	Yield ($t.ha^{-1}$)	1,000 $t.year^{-1}$	Yield[2] ($t.ha^{-1}$)	Yield[2] ($t.ha^{-1}$)
GO	917.1	76.33	886.0	76.60	74.88
MG	848.0	74.53	888.6	77.54	76.23
MS	647.4	76.47	621.6	73.06	71.17
MT	228.9	75.79	279.3	70.99	70.04
PR	569.1	62.37	635.5	71.03	69.50
SP	4,426.2	75.21	5,565.4	77.62	76.21
Brazil	8,589.2	72.23	9,505.3	75.64	74.28

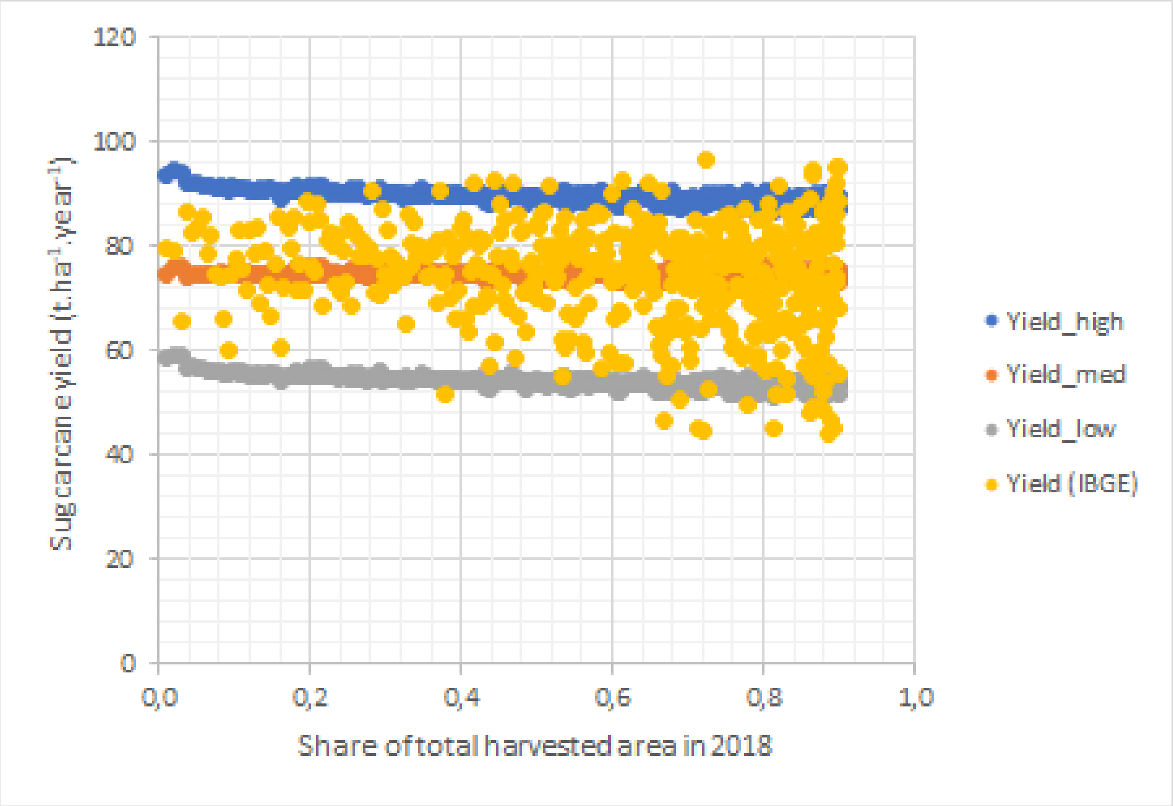
[1] Information for the harvest season 2018-2019.

[2] Estimated weighted yield, considering the production in each municipality.

- CONAB and IBGE data are not fully compatible. In principle, CONAB reports data on sugarcane used in the production of sugar and ethanol, while IBGE reports data on total sugarcane production, including other uses. Anyhow, in the cases of GO and MS, the production of sugarcane is higher in the CONAB than in the IBGE database.

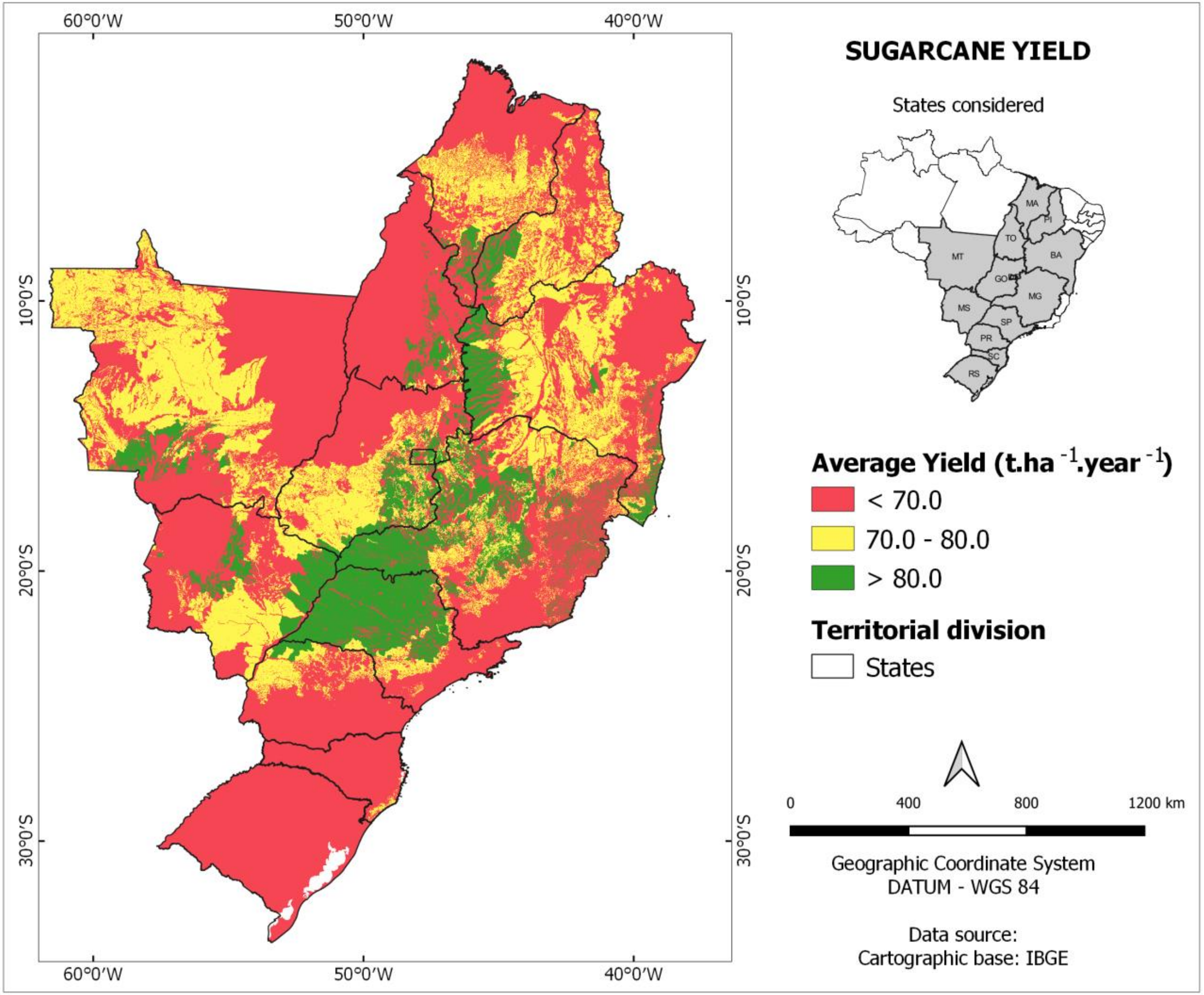
- According to CONAB, almost 90% of the production of sugarcane in 2018 (for sugar and ethanol production) was in the six states listed in the table.
- The statistical model for predicting yield was developed based on IBGE data.
- For aggregate results, on average the model's yield results are underestimated from 1.3%-2.7% compared to the IBGE results.

Estimated sugarcane yields



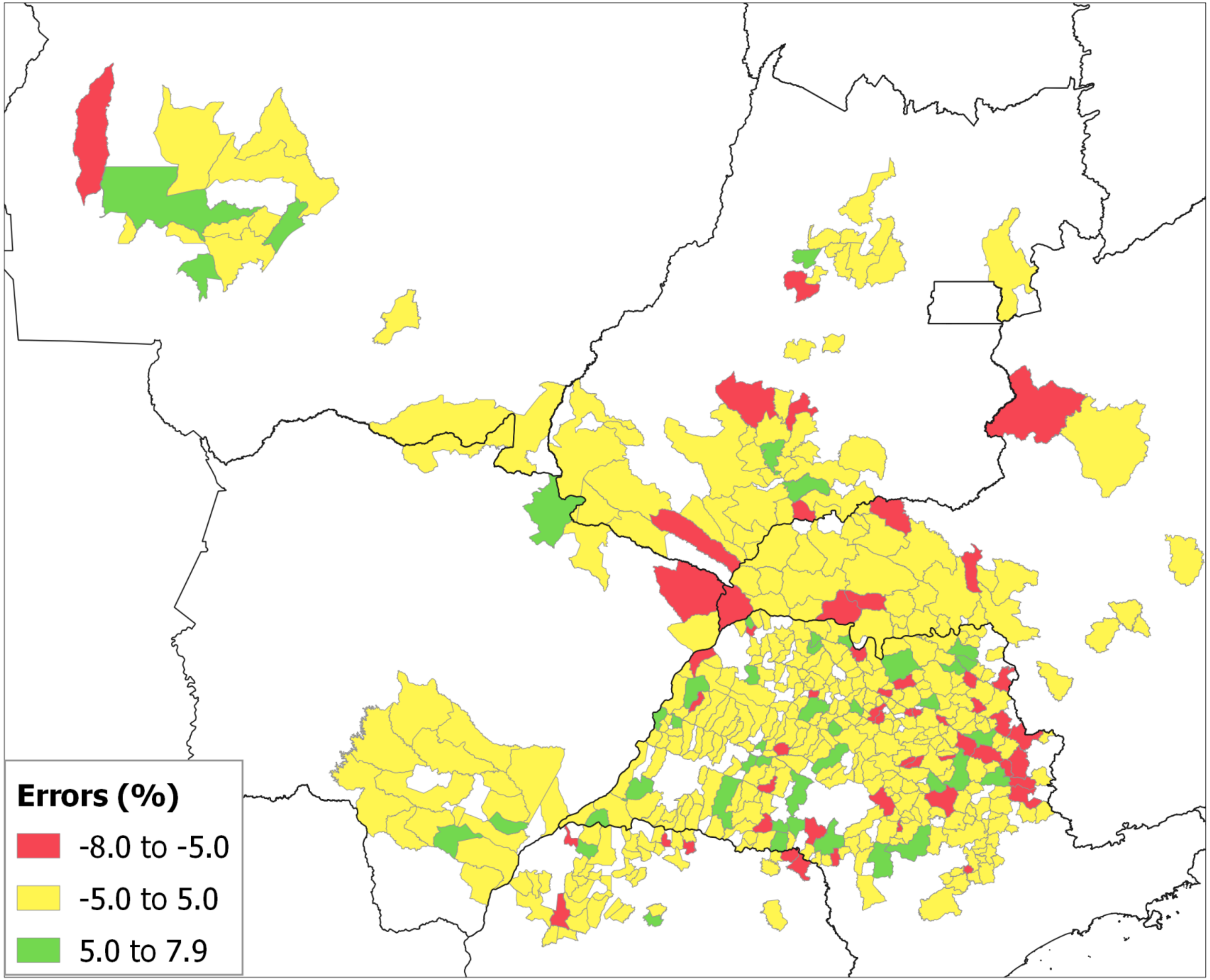
Estimated yields	High	Medium	Low
Maximum value	93.62	78.26	49.89
Minimum value	87.98	72.62	44.25
Average	90.91	75.55	47.18
Standard deviation	0.89	0.89	0.89

- The model allows the estimation of sugarcane yield (average values in a five year cycle) as function of the area cropped (a module area was assumed for estimating yields), air temperatures (annual average and annual minimum averages), total rainfall, and a set of dummy variables.
- The figure shows the predicted range of results, compared with the average values per municipality presented by IBGE. Only in few cases the actual yield values are outside the predicted range.
- The table shows some statistics for the ranges of high, medium and low yields.



Sugarcane yields

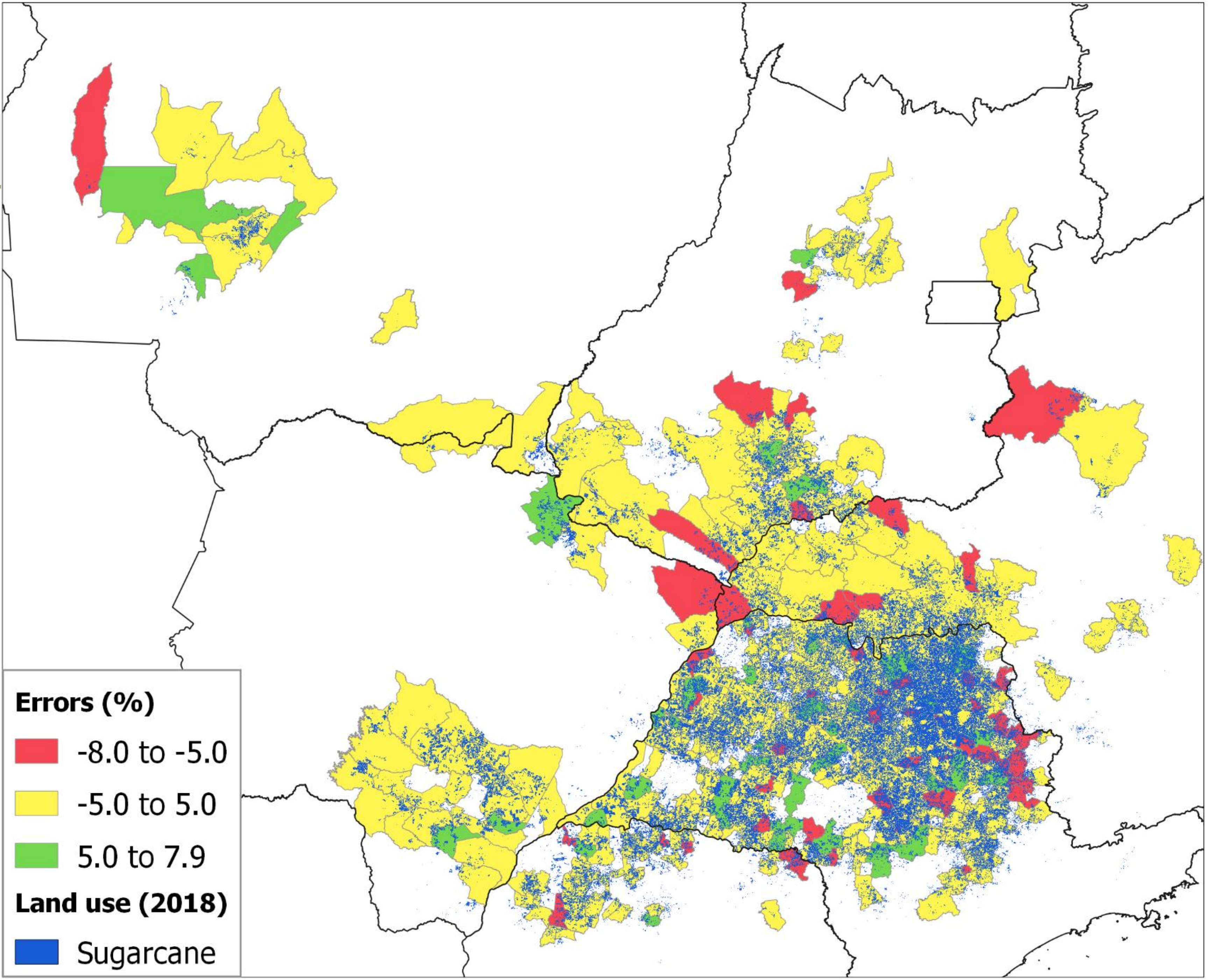
- The map shows the distribution of average yields in a five-year cycle.
- The model would be used to predicted yields in new sugarcane producing areas.
- The predicted values are slightly high in comparison to current average values, because of the lack of investments in recent years. However, predicted yields are compatible with estimates by Agrianual for predicting sugarcane costs (for this purpose the figures are in the 88-92 t.ha^{-1} range in the production cycle).



Validation (1)

SAFmaps

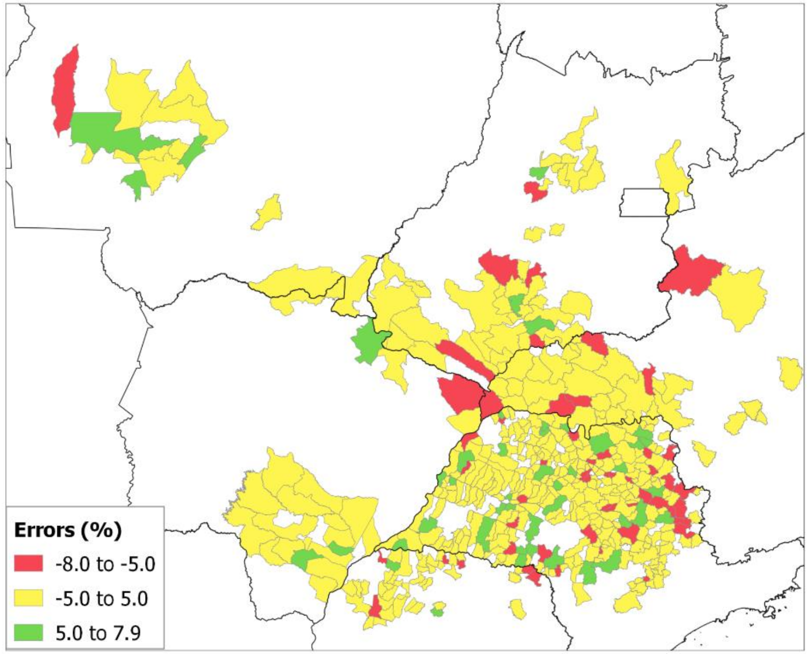
- The estimated yields were compared with the real average values. The figure shows the estimated errors (% in relation to the real value, based on IBGE (2018)), by municipality).
- Only municipalities with harvested area equal or higher than 5,000 hectares (in 2018) were considered.
- Assuming that yields based on IBGE's database are accurate, there are few municipalities in which the use of the model could result overestimation or underestimation. There is no case in which the error is larger than 8%.

