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ENVIRONMENTAL AND DIRECT LAND USE IMPACTS OF AVIATION BIOFUEL PRODUCTION IN BRAZIL: A GEOREFERENCED AND LIFE CYCLE ANALYSIS

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Orientadora: Joana Correia de Oliveira de Portugal Pereira

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IMPACTOS AMBIENTAIS E DO USO INDUZIDO DA TERRA DA PRODUÇÃO DE BIOCOMBUSTÍVEIS DE AVIAÇÃO NO BRASIL: UMA ANÁLISE GEORREFERENCIADA E DO CICLO DE VIDA

Clarissa de Souza Vicente
Fevereiro/2022

Orientadora: Joana Correia de Oliveira de Portugal Pereira
Programa: Planejamento Energético

O setor de aviação contribui com cerca de 2% das emissões antropogênicas globais de CO_2. Nesse contexto, a ICAO estabeleceu ambiciosas metas para mitigar essas emissões. Uma das alternativas para que essas metas sejam alcançadas é o desenvolvimento de combustível alternativo de aviação baseado em biomassa. O objetivo deste estudo é avaliar as emissões de GEE e os efeitos das mudanças no uso da terra da produção de biocombustíveis de aviação no Brasil. Para isso, estimou-se o potencial técnico das culturas de biomassa de cana, milho, soja, palma e macaúba. Em seguida, foi realizada uma análise do ciclo de vida das vias tecnologias selecionadas (ATJ e HEFA). Por último, foi desenvolvida uma matriz de mudança do uso do solo para estimar os efeitos das mudanças diretas do uso do solo. O potencial técnico de biomassa dedicada foi de aproximadamente 86.000 TJ/ano, sendo a maior parte dele da cana de açúcar. A rota HEFA de soja obteve o melhor desempenho ambiental na análise de ciclo de vida (20.1g CO_{2e}/MJ_{FUEL}) e a rota HEFA de macaúba de baixo rendimento obteve o pior resultado (71.8 g CO_{2e}/MJ_{FUEL}). Quando os efeitos de mudanças do uso do solo foram incluídos, foram validadas as rotas ATJ de cana no Cerrado e pastos, HEFA de palma na Amazônia e em pastos e HEFA de macaúba na Amazônia, Caatinga, Cerrado e pastos. As rotas ATJ de milho e HEFA de soja só se certificam quando a dLUC ocorre em pastos. Conclui-se que as rotas de combustível alternativo de aviação se adequam à certificação de sustentabilidade quando a expansão de área agrícola não sacrifica ecossistemas nativos fixadores de elevado teor de carbono e apenas quando a conversão de terras ocorre em pastagens.

Abstract of Dissertation presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Master of Science (M.Sc.)

ENVIRONMENTAL AND INDUCED LAND USE IMPACTS OF AVIATION BIOFUEL PRODUCTION IN BRAZIL: A GEOREFERENCED AND LIFE CYCLE ANALYSIS

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The aviation sector contributes about 2% of global anthropogenic CO_2 emissions. In this context, ICAO has set ambitious goals to mitigate these emissions. One of the alternatives for these goals to be achieved is the development of alternative aviation fuel based on biomass. The objective of this study is to evaluate GHG emissions and land use change effects of aviation biofuel production in Brazil. To do this, the technical potential of the biomass crops of sugarcane, corn, soybean, oil palm, and macaw was estimated. Next, a life cycle analysis of the selected technologies (ATJ and HEFA) was performed. Finally, a land use change matrix was developed to estimate the effects of direct land use changes. The technical potential of dedicated biomass was approximately 86,000 TJ/yr, most of it from sugarcane. The soybean HEFA route obtained the best environmental performance in the life cycle analysis (20.1g CO_{2e}/MJ_{FUEL}) and the low-yielding macaw HEFA route obtained the worst result (71.8 g CO_{2e}/MJ_{FUEL}). When the effects of land use change were included, the ATJ pathways of sugarcane in the Cerrado and grasslands, HEFA of oil palm in the Amazon and in grasslands, and HEFA of macaw in the Amazon, Caatinga, Cerrado and grasslands were validated. The ATJ routes from corn and HEFA from soybean are only certified when dLUC occurs in grasslands. It is concluded that the alternative aviation fuel routes are suitable for sustainability certification when the expansion of agricultural area does not sacrifice high carbon fixing native ecosystems and only when land conversion occurs in grasslands.

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1 Introduction

In 2017, the air transport sector was responsible for 2% of global greenhouse gas (GHG) emissions. Moreover, aviation sector is growing rapidly despite de momentaneous drop of demand due to the COVID19 pandemic. About 7.2 billion trips were expected by 2035, almost twice as many trips compared to the year 2019 - (IATA,2016). Therefore, thinking about alternatives to fossil fuels should be considered according to the environmental effects, safe operation of the aircraft engine, consistency, energy density and availability of resources to meet the growing demand (HEMIGHAUS et al. 2006; KUBICKOVA & KUBICKA 2010; HARI et al. 2015).

To address these issues, the International Civil Aviation Organization (ICAO) relies on scientific studies and data to guide the development of mitigating measures to address environmental impacts within the aviation industry (PRUSSI et al, 2021). One example and which came into effect in the year 2020 is the global CO_2 standard that regulates fuel efficiency for new aircraft, i.e., this standard suggests improvements in aviation fuel efficiency by at least 2% per year (PRUSSI et al., 2021). Another important achievement by ICAO was the creation of Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to help reduce GHG emissions in aviation (ICAO, 2019a).

The CORSIA was adopted by the 193 ICAO members in the year 2016 with the purpose of limiting CO_2 emissions from international aviation (ICAO, 2019a). Briefly, CORSIA requires airlines to offset any emissions above a given reference year (initially decided as the 2019 and 2020 average emissions, although the impact of the COVID-19 pandemic should presumably now be accounted for) (SCHEELHAASE 2018; SOEMARY, 2019; GRAY et al. 2021). This offset can be achieved through emission credits or use of CORSIA-eligible fuels so that international aviation achieves carbon-neutral growth from the year 2020 (ICAO, 2019b).

Although improvements in aircraft efficiency and air traffic management made in recent years have contributed to the reduction of CO2 emissions, decarbonization of the aviation sector is still a challenge in view of the expected growth of the sector (EASA, 2019; HILEMAN et al. 2013; ICAO 2019c; EUROPEAN COMMISSION, 2018). Some paths such as the use of liquid natural gas, hydrogen and electric propulsion have been proposed, but so far, they have only been tested at pilot scale and still need technical improvements to be implemented (HILEMAN & STRATTON, 2014). The use of these technologies for short/medium and long-range air operations is still impractical mainly because the mass of the battery required to store the required energy would be greater than the maximum allowable takeoff weight of the aircraft (GRAY et al. 2021). Thus, a more promising near-term path to reduce CO2 emissions in the aviation sector is the deployment of alternative fuels (HILEMAN & STRATTON, 2014; IRENA, 2017).

Alternative aviation fuels are derived from energy crops (such as sugarcane, corn, cassava soybeans, sugar beets, wheat and others) or from lignocellulosic biomass (non-food crops and inedible agricultural residues) (KOÇAR & CIVAS 2013; PURI et al. 2012; LIMAYEM & ROCKE 2012; ESCOBAR et al. 2009). The main reasons driving the introduction of biofuel in the world is related to its neutral character, being recognized as a renewable energy source, preventing air pollution, contributing to energy security, and promoting the development of agriculture and rural areas (MATSUDA & TAKEUCHI 2018).

Alternative fuels are commonly referred to as *drop-in* fuels, meaning they require no or limited modifications to the engine or aircraft system and no specified refueling infrastructure (HILEMAN & STRATTON, 2014; IRENA, 2017). In addition, within the

CORSIA scheme, these alternative aviation fuels must meet a set of sustainability criteria, such as GHG emissions must be at least 10% lower than conventional aviation fuel baseline and must not come from biomass obtained from land with high carbon stock (ICAO, 2019d).

However, increased demand for agricultural-based biofuels may promote the expansion of crop areas, potentially intensifying land use change, degradation of terrestrial ecosystem services and driving greenhouse gas (GHG) emissions. Land use change can happen broadly in two ways: (i) directly (dLUC), when conversion occurs on the same land as the new land use (SCHMIDT; WEIDEMA; BRANDÃO, 2015) or (ii) indirectly (iLUC), when the result of interactions between commodity markets, connections between agricultural and non-agricultural markets, and international trade can extend beyond biofuel-producing regions, regardless of the land use purpose, becoming induced land use change (KEENEY & HERTEL, 2008; HERTEL et al. 2010; TILMAN et al. 2006). Therefore, emissions associated with land use change have a large contribution to the life cycle of a biofuel and should be accounted for, as it is an extremely important factor for decision making.

To calculate the GHG emissions offered by a specific alternative fuel, CORSIA uses a life cycle assessment (LCA) approach, agreed upon by ICAO members in the year 2018 (ICAO, 2020). LCA refers to standardized environmental analysis methodology (ISO 2006a, IS0 2006b) commonly used to assess environmental impacts of biofuels and direct decision makers worldwide (USEPA, 2010). Therefore, for the principles of completeness, transparency, relevance, and accuracy to be met, all emissions caused by a product throughout its life cycle must be accounted for, especially those from land use change (GREENHOUSE GAS PROTOCOL, 2011; IS0 2006b).

Given this context, this thesis aims to assess the greenhouse gas emissions and land use change effects resulting from aviation biofuel production in Brazil. To this end, the analysis involves three methodological steps: (i) estimation of the technical potential of selected energy crops in Brazil (sugarcane, corn, soybean, oil palm, and macaw); ii) analysis of the environmental performance of each life cycle stage of each selected crop (cultivation and collection of the feedstock, transportation of the feedstock, conversion of the feedstock to fuel, and combustion of the fuel in the aircraft), based on an attributional life cycle assessment (ACVA) approach; and iii) quantifying the effects of direct land use change by developing a direct land use conversion emissions matrix.

This thesis consists of seven chapters. After this introduction, Chapter 2 covers a literature review on the main characteristics of conventional and alternative aviation fuels, aviation fuel certification schemes, the different technological routes to produce alternative fuels, and the implications on land use change in Brazil and worldwide. Chapter 3 presents the methodology applied and the database used in the study. Chapter 4 presents the results of the study. Chapter 5 discusses the results achieved in this work. Chapter 6 discusses the final considerations and recommendations for future work. Finally, chapter 7 presents the bibliography used as a basis for this study.

2 Sustainability of the aviation fuel

This section presents a literature review of aviation biofuels and associated sustainability issues. First, a characterization of each of the feedstocks used to produce alternative aviation fuels. This is followed by an overview an overview of aviation fuel specifications. Finally, the impacts of land use change on biofuel production and some existing methodologies for estimating these impacts are shown.

2.1 Biomass feedstock description

According to ANGELIS-DIMAKIS et al. (2011) biomass refers to the biodegradable fraction of products and waste generated by the agricultural, forestry, industrial, and the waste [1]sector itself. Some types of biomasses most used as feedstocks to produce biofuels come from soybean, oil palm, sunflower, canola, corn, sugarcane and other crops (de SOUZA, et al., 2019). Although there is a global concern regarding food security due to the occupation of new land for the expansion of biofuel production, Brazil besides being a reference in biofuel production, has favorable conditions in terms of climate, land and water availability (ESCOBAR, et al., 2009).

The feedstocks for production alternative fuels are derived from energy crops (such as sugarcane, corn, cassava soybeans, sugar beets, wheat and others) or from lignocellulosic biomass (non-food crops and inedible agricultural residues) (KOÇAR & CIVAS 2013; PURI et al. 2012; LIMAYEM & ROCKE 2012; ESCOBAR et al. 2009). Therefore, alternative fuels from biomass can produce bioenergy and the main reasons that make them potential substitutes for fossil fuels are: (i) the Kyoto Protocol considers biofuels to be carbon neutral, since the carbon stored in alternative aviation fuel is theoretically offset during feedstock growth (TAKEUCHI et al. 2018); (ii) alternative

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[1] According to the EPE, renewable sources of energy are considered inexhaustible, because their quantities are constantly renewed as they are used. Some examples of renewable sources are hydro (energy from river water), solar (energy from the sun), wind (energy from wind), biomass (energy from organic matter), geothermal (energy from the Earth's interior), and oceanic (energy from tides and waves).

aviation fuel are conceived to be a renewable energy because they are a non-exhaustible resource, which meets the definition[1] of renewable energy adopted by the Energy Research Company (EPE); (iii) they promote energy security (TAKEUCHI et al. 2018); and (iv) the increased demand for biofuels favors the development of agriculture and agricultural areas due to increased agricultural profit, employment and income generation, and intensified export of agricultural products in developing countries (KOIZUMBI 2007; HISANO 2008).

In this context, Brazil is a major producer of alternative fuels. Besides having a variety of arable land available for use - approximately 593 MHa - (ESCALANTE et al. 2021), it has favorable soil and climate conditions and a wide variety of feedstocks both in quantity and quality to produce aviation biofuels (CANTARELLA et al. 2015). In addition, Brazil has experience in the use of biomass for energy purposes and a well-consolidated agricultural sector since the Pro-Alcohol program in the decade of ‘70’s (GOLDEMBERG 2007; BNDES 2008).

In the legal context, Brazil has instruments and actions that encourage the production of alternative aviation fuels. The Biofuels Law (law n° 12,490 of 2011) considers only biomass derivatives as aviation biofuels. The Law nº. 14,248 of 2021 establishes, through the National Biokerosene Program, incentives for research and the promotion of energy production from biomass, aiming at the sustainability of Brazilian aviation. The National Biofuels Policy (RenovaBio) - Brazilian Law nº. 13,576 of 2016 - focuses on stimulating biofuels production in Brazil through considering predictability, sustainability (environmental, economic, and social), as well as market growth (MATSUURA et al. 2018).

There are some studies in the literature that estimate the potential for alternative jet fuel in Brazil. For example, CERVI et al. (2019) evaluated the current and future techno-economic potential of alternative aviation fuel production in Brazil and identified specific optimal combinations of biomass crop location and technological conversion pathways. CARVALHO et al. (2019) evaluated the potential for aviation biofuel production in Brazil by applying a georeferencing analysis. CERVI et al. (2020) evaluated the environmental potential of agricultural residues and the techno-economic potential of alternative aviation biofuel production in Brazil from two types of biomass residues (sugarcane straw and eucalyptus harvest residue) and four different technological pathways (jet alcohol, Fischer-Tropsch, hydrothermal liquefaction and pyrolysis). WALTER et al. (2021) presented an assessment of the conditions necessary for the sustainable production of alternative aviation fuel in Brazil. Later, WALTER et al. (2021) showed the results of this assessment considering three certified routes, based on dedicated production of eucalyptus, soy, sugar cane and corn.

However, some challenges such as the lack of technical mastery in the production of alternative feedstocks with higher energy density, lack of laboratory infrastructure for alternative aviation fuel certification, logistical issues, high cost of feedstocks and refining routes, lack of public-private investment, and food security still need to be resolved for the expansion of alternative jet fuel production in Brazil (CORTEZ et al. 2015; MARTINI et al. 2018; PASHAEI KAMALI et al., 2018).

In view of this, the following feedstocks were considered as objects of study for the present research: (i) sugarcane, (ii) corn, (iii) soybean, (iv) palm and (v) macaw. Their respective residues were also analyzed, straw and bagasse for sugarcane, stover for corn, straw for soy, empty bunches fruit for palm and husk for macaw. The following subsections detail each of the selected feedstocks.

2.1.1 Sugar Crops

In general, sugar crops are broadly classified into two types: saccharine and starchy. The saccharines refer to sources of sugars (glucose), such as sugarcane, sugar beets and sorghum, and are used both to produce sugar (food sector) and ethanol (energy sector). On the other hand, starches are sources of starch (glucose polysaccharide), such as corn, potatoes, cassava, wheat, among others, and are generally used for cereal, tuber, and root production (food sector) and ethanol (energy sector).

Sugarcane

Sugarcane is one of the main crops of the Brazilian agricultural sector and has a well-consolidated production chain. As of the 2020/21 harvest, more than 654 Mt were produced, making Brazil the largest sugarcane producer in the world (CONAB 2021). In Brazil, sugarcane can be found in all regions, but more than half of its production is concentrated in the Southeast. In the North and Northeast regions, sugarcane harvest occurs between November and April, while in the Mid-South, it is harvested from April to November (ROSSETTO *et al*., 2006).

In the context of biofuel production, sugarcane is one of the main energy feedstocks used due to its great potential for ethanol production. According to OLIVEIRA *et al*. (2019), in the 2019/2020 harvest around 34 billion liters of sugarcane-based anhydrous and hydrous ethanol were produced, which reflects a 5.1% increase compared to the previous harvest (2018/2019). Of this total, the Southeast region led the country's total ethanol production (59.6%), followed by the Midwest (28.7%), Northeast (6.2%), South (4.7%), and North (0.6%) regions.

Corn

Brazil is the third largest producer of corn in the world accounting for 116 Mt in 2021/22 (CONAB 2021), only behind the United States and China (FAO 2018). It is possible to produce up to three harvest per year with emphasis on the so-called second crop, which takes place in soybean production areas. The second crop is the largest in terms of area and amount harvested. As for the 2019/20 season, the second crop reached 75.1 Mt of corn, which is almost three times the production of the first crop (CONAB 2020). Unlike the other countries, corn cultivation in Brazil is not destined to ethanol production, but mostly for the food sector.

For ethanol production, corn has some favorable production characteristics, such as: i) high yields; ii) consolidated production and post-harvest technology; and iii) lower water consumption and harvest costs compared to sugarcane. However, corn productivity is much lower than sugarcane (around 5.5 tonnes of corn/ha versus approximately 76.1 tonnes of sugarcane/ha) and, unlike sugarcane, does not produce abundant biomass co-products to supply the mills energy demands. Lastly, the logistic chain of corn makes corn ethanol less competitive than sugarcane ethanol, mostly due to the high feedstock transportation costs (EMBRAPA 2019; CUSTODIO *et al*., 2016; CONAB 2020; QUINTERO *et al*. 2008). Nevertheless, the production of corn-based ethanol is growing in Brazil. According to CONAB (2020), between the 2018/2019 and 2019/2020, corn ethanol production more than doubled, growing from 0.79 billion to 1.64 billion liters of ethanol. The Midwest region is the largest producer, representing 98.7% of total corn ethanol production, while the South region represents around 1% of total production. Nonetheless, corn ethanol production is far from reaching sugarcane ethanol production levels (1.64 million liters of corn ethanol versus 34 billion liters of sugarcane ethanol in the 2018/2019 harvest season).

2.1.2 Oily Crops

Oil crops are feedstocks with high concentration of triglycerides with a combination of glycerol and fatty acids. The oil can be extracted from different parts of the plant, such as the seeds, fruit, mesocarp (pulp), or nuts. Oil crops are mostly destined to the food sector but are also used in the industry (for example, the pharmaceutical industry) and energy sector (to produce biodiesel).

Soybean

Soybean is the major crop in Brazil (135.9 million tonnes in the 2020/21 harvest), representing about 50% of the Brazilian cereal crop (CONAB, 2021). The Midwest region of Brazil is the largest oilseed producer (about 45% of production), followed by the South (about 31% of production), North and Northeast (14% of total production) and the Southeast (about 8% of total production). Although current production is concentrated in the Midwest, a tendency for soybean expansion in new agricultural frontiers in the North and Northeast regions is being observed (IBGE, 2015).

Brazil is the world's second largest soybean producer, behind only the US (EMBRAPA 2022). The crop can be grown in all regions of the country and has a mature and well-structured supply chain (CORTEZ et al. 2014). Despite its technical and economic advantages for alternative aviation fuel production, soy-based biofuels are widely used in the road transport sector and are the main options to reduce dependence on fossil fuels in Brazil in the coming years (MILANEZ, MANCUSO, GODINHO, & POPPE, 2017).

Palm

The palm tree (Elaeis guineensis), popularly known in Brazil as dendê palm, produces palm oil, which is the world's largest vegetable oil market, about 36% of total world production in 2019 -on a mass basis- (CARDOSO et al. 2020; USDA 2020). However, Brazilian production in 2019 represented less than 1% of the world total (AGRIANUAL, 2020). In Brazil, the palm production areas can be found in the north of the country, more precisely in the state of Pará and in the northeast in some regions east of the state of Bahia due to its edaphoclimatic specificities such as high rainfall demand or high solar radiation. Its main uses are present in cooking, food production, cosmetics, pharmaceutical products and as a raw material in biodiesel production (PATERSON et al., 2017).

The density of palm trees varies between 130 to 160 trees per hectare (RODRIGUES, et al., 2014). Oil palm has a high productivity (between 4,000 and 6,000 kg of oil per hectare) compared to soybean (between 400 and 600 kg of oil per hectare) (ESPAÑA et al. 2018; SOUZA et al. 2017). Palm oil, commercially known as crude palm oil (CPO) is extracted from the fruit pulp (mesocarp). In addition to crude palm oil, palm kernel oil is also extracted from the kernels, which is most used in the cosmetics industry. However, its soil and climate constraints and the local environmental impacts caused by oil palm cultivation limit the expansion of its production in Brazil. (WALTER et al. 2020; HANSEN et al. 2015; MUKHERJEE et al. 2014).

Macaw

The macaw palm (*Acrocomia Aculeata*) is naturally present in Cerrado biome and in semi-deciduous forests (WALTER et al. 2020). In Brazil there are records of macaw in almost every region. In the Northeast region it is present in the states of Bahia, Piauí and Maranhão. In the Center-West of Brazil the palm tree occurs in Goiás, Mato Grosso do Sul and Mato Grosso. The macaw can also be found in almost all the Southeast region, in the states of Minas Gerais, São Paulo and Rio de Janeiro. There are also records of macaw in Tocantins, in the northern region of the country (LIMA et al., 2018).

The main uses of macaw are concentrated in the food sector, in the medicinal use of fruit pulp and oil, in animal feed, as a mosquito repellent, and in soap manufacturing (COLOMBO et al., 2018). However, due to the high productivity (between 1500-5000 kg of oil per hectare per year) of the oil and has easier adaptation in different soil and climate zones, such as resistance to water scarcity - opposite of oil palm - (NAVARRO et al. 2014), it is being evaluated as a promising feedstock for biofuel production (MACHADO et al., 2016).

The oil can be produced from the mesocarp (pulp) or from the almonds (seeds) (WALTER et al. 2020). The macaw produces two types of vegetable oil, pulp oil (suitable for the energy sector) and kernel oil (suitable for the food and cosmetic sectors) (CARDOSO et al. 2020). Macaw pulp oil is like palm oil but has a higher percentage of fatty acids and is therefore more suitable to produce biofuels (biodiesel).

Because it is uncommon in the human diet, the use of palm oil for biofuel production does not compete with the food market which makes it a promising feedstock to produce alternative fuels (EVARISTO et al. 2016). In the year 2017 there were three initiatives for commercial production of macaw. Entaban Brasil, Soleá and the Inocas project invested, respectively, in 600, 1,000 and 2,000 hectares destined for biofuel production (COLOMBO et al. 2018). However, macaw plantations and farming practices are still under great uncertainties related to their high heterogeneity and limited knowledge about their ecophysiological and biochemical characteristics and optimal growing conditions (PIRES et al. 2013; BICALHO et al. 2015).

For this reason, this work assumes two different options of macaw cultivation: (1) conservative, with low fruit yield and plant density, and (2) optimistic, with high fruit yield and plant density. Details on the macaw cultivation options are presented in the next section. One way to understand the contribution of this biomass to the aviation biofuels market is to calculate the energy potential of each. Thus, together with georeferenced modeling of this information, it is possible to understand how the energy potential of the selected biomass is distributed in the Brazilian territory, according to its biophysical, agroecological, technical and economic conditions.

2.2 Alternative aviation fuel certification

Jet fuel refers to liquid petroleum fuel (generated from the refining process) designed specifically for commercial (known as JET A/JET-A1) and military (known as JP-4/JP-5) aircraft (WEI et al. 2019; CARVALHO, 2017). In general, conventional jet fuel is produced from the distillation of crude oil with a range of 205° C to 260°C (LIU, et al., 2013). In Brazil, jet fuel is entirely produced by jet distillation, followed by chemical treatment or hydroprocessing (CARVALHO, 2017).

