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Sustainable aviation fuels must control induced land use change: an integrated assessment modelling exercise for Brazil

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Abstract

Bio-sustainable aviation fuels (bio-SAFs) are an important pillar of the aviation sector decarbonisation strategy in the mid-term. Here we assess the induced Land-Use Change (LUC) implications of producing bio-SAFs in Brazil under different assumptions of forest conservation governance. We evaluate four bio-SAF routes via two main pathways: the Alcohol-to-Jet (ATJ) and the Hydroprocessed Esters and Fatty Acids (HEFA) syntheses. We chose the most promising agriculture-based feedstocks to produce bio-SAFs in all five macro-regions of Brazil, including sugarcane and maize ethanol to jet and palm and macaw HEFA routes. To this end, we calculated future projections of air transport demand in Brazil and used the Brazilian Land Use and Energy Systems integrated assessment model to estimate LUC greenhouse gas (GHG) emissions within five different levels of bio-SAF blends (10% to 50% of total aviation fuel demand) for each bio-SAFs evaluated. Estimated cumulated emissions vary widely, ranging from a carbon sequestration of -286.8 $gCO_2e.MJ^{-1}$ for a 10% blend of maize ATJ under a controlled deforestation scenario to a release of 15.0 $gCO_2e.MJ^{-1}$ for a 40% blend of high productivity macaw oil HEFA considering historical deforestation rates in the country. Results are highly sensitive to deforestation rate parameters, volume of bio-SAFs produced, the type of feedstock used, and methodological assumptions. Negative LUC GHG emissions were found under controlled deforestation assumptions and in low blends of bio-SAFs for maize and sugarcane ATJ routes. Under historical deforestation rates, the LUC GHG emissions are higher. Bio-SAF can be beneficial to reduce GHG emissions if effective land conservation policies are implemented. Therefore, large-scale bio-SAF production from sugar crops in Brazil may play an important role in the decarbonisation of the aviation sector if coupled with successful strategies to control deforestation. Additionally, when imposing bio-SAF demand, other biofuels demand reduces under the model optimal solution due to land restrictions.

1. Introduction

The aviation sector is a hard-to-abate sector; i.e. its transition towards decarbonisation is not straightforward (IEA 2021b, Jaramillo *et al* 2022). Currently, the sector represents nearly 2% of total anthropogenic CO_2 emissions (approximately 1 $GtCO_2$ yearly) or 12% of total transportation emissions (ATAG 2020, IEA 2021a). By 2050, the total air travelling demand is predicted to increase almost twofold globally, especially in developing countries (Smyth and Pearce 2008, Gallet and Doucouliagos 2014, Valdes 2015, Suryan 2017, Ventura *et al* 2020). There are four key challenges to move towards a low carbon pathway in aviation: (a) heavy dependence on liquid fossil fuels (today 99% is fossil jet-A fuel), (b) long timescale infrastructure 'lock-ins', (c) accelerated growth of demand for air transport, and (d) absence of market-ready technologies capable of reducing greenhouse gas (GHG) emissions on a large scale (Sharmina *et al* 2020).

Although international aviation is not explicitly included in the Nationally Determined Contributions (NDCs) of parties under the Paris Agreement, the climate agenda and related pledges of major organisations in the aviation sector reflect the urgency for decarbonisation. Both the International Civil Aviation Organisation (ICAO) and the International Air Transport Association (IATA) have announced aspirational goals to reduce their GHG emissions. For instance, ICAO pledged to achieve a *carbon neutral growth* from 2020 by 2050 and the improvement in fuel efficiency of 2% p.a. Part of ICAO's aspirational strategy includes improvements in aircraft operations, developing new innovative technologies, and increasing use of sustainable aviation fuels (SAFs) (ICAO 2022a). Furthermore, ICAO created the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) to curb the aviation impact on climate change. Similarly, IATA has committed to half net CO_2 emissions by 2050 relative to 2005 levels (IATA 2021).

SAFs are, nowadays, an upfront mitigation option for the sector in the mid-term. SAFs include a low-carbon bio or synthetic aviation fuels produced from renewable or waste feedstocks that meet CORSIA sustainability criteria. As of 2022, 53 airports distributed SAF blends corresponding to 360 thousand commercial flights, and 31.7 billion litres are under offtake agreements (ICAO 2022c). The deployment of bio-SAFs to reduce GHG emissions is associated with the consumption of agriculture-based feedstocks (IRENA 2021), which need to be assessed through their entire life cycles, including induced Land-Use Change (LUC)[2]. Since bio-SAF may require large scale deployment of bioenergy plantations, this may induce potential conflicts with other sustainable development priorities (Calvin *et al* 2021, Portugal-Pereira and Muller-Casseres 2022) CORSIA has developed a certification mechanism specifying that bio-SAFs must ensure life cycle GHG emission savings greater than 10% compared to conventional jet-A fuel, including direct and indirect land use changes intensity factors after a variety of literature studies. (ICAO 2021, Prussi *et al* 2021).

Induced LUC emissions of bio-SAFs are those related to additional land to be used to produce fuel, including both direct LUC GHG emissions (where bio-SAF production is taking place) and indirect LUC in other locations due to the displacement of cultivations (ICAO 2022b). ICAO has evaluated the LUC GHG emissions intensity of 17 bio-SAF pathways in five major biofuels producers and major petroleum jet fuel consumers (ICAO 2021, Zhao *et al* 2021). Brazil was included in the assessment with five bio-SAF pathways, namely sugarcane alcohol-/ethanol-to-jet and synthetic iso-paraffin, and soy/carinata oil Hydroprocessed Esters and Fatty Acids (HEFA) pathways. Nevertheless, additional routes may also be suitable to support the CORSIA scheme in Brazil.

