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DOI
10.1016/j.jclepro.2019.05.145

Publication date
2019

Document Version
Final published version

Published in
Journal of Cleaner Production

Citation (APA)
Wang, Z., Pashaei Kamali, F., Osseweijer, P., & Posada, J. A. (2019). Socioeconomic effects of aviation biofuel production in Brazil: A scenarios-based Input-Output analysis. *Journal of Cleaner Production*, *230*, 1036-1050. https://doi.org/10.1016/j.jclepro.2019.05.145

Journal of Cleaner Production 230 (2019) 1036–1050

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Socioeconomic effects of aviation biofuel production in Brazil: A scenarios-based Input-Output analysis

Zhizhen Wang, Farahnaz Pashaei Kamali, Patricia Osseweijer, John A. Posada*

Department of Biotechnology, Delft University of Technology, van der Maasweg 9, 2629, HZ, Delft, the Netherlands

ARTICLE INFO

Article history:
Received 5 March 2019
Received in revised form
16 April 2019
Accepted 13 May 2019
Available online 16 May 2019

Keywords:
Sustainability
Socioeconomic effect
Aviation biofuel
Input-output analysis
Employment
Social development

ABSTRACT

Derived from renewable feedstocks, aviation biofuel is generally perceived as inherently sustainable. However, its production involves a wide range of sectors and interacts with different actors in society. It is therefore important to understand and evaluate not only the environmental impacts of that process, but also its socioeconomic effects. At present, empirical studies assessing socioeconomic aspects of aviation biofuel are rare in scientific literature. The aim of this study, therefore, is to assess key effects of aviation biofuel production on employment, GDP, and trade balance. A scenarios-based Input-Output (IO) analysis was used to evaluate these socioeconomic effects, taking Brazilian aviation biofuel production to 2050 as an example. To address the uncertainty of IO analysis, we have proposed a stochastic simulation approach for the technical coefficients in the IO model. Four distinct scenarios were developed. In each, three potential combinations of technologies and feedstocks for producing aviation biofuel were evaluated: sugarcane via alcohol to jet (ATJ), macauba via hydro-processed esters and fatty acids (HEFA), and eucalyptus via Fischer-Tropsch (FT). Among other things, we found that the production of aviation biofuel would create around 12,000–65,000 jobs, while contributing US$200-1100 million to Brazil's GDP under different scenarios with different supply chains. The socioeconomic effects calculated deterministically were generally higher than the stochastic outcomes, which can be explained by factors such as technological learning and economic growth. Aviation biofuel production showed large positive net socioeconomic effects on employment and GDP, although some of the fossil sectors would be negatively affected. Overall, the macauba-HEFA chain (with the highest effects on employment and GDP, and the lowest effects on imports) seemed to be the most favorable of the scenarios studied, despite the relatively high level of uncertainty associated with it.

1. Introduction

Driven by climate change and the price volatility of fossil fuels, the importance of renewable energy sources has been widely recognized. In particular, biofuels are considered as key contributors to greenhouse gas (GHG) emissions reduction in the transport sector (Chum et al., 2011; IEA, 2019). However, sustainability concerns have been raised around biofuel production, in such aspects as land use change, food insecurity, and biodiversity loss (Fritsche et al., 2010; Goldemberg et al., 2008; Janssen and Rutz, 2011). On the other hand, producing biofuels shows positive impacts on social development by providing employment and stimulating local economic growth (Phalan, 2009; van Eijck et al., 2014; Walter et al., 2011). Therefore, the overall impacts of biofuel production call for a full investigation into various aspects of its sustainability (Parada et al., 2017; Darda et al., 2018). This holds particularly true in the case of aviation biofuel, where new feedstocks are being studied, new conversion technologies are being developed, and new supply chains are being established.

As a relatively new member of the biofuel family, aviation biofuel has entered early commercialization stage. So far, commercial production of aviation biofuel has been achieved only via the hydro-processed esters and fatty acids pathway (ICAO, 2019). According to the International Air Transport Association (IATA, 2018), more than 150,000 commercial flights using aviation biofuel have been performed. Based on the announced International Civil Aviation Organization's offtake agreements (ICAO, 2019), the annual production volume of aviation biofuel for 2020 is expected to be about 0.45 Mt.

Derived from renewable feedstocks, aviation biofuel is generally

* Corresponding author.
E-mail address: J.A.PosadaDuque@tudelft.nl (J.A. Posada).

https://doi.org/10.1016/j.jclepro.2019.05.145

perceived as sustainable (Agusdinata et al., 2011; Li and Mupondwa, 2014), due to its potential in emissions reduction and energy security enhancement (Hileman and Stratton, 2014; IATA, 2013). However, only a limited number of studies have analyzed the sustainability effects (i.e., environmental, economic, and social dimensions) of aviation biofuel production. In particular, social or socioeconomic impacts have only been analyzed in a generic and conceptual manner without a systematic methodology for empirical assessment. As a result, most of studies in literature have focused on evaluating environmental impacts (Cox et al., 2014; de Jong et al., 2017; Han et al., 2013), technical feasibility (Tongpun et al., 2019; Tzanetis et al., 2017; Vyhmeister et al., 2018), and economic competitiveness (Lu, 2018; Rutten et al., 2017; Vyhmeister et al., 2018) of aviation biofuel, while none has addressed its social or socioeconomic aspects in depth, as noticed by Kamali et al. (2018).

Nonetheless, the social pillar of sustainability plays an important role for aviation biofuel's future development (Cremonez et al., 2015b; Hari et al., 2015; Moraes et al., 2014). In order to ensure a sustainable aviation biofuel production, it is imperative to first understand its potential socioeconomic effects in details (Parada et al., 2018). This requires an assessment that takes into account the specifics of context, production volume, conversion technology, and potential feedstock. Differences in these specifics between aviation biofuel and other biofuels (i.e., bioethanol and biodiesel) can have large effects on the resulting socioeconomic impacts. This is why a focused analysis of aviation biofuel is necessary. Such an in-depth assessment of socioeconomic effects can provide deepened insights into the prospective socioeconomic benefits or concerns associated with aviation biofuel. The generated context-specific knowledge can facilitate communication and decision-making around sustainable aviation biofuel production.

Hence, the objective of this study is to assess key socioeconomic effects related to aviation biofuel production on employment, GDP, and trade balance. Brazil was selected as case study in this analysis as it has been a front-runner in biofuel development since the 1970s, when the government introduced a scheme to promote sugarcane ethanol production. Apart from its successful experiences with bioethanol, the availability of land and benign climatic conditions can also potentially contribute to the establishment of aviation biofuel production. Locally produced aviation biofuel offers Brazil the opportunity to facilitate its fast growing aviation sector in a more sustainable way (AGROPOLO, 2016).