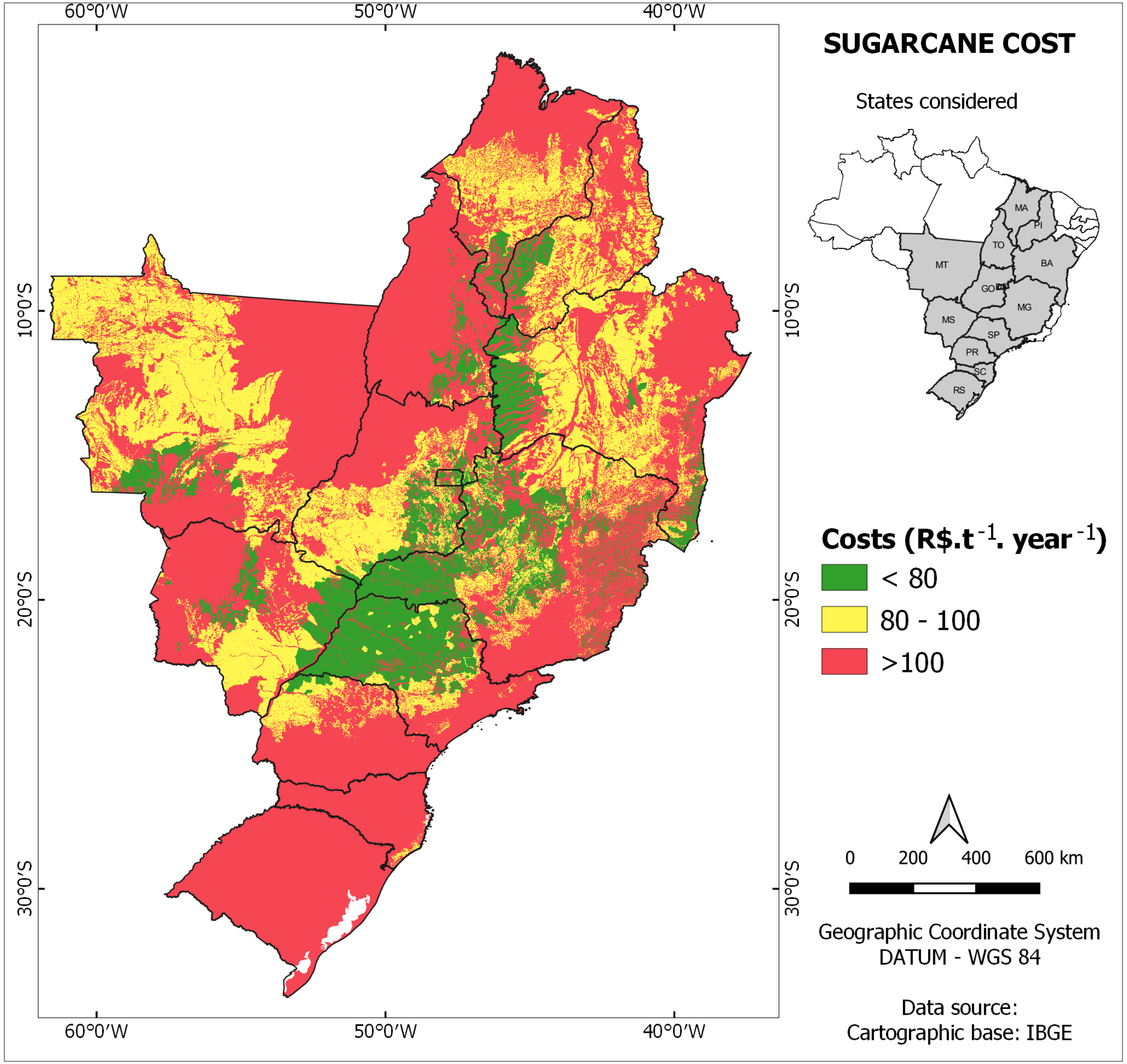


Validation (2)

SAFmaps

- Matching with MapBiomas (2018), it can been seen that there is no underestimation in important producing areas.
- Overestimations are mainly explained by the current low yields, due to the lack of investments in the sugarcane fields.

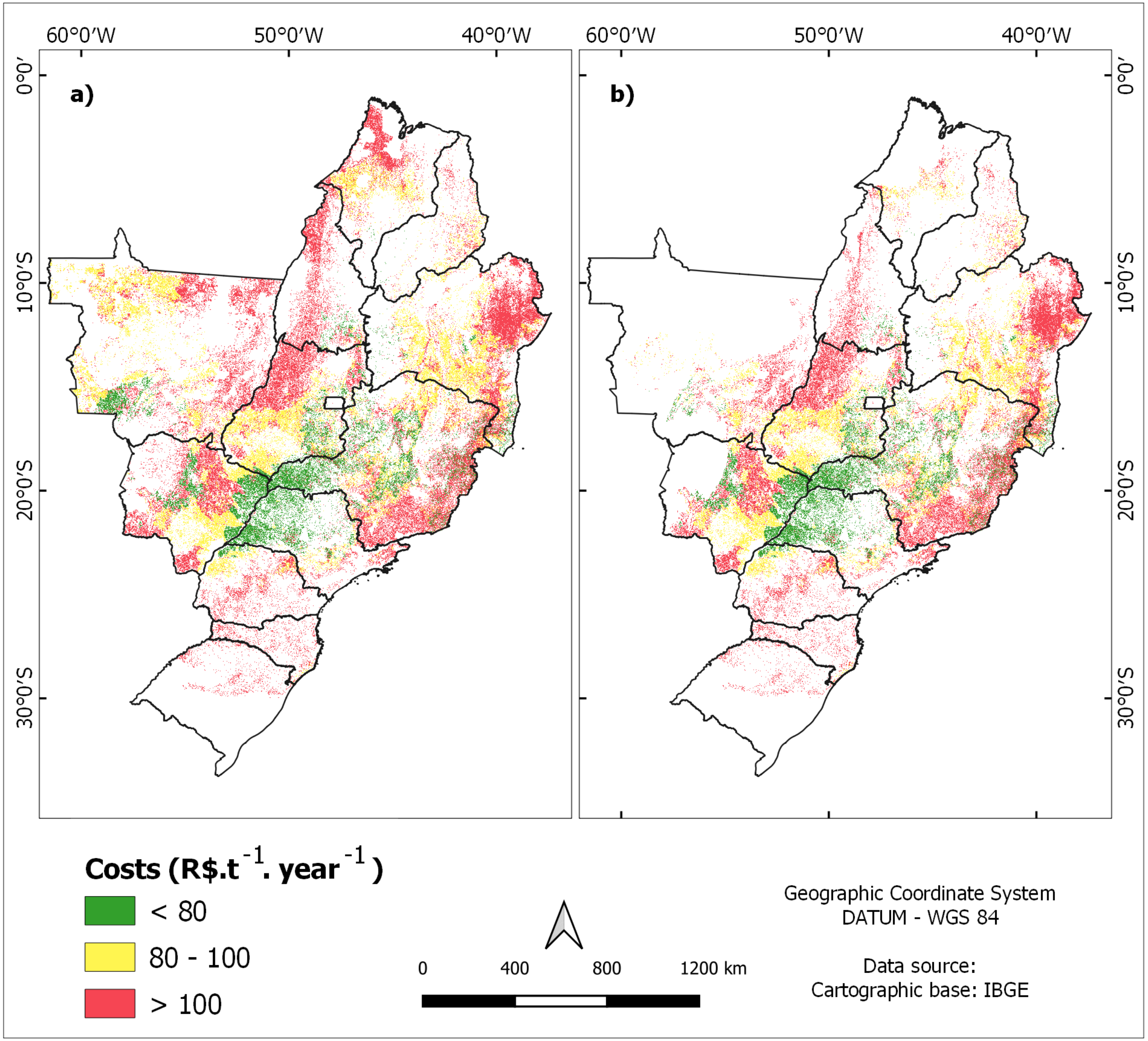




Sugarcane production costs (1)

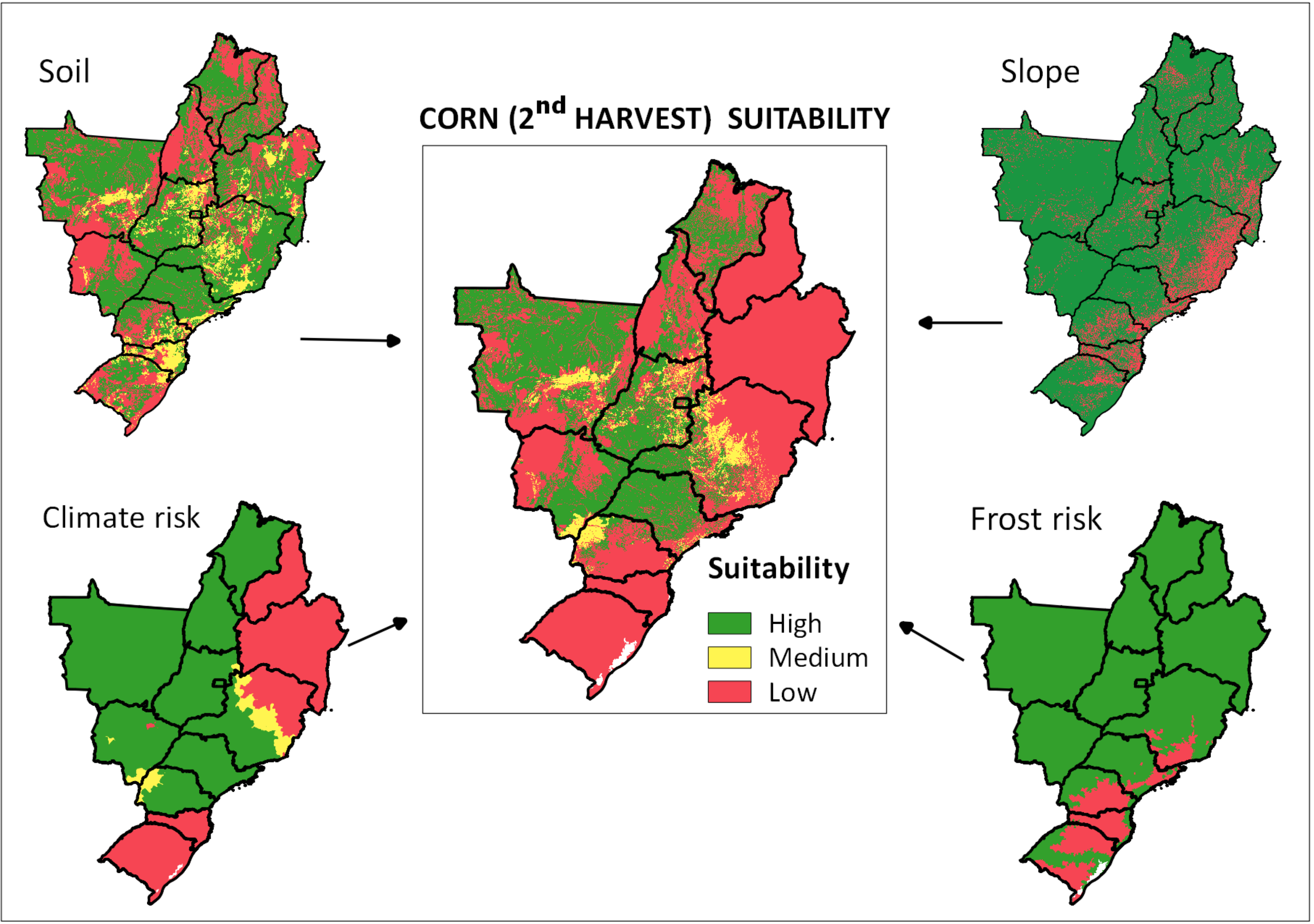
- The figure shows the estimated costs of sugarcane production, including harvest and transport to the mill, in R$(2018).$ha^{-1}$.$year^{-1}$ in a five-year cycle. Costs are impacted by yields.
- The cost structure and reference values were taken from Agrianual, which shows representative data for five states (SP, PR, MG, GO and MS; i.e. the most important producing states).
- The same cost structure for PR was applied to SC and RS, the same cost of MS to MT, and the same cost of GO to TO, BA, MA and PI.

Sugarcane production costs (2)



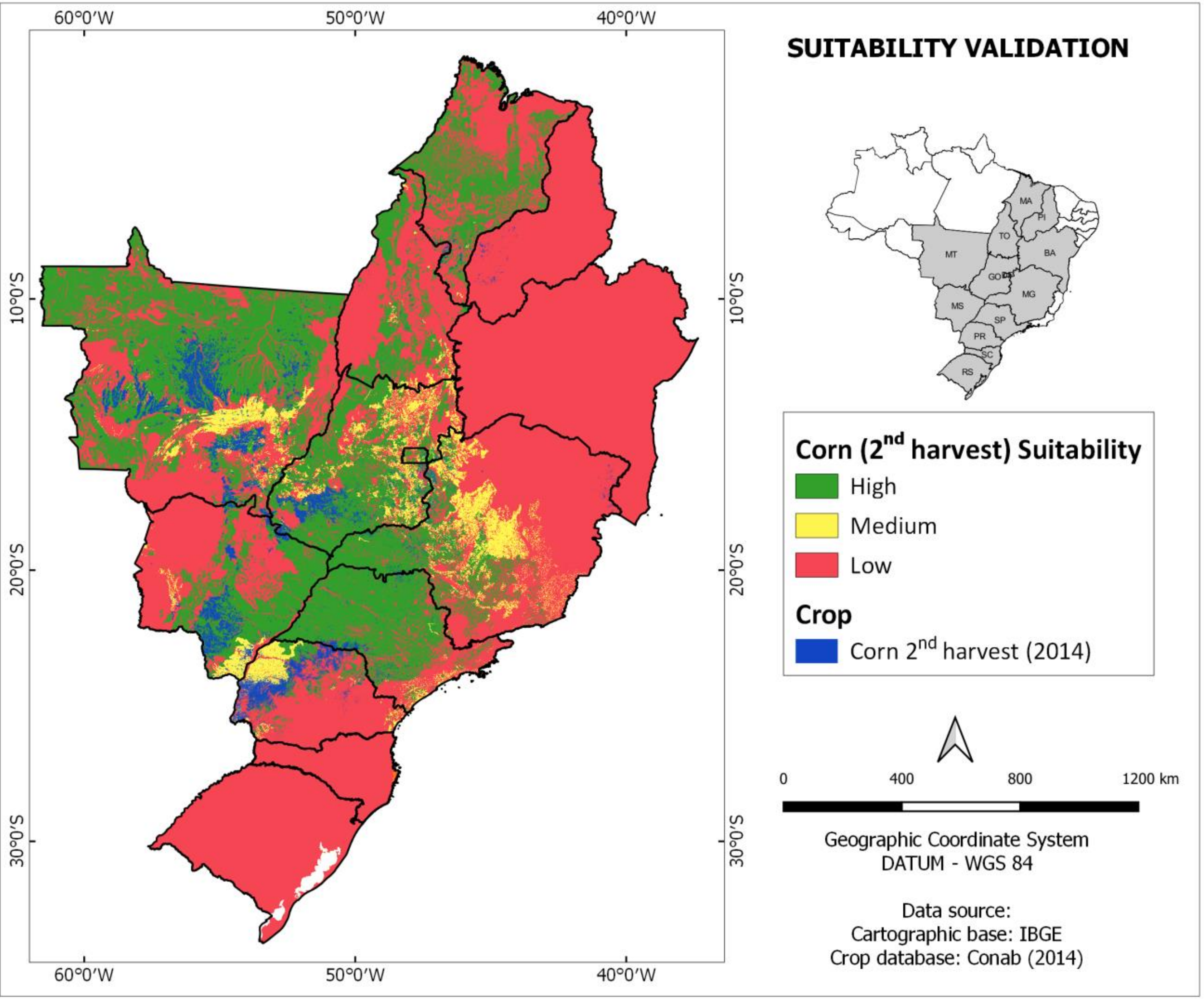
- The figure shows the estimated costs of sugarcane production only in areas that are pasturelands in 2018 (assuming that sugarcane expansion would be only over pasturelands).
- The map presented in right side (b) corresponds to set hypotheses assumed in this case study: (1) expansion just over pasturelands, (2) full exclusion of biomes Amazon and Pantanal, (3) exclusion of areas covered by natural vegetation in January 2008, (4) exclusion of all areas that are classified as reserves, protected areas, etc.

Corn suitability (1)

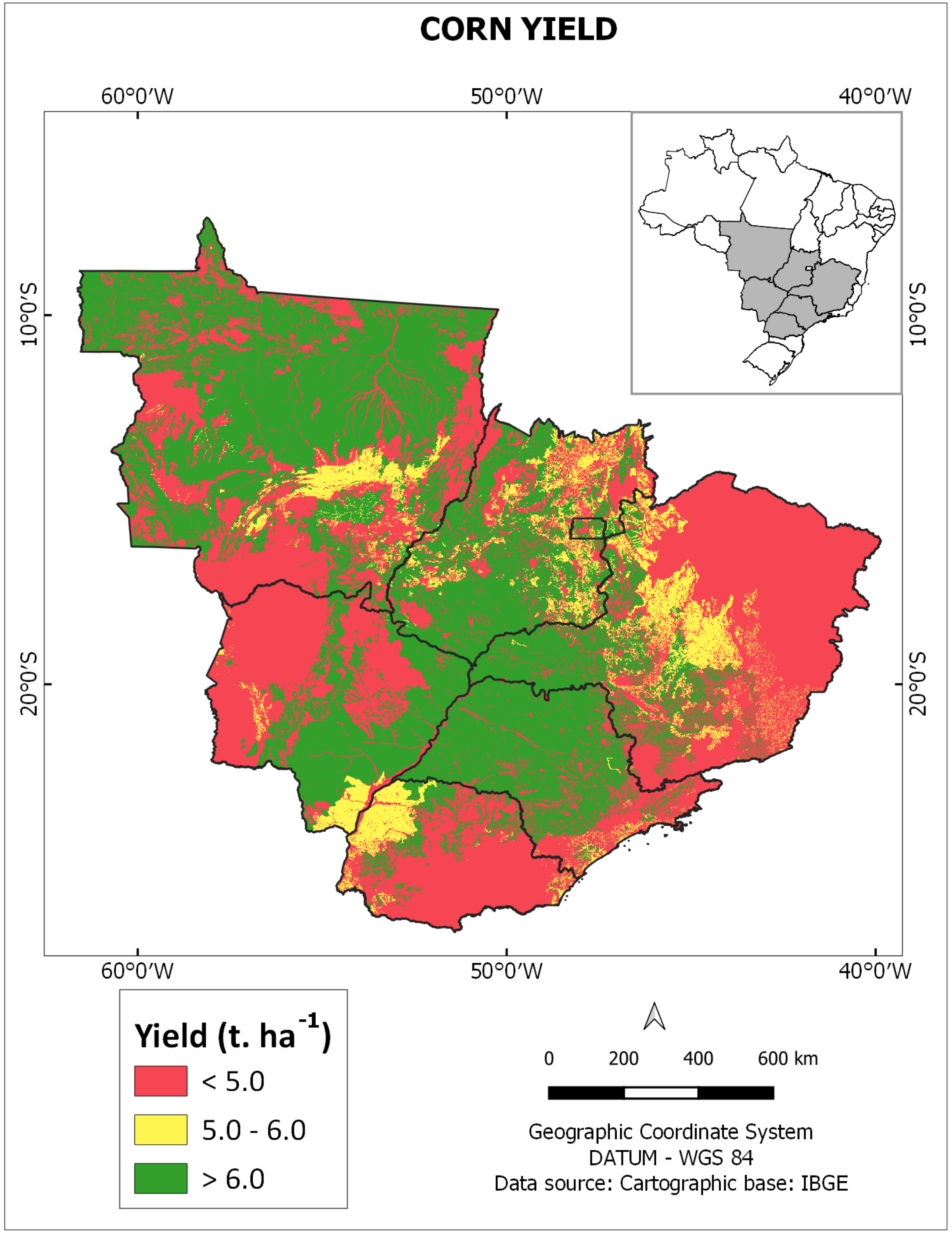


- The suitability of corn as second crop (or in second harvest) was defined as function of four parameters, as shown in the figure, being climate risk defined as function of water deficit and atmospheric temperatures (see Supplementary Material).
- It was used the information of the Agricultural Climate Risk Zoning for 2nd harvest corn (EMBRAPA, 2020). The procedure was adjusted in order to consider that corn would be sowed just after soybean harvest, significantly reducing the sowing period (to mid December-February).

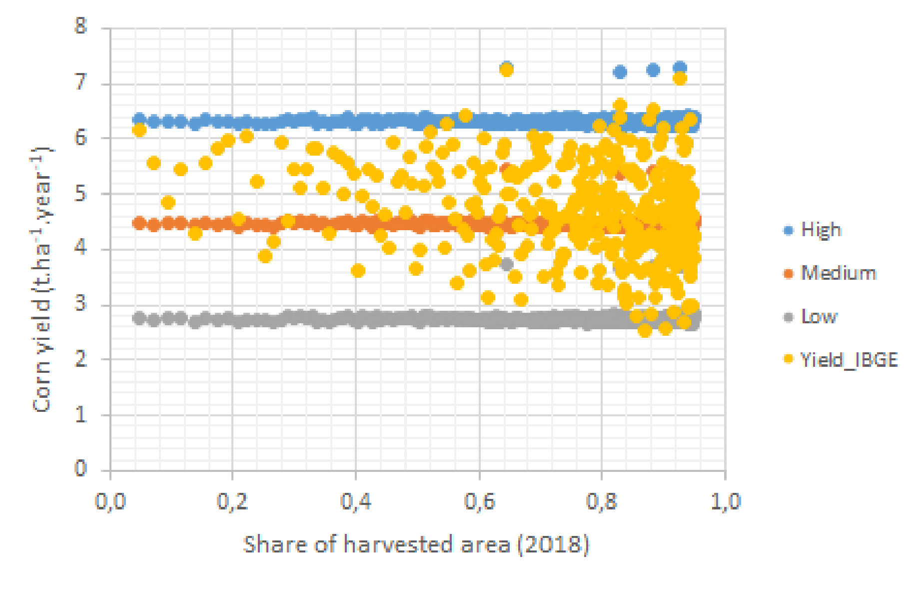
Corn suitability (2)



- The validation procedure is based on combining the suitability map with the map of corn production as second crop (the most recent map available is for 2014).
- It is importing to bear in mind that not all corn production as second crop is associated with soybean.
- It can be seen that the match is quite good, except in some areas in PR. The main reason is related with the resolution of the soil map. In fact, the matching is better if the image is enlarged.