Past studies have assessed bio-SAF GHG intensity and its interactions with LUC dynamics. Specifically in the context of the CORSIA scheme, Zhao *et al* (2021) have applied the Computable General Equilibrium (CGE) model Global Trade Analysis Project - Biofuel (GTAP-BIO) to evaluate SAF pathways. Also, Havlík *et al* (2011) have used the spatially explicit Integrated Assessment Model (IAM) Global Biosphere Management Model (GLOBIOM) to evaluate the LUC impacts of biofuels expansion targets. However, as highlighted by Malins *et al* (2020), Daioglou *et al* (2020) and Ahlgren and Di Lucia (2014), most LUC studies rely in economic models, resulting in a larger variability of results due to the complex dynamics of land use and poor data quality, making it difficult to generalise results and support policymakers.

In this context, this paper aims to assess the LUC implications of bio-SAF pathways produced in Brazil additionally to the ones already presented in the CORSIA scheme. We evaluate four bio-SAF routes via two main pathways: the Alcohol-to-Jet (ATJ) and the HEFA syntheses. We chose the most promising agriculture-based feedstocks to produce bio-SAFs in Brazil, including sugarcane and maize (second harvest/winter harvest) ethanol to jet, and palm and macaw HEFA routes. To this end, the Brazilian Land Use and Energy Systems (BLUES) IAM model (Rochedo *et al* 2021; IPCC, 2022) is applied, given future projections of air transport demand in the country and the life cycle assessment of selected routes. The most significant advantage of using an IAM is understanding if imposed additional bio-SAF demand would induce LUC or other integrated impacts in the global sectors of the Brazilian economy.

The novelty of this study is fourfold: (a) we expanded the BLUES model, a national IAM, to include bio-SAF routes and different blends to estimate associated LUC GHG emissions; (b) we assessed LUC GHG emissions intensity of four additional bio-SAF routes in Brazil as a contribution to the ICAO's CORSIA scheme, (c) we evaluated the implications of deforestation in the overall land use dynamics, and (d) we analysed how the inclusion of additional biofuel demand changes the overall optimisation for other transportation sectors due to a higher demand of bio-SAF.

This paper proceeds with a brief description of applied methods, detailing the future demand of air transport projection, the techno-economic and environmental characterisation of the selected bio-SAFs,

[2] In this work, following ICAO (2022b) definition, induced Land-Use Change (LUC) includes both additional direct land to be used to produce fuel and indirect land-use change in other locations due to the displacement of cultivations.

the BLUES model framework, and the design of scenarios (section 2). Section 3 presents the results disaggregated by LUC GHG emissions intensity and changes in land use dynamics of evaluated scenarios. In section 4, the discussion of results focuses on the implications of large-scale bio-SAF expansion to land use highlighting key messages of the study, policy recommendations, knowledge gaps, and suggestions for future studies. Lastly, section 5 presents concluding remarks.

2. Analytical framework

To evaluate the LUC implications of bio-SAF expansion in Brazil, we followed a three-step methodological approach. Firstly, we estimated the fuel demand for the aviation sector in Brazil, considering both the domestic and international markets. Secondly, we developed a techno-economic and environmental characterisation of the sugar/starch ATJ and vegetable oil HEFA routes. Lastly, we applied the BLUES model to estimate the implications of bio-SAF expansion scenarios in terms of land use, GHG emissions, and LUC. The following subsections detail the adopted framework.

2.1. Aviation fuel demand in Brazil

The aviation fuel demand in Brazil was estimated using as input an exogenous demand for passenger and freight services, as well as aircraft fuel intensities projections from 2010 to 2050, with a 5 year time step (equation 1).

$$F_y = \frac{D_{\text{pax},y}}{I_{\text{pax},y}} + D_{\text{freight},y} I\text{freight}, y \tag{1}$$

where:

F_y = total fuel demand in PJ, for each year 'y'.

$D_{\text{pax},y}$ = exogenous demand for passenger aviation services, measured in RPK (revenue passenger-kilometre), for each year 'y'.

$D_{\text{freight},y}$ = exogenous demand for freight aviation services, measured in FTK (revenue freight-tonne-kilometre), for each year 'y'.

$I_{\text{pax},y}$ = passenger fuel burning intensity, i.e. how much passenger transportation service is delivered by how much energy of the fuel needs to be burned, measured in passenger*km/PJ, for each year 'y'.

$I_{\text{freight},y}$ = freight fuel burning intensity, i.e. how much freight transportation service is delivered by how much energy of the fuel needs to be burned, measured in revenue-freight-tonne*km/PJ, for each year 'y'.

The fuel burning intensities (I) are based on Brazil's total aviation kerosene consumption from the National Agency of Petroleum, Natural Gas, and Biofuels (ANP 2022), and a 1% increase per year is assumed up to 2050 (Grewe *et al* 2021).

The exogenous demand for aviation as a service (D) is estimated per region and flight market type (international or domestic) (equation (2)). For all flights, demand was equally divided by origin and destination

$$D_t = D_{t-1} * \varepsilon * \left(\frac{\text{GDP}_t - \text{GDP}_{t-1}}{\text{GDP}_t}\right) * \text{MOD} + 1 \tag{2}$$

where:

D_t = demand for aviation services, measured in RPK for passenger and FTK for freight. 't' stands for future values, while 't-1' represents past values. For the first timestep, the 't-1' values are the historical values obtained from the literature. For all other timesteps, 't-1' stands for the last projected values.