Using a scenarios-based Input-Output (IO) analysis, we assessed the socioeconomic effects of aviation biofuel production in Brazil for 2050 under different scenarios. Additionally, a stochastic simulation was carried out to understand the uncertainties associated with the IO model and shed light on the robustness of assessment results. Although stochastic simulation has been applied in other IO studies (Wiedmann et al., 2007; Wiedmann, 2009), this approach is scarce in empirical case studies (Lenzen et al., 2010). To the best of the authors' knowledge, there has been no case study in the field of socioeconomic assessment of biofuel supply chains that applied stochastic simulation to capture uncertainty in the resulting socioeconomic effects.

The contributions of this study are two-fold. We present the first systematic, in-depth, and empirical assessment of socioeconomic effects of aviation biofuel production, considering specific regions, feedstocks, technologies, and future scenarios. Furthermore, in the field of *ex-ante* socioeconomic sustainability assessment of biofuels, we are also the first to apply stochastic simulation (and the first to use parameters calculated from historical IO data rather than assumed ones) to capture the uncertainty associated with employment, GDP, and trade balance resulting from IO analysis. Overall, this study complements the current sustainability assessments of aviation biofuel (which are dominated by GHG emission and techno-economic feasibility analysis), and contributes not only towards a well-informed decision-making for aviation biofuel production but also to the development of systematic methods for empirical assessment of sustainability.

The remainder of this paper is organized as follows. Section 2 describes the methodology, including scenarios, IO analysis, and stochastic simulation. Section 3 represents the results and discussion of the socioeconomic effects. Section 4 discusses the limitations of this study. And lastly, Section 5 concludes.

2. Methodology

2.1. Methodological choices

The scope of this study covered the main phases of the aviation biofuel supply chain, including feedstock production, pretreatment (if needed), biofuel conversion, and transportation. The supply chains studied were expected to produce aviation biofuel for two major local airports, Guarulhos in São Paulo and Galeão in Rio de Janeiro. These are both located in the Southeast of Brazil and together account for around 45% of national jet fuel consumption (Cortez, 2014).

We applied a scenarios-based IO analysis to evaluate the socioeconomic effects of aviation biofuel production. Given the current stage of aviation biofuel development, the uncertainty associated with its production is relatively high in various respects: from demand for fuel to the selection of feedstock and conversion technology (Moncada et al., 2019). In this regard, scenario analysis was helpful to integrate uncertainties about different aspects and to amalgamate them into plausible futures (Kishita et al., 2017; Kowalski et al., 2009). To explore how possible futures of aviation biofuel in Brazil may unfold, we applied the exploratory scenario approach. This provides implicit and descriptive representations of alternative futures. The time horizon of our scenarios was set at 2050, which is the reference year for the targets laid down in many international policies concerning climate change and renewable energy.

IO analysis has been commonly used to measure socioeconomic effects on employment, GDP, and trade balance associated with biofuel production from a macroeconomic perspective (Martínez et al., 2013; Silalertruksa et al., 2012; Souza et al., 2018). Despite some inherent shortcomings of this method (see Section 2.4), IO analysis is able to isolate the effects on an economy caused by a particular economic activity.

2.2. Scenarios

2.2.1. Identify driving forces

The construction of scenarios is influenced by many factors, particularly in the case of aviation biofuel where available knowledge and data are limited. These are the driving forces of the diverging futures. In the Brazilian context, three key drivers were identified through a review of the drivers of aviation biofuel development and bioenergy/biofuel scenarios defined by existing studies, namely the growth of the aviation industry, aviation and general biofuel policies, and technological advancement.

2.2.1.1. Growth of the aviation industry. As a key driver, “growth of aviation industry” was relatively predictable across the scenarios' timeline. There is a shared consensus in a number of studies that the global aviation industry will continue to grow rapidly in the next few decades, due to economic and demographic growth (AGROPOLO, 2016; Cortez, 2014; Rosillo-Calle et al., 2012). We thus considered this driver as a predetermined factor, regardless of the scenario being investigated.

For the Brazilian aviation sector, an annual growth rate of 4.5% was forecasted (AGROPOLO, 2016). The efficiency improvement of aircraft was estimated at 1.5% annually (ICAO, 2016). Together these percentages resulted in a 3% net increase in national demand for aviation fuel, reaching about 17.7 million tons by 2050 based on a demand of 5.6 million tons in 2011 (AGROPOLO, 2016; Cortez, 2014). The two airports in our case study together consume 45% of Brazil's aviation fuel (Cortez, 2014), equivalent to 8 million tons a year. This total demand for aviation fuel remained constant in all the scenarios developed below.

2.2.1.2. Biofuel policies. Policies and regulations regarding bioenergy in general and aviation biofuel in particular are bound to play a key role in shaping the market and introducing aviation biofuel application on a large scale (Hagemann et al., 2016). Effective policy incentives (e.g., subsidies and tax deductions) could attract investment to the aviation biofuel industry, while at the same time spreading confidence in the transition from fossil to biobased fuels (Mulholland et al., 2017; Peters and Thielmann, 2008). In many cases, schemes targeting climate change mitigation and sustainable development are effective incentives for the development of biofuels (Dias et al., 2016; Hagemann et al., 2016). For instance, the National Alcohol Program in Brazil has played a positive role in promoting ethanol production and country-wide consumption. On the other hand, in the absence of specific measures energy policies might exert little influence on aviation biofuel development.

As well as environmental advantages, social benefits of biofuels such as job creation, social inclusion, and rural development have also been acknowledged by Brazilian policy makers (Cremonez et al., 2015c). Similarly, blend mandates for aviation biofuel, as an extension of Brazilian biofuel policies, could potentially be an instrument favored politically. So far, however, and regardless of its potential benefits, no blend mandate has been enforced for aviation fuel in Brazil.

2.2.1.3. Technological advancement. While a number of conversion technologies are currently being researched, most have not been put into full-scale production. In fact, only four main conversion pathways have been ASTM certified: *hydro-processed esters and fatty acids (HEFA), Fischer-Tropsch (FT), direct sugars to hydrocarbon (DSHC),* and *alcohol to jet (ATJ)* (Alves et al., 2016; de Jong et al., 2015; Mawhood et al., 2016). Understanding how advanced these technologies are offers an insight into the feasibility of each in future scenarios. The technological bottleneck not only constrains the upscaling of aviation biofuel production, it also results in uncompetitive pricing compared with fossil aviation fuel (Hagemann et al., 2016; Hari et al., 2015). Large-scale production of aviation biofuel still has a long way to go. A technological breakthrough is highly desirable in order to open up the market for aviation biofuel, as this would allow the utilization of a wider range of feedstocks while lowering production costs.

2.2.2. Develop scenarios

Based on expected aviation industry growth and the diverging trends in the other two driving forces (i) biofuel policies (proactive or conservative), and (ii) technological advancement (gradual or breakthrough) four scenarios were compiled, as shown in Fig. 1. The narrative of each alternative future was depicted using four variables, namely market share of aviation biofuel, conversion technology, selection of feedstock, and competition for biomass (as summarized in Table 1). Elaborated rationales for the scenarios developed can be found in the Supplementary Material.