The composition of jet fuel is mainly C_8 to C_{16} hydrocarbons, and the chemical components are summarized by groups of paraffins, naphthene and aromatic compounds (CARVALHO, et al.2017; HILEMAN, et al., 2014). The content of each component has a direct relationship with the characteristics of jet fuel. Therefore, for a fuel to be classified as jet fuel, it must meet the following requirements: (i) energy content, (ii) freeze point, (iii) thermal stability, (iv) viscosity, (v) combustion characteristics, (vi) lubricity, (vii) material compatibility and (viii) safety. Table1 shows the requirements

Table 1- Jet fuel requirements

Requirement	Reason	Specification
Energy content	Affects aircraft range	Minimum energy density
Freeze point	Impacts upon ability to pump up fuel at low temperature	Maximum allowable freeze point temperature
Thermal stability	Coke and gum deposits can clog or foul fuel system and nozzles	Maximum allowable deposits in standardizes heating test
Viscosity	Impact's ability of fuel nozzles to spray fuel and of engine to relight at altitude	Maximum allowable viscosity
Combustion characteristics	Creation of particulates in combustor and in exhaust	Maximum allowable sulfur and aromatics content
Lubricity	Impacts upon ability of fuel to lubricate fuel system and engine controls	Maximum allowable amount of wear in standardized test
Material compatibility	Fuel meets large range of metals polymers and elastomers	Maximum acidity, maximum mercaptan concentration, minimum aromatic content
Safety	To avoid explosion in fuel handling and tanks	Minimum fuel electrical conductivity and minimum allowable flash point

Source: Own elaboration, based on CARVALHO (2017).

Besides needing all these requirements, the aviation industry relies on strict regulations for the deployment of new technologies, including those aimed at decarbonizing aircraft operations (ASTM, 2017). First, any new fuels must be compatible with existing aviation turbines and fuel delivery systems, i.e., being a drop-in fuel (ASTM, 2017). In addition, all new biofuels must be approved by the American Society for Test and Materials (ASTM) for use in existing aircraft and airport fueling systems (ZHAO, et al. 2021).

To ensure that aircraft are safe both during flights and on the ground, ASTM develops essential standards for aircraft construction, parts construction, maintenance, and aviation fuel. Therefore, to be certified and qualified, aviation fuel must comply with two standards: (i) ASTM D1G55 for conventional aviation fuel and which details the requirements necessary for petroleum distillates that meet a given distillation curve (ASTM, 2018) and (ii) ASTM D7566 for alternative aviation fuels (which contain synthesized hydrocarbons) (ASTM, 2017). It is worth noting that the standards are updated regularly, and new fuels may be added through a revision established by ASTM D4054 (WILSON et al. 2013).

In this context, as of today, eight ASTM-certified conversion technologies are available to produce agricultural-based drop-in alternative aviation fuel (IRENA 2021). However, obtaining ASTM certification does not in itself guarantee full commercialization of the route in question or the availability of commercial volumes of fuel (CAAFI, 2010). Table 2 below details information about each ASTM-qualified route:

Table 2-ASTM certified alternative aviation fuel routes

Pathway	Conversion Technology	Feedstock	Year of Certification	Blend (%)
Fischer-Tropsh hydroprocessed (FT- SPK)	Gasification	Agricultural and forest wastes	2009	50
Hydroprocessed Ester and Fatty Acids (HEFA-SPK)	Hydrotreatment	Plant oils and anima FOGs	2011	50
Synthesised Iso-Paraffins (SIP-SPK)	Fermentation	Sugar from any source	2014	10
Synthesised paraffinic kerosene with aromatics (SPK/A)	Gasification and FT synthesis	Coal and biomass	2015	50
Alcohol-to-jet (ATJ-SPK)	Fermentation	Sugars from starches and lignocellulosic biomass	2016 – Isobutanol; 2018 - Ethanol	50
Catalytic hydrothermolydid jet (CHJ-SPK)	Liquefation	Fatty acids esters and free fatty acids	2020	50
Hydroncarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK)	Hydro-carbon-hydroprocessed	microalgae	2020	10
Co-processing	Co-processing	lipids	2020	5

Source: Own elaboration. Based on IRENA (2021)

The aviation fuel mix for the routes detailed in the table above must be accompanied by the suffix SPK (synthesized paraffinic kerosene). Other technologies are currently in the process of certification, but the process is mostly time-consuming and rigorous, ensuring that all specifications are safely met. The present research considered the ATJ and HEFA routes as objects of analysis. The following subsections show details of each of these routes.

2.2.1 Alcohol to jet (ATJ)

The ATJ route is one of the most recent routes added to the list of alternative aviation fuels. Broadly speaking, the ATJ route refers to a technology that converts intermediate alcohols, such as methanol, butanol, and long-chain fatty alcohols (CARVALHO, 2017), into alternative aviation fuel through catalytic steps (HARI; YAAKOB; BINITHA, 2015; GELEYNSE et al. 2018). However, only ethanol and isobutane are certified by ASTM D7566 for alternative aviation fuels production and its use in aircraft (IATA, 2019). Figure 1 shows the ethanol production steps using the raw materials that are part of the scope of study, sugar cane and corn:

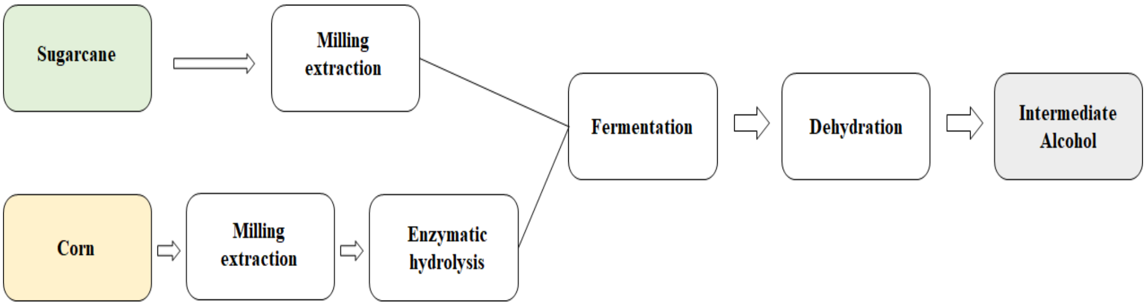


Figure 1 - Ethanol production steps.
Source: own elaboration.

Sugarcane, being a naturally sugary crop, already has glucose available in its composition. Thus, only extraction through milling is adequate to obtain a fermentable sugar solution. On the other hand, for starchy crops such as corn, the glucose is available in the form of polysaccharide molecules. Therefore, after the milling step, enzymatic hydrolysis is required to obtain fermentable sugars. Then, for both sugarcane and corn, the steps for intermediate alcohol production are basically fermentation and distillation (NOGUEIRA et al 2008).

In economic and social aspects, the ATJ route is an economically viable pathway, since the feedstocks are not very expensive, do not require large amounts of energy (HARI; YAAKOB; BINITHA, 2015) and represents a business opportunity for alcohol producers to enter in the alternative aviation fuel market, meeting the growing demand (GELEYNSE et al. 2018). In terms of conversion, it is an efficient catalytic process

(ICAO, 2011), however, a supply of hydrogen is required in the hydrogenation step, promoting additional production cost. But depending on the nature of the plant, a facility can purchase or produce hydrogen on site through several possibilities, including the use of a biomass feedstock (GELEYNSE et al. 2018). Moreover, it may not involve the use of special microorganisms and enzymes for fermentation if the production starts with the alcohol already produced by biochemical fermentation (CARVALHO, 2017). Although the ATJ route is most applied to sugarcane and corn facilities, it can also be operated with lignocellulosic feedstocks or other unconventional feedstocks (WYMAN, 2003).

The ATJ conversion process is basically carried out in four steps: (i) dehydration, (ii) oligomerization, (iii) hydrogenation and (iv) distillation. Figure 2 below shows all the ATJ conversion steps:

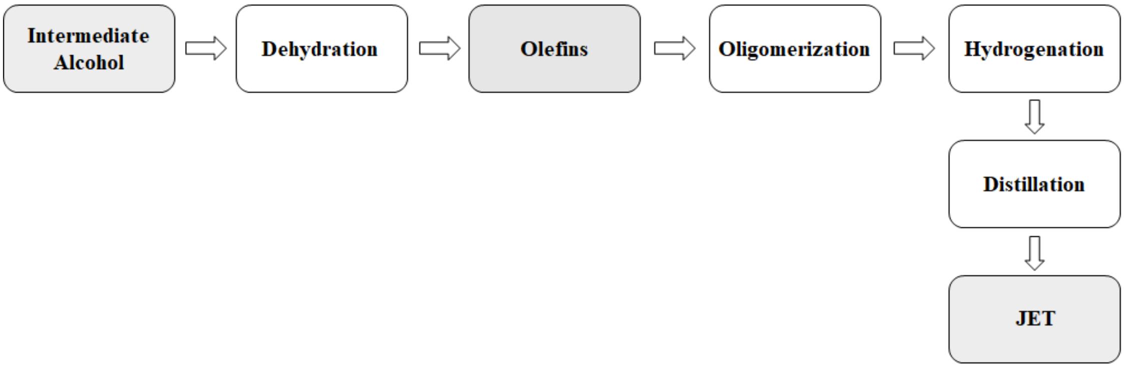


Figure 2- ATJ conversion steps.
Source: own elaboration.

Following the order of the previous scheme (Figure 2), the ATJ conversion process starts at dehydration. Basically, this first step involves the synthesis of water and ethylene through the removal of catalytic hydroxyls (e.g., zeolites, silicoaluminium phosphates and heteropolyacids). Subsequently, higher hydrocarbons are formed to reach the desired hydrocarbon chain (C_8-C_{16}) to meet the aviation fuel specifications. Next, hydrogenation saturating the remaining double bonds from the oligomerization process, ensuring the fuel's low reactivity. Finally, distillation is the last step and produces the final product – alternative aviation fuel - and its co-products (naphtha and diesel) (GELEYNSE et al. 2018).

Finally, it is worth mentioning that the ethanol production chain through sugarcane and corn are well structured. Added to that, production of alternative aviation fuels and its co-products via the ATJ route requires mature processes that already exist in the current chemical industries. However, the integration of ethanol and aviation kerosene processing facilities is not yet commercially available (CAAFI 2010; IRENA 2017; IEA Bioenergy 2021).

2.2.2 HEFA

The hydro processes esters and fatty acids (HEFA) was certified as jet fuel in July 2011 by ASTM for blends up 50% with conventional jet fuel, as earlier mentioned. Feedstocks include food oil crops (soy, palm, colza, macaw, etc.), non-food oil crops (jatropha, camelina, and halophytes), microalgae and cooking oil or tallow (CARVALHO, 2017). The scope of this study considers soybean, oil palm, and macaw as objects of analysis.

The HEFA route is composed of five steps: (i) oil extraction, (ii) hydrogenation, (iii) decarboxylation, (iv) hydro isomerization and hydrocracking and (v) distillation. Figure 3 shows the processes for obtaining alternative aviation fuel from oilseed crops.

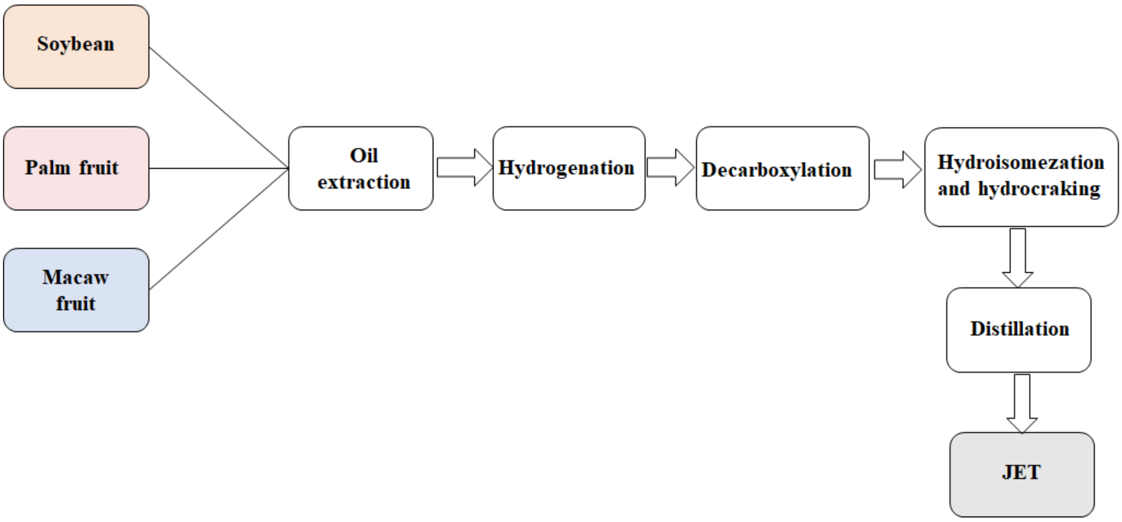


Figure 3- HEFA conversion steps.
Source: own elaboration.

Vegetable oils can be extracted by mechanical pressing, solvent extraction, or both techniques integrated (OLIVEIRA, 2015). Mechanical pressing consists of increasing the pressure, expelling the oil. Solvent extraction, on the other hand, is summarized in the mixture of ground oilseeds with the extraction solvent and stirring the mixture until the oil is extracted (OLIVEIRA, 2015). The extracted oil is composed of triglycerides - ester molecules derived from glycerol and three fatty acids - (TAO et al. 2017). These molecules have oxygen atoms and carbon-carbon double bonds in their composition, and therefore need hydrogenation to achieve the composition and specifications of alternative aviation fuel.

XU et al. (2021) point out that during the palm oil extraction stage (palm and macaw) an important emission source arises due to the discharge of wastewater (known as Palm Oil Mill Effluent - POME - or Macaw Oil Mill Effluent - MOME). This effluent generates adverse impacts to the environment and must be treated, which releases methane into the atmosphere. A capture plant can be inserted, capturing about 85% of the methane released to the atmosphere. This study will analyze the HEFA route of oil palm and macaw considering and disregarding this possible methane capture.

Hydrogenation converts the double bonds into a single bond and removes impurities such as oxygen, resulting in a straight, liquid hydrogen saturated chain, rich in paraffinic hydrocarbons. Next, decarboxylation ensures an alternative aviation fuel production like conventional jet fuel with good stability and maximum energy storage (CARVALHO, 2017). The penultimate step, on the other hand, converts linear hydrocarbon molecules to branched molecules through hydroisomerization, promoting good cold flow properties and high flash point (CARVALHO, 2017). Hydrocracking, on the other hand, produces lighter liquids and gas products (WANG; TAO, 2015). Finally, distillation results in the desired product – alternative aviation fuel - and its co-products naphtha and diesel (PERASLON 2011).

Alternative aviation fuel synthesis using vegetable oils is already a commercial process. However, biofuel production is still very limited because the high cost of feedstock makes alternative aviation fuels uncompetitive with conventional jet fuels. In the year 2018, according to IEA (2019), biofuel consumption represented less than 0.1% of total jet fuel consumption. One alternative would the integration of the biofuel plant with conventional oil refineries, reducing the costs of the hydrogenation step. (CORTEZ et al., 2014).

2.3 Life cycle assessment of alternative aviation fuel

The aviation industry consumes about 1.5 billion barrels of fossil fuel annually (ATG, 2015). Therefore, it accounts for approximately 2% of global anthropogenic CO_2 emissions from the combustion of fossil fuels (IATA, 2016). However, due to the lack of energy alternatives, the aviation industry is highly fossil fuels, which add up to approximately 30% of the sector's operating costs (CANTARELLA et al. 2015; SZKLO 2020).

In order to reduce GHG emissions and operating costs, ICAO has set ambitious targets. The main targets for mitigating GHG emissions are to achieve Carbon Neutral Growth from 2020 and reduce net CO_2 emissions by 50% by 2050 compared to 2005 levels (ICAO 2013; IATA 2017). For this, some actions such as improving fuel efficiency by 2% per year, market-based measures, improvements in air traffic management and the use of alternative fuels are necessary to achieve the established targets (ICAO 2013).

In view of the expected growth for the aviation sector, fossil fuel development has become the most appropriate option for the coming years. Similarly, other Low Carbon Policies (LCPs) have promoted the use of fossil fuels to mitigate global GHG emissions. In 2018, the Renewable Energy Directive (RED) was developed on the European continent, which establishes that at least 14% of the energy consumed in the transport sector comes from renewable sources by 2030 (EUROPEAN UNION 2018). The United States has committed to producing 36 billion gallons of biofuels by 2022 through the Renewable Fuel Standard (RFS) (US EPA 2010). And in Brazil, Renovabio was developed in order to reduce the intensity of CO2 emissions through the negotiation of Decarbonization Credits (CBIO) (BRAZIL 2017). In all regulatory schemes mentioned above, the GHG reduction potential of biofuels is commonly compared with its fossil equivalents, and in the case of the aviation sector, aviation kerosene.

To calculate GHG emissions offered at all stages of aviation biofuel production, CORSIA uses a life cycle assessment (LCA) approach agreed by ICAO members in 2018 (ICAO, 2020). Life cycle assessment refers to the standardized environmental analysis methodology (ISO 2006a, IS0 2006b) commonly used to assess the environmental impacts of biofuels and direct decision makers worldwide (US EPA, 2010). Therefore, through LCA approach it is possible to estimate the benefits of alternative aviation fuels of the well to wake up (WTW), that is, of all stages of synthesis and use of an aviation fuel, including recovery and transport of raw material, production of transport of the fuel and combustion of fuel during the operation of the aircraft (HAN et al 2013).

The carbon footprint focused on aviation biofuel production has been widely explored in the literature. WONG et al. (2008) examined the feasibility of using alternative aviation fuels for soybean oil biomass and palm oil. BALLIS & BAKA compared GHG emissions from alternative aviation fuels based on *Jatropha Curcas* with aviation fossil kerosene in Brazil. AGUSDINATA et al. (2011) revealed the extent to which alternative biomass aviation fuels dedicated to camelina oil and algae and lignocellulosic biomass (corn straw, grass and woody crops) reduce GHG emissions in the United States. HAN et al. (2013) did a life cycle analysis of bio-based aviation fuels. STEAPLES et al. (2014) verified the environmental and economic viability of alternative aviation fuel technologies based on sugarcane, corn grain and switchgrass. DE JONG et al. (2017) evaluated different alternative aviation fuel routes and explored different methods of co-product allocation. KLEIN et al. (2018) compared different alternative fuel production routes and aviation integrated with sugarcane biorefineries in Brazil. CARVALHO et al. (2019) evaluated the environmental performance of the alternative aviation fuel of soybean oil biomass. ABLE et al. (2020) performed an attributional life cycle assessment for ten alternative aviation fuel routes in Brazil considering environmental trade-offs.

These studies present a variety of results regarding the performance of alternative aviation fuels. The authors consider different raw materials, conversion technologies and supply chains, promoting this wide range of results. In addition, the criteria selected in the life cycle assessment, such as system limits, inventory assumptions, emission factors and how co-products are treated interfere in the accounting of fuel life cycle emissions (CAPAZ & SEBARA 2016)

2.4 Impacts of direct land use change

Currently, one of the main issues in the context of biofuels are the effects of land use changes caused by the expansion of biofuel production (IPCC, 2019; CREUTZIG et al. 2012; FINKBEINER, 2014; WARNER et al. 2014). Land conversions to meet increasing fuel demand can promote adverse impacts such as carbon stock loss, competition with food markets, biodiversity loss, and water scarcity that can compromise the sustainability of agricultural-based biofuels (VERSTEGEN et al. 2015).

Additionally, annual crops (e.g., cereals and vegetables) are harvested each year and thus, do not store a good amount of carbon in biomass in the long term (IPCC, 2019). On the other hand, perennial crops (e.g., vegetation in orchards, vineyards, and agroforestry systems) could store a significant amount of carbon in biomass (IPCC 2019). Therefore, the amount of carbon stored and emitted or removed from cropland depends on the type of crop, management practices, and soil and climatic factors (IPCC, 2019).

Although the carbon stored in biofuels is sequestered during feedstock production, land intensification and conversion can significantly alter the carbon balance (CARRIQUIRY et al. 2019; HERTEL et a. 2010; SEARCHINGER et al. 2008; TAHERIPOUR et al. 2017). Depending on the context, LUC emissions may be positive (net emissions) or negative (net sequestration) (de JONG et al. 2017). In general, positive emissions occur when areas of large carbon stocks are conversion, such as forests, into high-volume cultivation areas, such as corn and soybean crops, increasing LUC (de JONG et al. 2017) emissions. On the other hand, negative emissions occur when degraded land is conversion into cultivated areas, promoting a greater sequestration of carbon above and below ground than the reference vegetation (DUNN et al. 2013; DAVIS et al. 2011; WICKE et al. 2011).

In this context, land use change can happen widely in two ways: (i) directly (dLUC), when conversion occurs on the same land as the new land use (SCHMIDT et al2015) or (ii) indirectly (iLUC), when the result of interactions between commodity markets, connections between agricultural and non-agricultural markets and international trade may extend beyond the biofuel producing regions, regardless of the purpose of land use, making land use change induced (KEENEY & HERTEL, 2008; HERTEL et al. 2010; TILMAN et al. 2006). Thus, emissions associated with land use change have a large contribution to the life cycle of a biofuel and should be accounted for, as they are an extremely important factor for decision making.

As mentioned in the previous section, to calculate GHG emissions offered at all stages of aviation biofuel production, CORSIA uses a life cycle assessment (LCA) approach. Land-changing emissions play an important role in global CO_2 emissions, especially in developing countries that still face agricultural expansion (BRASIL, 2016; CASTANHEIRA & FREIRE 2013; SEARCHINGER et al. 2008) and should be considered in life-cycle evaluation studies of agricultural products (SINDEN et al. 2009; BAILIS & BAKA 2010; WEIDEMA et al. 2013; EDWARDS et al. 2014). Therefore, it is important that these emissions are accounted for in the biofuel life cycle, ensuring that the principles of completeness, transparency, relevance and accuracy are met (GREENHOUSE GAS PROTOCOL, 2011; IS0 2006b).

Despite its great weight in global GHG emissions, there is a wide pace of progress on which methods are best suited to estimate LUC emissions (ROSA et al2016; SCHMIDT et al. 2015). The impacts associated with LUC are highly dependent on local specificities, such as soil type, previous land use and management practices (de JONG et al. 2017), generating a wide range of results subject to a series of uncertainties (CASTANHEIRA & FREIRE 2013; FLYSJÖ et al 2012; PERSSON et al. 2014).

Currently, the methodologies most used in life cycle evaluation estimate direct emissions of LUC, that is, caused by changes in carbon stocks above and below ground, as a result of the change from the old land use to cultivate biomass for energy purposes (from JONG et al. 2017). For example, the partnership between the World Resources Institute (WRI), the Brazilian Research and Agriculture Company (EMBRAPA), and the State University of Campinas (UNICAMP) promoted the development of a tool to calculate GHG emissions using methodologies specific to the Brazilian reality and focused on non-mechanical sources of emissions, known as the GHG protocol methodology for agriculture (WRI 2015). The tool considers the Brazilian Agricultural Guidelines (DAB) and focuses on on-farm GHG emission and removal sources, ensuring consistency of GHG emissions results with the guidelines proposed by the Agricultural GHG Protocol Project. The results generated from these tools allow producers and companies in the value chains of agriculture, livestock, forestry, among others, to include the mitigation of GHG emissions in their production strategies and annual planning (WRI 2015).

The PAS 2050 guide provides a standard method for assessing the carbon footprint of a product. It is produced by British Standards and co-sponsored by the Carbon Trust and the Department for Environment, Food and Rural Affairs (Defra) and serves international stakeholders and experts in academic, business, government and non-governmental organizations (ONGs). Briefly, PAS 2050 teaches how to assess a product's emissions throughout its life cycle, from raw material emissions, and this includes direct emissions from land use change to all stages of production, such as distribution, use and disposal or recycling (BSI 2008).

Recent studies have been based on land availability in some countries to expand biofuel production without compromising other uses (CORNELISSEN et al., 2012, PRIELER et al., 2013). On the other hand, the expected increase in demand for food due to the expected growth of the world's population has raised controversies about the impacts that large-scale biofuel production can have on food production (CANTARELLA et al. 2015; van NOORDER et al. 2013). However, many studies advocate the possibility of reconciling food production and, at the same time, the expansion of biofuel production (CORNELISSEN et al., 2012, HORTA NOGUEIRA and CAPAZ, 2013, LYND and WOODS, 2011, PRIELER et al., 2013, WOODS et al., 2010).

