Received: 5 May 2019 | Accepted: 7 October 2019
DOI: 10.1111/gcbb.12659

ORIGINAL RESEARCH

GLOBAL CHANGE BIOLOGY BIOENERGY WILEY

Spatial modeling of techno-economic potential of biojet fuel production in Brazil

Walter Rossi Cervi[1,2] | **Rubens Augusto Camargo Lamparelli**[3] | **Joaquim Eugênio Abel Seabra**[4] | **Martin Junginger**[2] | **Sierk de Jong**[2] | **Floor van der Hilst**[2]

[1]School of Agriculture Engineering, University of Campinas, Campinas, SP, Brazil

[2]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands

[3]Interdisciplinary Center of Energy Planning, University of Campinas, Campinas, SP, Brazil

[4]Faculty of Mechanical Engineering, University of Campinas, Campinas, SP, Brazil

Correspondence
Martin Junginger, Vening Meineszgebouw A, Princetonlaan 8a, 3584 CB Utrecht, The Netherlands.
Email: H.M.Junginger@uu.nl

Funding information
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior; Be-Basic Foundation

Abstract
It is expected that Brazil could play an important role in biojet fuel (BJF) production in the future due to the long experience in biofuel production and the good agro-ecological conditions. However, it is difficult to quantify the techno-economic potential of BJF because of the high spatiotemporal variability of available land, biomass yield, and infrastructure as well as the technological developments in BJF production pathways. The objective of this research is to assess the recent and future techno-economic potential of BJF production in Brazil and to identify location-specific optimal combinations of biomass crops and technological conversion pathways. In total, 13 production routes (supply chains) are assessed through the combination of various biomass crops and BJF technologies. We consider temporal land use data to identify potential land availability for biomass production. With the spatial distribution of the land availability and potential yield of biomass crops, biomass production potential and costs are calculated. The BJF production cost is calculated by taking into account the development in the technological pathways and in plant scales. We estimate the techno-economic potential by determining the minimum BJF total costs and comparing this with the range of fossil jet fuel prices. The techno-economic potential of BJF production ranges from 0 to 6.4 EJ in 2015 and between 1.2 and 7.8 EJ in 2030, depending on the reference fossil jet fuel price, which varies from 19 to 65 US$/GJ across the airports. The techno-economic potential consists of a diverse set of production routes. The Northeast and Southeast region of Brazil present the highest potentials with several viable production routes, whereas the remaining regions only have a few promising production routes. The maximum techno-economic potential of BJF in Brazil could meet almost half of the projected global jet fuel demand toward 2030.

KEYWORDS
aviation, bioenergy costs, bioenergy potential, biofuels, geographic information system, land availability, land use, renewable jet fuels, techno-economic assessment

1 | INTRODUCTION

With the agreement established in 2015 at COP 21 in Paris, it is expected that biofuels have a large contribution to curb greenhouse gas (GHG) emissions in Brazil in the next decade (UNFCCC, 2015). Currently, biofuels for road transportation, largely represented by sugarcane ethanol and soybean biodiesel, are the main options to reduce the fossil fuel dependence in Brazil in the coming years (Milanez, Mancuso, Godinho, & Poppe, 2017). At a global level, biofuels for aviation, known as biojet fuels (BJF), are seen as an important emerging option to reduce the GHG emissions from the transportation sector (IATA, 2015; ICAO, 2010). Approximately 12% of the global GHG emissions of the transportation sector is caused by the aviation sector (ICAO, 2010), and this share is expected to grow strongly toward 2050 (de Jong, 2018). Given its significant experience with the production of biofuels and the potentially large availability and suitability for biomass production, Brazil has great potential to develop a BJF industry and mitigate GHG emissions in the aviation sector (Cortez, 2014).

The emission reduction target of 50% in 2050 relative to 2005 plus the carbon neutral growth from 2020 onward required by the International Air Transport Management (IATA, 2015) have led to voluntary targets for BJF consumption (FAA, 2011). Airline companies have committed to use BJF sourced from sustainable biomass crops (SAFUG, 2018). However, for large-scale application, it is rather difficult to quantify the potential of biomass to BJF due to uncertainties regarding land availability, the variety of biomass crops, and yield variability. In addition, there are important techno-economic barriers concerning the conversion of biomass to BJF, such as the current production cost gap with fossil jet fuel, technological risks, and high capital costs related to the development of new BJF technologies (Alves et al., 2017; Mawhood, Gazis, de Jong, Hoefnagels, & Slade, 2016).

The project "Flightpath for aviation biofuels in Brazil" provides an extensive review of the aforementioned constraints in the Brazilian context (Cortez, 2014; FAPESP, 2013). Furthermore, some studies assessed promising biomass feedstock for BJF production in Brazil (Cantarella, Nassar, Cortez, & Baldassin, 2015; Moraes, Nassar, Moura, Leal, & Cortez, 2014). However, none of them quantified the land availability that could be used for biomass production for BJF. The land availability largely determines the potential supply of biofuels (Souza, 2017) and its assessment is of great concern to avoid GHG emissions due to indirect land use change (Agusdinata, Zhao, Ileleji, & Delaurentis, 2011). Taking into account legal restrictions and biophysical parameters, Martini et al. (2018) mapped more than 3 Mha of land suitable for producing sugarcane derived jet fuel in Brazil. In that study, the spatial variability on the sugarcane yields was not considered, which could have great impact on the potential and the production costs. Murphy et al. (2015) found that in the short term, BJF may require extensive amounts of land with significant biomass production costs. The same authors (Herr et al., 2016) also mapped the potential of biomass to BJF production that could coexist with other land use functions as an alternative to optimize the land use while reducing biomass costs. However, none of these studies analyzed the spatial variation of the biomass production costs and their effect on the overall BJF production costs.

Differently from traditional bioenergy systems (e.g., sugarcane ethanol), biomass costs may not be the principal cost component of BJF supply chains (Hayward et al., 2015). Several studies have assessed the techno-economic performance of various BJF supply chain options for Brazil (Assumpcao, Pereira, Giraldi, Cervi, & Mariano, 2016; Klein et al., 2018; Santos et al., 2017; Silva Braz & Mariano, 2018). These studies highlight the potential contribution of the existing traditional biofuel industry to reduce the capital intensity in BJF production. Furthermore, Alves et al. (2017) show that BJF supply chains from uncommon biomass crops (e.g., macaw palm) may lead to competitive BJF production costs. However, these studies did not consider the variability in biomass yields and costs across regions and the impact on the economic viability of BJF.

Very few studies have been addressed the spatial distribution of biomass resources for assessing the techno-economic performance of BJF production. Carvalho et al. (2019) carried out a resource-focused assessment on production cost of different BJF supply chains in Brazil. However, the analysis is given temporally static and in a spatial aggregate level, which avoid a detailed spatiotemporal representation of the BJF cost components. de Jong et al. (2017) spatially explicitly optimized the location of potential BJF plants to minimize the production costs of BJF from forestry systems in Sweden. The authors recommended the use of temporal variable information on biomass cost–supply, infrastructure, and BJF technology development to increase the accuracy of the techno-economic assessment. To date, no study has assessed the techno-economic performance of BJF supply chains by integrating spatial and temporal data of various biomass crops while taking into account the development in different BJF technologies over time.

The objective of this paper is to assess the spatiotemporal production costs of BJF supply chains (hereafter named as BJF production routes) in Brazil and to quantify the techno-economic potential of location-specific optimal combinations of biomass crops and conversion pathways depending on local agro-ecological conditions. We focus on 2015 (reference year) and 2030 to address recent and short term expected techno-economic developments in BJF production routes. Although there might be a considerable potential of BJF produced from biomass residues, this paper focuses solely on BJF production from dedicated biomass crops. The study consists of three main steps: (a) selection of BJF production routes; (b) spatial assessment of land available to grow dedicated BJF biomass; (c) assessment of the techno-economic potential of the BJF production routes.

2 | BJF PRODUCTION ROUTES

Biojet fuel production routes are composed by biomass crops and BJF conversion technologies (so-called "technological pathways" or just "BJF technologies"; Figure 1). This study covers eight potential biomass crops from three different feedstock groups: corn, sugarcane, and sweet sorghum (starch and sugar); soybean, sunflower, macaw palm, and oil palm (oil crops); and eucalyptus (lignocellulosic). Brazil has ample experience with the cultivation and processing of most of these crops. In general, these biomass crops present desirable characteristics for biofuel production, compatibility with Brazilian agro-ecological conditions resulting in relatively high biomass yields, and are often produced in proximity to the main consumer spots. Furthermore, for most of these crops, there are spatially explicit and cost data available. The compliance of the biomass crops with these selection criteria is provided in Supporting Information S1 and the main characteristics of the biomass crops are described in Table 1.

Although there are many potential technological pathways for converting biomass to BJF, we select those currently certified by the American Society for Testing and Materials (ASTM; ASTM, 2018), accounting for their advanced fuel and technology readiness level (TRL). The technologies produce drop-in BJF with blending levels with fossil jet fuel varying from 10% to 50% depending on the technological pathway. Currently, four technological pathways are already certified by ASTM: hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch (FT), direct sugars to hydrocarbons (DSHC), and alcohol to jet (ATJ). Additionally, we also select hydrothermal liquefaction (HTL) because of the high conversion yield and the promising techno-economic results found by de Jong et al. (2015). All these technological pathways are owned by different companies and are in various development stages. In Supporting Information S1, we briefly describe the technical characteristics of the selected technological pathways.

3 | METHODS

We assess recent and future techno-economic potential of BJF production routes in Brazil taking into account the spatiotemporal developments in biomass potential and technical developments in the BJF production routes. The techno-economic assessment focuses on 2015 and 2030 time horizons, and analyzes the development in potential land availability for biomass for BJF production, given the development in other land use functions, and the spatial variation in agro-ecological suitability for the cultivation of different biomass crops. The resulting spatial distribution of biomass potential is used to calculate the biomass production costs (i.e., farmgate plus transportation costs). The BJF production costs are calculated considering an integrated greenfield feedstock production plant with a BJF biorefinery which converts the raw biomass to BJF. The BJF transportation costs are calculated assuming the shortest route from the BJF plant to the nearest airport in Brazil. Finally, the techno-economic potential is determined by selecting the location-specific minimum BJF total costs (BJF production cost plus the BJF transportation cost) across the production routes and compares this to the location-specific fossil jet fuel price range. All economic

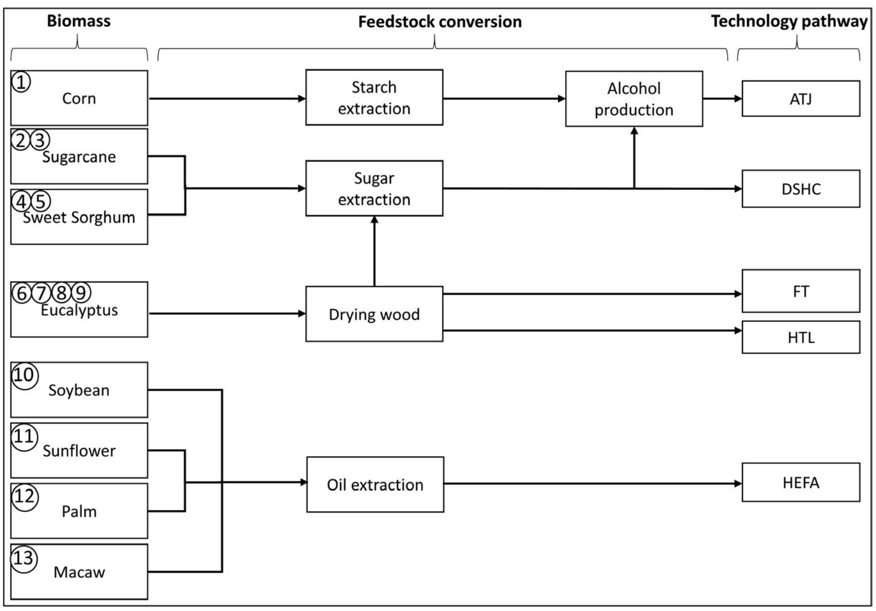

FIGURE 1 Biojet fuel (BJF) production routes: (1) BJF from corn ethanol via ATJ (C_ATJ); (2) BJF from 1G sugarcane ethanol via ATJ (SC_ATJ); (3) BJF from sugarcane sugars via DSHC (SC_DSHC); (4) BJF from sweet sorghum ethanol via ATJ (SS_ATJ); (5) BJF from sweet sorghum sugars via DSHC (SS_DSHC); (6) BJF from 2G eucalyptus ethanol via ATJ (EC_ATJ); (7) BJF from 2G eucalyptus sugars via DSHC (EC_DSHC); (8) BJF from eucalyptus via Fischer–Tropsch (EC_FT); (9) BJF from eucalyptus via HTL (EC_HTL); (10) BJF from soybean oil via HEFA (SB_HEFA); (11) BJF from sunflower oil via HEFA (SF_HEFA); (12) BJF from palm oil via HEFA (PO_HEFA); (13) BJF from macaw oil via HEFA (MP_HEFA)

TABLE 1 Key characteristics of the selected biomass crops for biojet fuel in Brazil

Biomass crop	Current production (2015)	Average biomass yield (2015)	Typical feedstock yield	Regions with highest agro-ecological suitability in Brazil	Common biofuel application in Brazil	Sources
Corn	85 Mt of grain	5.5 t/ha	660 kg of starches/t of grain	South, Center-West, and Northeast	1G Ethanol	IBGE (2015), Patzek (2006)
Sugarcane	750 Mt of stalks	74 t/ha	145 kg of sugars/t	Southeast, Center-West, and Northeast	1G 2G Ethanol	Jonker et al. (2015), UNICA (2018)
Sweet sorghum[a]	Unknown	—	120 kg of sugars/t	Northeast and Center-West	1G Ethanol	Jonker et al. (2015), May (2013)
Eucalyptus	130 Mt of wood	30 t/ha	1:1	South and Southeast	2G Ethanol (not currently employed)	IBÁ (2016), Mariano (2015)
Soybean	97 Mt of grain	3 t/ha	200 kg of oil/t of grain	South and Center-West	Biodiesel	Bergmann et al. (2013), IBGE (2015)
Sunflower	0.15 Mt of grain	1.3 t/ha	450 kg of oil/t of grain	South and Center-West	Biodiesel	Bergmann et al. (2013), IBGE (2015)
Oil palm	1.6 Mt of FFB	11 t/ha	220 kg of oil/t of FFB	North and Northeast coast	Biodiesel (1%–3% of the national production in 2018)	ANP (2019), Bergmann et al. (2013), IBGE (2015)
Macaw palm[a]	Unknown	—	220 kg of oil/t of FFB	Center-West	Biodiesel (not currently employed)	Cardoso et al. (2017)

Abbreviation: FFB, fresh fruit bunches.