Scenario 1: *"Low-Emission Flightpath".* Biofuel policies remain conservative for aviation, while conversion technologies see little innovation, rendering aviation biofuel commercially unappealing. This narrative results in low interest in producing aviation biofuel. Nevertheless, driven by strong commitment of the private sector to control emissions, aviation biofuel is expected to have a small share of the market by 2050. In line with the expected 3% net annual growth rate in demand for aviation fuel, it is assumed that 3% of that demand is supplied by biofuel. This amounts to 108 kt (based on the estimated total demand for aviation biofuel in Section 2.1.1). The aviation industry can thus expect to mitigate emissions growth by absorbing the net increase in the demand for fuel by means of biofuel. Due to technological constraints, the conversion of lignocellulosic biomass remains challenging. Only a mature supply chain is considered suitable for production. Since knowledge of macauba cultivation and processing in Brazil is not as established as knowledge of sugarcane, the sugarcane-ATJ chain is the only viable option in this scenario. Moreover, it is possible that aviation biofuel would need to compete for biomass resources with other biobased industries, potentially driving up the price of feedstock. Here, a 20% price increase for feedstock was assumed since detailed information on how biomass competition affects feedstock prices is not available.

Scenario 2: *"Go Bio".* The government recognizes the urgent necessity of emissions control for the fast-growing aviation industry. A biofuel blend mandate is in place and relevant policy incentives are provided. With technological development stagnated, however, it is still difficult to produce second-generation aviation biofuel on large scale. Regarding first-generation feedstocks, sugarcane is the primary crop facilitating Brazilian ethanol and sugar production. Producing aviation biofuel from sugarcane may therefore lead to competition for biomass with these industries. Nevertheless, the pressure of increasing sugarcane prices is likely to be eased by policy interventions such as subsidies on feedstocks or regulated expansion of sugarcane cultivation. Similarly, the government's proactive role promotes the cultivation of macauba, which is designated for producing aviation biofuel. In this case, competition for biomass can be considered negligible. As a result, the sugarcane-ATJ and the macauba-HEFA chains are both considered suitable for producing aviation biofuel.

In order to estimate the potential demand for aviation biofuel in this storyline, we turned to the World Energy Council's world energy scenarios analysis (WEC, 2016), in which three distinct scenarios are developed, complete with explicit projections for transportation fuel and the fractions taken up by biofuels. Given that literature on future demand for aviation biofuel under different technological or policy scenarios is limited, we consider the estimations in the WEC scenarios as the best available for our analysis. It is reasonable to assume that aviation biofuel in particular would follow a development trajectory similar to that for transportation biofuel in general. Scenario 2 in our study is comparable with the "Hard Rock" scenario proposed by the WEC, in which the main drivers are energy policies based on the local context in respect of energy security and sustainability issues, while technological advancement contributes very little. Consequently, aviation biofuel is assumed to substitute 8% (i.e., 288 kt; WEC, 2016) of conventional aviation fuel.

Scenario 3: ***"The Grand Leap"***. Proactive biofuel policies and technological breakthroughs go hand in hand, paving a promising pathway towards a sustainable aviation sector. Locality-specific policy plans are introduced, with executive measures to support biofuel production and local sustainability. An aviation biofuel blend mandate is backed by advanced technologies, including second-generation biofuel conversion. This contributes towards increasing the competitiveness of aviation biofuel, thereby fostering its smooth commercialization and rapid adoption. Hence,

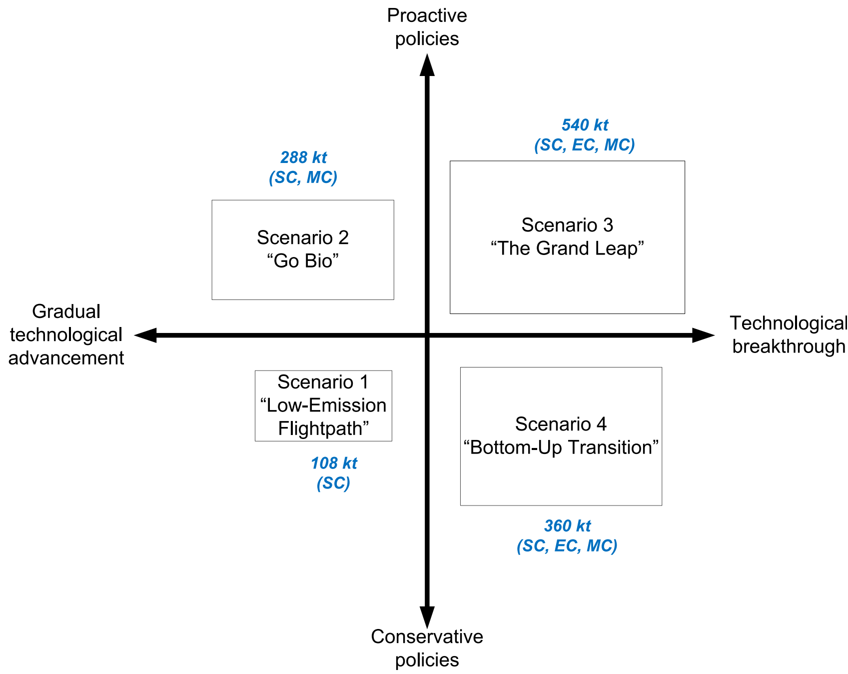

Fig. 1. Schematic presentation of scenarios for aviation biofuel development (SC: sugarcane, EC: eucalyptus, and MC: macauba).

Table 1
Summary of drivers and key variables in each scenario.

Scenarios	Narratives described with key features	
Scenario 1: "Low-Emission Flightpath"	Drivers	- Biofuel and climate policies remain conservative; - Technological advancement is gradual.
	Variable	- Market share of aviation biofuel is around 3%, i.e., 108 kt; - Candidate feedstock is sugarcane; - Aviation biofuel is produced via ATJ pathway; - Competition for biomass is expected and feedstock prices are driven up by 20%.
Scenario 2: "Go Bio"	Drivers	- Biofuel and climate policies are proactive and supportive; - Technological innovation is stagnated.
	Variable	- Market share of aviation biofuel is estimated to be 8%, i.e., 288 kt; - Candidate feedstocks are sugarcane and macauba; - Aviation biofuel is produced via ATJ and HEFA pathways, respectively; - Competition for biomass is expected, but feedstock prices stay stable due to supportive schemes.
Scenario 3: "The Grand Leap"	Drivers	- Biofuel and climate policies are proactive and enabling; - Technological advancement sees a breakthrough;
	Variable	- Market share of aviation biofuel reaches 15%, i.e., 540 kt; - Candidate feedstocks are sugarcane, macauba and eucalyptus; - Aviation biofuel is produced via ATJ, HEFA and FT pathways, respectively; - Competition for biomass is not expected and feedstock prices remain stable.
Scenario 4: "Bottom-Up Transition"	Drivers	- Biofuel and climate policies appear conservative; - Technological breakthrough is expected;
	Variable	- Market share of aviation biofuel is assumed to be 10%, i.e., 360 kt; - Candidate feedstocks are sugarcane, macauba and eucalyptus; - Aviation biofuel is produced via ATJ, HEFA and FT pathways, respectively; - Competition for biomass is foreseeable and feedstock prices increase by 10%.

the sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains are all considered viable for aviation biofuel production. No competition for biomass is anticipated in this case, regardless of the feedstocks concerned. Since the objective of its policies is to achieve quick adoption of aviation biofuel while improving local sustainability, the government is motivated to ensure the sustainable expansion of feedstock production. This is expected to stabilize feedstock prices. The market share of aviation biofuel in this scenario is comparable with that in the WEC's "Unfinished Symphony" scenario (WEC, 2016), in which governments take effective climate-change policy action while large-scale (renewable) energy integration is led by technological innovation, resulting in aviation biofuel accounting for 15% of demand (i.e., 540 kt).