ε = demand-income elasticities, for passenger or freight aviation demand, for domestic or international markets.

GDP_t = gross domestic product for each region in each year 't'.

MOD = Covid-19 pandemic growth modifiers relatively to non-pandemic conditions. In this work, a 2 year impact was considered.

The national income-demand elasticities ε are calculated using linear regression through the Ordinary Least Squares method with a natural logarithm applied in historical data (Smyth and Pearce 2008, Ventura *et al* 2020). For GDP, data are collected from the Institute of Applied Economic Research (IPEA 2021) and the Brazilian Support Service for Micro and Small Enterprises (Data Sebrae 2021). GDP forecasts are based on Rochedo *et al* (2021) under assumptions of the shared socioeconomic pathway '*Middle* of the *Road* '(SSP2) (Fricko *et al* 2015).

The National Civil Aviation Agency (ANAC 2022) is used as the main database for aviation data in this study, which is needed throughout all calculations. Additional data used are kerosene density and lower heating values, which were assumed as 0.799 t m^{-3} and 43.51 MJ kg^{-1}, respectively (EPE 2021). Data from fuel burning intensities, GDP projections, and passenger and freight income-demand elasticities are reported in the Supplementary Material.

2.2. Bio-based sustainable aviation fuels pathways

This work evaluates four bio-SAF routes. As feedstocks, sugarcane and maize were selected for the ATJ route, while macaw and palm oils were chosen for the HEFA route. Sugarcane is a major crop widely available in Brazil and mainly used to produce ethanol fuel and sugar (Goldemberg 2006). Double-crop maize has recently been identified as a potential sustainable bioenergy crop, as it is cultivated off-season with soybeans (Silva and Castañeda-Ayarza 2021). Additionally, we evaluate palm and macaw oils as aspirational oily crops in Brazil. Palm is the most productive oilcrop and macaw is abundant in Brazil and a promising raw material for biofuels production in

Table 1. Technological description of SAF production routes.

ATJ	Feedstock Sugarcane, maize	Step 1 Extraction	Step 2 Enzymatic hydrolysis (required for maize only)	Step 3 Fermentation	Intermediate product Ethanol
	Intermediate product Ethanol	Step 4 Dehydration	Step 5 Oligomerisation	Step 6 Hydrogenation	Final products Naphtha, <u>aviation kerosene</u> and diesel
HEFA	Feedstock Palm, macaw	Step 1 Extraction	Step 2 —	Step 3 —	Intermediate product Vegetable oil
	Intermediate product Vegetable oil	Step 4 Hydrogenation	Step 5 Hydroisomerisation	Step 6 Hydrocracking	Final products Naphtha, <u>aviation kerosene</u> and diesel

Source: Own elaboration based on Nogueira *et al* (2008); Geleynse *et al* (2018); Pearlson (2011); Tao *et al* (2017).
Note: Table 1. Further technical details are provided in Supplementary Material (Tables SM6-SM9).

Cerrado (Souza *et al* 2017). Since macaw plantations in Brazil are still extractivist and there is high uncertainty related to its commercial exploitation (Souza *et al* 2017), we assumed a low productivity and a high productivity of macaw oil. The detailed techno-economic and environmental analyses of these four routes and parameterisation of key input variables are available in the Supplementary Material.

Bio-SAF routes produce a synthetic paraffinic kerosene (SPK) with similar composition and properties when compared to the paraffinic components of the jet-A fuel blend. Hence, bio-SAFs obtained through these alternative routes are classified as drop-in fuels. Currently, ATJ and HEFA fuels are certified by American Society for Testing Materials (ASTM) D7566—Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (ASTM 2021). Their technology Readiness Level is 9 (commercial) for HEFA-SPK and 6 (full-scale technical evaluation) for ATJ-SPK (Mawhood *et al* 2016, IRENA 2017). Their use in aircrafts is allowed in blends with conventional fuel up to a limit of 50% in volume fraction (IATA 2019, ICAO 2022c). Table 1 provides a general technological description of both pathways.

2.3. The BLUES model

The BLUES model is a processed-based IAM with least-cost optimisation and mixed-integer programming that assumes a long-term perfect foresight to 2050 with 5 year optimisation time steps. BLUES represents Brazil's five macro-regions and details conventional and new technologies from energy, and land use systems (Rochedo *et al* 2021, IAMC Wiki 2020; IPCC 2022). BLUES' decision dynamics are based on mathematical constraints representing a given climate policy, with additional constraints for deforestation based on historical data.

For the purpose of this paper is important to detail the land use dynamics of the model. Food demand is an exogenous variable that considers the increase in national demand and exports. Additionally, BLUES has an endogenous demand for bioenergy commodities. Therefore, the imposed bio-SAF demand will add another demand for land in the model, and the model must optimise the demands given for Brazil. These demands are fully addressed within the national territory. The LUC dynamics are intrinsically hard-linked to the overall optimal decision, i.e. change in energy demand and profile (related to climate policies) can result in land-use changes. The BLUES model has ten changeable land covers. Land-cover changes result from endogenous optimisation to supply all the endogenous and exogenous demands. Each land cover change is associated with costs and emissions, resulting from the difference in carbon storage above and belowground in land covers. Rochedo *et al* (2021), Köberle (2018) and Angelkorte (2019) further detail BLUES' LUC dynamics, and the supplementary material presents exogenous food- and energy-crop total demand.