[a]Sweet sorghum and macaw palm are emerging potential biomass options for bioenergy and are not currently produced at large scale. Thus far, no national official survey has quantified the annual production of these biomass crops in Brazil.

values are expressed in 2015 US dollars, and the exchange rate assumed are 1 USD = 3 BRL and 1 USD = 0.9 EUR.

3.1 | Land availability for BJF production

The assessment on the development of land availability over time is based on the study of Van der Hilst, Verstegen, and Woltjer (2018). In that study, scenarios on the development of sugarcane ethanol expansion and the land demand for food, feed, and fiber in Brazil were modeled spatially explicitly. As a result, annual land use maps at 5 km grid cell resolution were generated for the period 2012–2030.

In this study, we make use of a reference scenario including an increase in ethanol production (Van der Hilst et al., 2018). We assume that all land not in use for other land use functions (i.e., cropland, pasture, rangeland, sugarcane, forest plantations, natural forest, urban areas, and conservation areas) are residual land that could potentially be used for biomass production for BJF. Hence, abandoned agricultural land (e.g., bare fallow) and shrubs and grasslands are the remaining land use types assumed to be potentially available for BJF production. These land use classes expand or contract over time as consequence of the development in other land use functions (Van der Hilst et al., 2018).

3.2 | Yield developments

Biomass yield levels (*Y*) are calculated by combining the land availability (*A*) with their respective agro-ecological suitability (*S*) for a specific biomass crop (*b*) and the maximum attainable yield (*M*; Equation 1). The land use maps (Van der Hilst et al., 2018) for the year 2015 and 2030 are converted to binary land availability maps (*A*), in which 0 refers to "not available land" and 1 to "available land" for biomass cultivation for BJF production.

$$Y_{b,a,y} = A_{a,y} \times S_{b,a} \times M_{b,y}, \quad (1)$$

where Y_{bya} is the yield of biomass *b* at location *a* in year *y* (t/ha), A_{ay} is the residual land availability at location *a* in year *y* (0, 1), S_{ba} is the agro-ecological suitability for biomass *b* at location *a* (%), and M_{by} is the maximum attainable yield of biomass *b* in year *y* (t/ha).

The spatially explicit agro-ecological suitability (*S*) data for sugarcane, sweet sorghum, corn, soybean, sunflower, and palm are acquired from International Institute for Applied Systems Analysis–Global Agro-Ecological Zones. These data refer to a baseline estimation based on historical climate data from 1960 to 1990 (see Supporting Information S2; Tóth, Kozlowski, Prieler, & Wiberg, 2012). Due to the absence of specific agro-ecological suitability data for eucalyptus and macaw palm, their suitability levels are estimated using species distribution modeling (SDM). Hence, Maxent model is used to measure the probability of the presence of a given species based on environmental variables (e.g., climate, slope, soil) and the location of species occurrence data (Phillips & Dudik, 2008; Supporting Information S3). The model output gives a probability range of 0–1, which indicates the suitability levels (Phillips, 2017). Also, other studies used SDM to assess the suitability for the cultivation of eucalyptus and macaw palm in Brazil and South America (Garcia, Ferraz, & Alvares, 2014; Plath et al., 2016). Lastly, the maximum attainable yield (*M*) of each biomass crop is presented in Table 2 from various sources, and their respective historical trends of annual yield growth rate (see Van der Hilst et al., 2018) used to calculate yield levels in 2030.

3.3 | Biomass production costs

The biomass production costs are calculated by summing the biomass farm-gate costs and biomass transportation costs (Equation 2). The biomass production costs vary over space (*a*) and time (*y*) due to spatiotemporal variations in biomass yield and transportation costs.

$$\mathrm{BC}_{b,a,y} = \mathrm{FC}_{b,a,y} + \mathrm{TC}_{b,a,y}, \tag{2}$$

where BC_{ay} is the biomass production cost of biomass b at location a in year y (US$/t), FC_{ay} is the biomass farm-gate cost of biomass b at location a in year y (US$/t), and TC_{ay} is the biomass transportation cost of biomass b at location a in year y (US$/t).

The biomass farm-gate costs comprise expenses for land clearing (i.e., from grasslands or shrublands to cropland; no land clearing is required for abandoned agricultural land), land costs, soil preparation, agricultural inputs (fertilizers and agrochemicals), crop management, harvest, and storage (for grains; Supporting Information S4). The farm-gate costs include fixed costs per hectare (i.e., cultivation management practices, e.g., soil preparation, planting, and herbicides) and variable costs per tonne of biomass (e.g., fertilizer application and harvest costs; Equation 3; Jonker et al., 2015). To allow for a cost comparison between annual crops (e.g., soybean, corn) and perennial crops (e.g., macaw, eucalyptus), the net present value is calculated of all cost items and biomass yields throughout the biomass cycle (i.e., lifetime plantation). Toward 2030, the biomass farm-gate costs reduce as function of projected yield increase. In this study, the available land is assumed to be new agricultural areas. Hence, we use cost data from biomass production systems representative for agricultural expansion areas in Brazil (Supporting Information S4).

$$\mathrm{FC}_{b,a,y} = \frac{\sum_{t=1}^{t=x} \frac{\sum_{n=1}^{N}\left(O_{n,b,t}\times C_{n,b,t}\right)+\sum_{m=1}^{M}\left(O_{m,b,t}\times C_{m,b,t}\times Y_{b,a,t,y}\right)}{(1+r)^{t}}}{\sum_{t=1}^{t=x}\frac{Y_{b,a,t,y}}{(1+r)^{t}}}, \tag{3}$$

where $\mathrm{FC}_{b,a,y}$ is the biomass farm-gate cost of biomass b at location a in year y (US$/t), $O_{n,b,t}$ is the occurrence of biomass fixed cost n of biomass b in lifetime t (#), $C_{n,b,t}$ is the cost of biomass fixed cost n of biomass b in lifetime t (US$/ha), $O_{m,b,t}$ is the occurrence of biomass variable cost m of biomass b in lifetime t (#), $C_{m,b,t}$ is the cost of biomass variable cost m of biomass b in lifetime t (US$/t), $Y_{b,a,t,y}$ is the yield of biomass b at location a in lifetime t and year y (t/ha), r is the annuity rate (%), and t is the annuity period (lifetime plantation; years).

The biomass transportation costs include truck depreciation costs, diesel, lubricants, and labor, which are directly related to the distance from the field to the BJF plant (Jonker et al., 2016). As we do not determine the location

TABLE 2 Maximum attainable yield for 2015 and the average annual yield increase up to 2030 for each biomass crop

Biomass	2015 maximum att. yield (t ha^{-1} year^{-1})	Source	Energy values (GJ/t)[a]	Annual yield growth rate (% per year)[b]
Corn grain	12	IBGE (2015)	18.5	1.4
Sugarcane stalks	130	UNICA (2018)	19.6	0.8
Sweet sorghum stalks	104	May (2013)	19.6	1.4
Eucalyptus wood	40	Stape et al. (2010)	18.4	1.4
Soybean grain	4.2	IBGE (2015)	23.5	0.9
Sunflower grain	3	IBGE (2015)	26.4	0.9
Palm FFB	25	Furlan et al. (2003)	24	0.9
Macaw FFB	25.5	Ciconini et al. (2013)	24	0.9

Abbreviation: FFB, fresh fruit bunches.

[a]Biomass energy content based on BioGrace (2018).

[b]Annual yield increase based on IBGE (2015) and Van der Hilst et al. (2018).

of the potential BJF plant, the transportation distance is based on the relative biomass density (D) within the gathering radius around each grid cell. This gathering radius is defined by the area required to support the input capacity (I) of the BJF plant (i.e., production route p; see Table 3). The average transportation distance represents two-third of the gathering radius (Hamelinck, Suurs, & Faaij, 2005). The biomass transportation cost per tonne-km (C) of 0.092 refers to secondary roads (i.e., mix of paved and non-paved roads) in good conditions (Van der Hilst & Faaij, 2012), and it is assumed to be equal for all the biomass crops in 2015 and 2030. Equation (4) describes the biomass transportation costs calculation.

$$\mathrm{TC}_{p,b,a,y} = C \times \frac{2}{3} \times I_{p,y}^{0.5} \times \left(Y_{b,a,y} \times D_{b,a,y}\right)^{-0.5}, \qquad (4)$$

where TC_{pbay} is the biomass transportation cost of production route p and biomass b at location a in year y (US\$/t), C_{pby} is the biomass unit transportation cost (US\$/t km), I_{py} is the input capacity of production route p in year y (t), Y_{bay} is the yield of biomass b at location a in year y (t/ha), and D_{bay} is the density of biomass b within the radius at location a in year y (%).

3.4 | BJF production costs

The BJF production costs assessment is based on de Jong et al. (2015) who assessed the economic feasibility of BJF plants in different development stages (i.e., pioneer plant and nth plant) and for various co-production strategies (e.g., greenfield, retrofitting). As our study exclusively deals with "new agricultural land" for BJF production, we assess only hypothetical greenfield BJF plants. The BJF plants convert raw biomass into feedstock and then to BJF. Hence, the production routes entail a BJF feedstock production plant (i.e., central upstream facility) and a BJF biorefinery (i.e., downstream facility; Figure 2). To address the current TRL, the assessment in 2015 comprises technological pathways in BJF pioneer biorefineries. Each technological pathway has a different cost growth factor that estimates the capital costs in BJF pioneer biorefineries considering the risks and shortfalls of building the "first of

TABLE 3 Biomass input capacity of the BJF feedstock production plant, preprocessing steps required (table footnotes) to convert raw biomass into dedicated feedstock for BJF production, the feedstock yield per unit of biomass input and their main co-products

Production routes ID	Raw biomass input capacity (Mt/year)		Input biomass	Feedstock conversion yield (t of feedstock/t of biomass)			FCI (US\$/t input)		OPEX (US\$/t input/year)	Source
	2015	2030		2015	2030	Source	2015	2030	2015–2030	
C_ATJ[a]	0.42	0.65	Corn grain	0.33	0.37	RFA (2016)	445	390	143	Kwiatkowski, McAloon, Taylor, and Johnston (2006)
SC_DSHC[b]	4	5.5	Sugarcane stalks	0.15	0.16	Jonker et al. (2015)	63	57	14	Jonker et al. (2015)
SC_ATJ[b]	4	5.5	Sugarcane stalks	0.06	0.07	Jonker et al. (2015)	63	57	14	Jonker et al. (2015)
SS_DSHC[c]	4	5.5	Sweet sorghum stalks	0.12	0.14	Jonker et al. (2015)	63	57	14	Jonker et al. (2015)
SS_ATJ[c]	4	5.5	Sweet sorghum stalks	0.04	0.05	Jonker et al. (2015)	63	57	14	Jonker et al. (2015)
EC_DSHC[d]	0.72	1.5	Wood chips	0.45	0.5	Jonker et al. (2015)	1,079	459	251–133	Seabra and Macedo (2011)
EC_ATJ[d]	0.72	1.5	Wood chips	0.22	0.29	Jonker et al. (2015)	1,079	459	251–133	Seabra and Macedo (2011)
EC_FT[e]	0.6	1	Wood chips	1	1	—	52	44	5	Diederichs (2015)
EC_HTL[e]	0.35	0.8	Wood chips	1	1	—	60	55	5	Diederichs (2015)
SB_HEFA[f]	0.66	0.95	Soybean grain	0.19	0.19	MAPA (2015)	185	166	20	Cheng and Rosentrater (2017)
SF_HEFA[g]	0.2	0.73	Sunflower grain	0.43	0.43	MAPA (2015)	266	180	25	Cheng and Rosentrater (2017)
PO_HEFA[h]	0.65	1	FFB	0.25	0.25	MAPA (2015)	94	83	13	Furlan et al. (2003)

(Continues)

TABLE 3 (Continued)

Production routes ID	Raw biomass input capacity (Mt/year) 2015	2030	Input biomass	Feedstock conversion yield (t of feedstock/t of biomass) 2015	2030	Source	FCI (US$/t input) 2015	2030	OPEX (US$/t input/year) 2015–2030	Source
MP_HEFA[i]	0.35	0.7	FFB	0.25	0.25	Ciconini et al. (2013)	113	92	13	Furlan et al. (2003)

Abbreviations: ATJ, alcohol to jet; BJF, biojet fuel; DSHC, direct sugars to hydrocarbons; FFB, fresh fruit bunches; FT, Fischer–Tropsch; HTL, hydrothermal liquefaction.

[a]The input capacity of 2015 is assumed a bit lower than the first greenfield corn ethanol plant established in 2016 in Brazil (FS Bioenergia, 2016). From 1999 to 2014, the scale of corn ethanol plants in United States increased by 6% per year on average (RFA, 2015). In our study, we assume a moderate increase of 3% per year, as the increase of corn ethanol in Brazil is more linked with the flexibility of sugarcane mills in producing corn ethanol during the sugarcane off-season (through corn grain storage), rather than greenfields corn ethanol plants (EPE, 2017). The major upstream processes of the corn ethanol plant are grinding, cooking, liquefaction, and 1G ethanol production. The corn ethanol cost is calculated by accounting the revenues of dried distillers grain soluble co-product.

[b]A medium to high input capacity of a current typical sugarcane mill in Brazil is assumed for 2015 (Jonker et al., 2015). In 2030, the scale moves to 5.5 million tonnes input (i.e., 37.5%), highly affected by the increasing biomass yield (acc. rate of 12%; Jonker et al., 2015). We assume that the scale of sugarcane mills does not increase beyond 5.5 million tonnes because studies have shown that the ethanol expansion in Brazil is mainly facilitated by decentralized sugarcane mills (Sant'Anna, Shanoyan, Bergtold, Caldas, & Granco, 2016). The sucrose (and other fermentable sugars) production is fully dedicated for BJF production in both technologies: ethanol in ATJ and sugars in DSHC. The major upstream processes are the sugarcane milling, juice extraction, and 1G ethanol production (only for ATJ plants). As co-product, the sugarcane mill cogenerates bioelectricity from sugarcane bagasse, which is used in the sugar/ethanol cost calculation accounting for the revenues from bioelectricity sales.

[c]For sweet sorghum, the same scale, configuration, and feedstock cost calculation method as for a typical sugarcane mill is assumed (Jonker et al., 2015). As co-product, bioelectricity is produced from bagasse.