Brazil is a very diverse country in terms of land use patterns, ecosystems and biodiversity. More than half of its territory is covered by native vegetation (BRASIL, 2015a; BRAZIL 2016; FAO 2016) is one of the largest producers and exporters of various agricultural commodities such as soybeans, sugarcane, corn, rice, cotton and others (BRASIL 2015b; OECD - FAO 2015). However, Brazilian agricultural areas have been expanding and intensified in recent years, being also of global concern in relation to emissions associated with LUC (DIAS et al. 2016; LAPOLA et al. 2014; NEPSTAD et al. 2014).

There are two important policy instruments for land use regulation in Brazil: Law No. 6,225 of 1975 and the ABC Plan. Law Nº 6,225 discriminates, through the Ministry of Agriculture, the mandatory execution of soil protection and erosion control plans (BRAZIL, 1975). The ABC Plan refers to the Sectoral Plan for Mitigation and Adaptation to Climate Change Aiming at the Consolidation of a Low Carbon Emission Economy in Agriculture (EMBRAPA, 2022). Thus, it is composed of a set of actions that aim to promote the broadening of the adoption of some sustainable agricultural technologies with high potential to mitigate GHG emissions and combat global warming, such as recovery of degraded pastures, crop-livestock-forest integration and agroforestry systems, direct planting systems, biological nitrogen fixation, planted forests, animal waste treatment, and adaptation to climate change (EMBRAPA, 2022).

Due to the diversity of soils and vegetation, there is a need for specific Life Cycle Inventories for each region of Brazil (CEDERBERG et al 2013; HELLWEG & CANALS 2014; RUVIARO et al. 2012). However, regionalized estimates of LUC are scarce in the literature and most estimate LUC emissions associated with agricultural production at the national level (FLYNN et al. 2012; PERSSON et al 2014) or for certain Brazilian states and regions (FIGUEIRÊDO et al. 2013, 2016; MACEDO et al. 2012; MACIEL et al. 2015). Recently, NOVAES et al. (2017) developed a methodology to estimate LUC scenarios of the last 20 years and CO_2 emissions for the 64 agricultural crops, pastures and forests in Brazil for each of its 27 states, based on agricultural statistics. TJERK et al. (2021) conducted an analysis to understand how direct land use emissions influence the demand for bioenergy to mitigate GHG emissions and how this affects the energy matrix, using Brazil as a case study. CAPAZ et al. (2021) estimated the carbon footprint of ten pathways comprising promising feedstocks (soy, palm, sugarcane, sugarcane residues, forest residues, used cooking oil, beef tallow, and steel off -gases) through the Hydroprocessed Fatty Acids, Jet Alcohol, and Fischer-Tropsch routes in Brazil.

In view of the importance of considering the specificities of each area of the Brazilian territory, this study developed a transition matrix of land use considering the different types of vegetation present in the Brazilian biomes. These types of vegetation are known as Phytoecological Regions and were designated by the Brazilian Institute of Geography and Statistics in 2019. Thus, direct emissions from land use for the conversion routes of alternative aviation fuels were estimated considering the conversion of Phytoecological Regions and pastures to the agricultural crops analyzed here. The following section will detail each of the Brazilian Phytoecological Regions.

2.5 The Phytoecological Regions

This section details the types of vegetation mapped by IBGE (2019). These vegetation types, called Phytoecological Regions, will serve as the basis for the land use transition matrix to be modeled in this research. Therefore, the land conversion considered in this work will start from the Brazilian Phytoecological Regions as initial land use.

The interaction between biotic (vegetation and animals) and abiotic (climate, rock, relief, and soil) components results in environments with diverse types of vegetation (IBGE, 2019). In Brazil there is a great diversity of vegetation, the result of these interactions, called Phytoecological Regions. The Phytoecological Regions were mapped by IBGE (2019) and are based on physiognomic-ecological criteria, obeying a hierarchy of formations delimited by the parameters of ecological environments schematized from two major classes of formations: forest and grassland.

Thus, in the current representation, nine types of Phytoecological Regions were mapped, named in (IBGE, 2019): (i) Dense Ombrophiles Forest, (ii) Open Ombrophiles Forest, (iii) Mixed Ombrophiles Forest, (iv) Semi decidual Seasonal Forest, (v) Decidual Seasonal Forest, (vi) Campinara, (vii) Savanna, (viii) Savanna-Sepic and (ix) Steppe (Campos Sulinos).

(i) The Dense Ombrophiles Forest (Floresta Tropical Fluvial) is characterized by the presence of large and medium sized trees. It occurs naturally in tropical climates with high temperatures (about 25°C) and high precipitation well distributed throughout the year (between 0 to 60 dry days only). In Brazil, it occupies part of the Amazon region and extends along the coast from the northeast to the southern tip of the country.

(ii) Considered a transition between the **Amazon Rainforest** and extra-Amazonian areas, the Open Ombrophiles Forest is composed of more widely spaced trees and less dense shrubs. Its environments occur under temperatures between 24°C and 25°C with approximately 120 dry days.

(iii) The **Mixed Ombrophiles Forest**, also known as mata-de-araucaria, is marked by the exclusive presence of the Southern Brazilian Plateau. It occurs in a hot and humid climate, with average annual temperatures of 18°C and there is no biologically dry period.

(iv) **Semi decidual Seasonal Forest** occurs in seasonal climate environments, causing partial deciduousness of the forest canopy foliage. In Brazil, it is present in the tropical climate region, with a rainy period and another dry period, and in the subtropical region, with a short dry period accompanied by a sharp drop in temperature.

(v) **Decidual Seasonal Forest** has a similar concept to the previous vegetation type. However, the dry period is more severe and can reach more than seven months in the tropical region and the cold is more pronounced and reaches more than five months in the subtropical region.

(vi) **Campinara** is present in hot and super-humid climate environments with torrential rainfall (approximately 4000 mm per year) and high temperatures (averages over 25°C). The vegetation occurs in flat and flooded areas with a wide variety of physiognomy, ranging from countryside formation to forest.

(vii) **Savanna** occurs in a variety of climatic environments, from the tropical seasonal ones with a dry period (between three and six months) to the ombrophiles ones (with no biologically dry period). It is characterized by the shared dominance of medium to low plants (3 to 10 meters) and by the grassy-ligneous stratum, strongly influenced by anthropic action.

(viii) **Savanna-Sepic** refers to a physiognomy present in the Caatinga, typically Brazilian. It is composed of trees, shrubs, and herbs, characterizing very well the types of vegetation in the northeastern arid areas.

(ix) **Steppe (Campos Sulinos)** is inserted in areas of flat or gently undulating relief and is dominated by vegetation that is essentially rural, with grasses predominating. The Campanha Gaúcha and the Argentine Pampas are examples of this vegetation.

Figure 4 shows the Brazilian Phytoecological Regions:

Figure 4- Brazilian Phytoecological Regions.
Source: IBGE (2019).

3 Methodology

This study applies a methodology to evaluate the potential for alternative aviation fuel production in Brazil and its implications for land use, identifying potential areas for its expansion within the country. Therefore, the methodology applied in this study is composed of three steps: (1) georeferenced analysis to assess the availability of the selected feedstocks from the comparison between theoretical and technical potentials; (2) development of an attributional life cycle assessment to estimate GHG emissions associated with the selected alternative jet fuel routes; and (3) elaboration of a land use change matrix based on the Intergovernmental Panel on Climate Change (IPCC) methodology to assess dLUC-related GHGs. Figure 5 shows the three stages of the study:

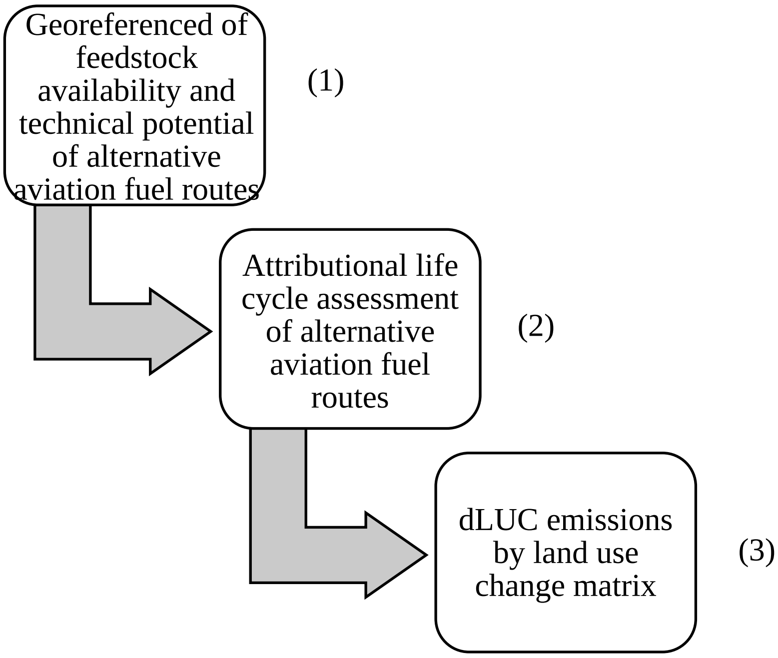


Figure 5- Methodological steps of the current study.

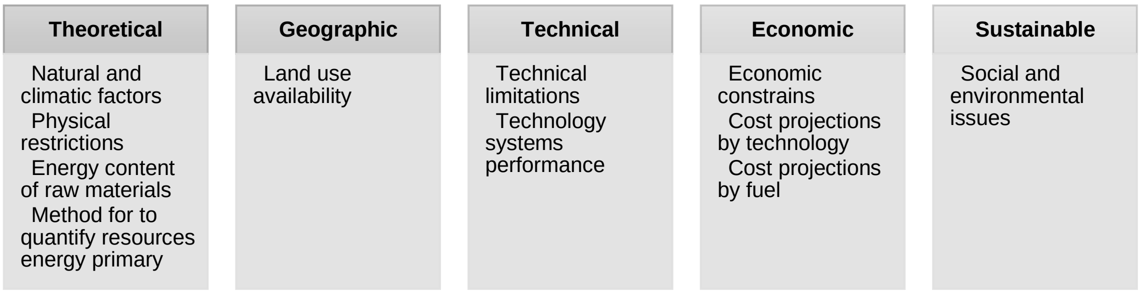
Source: own elaboration.

The first step will provide the biomass potential in Brazil to meet the growing demand for aviation biofuel. The second and third steps translate, respectively, into a life cycle attributional analysis and the direct emissions from land use change through a land use transition matrix. Subsequently, the total GHG emissions of the entire life cycle of biofuels will be the result of the sum between the GHG emissions of all life cycle steps of well-to-wake alternative aviation fuel production associated with each of the selected routes and the emissions associated with direct land use change.

Thus, the joint evaluation of the results obtained at each of these steps can be useful to identify areas of high potential for aviation biofuel production and locate available and suitable land for cultivation in a transparent and robust manner.

3.1 Feedstock availability

This section presents the methodology adopted to evaluate the available primary bioenergy potential of selected agricultural crops. The potential of energy crops can be classified as theoretical, geographical, technical, economic and sustainable (PORTUGAL-PEREIRA et al., 2015).



Theoretical	Geographic	Technical	Economic	Sustainable
Natural and climatic factors Physical restrictions Energy content of raw materials Method for to quantify resources energy primary	Land use availability	Technical limitations Technology systems performance	Economic constrains Cost projections by technology Cost projections by fuel	Social and environmental issues

Figure 6 illustrates the classifications of these potentials.

Theoretical	Geographic	Technical	Economic	Sustainable
Natural and climatic factors Physical restrictions Energy content of raw materials Method for to quantify resources energy primary	Land use availability	Technical limitations Technology systems performance	Economic constrains Cost projections by technology Cost projections by fuel	Social and environmental issues

Figure 6- Characterization of feedstock potentials.
Source: Based on PORTUGAL-PEREIRA et al. (2015).

In short, the theoretical potential defines the maximum energy available according to local soil and climate aspects, such as temperature, solar radiation, rainfall and pedology. The geographic potential, in turn, is the theoretical potential limited by local natural resources available for use. The technical potential considers technological feasibilities, logistics, and competition with non-energy uses (PORTUGAL-PEREIRA, et al., 2015). The economic potential, on the other hand, refers to the technical potential considering logistical constraints, costs, and competition from other non-energy uses of the selected crops (ECOFYS, 2008). Finally, the sustainable potential is restricted to the economic and ecological impacts promoted by energy projects (ANGELIS-DIMAKIS, et al., 2011).

This study quantified the technical and theoretical biomass potentials of sugarcane, corn, soybean, palm and macaw oils. The comparison between the two potentials has the function of visualizing spatially the distribution of the most suitable areas for energy crops and the points of production and consumption of the fuel, in order to understand the limitations between them and to propose improvements to achieve the expansion of the production of these fuels. Sugarcane and soy were chosen because of their current use for energy purposes in the country. The other crops were chosen because of their relevant planted area (in the case of corn) and their potential for product expansion.

The difference between the theoretical and technical potentials, in this study, is mainly due to the expansion area to be considered. The area considered in the theoretical potential refers to the entire planted area of each crop in Brazil in 2019. On the other hand, the potential areas for expansion of alternative fuel production considered in the technical potential study are within a 100 km radius of fuel consumption points (airports or ports) and ethanol plants (for the ATJ route) or biodiesel plants (for the HEFA route). This value represents an optimistic estimate for biomass transportation, representing twice the distance recommended by HOFFMANN et al. (2013) as an economically viable radius for biomass transportation for energy purposes. It is worth mentioning that it was not considered potential conflicts with other uses, such as food production and production of other alternative fuels (e.g.: ethanol or biodiesel) for the road transport sector.

The QGIS software, version 3.22.5, was used for the geospatial visualization of the potential expansion areas for aviation fuel production. For this, the buffer tool was used, which delimits a zone of influence from a defined radius, being very useful in environmental studies and projects. Thus, it was possible to identify for each crop and municipality its bioenergy potential, in TJ/year. The following subsections detail the frameworks used to calculate the technical potentials for the ATJ and HEFA routes.

3.1.1.1 **Alcohol-to Jet (ATJ) Potential**

The methodology adopted to estimate the theoretical and technical potentials of the ATJ route for sugarcane and corn crops was based on the average productivity of the crops, biomass conversion into intermediate fuel (ethanol), synthesis for alternative aviation fuel and the lower calorific value of conventional aviation fuel. For the case of the theoretical potential, the entire sugarcane and corn planted area in Brazil in 2019 was considered. For the technical potential case, limited areas within a 100 km radius of fuel consumption points and ethanol plants were considered. Therefore, considering the technical limitations described above, Equation 1 bellow shows the calculation of the potential was performed as follows:

Sugar crops:

$$SPi = \Sigma Ai \times Prod._{i} \times CETOH \times CATJ \times LHV\,JET \times 1000 \qquad \textbf{(1)}$$

Where:

SP_i: Sugar-based ATJ technical potential (TJ/year)

Ai: Area planted to crop i (ha/year) or Area available within a 100 km radius (ha)

$Prod._i$: *Sugar crop* productivity (tonne/ha/year)

C_{ETOH}: Conversion of biomass to ethanol (tonne of ethanol /tonne of biomass)

C_{ATJ}: Conversion of ethanol to ATJ jet (tonne jet/ tonne of ethanol)

LHV_{JET}: low heating value of ATJ jet (MJ/kg)

Data on area (Ai) and productivity (Pi) of sugarcane and corn were obtained from the Brazilian Institute of Geographic and Statistics (IBGE/SIDRA) database (IBGE 2019) and refer to municipal agricultural production. The conversion of biomass to ethanol (C_{ETOH}) from sugarcane (6%) and corn (33%) for ethanol were obtained of JONKER, et al. (2015) and RFA (2016), respectively. The alcohol-to-jet conversion (C_{ATJ}) factor (42%) was based on GELEYNSE, et al. (2018). Finally, the LHV $_{JET}$ (43,5 MJ per kg of jet fuel) was obtained from the ANP (2020) and EPE (2020). Table 3 provides a summary of the parameters used for each crop.

Table 3-Parameters of evaluated sugar crops.

Parameters	Unit	Sugarcane	Corn
Planted area in 2019	ha/year	10,109,413	17,776,669
Area within a 100 km radius	ha	1,124,987	3,149
Productivity	tonne/ha	74.5^{a}	5.6^{a}
Conversion $_{ETOH}$	tonne of ethanol/tonne of biomass	0.06^{b}	0.33^{c}
Conversion $_{ATJ}$	tonne jet/ tonne of ethanol	0.42^{d}	0.42^{d}
LVH $_{JET}$	MJ/kg	43.5^{e}	43.5^{e}

[a] IBGE (2019); [b] Jonker, et al. (2015); [c] RFA (2016); [d] Geleynse, et al. (2018); [e] EPE (2020); ANP (2020)

3.1.1.2 Hydrotreated Esters and Fatty Acids (HEFA) potential

The methodology adopted to estimate the theoretical potential of the HEFA route for soybean, palm and macaw crops was based on the average yield of the crops, the oil content in soybean and palm and macaw fruit, the efficiency of oil extraction, the synthesis for alternative aviation fuel and the lower calorific value of conventional aviation fuel. For the theoretical potential, the entire planted area of soybean and oil palm in Brazil in the year 2019 was considered. Due to the scarcity of data regarding macaw planted area in Brazil, an average of the areas of macaw farming companies presents in each municipality in Brazil in the year 2017 was considered. The areas for the technical potential were limited to a radius of 100 km from the fuel consumption points and biodiesel plants. Thus, considering the technical limitations described above, Equation 2 bellow shows the calculation of the potential was performed as follows:

$$\mathrm{OPi} = \mathrm{Ai} \times \mathrm{Prod.i} \times \mathrm{OSR} \times \mathrm{EE} \times \mathrm{CHEFA} \times \mathrm{LHV\,JET} \times 1000 \qquad \textbf{(2)}$$

Where:

OP_i: Oilseed HEFA technical potential (TJ/year)

Ai: Area planted to crop i (ha/year) or Area available within a 100 km radius (ha)

$Prod._i$: Oilseed productivity (tonne/ha)

OSR: Oil content in the oilseed (%m/m)

EE: Oil extraction efficiency (%)

C_{HEFA}: Conversion of oilseed to HEFA jet (tonne biojet/ tonne of biomass)

LHV_{JET}: low heating value of HEFA jet (MJ/kg)

The data on planted area and productivity (Pi) referring to soybean and oil palm were obtained from the municipal agricultural production database made available by IBGE/SIDRA (IBGE, 2019). In the case of macaw, the information present in the

IBGE/SIDRA database refers to the number of agricultural establishments producing macaw and their respective cultivation areas (hectare), categorized into minimum and maximum sizes. Thus, the area planted with macaw was obtained through the average between minimum and maximum size of each farm multiplied by the number of farms in each municipality in Brazil. Due to the scarcity of data associated with municipal production of macaw, two macaw cultivation options were selected (option 1 - conservative; option 2- optimistic), considering spacing between palms, number of trees per hectare, and kilograms of fruits per tree. Table 4 shows the details of the chosen options:

Table 4-- Parameters of macaw production.

Parameter	Option 1: Low productivity (conservative)	Option 2: High productivity (optimistic)
Spacing (m x m)	9m x 9m [a]	5m x 5m [c]
Tree density (trees/hectare)	143	400
kg of fruit per plant (kg of fruit/tree)	62 [b]	120 [d]

[a] Lima et al. (2002); Fernandes (2009); [b] Motoike, et al. (2013); Coppel, et al. (2018); Colombo, et al. (2017); [c] Mirisola Filho (2009); Entaban (2009); Motoike et al. (2013); [d] Colombo, et al., (2017); Coppel, et al., (2018).

It is worth noting that the conservative option is that the conservative option relies on cultivation practices that focus on environmental protection. This means that its main characteristics are based on lower application of inputs to the soil, less use of agricultural machinery in the planting areas, lower productivity, income, and generation of skilled jobs. By contrast, optimistic cultivation focuses on socio-economic development and therefore relies on greater amounts of inputs applied to the soil, intensive use of agricultural machinery in the cultivation areas, higher productivity, income, and generation of skilled employment.

Following with the parameters used to calculate HEFA potential, the data on oil content for each oilseed (OSR) was 20% for soybean (MAPA, 2015), 40% for palm (ESPAÑA, et al., 2021) and 25% for macaw (CIONINI, 2013). Oil extraction efficiency (EE) of 95% was considered for soybean and palm (SZKLO, et al., 2020) and 70% for macaw (JUNQUEIRA, et al., 2019). The conversion of oil to aviation fuel via the HEFA route (C_{HEFA}) (49.4%) is derived from PERASLON, et al. (2013). Finally, the lower calorific value of the jet fuel (LHV_{JET}) with the value of 43.5 MJ/kg was taken from ANP (2020) and EPE (2020). Table 5 provides a summary of the parameters used for each oilseed crop.

Table 5-Parameters of evaluated oilseed crops.

Crop	**Planted area (ha)**	**Area whitin a 100 km radius (ha)**	**Productivity (tonne/ha)**	**OSR (% m/m)**	**EE (%)**	**Conversion $_{HEFA}$ [I] (t biojet/t biomass**	**LHV $_{JET}$ (MJ/kg) [j]**
Soybean	35,930,334	9,267	3.2[a]	20%[d]	95%[g]	0.494	43.5
Palm	178,130	-	14.5[a]	40%[e]	95%[g]	0.494	43.5
Macaw (Low productivity)	164,445	-	8.8[b]	25%[f]	70%[h]	0.494	43.5
Macaw (High productivity)	164,445	-	48[c]	25%[f]	70%[h]	0.494	43.5

[a] IBGE (2019); [b] Based on Lima, et al. (2002); Motoike, et al. (2013);Coppel, et al. (2018); Colombo, et al. (2017); [c] Colombo, et al., (2017); Coppel, et al., (2018); Junqueira, et al. (2018); [d] MAPA (2015); [e] Queiroz, et al. (2012); Xu, et al. (2020); [f] Ciconini, et al. (2013); [g] Sklo, et al. (2020); [h] Junqueira, et al. (2019); [i] Peraslon, et al. (2013); [j] ANP (2020); EPE (2020).

3.2 Life cycle inventory analysis

The life cycle assessment was performed to evaluate the impact of GHG emissions from alternative aviation fuel production. The analysis considered GHG emissions, and therefore environmental impacts of other natures and social and economic aspects were disregarded. LCA follows ISO 1404-44 (2006) standards within a "well-to-wake" approach, Figure 7 presents the system boundary of this study, including all life stages of the alternative aviation fuel supply chain, from feedstock extraction to processing, manufacturing, distribution, use and storage or recycling. The SimaPro 9.2 software supported by the Ecoinvent 3.7.1 database was selected to analyze greenhouse gas emissions from the two alternative aviation fuel production pathways (ATJ and HEFA) analyzed in this study.

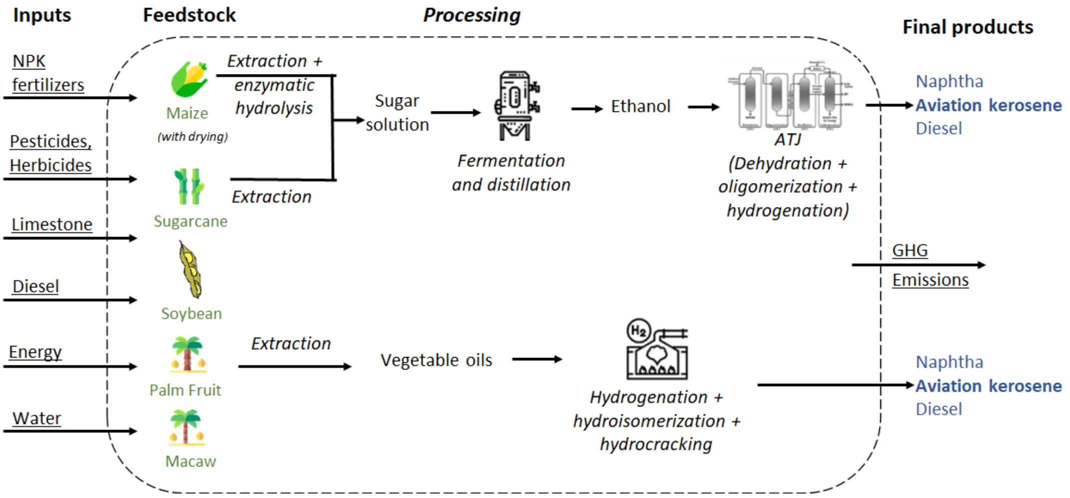


Figure 7- - System boundary of the study.
Source: PORTUGAL-PEREIRA et al. (2021).