2.4. Scenario design

To estimate the LUC associated with the expansion of bio-SAF production in Brazil, a set of fifty alternative scenarios and two reference scenarios was developed considering four bio-SAF routes, five ranges of blends and two trends of deforestation rates up to 2050 (figure 1). All scenarios considered no GHG budgets, i.e. the BLUES model has not assumed any caps on GHG emissions.

2.4.1. Bio-SAF demand

For each of the four bio-SAFs evaluated (see section 2.3), five different levels of bio-SAF blends were considered, ranging from 10% to 50% of total aviation fuel demand (see section 2.1). The combination of four bio-SAF routes and five levels of bio-SAF blends results in twenty-five scenarios. Additionally, these scenarios were compared against a reference scenario, in which no bio-SAF blends were considered.

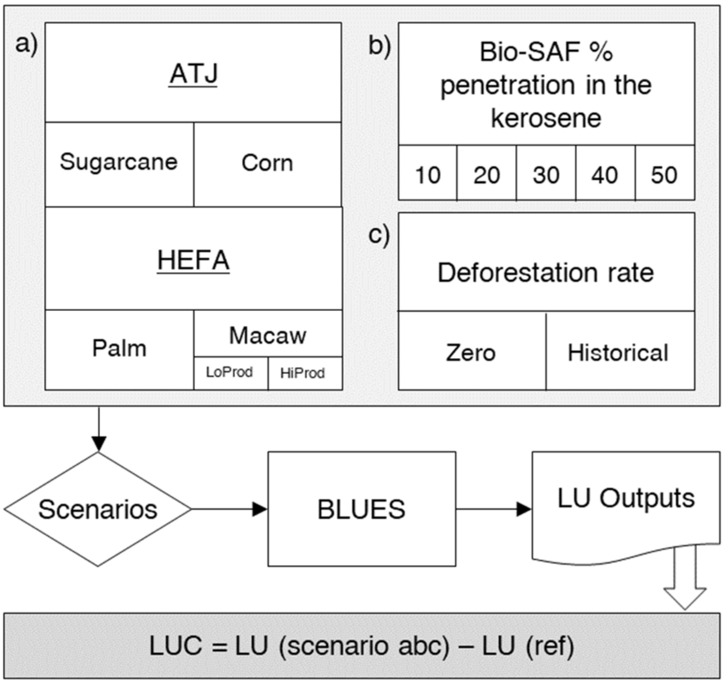

Figure 1. Framework of alternative scenarios used in the study. Scenarios are a combination of a b and c; (a) ATJ of HEFA route, (b) percentage Bio-SAF in the kerosene mixture, and (c) deforestation rates (either zero or historical).
Note: ATJ: alcohol to jet; HEFA: hydroprocessed esters and fatty acids; LUC: land use change; LUC: induced land use change.

2.4.2. Deforestation rate trajectories

Given the influence of deforestation in land use dynamics that may mask LUC GHGs associated with bio-SAF expansion, two trajectories for deforestation rates were investigated. One reference scenario considers deforestation rates in Brazil as constant from 2020 onwards according to the national historical data (2010–2020) (INPE 2021). Thus, under this reference scenario, the deforestation rate was assumed as 2.5 Mha p.a.$^{-1}$ up to 2050. We also considered a zero illegal deforestation scenario, reflecting the implementation of a set of current laws/policies as a premise. Under this scenario, Brazil's deforestation declines significantly and is eliminated by 2028. This is aligned with the Brazilian international pledge under the COP26 Deforestation Pact and Brazil's second NDC (GoB 2022). Thus, we also have scenarios that consider compliance with 2028 zero illegal deforestation commitment. Thereby, the 25 scenarios previously described were run with two different deforestation trajectories, one with current deforestation rates (Def) and another with zero deforestation in Brazil from 2028 onwards (ZeroDef). Thus, overall our analysis evaluates a total of 52 scenarios divided into two groups, and we have a set of scenarios that is more restrictive in terms of the availability of opening new cropland areas.

2.5. Induced LUC

To estimate the induced LUC GHG emissions of each scenario, we evaluated the difference between the land use of alternative and the reference scenarios. Therefore, we subtracted the LUC (dLUC + iLUC) GHG emissions from the reference scenario (zero bio-SAF penetration) from the other scenarios to estimate the LUC GHG emissions from different bio-SAF penetration scenarios. This is one of the outcomes of the BLUES model. Equations (3) and (4) show how the LUC was estimated based on the scenarios developed.

$$\mathrm{LUC}_{\mathrm{Scenario}(a,b,c)} = \mathrm{LU}_{\mathrm{Scenario}(a,b,c)} - \mathrm{LU}_{\mathrm{ref}(c)} \qquad (3)$$

Given that,

$$\mathrm{LUC}_{\mathrm{Scenario}(a,b,c)} = d\mathrm{LUC}_{\mathrm{Scenario}(a,b,c)} + i\mathrm{LUC}_{\mathrm{Scenario}(a,b,c)} \qquad (4)$$

where:

a is the bio-SAF technological route, *b* is the blend considered (10%–50%), and *c* is the deforestation rate considered.