Scenario 4: ***"Bottom-Up Transition"***. Policy support is limited as conservative policies reveal a reluctance to take risks and to promote aviation biofuel more ambitiously. On the other hand, research and development make significant progresses, enabling multiple conversion pathways and feedstocks for biofuel production. The private sector (biofuel companies and airlines) takes the lead in establishing a sustainable aviation biofuel supply chain. This has a positive impact on the market position of aviation biofuel. The sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains are all candidate supply chains, regardless of the possible competition for biomass resources. Here, a 10% price increase for the feedstocks is assumed due to biomass competition. Nonetheless, because of the positive market situation and the proactive private sector, the price increase in this case is lower than in Scenario 1. This scenario is comparable with the WEC's "Modern Jazz" scenario, which features market mechanisms and an energy landscape shaped by rapid technological innovation (WEC, 2016). Accordingly, aviation biofuel is expected to account for 10% of demand, equivalent to 360 kt.

Additionally, it is worth noting that producing aviation biofuel as a substitute for its fossil counterpart will likely induce a *displacement effect* (Lehr et al., 2008; Mukhopadhyay and Thomassin, 2011). This means, in simple terms, that the increase in demand for biofuel leads to less production of fossil fuels, thereby affecting the socioeconomic indicators of the sectors involved. Some of the socioeconomic effects related to fossil aviation fuel production might be displaced by the production of aviation biofuel. For example, whilst aviation biofuel production may create a large number of "green jobs", those originally producing the same amount of fossil aviation fuel could be lost. To shed light on this factor, we have investigated the *net* socioeconomic effects (using IO analysis) to account for the displacement effect.

2.3. Input-Output analysis

IO analysis is a technique commonly applied to evaluate macroeconomic effects resulting from a given (final demand) shock to the economic structure of a country (Miller and Blair, 2009). IO tables contain annual flows of products and services (in monetary terms) and represent the interdependence of different sectors in the economy. IO analysis can provide *ex-ante* estimations of macroeconomic effects related to new economic activities (producing aviation biofuel, in this case) on the national scale, which can then be translated into socioeconomic effects, namely employment, GDP, and trade balance (represented by imports, which inform us of the dependence of local aviation biofuel production on commodities produced outside the country), with the aid of the corresponding coefficients.

IO analysis was used in this study for two particular reasons: (i) because, due to the lack of data on actual aviation biofuel production, capturing the socioeconomic effects in a very precise way is challenging; and (ii) because IO analysis allows the evaluation of both direct and indirect effects in different economic sectors, thus enabling a relatively complete assessment of socioeconomic effects on both national and sectoral scales, directly and indirectly (Miller and Blair, 2009). The direct effects reflect the direct input requirements needed to produce the final demand for aviation biofuel, while the indirect effects reflect the intermediate inputs needed to fulfill intermediate production activities (Miller and Blair, 2009; Silalertruksa et al., 2012; Wicke et al., 2009).

The most recent version of the Brazilian IO tables, for the year 2010, include 67 industries and 110 commodities (IBGE, 2017). Since aviation biofuel is not specified in the IO tables, we consider its production as a new sector called "biojet", which can be added into the original IO model to help determine the macroeconomic effects of producing aviation biofuel, as described below.

The core of an IO model is the interindustry flows of products from each sector to each of all sectors (Miller and Blair, 2009). In monetary terms, the fundamental structure of an IO model is shown in Eq. (1):

$$\mathbf{X} = \mathbf{Z} + \mathbf{F}, \tag{1}$$

Where $\mathbf{X}$ represents total output of the economy, $\mathbf{Z}$ represents total interindustry transactions, and $\mathbf{F}$ represents total final demand. From here on, we use bold capital letters for matrices (e.g., $\mathbf{Z}$ in Eq. (1)), bold lower-case letters for column vectors (e.g., $\mathbf{z}$ in Eq. (6)), bold and italic lower-case letters for row vectors (e.g., $\boldsymbol{a}_{(n+1)}$ in Eq. (6)), *italic* lower-case letters for elements in corresponding matrices (e.g., z_{ij} in Eq. (2)), and Roman lower-case letters for values (e.g., $\mathrm{j_i}$ in Eq. (8)). Also, henceforth "input", "output", and "(final) demand" are all expressed in monetary terms.

Total output is the sum of total interindustry transactions and total final demand. One basic assumption of an IO model is that interindustry transactions are constant within a given timeframe, usually a year, and dependent on the total output within the same period (Allan, 2015; Miller and Blair, 2009). Thus, the interindustry transaction or intermediate transaction from sector i to sector j, denoted by a_{ij}, can be expressed in Eq. (2) as:

$$a_{ij} = \frac{z_{ij}}{x_j}, \tag{2}$$

where z_{ij} is the monetary value of products and services that sector j purchases from sector i in order to produce the total output x_j in of sector j. Here, a_{ij} is called a technical coefficient in IO models. For an economy with n sectors, the n × n matrix $\mathbf{A}$ consisting of all technical coefficients a_{ij} is called a technical coefficient matrix or technology matrix. The IO model can then be expressed by Eq. (3) as:

$$\mathbf{X} = \mathbf{AX} + \mathbf{F}. \tag{3}$$

Let $\mathbf{I}$ be the n × n identity matrix, meaning that the IO model can now be expressed by Eq. (4) as:

$$(\mathbf{I} - \mathbf{A})\mathbf{X} = \mathbf{F}. \tag{4}$$

It is clear now that IO models are demand driven, which is why the assessment of macroeconomic effects is determined by introducing a final demand change (or shock) to the model. To address the change in final demand, Eq. (4) can further be expressed by Eq. (5):

$$\Delta\mathbf{X} = (\mathbf{I} - \mathbf{A})^{-1}\Delta\mathbf{F}, \tag{5}$$

Where $(\mathbf{I} - \mathbf{A})^{-1}$ is also known as the "Leontief inverse matrix", $\Delta\mathbf{F}$ represents the change in final demand, and $\Delta\mathbf{X}$ represents the change in total (including direct and indirect) output in line with the change in final demand. The total output change can then be translated into socioeconomic effects on employment, GDP and imports with corresponding coefficients (Miller and Blair, 2009).