Thus, the LCA modeling adopted for the present work is summarized in the following main steps: (i) the agricultural phase, which has as its output the production and harvest of the selected energy crops; (ii) the transportation of feedstock to the processing facilities; (iii) the alternative aviation fuel production phase, which starts with the production of the intermediate fuel by synthesizing the feedstock and then transforming it into aviation biofuel; (iv) the distribution of alternative aviation fuel from [2]the processing facilities to the airports; and (v) the use of alternative aviation fuel in

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[2] NPK refers to the macronutrients present in fertilizers. The main ones are nitrogen (N), phosphorus (P), and potassium (K).

aircraft operation. The functional unit adopted was g CO_2/MJ of conventional fuel. Also, it is worth mentioning that the reuse of waste was considered, with the allocation of waste for different uses, from ground maintenance to electricity generation.

3.2.1 Agricultural phase

Input parameters like fertilizer application, pesticides, herbicides and energy consumption were inserted in the agricultural step based on Brazilian data. For the ATJ route, agricultural data for sugarcane and corn crops were considered, while for the HEFA route agricultural data for soybean, oil palm and macaw crops were considered. All the parameters for all the selected energy crops are detailed below.

3.2.1.1 Sugarcane

For sugarcane, an average yield of 77 tonnes/ha was assumed. This value refers to the average yield of the four largest producing states over the last five harvests (2016/2017 to 2020/2021): São Paulo, Minas Gerais, Mato Grosso do Sul and Goiás. These data were obtained from CONAB (2021).

The amount of sugarcane residue (straw) was calculated from the residue-to-product ratio (RPR) (%) present in PORTUGAL-PEREIRA et al. (2015). The inputs associated with lime, pesticides, and diesel were obtained from Virtual Sugarcane Refinery (VSB) Life Cycle Analysis (IEA Bioenergy, 2019). NPK[2] fertilizer values are also in accordance with the methodological framework of ICAO (CORSIA, 2019) and were obtained by the average of data present in the works of Macedo et al. (2008), Muñoz et al. (2013) and IEA Bioenergy (2019). Table 6 below shows the values adopted for sugarcane agricultural stage:

Table 6- Sugarcane agricultural inventory

Input	Unit	Value	Reference
Productivity	t/ha	77	CONAB, 2021
Residue	t/t	0,22	Portugal-Pereira et al. 2015; Daiaglou V., 2016

Seedling	unit/t	951,5	Macedo et al. 2008 Macedo et al. 2008; Muñoz et al. 2014; Pereira et al. 2019
$CaCO_3$	kg/t	5,21	
N-fertilizer	kg/t	0,55	
P2O5 fertilizer	kg/t	0,37	
K2O Fertilizer	kg/t	1,23	
Pesticide	kg/t	0,02	
Diesel (cultivation and harvest)	MJ/t	64,5	
Distance	tkm	100	this work

3.2.1.2 Corn

The average corn yield was determined from the average yields of the last 5 crop cycles (2016/17 to 2020/2021) in the five largest producing states (in crop) according to CONAB (2021): Mato Grosso, Paraná, Goiás, Mato Grosso do Sul and São Paulo. The productivity of 5.6 tonnes/hectare was assumed.

The amount of corn residue (stover) was calculated from the residue-to-product ratio (RPR) (%) present in PORTUGAL-PEREIRA et al. (2015). Data related to soil acidity correction (lime) was taken from EMBRAPA (2015). Nitrogen fertilizer input was obtained from WANG et al. (2015) and GREET (2018). Data for the other macronutrients, phosphorus and potassium, were taken from AGRIANUAL (2021). Pesticide and herbicide application values were established according to EMBRAPA (2015) recommendations. And finally, energy inputs from agricultural operations and electricity for grain drying were taken from AGRIANUAL (2021) and ARAÚJO (2005), respectively. Table 7 below shows the values adopted for corn agricultural stage:

Table 7-Corn agricultural inventory.

Input	Unit	Value	Reference
Productivity	t/ha	5,06	CONAB, 2021
Residue	t/t	1,53	Portugal-Pereira et al. 2015
Seeds	kg/t	3,95	Empresa Brasileira de Pesquisa Agropecuária (Embrapa). 2015
$CaCO_3$	kg/t	172,41	
N-fertilizer	kg/t	11,75	

P2O5 fertilizer	kg/t	7,94	
K2O Fertilizer	kg/t	17,46	
Pesticide	kg/t	0,04	
Herbicide	kg/t	0,3	
Diesel (production)	MJ/t	122,92	Ribeiro, J.P. 2005

3.2.1.3 Soybean

Soybean yields were obtained from the average of all Brazilian producing states, available in IBGE (2019). A value of 3.2 tonnes/hectare was assumed. The amount of soybean residue (straw) was calculated from the residue-to-product ratio (RPR) (%) present in PORTUGAL-PEREIRA et al. (2015). Data regarding limestone, primary macronutrients (NPK), diesel for agricultural operations was extrapolated from IEA BIOENERGY (2018). Values for pesticide and herbicide application were obtained from the works of RAUCCI et al. (2014) and MATSSURA et al. (2015), respectively.

Table 8 below shows the values adopted for soybean agricultural stage:

Table 8-Soybean agricultural inventory

Input	Value	Unit	Reference
Productivity	3,2	t/ha	IBGE (2019)
$CaCO_3$	230	kg/t	IEA-Bioenergy 2018 Cavallet (2008)
N-fertilizer	-	kg/t	
P2O5 fertilizer	10,56	kg/t	
K2O Fertilizer	20,43	kg/t	
Pesticide	4,04	kg/t	Matsuura et al. 2015
Herbicide	0,9	kg/t	
Diesel (production)	380	MJ/kg	IEA-Bioenergy 2018
Transport	100	tkm	this work

3.2.1.4 Palm Fruit

Palm fruit crop yields are based on data from the largest Brazilian oil palm producing state, according to IBGE (2020): Pará. Thus, a yield of 15 tonnes/hectare was assumed. For soil acidity correction (lime), phosphorus fertilizer and diesel for agricultural operations the values present in IEA BIOENERGY (2018) were assumed. Nitrogen and potassium fertilizer values were taken from the work of QUEIROZ et al. (2012). Finally, data regarding pesticide and herbicide application were taken from BORGES et al. (2006). Table 9 below shows the values adopted for palm fruit agricultural stage:

Table 9-Palm fruit agricultural inventory.

Input	Unit	Value	Reference
Productivity	t/ha	15.4	IBGE (2019)
Seeding	unit/t	11.7	Souza et al. 2010
$CaCO_3$	kg/t	11.6	VSB (2018)
N-fertilizer	kg/t	2.7	Souza et al. 2010
P2O5 fertilizer	kg/t	5.21	
K2O Fertilizer	kg/t	9.5	
Herbicides	kg/t	0.08	
Pesticides	kg/t	0.16	
Diesel	MJ/t	131.1	VSB (2018)
Distance	tkm	100	this work

3.2.1.5 Macaw Fruit

Considering that the macaw palm can occur in different Brazilian biomes, the inventory for this energy crop was based on soils of medium aptitude, according to the characteristics proposed in WALTER et al. (2020). In addition, two yields were evaluated, assuming low and high productivity, as already explained in section 2.1 (Biomass feedstock description).

Considering that the macaw palm can occur in different Brazilian biomes, the inventory for this energy crop was based on soils of medium aptitude, according to the characteristics proposed in WALTER et al. (2020). In addition, two yields were

evaluated, assuming low and high productivity, as already explained in section 2.1 (Feedstock description).

The low yield with the value of 8.8 tonnes/hectare was calculated taking as a basis the works of LIMA et al. (2002), MOTOIKE et al. (2013), COLOMBO et al. (2017) and COPPEL et al. (2018). On the other hand, a value of 48 tonnes/hectare was assumed for the high fruit yield of macaw calculated from the studies of COLOMBO et al. (2017), COPPEL et al. (2018) and JUNQUEIRA et al. (2019).

Data associated with limestone and nitrogen, phosphorus, and potassium fertilizers were parameterized based on the studies of COPPEL et al. (2018) and EVARISTO et al. (2018). Values for herbicide and pesticide application were adapted from COPPEL et al. (2018) and MOTOIKE et al. (2013), respectively. And lastly, diesel used in agricultural operations (corresponding to oil palm production) was obtained from IEA BIOENERGY (2018).

Table 10 below shows the values adopted for macaw fruit agricultural stage:

Table 10-Macaw fruit agricultural inventory.

Input	Unit	Low productivity	High productivity	Reference
Productivity	t/ha	8.8	48	Motoike, et al. (2013); Colombo, et al. (2017) Coppel, et al. (2018); Junqueira et al. (2019)
Seeding	units/t	14.4	8.6	Evaristo et al. (2018)
$CaCO_3$	t/t	0.083	0.016	Coppel, et al. (2018);
Nitrogen	t/t	0.015	0.015	
P_2O_5	t/t	0.014	0.002	
K_20	t/t	0.018	0.018	
Herbicides	kg/t	0.044	0.008	
Pesticides	kg/t	0.132	0.024	
Diesel	MJ/t	230	42	VSB (2018)
Distance	tkm	120	120	Coppel et al. (2018)

3.2.1.6 Biomass transport

The inventory considers the transport of biomass to the alternative aviation fuel processing facilities by means of a heavy-duty truck with a capacity greater than 32 tonnes and Euro III[3] emission class standard. In addition, the inventory also considers an average distance of 100 km from the field to the alternative aviation fuel production facilities.

3.2.2 Alternative aviation fuel production phase

This section details both the synthesis of intermediate fuels and their updates for alternative aviation fuels. Therefore, for the sugarcane and corn ATJ routes, the inventories consider that the facilities are integrated into existing sugarcane and corn ethanol distilleries. Thus, the lignocellulosic co-products generated, such as bagasse, are used to feed the heat and power needs for the ATJ sugarcane route. On the other hand, corn co-products such as distillers dried grains (DDGS) were used as animal feed, and therefore, the synthesis of corn ethanol is not self-sufficient. For the HEFA pathway, it was considered that soybeans and the fruits of palm and macaw were processed into vegetable oils in the industrial facilities to produce alternative aviation fuel.

3.2.2.1 Alcohol-to-Jet (ATJ)

Sugarcane

The production of intermediate alcohol starts from sugar cane and follows Table 11. The inventory data required for all ethanol production steps derives from TSIRAPOULOS et al. (2014).

In the first step, milling, the fermentable sugar solution (product) and bagasse (co-product) are generated. Next, the sugar solution is fermented with the help of the yeast *Sacchromvces cerevisiae,* and the resulting liquid goes through a separation process so

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[3] EURO III refers to the regulation on maximum emission limits that applies to gasoline and diesel cars, trucks, and automobiles and aims to reduce CO2 emissions.

that it can be transformed into hydrous ethanol. As for the bagasse, part of it is employed in cogeneration systems, covering all the energy requirements demanded in the process, and the entire remainder has the role of providing heat for the processing of aviation kerosene (TSIRAPOULOS et al. 2014).

Table 11 shows the inputs and outputs of ethanol production per tonne of sugarcane:

Table 11-Sugarcane ethanol inventory.

Input	**Unit**	**Value**
Sugarcane	tonne	1
Lubricating oil	kg	0.01
$CaCO_3$	kg	0.88
Sulphuric acid	kg	0,62
Biocides	kg	0.01
Organic chemicals	kg	0.06
Water	m^3	1.65
Output	**Unit**	**Value**
Ethanol	kg	66.84
Electricity	kWh	21.52

Source: Adapted from TSIROPOULOS et al. (2014)

The ethanol produced then goes through the four steps (dehydration, oligomerization, hydrogenation and distillation) of ATJ conversion, as shown in Table 12 Aviation kerosene (product) is synthesized from ethanol, generating naphtha and diesel as co-products. Table 12 shows the data, obtained from GELEYNSE et al. (2018), of inputs and outputs from ethanol processing to aviation kerosene:

Table 12-Sugarcane ATJ inventory.

Input	**Unit**	**Value**
Ethanol	tonne	1
Gaseous hydrogen	tonne	0.006
Wastewater	tm^3	0.38
Output	**Unit**	**Value**
Naphta	tonne	0.06
Aviation kerosene	tonne	0.42
Diesel	tonne	0.12

Source: Based on GELEYNSE et al. (2018).

Corn

Table 13 also details the production of intermediate alcohol from corn. The inventory data related to this synthesis was adapted to the Brazilian conditions and obtained from ANL (1999), KIM & DALE (2008), NOGUEIRA et al. (2008).

Unlike sugarcane, after the milling step, starch cultures form polysaccharide glucose units and therefore require enzymatic hydrolysis for the fermentable sugar solution to be formed. The subsequent steps, fermentation and distillation, occur in a similar way to sugarcane. The final product is corn, and the co-products are distillers dried grains with soluble (DDGS) -commonly used as animal feed- and corn oil. It is worth noting that the co-products from the synthesis of ethanol from corn are not self-sufficient, and therefore do not provide energy to produce aviation kerosene. As the main corn growing areas are within the Savannah biome, i.e., near forests, forest residual biomass was considered as an energy source for the industrial processes of the ATJ route. Forest residues are wood and other forest products that remain without a defined use due to technological or market limitations (IPEA, 2012). Typically, these residues are known as all organic materials except the stem, including wood chips, branches, leaves, stumps, roots and bark (SFB, 2011). The use of logs and roots is not usual, due to the difficult exploitation and the possibility of soil damage. It was considered that all forest biomass residues were used to supply the energy needs of the system.

It is worth mentioning that the references used here consider natural gas as the energy source for the industrial processes (both intermediate fuel and jet fuel). Therefore, the conversion efficiency of the boilers was readjusted and considered to an average of 89%, present in the work of VAKKILAINEN (2017).

Table 13 below details the input and output data used in the synthesis of corn ethanol:

Table 13-Corn ethanol inventory.

Input	**Unit**	**Value**
Corn	t	1
Alpha-amylase	kg	0.28
Gluco-amylase	kg	0.61
Yeast	kg	0.1
Cellulase	kg	0.4
Water	m³	1.37
Sulphuric acid	kg	2.07
Ammonia	kg	2
Sodium hydroxide	kg	2.51
Calcium oxide	kg	1.2
Fuel	MJ	3041.07
Electricity	kWh	104.87
Output	**Unit**	**Value**
Ethanol	kg	359.99
DDGS	kg	200.38
Corn Oil	kg	13.39

Source: Based on ANL (1999), KIM & DALE (2008), NOGUEIRA et al. (2008).

Once synthesized, corn ethanol goes through the four basic steps for aviation kerosene synthesis (dehydration, oligomerization, hydrogenation, and distillation), detailed in Table 14. It is worth pointing out, that the corn ethanol co-products do not supply the energy needs required for the synthesis of aviation kerosene. Table 14 details the inputs and outputs of aviation kerosene synthesis (GELEYNSE et al. 2018):

Table 14-ATJ corn inventory.

Input	**Unit**	**Value**
Ethanol	t	1
Gaseous hydrogen	t	0.006
Electricity	kWh	186.7
Steam	MJ	911.77
Refrigeration at -50º	MJ	943.12
Fuel	MJ	1645.74
Wastewater	m³	0.38
Cooling water	MJ	2452.71
Output	**Unit**	**Value**

Naphtha	t	0.06
Aviation kerosene	t	0.42
Diesel	t	0.12

Source: Based on GELEYNSE et al. (2018).

3.2.2.2 HEFA

Soybean

The synthesis of alternative aviation fuel through soybeans follows the general diagram present in Table 15. The inventory data was based on IEA BIOENERGY (2018) and PEARLSON (2011).

The extraction step results in the desired product, crude soybean oil and soybean meal as a co-product (MANDARINO et al. 2001). This co-product is commonly used for animal feed. Diesel is needed to start the boilers. After the extraction step, the crude palm oil goes through the stages of hydrogenation, decarboxylation, hydroisomerization and hydrocracking and distillation. Once these steps are completed, the desired product, aviation kerosene and its co-products, naphtha and diesel, is obtained. As with corn, the industrial processes of the soybean HEFA route is not energy self-sufficient and therefore the literature used considers the use of natural gas as the main energy source to supply heat and power demand in HEFA plants. Due to the fact that the natural gas distribution network by pipeline is not developed in the interior of Brazil, where the plantation areas are located, it was considered that the energy demand of the plants would be supplied by biomass residues. The biomass conversion values into energy to power the system were readjusted according to the premise of the present study, so a conversion efficiency of 89% present in the work of VAKKILAINEN (2017) was considered. Table 15 below details the input and output data used in the synthesis of aviation kerosene from soybeans:

Table 15-HEFA soybean inventory.

Input	**Unit**	**Value**
Soybean Oil	t	1
Hydrogen	t	0.08
Fuel	GJ	45.04
Electricity	kWh	109.32
Output	**Unit**	**Value**
Propane	t	0.08
GLP	t	0.12
Naphta	t	0.14
Diesel	t	0.48
Aviation kerosene	t	1

Source: Based on IEA BIOENERGY (2018) and PEARLSON (2011).

Palm Oil

The synthesis of alternative aviation fuel through the palm fruit follows the general diagram present in Figure 3. The inventory data was adapted from the studies of KLEIN et al. (2018), PEARLSON (2011) and XU et al. (2020).

The extraction process results in two products, crude palm oil and palm kernel oil, and a co-product, known as palm kernel expeller. This co-product is typically used for animal feed. After the extraction step, the crude palm oil goes through the stages of hydrogenation, decarboxylation, hydroisometrization and hydrocracking, and distillation. Once these steps are completed, the desired product, aviation kerosene, and its co-products, naphtha and diesel fuel, are obtained.

It is worth mentioning that the use of fibrous materials (such as dried fruit bunches) and shells for heat and electricity generation was considered in the fuel processing stages. However, a small amount of external electricity and diesel fuel is also required, for example, for process start-up.

Table 16 below details the input and output data used in the synthesis of aviation kerosene through palm fruit:

Table 16-HEFA palm oil inventory.

Input	Unit	Value
Palm oil	t	1
Electricity	kWh	208.57
Fuel	MJ	5663.68
Diesel	L	0.37
Gaseous hydrogen	t	0.04
Output	**Unit**	**Value**
Naphtha	t	0.06
Aviation kerosene	t	0.49
Diesel	t	0.23

Source: Based on KLEIN et al. (2018), PEARLSON (2011) and XU et al. (2020).

Macaw Fruit

The synthesis of alternative aviation fuel through the palm fruit follows the general diagram present in Figure 3. The inventory data were based on the studies by KLEIN et al. (2018), PEARLSON (2011), SILVA and ANDRADE (2014), and XU et al. (2020).

The extraction step results in two products, crude macaw oil and macaw kernel oil, and a co-product, known as macaw expeller. This co-product is typically used for animal feed. The diesel fuel is needed to start the boilers. After the extraction stage, the crude palm oil goes through the stages of hydrogenation, decarboxylation, hydroisometrization and hydrocracking, and distillation. Once these steps are completed, the desired product, aviation kerosene and its co-products, naphtha and gas oil, is obtained.

As with the palm fruit, fibers and shells are used to generate virtually all the heat and electricity needed to extract the macaw oil, with some external electricity and diesel fuel only for specific applications such as starting the process. In other words, all the fibrous material (such as dried fruit bunches) and shells are consumed in the synthesis of fuel for energy generation.

Table 17 below details the input and output data used in the synthesis of aviation kerosene through macaw fruit.

Table 17-Macaw oil HEFA inventory.

Input	Unit	Value
Macaw oil	t	1
Electricity	kWh	190.29
Fuel	MJ	5663.7
Diesel	L	0.37
Gaseous hydrogen	t	0.04
Output	**Unit**	**Value**
Naphtha	t	0.06
Aviation kerosene	t	0.49
Diesel	t	0.23

Source: Based on KLEIN et al. (2018), PEARLSON (2011), SILVA and ANDRADE (2014), and XU et al. (2020).

3.2.3 Alternative aviation fuel distribution

An average distance of 100 km and a conventional heavy Euro III truck, like biomass transport, were assumed for the distribution of alternative aviation fuel from the processing plants to the aircraft.

3.2.4 GHG Emissions

The non-CO_2 emissions (methane and nitrous oxide) estimated in this study were converted into a CO_2 equivalent basis using global warming potential metrics considering a 100-year time horizon (GWP100). The GWP100 values used are 29.8 and 273 for methane and N_2O, respectively (IPCC 2013).

Agricultural residue

The main function of the agricultural residues that remain in the field is to protect the soils (get better at this here). However, these residues can emit greenhouse gases and therefore their emissions must be accounted for in the life cycle analysis.

Therefore, the emission factor of residues from sugarcane (straw), corn (stover) and soybean (straw) were calculated according to Equation 4 and with the values present in Table 18, in which the amounts of above and below ground residues were considered. The total amount of above-ground residues was calculated based on the Residue-to-Product Ratio described for each crop in section 3.2.1. The moisture values were taken from the work of PORTUGAL-PEREIRA et al. (2015) and IPCC (2019). Equation 3 bellow shows the calculation:

$$EF_{crop\ residue} = (AGR\ x\ N_{AG})x\ (BGR\ x\ N_{BG})x\ \frac{44}{28} \qquad \textbf{(3)}$$

Where:

$EF_{crop\ residues}$ – emission factor for N$_2$O emission [kg N$_2$O (kg crop residue)$^{-1}$]

AGR – total amount of above-ground crop residue in dry mass for 1 kg of crop product [kg$_{dm}$ crop residues]

N_{AG} – N content of above-ground crop residues [kg N [kg$_{dm}$ crop residues]

BGR – total amount of below-ground crop residue in dry mass for 1 kg of crop product [kg$_{dm}$ crop residues]

N_{BG} – N content of below-ground crop residues [kg N [kg$_{dm}$ crop residues]

$\frac{44}{28}$ – Conversion of N emissions to N$_2$O emissions

The estimate of the amount of crop residue below-ground was calculated according to the RPR as shown in Equation 4.

$$BGR = (1 + RPR)\ x\ RS \qquad \textbf{(4)}$$

Where RS is the ratio of below-ground root biomass to above-ground shoot biomass [kg dm (kg dm)$^{-1}$]

Table 18-Parameters used to calculate the N2O emission factor of crop residues.

Product	**EFcrop residues**	AGR (kg dm year $^{-1)}$	N_{AG} [kg N (kg dm) $^{-1]}$	BGR (kg dm year $^{-1)}$	N_{BG} [kg N (kg dm) $^{-1]}$	RS kg dm ha $^{-1}$(kg dm ha $^{-1}$) $^{-1}$
Sugarcane	**3,44E-05**	0,22	0,008	0,2354	0,009	0,22
Corn	**1,15E-04**	1,53	0,006	0,528	0,007	0,22

Note: AGR - amount of above-ground crop residue, N_{AG} - N content of above-ground crop residues, BGR - amount of below-ground crop residue, N_{BG} - N content of above-ground crop residues, RS - ratio of below-ground root biomass to above-ground shoot biomass.

3.2.5 Conventional jet fuel

The present study considers the WTW life cycle of the conventional jet to obtain more consistent comparisons with the life cycle assessment of the alternative jet fuel routes evaluated here. In addition, following the methodological framework suggested by ICAO, an emission factor of 89 g CO_2/MJ of conventional fuel and a factor of 79 g CO_2/MJ of fuel, which refers to a value 10% lower than the emission factor of conventional fuel to ensure its certification was considered (ICAO 2020).

3.3 Land use change (LUC)

This section provides the methodology to calculate the change in biomass carbon stock due to the conversion of Brazilian phytoecological regions determined by IBGE (2019) and other land uses for cropland, including the conversion of pastures in good condition and degraded for the energy crops analyzed in this study. The methodology selected is in the fourth volume of the Intergovernmental Panel on Climate Change (IPCC, 2006) known as Agriculture, Forestry and Other Land Use (AFOLU) and the IPCC 2019 refinement.