The LUC GHG intensity is estimated based on the ratio of total cumulative GHG emissions from LUC the total cumulative bio-SAF demand (TBS) of each scenario, over the 25 year amortisation period, as adopted by ICAO CORSIA methodology to certify bio-SAFs (ICAO 2021, Zhao *et al* 2021) (equation (5)). As highlighted by Newell and Vos (2012), Nemecek *et al* (2019) and Maciel *et al* (2022), a dynamic time period to amortise LUC emissions should be applied to better reflect the complexity of carbon fluxes during land conversion processes. However, in order to compare our results with ICAO

CORSIA guidelines we opted to consider a uniform amortisation period of 25 years.

$$\text{LUC intensity}_{\text{Scenario}(abc)} = \frac{30 \cdot \text{LUC}_{\text{Scenario}\,(abc)}}{25 \cdot \text{TBS}_{(abc)}}. \quad (5)$$

3. Results

3.1. Aviation fuel demand

We estimated a total aviation fuel demand for Brazil of 535 PJ in 2050 (figure 2), corresponding to a 156% increase in relation to 2020. This estimation considers the economic and activity discrepancies related to the Covid-19 pandemic that reduce travel demand until 2025. The substitution of conventional jet-A fuel by bio-SAF blends from 10% to 50% would demand between 54–268 PJ of bio-SAFs.

3.2. Bio-SAF routes GHG induced land use emissions

Table 2 depicts the LUC GHG emissions estimated for the four technological routes with different blendings and under two premises of deforestation rates up to 2050. Results reveal a wide variation of LUC emissions across all evaluated scenarios, varying between −298.0 and 15.0 $gCO_2e.MJ^{-1}$. LUC GHG emissions are highly sensitive to deforestation rates that constrain land use dynamics. All scenarios considering the control of deforestation (ZeroDef) and reinforcement of land conservation practices indicate a negative LUC emissions intensity, suggesting a carbon sequestration potential due to the expansion of bio-SAFs. On the contrary, when historical deforestation rates (Def) were considered, LUC GHG emissions intensities are high and carbon sequestration only occurs for bio-SAF blended up to 20%, except for palm that occurs only 10%. Feedstock types and volume of produced bio-SAF are also key factors for LUC GHG emissions ranges. In general, scenarios with lower blends of bio-SAFs and zero illegal deforestation assumptions result in high levels of carbon sequestration. Figure 3 presents the cumulative land cover change between 2020 and 2050 for scenarios of controlled deforestation. To grow crops necessary for bio-SAF production these scenarios show conversion of degraded pastures (4–8 Mha) to crop plantations or integrated systems. However, historical deforestation rate scenarios with 30%–50% penetration of bio-SAF presented positive LUC GHG emissions, suggesting a release of carbon from land use change. These scenarios required an increase in cumulated deforestation. For example, scenarios of bio-SAF blends of 40%–50% from the HEFA route produced with a low productivity macaw presented an expansion of monoculture areas (11%–35% growth), and deforestation of 74.4–74.9 Mha, even with a conversion of 1–4 Mha of degraded pasture to crop areas. The only exception for the positive emissions with historical deforestation rates is ATJ from maize. Scenarios with ATJ from maize considered maize as a second harvest crop and resulted in negative LUC emissions.

Scenarios that considered zero deforestation (ZeroDef) after 2028 show that adding bio-SAF in the kerosene mixture could result in LUC negative emissions in relation to no bio-SAF. However, these scenarios projected that 20 Mha from natural vegetation would be suppressed until 2028. The negative emission peak is with 10% bio-SAF in the kerosene mixture and GHG removal reduces with bio-SAF penetration increase. Additionally, the scenarios with ATJ show more GHG removal than with HEFA. Sugarcane needed between 0.5 and 1 Mha of additional energy cropland to supply 10% and 20% of ATJ in the fossil jet fuel blend, respectively. To include HEFA in the kerosene, palm and macaw low productivity crop areas increase 15% and 35%, respectively, considering a 20% blend. When 50% of HEFA is supplied through low productivity macaw, the model shows a 0.6 Mha savannah suppression and reduces planted forest areas (1.7 Mha), in addition to convert 2.5 Mha of degraded pastures in Macaw plant.

Table 3 shows the total cropland area change between 2020–2050 in 10% and 50% bio-SAF penetration in Jet-A fuel blends. The model considers different productivity and cost values for agricultural production for the five macro-regions of Brazil. Considering that the model aims to minimise costs, it will always migrate to solutions with lower costs, which in some cases are the ones with the lowest GHG emissions. To accommodate the growing demand to produce bio-SAFs, results show a migration of food crop production to other regions and production systems with higher productivity. Initially, the production of crops destined for bio-SAF production is restricted to regions more favourable for its production: Brazil's Southeast for sugarcane, macaw (low productivity and high productivity), and maize, while the Midwest demonstrates advantages for second crop maize and Northeast region for palm production. When increasing the volume of bio-SAF production to supply blends of 40% and 50%, maize, sugarcane and palm cropland expands to less productive areas in the Northern and Midwestern regions of Brazil.

This dynamic of changes in agricultural production technologies and migration of crops between the BLUES' regions was one of the reasons for GHG emissions to be higher in the Def scenarios than in the ZeroDef scenario. Additionally, the Def scenarios had enough available areas for agricultural and bio-SAF production, due to deforestation (mainly in the North region). Nevertheless, the model