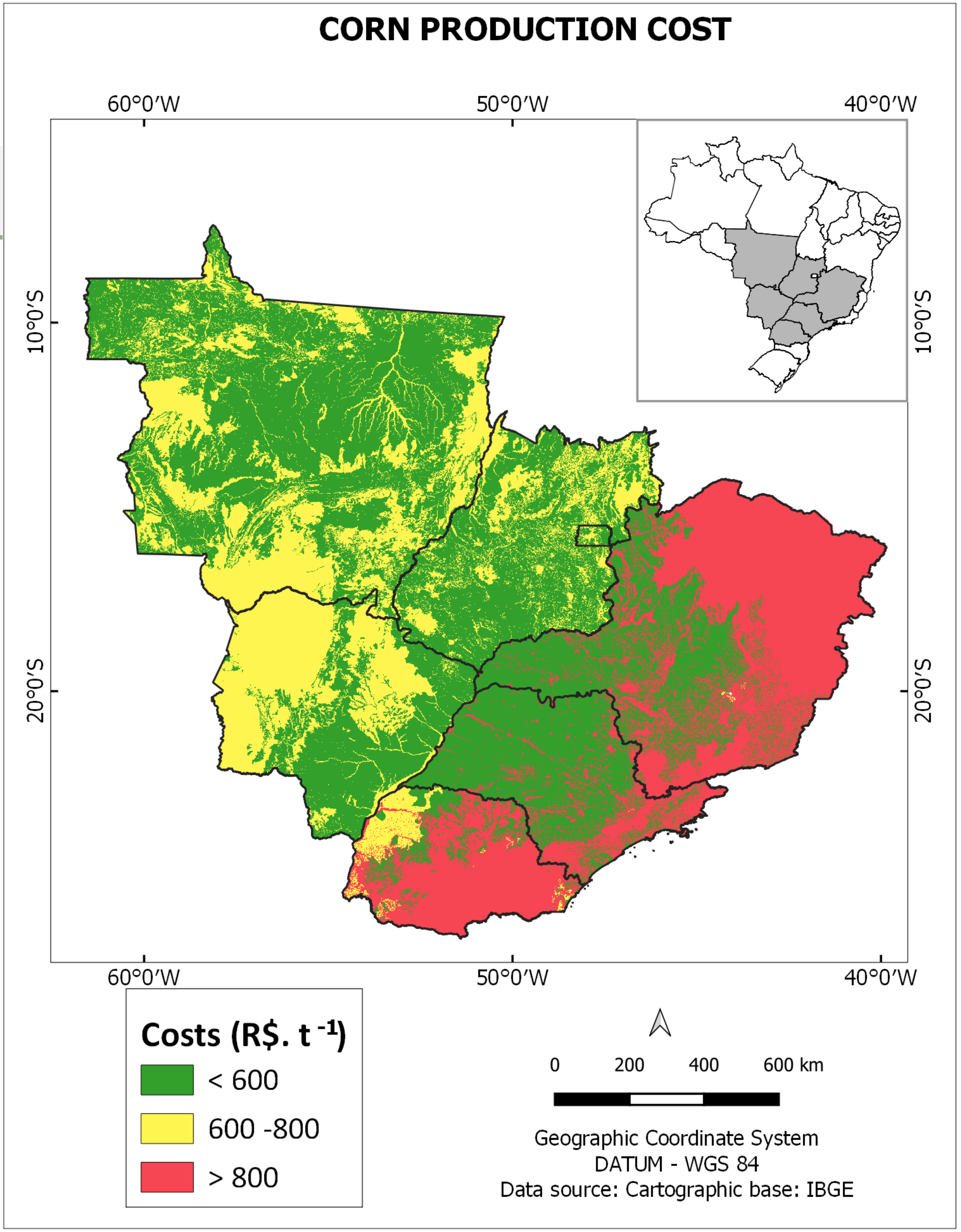


Corn yield



- The figure shows the results of the estimated yields, compared with actual values, on municipal basis (average for three crops).

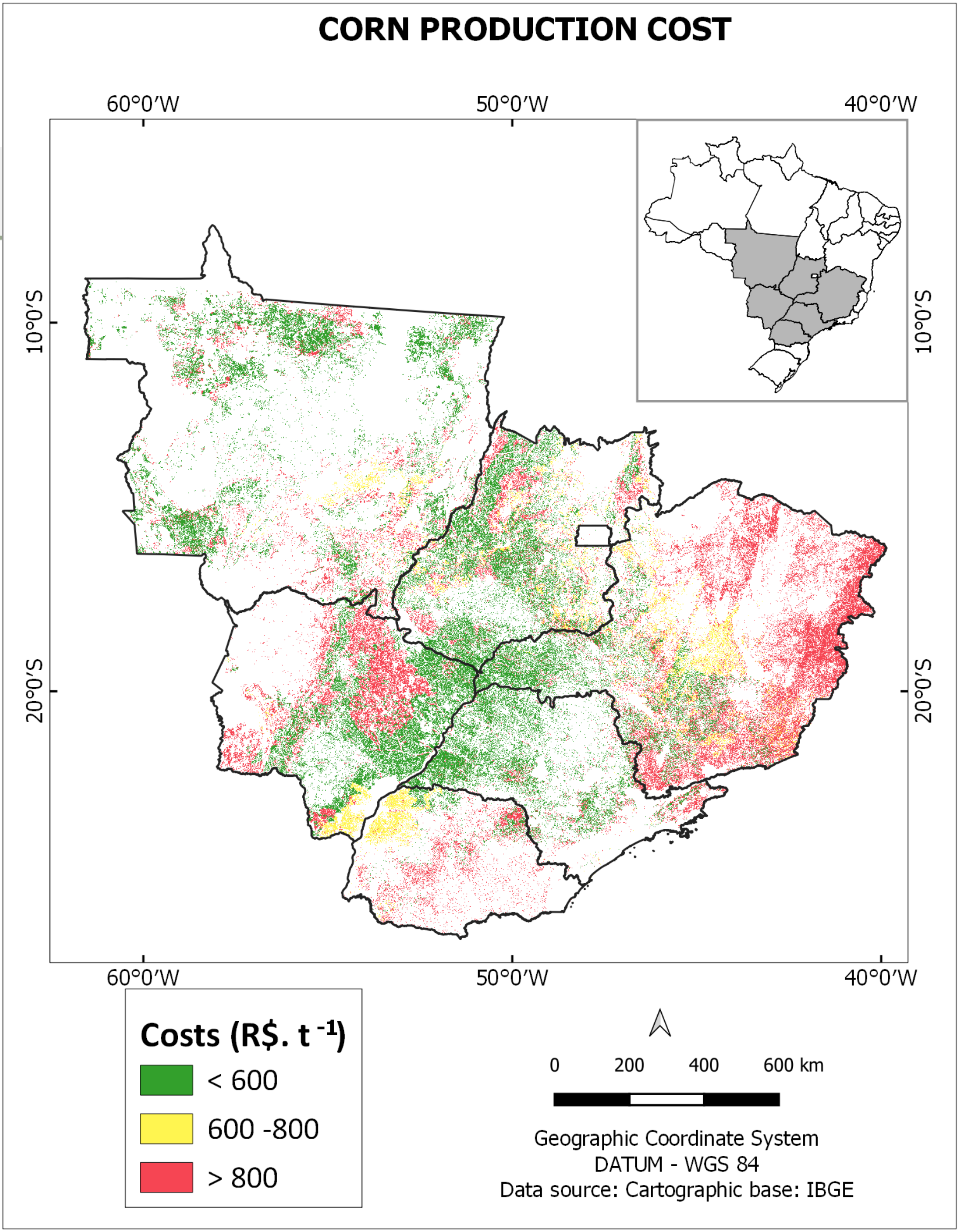
- A statistical model was developed in order to predict corn yields, as 2nd crop, in the six states.
- Explanatory variables include rainfall and air temperature in the months of the corn cycle, an index that relates to the annual rainfall distribution (IDP) and a set of dummy variables. Dummies make it possible to differentiate between conventional and transgenic corn (higher yield) and also soil quality.



Corn costs (1)

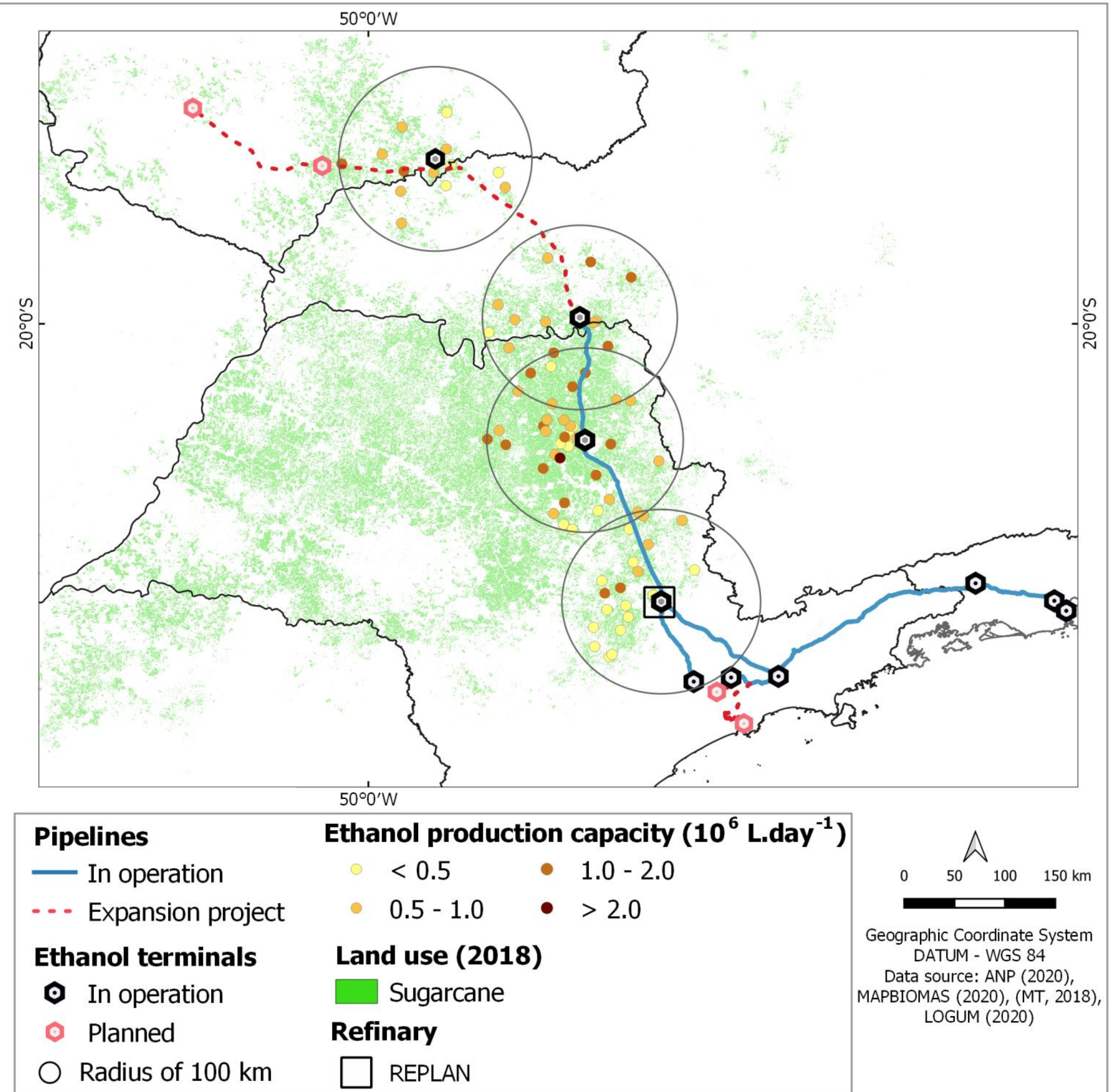
- Corn costs are estimated according to the cost structure reported by Agrianual for five states (MT, MS, GO, SP and PR). For MG we have combined information for SP and GO.
- Costs include harvesting, transport to nearby warehouses and storage for one month. Thus, costs reflect the availability of corn at an intermediate point between the harvest and the ethanol unit.
- The figure shows the predicted cost distribution in six states, for transgenic corn. Due to the higher yield, costs in mass basis are lower. Here it was assumed that all corn production for the purpose of producing ethanol would be based on transgenic corn.

Corn costs (2)

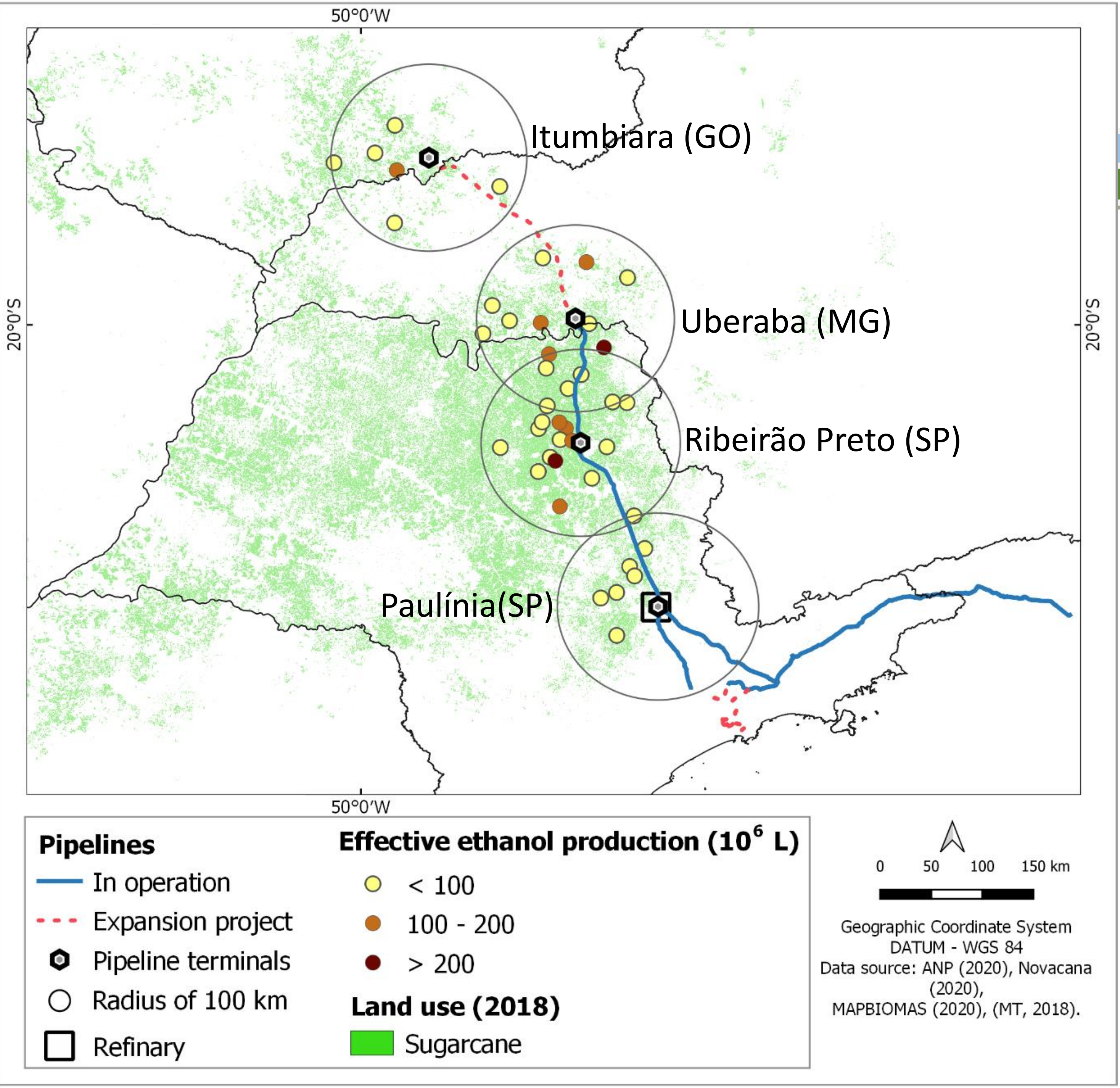


- The distribution of estimated corn costs in the six states, only in areas where it would be possible to expand corn production in a second harvest (most likely in association with soybean, but not restricted to this option), according to the premises made here, is shown in the figure. The areas are those which are pasturelands in 2018, according to MapBiomas.
- The absolute costs and the yields are related to the production of transgenic corn.
- In the case study in which it is assumed expansion of ethanol production from sugarcane and corn, this map was combined with similar information related to sugarcane in order to identify the most suitable areas

Case study 1 (1)

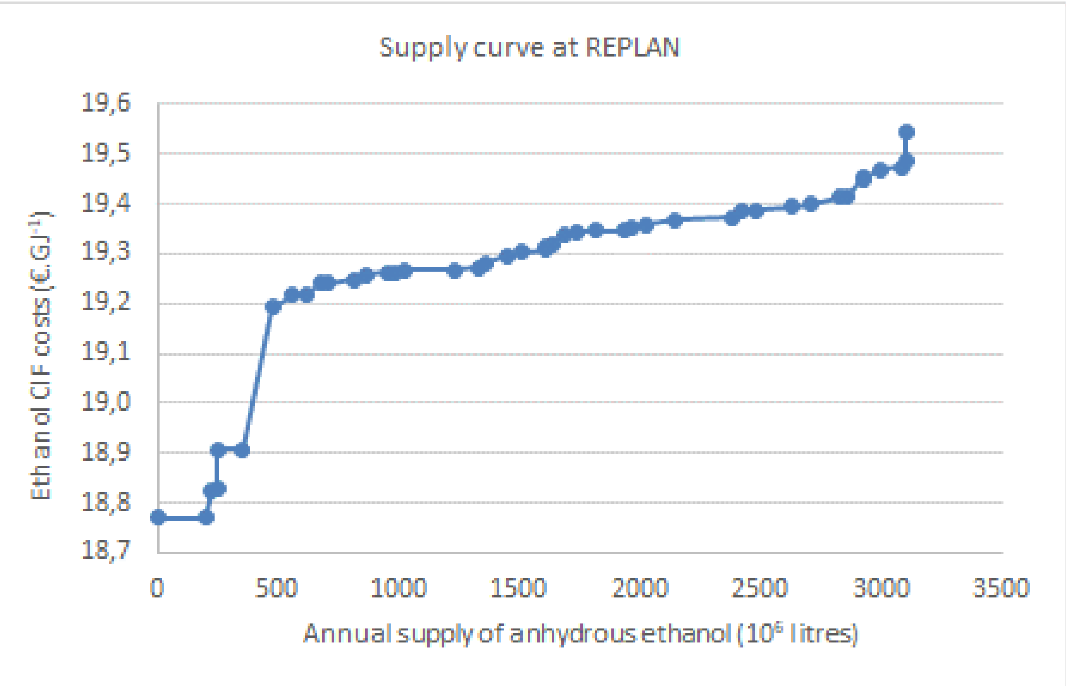


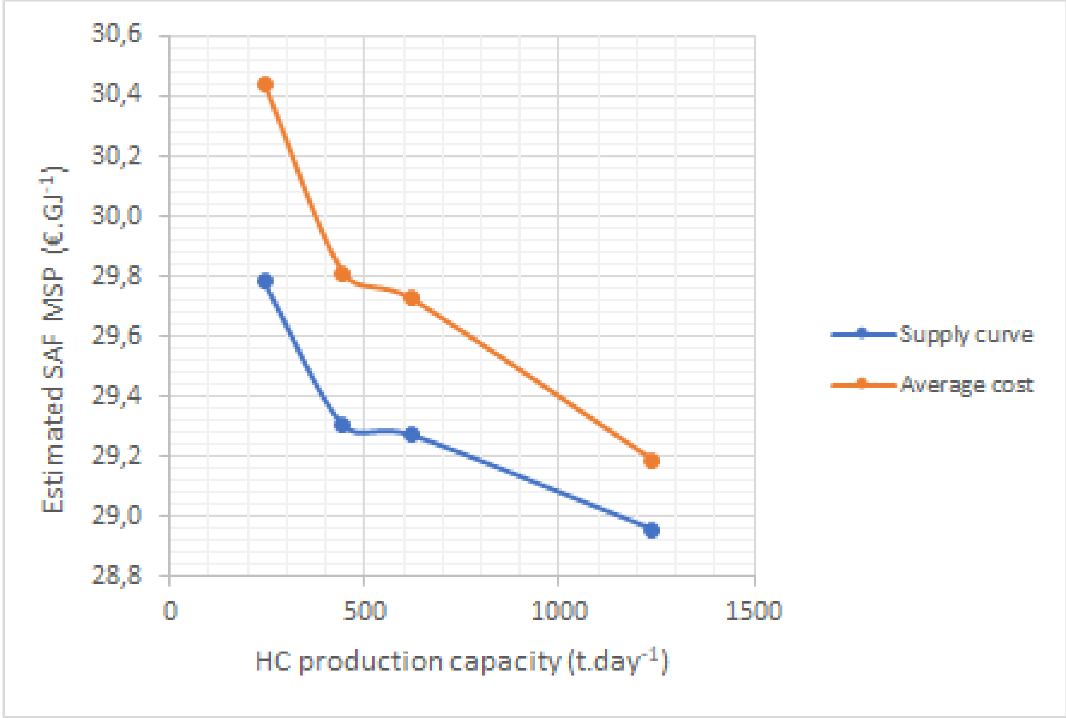
- There is a pipeline system connecting Uberaba (MG) to REPLAN, in Paulínia (SP). The system has a terminal in Ribeirão Preto (SP). In the future the pipeline will start in Itumbiara (GO), and another two terminals are predicted in GO.
- It was considered that SAF production would be at REPLAN, based on anhydrous ethanol that was produced (in 2019-2020) in mills located around 100 km of the four terminals of this pipeline (considering REPLAN as a terminal).
- Ethanol would be transported by trucks from the mills to the terminals.