To analyze the macroeconomic effects attributed to aviation biofuel production, the new sector "biojet" is added into the original technology matrix $\mathbf{A}$ (Miller and Blair, 2009; Wicke et al., 2009), which then becomes $\mathbf{A}_{\mathrm{new}}$ in Eq. (6):

$$\mathbf{A_{new}} = \begin{bmatrix} \mathbf{A}^{*} & \mathbf{a_{new}} \\ \boldsymbol{a}_{(n+1)} & a_{(n+1)new} \end{bmatrix}, \tag{6}$$

where $\boldsymbol{a}_{(n+1)}$ is a row vector representing the inputs needed from the new sector to produce a unit of output by the original sectors. Here we assume that: (i) no input is required from the new sector to produce outputs by original sectors; and (ii) the addition of the new sector does not change the structure of the intermediate inputs to the original sectors. Matrix $\mathbf{A}^{*}$ is the new technology matrix of the original sectors. Further, $\mathbf{a_{new}}$ is a column vector of the newly added technical coefficients of the "biojet" sector. And $a_{(n+1)new}$ is the input from the new sector required to produce one unit of output of the new sector itself. In this case it is assumed that there is only one product in the "biojet" sector (i.e., aviation biofuel), and that no input is needed from the "biojet" sector to produce itself.

In short, the new technology matrix A_{new} was constructed by adding a new sector "biojet" to the original technology matrix A. This new sector was included as an additional column of its technical coefficients that represent the production of aviation biofuel. The new sector's technical coefficients were calculated with the inputs needed from the original sectors to produce one unit of output of the new sector. To distinguish different feedstock-based supply chains, different sets of the new technical coefficients of the "biojet" sector were added to construct different A_{new}.

Eq. (5) is now expressed as Eq. (7):

$$\Delta \mathbf{X_{new}} = (\mathbf{I} - \mathbf{A_{new}})^{-1} \Delta \mathbf{F_{new}}, \tag{7}$$

Where $\Delta\mathbf{X_{new}}$ is the change in total output and $\Delta\mathbf{F_{new}}$ is the change in final demand, which is in line with the estimated demands for aviation biofuel in the scenarios. Eq. (7) is now solvable, meaning that the change in total output $\Delta\mathbf{X_{new}}$ can be calculated. Here, $\Delta\mathbf{X_{new}}$ represents the total macroeconomic effects due to the new production activities in the "biojet" sector. Each element in $\Delta\mathbf{X_{new}}$ represents the total macroeconomic effects in each corresponding sector.

The direct macroeconomic effects are direct input requirements in sectors directly involved in producing aviation biofuel. These direct effects were determined by breaking down the production costs of aviation biofuel and then allocating them to the corresponding sectors. Next, the indirect macroeconomic effect in each sector was calculated by subtracting the sectoral direct effect from the sectoral total effect.

2.4. Link scenarios with socioeconomic effects

As a result of the scenarios, a demand for aviation biofuel production was projected for each scenario and also used to shock the IO model in the subsequent IO analysis .[1] In response to the final demand shock, the IO analysis simulated the change of total outputs in each sector, that is, the macroeconomic effects in each sector caused by aviation biofuel production with each supply chain. Subsequently, these sectoral macroeconomic effects were translated into the socioeconomic effects on employment, GDP, and imports, with the help of employment coefficients (number of jobs per million USD), GDP coefficients (million USD GDP per million USD output), and import coefficients (million USD imports per million USD output), respectively. For each sector, these employment, GDP, and import coefficients were calculated with the number of jobs, value of GDP, and value of imports in the concerned sector divided by the total output of this sector, using official data (Souza et al., 2018).

To provide an insight into the displacement effects caused by aviation biofuel production on the fossil jet fuel production, the *net* socioeconomic effects of each supply chain under each scenario were calculated. This was achieved by shocking the IO model with a net final demand, which was the difference between two demands: (i) the fraction of total demand for aviation fuel covered by of biofuel (as projected under each scenario in Section 2.2), with fossil fuel accounting for the remainder; and (ii) total demand for aviation fuel fulfilled entirely by fossil fuel.

[1] Note that for scenarios with multiple biofuel supply chains, demand was fulfilled by each supply chain individually. No mix or combination of multiple supply chains was considered. In other words, the model considers only on supply chain at a time. For example, in Scenario 3 the demand for 540 kt of aviation biofuel was expected to be met solely by either the sugarcane-ATJ chain, the eucalyptus-FT chain, or the macauba-HEFA chain.

2.5. Uncertainty analysis

Although IO analysis is useful for estimating socioeconomic effects, the method has certain inherent drawbacks as elaborated and discussed in several notable studies (Allan, 2015; Miller and Blair, 2009; Wicke et al., 2009). One of the main drawbacks is the assumed constant return to scale (Allan, 2015; Miller and Blair, 2009). Since IO models are linear, the calculated economic effects are proportional to the demand shock regardless of the scale of that shock. This means that IO models do not consider price fluctuations and market mechanisms. Another drawback lies in the time-lag between the year of assessment and the year of the latest available IO table. The underlying assumption here is that the economic structure and the interdependence of different sectors stay constant over time. However, it is unclear how suitable the "old" IO table is to assess the "new" economic activities. These shortcomings of IO models are reflected in the fixed technical coefficients, which are important sources of uncertainties in the model outcomes. Ignoring these uncertainties may lead to inaccurate estimation, and hence to ill-informed decision-making. In order to understand how robust and reliable our results are, we therefore examined the uncertainty of our IO analysis by means of stochastic simulation. Specifically, a Monte Carlo (MC) simulation was performed for all technical coefficients (a_{ij}) in the IO matrix. The MC approach allows stochastic analysis of variables based on their distributions, and provides probability distribution for the model outcomes (Lenzen et al., 2010; Wilting, 2012; Yamakawa and Peters, 2009).

The uncertainty analysis started with a reorganization of the IO tables for different years. Time-series data regarding technical coefficients was obtained from Brazilian IO tables for previous years (i.e., 2010, 2005, 2000, 1996, 1995, 1994, 1993, 1992, 1991, and 1990). However, the sectoral structure in the different IO tables varies. Specifically, the 2010 tables contains 67 sectors; the 2005 and 2000 tables contain 55 sectors; and the 1996, 1995, 1994, 1993, 1992, 1991, and 1990 tables contain 43 sectors. Bearing in mind that the sectors were structured and aggregated differently throughout the years, we prepared the data as follows. Based on the IO table summarizing the intermediate transactions on the "product-to-sector" level, it was clear how much of each product in sector i was needed to produce the total output of sector j. We reorganized the sectors (by aggregating/disaggregating them) according to the product-sector compositions referred to in the 2010 table (the latest version containing such information). The interindustry transactions were reorganized, and then the corresponding technical coefficients were recalculated based on Eq. (2). Ideally, this would lead to a 67*67 technology matrix containing 4489 technical coefficients, each of which would have a data-input set consisting of ten historical coefficients from different years. Due to technological and economic developments over time, however, some relatively new sectors were not represented in IO tables before 2010. In these cases, the technical coefficients had less than ten historical coefficients. As a result, 3011 technical coefficients in the reorganized technology matrix did have ten historical coefficients, whilst 776 had three and 702 had one. Due to the limited amount of data available for each technical coefficient, testing for distribution was not feasible. Nevertheless, normal distribution was assumed for the technical coefficients with ten or three historical coefficients. We calculated the mean value and the standard deviation as the input parameters for MC simulation. For the technical coefficients with one historical coefficient, no distribution type was assumed. These technical coefficients stayed unchanged during the MC simulation. The calculated parameters were then used as inputs to run an MC simulation with 5000 iterations. The stochastic simulation was implemented in the software MATLAB© R2017b.