The methodology present in IPCC (2006) and IPCC (2019) proposes three types of approaches, named three different tiers for determining activity data and emission factors, based on the detail of data. Tier 1 is based only on theoretical and general land use data (e.g., global agricultural or forestry statistics). In Tier 2, calculations are structurally like Tier 1, but with country-specific data rather than standard data. Finally, Tier 3, requires spatially explicit and complete experimental observations that allow monitoring of use, change of use, emissions, and associated GHG removals.

In this study, GHG emissions from land use conversion were calculated according to the Tier 2 methodological approach, whenever Brazilian and regional data were available. Thus, area estimates for land conversion to agricultural land were disaggregated according to the phytoecological regions defined by IBGE (2019). Carbon stocks immediately after conversion were not necessarily assumed to be zero, as suggested by the Tier1 calculation. Carbon losses in burning and decay processes are outside the scope of this analysis.

(i) <u>Calculation of carbon stock variation</u>

Direct land use change related carbon dioxide emissions are estimated based on the different between the carbon stock in previous land use and new bioenergy feedstocks to produce alternative aviation fuels. Annual values were calculated by dividing by the 25-year period (average between the 20 years adopted in the European Union RED, and 30 years assumed by the United States (DAVIS et al. 2013; US EPA 2010) as suggested by ICAO (2019), that carbon pools take to reach equilibrium after conversion. Equation 5 below details the calculations performed:

$$E = \sum(CSRi - CSAi)\ x\ Ai\ x(44/12)\ x\ (1/25) \qquad \textbf{(5)}$$

Where:

E (t CO_2.ha^{-1}. year ^{1}) = the annual GHG emissions from change in

carbon stock change due to land conversion.

CSR_i = the carbon stock associated with the reference (previous) land use (t C. ha^{-1});

CSA_i = the carbon stock associated with the current use (sugarcane, corn, soybean, palm and macaw cultivations) (t C. ha^{-1});

A_i = area converted to crop *i* (hectare)

The 44/12 fraction was used to obtain the results in mass units of CO_2

For the present study, it was considered as real land use the Phytoecological Regions, that is, all the vegetation types present in all the Brazilian biomes. The reference use refers to the land use after conversion, that is, the agricultural crops considered in the study. Equation 6 provides the way to calculate land carbon stocks for both reference land use (CSR_i) and actual land use (CSA_i):

$$CSi = (SOC + CVEG) \tag{6}$$

where:

CSi = the carbon stock per unit area associated with the land use i (measured as mass of carbon per unit area, including both soil and vegetation

SOC = soil organic carbon (measured as mass of carbon per hectare);

C_{VEG} = above and below ground vegetation carbon stock (measured as mass of carbon per hectare)

The SOC and C_{VEG} data of land conversion (CSA) for the Phytoecological Regions were obtained from the Forest Information System (NFIS) and refer to the year 2015 (SNIF 2015). The CSA of pastures were extracted from NOVAES et al. (2017). Pasture areas were disaggregated into planted and natural. Annex A1 shows details the emissions factors of total carbon stocks before land use change.

Carbon stock values after conversion (CSR), that is, the total carbon of the energy crops analyzed here, were taken from NOVAES, et al. (2017). Therefore, an average of the carbon stocks of the 27 Brazilian states was considered for each land use category. For soybean and corn the value present in the "Arable" category was assumed, and for oil palm and macaw the value of the "Permanent Crops" category was assigned. Annex A2 shows the details the emissions factors of total carbon stocks after to land use change.

<u>(ii) Direct Land Use Change Balance</u>

Following the methodological framework suggested by Tier 2 (IPCC, 2019, Vol 4), the direct land use change balance was developed. The idea is to summarize the carbon stocks after conversion to cropland. Thus, a land use change matrix guarantees consistency of accounting for all carbon pools. The baseline values for comparative purposes assumed by this document are the values suggested by CORSIA (2021) for land use change emissions for alternative aviation fuel production. These CORSIA default values refer to induced land use change (iLUC), i.e., the sum of direct and induced emissions. Furthermore, for the case of Brazil, these values are only depicted in ATJ from sugarcane and HEFA from soy. Therefore, the other routes were compared to ATJ of corn from the United States and HEFA of palm from Indonesia and Malaysia, being another limitation of this analysis. The CO_2 emissions resulting from the production of dLUC from ATJ were obtained by Equation 7:

$$EATJ = dLUC\ factor\ x\ \left(\frac{1}{prod}\right) x\ \left(\frac{1}{etOH} conversion\right) x\ \left(\frac{1}{ATJ} conversion\right) x\ \left(\frac{1}{PCI} jet\right)$$

(7)

Where:

$E_{ATJ} =$ CO_2 emissions from ATJ production (g CO_2/ MJ_{FUEL})

dLUC factor = dLUC factor from LUC matrix (tonne CO_2/ hectare of crop $_{i)}$

Prod = productivity of $crop_i$ (kg of $crop_i$/ hectare)

EtOH conversion = ethanol conversion (kg of ethanol/ kg of $crop_i$)

ATJ conversion = Alcohol-to-jet conversion (kg of jet/ kg of ethanol)

PCI jet = lower heating value of jet (MJ jet/ kg jet)

And CO_2 emissions resulting from dLUC from HEFA production were obtained by Equation 8:

$$EHEFA = dLUC\ factor \times \left(\frac{1}{prod}\right) \times \left(\frac{1}{OSR}\right) \times \left(\frac{1}{EE}\right) \times \left(\frac{1}{HEFACONVERSION}\right) \times \left(\frac{1}{PCIJET}\right) \qquad \textbf{(8)}$$

E_{HEFA} = CO_2 emissions from HEFA production (g CO_2/ MJ fuel)

dLUC factor = dLUC factor from LUC matrix (tonne CO_2/ hectare of crop $_{i}$)

Prod = productivity of $crop_i$ (kg of $crop_i$/ hectare)

OSR = oil content (%)

EE = extraction efficiency (%)

HEFA conversion = Alcohol-to-jet conversion (kg of jet/ kg of crop i)

PCI jet = lower heating value of jet (MJ jet/ kg jet)

It is worth mentioning that the GHG emissions from direct land use change were calculated according to the potential areas of expansion of each agricultural crop. For example, the emissions for sugarcane, corn and soy were calculated based on the vegetation present in the Savannah and Atlantic Forest biomes. For palm these emissions consider the initial land use in the vegetations of the Amazon biome. For macaw, the emissions were validated from the vegetations present in the Amazon, Cerrado, Caatinga and Atlantic Forest biomes. Finally, for all cases, planted and degraded pastures were considered as initial land use for the calculation of dLUC.

4 Results

This section presents the results obtained in this study. Section 4.1 details the theoretical and technical biomass potentials of the feedstocks considered in this research. Then (section 4.2), it shows the comparison of alternative jet fuel routes with conventional fossil fuel jets to assess the sustainability of the alternative jet fuel routes evaluated in Brazil, according to the criteria defined by the ICAO CORSIA certification scheme (ICAO 2019). Section 4.3 shows CO2 emissions from land use change. The Phyto-ecological Regions present throughout the Brazilian territory were considered as initial land use and for the final land use the energy crops analyzed here were considered.

4.1 Feedstock availability

This section presents the technical biomass potential of the feedstocks considered in this research (as described in Chapter 2). The total theoretical and technical potentials estimated for Brazil considering the ATJ and HEFA routes were, respectively, 2 million TJ/yr and 86,619 TJ/yr. Table 19 below summarizes the theoretical and technical biomass potentials for sugarcane, corn, soybean, palm and macaw:

Table 19-- ATJ and HEFA technical potentials.

Resource	Theoretical Potential Brazil (TJ/year)	Technical Potential Brazil (TJ/year)
Sugarcane	825,323	82,666
Corn	609,775	1,281
Soybean	466,552	2467.8
Palm fruit	21,095	204.1
Macaw fruit (low productivity)	470	-
Macaw fruit (high productivity)	2,970	-

Considering the technical biomass potentials, sugarcane ATJ has the highest weight, contributing about 42% of the total. Next, corn ATJ potential accounts for 32%

of all potential, followed by soybean with 24% of the total, oil palm with only 1%, and the two types of macaw production with less than 1% of all potential available in Brazil.

The technical potentials, as expected, obtained lower results as a result of the assumptions established in this study. Among the technical potentials, that of ATJ sugarcane obtained the highest contribution relative to the others (95%), followed by soybean HEFA (2.8%), ATJ corn (2%) and palm HEFA (0.2%). According to the assumptions considered in the study, the technical potentials of low and high yielding arroyo were null. The following sections detail the ATJ and HEFA potentials for each of the selected biomasses.

4.1.1 Sugarcane

Sugarcane is a traditional crop in Brazil's agricultural sector and has a well-consolidated production chain that operates within a sustainable environment. (CONAB, 2020). In the year 2019, according to IBGE (2020), the total planted area was just over 10 million hectares that resulted in a production of approximately 752 million tonnes of sugarcane. Sugarcane plantation areas can be found in all regions of Brazil, especially in the southeastern region, specifically in the state of São Paulo, which accounts for more than half of all sugarcane production. However, it is worth mentioning that new sugarcane plantation areas are emerging in the central-western region, especially in the state of Goiás, the second largest sugarcane producer in Brazil (approximately 12% of the total).

In the context of biofuel production, sugarcane is one of the main raw materials due to its great potential for biofuel production. Figure 8 shows a table showing the location of the areas of greatest theoretical potential (left side) and the potential areas established by technical potential (right side) for the production of sugarcane-based alternative jet fuel.

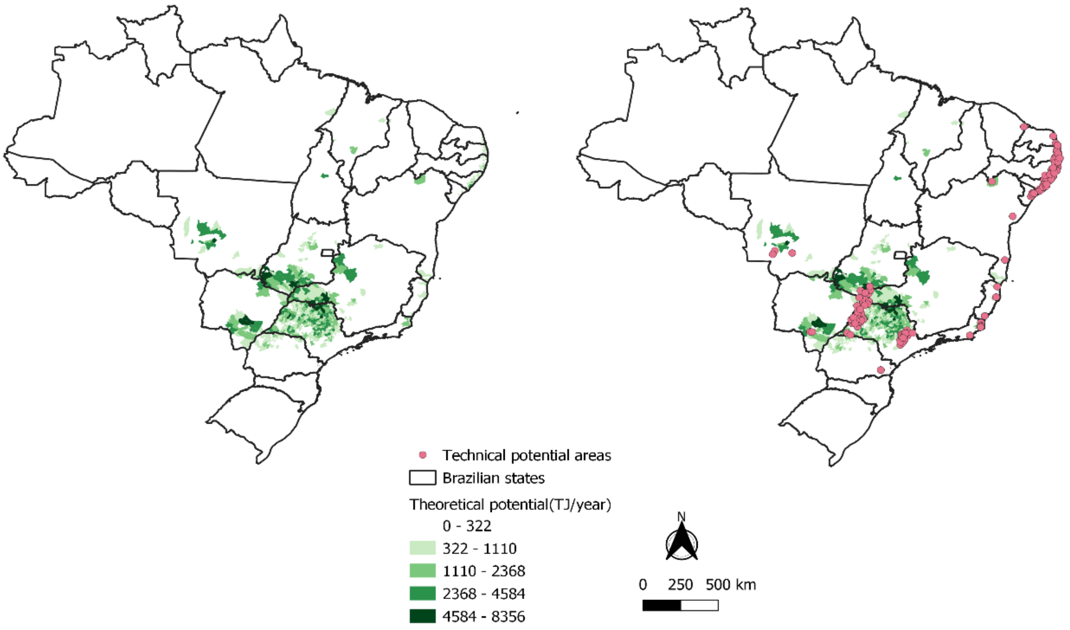

Figure 8-Sugarcane ATJ potential distributed for each municipality
Source: own elaboration.

The total theoretical potential, in terajoules/year (TJ/year), considering the year 2019 for the production of the ATJ route was approximately 825,400 TJ/year. As expected, the Southeast region comprises more than half of the entire potential (about 67%). The second largest potential was the Midwest region (20%), followed by the Northeast region (7%), the South region (6%) and lastly, the North region (1%).

The technical potential resulted in 82,666 TJ/year. The technical potential area means all potential energy crop areas within a 100 km radius that contain aviation fuel consumption points (ports or airports) and ethanol plants and that were considered for the expansion of aviation fuel production.

For sugarcane, these areas are concentrated in three Brazilian regions: the Northeast, Midwest and Southeast. The state of São Paulo had the highest technical potential, with approximately 85% of the total value, followed by the states of Alagoas (3.5%), Minas Gerais (3.1%), Goiás (3.1%) and Pernambuco (2%). The other states, Bahia, Espírito Santo, Mato Grosso do Sul, Rio de Janeiro, Rio Grande do Norte, and Sergipe contributed less than 1% of the total potential.

4.1.2 Corn

Brazil is the third largest corn producer in the world, behind only the United States and China (ECKERT et al 2017). Its production is concentrated in the Midwest and South regions, contributing 78% of total production (IBGE 2019). Unlike other countries, corn cultivation in Brazil is not destined for ethanol production, but mainly for the food sector. However, the production of corn-based ethanol has been growing in Brazil.

According to CONAB (2020), between 2018/2019 and 2019/2020, corn ethanol production more than doubled from approximately 791,431 thousand liters to 1,641,686 million liters of ethanol. For ethanol production, corn has some favorable production characteristics, such as: i) high yields; ii) consolidated production and post-harvest technology; and iii) lower water consumption and harvesting costs compared to sugarcane ethanol. However, corn productivity is lower than sugarcane (about 5.5 tonnes of corn/ha and 77 tonnes of sugarcane/hectare) and the corn logistics chain, mainly associated with the transportation of the raw material, is not efficient, making corn ethanol less competitive (EMBRAPA, 2019; CJS, et al., 2016; CONAB, 2020; JA, et al., 2008). Figure 9 below shows the alcohol-to-jet (ATJ) potentials through corn in Brazilian municipalities:

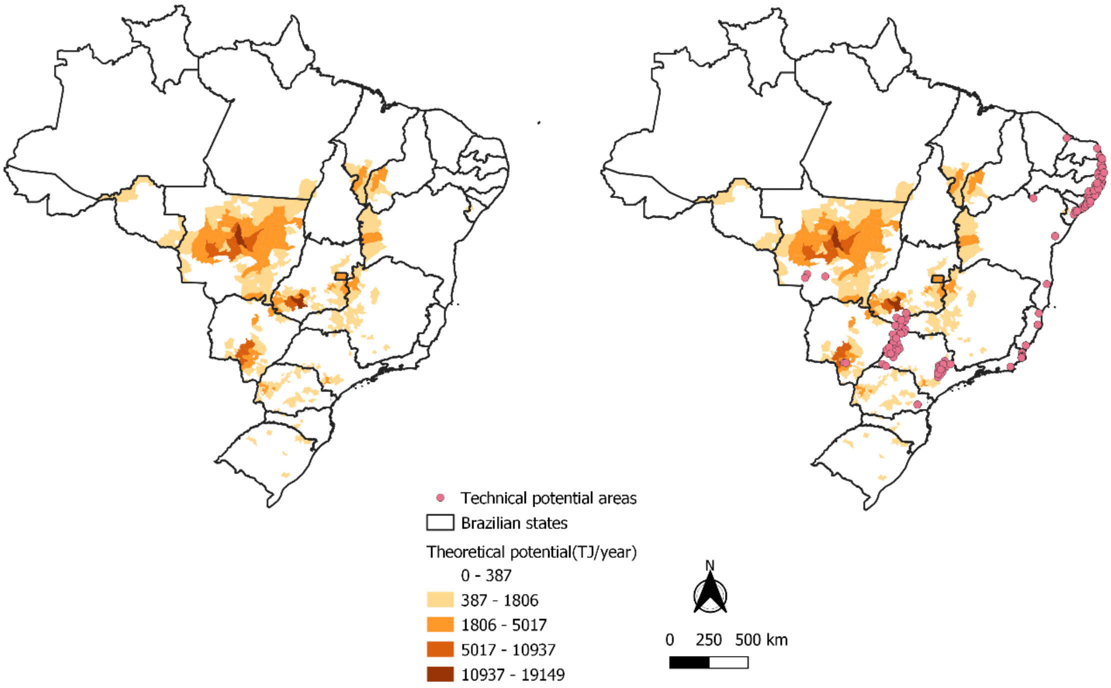

Figure 9-Corn ATJ potential distributed for each municipality
Source: own elaboration.

The total theoretical potential, in terajoules/year (TJ/year), considering the year 2019 for the ATJ route using corn was approximately 610,000 TJ/year. The Midwest region comprises more than half of the entire potential (about 53%). The second largest potential was the South region (25%), followed by the Southeast region (12%), the Northeast region (7%) and lastly, the North region (3%).

The technical potential resulted in 1281 TJ/year. The technical potential area means all potential energy crop areas within a 100 km radius that contain aviation fuel consumption points (ports or airports) and ethanol plants and that were considered for the expansion of aviation fuel production.

For corn, these areas are concentrated in four Brazilian regions: the Northeast, Midwest, Southeast, and South. The state of Goiás had the highest technical potential, with approximately 32% of the total value, followed by the states of São Paulo (26.8%), Paraná (23.4%), Alagoas (9%) and Minas Gerais (5.5%). The other states, Bahia, Ceará, Espírito Santo, Mato Grosso do Sul, Paraíba, Rio Grande do Norte, and Sergipe contributed less than 1% of the total potential.

4.1.3 Soybean

Brazil is the largest producer and exporter of soybeans in the world (WALTER et al. 2020). In 2019 production was over 114 million tonnes and a total planted area of approximately 36 million hectares (IBGE 2020). Soy production is concentrated in the Midwest region (approximately 46% of the total) (IBGE 2020). As to produce biofuels, most of the biodiesel production in Brazil (about 80%) is produced from soybean oil (WALTER et al. 2020).

Figure 10 below shows the geographical distribution of soy based HEFA potentials in Brazil's municipalities:

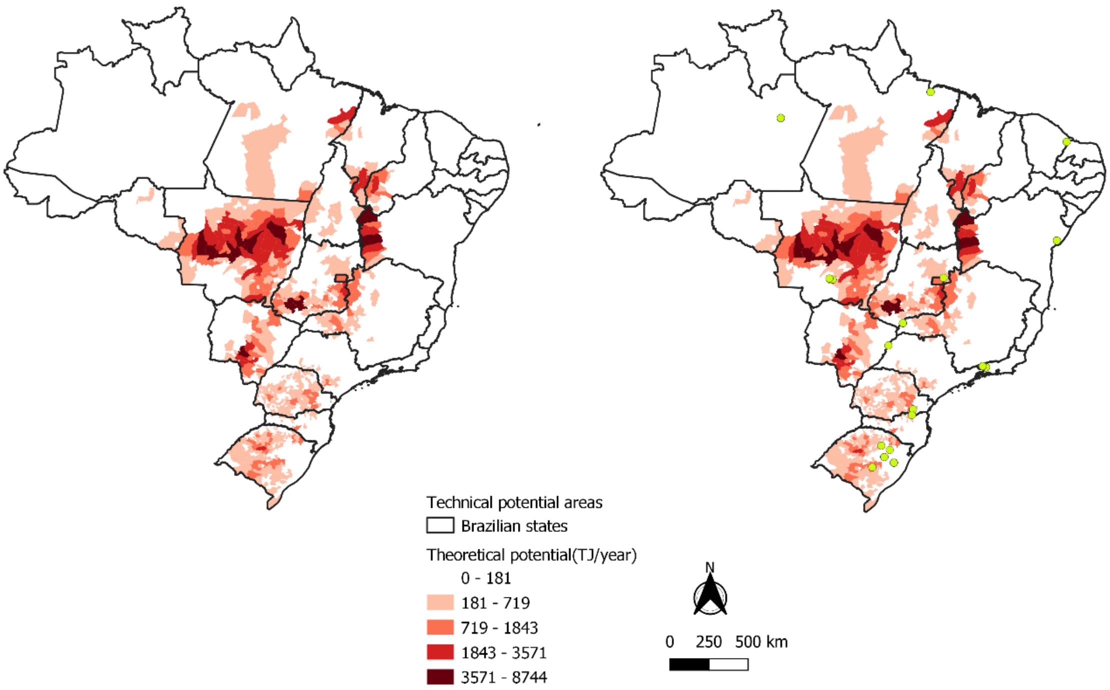

Figure 10-Soybean HEFA potential distributed for each municipality
Source: own elaboration.

The total theoretical potential, in terajoules/year (TJ/year), considering the year 2019 for the HEFA route using soybeans was approximately 467,000 TJ/year. The Midwest region comprised almost half of the entire potential (about 46%). The second largest potential was the South region (32%), followed by the Northeast region (9%), the Southeast region (8%) and lastly, the North region (5%).

The technical potential resulted in 2467.8 TJ/year. The technical potential area means all potential energy crop areas within a 100 km radius that contain aviation fuel consumption points (ports or airports) and ethanol plants and that were considered for the expansion of aviation fuel production.

For soybeans, these areas are concentrated in two Brazilian regions: the Midwest and the South. The state of Rio Grande do Sul had the highest technical potential, with approximately 55.5% of the total value, followed by the states of Paraná (35.3%), Goiás (9%) and Mato Grosso do Sul with less than 1% contribution in the total soybean HEFA potential.

4.1.4 Palm Fruit

The palm tree (Elaeis guineensis), popularly known in Brazil as palm heart, is the world's largest market for vegetable oils, about 36% of world production (CARDOSO, et al., 2020; USDA 2020). In Brazil, the palm tree occurs naturally in the Amazon biome, more precisely in the areas closest to the equator. About 98% of all Brazilian production is present in the state of Pará and only 2% in some areas east of the state of Bahia. In the context of biofuel production, palm has a prominent role due to its high productivity (between 4,000 and 6,000 kg of oil per hectare) compared to soy, the main feedstock for biodiesel production in Brazil (between 400 and 600 kg of oil per hectare). In addition, it is a perennial crop with one harvest per year (RODRIGUES, et al., 2014).

However, despite being a high productivity crop, oil palm cultivation is restricted to the north of the country due to its soil and climate specifications, such as high demand for rainfall or irrigation. Therefore, the expansion of oil palm cultivation should be cautious as it can promote forest deforestation, biodiversity loss, and significant greenhouse gas emissions (CARDOSO, et al., 2020). Figure 11 shows oil palm production concentrated in the states of Pará and Bahia:

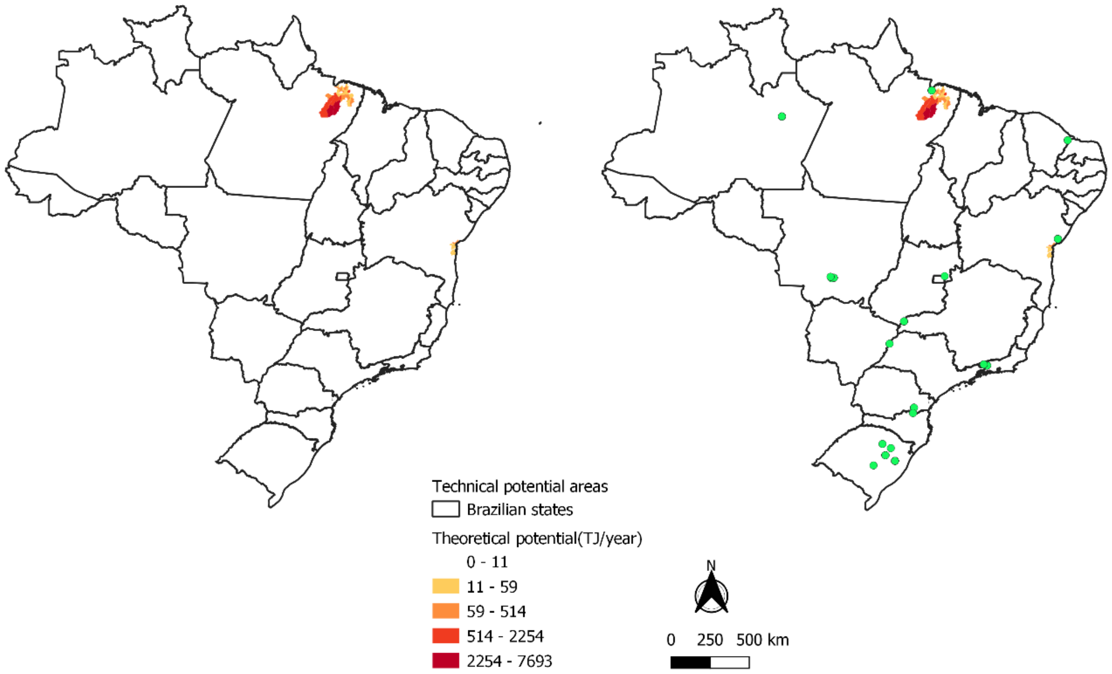

Figure 11-Palm oil HEFA potential distributed for each municipality
Source: own elaboration.