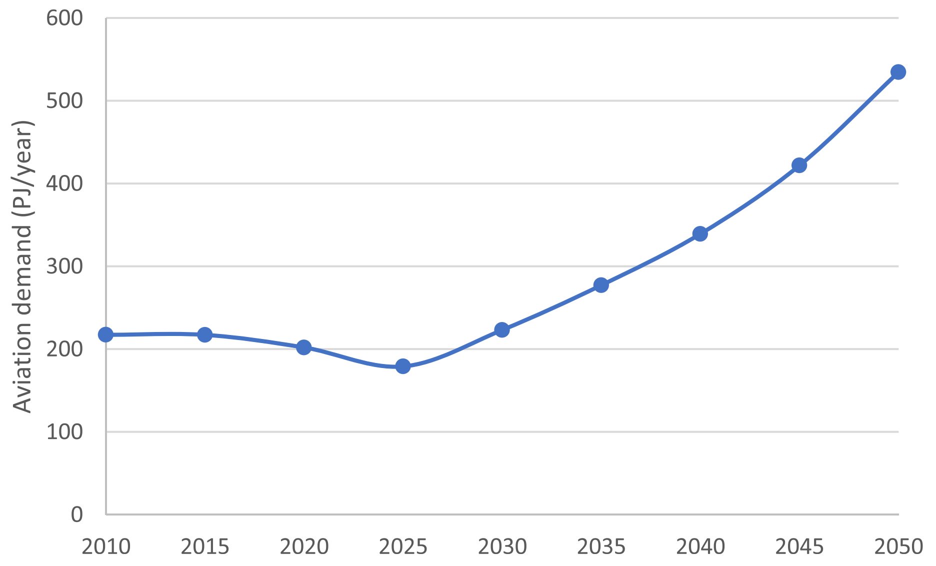

Figure 2. Total aviation fuel demand up to 2050 in Brazil.

Table 2. Cumulative LUC GHG emissions of the assessed scenarios (gCO_2e/MJ) in 2050.

Bio-SAF blends	Maize		Sugarcane		Palm		Macaw low productivity		Macaw high productivity	
	Def	ZeroDef	Def	ZeroDef	Def	ZeroDef	Def	ZeroDef	Def	ZeroDef
10%	−298.0	−286.8	−108.9	−186.9	−169.5	−125.0	−208.0	−170.7	−223.8	−196.8
20%	−74.5	−95.2	−13.7	−107.8	−22.0	−98.8	−3.8	−58.0	7.2	−43.1
30%	−48.9	−53.3	1.0	−36.6	5.4	−31.7	9.2	−34.0	12.5	−24.2
40%	−56.9	−64.0	−5.1	−33.7	3.8	−21.6	15.0	−18.8	10.3	−17.0
50%	−48.4	−37.4	0.2	−23.5	3.8	−13.7	10.4	−4.3	7.9	−13.6

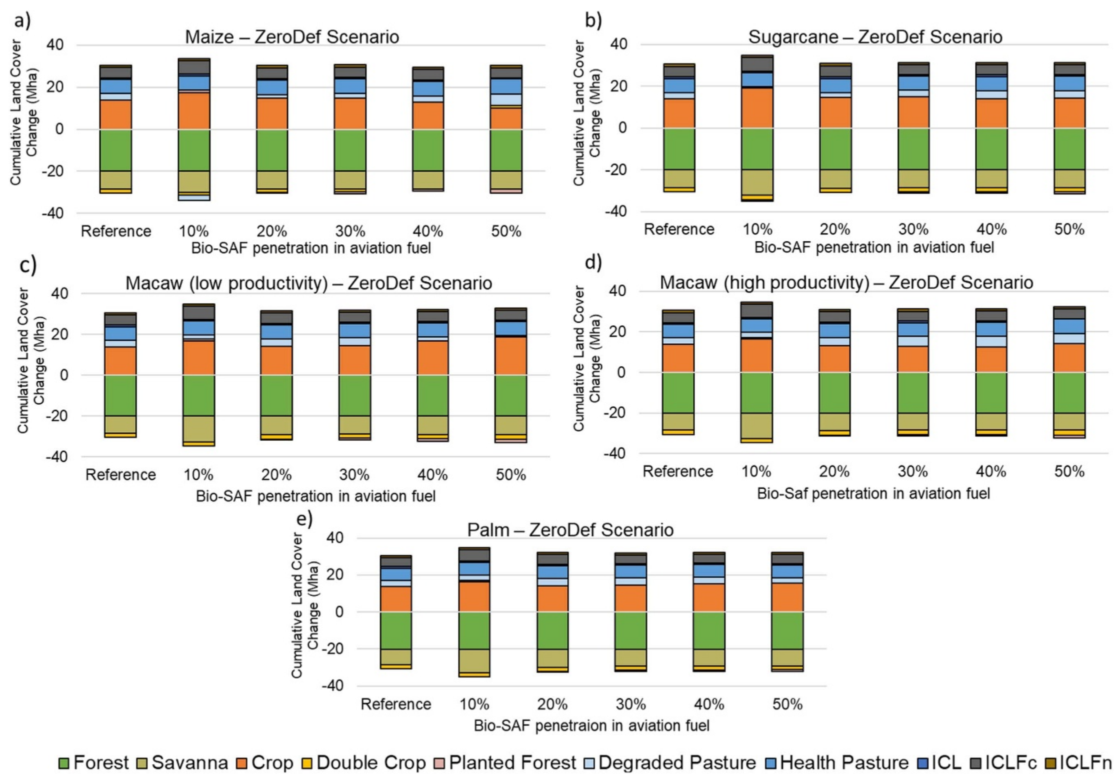

Figure 3. Cumulative land cover change between 2020 and 2050 for ZeroDef scenarios group. ICL—integration crop-livestock; ICLFc—integration crop-livestock-commercial forest (eucalyptus or pines); ICLFn—integration crop-livestock-native forest."

Table 3. Cropland area change between 2020–2050 in 10% and 50% bio-SAF in jet fuel blends.