Case study 1 (2)

- Using the database of existing mills, it was identified 80 ethanol producing units in the circles around Itumbiara (GO), Uberaba (MG), Ribeirão Preto (SP) and Paulínia (SP).
- The information was analyzed, checking consistency and effective production of anhydrous ethanol in 2019-2020. Thus, 43 out 80 mills were considered in the case study.
- The anhydrous ethanol production of these mills summed-up 3.1 x 10^9 litres in 2019-2020. In the same period, the total national production of anhydrous ethanol was 10.4 x 10^9 litres.

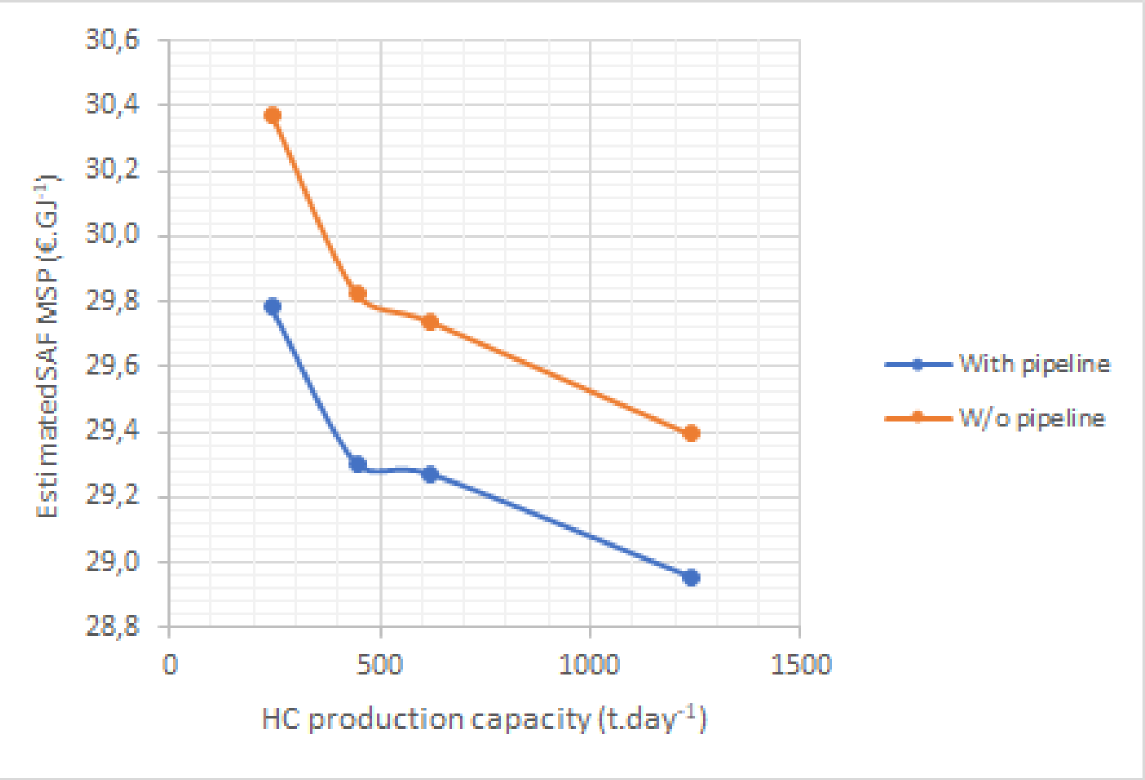




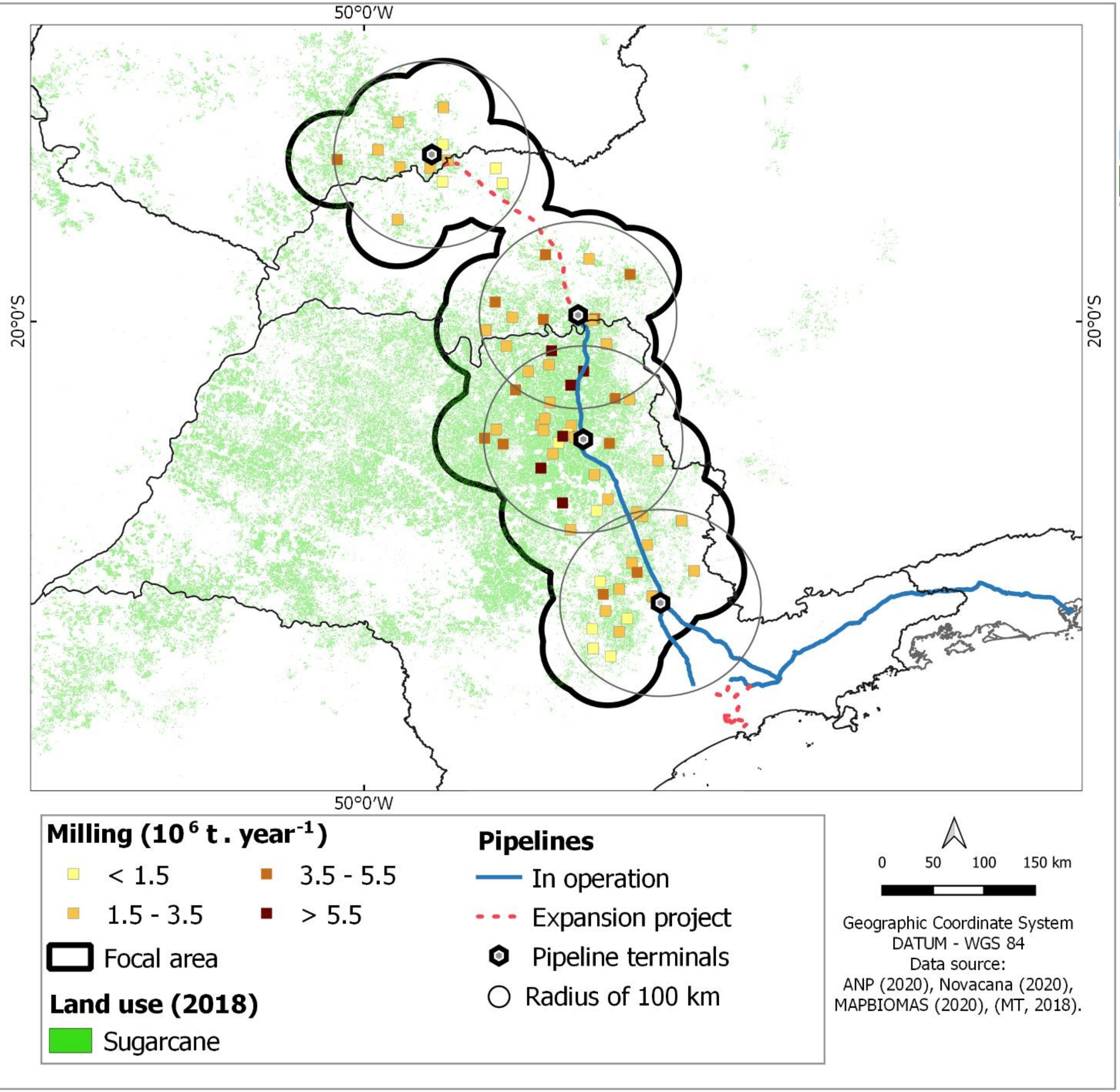
Case study 1 (3)

- Upper figure shows the supply curve at REPLAN, assuming that all anhydrous production in 2019, in the 43 mills considered, would be potentially available for SAF production.
- The maximum ethanol annual requirement would be 1.02 x 10^9 litres (i.e. about one third of the total production of these mills, and almost 10% of the national production in 2019).
- The bottom figure shows the estimated minimum selling price (MSP) of SAF considering four industrial capacities. The results correspond to two different hypotheses: (1) observing the supply curve, the production of 15 mills, out of 43, would be enough to assure the required annual supply ("supply curve"), and (2) assuming that all plants would proportionally contribute to match the required supply (in this case, the CIF cost would be the average of all units) ("average cost").
- In all cases the opportunity cost is the average price paid to producers of anhydrous in 2018, considering particularities of each state (see Supplementary Material). Prices paid in GO are lower than in MG and SP. The shape of the supply curve is also due to costs of transport, as function of the distances to the pipeline and to REPLAN.

Case study 1 (4)



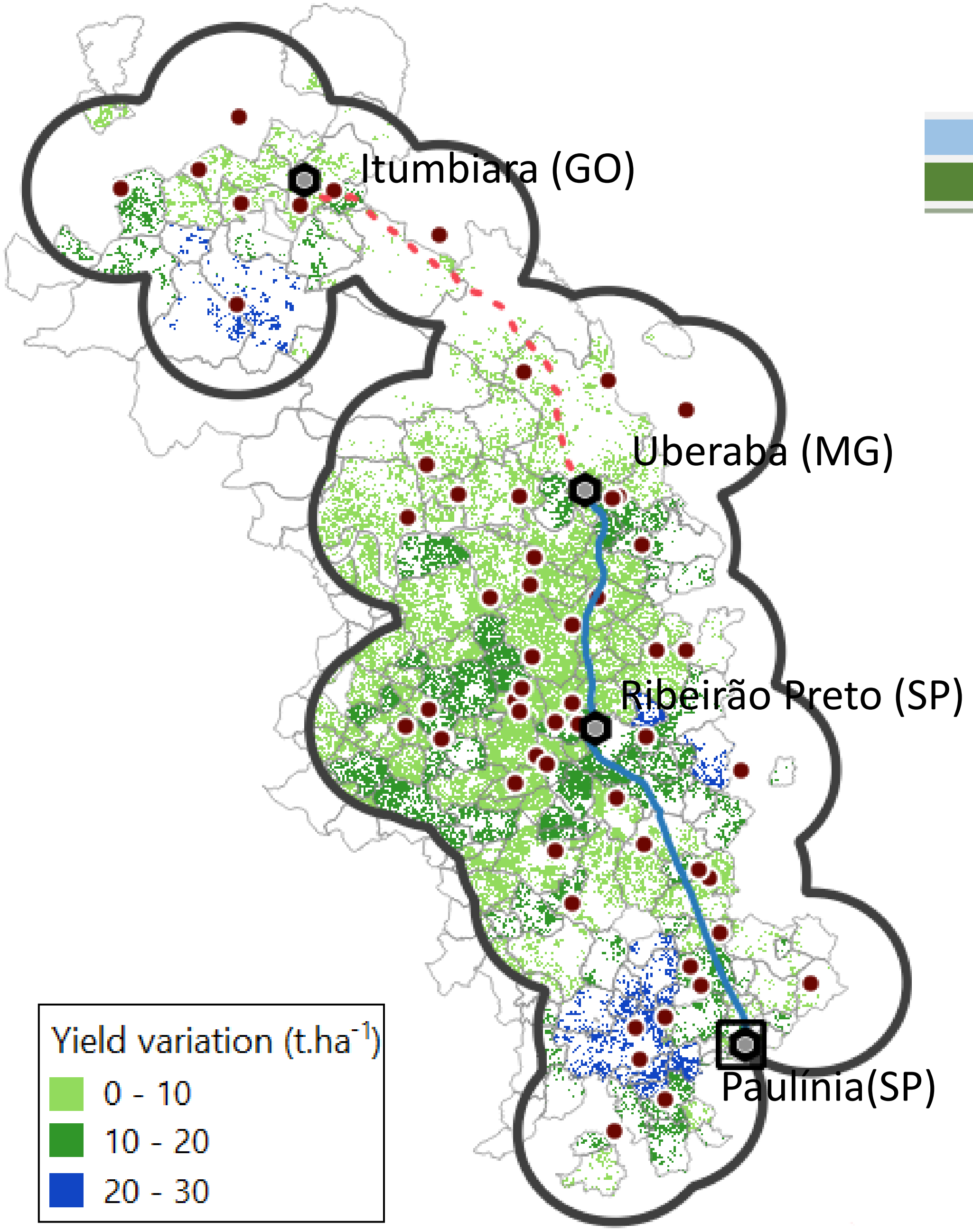
- Assuming the hypothesis that ethanol supply would be according to the economic merit of the 43 potential suppliers, the impact of transporting the feedstock by pipeline was explored; the MSP results are presented in the figure.
- The impact of transporting ethanol only by trucks from the mills to REPLAN represents an additional 1.5-2.0% in SAF MSP, depending on the scale of SAF production. More important than the impact on the MSP, it could be predicted a significant negative impact on the carbon footprint of this alternative.
- Transporting – as much as possible – ethanol by pipelines implies that the best suppliers are five mills in GO, because there the price paid to producers is lower. On the other hand, in case it would be necessary to transport ethanol just by trucks, the best supply options would be six mills that are closer to REPLAN.



Case study 2 (1)

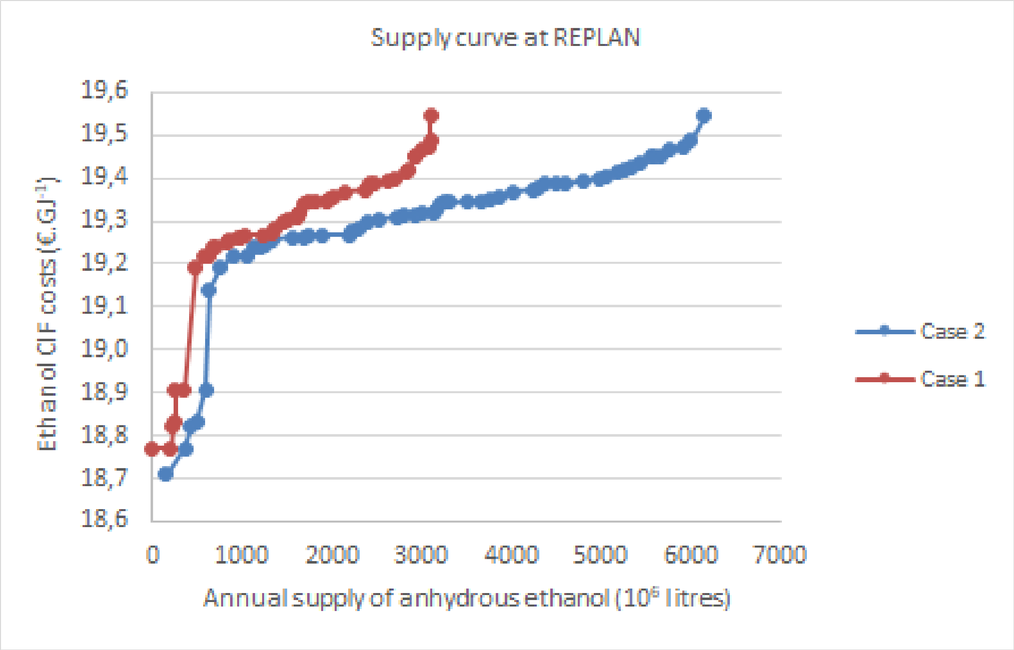
- Again, considering the set of mills (80) close to the pipeline system, the rationale now is that it would be possible to enlarge anhydrous ethanol production in the existing mills.
- Therefore, the action would be to produce more ethanol, (1) going to the limit of the crushing capacity, seeking to increase the cane yield in the producing areas and, additionally, (2) prioritizing the production of anhydrous ethanol, seeking the limit of its installed capacity.
- Out of the existing mills close to the pipeline, 55 were identified as able to produce more anhydrous. The sugarcane production areas would be those within a 50 km circle around each of the mills considered.

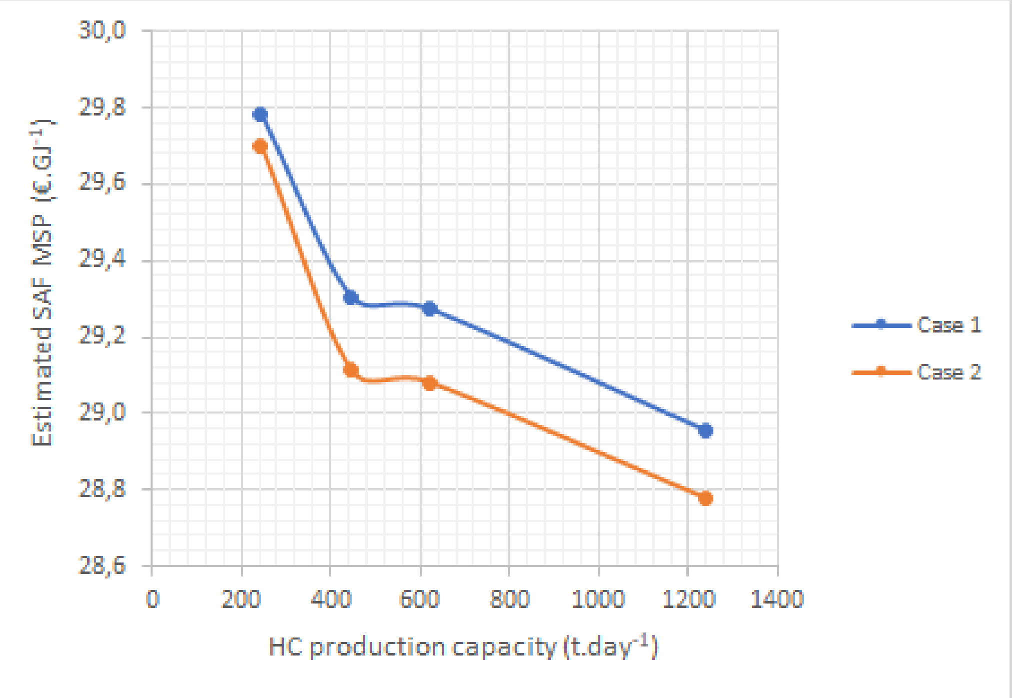
Case study 2 (2)



- The figure shows the differences between estimates of sugarcane yield and the reference value in 2018 (based on IBGE). The green and blue areas are those in which there would be a potential to increase sugarcane production, provided there are investments in the field.
- The analysis related to enlarge sugarcane crushing was done for the set of mills close to each terminal, because the information available is not precise mill by mill.
- The table shows the estimated results: potential additional sugarcane production, how much could be effectively crushed and the estimate of incremental anhydrous production.