[d]The 2G ethanol plant from eucalyptus is considered as pioneer plant as "none of kind" is currently operating in Brazil. Hence, a cost growth factor of 0.53 in the feedstock production plant is assumed (Kazi, Fortman, & Anex, 2010). The input capacity of eucalyptus 2G plant in 2015 is based on Jonker et al. (2016). The 2G ethanol as BJF feedstock is selected due to high potential for Brazil and the high availability of techno-economic data. The woody residues (lignin) are assumed as feedstock to cover bioelectricity demand of the plant and the surpluses are dispatched to the national grid (Jonker et al., 2015). The progress on scale is less optimistic than the 2030 projected by Jonker et al. (2016) for dedicated 2G ethanol plants. As ethanol is not our main product, a conservative 1.5 Mt of wood input is assumed aligned with the expected development of the pulp and paper industry (Silva, Bueno, & Neves, 2017). Therefore, biomass yield development and learning effects on both biomass pretreatment and ATJ technology are the main drivers for increasing the scale toward 2030. The major upstream processes are the biomass pretreatment, hydrolysis, and 2G ethanol production (only for ATJ plant).

[e]In the feedstock production plant, the eucalyptus wood is grinded, chopped, and dried (Swanson, Satrio, Brown, & Hsu, 2010). All the forthcoming processes belong to the FT and HTL biorefineries (e.g., gasification, bio-crude production). The 2015 scale for both FT and HTL is based on approximations of dedicated studies (Diederichs et al., 2016; Swanson et al., 2010; Tzanetis, Posada, & Ramirez, 2017). By 2030, HTL may achieve a scale of 800 kt biomass input, close to the maximum capacity projected by de Jong et al. (2018) while for the FT process, 1 Mt of dry wood is assumed according to the projections developed in the United Kingdom (E4tech, 2017). No co-product is considered in the feedstock processing plant.

[f]A scale of (2,200 t/day) is assumed, equal to the capacity of 20% of the soybean pressing plants in Brazil. A 2.3% per year historical progress rate of soybean processing plants is verified (ABIOVE, 2018) and extrapolated to 2030. The learning effects are not considered for HEFA, which is already a mature technology (Mawhood et al., 2016). The major upstream processes are the grain pressing, cleaning, and oil extraction. To calculate the soybean oil cost, the soybean meal is considered as co-product.

[g]The maximum input capacity of the largest sunflower oil plant in Brazil (i.e., operating with a daily input capacity of 600 t of grain/day in 11 months) is assumed for 2015 (Parecis S/A, 2015). In the company's projection, the insertion of sunflower oil in the biodiesel industry shall be higher, thereby more than doubling the current scale. In both soybean and sunflower, we consider the similar upstream process. In addition, sunflower meal co-product is considered at half (175 US$/t) of soybean meal prices due to lower protein content.

[h]A typical scale for palm fruit processing plants in Brazil is assumed based on the study of de Andrade (2015). In Southeast Asia, the capacity of palm oil mills increased by 15%–20% in line with the trends of the palm oil industry (Mahlia, Yong, Safari, & Mekhilef, 2012). In addition, it is expected that palm oil will contribute 8% to the Brazilian biodiesel production in 2030 (APROBIO, 2016). Based on these drivers, we assume that the scale of palm oil processing plants will increase to 1 Mt of FFB by 2030, similar to the largest Biopalma greenfield plant (to be built in the coming years in Pará/Brazil; Biopalma, 2016). The major upstream processes are the fruit sterilization and pressing, and palm oil extraction. The kernel press cake is used for animal feed (Furlan et al., 2003), whereas the kernel oil co-product is used by the food industry (Villela, 2009).

[i]For macaw palm, the same industrial process and co-products as for oil palm are assumed (Klein et al., 2018). To the best of our knowledge, no large-scale macaw oil extraction plant is currently operating in Brazil nor anywhere else in the world. Hence, we assume a hypothetical input capacity half of the palm oil plant scale in 2015. This represents the current medium size palm oil plants in Brazil (de Andrade, 2015). We assume the scale will double toward 2030, due to expected investments in R&D for macaw palm in the coming years (Cardoso et al., 2017).

kind BJF biorefinery" (Table 4; Anex et al., 2010; de Jong et al., 2015; Merrow, Phillips, & Myers, 1981). Hence, all the BJF biorefineries have a higher capital intensity in 2015 compared to 2030. The cost growth factor is not applied in most of the feedstock production plant as these technologies are already mature, except for the 2G sugar/ethanol plant (Table 3). In 2030, the BJF biorefineries are assessed as *n*th biorefineries, that is, assuming that all the technologies would be available at commercial scale with similar TRL.

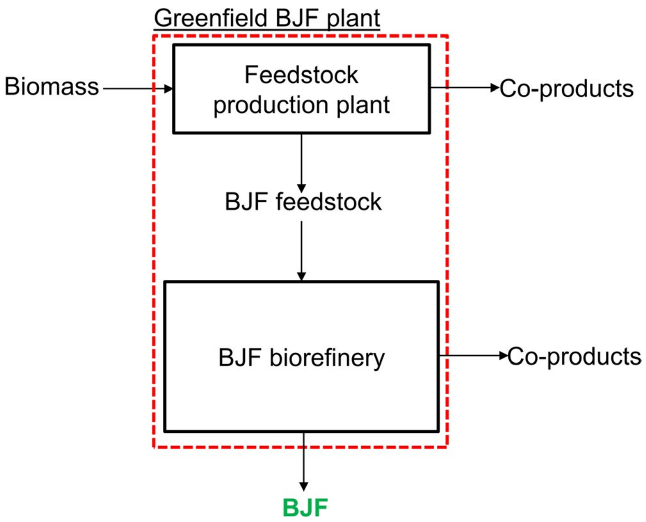

FIGURE 2 Schematic representation of the greenfield biojet fuel (BJF) plant

The BJF plants are assumed to operate at full capacity (i.e., process the entire input capacity), whereby all the feedstock produced is dedicated to supply the BJF biorefinery. Additionally, all the BJF plants have an operating time range of 300–330 days/year with constant BJF feedstock supply (e.g., ethanol and vegetable oil). The assumed input capacities of the BJF plants in 2015 are based on either typical scales of existing feedstock production plants in Brazil or approximations from simulated bioenergy plants in Brazil (see each footnote in Table 3). Some of these scales could consider to be very optimistic for a new BJF plant. However, these scales are not necessarily high considering the current bioenergy industry in Brazil (e.g., sugarcane ethanol and biodiesel soybean plants). Hence, we assess the techno-economic potential of greenfield BJF plants within the national bioenergy context. The greenfield BJF plants are projected to increase their input capacities toward 2030 driven by technological development, biomass yield, and the introduction of BJF in the market (ABEAR, 2017; see the details for each production route in Table 3).

3.4.1 | Biomass to BJF conversion

The conversion of raw biomass into BJF is done in two steps: the conversion of biomass to dedicated feedstock and feedstock to BJF. The latter consists of the distillation fraction into hydrocarbon products (e.g., green diesel, BJF). The amount of BJF output depends on the downstream characteristics of the final fractioning step, which is to some extent determined by the demand of a given hydrocarbon fuel (Norden, 2016). In this study, we assume BJF as the main hydrocarbon output product, and therefore, a maximum BJF output per tonne of feedstock input remains constant for both periods (Table 4). The developments of biomass to BJF conversion over time are exclusively driven by improvements in the upstream conversion of biomass to dedicated feedstock (Table 3).

3.4.2 | BJF production costs calculation

The BJF production costs are calculated using the levelized cost of energy. First, we calculate the feedstock costs based on the fixed capital investment (FCI; i.e., all the initial installation costs plus the working capital to start up the plant), operational expenditures (OPEX; annual costs for industrial maintenance, labor, and utilities; see footnotes of Table 3), and biomass costs (Section 3.3). The revenues from co-products (e.g., soybean meal, dried distillers grain soluble) are accounted for by applying economic allocation (i.e., based on feedstock market prices; see footnotes of Table 3; for the market prices assumed, see Supporting Information S5). Secondly, we calculate the BJF production cost at the BJF biorefinery gate (Equation 5), which comprises the FCI (i.e., all the initial installation costs plus the working capital to start up BJF biorefinery) and the OPEX (e.g., maintenance, labor, electricity, yeasts, hydrogen supply; Table 4). As the outputs of the BJF biorefinery are hydrocarbons (Table 4), we simplify the BJF production costs calculation using mass allocation method for all the production routes, except for FT technology that also yields electricity surplus, thereby accounting revenues from electricity sales. In the BJF production cost calculation, important economic assumptions (e.g., discount rate, project finance) are adapted to the reality of bioenergy projects in Brazil (Supporting Information S5).

$$\mathrm{BJFC}_{B,P,y} = \frac{\sum_{t=1}^{n}\left(I_{B,P,y}+M_{B,P,y}+\mathrm{FC}_{B,P,y}-\mathrm{Rev}_{B,P,y}\right)\times(1+r)^{-t}}{\sum_{t=1}^{n}\mathrm{Output}_{B,P,y}\times(1+r)^{-t}}, \quad (5)$$

where BJFC_{BPy} is the BJF costs of Biorefinery B in production route P in year y (US\$/t), I_{BPy} is the FCI of Biorefinery B in production route P in year y (US\$), M_{BPy} is the OPEX of Biorefinery B in production route P in year y (US\$), FC_{BPy} is the Feedstocks' costs of Biorefinery B in production route P in year y (US\$), Rev_{BPy} is the non-hydrocarbon revenues of Biorefinery B in production route P in year y (US\$), Output_{BPy} is the hydrocarbon outputs of Biorefinery B in production route P in year y (t), t is the plant lifetime (year), and r is the discount rate (%).

The FCI and OPEX for the BJF biorefinery used as economic input data are mostly sourced from de Jong et al. (2015), Diederichs (2015), and Diederichs, Mandegari, Farzad, and Görgens (2016) (Table 5). These input cost data are rescaled to the input capacity of the BJF biorefinery by

TABLE 4 Conversion yield of and co-products of BJF production and Input capacity, FCI and OPEX of the BJF biorefineries

ID	BJF input capacity (kt of feedstock)[a]		Conversion yield (t BJF/t feedstock)[b]		Cost growth factors (pioneer biorefineries)[c]	FCI[d] (US$/t)		OPEX[d] (US$/t)		Sources	Co-products[e]
	2015	2030	2015/2030	Source		2015	2030	2015	2030		
C_ATJ[f]	139	241	0.523	Santos et al. (2017)	0.42	589	210	122	51	de Jong et al. (2015)	D
SC_DSHC[g]	600	913	0.136	Santos et al. (2017)	0.42	602	387	41	30	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D, N
SC_ATJ[f]	252	390	0.523	Santos et al. (2017)	0.73	493	181	122	51	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D
SS_DSHC[g]	500	770	0.136	Santos et al. (2017)	0.42	636	408	41	30	de Jong et al. (2015)	D, N
SS_ATJ[f]	189	303	0.523	Santos et al. (2017)	0.73	537	196	122	51	de Jong et al. (2015)	D
EC_DSHC[g]	324	750	0.136	Santos et al. (2017)	0.42	724	411	41	30	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D, N
EC_ATJ[f]	164	437	0.523	Santos et al. (2017)	0.73	560	175	122	51	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D
EC_FT[h]	600	1,000	0.151	Alves et al. (2017)	0.47	2,061	831	68	30	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	N, E
EC_HTL[i]	350	800	0.15	Tzanetis et al. (2017)	0.40	2,704	844	263	91	de Jong et al. (2015), Tzanetis et al. (2017)	D, G
SB_HEFA[j]	129	185	0.494	Pearlson, Wollersheim, and Hileman (2013)	0.86	1,659	1,279	177	152	Diederichs (2015) Diederichs et al. (2016), de Jong et al. (2015)	D, N
SF_HEFA[j]	87	317	0.494	Pearlson et al. (2013)	0.86	1,866	1,088	177	152	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D, N
PO_HEFA[j]	162	250	0.494	Pearlson et al. (2013)	0.86	1,547	1,169	177	152	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D, N
MP_HEFA[j]	87	175	0.494	Pearlson et al. (2013)	0.86	1,863	1,301	177	152	Diederichs (2015), Diederichs et al. (2016), de Jong et al. (2015)	D, N

Abbreviations: ATJ, alcohol to jet; BJF, biojet fuel; DSHC, direct sugars to hydrocarbons; FCI, fixed capital investment; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction; OPEX, operational expenditures.

[a]The input capacities of the BJF biorefineries are equal to the total feedstock output from the feedstock production plants.

[b]Maximum BJF distillation (i.e., t of BJF/t of feed input) is in line with the literature, and is assumed to remain constant over time.

[c]Cost growth factors of the BJF technological pathways. Sourced from the techno-economic assessment of de Jong et al. (2015).

[d]The cost growth factors are only applied to the FCI and OPEX of the BJF pioneer biorefineries.

[e]Co-products from the BJF conversion plant: D, diesel; E, electricity; G, gasoline; N, naphtha.

[f]Main downstream processes: Dehydration, oligomerization, and hydrogenation (off-site hydrogen supply; de Jong et al., 2015).

[g]Main downstream processes: Separation, hydrocracking, and fermentation. Off-site hydrogen supply is assumed (de Jong et al., 2015).

[h]Main downstream processes: syngas production, gas cleaning, upgrading, and separation. In this design, the hydrogen is produced on-site with a hydrocracker recovery plant (Diederichs, 2015).

[i]Main downstream processes: biocrude production and upgrading. The hydrogen is produced on-site through steam reform (de Jong et al., 2015).

[j]Main downstream processes: hydrotreating, hydrocracking, and separation. Off-site hydrogen supply is assumed (de Jong et al., 2015).

using a general scale factor of 0.7. Moreover, the Brazilian inflation index (IGP-DI; van den Wall Bake, Junginger, Faaij, Poot, & Walter, 2009) is employed to standardize all the outdated costs to 2015 year (Supporting Information S5).

3.5 | BJF transportation cost

Currently, the jet fuel transportation in Brazil is predominantly done by trucks, as the pipelines from oil refineries are only connected to the major international airports in São Paulo and Rio de Janeiro. To standardize the assessment of the BJF transportation costs, we assume that the BJF transportation is entirely deployed by trucks, from the BJF facility to the nearest airport, where a blending terminal is located.

In a geographic information system environment, we calculate the least cost distance from each biomass grid cell to the nearest existing airport that currently have jet fuel storage terminals (Supporting Information S6). The distance is multiplied by the unit BJF transportation cost of the two road classes: primary roads in good conditions (road network; Supporting Information S6) and secondary roads in poor conditions (i.e., all the areas that have no intersection with road network; Table 5). For 2030, we add the planned and under construction road network while the airports we assume to be the same, as no relevant airport is planned to be built in the next years. Instead, it is expected that current small airports increase their departures due to the upscaling of regional aviation in Brazil (Brazilian Infrastructure Ministry, 2018).