The total theoretical potential, in terajoules/year (TJ/year), considering the year 2019 for the HEFA route using palm fruit was approximately 21,100 TJ/year. Virtually all the potential is present in the state of Pará (about 99%), followed by the areas to the east of the state of Bahia, with only 1% of the entire potential.

The technical potential resulted in 204.15 TJ/yr. The technical potential area means all potential energy crop areas within a 100 km radius that contain aviation fuel consumption points (ports or airports) and ethanol plants and that were considered for the expansion of aviation fuel production.

In the case of oil palm, these areas are concentrated only in the northern region. The state Pará contains all the technical HEFA potential of oil palm.

4.1.5 Macaw fruit

The macaw palm (Acrocomia Aculeata) is native to the tropical rainforests of Latin America, extending from Mexico to Argentina (NAVARRO et al, 2014). The macaw is the most geographically dispersed palm tree in Brazil and can be found in the states of Bahia, Piauí, Maranhão, Tocantins, Goiás, Mato Grosso, Mato Grosso do Sul, Minas Gerais and São Paulo (CARDOSO, et al., 2020; EVARISTO et al., 2016; LIMA et al., 2018). IBGE recorded a small commercial production of macaw fruit in 2017 (133 tonnes). Only four states covered most of the production: MG (41%), CE (23%), MT (11%) and TO (%).

Figure 12 below shows the geographical location of potential HEFA of macaw fruit considering the areas available by IBGE (2017):

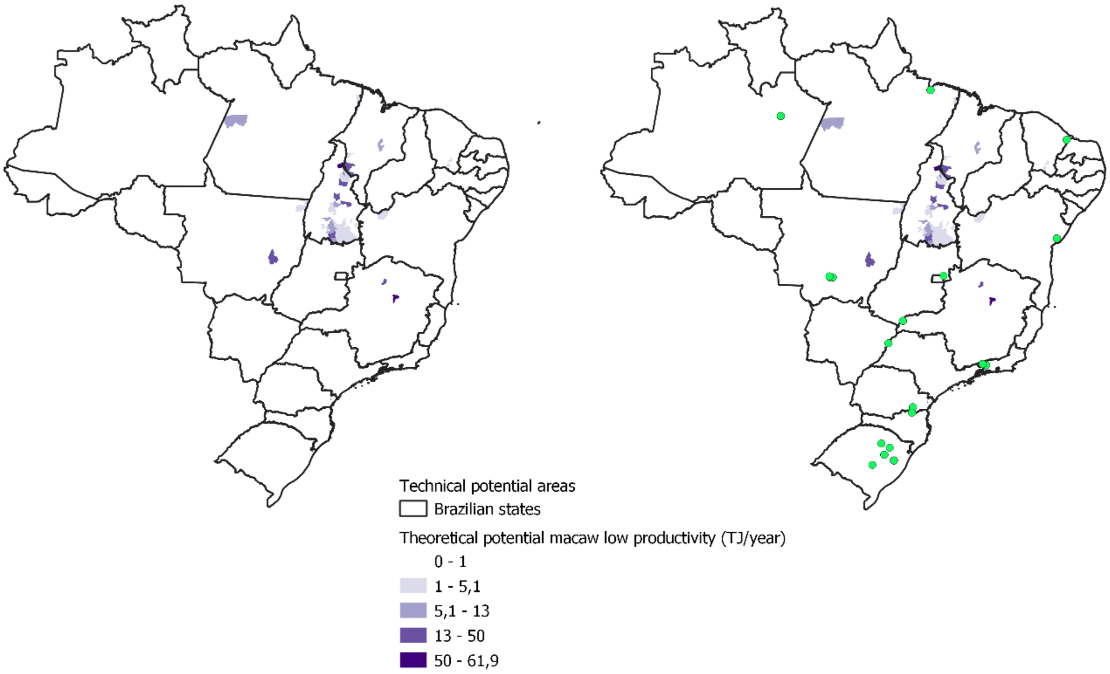

Figure 12-Macaw oil HEFA potential distributed for each municipality
Source: own elaboration.

The macaw has been considered a promising feedstock for biodiesel and alternative aviation fuel production because macaw productivity produces between 1500-5000 kg of oil per hectare per year (NAVARRO, et al., 2014). The total theoretical potential, in terajoules/year (TJ/year), considering the year 2017 for the HEFA route using macaw fruit was approximately 470 TJ/year considering a low productivity of macaw fruit. About 70% of the whole potential is concentrated in the North region, followed by the Southeast region (15%), Northeast region (9%) and Midwest region (6%). On the other hand, the total HEFA potential considering a high productivity of macaw fruit was approximately 2,970 TJ/yr., with the potentials distributed with similar proportions as HEFA with low productivity of macaw fruit. It is worth noting that there are no records, by IBGE (2017), of macaw production areas in the southern region of Brazil.

The technical potential area means all potential energy crop areas within a 100 km radius that contain aviation fuel consumption points (ports or airports) and ethanol plants and that were considered for the expansion of aviation fuel production. Due to the limitations established in the study, the potential for macaw was null.

4.2 Life cycle assessment of alternative aviation fuels

This section presents the comparison between the CO_2 emissions results from the alternative aviation fuel routes in Brazil and the CO_2 emissions from conventional jet fuel. The fuel life cycle is divided into the well-to-pump (WTP) and pump-to-wake (PTW) stages, which together form the well-to-wake (WTW) fuel cycle. The WTP stage is divided into four processes: (i) cultivation of sugarcane, corn, palm and macaw grains, (ii) transportation of energy crops from agricultural fields to processing facilities, (iii) production of aviation kerosene, and (iv) distribution of alternative aviation fuel to airports. The PTW step refers to the use of biofuel in aircraft. The functional unit chosen is MJ for GHG emissions and fossil fuel consumption results.

For comparison and validation purposes, a supporting document from CORSIA (ICAO, 2019) that presents detailed information for the aLCA of ATJ production from sugarcane and corn and HEFA production for oil palm was used. To date, no official values evaluated by ICAO are available for the macaw-based jet fuel, and therefore, the values associated with palm oil were used as a basis for comparison. Table 20 presents emissions of stages of aLCA results for all routes and variations, as well as CORSIA values for comparison (where available):

Table 20-GHG emissions of all stages of aLCA results.

Alternative aviation fuel routes	**Model**	**Agricultural phase (gCO$_{2e}$ / MJ FUEL**	**Feedstock transportation (gCO$_{2e}$ / MJ FUEL**	**Feedstock to fuel (gCO$_{2e}$ / MJ FUEL**	**Fuel transportation (gCO$_{2e}$ / MJ FUEL**	**Total (gCO$_{2e}$ / MJ FUEL**
ATJ sugarcane	this work	11.9	4.3	1.48	4.7	**22.4**
	CORSIA	17	1.6	5.9	0.4	**24.1**
ATJ corn	this work	28.1	0.26	10.9	0.71	**39.5**
	CORSIA	26.3	1.7	37.4	0.4	**65.7**
HEFA soybean	this work	9.8	0.3	9.67	0.48	**20.1**
	CORSIA	19.5	1	13.5	0.5	**40.4**
HEFA palm (without methane capture)	this work	12.8	0.85	33.7	0.91	**48.3**
	CORSIA	15.6	0.9	39.4	0.4	**60**
HEFA palm (assuming 85% methane capture)	this work	12.8	0.85	14	0.91	**28.6**
	CORSIA	15.6	0.9	37.4	0.4	**37.4**
HEFA macaw low (without methane capture)	this work	38.3	0.91	31.7	0.91	**71.8**
HEFA macaw low (assuming 85% methane capture)	this work	39.4	0.91	13.6	0.91	**53.7**
HEFA macaw high production (assuming 85% methane capture)	this work	20.1	0.91	13.6	0.91	**35.5**
HEFA macaw high production (without methane capture)	this work	20.1	0.91	31.7	0.38	**53.7**

Source: own elaboration.

As shown in Table 20, the total WTW GHG emissions are disaggregated by the four WTP processes. The soybean HEFA route showed the best performance, adding 20.1 g CO_{2e}/MJ_{FUEL} adding the four production phases. The macaw HEFA route without considering methane capture had the worst performance, adding 71.8 g CO_2e/MJ_{FUEL} in all phases of its life cycle.

Starting the analysis with the ATJ sugarcane route, the agricultural and the fuel feedstock phase have CO_{2e} emissions values (11.9 and 1.48 g CO_{2e}/MJ_{FUEL}, respectively) below the reference values established by CORSIA, 17 and 5.9 g CO_{2e}/MJ_{FUEL}, respectively. Emissions from biomass transport (4.3 g CO_{2e}/MJ_{FUEL}) and biofuel transport (4.7 g CO_{2e}/MJ_{FUEL}) were higher than those reported by CORSIA (1.06 and 0.4 g CO_{2e}/MJ_{FUEL}, respectively).

The ATJ corn route had emissions of 39.5 g CO_{2e}/MJ_{FUEL}, below the CORSIA standard values (65.7 g CO_{2e}/MJ_{FUEL}). Emissions associated with the agricultural phase had the greatest weight during the life cycle, contributing about 71% of the emissions. Emissions from the conversion of corn to fuel in the modeled hypothetical biorefinery, 10.9 g CO_{2e}/MJ_{FUEL}) were lower than the CORSIA standard values, 37.4 g CO_{2e}/MJ_{FUEL}). However, in both the biomass transport and biofuel transport phases, the emissions contribution (0.26 and 0,.71 g CO_{2e}/MJ_{FUEL}, respectively) was lower than the CORSIA values (1.7 and 0.4 g CO_{2e}/MJ_{FUEL}, respectively).

The CO_2 emissions associated with the four stages of the HEFA soybean route (20.1 g CO_{2e}/MJ_{FUEL}) were lower than the ICAO proposed value (40.4 g CO_{2e}/MJ_{FUEL}). The agricultural stage had lower emissions than the CORSIA default values (9.8 and 19.5 CO_{2e}/MJ_{FUEL}, respectively. The fuel synthesis stage had the highest emissions among the four stages of the route (12.9 g CO_{2e}/MJ_{FUEL}), contributing about 54% of the whole life cycle emissions. Finally, emissions from the biomass transportation (0.3 g CO_{2e}/MJ_{FUEL})

and biofuel transportation (0.48 g CO_{2e}/MJ_{FUEL}) stages obtained lower emissions than those indicated by CORSIA (1.0 and 0.5 g CO_{2e}/MJ_{FUEL}, respectively).

The palm HEFA route was analyzed considering methane capture and no methane capture. The total emissions obtained for the route with methane capture 28.6 g CO_2/MJ_{FUEL} and without methane capture 48.3 g CO_{2e}/MJ_{FUEL} are lower than those proposed by ICAO (37.4 and 60 g CO_{2e}/MJ_{FUEL}, respectively). The emissions associated with the agricultural phase, 12.8 g CO_{2e}/MJ_{FUEL}, were lower than the CORSIA values (15.6 g CO_{2e}/MJ_{FUEL}). The largest carbon footprints in the route without carbon capture are present in the kerosene synthesis stage (33.7 g CO_{2e}/MJ_{FUEL}) but are lower than the CORSIA values (39.4 g CO_{2e}/MJ_{FUEL}). The processing stage considering methane capture from POME effluents obtained emissions of 14 g CO_{2e}/MJ_{FUEL}, significantly lower than CORSIA (37.4 g CO_{2e}/MJ_{FUEL}), which means that CORSIA processes probably consider less than 85% of CH_4 capture, which was assumed for this activity.

Biomass transport contributed emissions of 0.85 g CO_{2e}/MJ_{FUEL}, lower than the value present in CORSIA, 0.9 g CO_{2e}/MJ_{FUEL}. It is worth mentioning that the HEFA processes in the CORSIA document consider the intermediate transport between the palm oil extraction facilities and the biorephyseary itself, which were excluded from the comparison for consistency reasons. Finally, the emissions associated with biofuel transportation (0.91 g CO_{2e}/MJ_{FUEL}) were higher than the emissions proposed by CORSIA (0.4 g CO_{2e}/MJ_{FUEL}).

Emissions from macaw low-productivity HEFA plowing with methane capture (53.7 g CO_2/MJ_{FUEL}) and without methane capture (71.8 g CO_{2e}/MJ_{FUEL}) were higher than emissions from the oil palm HEFA route (30.8 and 50.5 g CO_{2e}/MJ_{FUEL}, respectively). Emissions from the route with and without methane capture were concentrated in the agricultural phase (39.4 g CO_{2e}/MJ_{FUEL}), which are associated with a large volume of agrochemicals in the first years of cultivation. Similarly, HEFA emissions for the high-yielding macaw crop considering methane capture (35.5 g CO_{2e}/MJ_{FUEL}) and without methane capture (53.7 g CO_{2e}/MJ_{FUEL}) were higher than for the HEFA palm route. However, emissions from the route with methane capture were concentrated in the agricultural phase (20.1 g CO_{2e}/MJ_{FUEL}), while in the route without methane capture, emissions were concentrated in the biofuel processing phase (31.7 g CO_{2e}/MJ_{FUEL}).

4.3 Direct land use change emissions

This section presents a simulation of CO_2 emissions from direct land use change in order to expand aviation fuel production in Brazil. Note that factors such as legal land use restrictions, biophysical constraints, and economic feasibility were not considered. The simulations were performed on vegetations that have soils of medium to high suitability for each of the energy crops considered here. For example, the soils of the vegetations present in the Cerrado and Atlantic Forest biomes were considered for conversion into sugarcane, corn and soybean crops. In the case of oil palm, the areas of the Amazon biome were considered. In the case of macaw, the soils of the vegetations present in the Amazon, Caatinga, Cerrado and Atlantic Forest biomes were considered. In all cases, soil conversion from pasture (natural and anthropized) to the selected crop was simulated. In addition, the default value of CORSIA refers, as mentioned earlier, to iLUC (dLUC+dLUC).

Table 21 below presents the results of the emissions related to the conversion of vegetation and pasture into sugarcane:

Table 21-Direct land use change from sugarcane crop CO2 emissions

Initial use	Final use	Emissions (g CO_2/MJ_{FUEL})	CORSIA Default iLUC value (g CO_2/MJ_{FUEL})
Savannah			
Seasonal Semidecidual Forest	Sugarcane crop	131.7	8.7
Forested Savannah	Sugarcane crop	67.8	
Wooded Savannah	Sugarcane crop	29.8	
Park Savannah	Sugarcane crop	8.2	
Grassy Savannah	Sugarcane crop	0.8	
Atlantic Forest			
Dense Ombrophylous Forest	Sugarcane crop	147.8	
Open Ombrophilous Forest	Sugarcane crop	147.6	
Mixed Ombrophilous Forest	Sugarcane crop	148.7	
Decidual Seasonal Forest	Sugarcane crop	114.7	
Semidecidual Seasonal Forest	Sugarcane crop	94.0	
Pasture			
Pasture man made	Sugarcane crop	0.4	
Grassland natural	Sugarcane crop	2.4	

Source: own elaboration.

Carbon dioxide emissions associated with dLUC in the Cerrado biome were concentrated in the Seasonal Semidecidual Forest conversion (131.7 g CO_2/MJ_{FUEL}) while the lowest are present in the Grassy Savanna (0.8 g CO_2/MJ_{FUEL}). So, in the Cerrado, conversion emissions occurring in Park Savannah (8.2 g CO_2/MJ_{FUEL}) and Grassy Savannah (0.8 g CO_2/MJ_{FUEL}) areas resulted in emissions below the value proposed by CORSIA. In the Atlantic Forest biome, the highest CO_2 emissions are present in the Dense Ombrophilous Forest (147.8 g CO_2/MJ_{FUEL}) and the lowest in the Seasonal Semidecidual Forest, with emissions of 94 g CO_2/MJ_{FUEL}. The best performances and those below the values proposed by CORSIA (8.7g CO_2/MJ_{FUEL}) are the conversion of food masses in the sugarcane cultivation area, especially in anthropized masses, with emissions of 0.4 g CO_2/MJ_{FUEL} versus 2.4 g CO_2/MJ_{FUEL} considering natural food masses.

Table 22 below presents the results of CO_2 emissions from the conversion of vegetation and pasture into corn crops:

Table 22-Direct land use change from corn crop CO2 emissions

Initial use	Final use	Emissions (g CO_2/MJ_{FUEL})	CORSIA Default iLUC value (g CO_2/MJ_{FUEL})
Savannah			25
Seasonal Semidecidual Forest	corn crop	401.4	
Forested Savannah	corn crop	247.0	
Wooded Savannah	corn crop	155.1	
Park Savannah	corn crop	102.9	
Grassy Savannah	corn crop	85	
Atlantic Forest			
Dense Ombrophylous Forest	corn crop	440.6	
Open Ombrophilous Forest	corn crop	440.1	
Mixed Ombrophilous Forest	corn crop	442.6	
Decidual Seasonal Forest	corn crop	360.5	
Semidecidual Seasonal Forest	corn crop	310.3	
Pasture			
Pasture man made	corn crop	1.1	
Grassland natural	corn crop	5.9	

Source: own elaboration.

The emissions present in the conversion of the vegetation of the Cerrado biome into corn growing areas had the highest weight when occurring in the Semidecidual Seasonal Forest (401.4g CO_2/MJ_{FUEL}) and the lowest weight occurring in Cerrado with emissions of 85g CO_2/MJ_{FUEL}. In the Atlantic Forest biome, emissions were more intense, with the highest occurring in Dense Ombrophylous Forest (440.6g CO_2/MJ_{FUEL}) and the lowest occurring in Semidecidual Seasonal Forest (310.3g CO_2/MJ_{FUEL}). As seen in the previous case, the conversion of pastures into corn growing areas had the best performance and are the only ones that stay below the value established by CORSIA (25g CO_2/MJ_{FUEL})

showing emissions of 1.1 g CO_2/MJ_{FUEL} considering anthropized pastures and 5.9 g CO_2/MJ_{FUEL} taking into account natural pastures.

Table 23 below presents the results of CO_2 emissions simulated in the conversion of vegetation and pasture into soybean cultivation areas:

Table 23-Direct land use change from soybean crop CO2 emissions

Initial use	Final use	Emissions (g CO_2/MJ_{FUEL})	CORSIA Default iLUC value (g CO_2/MJ_{FUEL})
Savannah			27
Seasonal Semidecidual Forest	soybean crop	403.7	
Forested Savannah	soybean crop	238.2	
Wooded Savannah	soybean crop	100.8	
Park Savannah	soybean crop	265.9	
Grassy Savannah	soybean crop	219.7	
Atlantic Forest			
Dense Ombrophylous Forest	soybean crop	113.9	
Open Ombrophilous Forest	soybean crop	113.7	
Mixed Ombrophilous Forest	soybean crop	114.4	
Decidual Seasonal Forest	soybean crop	93.2	
Semidecidual Seasonal Forest	soybean crop	80.2	
Pasture			
Pasture man made	soybean crop	2.4	
Grassland natural	soybean crop	3.7	

Source: own elaboration.

The emissions present in the conversion of the Cerrado biome vegetation into soybean growing areas had the highest weight when they occurred in the Seasonal Semidecidual Forest (403.7 g CO_2/MJ_{FUEL}) and the lowest weight when they occurred in the Wooded Savannah with emissions of 100.8 g CO_2/MJ_{FUEL}. In the Atlantic Forest biome, the highest emissions are in the Mixed Ombrophilous Forest (114.4 g CO_2/MJ_{FUEL}) and lowest weight occurring in the Seasonal Semidecidual Forest (80.2 g CO_2/MJ_{FUEL}). As seen in the previous case, the conversion of pastures into soybean cultivation areas had the best performance, showing emissions of 2.4g CO_2/MJ_{FUEL} considering anthropized pastures and 3.7 g CO_2/MJ_{FUEL} considering natural pastures.

Table 24 below presents the results of simulated CO2 emissions when converting vegetation and grassland into oil palm cultivation areas:

Table 24-Direct land use change from palm crop CO2 emissions

Initial use	Final use	Emissions (g CO_2/MJ_{FUEL})	CORSIA Default iLUC value (g CO_2/MJ_{FUEL})
Amazon			39.1
Dense Ombrophilous Forest	Palm	212	
Open Ombrophilous Forest	Palm	163.8	
Decidual Seasonal Forest	Palm	114.8	
Semidecidual Seasonal Forest	Palm	129.6	
Gramineous-Landscrub Forest	Palm	-8.1	
Forested Savanna	Palm	31.6	
Wooded Steppe Savannah	Palm	-18.8	
Wooded Steppe Savannah	Palm	-27.2	
Wooded Savannah	Palm	-10.4	
Park Savannah	Palm	-29.1	
Graminous Savannah	Palm	-36	
Gramineous-Lenous Steppe Savannah	Palm	-40.2	
Steppe Savannah Park	Palm	-39.9	
Secondary Vegetation	Palm	-23.3	
Pasture			
Pasture man made	Palm	-3.4	
Grassland natural	Palm	-2	

Source: own elaboration.

Due to the edaphoclimatic constraints of oil palm cultivation, direct emissions from land use change were considered only for the Amazon biome and in grasslands. Remembering also that emissions from macaw were compared to palm values, since emissions for macaw have not been calculated so far. Emissions present in the conversion of vegetation in the Amazon biome to oil palm cultivation areas had the highest weight when occurring in the Dense Ombrophylous Forest (212g CO_2/MJ_{FUEL}). Unlike previous results, dLUC emissions from oil palm are below the value established by CORSIA (39.1 g CO_2/MJ_{FUEL}) in ten vegetation types, with negative emissions ranging from -8 g CO_2/MJ_{FUEL} for the case of Gramineous-Landscrub Forest to -40.2 g CO_2/MJ_{FUEL} in

Gramineous-Lenous Steppe Savannah areas. In addition to these areas, the conversion of grassland to oil palm plantations also falls below the value established by CORSIA, being -3.4 g CO_2/MJ_{FUEL} in pasture man made and -2 g CO_2/MJ_{FUEL} in natural grassland.

Table 25 below presents the results of CO_2 emissions simulated in the conversion of vegetation and grasslands into low and high yielding macaw cultivation areas:

Table 25-Direct land use change from macaw crop CO2 emissions

Initial Use	**Final use**	**Emissions (g CO_2/MJ_{FUEL})**	**CORSIA Default iLUC value (g CO_2/MJ_{FUEL})**
Amazon			
Dense Ombrophilous Forest	Macaw low/Macaw high	908.7/143.9	39.1
Gramineous-Lenous Steppe Savannah	Macaw low/Macaw high	-17.2/-27.3	39.1
Caatinga			
Wooded Steppe Savannah	Macaw low/Macaw high	-9.1/-14.4	39.1
Steppe Savannah Park	Macaw low/Macaw high	-20.4/-32.3	39.1
Cerrado			
Seasonal Semidecidual Forest	Macaw low/Macaw high	218.7/34.6	39.1
Grassy Savannah	Macaw low/Macaw high	-15.5/-24.6	39.1
Atlantic Forest			
Dense Ombrophylous Forest	Macaw low/Macaw high	264.9/41.9	39.1
Semidecidual Seasonal Forest	Macaw low/Macaw high	111.1/17.6	39.1
Pasture			
Pasture man made	Macaw low/Macaw high	-14.5/-22.91	39.1
Grassland natural	Macaw low/Macaw high	-8.8/-13.89	39.1

Source: own elaboration.