The calculation time of the simulation was about 105 s for 5000 iterations. The distributions of all simulated outcomes were thus obtained, which offered us insights into the uncertainty associated with technical coefficients and the robustness of the outcomes. Specifically, the mean values and the standard deviations around the outcomes of the simulation were calculated. In addition, the 95% confidence intervals were calculated with Student's t distribution (with t value of 1.96) and the standard deviation (of stochastic outcomes).

2.6. Data inputs and basic assumptions

Initially, three potential supply chains for aviation biofuel production were selected for the Brazilian context, namely the sugarcane-ATJ chain, the eucalyptus-FT chain, and the macauba-HEFA chain. The sugarcane fields were assumed to be located in São Paulo, while for eucalyptus and macauba the fields were expected to be located in Minas Gerais. The biorefineries were assumed to be located at the feedstock cultivation sites, for economic and environmental reasons. Each supply chain started with feedstock production, followed by transport to the biorefinery where pretreatment (if needed) and conversion took place. The produced aviation biofuel was then transported to the two airports. Average distances of 10 km, 150 km, and 570 km were assumed for the transportation of feedstock to biorefinery, aviation biofuel to Guarulhos Airport, and aviation biofuel to Galeao Airport, respectively (Santos et al., 2017). The production costs in each supply chain were derived from the studies by Alves et al. (2016) and Santos et al. (2017), which contain comprehensive techno-economic analyses of aviation biofuel production in Brazil. The breakdown of production costs (in monetary values) were converted to USD_{2010}. The inventory production costs for different supply chains are presented in Table S1 and Table S2 in the Supplementary Material. Various versions of IO tables were obtained from the Brazilian Institute of Geography and Statistics IBGE (2017). Sectoral data on employment, GDP, and imports were derived from IBGE (2017) and the Ministry of Labour and Employment (MTE, 2017).

3. Results and discussion

3.1. Socioeconomic effects

3.1.1. Total effects on employment, GDP, and imports

The calculated socioeconomic effects increase with the estimated demand for aviation biofuel under the different scenarios. Table 2 shows that the largest number of jobs is generated in Scenario 3 55,840–65,037 in all, taking all the different supply chains into consideration , followed by Scenario 4 (38,363–44,740 jobs) and Scenario 2 (29,781–34,686 jobs). Relatively low levels of employment are created in Scenario 1, with 11,850 jobs contributed by the sugarcane-ATJ chain alone (the number here is a single value rather a range, as only one supply chain is considered viable in this scenario). Similarly, in respect of GDP Scenario 3 contributes US$1044-1087 million to national GDP. This is 47–48%, 46–47%, and 382% higher than those in Scenario 4, Scenario 2, and Scenario 1, respectively. The import requirements in Scenario 3 equal to US$280–374 million, higher than those in Scenario 4, Scenario 2, and Scenario 1 by 32–33%, 46–47%, and 389%, respectively.

Scenario 3 therefore has the greatest effects in terms of increasing employment, GDP, and imports, suggesting that proactive biofuel policies and advanced technologies lead to the most pronounced socioeconomic effects. The results also indicate that when policies shift from conservative towards proactive and technological advancement moves from gradual towards a breakthrough, not only do the socioeconomic effects increase but more feedstocks and technologies become available for producing aviation biofuel.

3.1.2. Direct and indirect effects

Breaking down the socioeconomic effects by type (direct and indirect) shows that indirect effects make a larger contribution towards total employment and total GDP in all scenarios. This suggests that the production of aviation biofuel could positively stimulate economic activities in its supporting sectors, especially trade, as shown in Fig. 2 and Fig. 3. These stimulated supporting sectors are important, as their outputs are the intermediate inputs required by the direct sectors. On the other hand, the direct employment and GDP effects are concentrated predominately in the feedstock sectors. This is due to (i) the large amount of biomass needed as raw material for aviation biofuel production, and (ii) the labor-intensive nature of these sectors. By comparison, the majority of import effects are associated with the chemicals sector, directly and indirectly, meaning that producing aviation biofuel would be highly dependent on chemicals produced outside the country.

3.1.3. Supply chains

Regardless of scenarios, the macauba-HEFA chain leads to the highest level of employment creation greater than both the eucalyptus–FT chain (by 15–16%) and the sugarcane-ATJ chain (by 16–17%). Similar patterns are observed for GDP, where the macauba-HEFA chain results in larger effects than either the eucalyptus–FT chain or the sugarcane-ATJ chain by 1–2% or 3–4%, respectively. By contrast, the largest import effects are found in the sugarcane-ATJ chain: 31–32% higher than those in the eucalyptus-FT chain and 33–34% higher than those in the macauba-HEFA

Table 2
Summary of total effects of aviation biofuel production on employment, GDP, and imports.

Socioeconomic effects	Employment (Number of jobs)				GDP (Million US$)				Imports (Million US$)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Sugarcane-ATJ chain												
Total	11850	29781	55840	38363	216.52	556.72	1043.86	708.81	76.59	199.75	374.54	252.49
Direct	4626	11014	20652	14594	70.23	176.40	330.75	227.29	33.61	88.97	166.83	111.62
Indirect	7224	18767	35188	23769	146.29	380.32	713.10	481.82	42.98	110.78	207.71	140.87
Macauba-HEFA chain												
Total	N.A.	34686	65037	44740	N.A.	579.57	1086.69	736.06	N.A.	149.51	280.32	188.34
Direct	N.A.	15946	29898	21199	N.A.	220.12	412.73	285.56	N.A.	67.59	126.74	85.78
Indirect	N.A.	18741	35139	23540	N.A.	359.45	673.96	450.50	N.A.	81.92	153.58	102.56
Eucalyptus-FT chain												
Total	N.A.	N.A.	56634	38464	N.A.	N.A.	1069.70	719.07	N.A.	N.A.	284.58	190.47
Direct	N.A.	N.A.	21000	14649	N.A.	N.A.	364.03	248.02	N.A.	N.A.	122.63	82.42
Indirect	N.A.	N.A.	35634	23815	N.A.	N.A.	705.67	471.06	N.A.	N.A.	161.95	108.05