Mills around	Idle capacity	Potential (10^6 t.year^{-1})	Share to be crushed	Additional anhydrous (10^6 L.year^{-1})
Itumbiara	7.0%	2.9	47.8%	111.3
Uberaba	6.4%	6.6	50.1%	263.0
Ribeirão	13.7%	17.0	71.6%	957.8
Paulínia	13.7%	5.0	81.8%	327.9

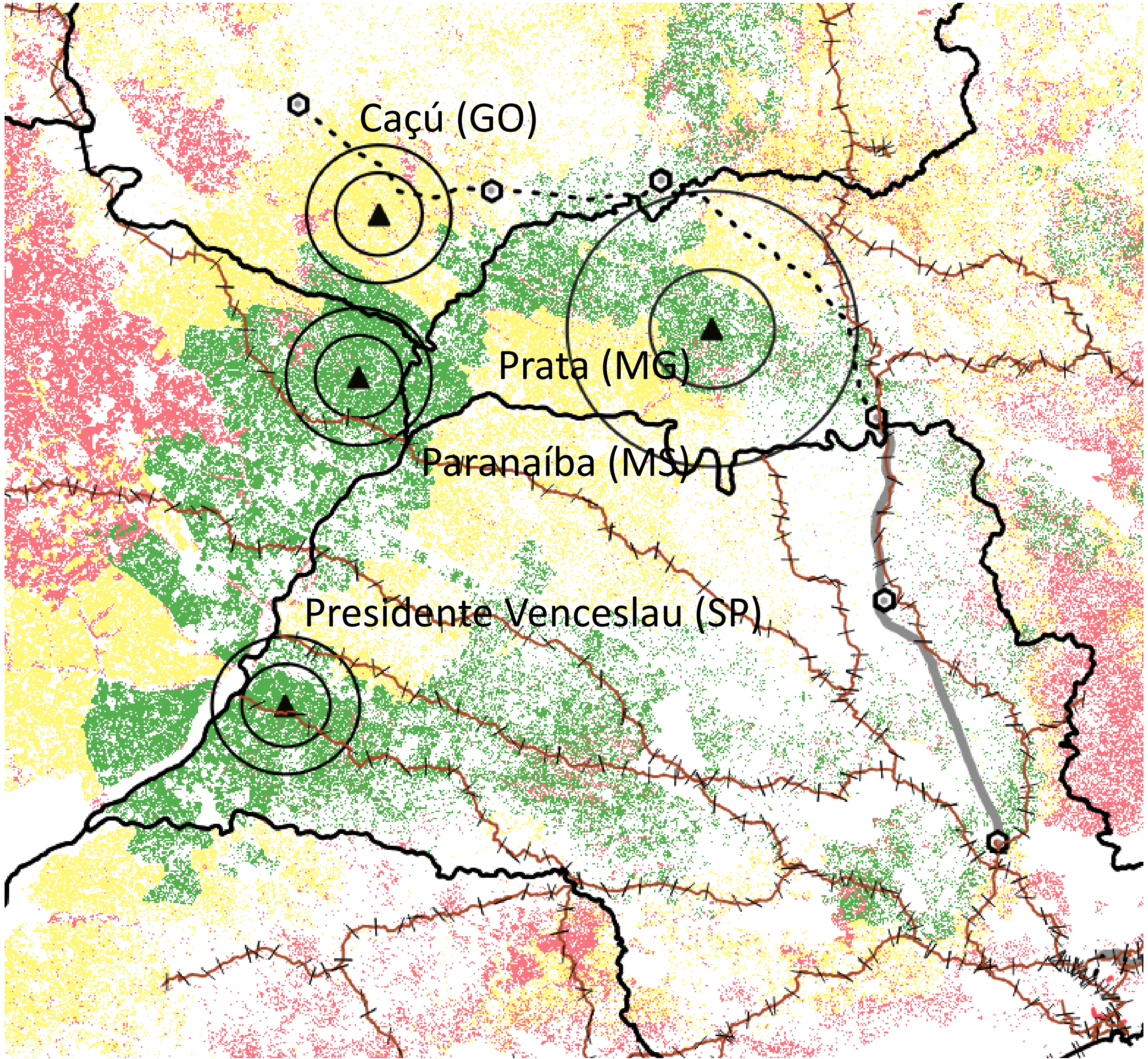




Case study 2 (3)

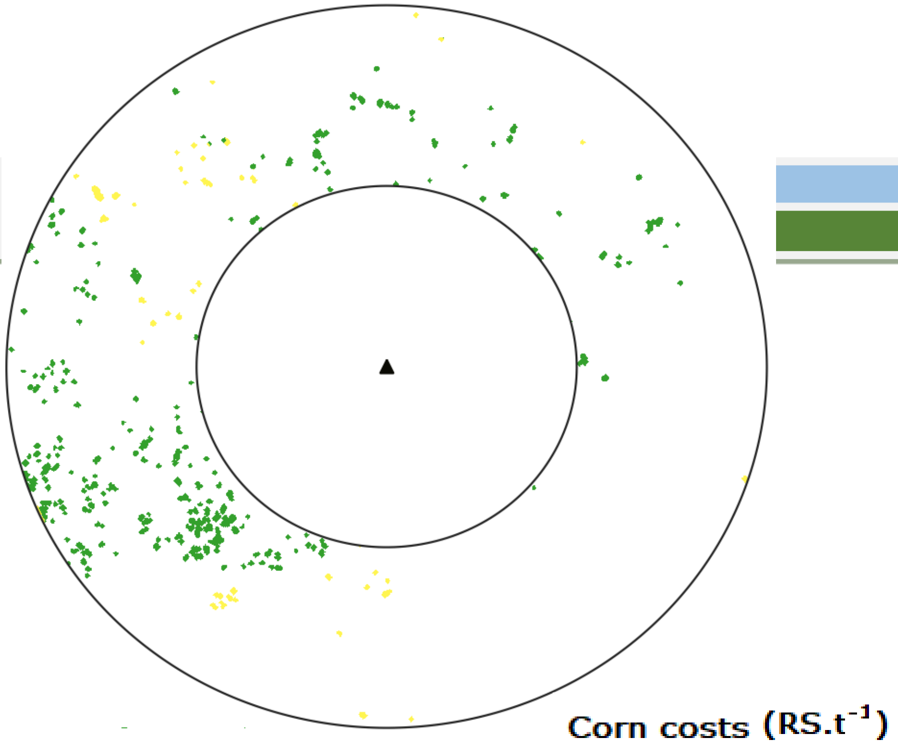
- Seeking both the limits of crushing sugarcane capacity and of anhydrous ethanol production in the 55 mills assessed, the results on the supply curve are presented in the upper figure: the maximum anhydrous supply almost doubles, reaching 6.1 x 10^9 litres.year^{-1}.
- Few plants - nine out of 55 - would be able to supply all the anhydrous needed in the case of SAF's largest production unit. The advantage would be for mills with larger capacity of anhydrous production, located in GO (i.e. lower opportunity cost) and/or those located closer to the terminals (i.e. lower transport cost – by truck).
- As the assumption in this variant of the case study is that anhydrous producers would continue to receive the value corresponding to opportunity costs in 2018 (i.e. market prices), the impact on the SAF's estimated MSP is tiny – less than 1%, or 0.2 €.GJ^{-1}, maximum.

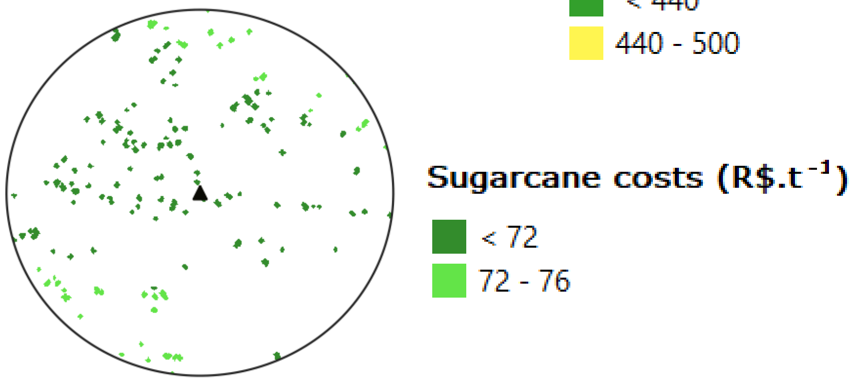
Case study 3 (1)



- The rationale of the third version of this case study is that the production of ethanol would take place in new anhydrous production units, using sugarcane and corn as raw material (the so-called flex plants).
- A second assumption is that these new mills would be close to the pipeline (i.e. to the existing branch or to the branch that is planned to be built) or, alternatively, to railroads.
- The procedure requires a combination of basic information for sugarcane and corn (i.e. suitability, yields and costs). The green areas in the figure are those in which there is both suitability for the production of sugarcane and corn as second crop.
- The four sites chosen are close to Prata (MG), Caçú (GO), Paranaíba (MS) and Presidente Venceslau (SP). The circles indicate the areas assessed for the production of sugarcane and corn.

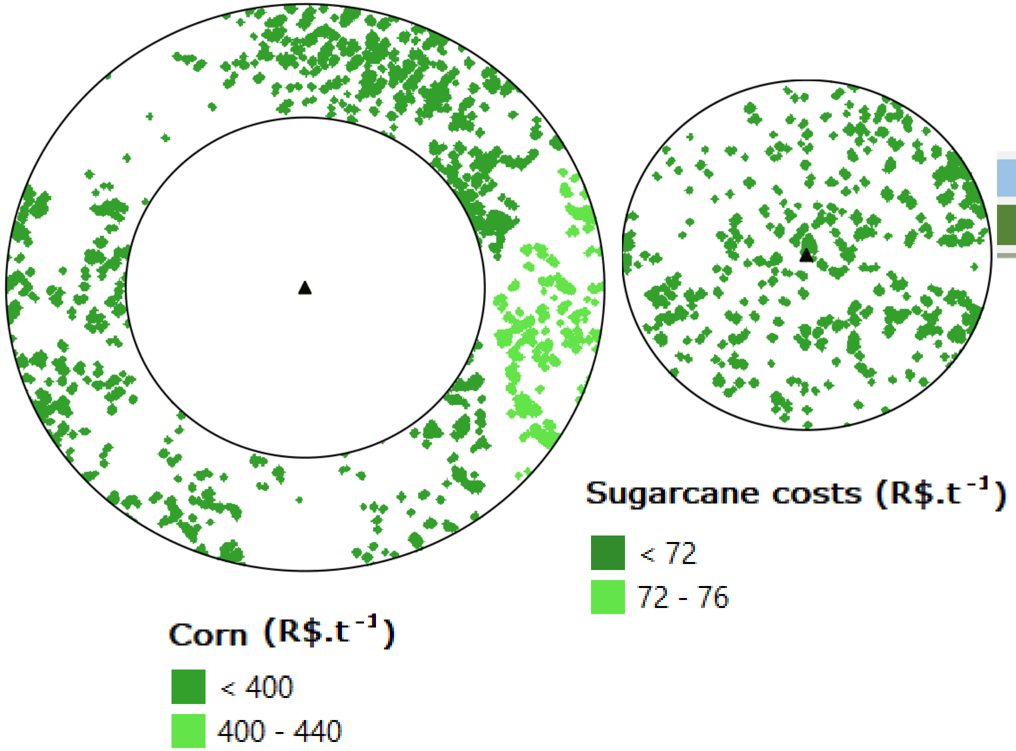
Case study 3 (2)

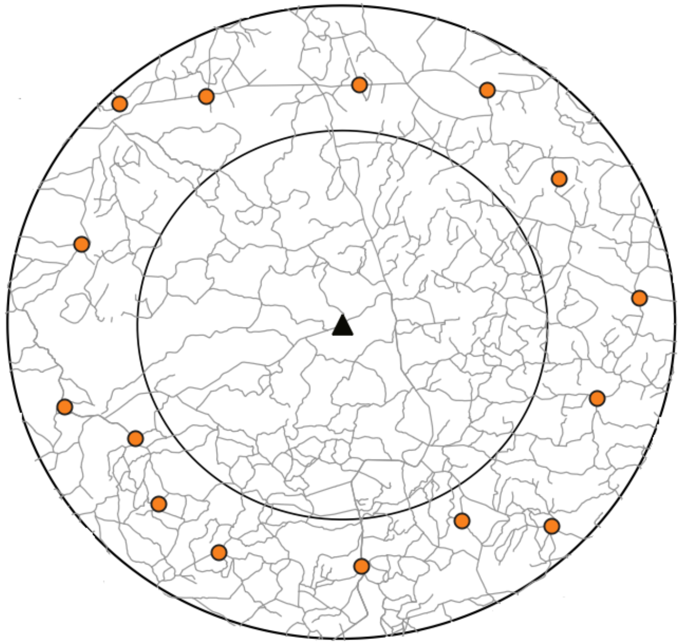




- In the assessment, 100 hectares was assumed to be the minimum level of aggregation (considering the need for mechanization of planting and harvesting, both for sugarcane and corn). Depending on the case, this assumption results in the failure to consider larger potentially suitable areas.
- This was the case in Prata (MG), as can be seen in the figures, with impact on the potential of crops and on the size of the ethanol plant.
- It was assumed that sugarcane production would occur within the 30 km radius circle with the center at the location chosen for the plant, while the production of corn would occur in the surrounding ring, which has an external 50 km radius. In the case of Prata, 70 km and 100 km were considered, respectively for the inner and outer radius.
- The estimated costs of sugarcane include the transport to the mill (for this reason, the production would be concentrated around the unit), while the corn costs include the transport to intermediate warehouses.

Case study 3 (3)



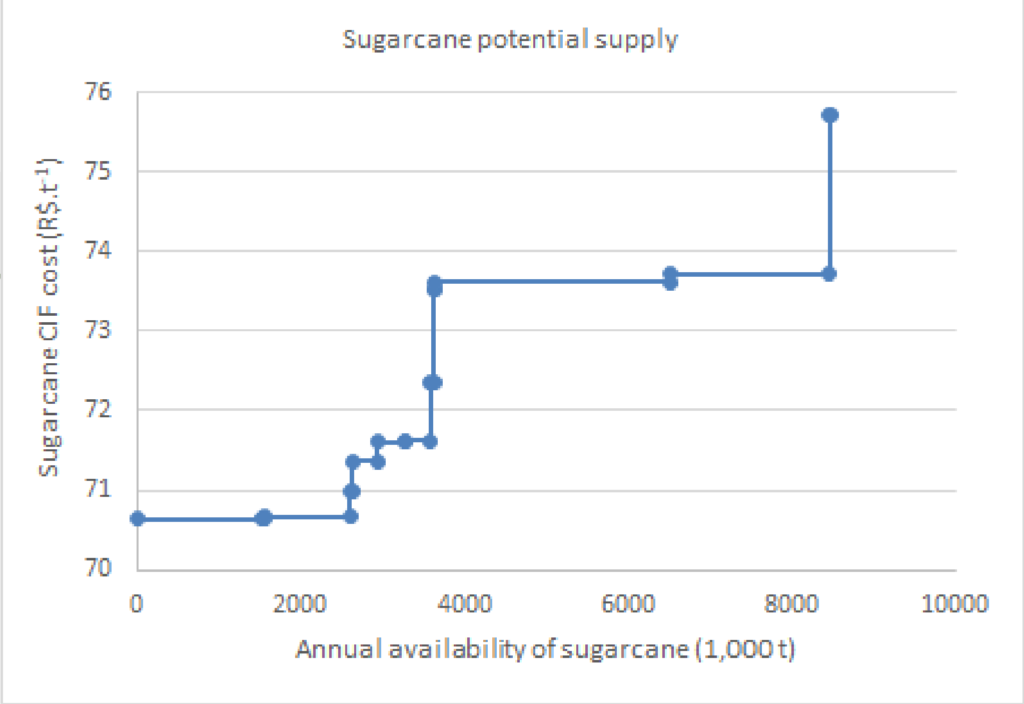


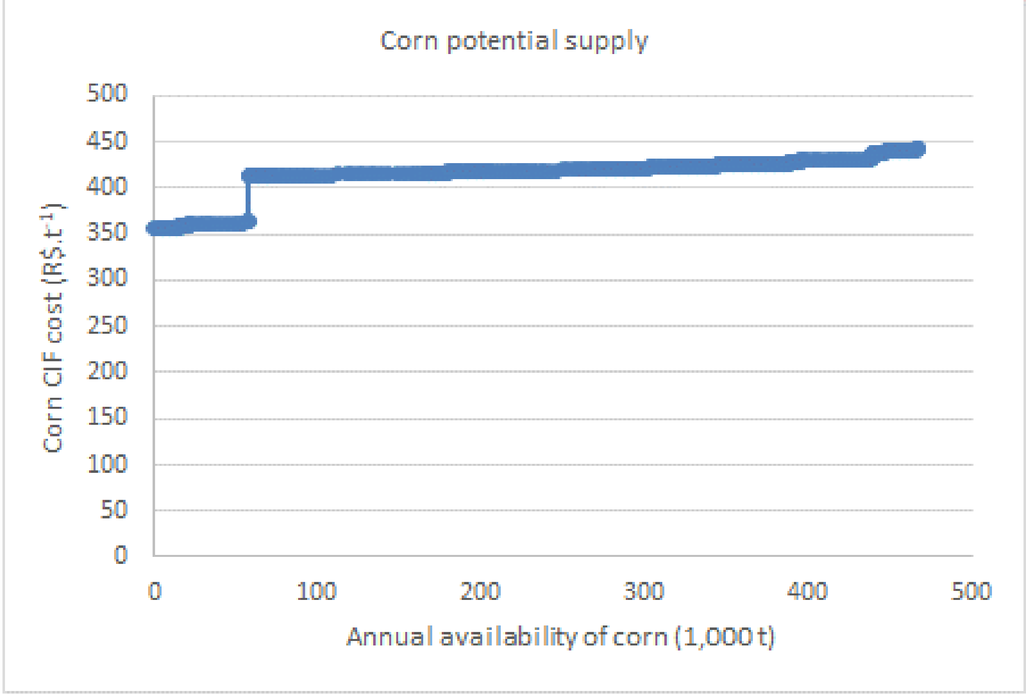
- The upper figures show the estimated selected areas for sugarcane and corn production around Paranaíba (MS). In the inner circle 72.8 thousand hectares could be used for sugarcane production, while in the external ring 141.6 thousand hectares is the estimated area for crop production.
- The figure below illustrates the rationale used to define the position of the corn warehouses (the dots distributed along the external ring), which are intermediate between the planting areas and the mills. They were distributed along the area, close to paved roads, maintaining an average minimum distance of 25 km from each other. From these warehouses corn would be transported by truck to mill.

Case study 3 (4)

Feedstock	# of operating days	Capacity 1	Capacity 2	Capacity 3	Capacity 4
Sugarcane (operation and processing capacities)	200	2,000 kt.year^{-1}	2,500 kt.year^{-1}	3,500 kt.year^{-1}	4,000 kt.year^{-1}
Corn (operation and processing capacities)	120	262.8 kt.year^{-1}	328.5 kt.year^{-1}	459.8 kt.year^{-1}	591.2 kt.year^{-1}
Anhydrous annual production (10^6 L.year^{-1})	Only sugarcane	171.0	213.8	299.3	384.8
Anhydrous annual production (10^6 L.year^{-1})	Sugarcane + corn	270.8	338.5	473.8	609.2

- The industrial configuration of ethanol production corresponds to one of the various alternatives presented in BNDES (2014), supposing just anhydrous production (i.e. autonomous distillery). The unit would be able to produce ethanol from sugarcane along seven months and, complementarily, from corn along almost five months. Sugarcane residues (bagasse and straw) would be used as fuel all over the operating period. The reference unit would process 3,000 kt of sugarcane per year. Some information of the four industrial capacities of anhydrous production considered here are presented in the table.
- The investments and operational costs presented by BNDES (2014) were assumed in this case study, and these costs (for the reference unit) were scaled based on a study for World Bank (Gouvello, 2010). The costs were corrected to 2018 using the IGP-M.
- In the procedure for estimating anhydrous production costs, revenues from the sale of surplus electricity and DDG were considered. See Supplementary Material for details.