TABLE 5 Road transportation characteristics and BJF transportation cost

Road type	BJF transportation cost (US$/t km)[c]
Primary roads[a]	0.054
Dirty roads[b]	0.22

[a]Paved highways at national or regional scale.

[b]Local roads in poor conditions and segments with gravel road.

[c]de Jong et al. (2017), Van der Hilst and Faaij (2012).

3.6 | Techno-economic potential assessment

The techno-economic potential is defined by the minimum BJF total cost (i.e., lowest BJF total cost at the airport) for each grid cell across the production routes in 2015 and 2030. This criterion also determines which production route achieved the minimum BJF total cost for each grid cell. The minimum BJF total cost is compared to the range of current fossil jet fuel prices at the airports in Brazil (19–65 US$/GJ; FAB, 2018) to assess the techno-economic potential. In reality, these jet fuel prices also contain other components (e.g., profits, income, and state taxes). However, these are not accounted for the BJF total cost calculation due to high uncertainty of local contextual factors and limited data availability. Finally, for each grid cell, we assess if multiple production routes can achieve viable BJF total costs compared to the fossil jet fuel price of the nearest airport. Therefore, we assess the range of production routes that could potentially achieve BJF total costs lower than the fossil price counterpart.

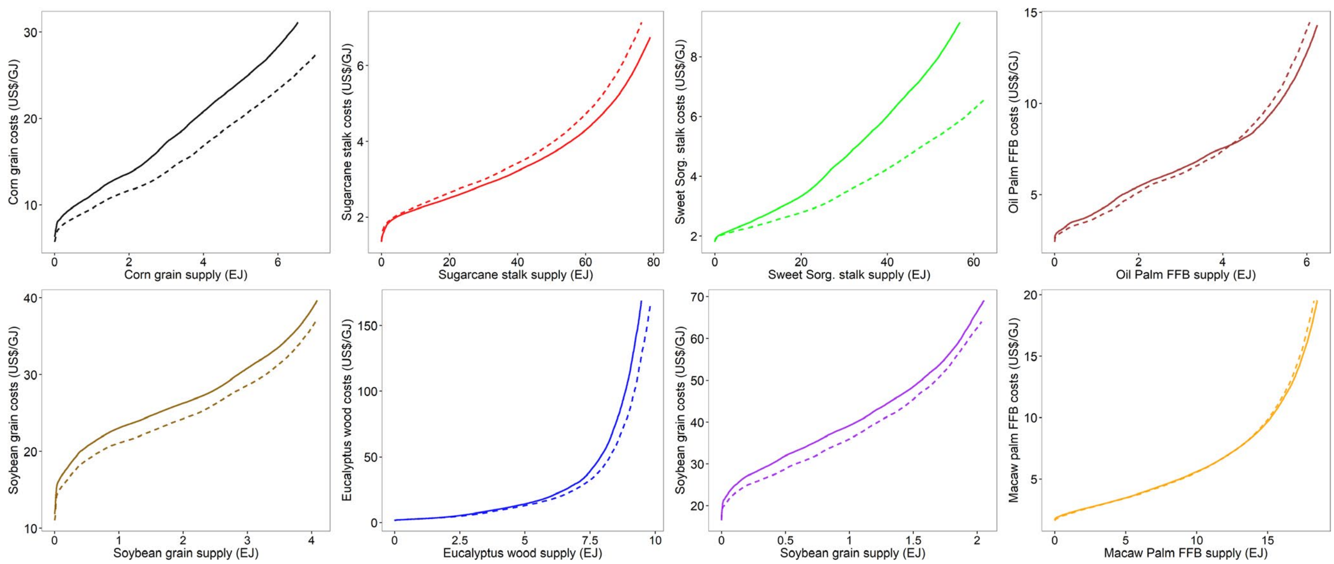

FIGURE 3 Biomass cost–supply curves of corn, sugarcane, sweet sorghum, oil palm, soybean, eucalyptus, sunflower, and macaw palm projected to be cultivated on available land for biojet fuel production in 2015 (solid line) and 2030 (dashed line)

3.6.1 | Sensitivity analysis of techno-economic potential

A sensitivity analysis is carried out for assessing the uncertainty of the techno-economic potential in three different scenarios. In the first scenario, we exclude MP_HEFA and EC_HTL production routes as they represent the most uncertain biomass and technological pathway, respectively. Currently, macaw palm is not produced on a large scale, there is limited experience in cropping it as monoculture, and it has not been used as an energy crop (Sharma et al., 2016). These factors make its successful deployment far more uncertain than all other biomass crops considered in this paper. With regard to the selected technological pathway, HTL has the lowest TRL with only two pilot plants currently available in the world, whereas many of the others (e.g., HEFA, ATJ) are either already deployed or near to market deployment (Mawhood et al., 2016). The second scenario assesses the effect of using current biomass market prices on the techno-economic potential of BJF (see the biomass market prices in the Supporting Information S5). Although the objective of this study is to modeling biomass and BJF production costs in integrated supply chains, it is likely that farmers (i.e., biomass producers) will sell their biomass to the highest bidder, and thus, the production costs used may be too optimistic. In the third scenario, we assume a conservative approach with no biomass yield growth toward 2030. This scenario takes into account the uncertainty in projecting biomass yield developments, which can be largely affected by climate effects, land quality, and management factors (Batidzirai et al., 2016).

4 | RESULTS

4.1 | Biomass potential and costs

Due to the increase in land demand for other functions (food, feed, and fiber), the land availability for biomass cultivation for BJF decreases from 121.5 Mha in 2015 to 108.1 Mha in 2030. However, due to the projected yield increase of the selected biomass crops, biomass potentials increase and biomass production costs generally decrease toward 2030 (Figure 3). The biomass costs in 2030 are on average 4% lower than in 2015. Especially, the annual crops (i.e., corn, soybean, and sunflower) present significant biomass cost reduction in the future (Figure 4) with high potentials and relatively low production costs at the border of the North* and Northeast regions (Figure 3). The soybean and sunflower supply potential increases very little up to 2030, whereas the contraction of available land does not constrain the corn supply potential in 2030 (Figure 3). The eucalyptus potential has a little cost–supply variation between 2015 and 2030. In this case,

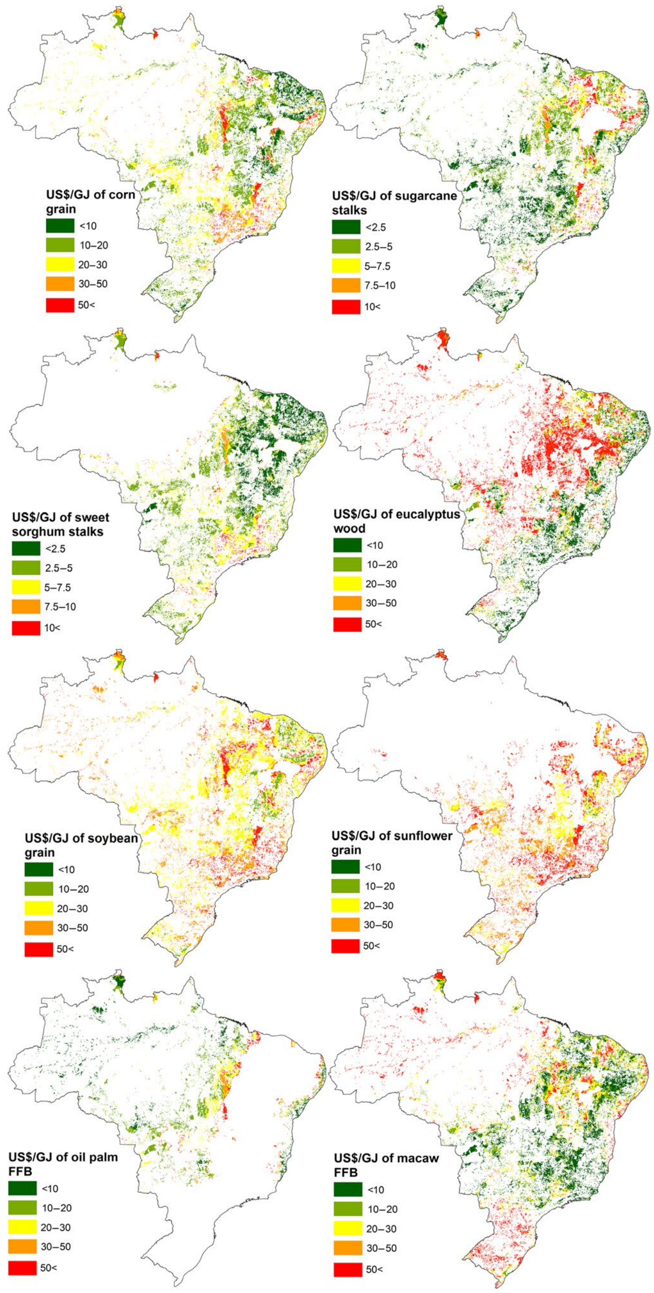

FIGURE 4 Spatial distribution of production costs of biomass crops for biojet fuel production in 2030. The land availability is the same for all crops, but areas where the agro-ecological suitability for a specific crop equals zero are excluded from the analysis for that crop

there is a trade-off between the reduction in land availability, which reduces the amount of suitable land for eucalyptus and the transportation costs, and the increasing eucalyptus yield, which reduces the farm-gate costs. Similarly, for sugarcane, the agro-ecological suitable land is projected to be already occupied by sugarcane for conventional ethanol production for road transportation by 2030. Hence, sugarcane cultivation for BJF at the available less suitable land results in higher costs in 2030.

The potential location for low cost sugarcane production remains located in the Southeast region, while those of eucalyptus can be found in areas from the South to the Northeast (Figure

*The spatial distribution of the results normally refers to the administrative division of Brazilian macro-regions and states. For a clearer comprehension (see Supporting Information S7).

4). The main advantage of sweet sorghum is the good agro-ecological conditions for growing on marginal lands in the North of Minas Gerais and South of Bahia (Figure 4). In these regions, sweet sorghum has competitive farm-gate costs compared to the sugarcane in 2030. The macaw palm and oil palm are able to grow over highly suitable areas in the Cerrado (Savannah) and Amazon biomes, respectively (Figure 4). Their cost–supply curves present the narrowest variation over time of the biomass crops assessed. If no major on-farm improvement is introduced, the production costs for these palm trees can be higher in the coming years as the dynamics of land availability are projected to negatively affect the suitable areas of these perennial crops.

4.2 | BJF production costs

The average BJF plant gate production cost of the first quartile (i.e., 25% of the land availability pixels with the lowest BJF production cost) ranges from 23 to 185 US$/GJ in 2015 and from 20 to 102 US$/GJ in 2030 depending on the production route (Figure 5). The remaining 75% of the pixels involves costly biomass production areas, which result in very high BJF production costs. As shown in Figure 5, we find high BJF production costs variability in EC_DSHC and EC_ATJ as a result of sparse suitable land available (i.e., high yield variability). These production routes also have a very high conversion costs mainly in 2015 due to investments required in the 2G plant and BJF biorefinery. The highest BJF production costs are from production routes with DSHC technology, whereas the lowest production costs are found for HEFA-based production routes. The difference in BJF distillation yield is the primary reason for the difference in BJF production costs between these production routes. Comparing the cost reductions over time, the most relevant ones are EC_DSHC, EC_ATJ, EC_FT, EC_HTL due to learning effects for 2G plant (EC_DSHC and EC_ATJ) and for the BJF thermochemical pathways (EC_FT and EC_HTL). The HEFA-based production routes present the least cost reduction over time because of the already high readiness of technology.

The overall BJF production costs aggregated in Figure 5 consist of four major cost components: biomass costs (i.e., biomass farm-gate and transportation costs), biomass to feedstock conversion costs in the upstream plants, and capital and operational costs of the BJF biorefinery. In Figure 6, the cost breakdown of BJF at plant gate in 2015 and 2030 is depicted for the production routes assessed. All production routes present cost reductions toward 2030, as result of the decrease in biomass costs, feedstock conversion yield improvements, and the technological learning through the BJF production in *n*th BJF biorefineries. In general, the biomass costs represent the largest contribution to the BJF production cost (Figure 6), with the exception of FT and HTL routes.

In 2015 and 2030, the EC_DHSC present the highest BJF production costs due to low sugar to farnesene yield and the high investment needed for the upstream 2G plant that converts the dry wood into fermentable sugars. The production routes based on the ATJ technological pathway have the lowest BJF capital cost contribution as all the biomass input is converted to ethanol, thereby increasing the feedstock input capacity of ATJ biorefineries. In 2015, the lowest BJF production cost is achieved by the production routes from macaw palm and oil palm using HEFA technology. This is explained by low initial investments required for the HEFA biorefinery, and also the high oil content of fresh fruit bunches (FFB). Hence, the specific investments in macaw and palm oil plants are much lower than the plants fueled by annual oilseed crops (e.g., soybean and sunflower). Thermochemical pathways (FT and HTL technologies) display a high capital intensity. However, they show decreasing BJF production costs toward 2030, due to the increasing scale and the high output of hydrocarbon co-products (e.g., diesel and gasoline).