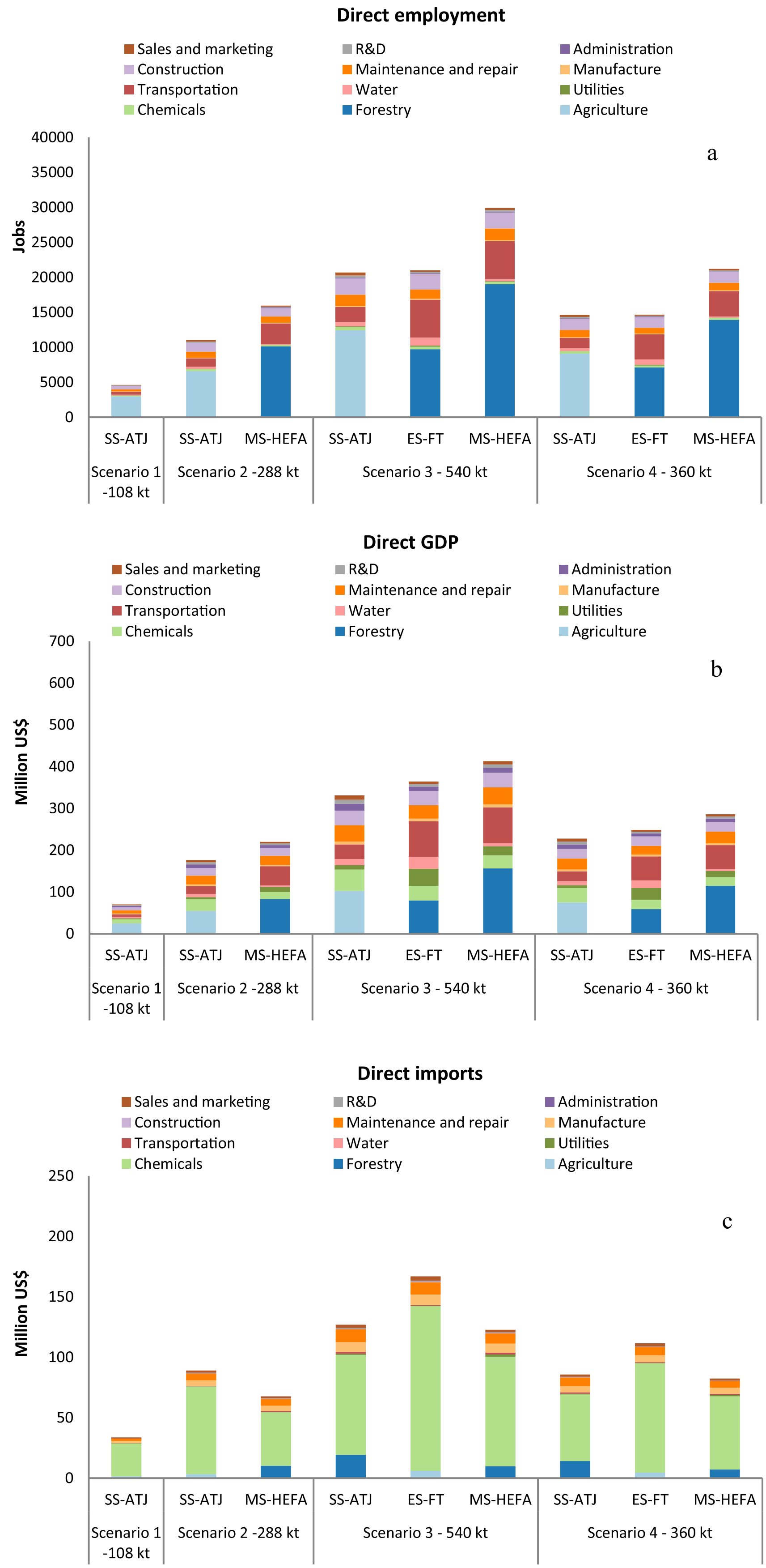

Fig. 2. Composition of direct effects on (a) employment, (b) GDP, and (c) imports by sector (SS: sugarcane-based supply chain, ES: eucalyptus-based supply chain, and MS: macauba-based supply chain).