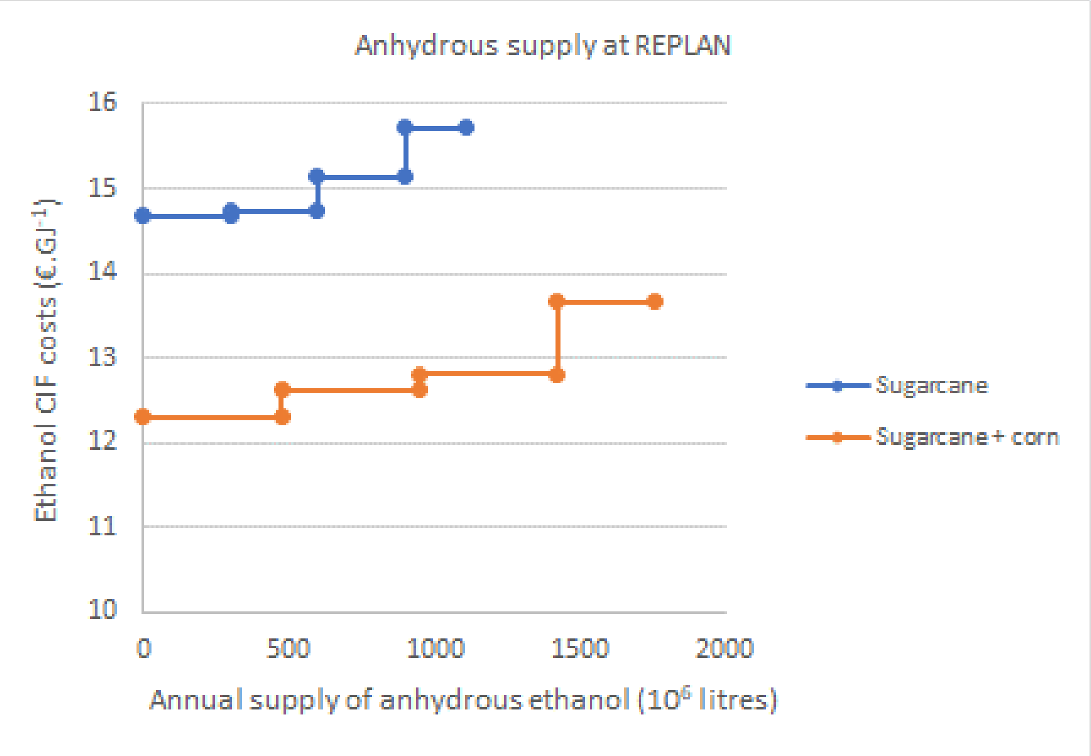




Case study 3 (5)

- As an illustration, here the supply curves of sugarcane and corn at the mill in Presidente Venceslau are presented.
- The upper figure shows the supply curve for sugarcane at the mill site. The maximum potential supply considering the circle of 30 km radius is about 8.5 million tonnes per year, and CIF costs vary from 70.6 R$.t^{-1} to 75.3 R$.t^{-1}.
- The second figure shows the supply curve of corn at the mill site, also considering the transport cost from warehouses to the mill. The maximum supply was estimated at 467 kt.year^{-1} and CIF costs vary from 356.4 R$.t^{-1} to 428.7 R$.t^{-1}.
- In order to standardize the analysis, and reduce the impacts of scale, in three sites the plant size was defined as “Capacity 3” (see previous slide), but in Prata (MG), due to the restrictions previously mentioned, the plant size was defined as “Capacity 2”.

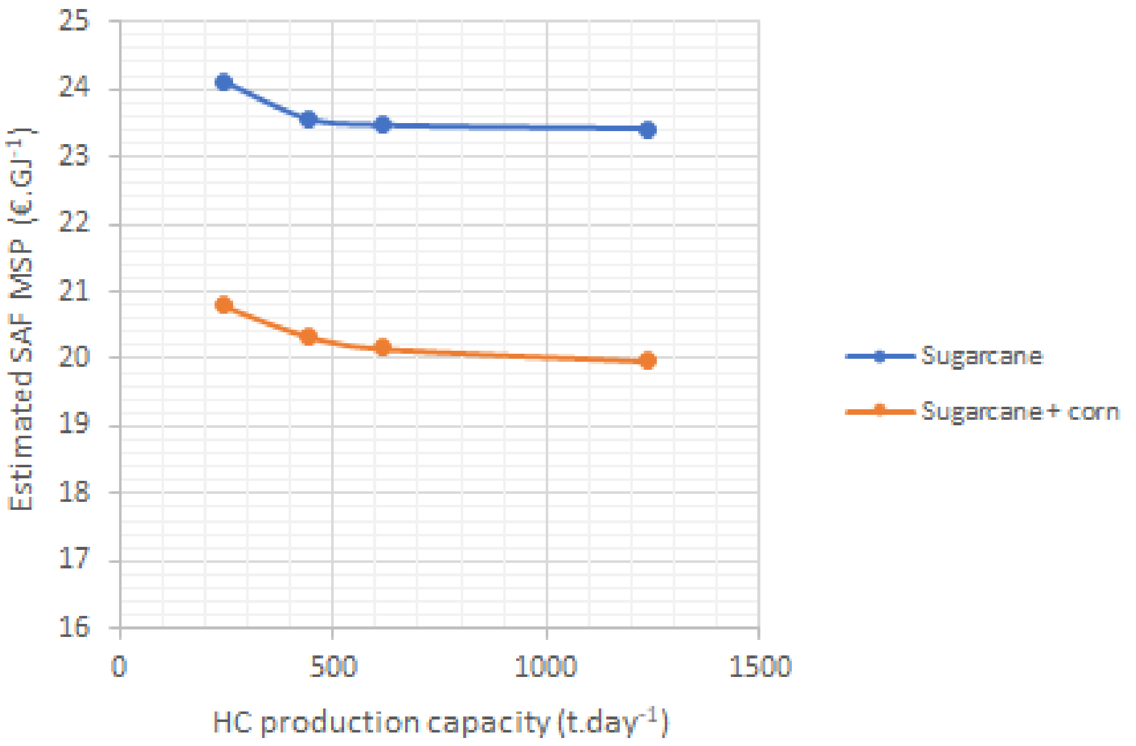
Case study 3 (6)



- The best options of transporting ethanol to REPLAN would be by pipeline in case of Caçú (GO) and Prata (MG) (using the terminals in Quirinópolis and Itumbiara, respectively), and railway in the cases of Presidente Venceslau and Paranaíba (in the last case, first transporting from the mill to Aparecida do Taboado, by trucks – the distance is less than 60 km). Transport costs represent 3.5-5.0% of the CIF costs at REPLAN.

- The figure shows the supply curve of anhydrous ethanol from the four sites considered. The combined production from sugarcane and corn reduces CIF costs at REPLAN 15-20% and enlarge the maximum supply by 58%.
- Assuming production only from sugarcane, the best producer site would be Presidente Venceslau (SP), but assuming combined production the best supply site would be Paranaíba (MS).
- For the maximum capacity of SAF production at REPLAN (305.5 $kt.year^{-1}$) it would be necessary to supply 1,019.8 x 10^6 $L.year^{-1}$ of anhydrous. Assuming that anhydrous would be produced just from sugarcane, all four sites would contribute, being Prata (MG) the site with higher costs. However, assuming the combined production from sugarcane and corn, the contribution of Prata would not be necessary.

Case study 3 (7)



- The figure shows the results of the estimated minimum selling prices (MSP) of SAF, for four industrial capacities (SAF production varies from 60 to 305.5 kt.year^{-1}).
- Anhydrous production from sugarcane and corn lead to a reduction of about 14% on SAF's MSP.
- As the cost of the raw material represents a large part of the MSP (87% in the case of the largest unit; anhydrous produced from sugarcane and corn), the scale effect of the industrial SAF production unit is less pronounced. Considering the extreme cases (the smallest and the largest plants), the MSP variation is less than 5%.

Analysis of the results (1)

- Table presents the best results in each of the three variants here considered for the assessment of the ATJ route.
- In all three cases the smallest MSP is for an industrial plant able to produce 930 $t.day^{-1}$ of SAF, or 305.5 thousand $t.year^{-1}$. This unit requires 1,020 x 10^6 million litres of anhydrous per year.
- In all cases the SAF production would be at REPLAN and anhydrous would be transported (mainly) by pipeline or railway.

Feedstock	MSP (€.t^{-1})	MSP (€.GJ^{-1})	Comments
Case 1	1,239.3	29.0	Based on anhydrous produced in 2019[1]
Case 2	1,231.7	28.8	Based on anhydrous produced and additional production[2]
Case 3	855.0	20.0	Ethanol production in four sites, in new mills[3]

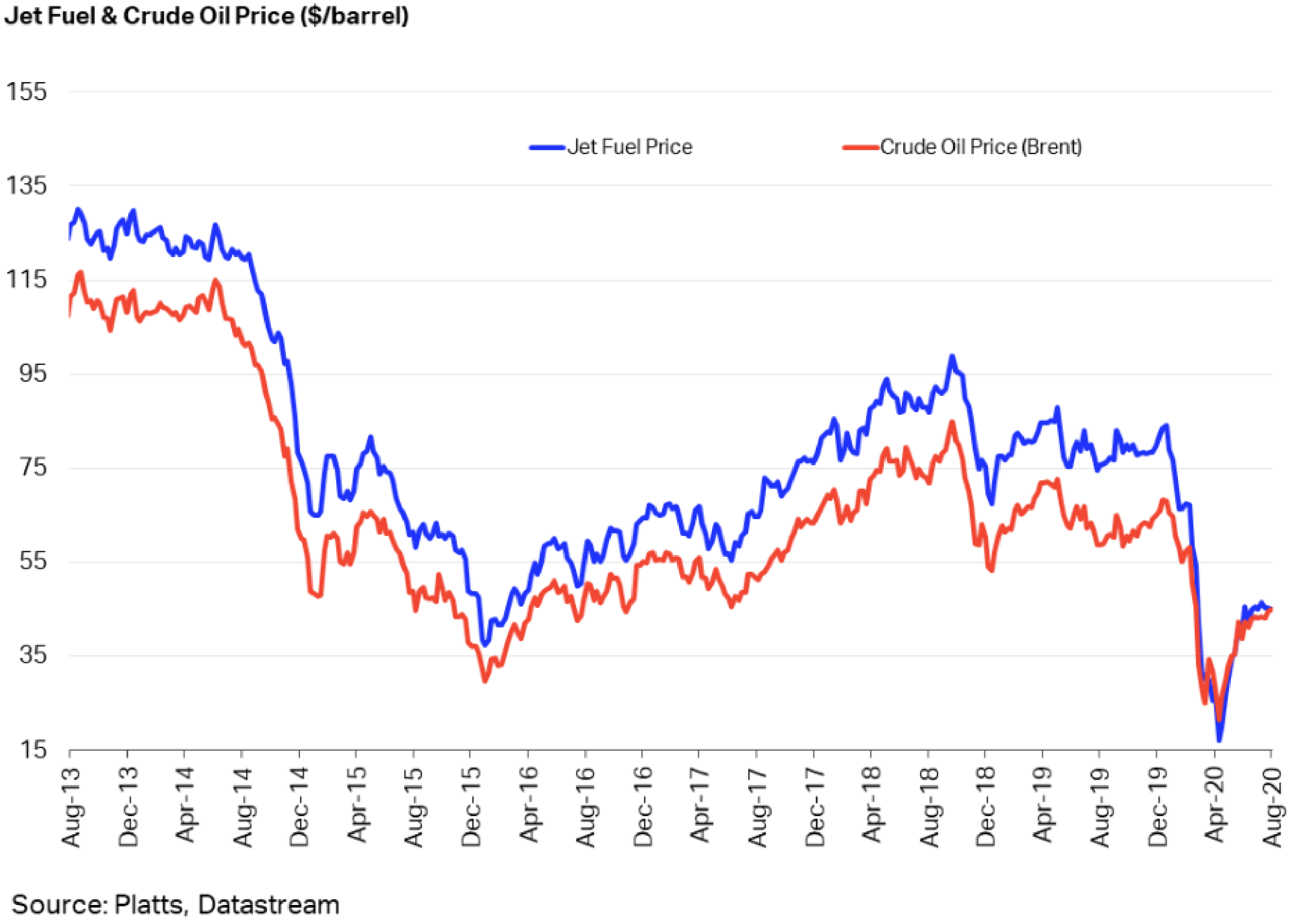
[1] Potential supply from 43 mills nearby an existing pipeline, being 16 the mills with lower CIF costs.

[2] Potential supply from 55 mills, being nine the mills with lower CIF costs To increase production, additional crushing of sugarcane was considered and also the shift from hydrous to anhydrous ethanol production.

[3] Anhydrous ethanol production from sugarcane and corn (flex mill). 23.4 €.GJ^{-1} in case of ethanol from sugarcane.

- MSP results could be compared to 52-78 €.GJ^{-1}, which is the range presented by de Jong et al. (2015) assuming the production in Europe based on the ATJ-SPK pathway, from 2nd generation (2G) ethanol (production not yet commercial). The industrial plant assumed in the reference study is lower (182.6 $t.day^{-1}$ of SAF) than the cases reported in the table.
- Also considering the SAF production from 2G ethanol, Bosch et al. (2017) estimated the MSP in the 2,300-3,500 €.t^{-1} range (ethanol produced from forest residues and wheat straw, respectively).
- According to Platts Global Index the conventional jet fuel price was 622 €.t^{-1} in May 2018 (see next slide).

Comparing MSPs with jet fuel prices



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

- Jet fuel market prices is extremely correlated with international oil prices, as shown in the figure.
- Platts Global estimated the jet fuel price at 622 €.t^{-1} in May 2018, but in August 2020 the price was close to 300 €.t^{-1} due to the low international oil price.
- The Platts Global Index indicates that the index price in Latin America is about 12% higher than the global figure. Compared with the world average, in Europe it is about 6% lower and in North America about 8% higher (see Supplementary Material).

Analysis of the results (2)

- Considering the opportunity cost of anhydrous ethanol in Brazil in 2018 (18-19 €.GJ^{-1}), the MSP of SAF (ATJ-SPK route) would be close to 30 €.GJ^{-1}, which would make the option barely feasible in case economic incentives do not exist. However, considering the production of self-dedicated ethanol it would be possible to reach MSP in the 20-24 €.GJ^{-1} range, depending on the scale of anhydrous and SAF production.
- For the estimated MSPs the break-even price of jet-fuels would be about 130 US$ and 185 US$.$barrel^{-1}$, for the results of Case 3 and Cases 1-2, respectively. As can be seen on the previous slide, international oil prices compatible with those of 2014 would make the production of SAF from anhydrous viable (considering self-dedicated production).
- Potentially, the production of sugarcane and corn (here considered corn as a complementary feedstock) reduces ethanol costs. In this case, as is known from the current experience of ethanol production in Brazil, a fundamental aspect is the availability of cheap corn (for example, as a second crop).
- Despite the fact that the impacts on the SAF's MSP of transporting ethanol would be relatively small, it is predicted that the impacts on the carbon footprint could be considerable.

Eligibility under CORSIA (1)

SAFmaps

- Eligible fuels in the context of CORSIA include Sustainable Aviation Fuels (SAF) (produced from biomass or residues) and Lower Carbon Aviation Fuels (LCAF) (from fossil energy sources). In both cases the production must be certified according sustainability. For SAF, in the CORSIA pilot phase (2021-2024) stricto sensu only two principles must be accomplished (see Supplementary Material): 1) SAF must contribute with lower carbon emissions on a life cycle basis, and 2) should not be made from biomass obtained from land with high carbon stocks. However, sustainability schemes must require the accomplishment to other sustainability principles.
- Here, the accomplishment of Principle 2 is assured by the fact that the production of sugarcane and corn would occur displacing pasturelands, in areas that were not converted after January 2008.
- Regarding Principle 1, the Default Life Cycle Emissions Value for the ATJ route based on sugarcane ethanol in Brazil indicates a Core LCA value of 24.1 $gCO_2eq.MJ^{-1}$, while the estimated ILUC LCA is 8.7, totalling 32.8 $gCO_2eq.MJ^{-1}$ of the bio-jet fuel (ICAO, 2019). As the carbon footprint of the fossil jet fuel is 89 $gCO_2eq.MJ^{-1}$, avoided GHG emissions on life cycle basis would be 63.1%. However, the total default value for SAF production from corn grains in US is estimated at 90.8 $gCO_2eq.MJ^{-1}$ (65,7 + 25.1 $gCO_2eq.MJ^{-1}$) what makes not possible the accomplishment of Principle 1.

Eligibility under CORSIA (2)

- It is predicted that the results could be better in case of using corn produced as 2nd crop, as it is reported below. However, as foreseen in CORSIA, in this case the producer would have to develop his own evaluation, associated with the particularities of the case.
- In BNDES (2014), results of GHG emissions due to the production of 1 MJ of hydrated ethanol are presented, considering the "cradle to the grave", attributional procedure. The results that correspond to the configuration here used as reference (ethanol production from sugarcane, having corn as supplementary feedstock) shows emission factor equal to 29.1 $gCO_2eq.MJ^{-1}$.
- Moreira et al. (2020) assessed the production of ethanol from corn in Mato Grosso (Centre-West of Brazil). For emissions calculated via the 'separate treatment' approach, as mentioned by the authors, the emissions resulted in 25.9 $gCO_2eq.MJ^{-1}$, while when the economic allocation approach was used, the emissions dropped to 18.3 $gCO_2eq.MJ^{-1}$.
- In Moreira et al. (2020) it is considered that eucalyptus would be used as fuel and this can have a positive impact depending on where eucalyptus would be produced. This hypothesis was not used here.
- A controversial issue could be the ILUC (Indirect Land Use Change) share. In the published CORSIA default life cycle emissions values the ILUC component is 7.3 $gCO_2eq.MJ^{-1}$ for ATJ based on sugarcane in Brazil, and 27.0 for HEFA-SPK from soy oil (CORSIA, 2019).

Other sustainability aspects

- Producers can be criticized for practicing extensive monocultures. It was estimated that for supplying feedstock to new mills, sugarcane would cover from 10% to 14% of the total areas inside the circles with 30 km radius, and corn would cover no more than 13% of the total areas assessed (in case of Prata, much less than that both for sugarcane and corn, due to the constraints previously mentioned).
- It is worth remembering that the areas evaluated for the cultivation of sugarcane and corn were occupied by pastures in 2018. In the case of corn, production was assumed in association with another crop (it was considered that this would be soybean).
- The possible impacts on biodiversity would be minimized, since in the assessment presented here sensitive ecosystems and preserved areas were defined as no-go areas.
- The same can be said in relation to socioeconomic impacts, as indigenous reserves, afro-descendant settlements and municipalities with reported violations of land use and water use rights were considered areas of exclusion.

Conclusions

- The reported case study addresses the production of SAF through the route ATJ-SPK, from anhydrous ethanol produced from sugarcane or sugarcane and corn. Three variants were developed, being two of them based on existing assets of ethanol production from sugarcane. The third variant considers new producing areas and new mills, with production based on sugarcane or sugarcane plus corn.
- Assuming that ethanol producers would be paid by the opportunity cost (2018 values were used), the estimated minimum selling price (MSP) of SAF production is not as encouraging, since the MSP would be between 29-30.5 €.GJ^{-1}, depending on the hypotheses considered. However, considering self-dedicated production of anhydrous ethanol in new mills located in favorable locations (e.g. considering yields, costs and transportation facilities) - therefore the most favorable scenario that could be defined, the MSP drops to 23-24 €.GJ^{-1} in the case of ethanol production only from sugarcane and to 20-21 €.GJ^{-1} in case of production from sugarcane and corn, where the cost of corn (as a second crop) is not high. Obviously that feasibility would be significantly enhanced.
- The chances of being effectively considered sustainable aviation fuel would be high, based on the premises considered in this case study. Avoided GHG emissions would be equivalent to 63% in the case of production from sugar cane ethanol, but avoided emissions would have to be estimated specifically for the case of production from sugarcane and corn - an mainly regarding the ILUC share. However, according to studies available in the literature, it is possible to be optimistic.
- For the other aspects of sustainability, the case study was developed taking into account that the potential risks must be minimized to the maximum. Therefore, it is reasonable to consider that no major problem would be raised.