Scenarios	Total cropland change between 2020-2050 Mha (SAF blend—%)	Crop area for bio-SAF in 2050 Mha (SAF—blend %)—ZeroDef
Sugarcane—ZeroDef	19.0(10% bio-SAF); 14.2(50% bio-SAF)	0.6(10%); 2.9 (50%)
Maize—ZeroDef	17.5(10% bio-SAF); 10.1(50% bio-SAF)	1.6(10%); 8.2 (50%)
Palm oil—ZeroDef	16.3(10% bio-SAF); 15.7(50% bio-SAF)	1.9(10%); 5.2 (50%)
Macaw oil—ZeroDef	Low productivity: 16.9(10%); 18.7(50%) High productivity:16.3 (10%); 14.2(50%)	Low productivity: 1.7(10%); 8.6 (50%) High productivity:0.3 (10%); 1.4 (50%)

optimises with increase agricultural areas in the Midwest, South and Southeast regions, resulting in additional deforestation since production in these regions is economically more viable. Thus, there is an increase between 0.1 and 0.6 in cumulated deforestation in the Def scenarios.

3.3. Changes in other sectors

When we impose bio-SAF demand to BLUES, it alters the optimal land use solution. The supply of bio-SAF from a determined production route modifies the use of the area where other agricultural goods were previously produced (food-crops and non-bio-SAF biofuels). Therefore, moving the previous production to other areas where their supply can become more expensive and less competitive, changing the optimal decision of the model in an integrated way. This will also change the integrated assessment of land use dynamics.

The use of IAMs allows for an early understanding of possible integrated impacts caused by adopting new sectoral climate policies, and the imposition of a bio-SAF demand changed the optimal results. Results show an unexpected reduction in the crop area change (2020–2050) in scenarios with higher bio-SAF blends (table 3). Those can be explained by (a) the reduction of other transportation biofuel demand in 2050 for the 50% blend scenarios compared to the 10% scenarios, and (b) the change in the share of other biofuels in the transportation sector. Given that biofuel demand is endogenous to the BLUES model and the ZeroDef scenario constrains the expansion of cropland, we observe a reduction of biofuel demand of 50% compared to the Def scenario (from 4 to 2 EJ). Additionally, in 50% bio-SAF scenarios, biodiesel participation (0.6 EJ $year^{-1}$) is larger than in 10% scenarios (0.1 EJ $year^{-1}$). On the other hand, bio-SAF blend scenarios project a greater share of ethanol (0.8–1.2 EJ) and green diesel (1.4 and 1.6 EJ). These fuel changes derive from a modification of the transportation and biofuel production sectors.

BLUES is an integrated hard-link assessment model, where all sectors are optimised together. The results show a direct cause-effect relationship between changes in the bio-SAF blends and the Agriculture, Forestry an Other Land Use (AFOLU) and transport sectors. In this context, mainly in ZeroDef scenarios, the increased bio-SAF demand resulted in increased mechanisation and chemical inputs in the agricultural sector. Thus, crop yields increase without a proportional increase in emissions. In the ZeroDef scenarios, there was a decrease in the demand for other biofuels in scenarios with high penetration of bio-SAF (50%). Since in ZeroDef, deforestation is not allowed after 2028, there is a greater restriction of areas available for bioenergy crops. Consequently, it is more economically feasible to increase the production of fossil fuels than biofuels.

4. Discussion

Bio-SAFs are an important pillar of the aviation sector decarbonisation strategy in the mid-term. Here we investigated the implications for LUC of four bio-SAFs routes in different blended scenarios in Brazil. We considered both ATJ and the HEFA routes. Since LUC can not be directly measured, we used a national IAM (the BLUES model) to investigate how different bio-SAF blends could impact LUC in Brazil under different assumptions of forest conservation governance.

To understand the potential LUC GHG emissions of different bio-SAF technologies in Brazil, our first step was to estimate the projected Brazilian demand of jet fuel up to 2050. Our projections suggest that by mid-century fossil jet demand will increase more than twofold due to rising air travel demand in the country. Although this finding is aligned with that of Zhao *et al* (2021), these authors did not account for the Covid-19 pandemic disruptions. The projected Brazilian demand for jet fuel is susceptible to several background assumptions (e.g. GDP, air travel elasticity, fleet typology of aircraft, geopolitics, and others). Aiming to deal with the uncertainty of SAF demand in the finished jet fuel blend, we opted to include a wide range of bio-SAF blends (between 10 and 50%) in our scenario design.

Given the projected future air transportation demand, we used the BLUES model to estimate the bio-SAF penetration of maize and sugarcane through the ATJ route and palm and macaw oils through HEFA route. Previously, the LUC from these routes were found to be 7.4 $gCO_2e.MJ^{-1}$ for sugarcane-ATJ route estimated with a CGE (Zhao *et al* 2021). In comparison, we found a wide range from −186.9

$gCO_2e.MJ^{-1}$ in the controlled deforestation and 10% blend scenario to 1.0 $gCO_2e.MJ^{-1}$ in the historical deforestation rates and 30% blend scenario.

The LUC estimations on those studies demonstrate the variability around the bio-SAF LUC, mainly related to the demand for fuels and previous uses of land. For this reason, an IAM is crucial to understanding which blends of bio-SAFs could reduce LUC and result in high carbon sequestration levels. The most significant advantage of using this methodological approach is to show the optimal result possible when considering different scenarios and understand the possible consequences of a new policy.