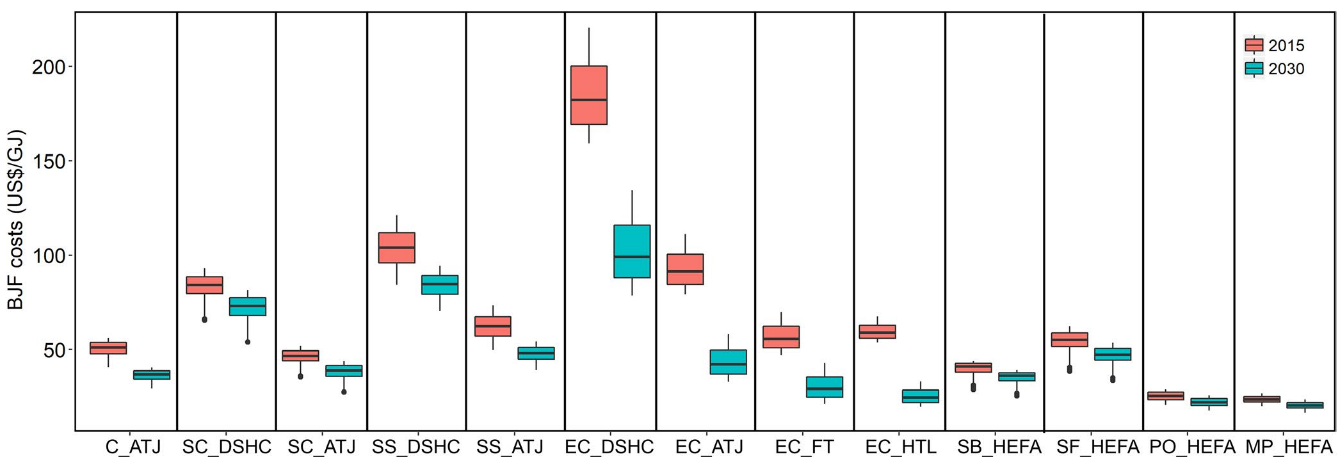

FIGURE 5 Biojet fuel (BJF) production costs variability in first quartile for each production route in 2015 and 2030. This first quartile consists of the 25% pixels with the lowest BJF production cost for each route. ATJ, alcohol to jet; BJF, biojet fuel; DSHC, direct sugars to hydrocarbons; FCI, fixed capital investment; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction

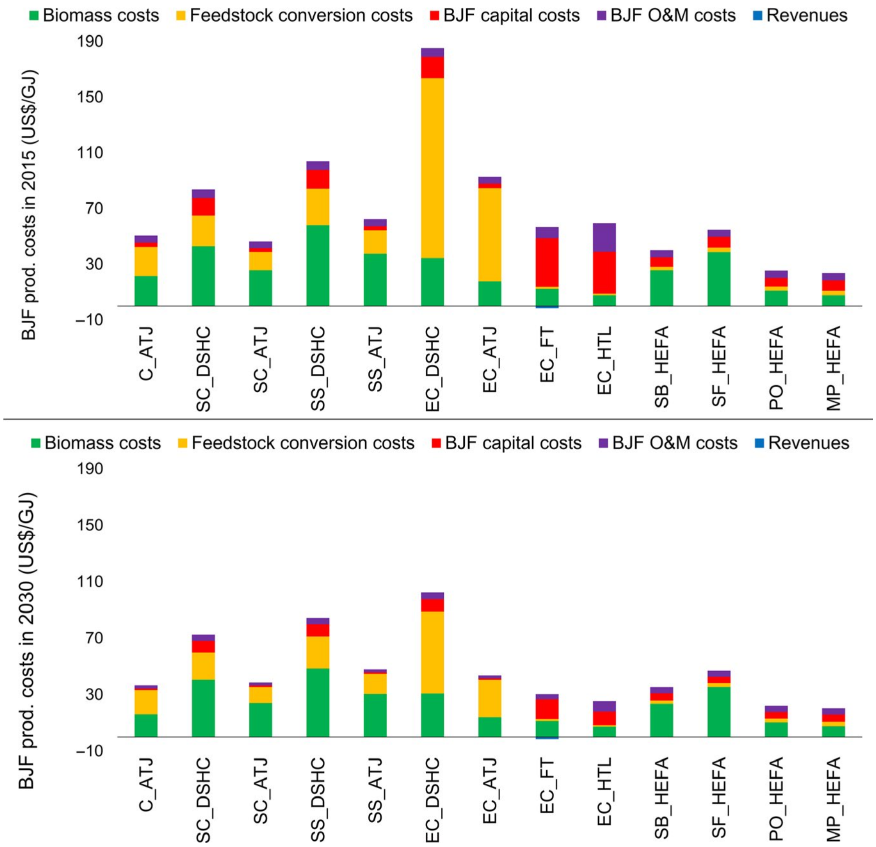

FIGURE 6 Biojet fuel (BJF) production cost breakdown at plant gate in 2015 and 2030. The costs included in this figure represent the average of the first quartile of the pixels for each production route assessed. ATJ, alcohol to jet; BJF, biojet fuel; DSHC, direct sugars to hydrocarbons; FCI, fixed capital investment; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction

4.3 | BJF transportation cost

The BJF transportation costs have a low contribution to the total BJF total costs, representing an average range of 1%–7% of the BJF total cost composition regardless of the year and the production route. The BJF transportation costs vary across the production routes due to the spatial variability of biomass production areas and their proximity to the road network and airports. On average, the BJF transportation costs from the BJF plant to the nearest airport range from 0.29 to 0.4 US$/GJ over Brazilian territory in 2015. With the expected full paving of important federal highways (e.g., BR-163) and the construction of planned roads toward 2030, the BJF transportation costs decrease by 20% on average, ranging between 0.23 and 0.3 US$/GJ of BJF transportation cost range.

Figure 7 shows the spatial variation of the BJF transportation cost in Brazil for four production routes for 2015 and 2030. The SC_DSHC and SC_ATJ production routes (a) have low BJF transportation costs (i.e., < 0.5 US$/GJ) in the Southeast region due to the land availability for sugarcane and the high density of airports. This is also true for corn, soybean, and sunflower (b) based production routes, which also have land available in the South/Southeast regions of Brazil. In these regions, the BJF transportation costs do not have major influence on the BJF total costs. Differently, regionally concentrated PO_HEFA (c) has a limited land available in the Amazon area and there is also low infrastructure availability in that region. Therefore, it is projected to be rather costly to distribute (by road) oil palm-based BJF to the surrounding airports in the great Amazon area.

4.4 | BJF total costs and techno-economic potential

The techno-economic potential is calculated by selecting the minimum BJF total costs per grid cell across the 13 production routes assessed in 2015 and 2030. The minimum BJF cost–supply curves are drawn (Figure 8) representing the amount of BJF that can be supplied for minimum BJF total costs lower than the maximum fossil jet fuel price (65 US$/GJ). More than 99% (i.e., 6.4 EJ of BJF in 2015 and 7.8 EJ of BJF in 2030) could be produced at cost below the maximum fossil jet fuel price of 65 US$/GJ. The majority of the techno-economic potential of BJF can be supplied at costs below the average fossil jet fuel price in Brazil (i.e., <32.4 US$/GJ; Figure 8). In total, the techno-economic potential is represented by eight production routes, dominated by contributions from PO_HEFA and MP_HEFA in 2015 (Figure 8, right hand side), complemented with EC_HTL in 2030. The other production routes each only have (very) minor shares and contribute less than 10% to the total BJF potential.

MP_HEFA and EC_HTL production routes are the two most dominant production routes in 2030 (see the cost–supply

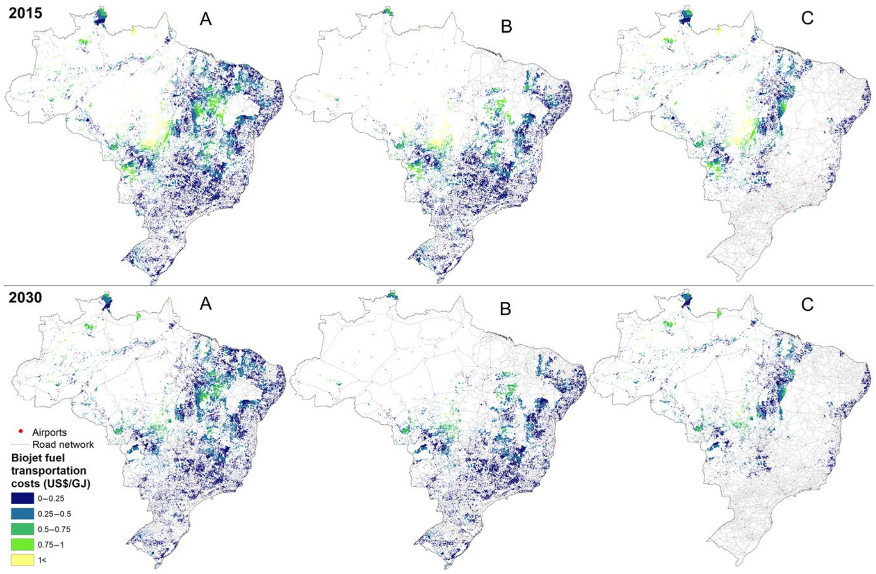

FIGURE 7 Spatial variation in biojet fuel transportation cost in 2015 and 2030. (A) SC_DSHC and SC_ATJ; (B) SF_HEFA production route; (C) PO_HEFA production route. ATJ, alcohol to jet; DSHC, direct sugars to hydrocarbons; HEFA, hydroprocessed esters and fatty acids

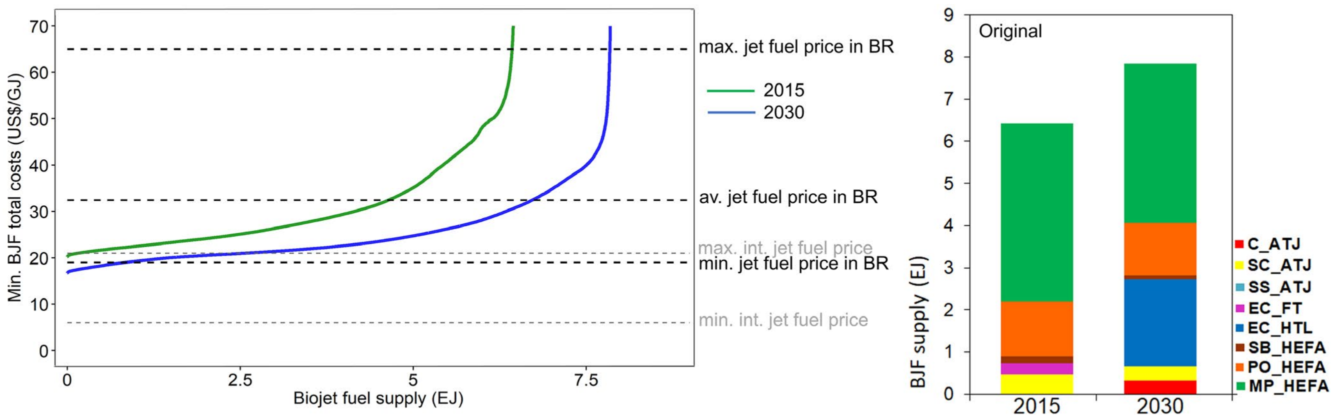

FIGURE 8 Left: biojet fuel (BJF) cost–supply curves of the minimum BJF total cost produced at the potential available land for BJF in 2015 and 2030. The horizontal dashed lines are the fossil jet fuel price range in the Brazilian airports (in black; FAB, 2018), of which the maximum represents the cutoff point of the techno-economic potential of BJF. The gray lines are the amplitude of international jet fuel prices not in the airports (i.e., U.S. Gulf Coast kerosene jet fuel spot price; Index Mundi, n.d.). On the right hand side: corresponding production routes of the techno-economic potential of BJF. ATJ, alcohol to jet; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction

curve of each individual production route in Figure 1 of Supporting Information S8). However, while HEFA technology is already mature, large-scale macaw palm monocultures have not been commercially employed. Vice versa, while eucalyptus (the biomass crop assumed for HTL) is well established, the current TRL level of HTL ranges between 3 and 5 (E4tech, 2017). Therefore, for these two production routes, the projected BJF production costs in 2030 are subject to large uncertainty. To test the robustness of our techno-economic potential, a sensitivity analysis is performed by excluding EC_HTL and MP_HEFA production routes (Figure 2 in Supporting Information S8).

The exclusion of EC_HTL and MP_HEFA leads to an increase of both the SC_ATJ and EC_FT production routes in 2015. These production routes could supply the same amount of BJF at similar BJF totals costs (Figure 1 in Supporting Information S8). In 2030, the impact of excluding these routes is less severe as the competitiveness of the MP_HEFA route already decreased in the original assessment. In addition, by 2030, the EC_FT production route produce BJF at costs close to those of EC_HTL (Figure 1 in Supporting Information S8) with similar yields. The three alternative production routes that most increase their share in the overall techno-economic potential at the expense of the excluded ones in 2030 are EC_FT, SC_ATJ, and C_ATJ. Therefore, even when promising production routes for BJF development in Brazil are excluded, there are still several options to provide a diversified and significant

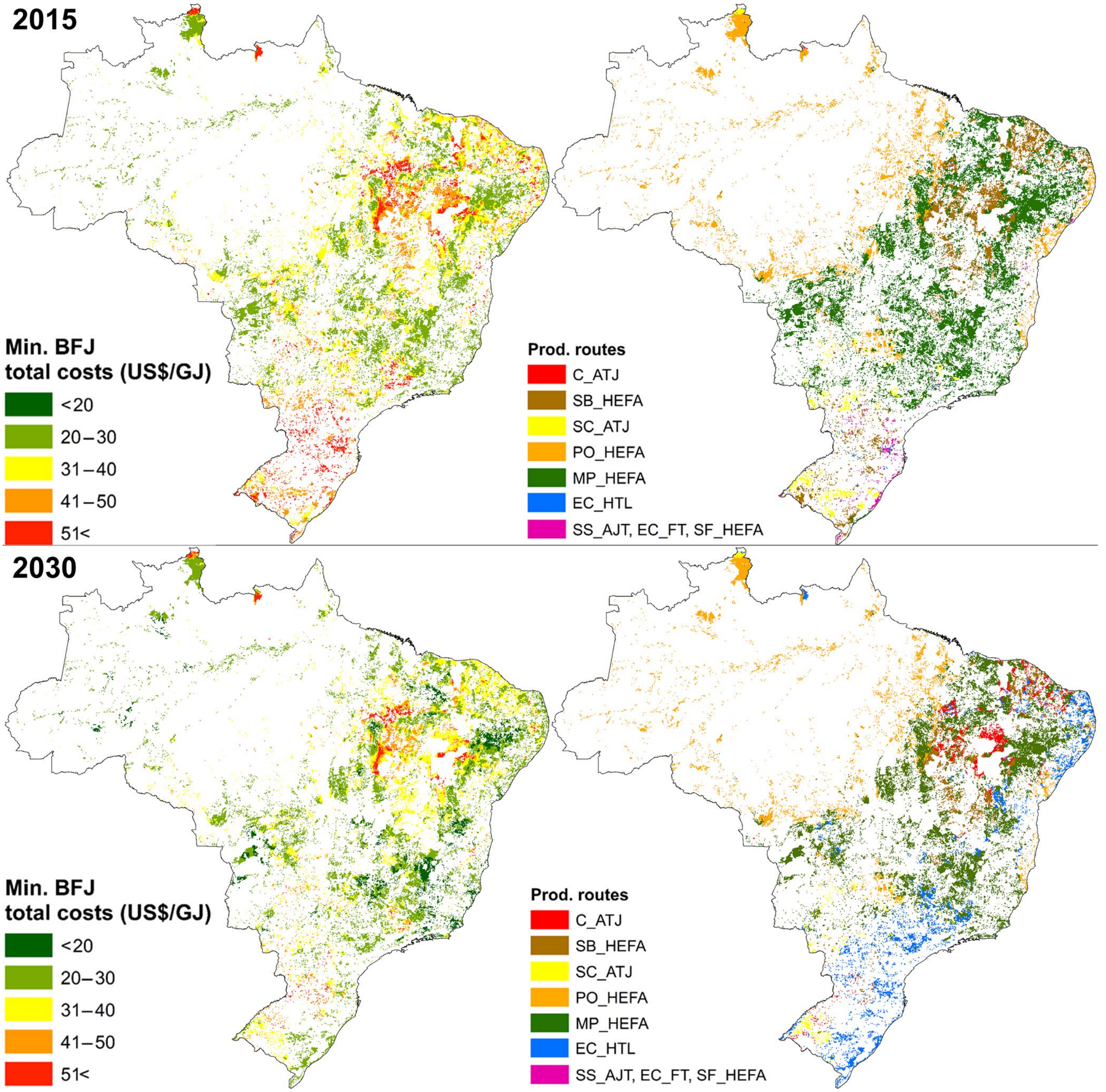

FIGURE 9 Minimum biojet fuel (BJF) total cost of the 13 production routes assessed and the corresponding production route. ATJ, alcohol to jet; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction

techno-economic potential of BJF in 2030 (Figure 2 in Supporting Information S8).