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

Case study: ATJ pathway / ethanol from sugarcane and corn Supplementary Material

SAFmaps

UNICAMP

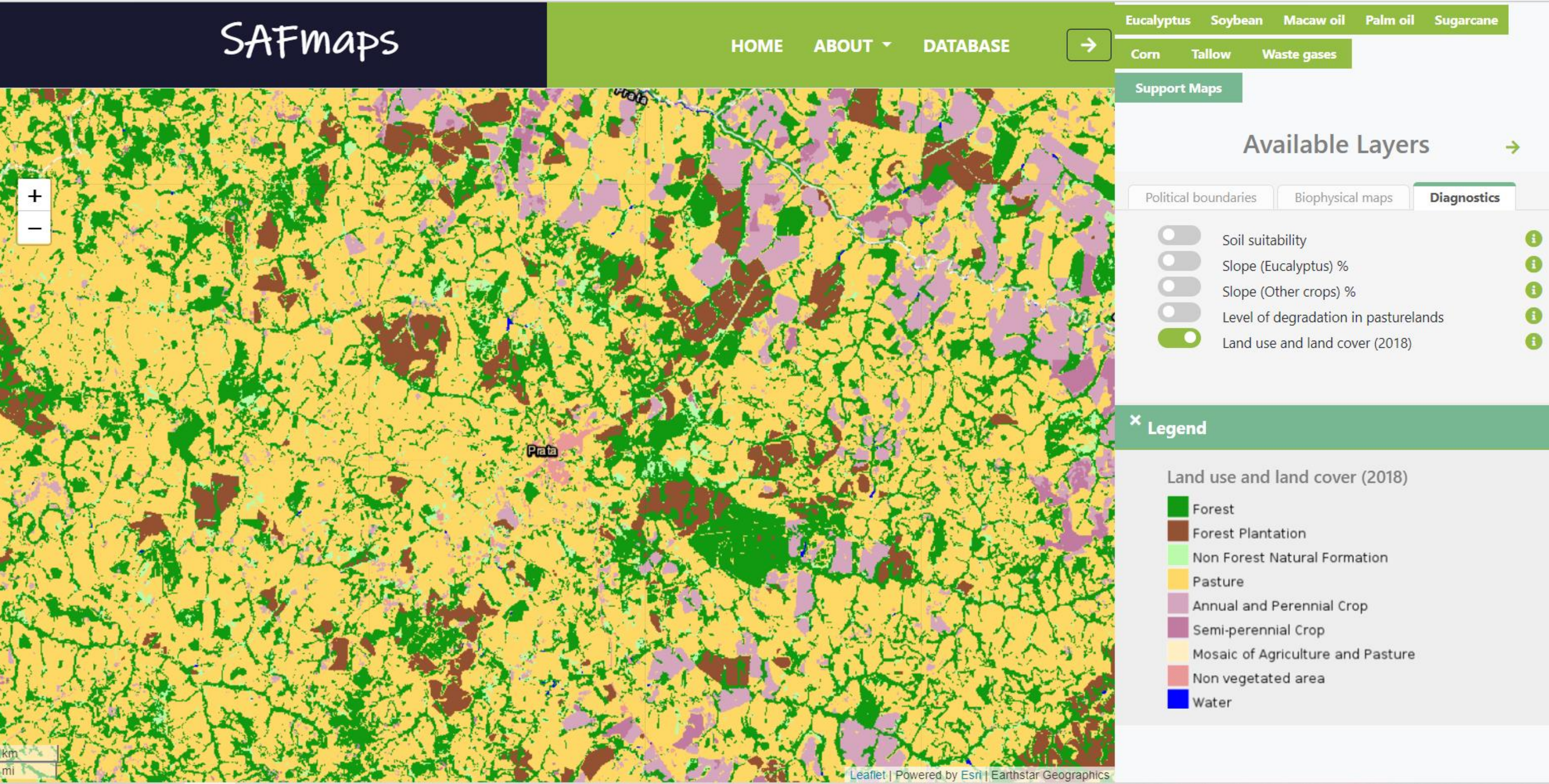
List of Contents

- Land use and land cover;
- Sensitive areas;
- Reported violations to land use and water use rights;
- Zoning for corn as 2nd crop;
- Transport by rail and/or pipeline;
- Prices paid to ethanol producers;
- Jet fuel prices;
- About CORSIA and eligible fuels;
- Agricultural costs;
- Ethanol producing costs;
- SAF industrial costs.

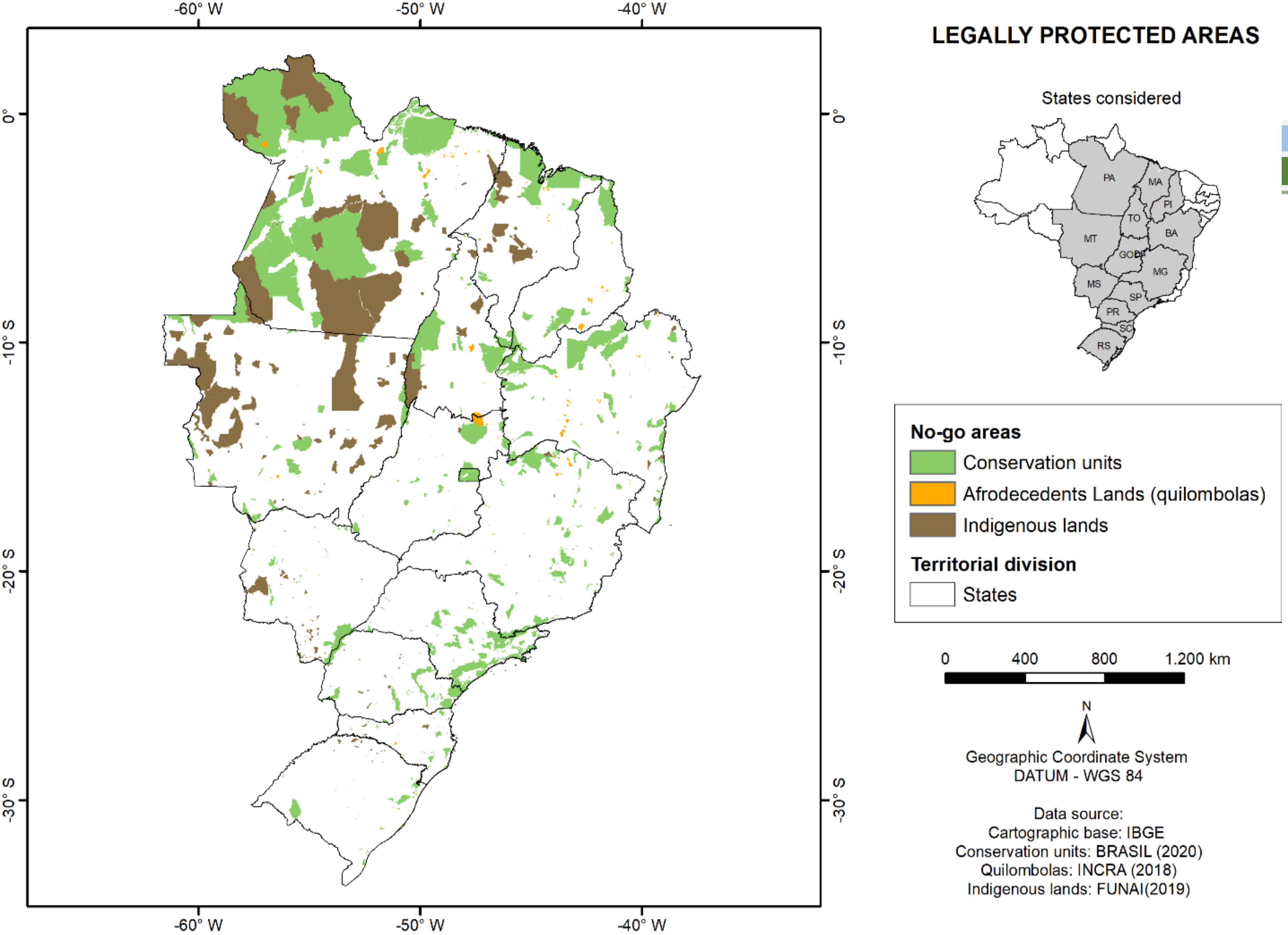
Land use and land cover in 2018

- Information of land use and land cover available at the platform database corresponds to 2018. The source is MapBiomas.
- Figure shows the land use & land cover map available at the platform and used in this study. The image available at the platform does not present details for state of Pará, but all images from the MapBiomas project can be accessed through “Useful links”.
- The next slide shows a zoom-in image for Prata, Minas Gerais.

Land use and land cover in 2018 – zoom-in in Prata (MG)

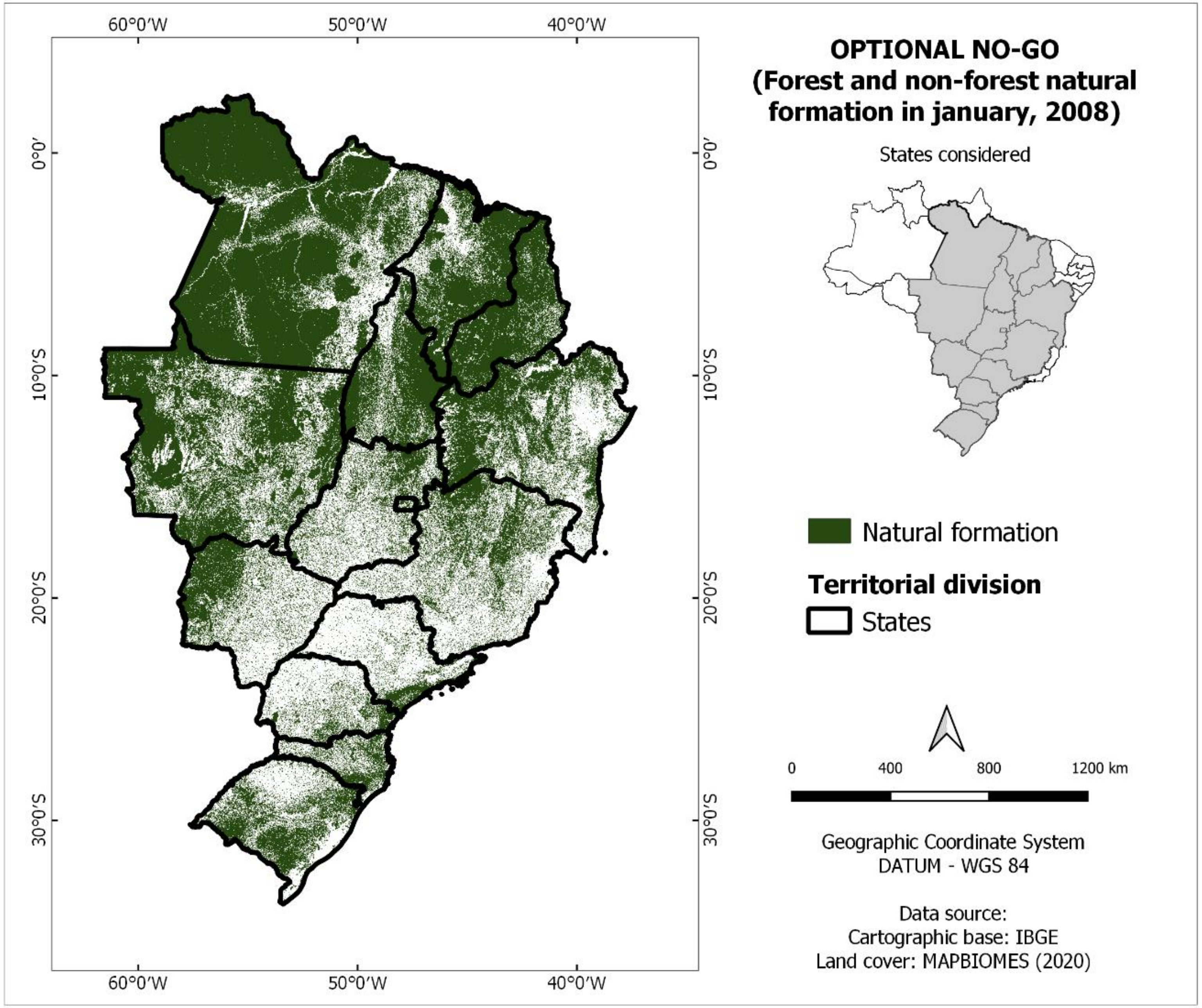


Sensitive areas (1)

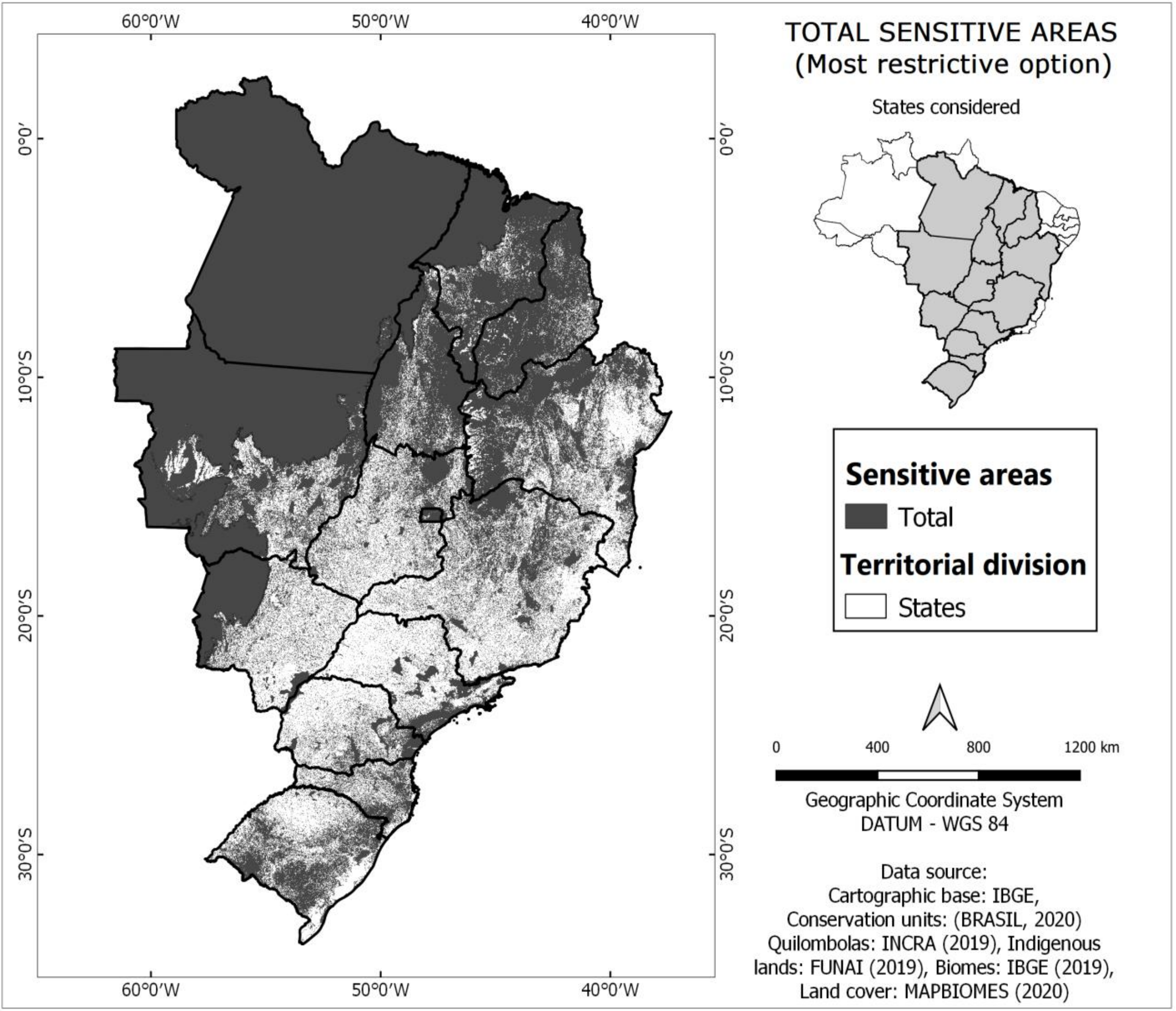


- Feedstock production cannot occur in legally protected areas.
- Legally protected areas include conservation units (for environmental reasons), the land that belongs to Afro-descendants (i.e. quilombola areas, or Afro-Brazilian settlements) and reserves of indigenous peoples.

Sensitive areas (2)

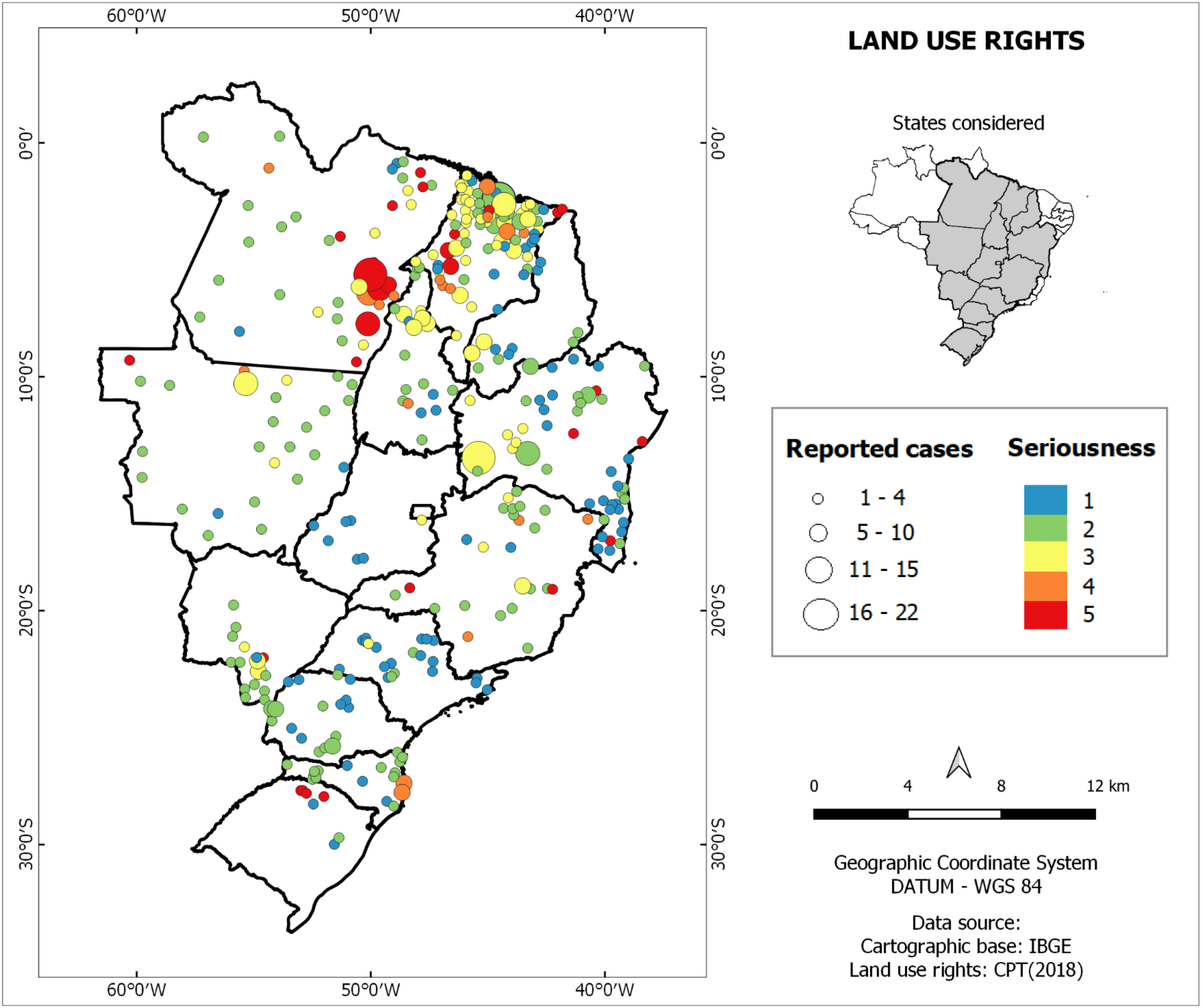


- According to CORSIA, SAF cannot be made from feedstocks obtained in certain areas (for example, primary forests, wetlands, etc.) where land was converted after January 1, 2008 (see information about CORSIA).
- In this sense, a map of land uses and land cover by the end of 2007 was used to define - 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)