Unlike palm oil, the macaw is able to adapt and thrive in different soil and climate environments. Therefore, direct land use change emissions for the macaw were assessed in almost all Brazilian biomes, except Pantanal and Pampas. The emissions present in the conversion of vegetation of the Amazon biome into low and high productivity macaw cultivation areas had the highest weight when they occurred in the Dense Ombrophylous Forest (908.7g CO_2/MJ_{FUEL} and 143.9g CO_2/MJ_{FUEL}, respectively) and the lowest weight when they occurred in the Savanna of the Gramineous-Ligneous steppes with emissions of -17.2g CO_2/MJ_{FUEL} for low-productivity macaws and -27.3g CO_2/MJ_{FUEL} for high-productivity macaws, the latter two being below the value estimated by CORSIA (39. 1 g CO_2/MJ_{FUEL}). In the Caatinga biome all emissions fall within the value established by CORSIA and were negative in all existing vegetations and the two productivity types, with the lowest emissions present in the Savanna Steppe Grassy with emissions of -17.2 g CO_2/MJ_{FUEL} for low productivity macaw and -27.3 g CO_2/MJ_{FUEL} for high productivity macaw. Emissions from conversion in the vegetations of the Cerrado biome were most intense when they occur in the Seasonal Semidecidual Forest (218 g CO_2/MJ_{FUEL} As seen in the previous cases, the conversion of pastures into soybean cultivation areas had the best performance and were below the value proposed by CORSIA, showing emissions of 2.4 g CO_2/MJ_{FUEL} considering anthropized pastures and 3.7 g CO_2/MJ_{FUEL} considering natural pastures. As seen in the previous case, the conversion of pasture to oil palm cultivation had the best performance, showing negative emissions of -3.4g CO_2/MJ_{FUEL} considering deforested pasture and -2g CO_2/MJ_{FUEL} considering natural pasture.

5 Discussion

This section aims to combine and discuss the results obtained and presented in the previous sections to evaluate the Brazilian potential for alternative aviation fuel production.

The introduction of alternative aviation fuels as substitutes for conventional fossil fuels in aviation is primarily motivated by the possibility of decarbonizing the air transport sector. In terms of potential, Brazil's theoretical dedicated biomass potential for the year 2019 was estimated at 2,000,000 TJ/yr and 86,000 TJ/yr, respectively. CERVI et al. (2019) arrived at a techno-economic potential for alternative aviation fuel production ranging from 0 to 6.4 EJ in 2015 and between 1.2 and 7.8 EJ in 2030, most of which is concentrated in the Northeast and Southeast regions of Brazil (CERVI et al. 2019). This potential, according to the authors, could meet almost half of the projected global aviation fuel demand in 2030. The results of CARVALHO et al. (2019), on the other hand, show that the biomass availability for each crop in the hotspots, mainly soybean and corn, would be sufficient to feed the alternative aviation fuel conversion plants proposed in the study.

It should be remembered that the theoretical potential mentioned here considers that the entire planted area of the selected agricultural crops is exclusively for aviation fuel production, i.e., it does not consider conflicts with other uses, such as the food sector and road fuel sector, and also does not consider distances from agribusinesses and consumption points.

The technical potential calculated in this study also considers that the potential areas available for expansion of jet fuel production do not compete with other economic sectors. However, these areas are limited to a 100 km radius between consumption points (airports and ports) and ethanol plants (for the ATJ routes) and biodiesel plants (for the HEFA route). The maps shown in section 4, show the differences, in a spatialized way between the two potentials considered in this study. For example, sugar cane presents theoretical potential concentrated in large areas of the Southeast and Midwest regions. However, when considering the assumptions of this study, only a portion of these areas are close to the points of consumption and ethanol plants, significantly reducing the potential areas for expansion. However, the fact that Brazil is one of the largest producers of sugarcane ethanol, and, consequently, has a well consolidated agroindustrial structure close to the cultivation areas, makes its bioenergy potential higher compared to the other energy crops analyzed in this study. However, it is worth noting that the technical potential of ATJ from sugarcane, in this study, does not consider conflicts of uses with Brazilian ethanol.

Same thing for the case of corn. In fact, the total area planted with corn in Brazil is present in most of the national territory, but far from ports, airports and ethanol plants. This corn issue brings us to the following question: corn as an alternative fuel has been growing and structuring itself in recent years (CONAB, 2019), but it is something relatively recent in Brazil, since the corn crop is strongly present in the food sector, and perhaps because of this, corn growing areas are not close to these consumption points and ethanol plants. Therefore, the establishment of biodiesel plants in the Midwest region may be an attractive option, given the expected growth of corn's bioenergy potential in Brazil.

Soy is one of the main raw materials for biodiesel production in Brazil. However, when calculating the technical HEFA potential of soy in this study, it is apparent that the main soybean growing areas, located in the Center-West, are not close to the consumption points established here. Therefore, its potential, considering the premises of this study, is concentrated in the Southern region of the country.

The technical potential of oil palm is restricted to the north of the country, in the state of Pará, due to specific soil and climate requirements of the crop, such as rainfall and solar incidence. Therefore, the potential palm areas are distant from several consumption points and from the infrastructure for fuel processing. Thus, the establishment of more biodiesel plants in this region can increase the production of aviation biofuels.

Finally, the macaw is a new option in the range of energy crops in the country. Therefore, data on this crop is still undergoing adjustments and studies. For example, the potential of macaw, following the assumptions of this study, is null. This does not mean that there is no potential for macaw HEFA in Brazil, it means that the potential areas for cultivation of macaw are not close to the points of consumption or biodiesel plants. The areas considered in this study were based on the areas of agricultural enterprises of macaw cultivation published in the IBGE database and refer to the year 2017. However, the work of WALTER et al. (2020) points out potential areas in other states not considered in this study, such as Minas Gerais, São Paulo and Mato Grosso and that would possibly have technical potential applying the assumptions of this study. However, due to data incompatibility, it was decided to use the IBGE data.

In summary, Brazil has the potential to produce alternative aviation fuels. However, the demand for other uses of these biomasses, such as soy-based biodiesel production, sugarcane and corn ethanol for the food sector, and now corn ethanol, compromise the use of these feedstocks for the production of alternative aviation fuels (CREMONEZ ET AL. 2015). The potential of oil palm and macaw were included because it has high agricultural yields and is an oilseed crop already cultivated in Brazil with considerable potential for expansion (CAPAZ et al. 2021).

GHG emissions from the selected routes were analyzed considering average production conditions using the aLCA approach and evaluated according to the values established by CORSIA. All life cycle allocations were established on an energy basis, since fuels are energy sources and are commonly seen in these plants. Thus, the environmental performance of the routes was assessed by summing the GHG emissions (gCO_2/MJ_{FUEL}) from each phase of the alternative aviation fuel life cycle, from feedstock production to fuel use. This value was then compared to fossil kerosene (Jet A, 89 g CO_2/MJ_{FUEL}) and with a value of 79.9 g CO_2e/MJ_{FUEL} (VALUE 10% lower than conventional fossil fuel) as there is an intention to replace it (ICAO, 2020). Without considering the effects of dLUC, all routes evaluated in these studies showed lower CO_2 emission values than fossil fuel and the alternative value of 79.9 g CO_2e/MJ_{FUEL}.

The total emissions of the ATJ sugarcane routes (22.38 g CO_2e/MJ_{FUEL}) were lower than the emissions proposed by CORSIA (24.1 g CO_2e/MJ_{FUEL}). These results make sense because the sugarcane crop has low agrochemical application, and the sugarcane agroindustry is well structured and consolidated in Brazil. Comparing with literature, the values of the studies conducted by Klein et al. (2018) (20.5 g CO_{2e}/MJ_{FUEL}) and by JONG et al. (2017) (26 g CO_{2e}/MJ_{FUEL}), since the inventories adopted by these authors were based on GREET (ANL 2020). Similarly, CAPAZ et al (2021) estimated 32. 9 g CO_2/MJ_{FUEL} mainly due to differences in the agricultural phase.

Nevertheless, emissions from the upstream field constitute more than half of the total carbon footprint of the sugarcane agricultural phase (53%) due to direct emissions of N_2O from the decomposition of crop residues and CH_4 emitted from bagasse, but the result is below the value suggested by CORSIA (17g CO_2e/MJ_{FUEL}). The emissions associated with fuel synthesis were the lowest in the life cycle of this route, since the system is energy self-sufficient, contributing to these results. The emissions associated with the transportation steps of the sugarcane biomass as well as the final fuel were significant (19% of total emissions associated with biomass transportation and 21% associated with fuel transportation) due to longer distances and less restrictive emission standards for older trucks (Euro III standard). In addition, it is worth remembering that the allocations made in the life cycle of this study are on an energy basis and this may have influenced the weight of emissions associated with the transportation of sugarcane ATJ route.

The total emissions of the corn ATJ route (39.97 g CO_2e/MJ_{FUEL}) were lower than the emissions proposed by CORSIA (65.7 g CO_2e/MJ_{FUEL}). This difference can be justified mainly by the use of biogas, derived from residual forest biomass, considered as an energy source for fuel synthesis. CORSIA has as a reference the ATJ corn route of the United States, where natural gas is commonly used as an energy source. Other examples are the work of HAN et al. (2017) estimated 65.6 g CO_{2e}/MJ_{FUEL} using the GREET model, which is based on the reality of growing and processing American corn. STAPLES et al. (2014) reached a carbon footprint for ATJ corn of 47.5 g CO_{2e}/MJ_{FUEL} to 117.5 g CO_{2e}/MJ_{FUEL} by dividing the alternative aviation fuel production process into four stages (pretreatment, fermentation, extraction and upgrading) and making process assumptions for each stage, such as efficiency, energy and mass balance.

Unlike the sugarcane crop, the corn crop requires a greater volume of agrochemicals and, therefore, the emissions associated with the agricultural phase are higher than those of sugarcane (28.1 g CO_{2e}/MJ_{FUEL} for corn and 11.9 g CO_{2e}/MJ_{FUEL} for sugarcane). So, the agricultural phase associated with the ATJ route of corn contributes 70% of the emissions of the entire life cycle, mainly due to the direct emissions of N_2O from the decomposition of crop residues. The emissions associated with the fuel synthesis stage were also significant (27% of the entire life cycle), even considering biogas as the energy source of the system. Brazil has no experience in corn biofuel production, and this may have contributed to these results in the processing stage. After ethanol production, none of the by-products were considered useful for subsequent activities - the opposite when compared to the sugar cane process, where all the bagasse was used to generate electricity for the plant. Due to the high protein content, the by-product of corn processing (DDGS) is commonly used as animal feed. It is worth noting that the transport emissions for this route was not as significant (0.26 g CO_2e/MJ_{FUEL} for biomass transport and 0.71 g CO_2e/MJ_{FUEL} from fuel transport) compared to the sugarcane ATJ route (4.3 g CO_2e/MJ_{FUEL} from biomass transport and 4.7 g CO2e/MJ_{FUEL} from fuel transport), since the life cycle allocations are on an energy basis.

The total emissions from the HEFA soybean routes (20.1 g CO_2e/MJ_{FUEL}) were lower than the emissions proposed by CORSIA (40.4 g CO_2e/MJ_{FUEL}). This difference can be justified mainly by the use of biogas, derived from residual forest biomass, considered as an energy source for fuel synthesis. Compared to other results available in the literature, the emissions reported here in this study are lower than those reported by VÁSQUEZ et al. (2019) (40.1 g CO_2e /MJ_{FUEL}) for Brazil, or by CAPAZ et al. (2021) (41.5 g CO_2e/MJ_{FUEL}). HAN et al. (2013) estimated for soybeans produced in the United States, CO_2e emissions equivalent to 39.0 g CO_2e/MJ_{FUEL}. On the other hand, KLEIN et al. (2018) reported lower results than in this study, of 22.0 g CO_2e/MJ_{FUEL} for Soybeans/HEFA. These differences occur mainly due to differences in agricultural stage and calculated utility requirements and yields for the alternative aviation fuel conversion process.

Emissions from the soybean HEFA agricultural phase (9.8 g CO_2e/MJ_{FUEL}) are mainly associated with fertilizer use and soybean harvesting operations. In the fuel synthesis phase, the use of hydrogen is the main contributor to the biofuels processing phase emissions (9.67 g CO_2e/MJ_{FUEL}), but the emissions from this phase are lower than those indicated by CORSIA (13.5 g CO_2e/MJ_{FUEL}). The emissions originating in the biomass and fuel transportation phases (0.61 g CO_2e/MJ_{FUEL} and 0.48 g CO_2e/MJ_{FUEL}, respectively) are mainly caused by the use of diesel fuel in the trucks performing these operations and are below the values suggested by CORSIA for both cases (0.85 g CO_2e/MJ_{FUEL} and 0.91 g CO_2e/MJ_{FUEL} for biomass and fuel transportation respectively).

The total emissions of the palm HEFA routes with methane capture (28. 56g CO_2e/MJ_{FUEL}) and without methane capture (48.26g CO_2e/MJ_{FUEL}) were below the values suggested by CORSIA (37.4 g CO_2e/MJ_{FUEL} and 60 g CO_2e/MJ_{FUEL}) respectively. These significant differences can be justified by the fact that CORSIA has Asian countries' palm cultivation as a parameter and therefore, differences in agricultural, industrial and transportation inputs may have affected these emission differences. Compared to some results found in the literature, KLEIN et al. (2018) estimated 17.0 g CO2/MJFUEL for Palm/HEFA due mainly to the integration between integrated ethanol distilleries with on-site hydrogen from electrolysis water. The energy demand would presumably be met by the surplus energy generated at the ethanol distilleries. VÁSQUEZ et al. (2019) also estimated lower values for the HEFA route for oil palm in Brazil (14.2 g CO2/MJFUEL). On the other hand, HAN et al. (2013) developed a study in Malaysia and reported values of 34.0 g CO2/MJFUEL and CAPAZ et al. (2021) estimated emissions of 31.4 g CO2/MJFUEL. The main differences arise in the agricultural phase.

The lowest life cycle emissions of the palm HEFA route are in the agricultural phase (12.8 g CO_2e/MJ_{FUEL}) and were below the value suggested by CORSIA (16g CO_2e/MJ_{FUEL}). In perennial crops, such as oil palm, pesticides are introduced in the early years, and this may have contributed to this result. The fuel synthesis phase accounts for most of the palm HEFA emissions with and without methane capture (50% and 70% of total emissions). It is notable that POME treatment is an important issue for calculating GHG emissions for the palm HEFA route. Assuming that POME is treated in open ponds without gas capture systems, as is currently done in Brazil (AGROPALMA 2017), CO_2e

emissions from palm HEFA could reach 28.56 g CO_2/MJ_{FUEL}, which translates into GHG reductions of 70% compared to fossil kerosene.

First of all, it is worth remembering that the emissions The emissions from the low productivity macaw route HEFA were estimated at 53.7 g CO_2/MJ_{FUEL} considering methane capture and 71.8 g CO_2/MJ_{FUEL} disregarding methane capture, both above the values established by CORSIA (37.4 g CO_2e/MJ_{FUEL} and 60g CO_2e/MJ_{FUEL}, respectively). On the other hand, emission estimates from the high-productivity macaw resulted in 35.52 g CO_{2e}/MJ_{FUEL} considering methane capture and 57.4 g CO_{2e}/MJ_{FUEL} without considering methane capture, lower than the values proposed by CORSIA (37.4G CO_2e/MJ_{FUEL} and 60 g CO_2e/MJ_{FUEL}, respectively. These differences are mainly in the agricultural phase of low-productivity macaw (38.3 g CO_2e/MJ_{FUEL}) and high productivity (20.1 g CO_2e/MJ_{FUEL}). They can be justified due to the difference between the number of agrochemicals used in each. In macaw cultivation with high productivity, the volumes of agrochemicals are lower due to the gains of scale. However, uncertainties and limited knowledge and applicability raise questions about the results of alternative aviation fuel routes using macaw.

At the fuel synthesis stage, it is notable that POME treatment is an important issue for calculating GHG emissions for macaw HEFA routes. Assuming that POME is treated in open ponds without gas capture systems, as is currently done in Brazil (AGROPALMA 2017), CO_2e emissions from this phase of low and high yield macaw HEFA can provide emission reductions of 40% and 60%, respectively, compared to fossil kerosene. No estimates of GHG emissions for jet fuel routes were found in the literature. Uncertainties and limited know-how and applicability, as discussed in previous sections, may explain this result.

Changes in soil carbon stocks due to land use change (LUC) are important in biobased life cycles. The main factors that alter CO_2 LUC emissions are changes in above- and below-ground carbon stocks and agricultural yields, arising mainly from soil management practices and seasonality of agricultural crops. These (soil) carbon variations are especially heterogeneous and can reduce or even negate the possible benefits related to replacing fossil fuels with alternative fuels (BAILIS and BAKA, 2010; MOREIRA et al., 2014; STRATTON et al., 2010; WONG, 2008).

In this context, land use change represents an important part of the life cycle of CO_2 emissions of a product, such as agriculturally based alternative aviation fuels. While alternative fuels are potential sources of energy security, they can also negatively impact ecosystem services. Therefore, direct LUC (dLUC) was included in the CO_2 emissions resulting from LCA, which addresses changes only within the assessed boundaries (ISO, 2018).

According to the different land use transition possibilities shown in this study, the total emissions of the ATJ sugarcane route obtained the following results, observed in Figure 13:

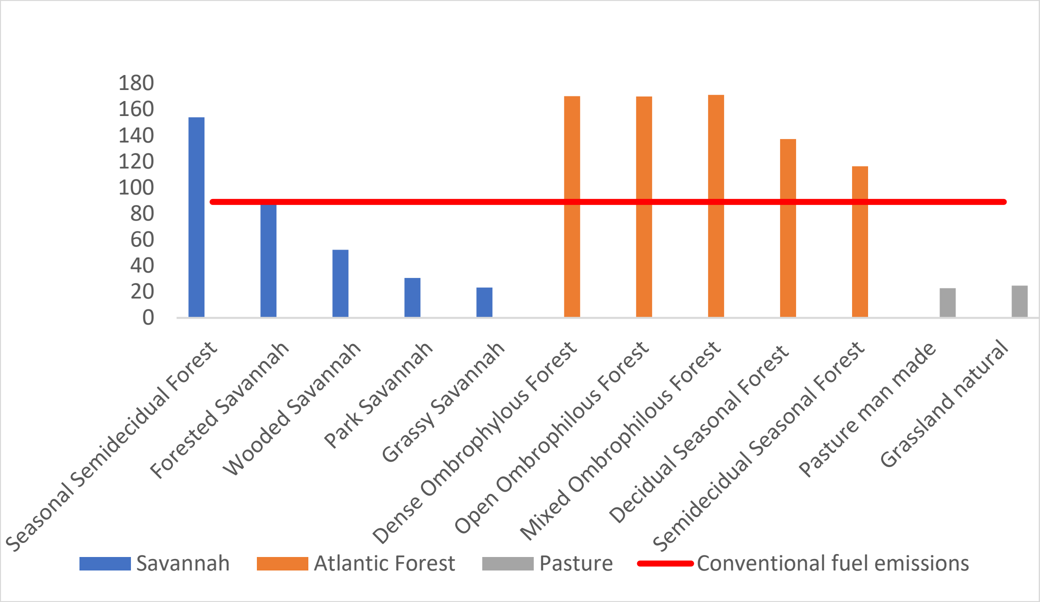

Figure 13- ATJ sugarcane overall GHG emissions (gCO_2e/MJ_{FUEL})
Source: Own elaboration.

As mentioned previously, the areas with the highest suitability for sugarcane cultivation are concentrated in the Cerrado, Atlantic Forest and pasture biomes. The largest emissions are concentrated in areas of semideciduous seasonal forest due to the fact that they are large carbon sinks. Therefore, converting these forest areas into cultivation areas can lead to mismatches in the carbon balance, making emissions much higher than normal (154 g CO_2e/MJ_{FUEL}). Thus, the emissions associated with this type of conversion are significantly higher than the emissions from conventional aviation fuel. However, in all other types of vegetation in the Cerrado biome, when converted, emissions become lower than conventional fuel emissions because they are areas of lower tree density such as the Grassy Savannah (23.2 g CO_2e/MJ_{FUEL}).

When conversions occur on Atlantic Forest soils, all total emissions, i.e., the sum of the attributional life cycle analysis and direct land use change, are above the value of fossil fuel emissions, ranging from 116.3 g CO_2e/MJ_{FUEL} and 170.2 g CO_2e/MJ_{FUEL}. In general, the Atlantic Forest biome is dominated by dense forests and therefore, the conversion of these areas into agricultural crops can not only unbalance the carbon balance but also bring harm to the functioning of ecosystems.

Finally, conversions to pasture have significantly lower emissions when compared to emissions from conventional fuels. In anthropized pastures the total emissions from the ATJ route of sugarcane can reach 22.8 g CO_2e/MJ_{FUEL} while in natural pastures these emissions can go up to 24.8 g CO_2e/MJ_{FUEL}.

The total emissions of the ATJ corn route obtained the following results, observed in Figure 14:

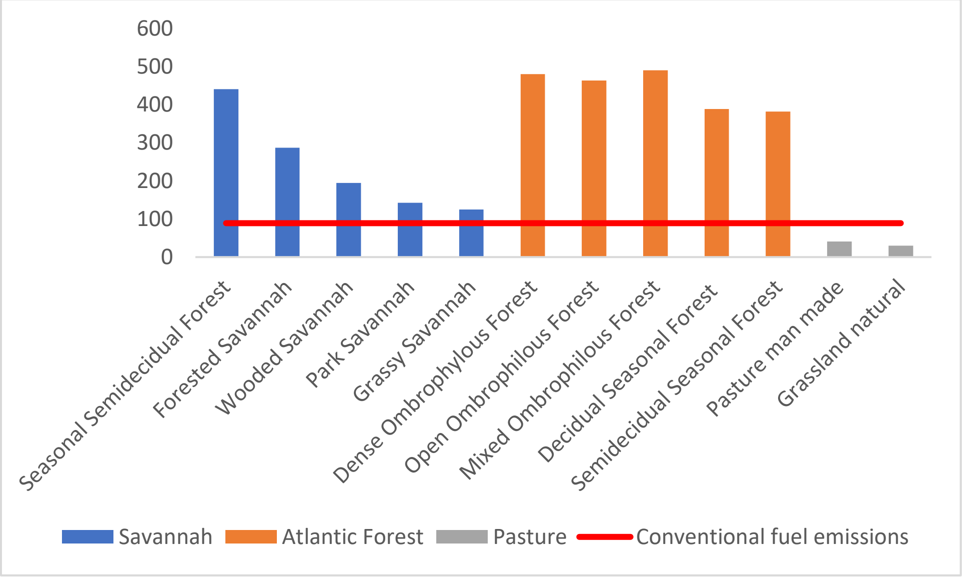

Figure 14-ATJ corn overall GHG emissions (gCO_2e/MJ_{FUEL})
Source: Own elaboration.

As mentioned previously, the areas with the greatest suitability for corn cultivation are concentrated in the Cerrado, Atlantic Forest and pasture biomes. The largest emissions are concentrated in areas of semideciduous seasonal forest due to the fact that they are large carbon sinks. Therefore, the conversion of these forest areas into crop areas can lead to mismatches in the carbon balance, making emissions much higher than normal, ranging from 125g CO_2e/MJ_{FUEL} in grassy savannah areas up to 441.3 g CO_2e/MJ_{FUEL}. Thus, the emissions associated with converting grassy savannah vegetation areas to corn growing areas are significantly higher than the emissions from conventional aviation fuel.

When conversions occur on Atlantic Forest soils, all total emissions, i.e., the sum of the attributional life cycle analysis and direct land use change, are above the value of fossil fuel emissions, ranging from 350 g CO_2e/MJ_{FUEL} to 480 g CO_2e/MJ_{FUEL}. In general, the Atlantic Forest biome is dominated by dense forests and, therefore, the conversion of these areas to agricultural crops can not only unbalance the carbon balance, but also bring damage to the functioning of ecosystems. It is worth mentioning that the Atlantic Forest biome has a large part of its vegetation under permanent environmental protection regime and therefore the conversion of these areas to any kind of crop is quite limited and may provide adverse effects to the maintenance and functioning of the ecosystems associated with it.

Finally, conversions to pasture have significantly lower emissions when compared to emissions from conventional fuels. In anthropized grasslands, total emissions from the ATJ corn route can reach 41.9 g CO_2e/MJ_{FUEL}, while in natural grasslands these emissions can reach 45.8 g CO_2e/MJ_{FUEL}, which means almost 50% less CO_2 emissions compared to fossil fuels.