Two other sensitivity scenarios are explored: the use of biomass market prices rather than production costs and the impact of no yield increase until 2030. The impact of using biomass at market prices may decrease the BJF total costs. In the original assessment, the techno-economic potential presents a range of average BJF total costs of 28–33 US$/GJ of BJF over time, whereas the introduction of biomass at market prices decreases to 23–26 US$/GJ. This cost reduction only occurs because the largest part of the techno-economic potential (i.e., >2.5 EJ) containing high biomass costs is overshadowed by the use of fixed biomass market prices (Figure 3 in Supporting Information S8). In reality, using biomass market prices for assessing the techno-economic performance of emerging bioenergy system can be misleading as the increasing demand for a given biomass may completely change the existing price. Lastly, assuming no biomass yield growth toward 2030, the techno-economic potential reduces by 1 EJ compared to the original assessment, hampering the BJF total cost reduction over time (Figure 4 in Supporting Information S8). This highlights the importance of selecting

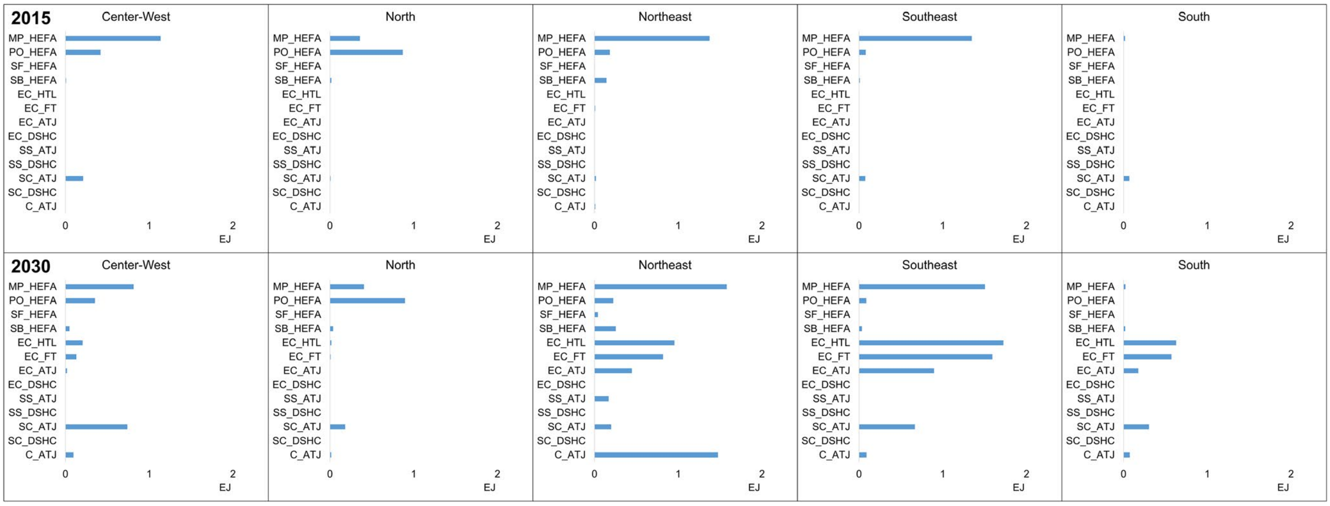

FIGURE 10 Biojet fuel (BJF) supply potential from production routes that present BJF total costs below the fossil jet fuel price in 2015 and 2030 displayed per region. Note that the supply potentials per production route cannot be summed to the total potential per region, as each grid cell could accommodate multiple production routes with BJF cost below fossil jet fuel prices. ATJ, alcohol to jet; DSHC, direct sugars to hydrocarbons; FCI, fixed capital investment; FT, Fischer–Tropsch; HEFA, hydroprocessed esters and fatty acids; HTL, hydrothermal liquefaction

the appropriate biomass crop for a given production route, taking into account its potential yield development in order to reduce BJF costs and to support the planning of BJF expansion.

The spatial variation of the minimum BJF total costs for 2015 and 2030 is presented in Figure 9. Costly areas with a high minimum BJF total cost (shades of yellow, orange, and red) are mostly located in the Northeast of Brazil, which is characterized by limited agro-ecological suitability for all biomass crops assessed. In 2030, the minimum BJF total costs below 20 US$/GJ are achieved mainly in the Southeast region (particularly in Minas Gerais state due to low cost MP_HEFA production). On the right hand side, Figure 9 presents the corresponding production routes to the minimum BJF costs. The production routes PO_HEFA and MP_HEFA are dominant in 2015. In addition, PO_HEFA could be a promising option in the Amazon region (e.g., Pará state and east of Amazonas) as it presents minimum BJF total costs twice as low as all other production routes in that region. MP_HEFA is surpassed by other production routes in the Center-West toward 2030 (e.g., EC_HTL, SC_ATJ, C_ATJ), as the macaw palm cultivation costs are not expected to reduce. Therefore, different than macaw palm, the fact that costs of oil palm are not strongly reduced by 2030 does not affect its consolidation as a promising biomass source for BJF production in the North of Brazil.

The BJF total costs of C_ATJ are expected to decrease toward 2030, and are projected to outcompete SB_HEFA in the Northeast mainly. This is explained by the relatively high agro-ecological suitability for corn in this region and the expected significant improvements of C_ATJ compared to SB_HEFA (e.g., increasing ethanol conversion yield and capital cost reduction). Moreover, the decreasing amount of suitable areas for sugarcane production in 2030 may also benefit C_ATJ and EC_HTL. The latter is expected to be very relevant in 2030, being concentrated mainly in the South and the Northeast, as well as some inland areas (e.g., Paraná state).

The other production routes that achieve the minimum BJF total costs (Figure 9; e.g., SS_ATJ, SF_HEFA, and EC_FT) present significant coverage in the South of Brazil in 2015, but are progressively outperformed by EC_HTL toward 2030. Overall, the MP_HEFA production route has the highest potential in both 2015 and 2030 with 4.2 and 3.7 EJ, respectively. The EC_HTL presents the steepest increase from 0 to 2 EJ between 2015 and 2030, and largely outcompetes SC_ATJ, even in typical sugarcane production areas (e.g., state of São Paulo).

We compare the BJF total costs of each production route in 2015 and 2030 to the fossil jet fuel selling price (Figure 10). The size of the bars in Figure 10 indicates the quantity of BJF that each production route can supply with BJF total costs below the fossil jet fuel price per Brazilian macro-region. In practice, a single grid cell of potentially available land for biomass cultivation for BJF production can be suitable for multiple production routes to achieve BJF total costs below the fossil counterpart. In 2030, depending on the region, up to 10 production routes may achieve competitive BJF total costs, although their potential varies between a few PJ and close to 2 EJ in Northeast and Southeast regions. Despite the high fossil jet fuel prices, the North region presents the lowest heterogeneity of competitive production routes: in most areas in this region, PO_HEFA and MP HEFA are the only production routes with competitive BJF total costs. Differently, in some areas of the Northeast and Southeast regions, a high diversity of viable production routes is found due to the suitability of the available land for various biomass crops. Therefore, instead of selecting the best production route based on the lowest BJF cost, it is important to explore a broader portfolio of viable BJF production routes to comprehend the capabilities of a specific region.

5 | DISCUSSION AND CONCLUSIONS

5.1 | Land availability and biomass supply costs

Several of the assumptions made on land availability and possible deployment of new biomass crops have impacts on supply chain potential costs. Although we assume that all the residual land available is dedicated for BJF production, we did not account for the potential land competition with emerging biobased activities (e.g., bioproducts, biomaterials), which could limit techno-economic potential of BJF. Between 2015 and 2030, the residual land available is projected to decrease from 121.5 to 108.1 Mha. This affects the biomass costs, both positively and negatively, depending on the suitability of the available land for each biomass crop. In addition, the biomass cost data used in this study are sourced from various studies, which made different assumptions in terms of, for example, agricultural systems, expansion areas, system boundaries, and cost items. Therefore, the reported biomass costs should be interpreted with care.

The typical Brazilian annual crops (i.e., soybean and corn) present the highest suitability for most of the available land and their costs decrease over time. Their utilization in the coming years could be an initial driver for scaling up BJF technologies, as the use of alternative biomass crops (e.g., oil palm and macaw) may take time to develop. Differently, the suitable areas for sugarcane cultivation for BJF production are limited as most of the suitable agro-ecological areas for sugarcane are already occupied by the projected expansion of 1G ethanol in 2030 (Van der Hilst et al., 2018). As an alternative sugar/ethanol source, sweet sorghum has relatively low production costs and it could be a supplementary source of sugars in marginal areas in the Northeast. Even so, efforts are needed for the development of new varieties and management practices to be cultivated closer to the sugarcane industry to realize the cost reductions projected in the results (Embrapa Agroenergia, 2011).

Although regionally concentrated, perennial oil crops (i.e., macaw and oil palm) are of interest due to high agro-ecological suitability in their respective regions and the significant average oil yield per hectare compared to annual oilseed crops (Ciconini et al., 2013). The development in land availability is a constraint for their cost reductions as part of their suitable areas are projected to be used by other land uses in 2030 (Van der Hilst et al., 2018). Moreover, these perennial crops require high initial agricultural investments and their yield peak is only achieved 5–10 years after planting, which represents an additional risk for the large capital invested in the BJF project. For both 2015 and 2030, macaw palm shows lower FFB costs compared to oil palm due to the higher agro-ecological suitability. However, this is also a result of the assumption that both are cultivated under the same traits, while, in practice, oil palm is currently cultivated in large-scale monoculture systems, whereas macaw is only cultivated at small scale combined with other land uses (e.g., pasture, shrubs, forest; Cardoso et al., 2017). Therefore, the data to assess the biomass production cost of macaw palm are highly uncertain (Pimentel, Motoike, Costa, Manfio, & Bruckner, 2009).

5.2 | Technological pathways and BJF production costs

The BJF production costs at plant gate have a large range (23–180 US$/GJ) in 2015 (BJF pioneer biorefinery). By 2030, the range is smaller (20–97 US$/GJ) as it is assumed that BJF is produced at *n*th BJF biorefineries, which reduces capital costs disparities across the production routes (de Jong et al., 2015). Note that these BJF production costs represent the average of 25% of the land availability with the highest biomass yields and presumably have the best conditions for BJF production. Reference studies, such as Diederichs et al. (2016), found a range of BJF minimum selling prices between 50 and 77 US$/GJ across different production routes, whereas de Jong et al. (2015) observed a minimum selling price reduction from 33 US$/GJ (BJF pioneer plant) to 23 US$/GJ (BJF *n*th plant). In hypothetical Brazilian biorefineries, the studies of Klein et al. (2018) found a range of 9–32 US$/GJ, and Santos et al. (2017) verified 2G production routes with minimum prices between 39 and 81 US$/GJ. The comparison with other studies must be carefully interpreted as the BJF production costs assessed herein are within the Brazilian context, sourced from high biomass yields, and take into account the location effect on the BJF cost components (e.g., biomass costs, transportation costs).

We find that the production routes using DSHC technology have the highest BJF production costs, even when dedicating all the fermentable sugars to the BJF plant. This is also illustrated in practice as Amyris produced BJF from SC_DSHC in Brazil, but techno-economic barriers hampered its commercialization (Mawhood et al., 2016). Of the biochemical production routes, SC_ATJ has the lowest BJF production costs due to low capital costs required. This is line with the findings of Santos et al. (2017) and Alves et al. (2017). When it comes to ATJ in 2G plants, the BJF production cost reduction over time is more relevant than 1G plants due to expected learning effects that may reduce the capital intensity of the feedstock production plant.

The lowest BJF production costs are achieved by PO_HEFA and MP_HEFA, as a result of low biomass and feedstock production costs, and low conversion cost to BJF. However, these results should be carefully interpreted given the current status of the palm and macaw oil market in Brazil. Although they have high potential oil yields, these biomass crops marginally contribute to the current biofuel industry (e.g., biodiesel; ANP, 2019). The opportunity cost of producing BJF from these oil crops is high considering the spectrum of high added value bioproducts (e.g., biochemicals, food industry) that can be produced from these vegetable oils (Brandao & Schoneveld, 2015; Cardoso et al., 2017). Furthermore, a key advantage of producing BJF in Brazil from energy crops is the low BJF feedstock costs (e.g., vegetable oil, ethanol) due to the high biomass yield and the land availability around existing infrastructure. However, we do not account for possible options of decentralized BJF biorefineries supplied by feedstock at market prices, which may change the BJF production costs.

Promising results are also achieved by EC_HTL, which shows significant BJF production cost reduction in 2030 as a result of the assumed technological learning of the BJF biorefinery. Despite not being approved by ASTM so far, the recent established "Steeper plant" in Norway is an example that HTL technology has been recognized as a technically viable option. However, its future development highly depends on investments that are needed to overcome techno-economic barriers and enable technological learning and associated cost reductions in the coming years. As an example, two decades ago, the expected progress for thermochemical pathways (e.g., FT; Tijmensen, Faaij, Hamelinck, & Hardeveld, 2002) did not materialize until today. Hence, more empirical information (i.e., more plants to be built) is needed to support the projections on techno-economic development of thermochemical pathways (de Jong, Stralen, Londo, Hoefnagels, & Junginger, 2018). In addition, BJF production costs could decrease if alternative low-cost residual biomass (e.g., sugarcane bagasse, woody residues) is available as supplementary biomass source. The availability of residual biomass for BJF production is assessed in a forthcoming work (Cervi et al., forthcoming).