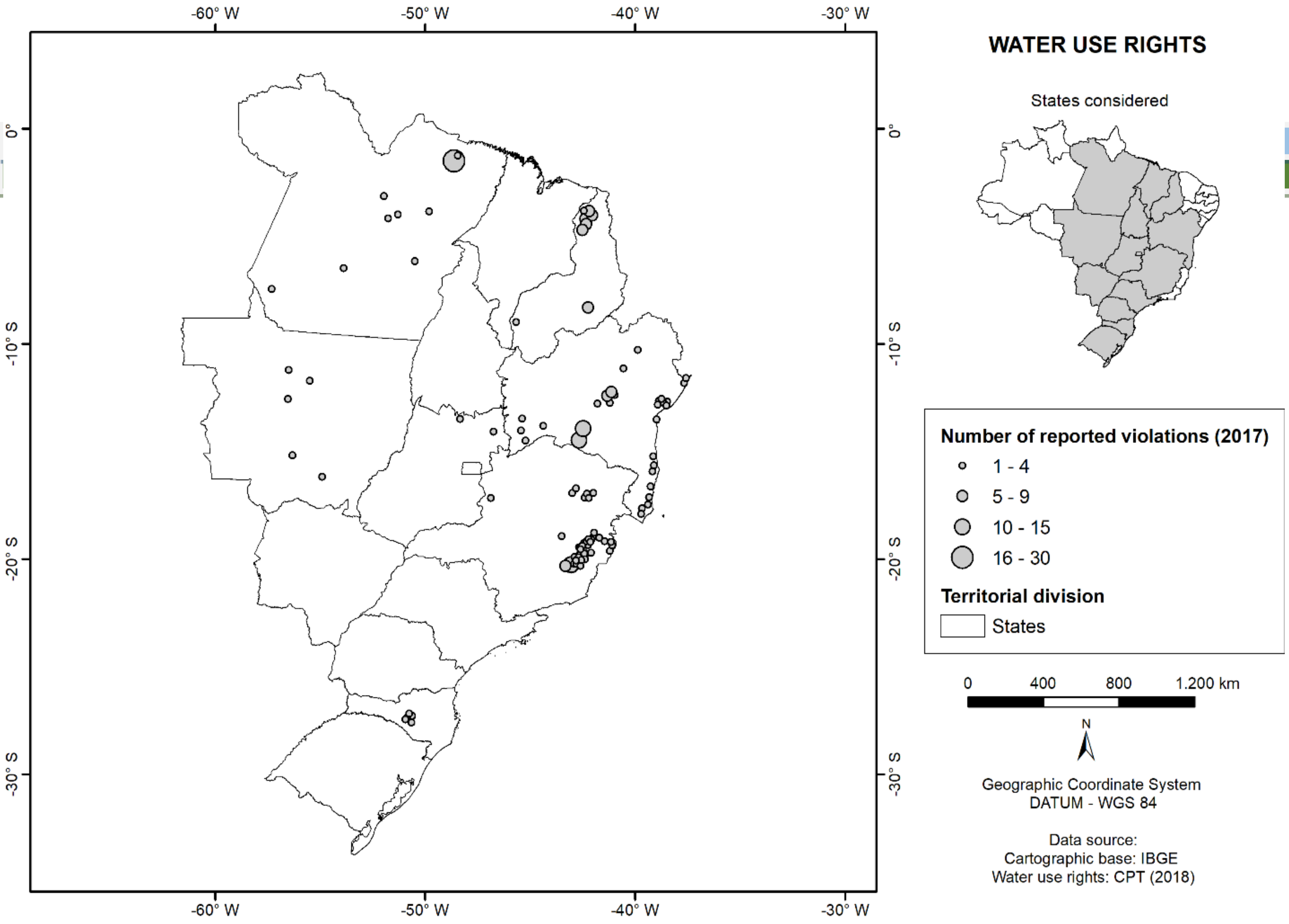
- CPT – Comissão Pastoral da Terra – is an organization linked to the Catholic Church (https://www.cptnacional.org.br/).
- CPT compiles information of reported violations to land use and water use rights.
- The figure shows the locations of reported violations to land use, in the 2016-2018 period.
- 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).



Land use rights

- CPT – Comissão Pastoral da Terra – is an organization linked to the Catholic Church (https://www.cptnacional.org.br/).
- CPT regularly 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). Reported cases is the number of registers in CPT database (in each municipality).

Water use rights



- The number 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.
- Both for land and water use, the reported violations are related to different economic activities (not just to agriculture).

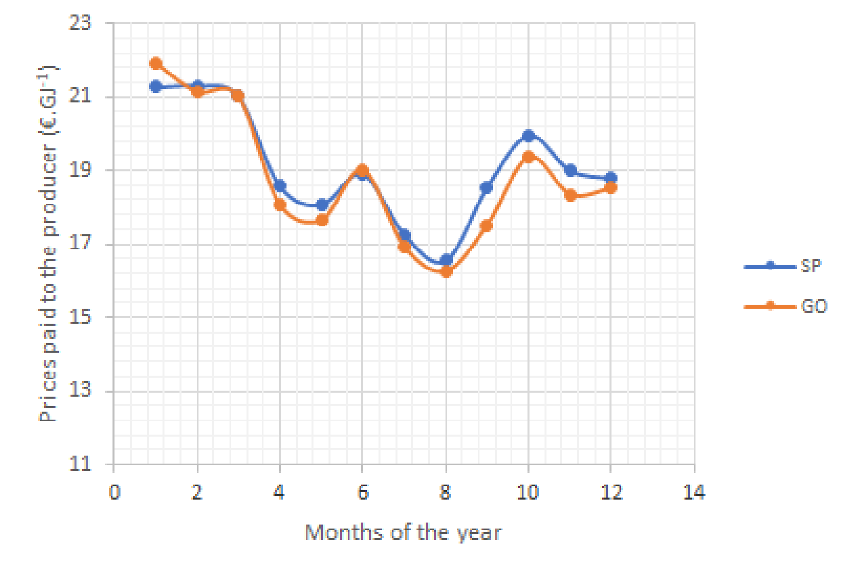
Agro-zoning for crop as 2nd crop

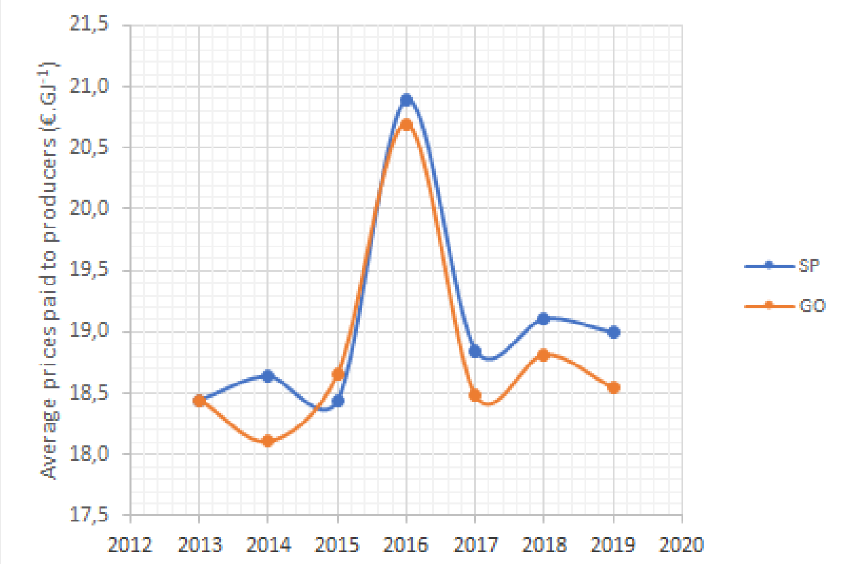
- In order too define climate suitability, the results of the Climate Risk Agricultural Zoning were used (EMBRAPA, 2020), study that identifies the municipalities suitable and the sowing periods for the cultivation of 2nd harvest corn. Three levels of risk were defined in the procedure: 20%, 30% and 40%. Here, risk of up to 20% was associated with suitability while, to be more conservative, risk 40% (at least) was associated with non suitability. By difference, the marginal areas from the climatic point of view were defined.
- In the study, the risk classification was defined in each sowing period based on the frequency of the ISNA parameter and also on the thermal limit. It was not considered the use of irrigation systems.
- In the Centre-West, Southeast and in some regions of the State of Paraná, there is a high coincidence between the municipalities with soybean and 2nd crop corn plantations and, for this reason, the procedure applied here also took into account suitability for soybean (Landau et al., 2015).
- In the case of the Northeast and North regions, the data made available by IBGE referring to the 2nd annual corn harvest correspond, in fact, to the 1st agricultural corn harvest, which is planted at the same time of the year in which much of the country occurs the plantings of the 2nd agricultural harvest (Landau et al., 2015). North and Northeast regions were excluded from the procedure of estimating yields.

Transport by rail and/or by pipeline

- In order to estimate the cost of transporting ethanol by rail instead of by truck, a literature review was carried out. Freight costs vary with several factors, especially with the distance and the number of transfers. The same estimated road distance between the embarkation point and the SAF industrial production unit (REPLAN) was assumed for the railway distance. No transfer was assumed between the source and the destination.
- From the literature review (Forkenbrock, 1998; Leite et al. 2016; Lemos, 2020), it was observed that the cost ratio of rail/road freight, expressed in $\$.t^{-1}.km^{-1}$, varies between 0.31 and 0.74 for distances greater than 1,000 km, with a clearer indication that 0.50 could be used for a preliminary assessment (value assumed here).
- The existing pipeline connects Itumbiara (GO) to REPLAN, in Paulínia (SP). It is predicted two new terminals, in Jataí (GO) and Quirinópolis (GO). The lengths of each segment are know, and the total extension from Jataí to REPLAN would be 916 km.
- Vassalo (2015) states that the transport of liquids by pipeline is 4.5 to 5.7 times cheaper (in $\$.t^{-1}.km^{-1}$) than the transport by trucks. Here it was used 5.1 for estimating the costs.

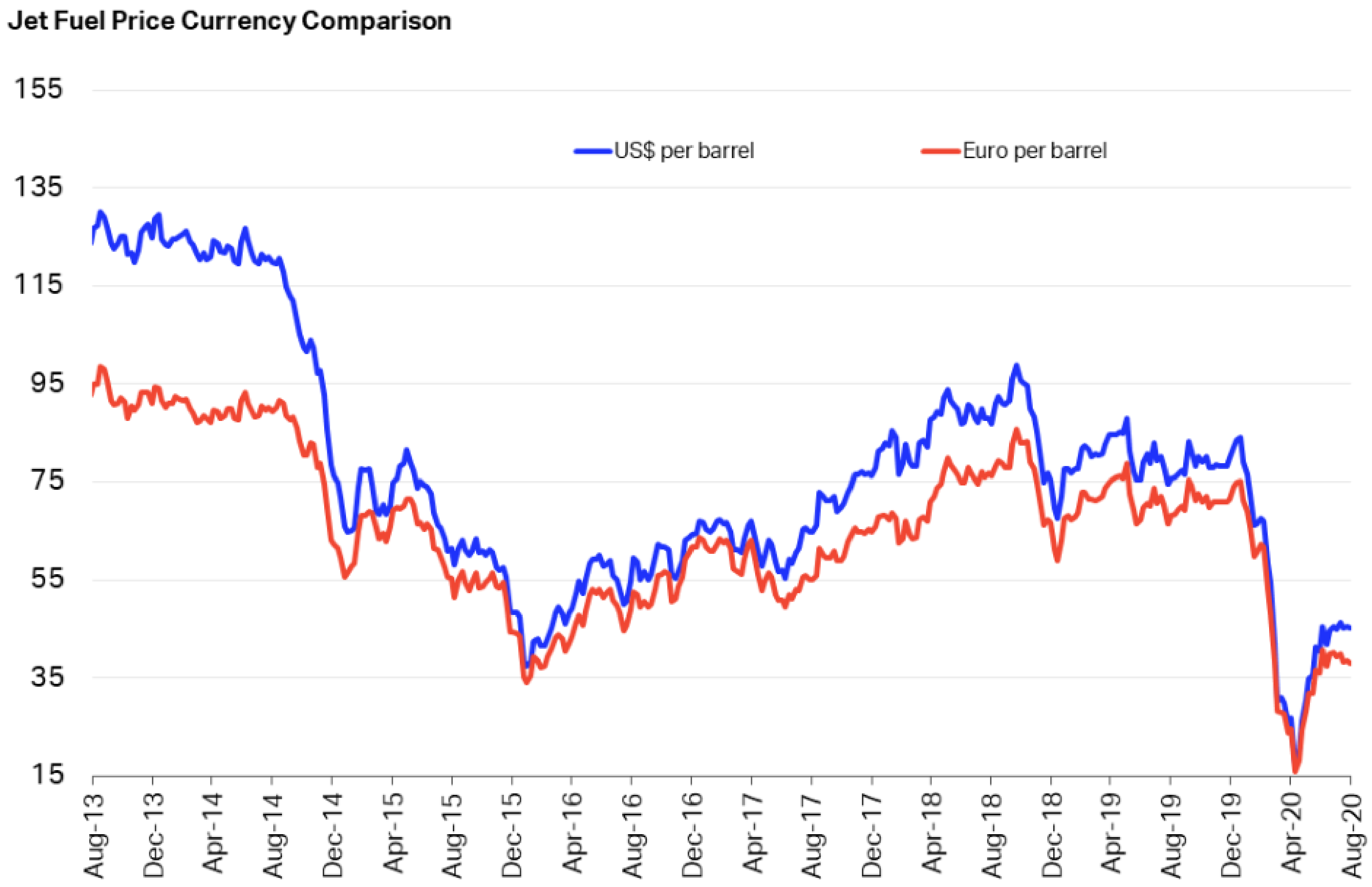
Prices paid to ethanol producers





- CEPEA is a research center belonging to the School of Agronomy (ESALQ) at the University of São Paulo (USP). Among other duties, CEPEA regularly surveys the prices of agronomic products. In the case of ethanol, its web page publishes the prices paid to producers of hydrated and anhydrous ethanol in nine producing states (average values), on a weekly or monthly basis (CEPEA, 2020). Here it was taken the data series for anhydrous in São Paulo and Goiás.
- As an illustration, the figures show the prices paid to producers along 2018, in São Paulo and Goiás (the upper one) and the average prices paid in the 2013-2019 period in both states (at the bottom).
- For the Cases 1 and 2 it was considered the average prices paid to producers in 2018.

Jet fuel prices: historical data and worldwide variations



Source: Platts, Datastream

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

- Figure shows the evolution of jet fuel prices (global average) from August 2013 to August 2020.
- Table below shows, as an illustration, the jet fuel average prices in different regions, in May 15, 2020.

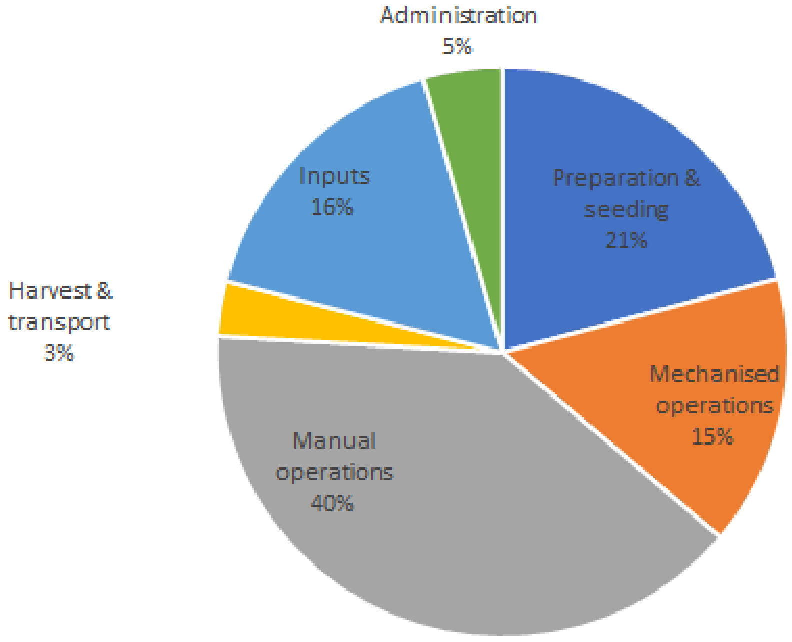
Region	US$.barrel^{-1}	US$.t^{-1}
Global average	30.38	239.84
Asia & Oceania	29.47	232.84
Europe & CIS	28.49	224.50
Middle East	25.72	202.93
Africa	25.72	202.93
North America	32.75	258.73
Latin America	34.13	269.63

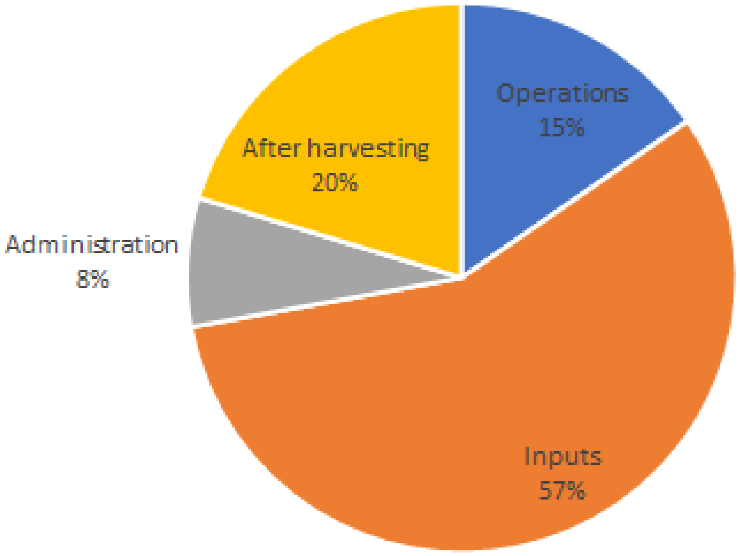
CORSIA and eligible fuels

- 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. ICAO is the International Civil Aviation Organization.
- 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.
- In the CORSIA pilot phase, the two principles (and their criteria) that must be met by SAF producers 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)





Agricultural costs

- The costs of production of sugarcane and corn, as 2nd crop, were estimated based on the information provided by Agrianual for different producing states.
- In the case of sugarcane, the costs are related to preparation and seeding, and to the costs of producing in a cycle of five years. The costs, per tonne of sugarcane, include harvesting (full mechanization) and transportation to the mill (that should be nearby). The upper figure illustrates the cost structure for São Paulo.
- In the case of corn, the costs correspond to the production of transgenic grain (with higher yields), as 2nd crop. The bottom figure shows the cost structure for the production in Goiás. Harvesting costs are included in “operations”. After harvesting include the transport and storage of corn during one month in nearby warehouses.

Ethanol production costs

Parameter	Value	Unit
Input as sugarcane	3,000	$Kt.year^{-1}$
Input as corn	394.14	$kt.year^{-1}$
Anhydrous production	85.5	$L.t^{-1}$ of sugarcane
Anhydrous production	379.6	$L.t^{-1}$ of corn
DDG production	280	$kg.t^{-1}$ of corn
Revenue due to DDG	500	$R\$.t^{-1}$
Surplus electricity	56.7	$kWh.t^{-1}$ of sugarcane
Revenue due to electricity	150	$R\$.kWh^{-1}$
Days processing sugarcane	200	
Days processing corn	120	

- The costs of producing ethanol in a flex mill (i.e. producing from sugar cane and corn, this as a complementary feedstock) are based on BNDES (2014). Among the configurations presented in the reference, the one that corresponds to the parameters shown in the table was chosen. This is not the configuration that leads to lower ethanol costs, but the cost difference is not as pronounced (about 5%).
- In the CAPEX and OPEX estimation, the scale effects were addressed based on Gouvello (2010). Inputs and outputs were corrected in proportion to the processing capacity of sugarcane and corn.
- OPEX was estimated assuming fixed and variable components: 2.5% and 4% of the investment due to each feedstock, per year, and 10.1 and 36.3 $R\$.t^{-1}$, respectively, for sugarcane and corn.

Industrial costs

- Here, the main reference is de Jong et al. (2015), since it is based on a comprehensive review of performance factors and costs for different pathways.
- It is assumed that SAF is one of the hydrocarbons that can be produced; the production shares are presented in the table below. The revenue for each product was considered in estimating the MSP of SAF.
- In the base case 0.5042 tonne of hydrocarbons could be produced from one tonne of ethanol. This parameter was taken from de Jong et al. (2017).
- In the reference case, the production of bio-jet fuels would be equal to 182.6 tonnes of bio-jet per day, operating all over the year with a 90% capacity factor.
- Based on the reference, the estimated (adjusted) total cost investment would be 51.03 million € (2018).
- For estimating the MSP in each case, a spreadsheet was developed and the procedure was validated against the results presented by de Jong et al. (2015).

Economic hypotheses used by de Jong et al. (2015) for estimating the MSP of bio-jet fuels, and 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 – total cost investment – 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%

Hydrocarbons produced	Corrected producing share (%)
Jet-fuel	75.1
Diesel oil	76.9
Naphtha	2.0