We investigated how bio-SAF demand could affect Brazil's land use. Scenarios with a lower blend of bio-SAFs present generally better climate benefits. We showed that a 10% bio-SAF blend for any of the four pathways analysed could result in GHG emission reductions. Furthermore, ATJ pathways appear to be better in terms of climate mitigation than HEFA pathways. Under low blends of bio-SAFs (10%–20%), degraded pasture areas could be converted to fulfil the required additional energy cropland. As degraded pastures have lower carbon content than cropland, this explains the negative GHG emission estimation in several scenarios considering lower biofuel penetrations.

There is an interesting variation in results from the group of scenarios considering current deforestation and the group that considers conservation commitments. Therefore, the assumed deforestation rate is another crucial driving force in relation to LUC from bio-SAF production. The exploration of two deforestation scenarios showed how deforestation reduction policies could also benefit the promotion of SAF. The zero-deforestation scenarios consistently demonstrated the possibility of producing SAF with GHG removal in terms of LUC. Most pathways analysed had LUC positive emissions from 30% penetration forward in scenarios without a zero deforestation policy. On the contrary, these pathways resulted in GHG removal when action is taken to protect natural vegetation. When natural vegetation is protected, the optimal solution is to recover degraded pasture to convert to energy crop plantations to produce bio-SAFs. Therefore, also promoting soil improvement and more sequestered carbon below ground.

Regarding policy implications, it is always important to highlight that in Brazil, the most critical action to reduce GHG emissions is to contain deforestation (e.g. Rochedo *et al* 2021). We added to this discussion by showing that even bio-SAF LUC sectorial emissions could be positively impacted by forest conservation. Furthermore, it is important to control deforestation independently of the legal amount allowed. Moreover, bio-SAF should be produced in available degraded areas in Brazil for better climate benefits. Moreover, any incentive to bio-SAF should consider consequences to other sectors, for example, providing additional incentives to the transportation sector to avoid delayed actions for decarbonisation in the road and maritime transport. Our study reinforces the need to implement integrated climate policies and shows that isolated sectoral mitigation measures in the aviation sector that are not supported by integrated policies in other sectors do not translate into effective emission reductions. Additionally, given the current difficulty associated with LUC estimations, the use of LUC GHG emissions intensities to support sustainability certification schemes is under debate. This is particularly relevant when considering the inconsistencies associated with the arbitrary definition of amortisation factors (Maciel *et al* 2022).

While there is a limited confidence level for absolute LUC factors, our study shows clear trends that reveal benefits for sugar ATJ routes, sustainable intensification practices and land conservation policies. Although results are not entirely comparable with CORSIA standards, we showed that it is possible to achieve considerable low-emissions bio-SAF production in Brazil mainly if deforestation rates are controlled. This means that production can be sustainable if environmental policies are enforced, but it does not mean that bio-SAF percentages in the jet fuel blends are certifiable once certification requires a ground audition, among other things. This is an important finding to assist Brazilian decision makers designing science-based policy to support the Paris Agreement temperature goals and the COP26 zero deforestation pledge.

This exploratory study presents limitations that should be further investigated in future works, namely:

(a) Air travel demand is dependent on price and service elasticities, sociocultural and behavioural patterns and modal shift factors that should be refined to estimate fossil fuel demand in Brazil;
(b) Other important demand inputs and parameters for scenario projection could influence overall results of LUC. For instance, different food-crop demands and distinct fuel prices could modify estimations of land pressure and fuel demand projections, respectively.
(c) LUC estimates could be evaluated with a global IAM model to verify impacts beyond the Brazilian national territory;
(d) Bio-SAF production routes are yet to be available at a commercial scale, and conversion yields should consider different technological curves and efficiency sensitivities;
(e) The BLUES model used in this study is a spatially implicit, least-cost optimisation model that aggregates results in five macro-regions in Brazil. Future studies could explore explicitly geospatial analyses with better granularity to identify hotspots of LUC emissions and

more accurate patterns and drivers of land-use changes;

(f) Land-use dynamics are complex and involved in multiple socioeconomic and cultural drivers that determine the pressure on land resources, which are not considered in this study. Further analyses, based on agent-based modelling could bridge this gap if linked with our in-house IAM model;

(g) LUC GHG intensity factors were estimated based on static GWP_{100} metrics, without considering the temperature and time factors that influence the global warming potential of GHG.

5. Concluding remarks

This study sought to evaluate the LUC GHG emissions intensity associated with the expansion of bio-SAFs from sugarcane and maize ATJ and palm and macaw oil HEFA routes in Brazil using a well-established national IAM, the BLUES model. The estimated LUC GHG emissions intensities vary widely, ranging from a carbon sequestration of—298.0 $gCO_2e.MJ^{-1}$ for a 10% blend of maize ATJ to a release of 15.0 $gCO_2e.MJ^{-1}$ for a 40% blend of high productivity macaw oil HEFA considering historical deforestation rates. Our results indicate a high sensitivity to the deforestation rate parameters, volume of bio-SAF produced and type of feedstock used. In general, LUC GHG emissions are negative, which suggests a potential carbon soil and feedstock sequestration, under controlled deforestation assumptions and in low blends of bio-SAFs for maize and sugarcane ATJ routes. On the other hand, under historical deforestation rates, LUC GHG emissions are mainly higher, indicating that large-scale production of bio-SAF is more beneficial to reduce GHG emissions if effective natural vegetation conservation policies are successfully implemented and reinforced. Consequently, this study reveals that without controlling deforestation bio-SAF blends above 20% will put more stress on the land-use sector and release GHG due to an increase of LUC. Therefore, large-scale bio-SAF production from sugary crops in Brazil only plays an important role in decarbonising the domestic aviation sector and supports the ICAO CORSIA if coupled with strategies to control successfully deforestation in Brazil.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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