5.3 | Techno-economic potential of BJF in Brazil

Our spatially explicit approach provides location-specific information on the techno-economic potential of BJF production routes. The techno-economic potential is based on the minimum BJF total cost for each pixel of available land achievable through the 13 production routes included in the analysis. Compared to the range of jet fuel price in Brazil (19–65 US$/GJ), the techno-economic potential ranges between 0 and 6.4 EJ in 2015 and from 1.2 to 7.8 EJ in 2030. This wide range is explained by the fossil jet fuel prices used in our assessment, which is based on the price data of all airports in Brazil. Depending on the airport location, fossil jet fuel prices could be up to three times higher than the Brazilian average prices at the refineries, due to differences in profit margins, logistic costs, state taxes (7%–25% across the states), and import taxes (ABEAR, 2019). This implies that niches may exist, where a combination of low BJF costs and high fossil kerosene prices may offer opportunities for (near) competitive deployment of first BFJ production plants.

The techno-economic potential and its variations addressed in the sensitivity analysis are comparable with the projected technical potential of BJF in the Sub-Saharan Africa in 2050, which varies from 4 to 11.4 EJ (Bole-Rentel, Fischer, Tramberend, & van Velthuizen, 2019). Our results are well beyond the recent annual jet fuel demand of 0.26 EJ in Brazil (Petrobras, 2016) and the expected consumption of 0.38 EJ around 2030 (MME, 2017). The projected techno-economic BJF potential of Brazil could also contribute to the global jet fuel demand of 12 EJ in 2015 and 19 EJ in 2040 (IEA, 2016). Given that, it is recommended that future studies also consider the BJF distribution to international markets.

The techno-economic potential should not be restricted to the production route of the minimum BJF total costs. The results show that up to 10 production routes could produce BJF total costs below the fossil jet fuel price depending on the region. The heterogeneity of viable production routes suggests higher chances for BJF development in a given region. Unlike in the United States and Europe, where the demand for jet fuel is geographically more distributed; in Brazil, the regions with higher demand are concentrated in the Southeast and Northeast regions, which together account for more than 75% of the jet fuel consumed in Brazil (ANP, 2018). In these regions, the land availability to grow dedicated biomass for BJF is assumed to become scarcer over time due to the development in other land use functions (e.g., food demand increase; Van der Hilst et al., 2018). Hence, demand-driven assessments should be further explored as the BJF may be supplied from other regions, thereby impacting techno-economic results. This study only quantifies the potential of BJF under techno-economic constraints and at a large geographical scope. This is relevant for decentralizing energy policies toward a specific region for certain production routes. However, the introduction of BJF in the market requires a more detailed comprehension of local contextual factors (e.g., agronomic, infrastructure), which have to be addressed in future studies. In addition to the techno-economic aspect, the acceptance of BJF also relies on its environmental performance. Therefore, it is highly recommended to assess the effect of environmental constraints on BJF potentials.

ACKNOWLEDGEMENTS

The study has been co-funded by a scholarship from the Coordination of Improvement of Higher Education (CAPES/Brazil), and Be Basic Flagship 9.1 project "Identifying, Quantifying and Qualifying Sustainability for the Biobased Economy".

ORCID

Walter Rossi Cervi https://orcid.org/0000-0003-4769-2027
Rubens Augusto Camargo Lamparelli https://orcid.org/0000-0003-4344-1263
Joaquim Eugênio Abel Seabra https://orcid.org/0000-0002-1463-7104
Martin Junginger https://orcid.org/0000-0002-5010-2051
Sierk de Jong https://orcid.org/0000-0002-8110-4527
Floor van der Hilst https://orcid.org/0000-0002-6839-9375

REFERENCES

ABEAR. (2017). *Aviação Comercial Perspectivas de Mercado para Bioquerosene de Aviação*. Retrieved from http://pages.cnpem.br/wectbe/wp-content/uploads/sites/83/2017/08/Rogerio_Benevides.pdf. Campinas.

ABEAR. (2019). *Panorama da aviação brasileira*. Retrieved from http://panorama.abear.com.br/dados-e-estatisticas/custos-das-empresas/

ABIOVE. (2018). Monthly statistics. https://doi.org/10.6161/jgs.2014.73.05

Agusdinata, D. B., Zhao, F., Ileleji, K., & Delaurentis, D. (2011). Life cycle assessment of potential biojet fuel production in the United States. *Environmental Science & Technology*, *45*(21), 9133–9143. https://doi.org/10.1021/es202148g

Alves, C. M., Valk, M., de Jong, S., Bonomi, A., van der Wielen, L., & Solange, M. (2017). Techno-economic assessment of biorefinery technologies for aviation biofuels supply chains in Brazil. *Biofuels, Bioproducts and Biorefining*, *11*, 67–91. https://doi.org/10.1002/bbb.1711

Anex, R. P., Aden, A., Kazi, F. K., Fortman, J., Swanson, R. M., Wright, M. M., … Dutta, A. (2010). Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways. *Fuel*, *89*(SUPPL. 1), S29–S35. https://doi.org/10.1016/j.fuel.2010.07.015

ANP. (2018). *Oil, natural gas and biofuels statistical yearbook 2018*. Rio de Janeiro. Retrieved from https://doi.org/http://www.anp.gov.br/wwwanp/images/publicacoes/Anuario_Estatistico_ANP_2016.pdf

ANP. (2019). *Biodiesel production per source*. Rio de Janeiro, Brazil. Retrieved from http://www.anp.gov.br/images/PROD_FORN_BIOCOMBUSTIVEIS/Biodiesel/Processamento_de_materias-primas.xlsx

APROBIO. (2016). Biodiesel: Oportunidades e desafios no longo prazo. Retrieved from http://abiove.org.br/publicacoes/biodiesel-oportunidades-e-desafios-no-longo-prazo/

Assumpcao, D. C., Pereira, G. C. Q., Giraldi, L. A., Cervi, W. R., & Mariano, A. P. (2016). Techno-economic analysis of jet fuel production from ethanol in first and second generation sugarcane biorefineries. In *Proceedings of 21st Brazilian Congress of Chemical Engineering* (pp. 1–8). Fortaleza, Brazil: Brazilian Association of Chemical Engineering.

ASTM. (2018). *D7566–19: Standard specification for aviation turbine fuel containing synthesized hydrocarbons*. West Conshohocken, PA. Retrieved from https://www.astm.org/Standards/D7566.htm

Batidzirai, B., Valk, M., Wicke, B., Junginger, M., Daioglou, V., Euler, W., & Faaij, A. P. C. (2016). Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa. *Biomass and Bioenergy*, *92*, 106–129. https://doi.org/10.1016/j.biombioe.2016.06.010

Bergmann, J. C., Tupinambá, D. D., Costa, O. Y. A., Almeida, J. R. M., Barreto, C. C., & Quirino, B. F. (2013). Biodiesel production in Brazil and alternative biomass feedstocks. *Renewable and Sustainable Energy Reviews*, *21*, 411–420. https://doi.org/10.1016/j.rser.2012.12.058

BioGrace. (2018). *Condensed list of standard values, Version 4 – Public*. Retrieved from http://www.biograce.net/content/ghgcalculationtools/standardvalues

Biopalma. (2016). Relatório de Sustentabilidade Biopalma 2016. *Relatório de Sustentabilidade*. Retrieved from http://www.biopalma.com.br/pdf/relatorio-sustentabilidade-2016.pdf

Bole-Rentel, T., Fischer, G., Tramberend, S., & van Velthuizen, H. (2019). Taking off: Understanding the sustainable aviation biofuel potential in sub-Saharan Africa. Retrieved from https://www.wwf.org.za/our_research/publications/?26941/taking-off-understanding-the-sustainableaviation-biofuel-potential-in-sub-saharan-africa

Brandao, F., & Schoneveld, G. (2015). *The state of oil palm development in the Brazilian Amazon*. Retrieved from https://www.researchgate.net/profile/Frederico_Brandao2/publication/286921822_The_state_of_oil_palm_development_in_the_Brazilian_Amazon_Trends_value_chain_dynamics_and_business_models/links/566fbedd08ae4d9a42577835/The-state-of-oil-palm-development-in-the

Brazilian Infrastructure Ministry. (2018). *Plano Aeroviário Nacional 2018–2038*. Brasília.

Cantarella, H., Nassar, A. M., Cortez, L. A. B., & Baldassin, R. (2015). Potential feedstock for renewable aviation fuel in Brazil. *Environmental Development*, *15*, 52–63. https://doi.org/10.1016/j.envdev.2015.05.004

Cardoso, A., Laviola, B. G., Santos, G. S., de Sousa, H. U., de Oliveira, H. B., Veras, L. C., & Favaro, S. P. (2017). Opportunities and challenges for sustainable production of *A. aculeata* through agroforestry systems. *Industrial Crops and Products*, *107*, 573–580. https://doi.org/10.1016/j.indcrop.2017.04.023

Carvalho, F., Szklo, A., Program, E. P., Tecnologia, C. D., Janeiro, R. D., Portugal-pereira, J., … Janeiro, R. D. (2019). Potential for biojet production from different biomass feedstocks and consolidated technological routes: A georeferencing and spatial analysis in Brazil. *Biofuels, Bioproducts and Biorefining*, 1–22. https://doi.org/10.1002/bbb.2041

Cervi, W. R., Augusto, R., Lamparelli, C., Gallo, B., Bordonal, R. de O., Seabra, J., & Van der Hilst, F. (forthcoming). Mapping the

environmental and techno-economic potential of biojet fuel production from biomass residues in Brazil.
Cheng, M.-H., & Rosentrater, K. A. (2017). Economic feasibility analysis of soybean oil production by hexane extraction. *Industrial Crops and Products*, *108*(August), 775–785. https://doi.org/10.1016/j.indcrop.2017.07.036
Ciconini, G., Favaro, S. P., Roscoe, R., Miranda, C. H. B., Tapeti, C. F., Miyahira, M. A. M., … Naka, M. H. (2013). Biometry and oil contents of *Acrocomia aculeata* fruits from the Cerrados and Pantanal biomes in Mato Grosso do Sul, Brazil. *Industrial Crops and Products*, *45*, 208–214. https://doi.org/10.1016/j.indcrop.2012.12.008
Cortez, L. A. B. (2014). *Roadmap for sustainable aviation biofuels for Brazil: A flightpath to aviation biofuels in Brazil* (2nd ed.). São Paulo, Brazil: Blucher.
de Jong, S. (2018). *Green Horizons: On the production costs, climate impact and future supply of renewable jet fuels*. Utrecht, the Netherlands: Utrecht University.
de Jong, S., Hoefnagels, R., Faaij, A., Slade, R., Mawhood, R., & Junginger, M. (2015). The feasibility of short-term production strategies for renewable jet fuels – A comprehensive techno-economic comparison. *Biofuels, Bioproducts and Biorefining*, *9*(6), 778–800. https://doi.org/10.1002/bbb.1613
de Andrade, E. (2015). *A cadeia produtiva da palma de óleo no Estado do Pará: Uma avaliação crítica* (pp. 1–51). Brasília, Brazil: Audiência Pública sobre o Programa nacional de Produção Sustentável de Óleo de Palma. Retrieved from https://www2.camara.leg.br/atividade-legislativa/comissoes/comissoes-permanentes/capadr/audiencias-publicas/audiencias-publicas-2015/audiencia-publica-26-de-marco-de-2015-faepa
de Jong, S., Hoefnagels, R., Wetterlund, E., Pettersson, K., Faaij, A., & Junginger, M. (2017). Cost optimization of biofuel production – The impact of economies of scale, integration, intermodal transport and distributed supply chain configurations. *Applied Energy*, *195*, 1055–1070. https://doi.org/10.1016/j.apenergy.2017.03.109
de Jong, S., Stralen, J. V., Londo, M., Hoefnagels, R., & Junginger, M. (2018). Renewable jet fuel supply scenarios in the European Union in 2021–2030 in the context of proposed biofuel policy and competing biomass demand. *GCB Bioenergy*, *10*, 661–682. https://doi.org/10.1111/gcbb.12525
Diederichs, G. W. (2015). *Techno-economic assessment of processes that produce jet fuel from plant-derived sources*. Stellenbosch, South Africa: Stellenbosch University.
Diederichs, G. W., Mandegari, M. A., Farzad, S., & Görgens, J. F. (2016). Techno-economic comparison of biojet fuel production from lignocellulose, vegetable oil and sugar cane juice. *Bioresource Technology*, *216*, 331–339. https://doi.org/10.1016/j.biortech.2016.05.090
E4tech. (2017). *Advanced drop – In biofuels UK production capacity outlook to 2030 final report*. UK Department for Transport. Retrieved from https://www.gov.uk/government/publications/advanced-drop-in-biofuels-uk-production-capacity-outlook-to-2030
Embrapa Agroenergia. (2011). Sorgo sacarino na Embrapa: Histórico, importância e usos. *Agroenergia Em Revista*, 1–52.
EPE. (2017). *Cenários de Oferta de Etanol e Demanda do Ciclo Otto: versão estendida 2030*. Retrieved from https://goo.gl/rMkOKf
FAA. (2011). *Federal Aviation Administration: Destination 2025*. Retrieved from https://www.faa.gov/about/plans_reports/media/Destination2025.pdf
FAB. (2018). *Logistic centre: Jet fuel prices*. Retrieved from http://www2.fab.mil.br/celog/images/combav/QUEROSENE.xlsx
FAPESP. (2013). *Plano de voo para biocombustíveis de aviação no Brasil: Plano de ação* (Vol *1*). Retrieved from http://www.fapesp.br/publicacoes/plano-de-voo-biocombustiveis-brasil-pt.pdf
FS Bioenergia. (2016). *FS Bioenergia launches the first corn-only ethanol plant in Brazil*. Retrieved from http://www.fsbioenergia.com.br/en/news-id/fs-bioenergia-launches-the-first-corn-only-ethanol-plant-in-brazil/2
Furlan, L. F., Rodrigues, F. D. S., Planejamento, S. A. D., Lima, I. A., Planejamento, D. D., Maria, E., …Iank, O. (2003). SUFRAMA 1. Zona Franca de Manaus : Potencialidades – Estudo de Viabilidade Econômica 2. SUFRAMA Potencialidades – Estudo de Viabilidade Econômica 3. Potencialidades – Estudo de Viabilidade Econômica. Retrieved from http://www.suframa.gov.br/publicacoes/proj_pot_regionais/dende.pdf
Garcia, L. G., Ferraz, S. F. D. B., & Alvares, C. A. (2014). Scientia Forestalis Modelagem da aptidão climática do *Eucalyptus grandis* frente aos cenários de mudanças climáticas no Brasil Modeling suitable climate for *Eucalyptus grandis* under future climates scenarios in Brazil (pp. 503–511).
Hamelinck, C. N., Suurs, R. A. A., & Faaij, A. P. C. (2005). International bioenergy transport costs and energy balance. *Biomass and Bioenergy*, *29*(2), 114–134. https://doi.org/10.1016/j.biombioe.2005.04.002
Hayward, J. A., O'Connell, D. A., Raison, R. J., Warden, A. C., O'Connor, M. H., Murphy, H. T., … Rye, L. (2015). The economics of producing sustainable aviation fuel: A regional case study in Queensland, Australia. *GCB Bioenergy*, *7*(3), 497–511. https://doi.org/10.1111/gcbb.12159
Herr, A., Braid, A., Carter, J., McIvor, J., Murphy, H. T., O'Connell, D., … Poole, M. (2016). Cut your grass and eat it too- is aviation biofuel production and grazing in the Australian tropics possible? *Renewable and Sustainable Energy Reviews*, *53*(November 2015), 1377–1388. https://doi.org/10.1016/j.rser.2015.09.052
IATA (2015). *IATA sustainable aviation fuel roadmap*.
IBÁ. (2016). *Relatório Anual – 2016. Indústria Brasileira de Árvores*. https://doi.org/10.1017/CBO9781107415324.004
IBGE. (2015). Sistema IBGE de Recuperação Automática – SIDRA.
ICAO. (2010). *Aviation's contribution to climate change. ICAO environmental report 2010*. Retrieved from http://www.icao.int/environmental-protection/Documents/EnvironmentReport-2010/ICAO_EnvReport10-Ch1_en.pdf
IEA. (2016). *World energy outlook 2016*. Paris. https://doi.org/10.1787/weo-2016-en
Index Mundi. (n. d.). *U. S. Gulf Coast kerosene-type jet fuel spot price FOB, US$ per gallon*. Retrieved from https://www.indexmundi.com/commodities/?commodity=jet-fuel
Jonker, J. G. G., Junginger, H. M., Verstegen, J. A., Lin, T., Rodriguez, L. F., Ting, K. C., … van der Hilst, F. (2016). Supply chain optimization of sugarcane first generation and eucalyptus second generation ethanol production in Brazil. *Applied Energy*, *173*, 494–510. https://doi.org/10.1016/j.apenergy.2016.04.069
Jonker, J. G. G., van der Hilst, F., Junginger, H. M., Cavalett, O., Chagas, M. F., & Faaij, A. P. C. (2015). Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies. *Applied Energy*, *147*, 593–610. https://doi.org/10.1016/j.apenergy.2015.01.090
Kazi, F. K., Fortman, J., & Anex, R. (2010). Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol. *National Renewable Energy Laboratory-NREL*, (June), 102. Retrieved from https://doi.org/NREL/TP-6A2-46588