The total emissions of the HEFA soja route obtained the following results, observed in Figure 15:

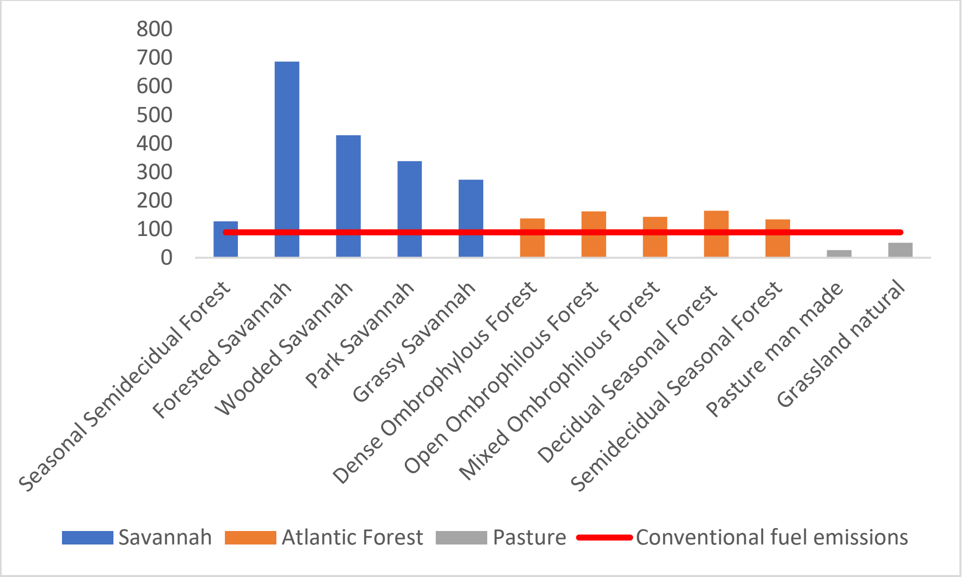

Figure 15-HEFA soybean overall GHG emissions (gCO_2e/MJ_{FUEL})
Source: Own elaboration.

As mentioned previously, the areas with the greatest suitability for soy cultivation are concentrated in the Cerrado, Atlantic Forest and pasture biomes. In the Cerrado biome, the largest emissions are concentrated in Forested Savannah areas due to the fact that they are large carbon sinks. Therefore, the conversion of these forested areas into cultivated areas can lead to imbalances in the carbon balance, making emissions much higher than normal, ranging from 127.6g CO_2e/MJ_{FUEL} to 704.1 g CO_2e/MJ_{FUEL} in vegetations present in the Cerrado. Thus, the emissions associated with the conversion of Cerrado vegetation areas to soybean cultivation areas are significantly higher than the emissions from conventional aviation fuel.

When conversions occur on Atlantic Forest soils, all total emissions, i.e., the sum of the attributional life cycle analysis and direct land use change, are above the value of fossil fuel emissions, ranging from 104.1 g CO_2e/MJ_{FUEL} to 137.8 g CO_2e/MJ_{FUEL}. In general, the Atlantic Forest biome is dominated by areas of high tree density and, therefore, the conversion of these areas into agricultural crops can not only unbalance the carbon balance, but also bring damage to the functioning of ecosystems. It is worth mentioning that the Atlantic Forest biome has a large part of its vegetation under permanent environmental protection regime and therefore the conversion of these areas to any kind of crop is quite limited and may provide adverse effects to the maintenance and functioning of the ecosystems associated with it.

Conversions to pasture have significantly lower emissions when compared to emissions from conventional fuels. In anthropized grasslands, total emissions from the HEFA soybean route can reach 26.3 g CO_2e/MJ_{FUEL}, while in natural grasslands these emissions can reach 27.3 g CO_2e/MJ_{FUEL}, which means about 70% less CO_2 emissions compared to fossil fuels.

The total emissions of the HEFA palm route obtained the following results, observed in Figure 16:

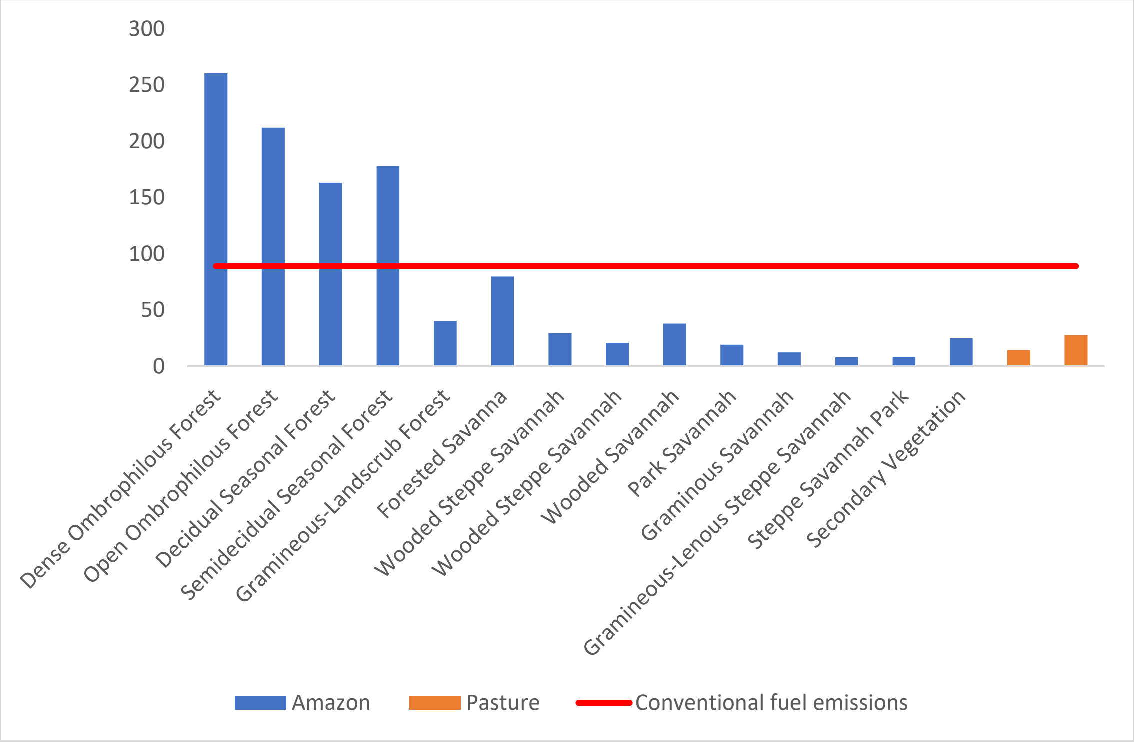

Figure 16-HEFA palm overall GHG emissions (gCO_2e/MJ_{FUEL})
Source: Own elaboration.

As previously mentioned, the areas with greatest suitability for oil palm cultivation are strictly present in the Amazon biome due to its soil and climate restrictions. Moreover, to keep a more conservative line, only the palm HEFA route emissions without methane capture were analyzed.

Because it is a crop commonly found in the Amazon, the sum of attributional life cycle emissions and direct land use change emissions is lower than that of fossil fuel in most cases. However, in areas of dense forests, such as Dense Ombrophilous Forest, emissions are significantly high (260.2 g CO_2e/MJ_{FUEL}).

Conversions to pasture have significantly lower emissions when compared to emissions from conventional fuels. In anthropized grasslands, total emissions from the oil palm HEFA route can reach 44.8 g CO_2e/MJ_{FUEL}, while in natural grasslands these emissions can reach 46.2 CO_2e/MJFUEL, which means about 50% less CO2 emissions compared to fossil fuels.

The total emissions of the HEFA macaw low productivity and high productivity route obtained the following results, observed in Figure 17 and Figure 18:

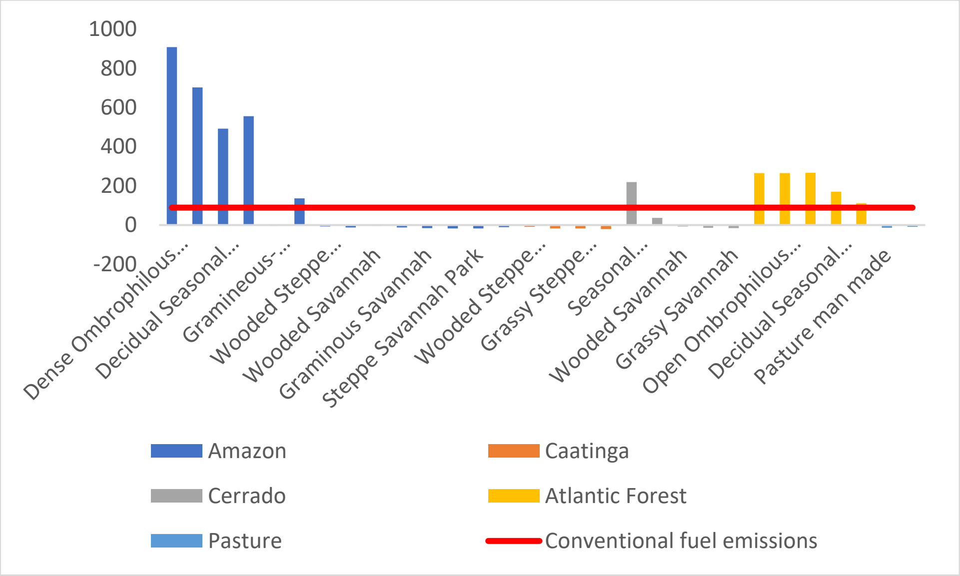

Figure 17-HEFA macaw low productivity overall GHG emissions (gCO_2e/MJ_{FUEL})
Source: Own elaboration.

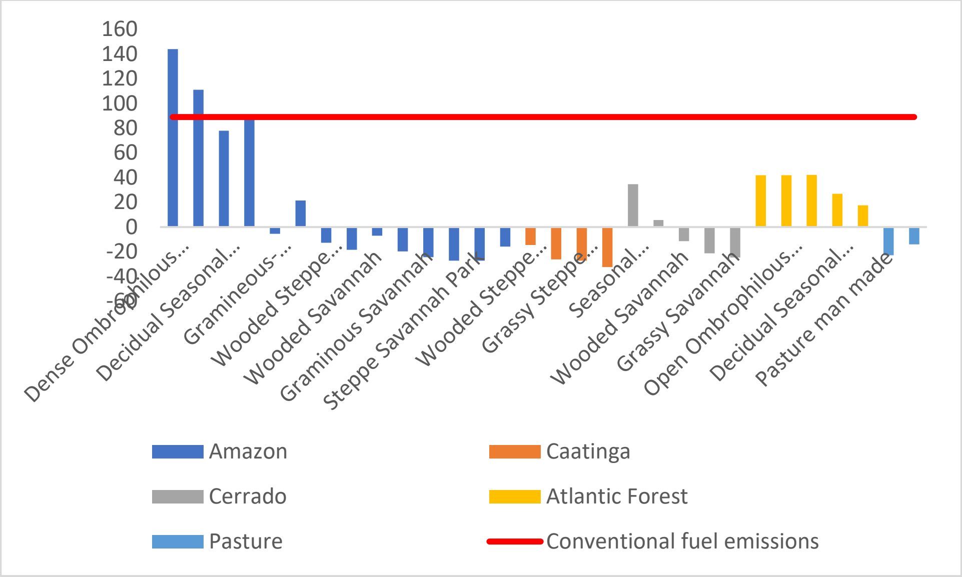

Figure 18-HEFA macaw high productivity overall GHG emissions (gCO2e/MJFUEL)
Source: Own elaboration.

The macaw easily adapts to different soil and climate conditions and therefore can be found in virtually all Brazilian biomes. For this study we did not consider the conversion of Pantanal vegetation areas to macaw because they are highly sensitive vegetation and are mostly environmental preservation areas. We also did not consider total emissions from land use changes in the Pampas, since the soils of this biome are not compatible with the soil and climate requirements of the macaw. Furthermore, to keep a more conservative line, only the emissions of the macaw HEFA pathway without methane capture were analyzed.

As with the palm HEFA pathway, the sum of attributional life cycle emissions with direct land use change emissions in vegetation of the Amazon biome for the macaw HEFA pathway is lower than for fossil fuel in most cases. However, in areas of dense forests, such as Dense Ombrophilous Forest, emissions are significantly high (908.7 and 143.9 g CO_2e/MJ_{FUEL} for low and high yielding macaw).

When conversions occur on Caatinga soils, all total emissions, i.e., the sum of the attributional life cycle analysis and the direct land use change, are below the value of fossil fuel emissions, ranging from 54.3 g CO_2e/MJ_{FUEL} to 62.7 g CO_2e/MJ_{FUEL} considering low productivity macaw cultivation and 25.9 g CO_2e/MJ_{FUEL} to 38.3 g CO_2e/MJ_{FUEL} considering high productivity macaw. In general, caatinga soils lack macronutrients and have a low efficiency of carbon uptake. Although the potential areas for the expansion of macaw cultivation, calculated from the premises present in this study, are not present in areas of Caatinga vegetation, the suitability of macaw in these areas already exists and is studied. It is worth remembering that the macaw is a new energy crop in the range of possible options for the production of alternative fuels and therefore data on this palm is still being adjusted by various corporate and academic institutions.

The Cerrado biome contains the most fertile soils for the cultivation of macaw, according to the studies of WALTER et al. (2020). As also stated before, due to lack of data compatibility, the present study only considered potential expansion areas of macaw cultivation available in the IBGE database from the year 2017. However, most of the total emissions from this route, considering land conversion in the Cerrado, fall below emissions from conventional fuels. For example, in the Wooded Savannah, Park Savannah and Grassy Savannah vegetations the emissions are around 64.7, 58.5 and 56.4 g CO_2e/MJ_{FUEL}, respectively, considering the low productivity of macaw and for the high productivity of macaw the emissions are around 42.4, 32 and 29.3 g CO_2e/MJ_{FUEL}, respectively.

In general, the Atlantic Forest biome is dominated by areas of high tree density and, therefore, the conversion of these areas into agricultural crops can not only unbalance the carbon balance, but also bring damage to the functioning of ecosystems. Although small areas in this biome, basically in the transition belt between Atlantic Forest and Cerrado, are very suitable for macaw, emissions are above emissions from fossil fuels because they are areas that store large volumes of CO_2. For example, in areas of Dense Ombrophylous

Forest these emissions can reach 336.8 g CO_2e/MJFUEL for low productivity macaw and 100.4 g CO_2e/MJ_{FUEL} considering high productivity macaw.

Conversions to pasture have significantly lower emissions when compared to emissions from conventional fuels. In anthropized grasslands, total emissions from the macaw HEFA route can reach 57.4 g CO_2e/MJ_{FUEL} and 31 g CO2e/MJ_{FUEL} for low and high productivity macaw respectively, while in natural grasslands these emissions can reach 63.1 CO2e/MJ_{FUEL} for low productivity macaw and 40g CO_2e/MJ_{FUEL} for low productivity macaw.

In light of the above, it can be seen that the routes with potential for certification in Brazil are: (i) ATJ of sugarcane when dLUC occurs in two types of Cerrado vegetation and in pastures; (ii) ATJ of corn when dLUC occurs only in pastures; (iii) HEFA of soybean with dLUC occurring only in pasture areas; (iv) palm HEFA with dLUC occurring in several vegetation areas of the Amazon Biome and in pasture areas; and (v) macaw HEFA in most vegetation areas of the Amazon Biome, all vegetation areas of the Caatinga, three vegetation areas of the Cerrado, and in pastures.

However, the present study did not consider an integrated analysis, i.e. conflicts with other land uses are not part of the analysis. It is important to highlight this because the growing global demand for agricultural crops has increased the concerns that agricultural expansion can bring, such as effects on biodiversity, imbalances in the carbon balance in forests, and competition with agricultural areas destined for the food sector. Although the major land use conflicts are associated with food production areas, the increasing use of traditional crops (such as sugarcane, corn and soy in the case of Brazil) represents a new source of incremental demand for the same products, but with new uses, making agribusiness increasingly complex as social demands increase.

6 Concluding remarks

This study sought to assess greenhouse gas emissions from aviation biofuel conversion routes in Brazil and to determine carbon dioxide emissions from direct land use change for different vegetation types in the country. In addition, the technical potential of alternative aviation fuel production for selected technological routes was analyzed. The crops considered to determine the feedstock potential were sugarcane, corn, soybeans, oil palm, and macaw. Among the different production routes available, the Alcohol-to-jet (ATJ) route and the (HEFA) route were chosen due to their technological maturity and approval by ASTM specifications. Next, their environmental performance was evaluated through a life cycle analysis performed in the SimaPro model.

The feedstock availability analysis revealed that the feedstocks are available in different areas of the country and have an energy potential of approximately 86,000TJ/yr, according to the assumptions established in this study. It is worth mentioning that this potential does not consider conflicts with other economic sectors, such as food and road fuels. Sugarcane biomass contributes 94% of the whole potential, followed by soy (2.8%), corn (1.5%) and palm (1.7%). Macaw's potential was null when applying the study constraints. The QGIS software was useful to evaluate the distribution of aviation biofuel in each municipality, from a radius of 100km away from consumption points (ports and airports) and fuel processing plants. The maps generated were useful to define the potential areas for alternative aviation fuel production. Their analysis revealed that the potential for sugarcane is concentrated in the Southeast region, for corn in the Midwest, for soybeans in the South and for palm oil in the North. The potential areas for macaw in this study were concentrated in the North of Brazil, but there are other studies estimating this potential in the Southeast and Center-West regions. Combining the results obtained in the analysis of feedstock availability confirms the potential for alternative aviation fuel production in Brazil, mainly in the Southeast and Midwest regions.

The aLCA performed in this study revealed important reductions in GHG emissions and fossil fuel consumption, since the alternative fuels evaluated showed considerable reductions. The best case was for the HEFA route from soybean biomass, with emissions of 20.1g CO_2/MJ_{FUEL}, which means a reduction of approximately 75% in GHG emissions compared to conventional aviation fuel. The low efficiency HEFA macaw route, disregarding methane capture, had the worst performance, emitting about 71.8 g CO_2/MJ_{FUEL}, amounting to a 20% reduction in GHG emissions compared to fossil fuels. These results were useful to confirm the advantages of alternative aviation fuel production in Brazil. However, important environmental indicators, such as impacts on biodiversity and water use, which could compromise the sustainability of these biofuels, were not considered.

From the results of dLUC emissions, it was possible to verify the potential areas of expansion of agricultural areas with emissions below the CORSIA default values. As mentioned throughout the study, the CORSIA default values refer to ILUC, this being a limiting factor in this analysis. Furthermore, in the case of pasture areas, only two was analyzed, the possibility of expansion of sugarcane agricultural areas from two vegetation types present in the Cerrado and in pastures was verified. The expansion of oil palm plantations can occur in ten vegetation types present in the Amazon biome and in pastures. For the macawthere are several possibilities, through ten vegetation types of the Amazon biome, in all the vegetation types existing in the Caatinga and in three different vegetation areas of the Cerrado and in pastures. For corn and soybean, the dLUC emissions were only below the values established by CORSIA when they occur in grasslands.

Finally, it is worth mentioning that all the routes analyzed here have production and certification potential when the expansion of crop areas takes place in pastures. The conversion of pasture into agricultural areas can improve ecosystem services and promote an increase in carbon stocks, contributing to the reduction of GHG emissions.

Total emissions (aLCA+dLUC) revealed that the following routes can be certified: (i) ATJ of sugarcane when dLUC occurs in two types of Cerrado vegetation and in pastures; (ii) ATJ of corn when dLUC occurs only in pastures; (iii) HEFA of soybean with dLUC occurring only in pasture areas; (iv) palm HEFA with dLUC occurring in several vegetation areas of the Amazon Biome and in pasture areas; and (v) macaw HEFA in most vegetation areas of the Amazon Biome, in all Caatinga vegetation areas, in three Cerrado vegetation areas, and in pastures.

However, technological and logistical challenges must be evaluated. Policy instruments, such as RenovaBio, are needed to help with these issues. In addition, uncertainties associated with land use change can also be reduced with the support of public funds, such as the ABC Plan, which encourages the expansion of agricultural crops on pasture.

Despite the efforts to conduct an accurate analysis of the potential areas for expansion of alternative aviation fuel production in Brazil, this study has limitations that should be reviewed in future work to increase the reliability of the results. First, the main limitation associated with the technical potential is that it was assessed from a sectoral perspective, i.e. competition from other uses, such as the food sector and the road transport sector, was not considered. In addition, the evaluation of the bioenergy potential of dedicated biomass was treated from the national average productivity and should be adjusted to the specific reality of each Brazilian municipality.

The bioenergy potential of macaw was assigned based on assumptions of productivity and planted area, due to the scarcity of data on this crop in large-scale and commercial plantations. The biomass transport distance of 100 km was considered, and should also be adjusted, since this distance may vary depending on the location of the hot spots of each crop in the country. Second, the limitations of the attributional life cycle analysis are that the input data refers to an average of values found in the literature and national statistics. In addition, the methodology for assigning the products and co-products in the SimaPro model may have influenced the results of the aLCA analysis. For example, in the synthesis of sugarcane intermediate fuel, bagasse was used as an energy source to feed the synthesis of alternative aviation fuel. Unlike the sugarcane ethanol synthesis, corn ethanol is not self-sufficient with respect to energy requirements and does not provide energy in the alternative aviation fuel synthesis. In the case of the HEFA soybean route, a fraction of the co-product was directed to animal feed. And in the case of the palm and macaw HEFA routes, the co-products were directed to the food and cosmetic sectors, respectively. And also, the aLCA allocations in this study were made on an energy basis and this may have influenced the results. Third, this study simulated only dLUC, not considering integrated modeling and indirect LUC. In addition, the input data regarding Tier 2 of the direct land use matrix, specifically the total biomass dedicated to carbon are national averages and should be adjusted to the reality and specificities of each Brazilian municipality. In addition, some factors such as legal restrictions on land use, biophysical constraints and economic feasibility were not considered in the dLUC CO2 emission estimates. These values should be adjusted taking into account the mentioned factors. Finally, the dLUC emission results of this study were compared to the default values regarding iLUC from CORSIA.

Finally, it is suggested for future work: (i) integrated modeling to analyze the bioenergy potential of Brazilian agricultural crops considering competition with other energy sectors; (ii) more detail on crop productivity; (iii) perform a life cycle analysis with different allocations to compare other results; (iv) evaluation of direct land use changes through integrated modeling; (v) evaluation of indirect land changes through computable general equilibrium or integrated process models.

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8 Annex

A1 – Emissions factors of carbon stocks before land use change:

Biomes	**Total Carbon (tonne/ha)**	
Amazon		Snif (2015)
Dense Ombrophilous Forest	252.47	
Open Ombrophilous Forest	212.19	
Decidual Sazonal Forest	171.24	
Semidecidual Sazonal Forest	183.62	
Gramineous-Landscrub Forest	68.64	
Forested Savanna	101.8	
Wooded Steppe Savannah	59.7	
Wooded Steppe Savannah	52.67	
Wooded Savannah	66.75	
Park Savannah	51.07	
Graminous Savannah	45.36	
Gramineous-Lenous Steppe Savannah	41.84	
Steppe Savannah Park	42.08	
Secondary Vegetation	55.95	
Caatinga		
Wooded Steppe Savannah	57.65	
Wooded Steppe Savannah	43.21	

Grassy Steppe Savannah	41.79	
Steppe Savannah Park	35.7	
Cerrado		
Seasonal Semidecidual Forest	118.01	
Forested Savannah	82.45	
Wooded Savannah	61.3	
Park Savannah	49.29	
Grassy Savannah	45.17	
Atlantic Rainforest		
Dense Ombrophylous Forest	127.02	
Open Ombrophilous Forest	126.91	
Mixed Ombrophilous Forest	127.48	
Decidual Seasonal Forest	108.59	
Semidecidual Seasonal Forest	97.04	
Pantanal		
Seasonal Semidecidual Forest	136.97	
Pampa		
Wooded Steppe	59.25	
Gramineous-Leny Steppe	57.86	
Pasture		
Pasture man made	47.2	NOVAES et al. (2020)
Grassland natural	58.3	

A2- Emissions factors of carbon stocks after land use change:

Biomassa (tC stock/ha)		
Sugarcane	44.7	NOVAES et al. (2017)
Arable (corn and soybean)	25.6	
Permanent crops (palm and macaw)	75.4	