Klein, B. C., Chagas, M. F., Junqueira, T. L., Rezende, M. C. A. F., de Fátima Cardoso, T. F., Cavalett, O., & Bonomi, A. (2018). Techno-economic and environmental assessment of renewable jet fuel production in integrated Brazilian sugarcane biorefineries. *Applied Energy*, *209*(August 2017), 290–305. https://doi.org/10.1016/j.apenergy.2017.10.079

Kwiatkowski, J. R., McAloon, A. J., Taylor, F., & Johnston, D. B. (2006). Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Industrial Crops and Products*, *23*(3), 288–296. https://doi.org/10.1016/j.indcrop.2005.08.004

Mahlia, T. M. I., Yong, J. H., Safari, A., & Mekhilef, S. (2012). Techno-economic analysis of palm oil mill wastes to generate power for grid-connected utilization. *Energy Education Science and Technology Part A: Energy Science and Research*, *28*(2), 1111–1130.

MAPA. (2015). *Anuário estatístico de agroenergia 2014*.

Mariano, A. P. (2015). How Brazilian pulp mills will look like in the future? *O Papel*, *76*(Jun), 55–61.

Martini, D. Z., & Aragão, L. E. O. E. C., Sanches, I. D. A., Galdos, M. V., da Silva, C. R. U., & Dalla-Nora, E. L. (2018). Land availability for sugarcane derived jet-biofuels in São Paulo—Brazil. *Land Use Policy*, *70*(February 2017), 256–262. https://doi.org/10.1016/j.landusepol.2017.10.035

Mawhood, R., Gazis, E., de Jong, S., Hoefnagels, R., & Slade, R. (2016). Production pathways for renewable jet fuel: A review of commercialization status and future prospects. *Biofuels, Bioproducts and Biorefining*, *10*(4), 462–484. https://doi.org/10.1002/bbb.1644

May, A. (2013). *Cultivo de sorgo sacarino em áreas de reforma de canaviais* (pp. 1–36). Sete Lagoas, Brazil: Embrapa, Circular Técnica 186. Retrieved from https://www.infoteca.cnptia.embrapa.br/bitstream/doc/966886/1/circ186.pdf

Merrow, E. W., Phillips, K. E., & Myers, C. W. (1981). *Understanding cost growth and performance shortfalls in pioneer process plants* (pp. 1–118). Santa Monica, CA: The Rand Corporation. Retrieved from https://www.rand.org/content/dam/rand/pubs/reports/2006/R2569.pdf

Milanez, A. Y., Mancuso, R. V., Godinho, R. D., & Poppe, M. K. (2017). *O Acordo de Paris e a transição para o setor de transportes de baixo carbono: o papel da Plataforma para o Biofuturo. BNDES Setorial* (Vol. *45*).

MME. (2017). *Modelo RenovaBio: Cenário, Meta, Premissas e Impactos*. Retrieved from http://www.mme.gov.br/documents/10584/74698855/2a+Reunião+Aberta+CRBio+-++MME.+1+Modelo+Metas+de+Redução+de+Emissões+-+Cenário+e+Premissas+-+03-05-2018+-+Auditorio+MCTIC/fe66806b-a71c-44c6-8c8d-dd8064526e18;jsessionxml:id=92450C84ABC54D461A6BB89C398DFF0A.srv1

Moraes, M. A. F. D., Nassar, A. M., Moura, P., Leal, R. L. V., & Cortez, L. A. B. (2014). Jet biofuels in Brazil: Sustainability challenges. *Renewable and Sustainable Energy Reviews*, *40*, 716–726. https://doi.org/10.1016/j.rser.2014.07.210

Murphy, H. T., O'Connell, D. A., Raison, R. J., Warden, A. C., Booth, T. H., Herr, A., … Rye, L. (2015). Biomass production for sustainable aviation fuels: A regional case study in Queensland. *Renewable and Sustainable Energy Reviews*, *44*, 738–750. https://doi.org/10.1016/j.rser.2015.01.012

Norden. (2016). Sustainable jet fuel for aviation: Nordic perpectives on the use of advanced sustainable jet fuel for aviation. Retrieved from https://www.nordicenergy.org/wp-content/uploads/2016/09/FULLTEXT_Sustainable_Jet_Fuel_for_Aviation.pdf

Parecis S/A. (2015). *Presentation: PARECIS S/A*. Retrieved from https://www.embrapa.br/documents/1355202/1529289/jesur_jose_cassol.pdf/3d03855a-2c97-4823-b4b4-7ce9bb5ddb84

Patzek, T. W. (2006). A statistical analysis of the theoretical yield of ethanol from corn starch. *Natural Resources Research*, *15*(3), 205–212. https://doi.org/10.1007/s11053-006-9022-5

Pearlson, M. N., Wollersheim, C., & Hileman, J. I. (2013). A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioproducts and Biorefining*, *7*, 89–96. https://doi.org/10.1002/bbb.1378

Petrobras. (2016). Suprimento de QAV Da Produção e Importação aos Aeroportos. In *1° Workshop sobre Compras Centralizadas – Centro Logístico da Aeronáutica*. Retrieved from http://www2.fab.mil.br/celog/images/workshop/WorkShop_Petrobras.pdf

Phillips, S. J. (2017). *A brief tutorial on Maxent*. Retrieved from https://biodiversityinformatics.amnh.org/open_source/maxent/Maxent_tutorial2017.pdf

Phillips, S. J., & Dudik, M. (2008). Modeling of species distribution with Maxent: new extensions and a comprehensive evalutation. *Ecograpy*, *31*(December 2007), 161–175. https://doi.org/10.1111/j.2007.0906-7590.05203.x

Pimentel, L. D., Motoike, S. Y., de Costa, E. W. D. A., Manfio, C. E., & Bruckner, C. H. (2009). Estimativa de custo de produção e viabilidade econômica do cultivo da palmeira macaúba (*Acrocomia aculeata*) para a produção de óleo vegetal. *Proceedings of 6° Brazilian Congress of Oil Plants, Fats and Biodiesel, Montes Cla, 30–35*. Retrieved from http://entabanbrasil.com.br/downloads/Estudo-de-Viabilidade-Economica-Macauba-Leonardo-Pimentel.pdf

Plath, M., Moser, C., Bailis, R., Brandt, P., Hirsch, H., Klein, A.-M., … von Wehrden, H. (2016). A novel bioenergy feedstock in Latin America? Cultivation potential of *Acrocomia aculeata* under current and future climate conditions. *Biomass and Bioenergy*, *91*, 186–195. https://doi.org/10.1016/j.biombioe.2016.04.009

RFA. (2015). *Ethanol plants in the U.S. from 1999 through 2014 (Renewable Fuels Association)*. Retrieved from https://www.afdc.energy.gov/data/widgets/10342

RFA. (2016). 2016 Ethanol industry outlook. Retrieved from https://ethanolrfa.org/wp-content/uploads/2016/02/Ethanol-Industry-Outlook-2016.pdf

SAFUG. (2018). *Our commitment to sustainable options*. Retrieved from http://www.safug.org/safug-pledge/

Sant'Anna, A. C., Shanoyan, A., Bergtold, J. S., Caldas, M. M., & Granco, G. (2016). Ethanol and sugarcane expansion in Brazil: What is fueling the ethanol industry? *International Food and Agribusiness Management Review*, *19*(4), 163–182. https://doi.org/10.22434/IFAMR2015.0195

Santos, C. I., Silva, C. C., Mussatto, S. I., Osseweijer, P., van der Wielen, L. A. M., & Posada, J. A. (2017). Integrated 1st and 2nd generation sugarcane bio-refinery for jet fuel production in Brazil: Techno-economic and greenhouse gas emissions assessment. *Renewable Energy*, *129*, 733–747. https://doi.org/10.1016/j.renene.2017.05.011

Seabra, J. E. A., & Macedo, I. C. (2011). Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil. *Energy Policy*, *39*(1), 421–428. https://doi.org/10.1016/j.enpol.2010.10.019

Sharma, N., Bohra, B., Pragya, N., Ciannella, R., Dobie, P., & Lehmann, S. (2016). Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. *Food and Energy Security*, *5*(3), 165–183. https://doi.org/10.1002/fes3.87

Silva Braz, D., & Mariano, A. P. (2018). Jet fuel production in eucalyptus pulp mills: Economics and carbon footprint of ethanol vs. butanol pathway. *Bioresource Technology*, *268*(July), 9–19. https://doi.org/10.1016/j.biortech.2018.07.102

Silva, C. A. F. E., Bueno, J. M., & Neves, M. R. (2017). A industria de celulose e papel no Brasil. *Guia ABTCP, FORNECEDORES&FABRICANTES; Celulose e Papel, 2016|2017*, 16–28. Retrieved from http://www.poyry.com.br/sites/www.poyry.com.br/files/media/related_material/16out27a-abtcp.pdf

Souza, K. R. D. O. V. (2017). *Potential, spatial distribution and sustainability of sugarcane ethanol in Brazil: Projections to 2030*. Viçosa, Brazil: Viçosa University.

Stape, J. L., Binkley, D., Ryan, M. G., Fonseca, S., Loos, R. A., Takahashi, E. N., … Azevedo, M. R. (2010). The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production. *Forest Ecology and Management*, *259*(9), 1684–1694. https://doi.org/10.1016/j.foreco.2010.01.012

Swanson, R. M., Satrio, J. A., Brown, R. C., & Hsu, D. D. (2010). Techno-economic analysis of biofuels production based on gasification *Alexandru Platon*. *Energy*, *89*(November), S11–S19. https://doi.org/10.1016/j.fuel.2010.07.027

Tijmensen, M. J. A., Faaij, A. P. C., Hamelinck, C. N., & van Hardeveld, M. R. M. (2002). Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass and Bioenergy*, *23*, 129–152. https://doi.org/10.1093/nq/s6-VI.150.396-c

Tóth, G., Kozlowski, B., Prieler, S., & Wiberg, D. (2012). *Global agro-ecological zones user's guide, 74*. Retrieved from http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/GAEZ_User_Guide.pdf

Tzanetis, K. F., Posada, J. A., & Ramirez, A. (2017). Analysis of biomass hydrothermal liquefaction and biocrude-oil upgrading for renewable jet fuel production: The impact of reaction conditions on production costs and GHG emissions performance. *Renewable Energy*, *113*, 1388–1398. https://doi.org/10.1016/j.renene.2017.06.104

UNFCCC. (2015). *Intended nationally determined contribution of Brazil*. Paris. Retrieved from https://www4.unfccc.int/sites/submissions/INDC/PublishedDocuments/Brazil/1/BRAZILiNDCenglishFINAL.pdf

UNICA. (2018). *Histórico de produção e moagem (Production history)*. Retrieved from http://www.unicadata.com.br/historico-de-producao-e-moagem.php?idMn=32&tipoHistorico=4

van den Wall Bake, J. D., Junginger, M., Faaij, A., Poot, T., & Walter, A. (2009). Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, *33*(4), 644–658. https://doi.org/10.1016/j.biombioe.2008.10.006

Van der Hilst, F., & Faaij, A. P. C. (2012). Spatiotemporal cost-supply curves for bioenergy production in Mozambique. *Biofuels, Bioproducts and Biorefining*, *6*, 405–430. https://doi.org/10.1002/bbb.1332

Van der Hilst, F., Verstegen, J. A., & Woltjer, G. (2018). Mapping direct and indirect land use changes resulting from biofuel production and the effect of LUC mitigation measures land use change resulting from biofuel production. *GCB Bioenergy*, *10*, 804–824. https://doi.org/10.1111/gcbb.12534

Villela, A. A. (2009). O dendê como alternativa energética sustentável em áreas degradadas da Amazonia (Federal University of Rio de Janeiro). Retrieved from http://www.ppe.ufrj.br/index.php/pt/publicacoes/dissertacoes/2009/1002-o-dende-como-alternativa-energetica-sustentavel-em-areas-degradadas-na-amazonia

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S, van der Hilst F. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. *GCB Bioenergy*. 2020;12:136–157. https://doi.org/10.1111/gcbb.12659