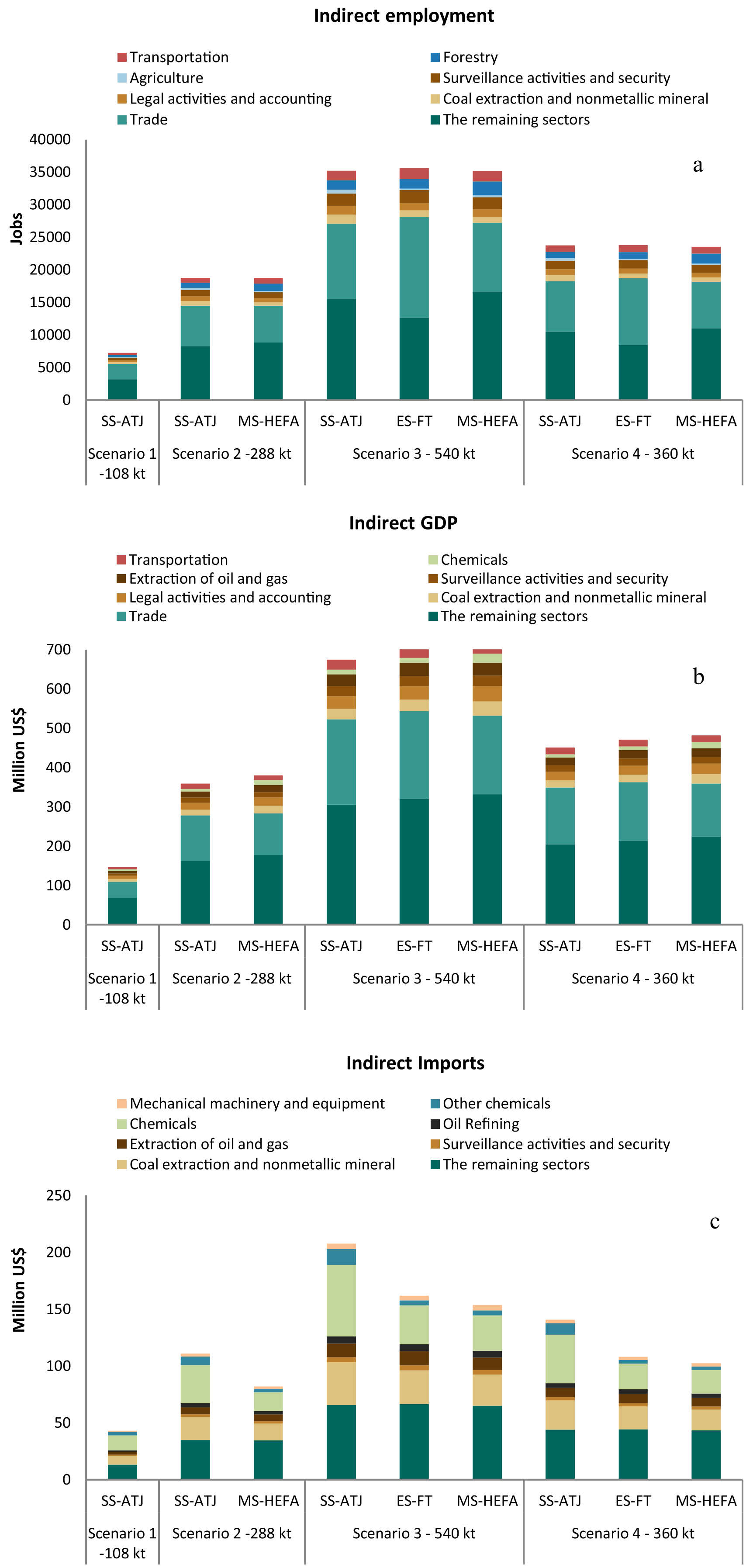

Fig. 3. Composition of indirect effects on (a) employment, (b) GDP, and (c) imports by sector, demonstrated with top 7 sectors and the remainder (SS: sugarcane-based supply chain, ES: eucalyptus-based supply chain, and MS: macauba-based supply chain).

chain. The disparities between these effects can be explained by the different configurations of the supply chains (including type of feedstock involved, conversion technology used, and location of biorefineries), different sectoral socioeconomic (i.e., employment, GDP, and imports) coefficients, and different technical coefficients of the "biojet" sector. In the macauba-HEFA chain, for instance, the high costs of biomass and the labor-intensive nature of the feedstock sector are two main factors responsible for its large employment and GDP effects. Meanwhile, the large import effects in the sugarcane-ATJ chain are due to the high demand for inputs from the chemicals sector, which are associated with a relatively high imports coefficient.

Higher proportions of indirect jobs are estimated for the sugarcane-ATJ chain (61–63%) and for the eucalyptus-FT chain (62–63%) than for the macauba-HEFA chain (53–54%). This may indicate that the sugarcane-ATJ and the eucalyptus-FT chains rely more on intermediate inputs from supporting sectors to produce aviation biofuel. Note that in all the supply chains, the transportation sector is associated with relatively large effects on direct employment and direct GDP. This could be due to two factors: (i) the transportation of biofuel from the biorefinery to the airport was also considered in this study, revealing a high input requirement in this sector, and (ii) labor intensity is relatively high in this sector.

3.1.4. *Net effects*

When taking displacement into account, the net socioeconomic effects decrease by 19–24% for employment, 38–42% for GDP, and 32–49% for imports. Moreover, disaggregating net effects by sector reveals negative effects in certain sectors. The main sectors showing large displacement effects include extraction of oil and gas, and also oil refining (as shown in Table S3). This confirms the assumption that a fraction of the socioeconomic benefits (employment and GDP) will be reallocated from the fossil sectors to the new "biojet" sector. GDP is more negatively affected than employment, due to the relatively high GDP coefficients in the affected sectors.

At the national level, all the scenarios lead to positive net socioeconomic effects, as shown in Fig. 4. The positive net effects on employment and GDP suggest that, overall, no net jobs and added value will be lost due to the development of aviation biofuel. The positive net import effects, however, suggest that producing aviation biofuel requires more imported goods than fossil aviation fuel, which reveals a negative impact on trade balance. At the sector level, although the scales of the negative effects are considerably low compared with the overall net effects (less than 0.1% in the case of employment and less than 2% for GDP), these potential negative socioeconomic effects of aviation biofuel production should not be overlooked.

3.2. *Uncertainty analysis*

To analyze the uncertainty related to IO analysis, we compared the results calculated for the deterministic case (based on the latest IO table) and for the stochastic simulation (in Fig. 5). The descriptive statistics are presented in Tables S3–S6. For total effects on employment, GDP, and imports, the confidence intervals are about 10–15%, 10–13%, and 12–14% around the mean values, respectively. Similar ranges of uncertainty are observed for the net effect on employment, GDP, and imports, with confidence intervals of 10–16%, 12–16%, and 16–18% around the mean values, respectively. Based on the values of the relative standard deviation, the sugarcane-ATJ chain appears to be associated with a higher level of uncertainty than both the macauba-HEFA chain (by 32–45% for total employment, 30–32% for total GDP, and 13–17% for total import effects) and the eucalyptus-FT chain (by 16–38% for employment, 25–26% for total GDP, and 13–17% for total import effects).

At the sector level, the confidence intervals were also calculated for each supply chain under each scenario. The relative standard deviation values disaggregated to each sector range from 2% to 50% for total employment effects, from 2% to 55% for total GDP effects, and from 1% to 50% for total import effects (as shown in Table S4). Sectors associated with high uncertainties include feedstock and mining (e.g., extraction of oil and gas, coal extraction, and metal extraction). One possible explanation for these high uncertainties could be that these sectors are associated with notable changes in the national economy throughout the past two decades. For those sectors, therefore, it is recommended that the input data and results to be handled with discretion. More accurate and detailed data can help lower the level of uncertainty in the analysis.

The socioeconomic effects calculated in the deterministic case are generally higher than the stochastically simulated mean values. Specifically, in terms of total effects on employment, GDP, and imports, the variances between the deterministic results and the stochastically simulated mean values are 15–22%, 21–25%, and 13–21%, respectively. Furthermore, the deterministic results of employment, GDP, and import effects are generally close to the maximum value resulting from the stochastic simulation. The differences between the outcomes calculated for the deterministic case and the stochastic simulation are caused mainly by such factors as technological learning and economic development over time, since the stochastic results are decided by historical data while the deterministic results represent the most recent data available for each sector. From a retrospective point of view, this implies the current economy has grown to a relatively high level but might have experienced some kind of setback such as an economic crisis (such that the deterministic results do not exceed the maximum values of the stochastic results). Additionally, different levels of variations were found in the uncertainty analyses of employment, GDP, and import effects, which could be attributable to other parameters such as employment, GDP, and import coefficients, whose uncertainties were not included in the stochastic simulation.

3.3. *Understanding the results in the Brazilian context*

In this study, the sugarcane-ATJ chain is located in São Paulo due to the siting of the airports concerned. Nevertheless, other areas such as the Northeast of Brazil have also become potential locations for sugarcane expansion (Guilhoto et al., 2002; Macedo, 2005; Martínez et al., 2013). Aviation biofuel could thus become a product of an expanded sugarcane industry in the Northeast, providing fuel for nearby airports. Meanwhile, the eucalyptus and macauba chains will likely be located in the Minas Gerais area. Locating aviation biofuel production out of the traditional feedstock-growing regions could have positive consequences. First, it would ease pressure on the already intensive production in traditional biofuel areas, and thereby avoiding competition for agricultural land with other bio-based production. Second, establishing aviation biofuel supply chains can lead to positive socioeconomic effects at the regional level, including rural development and job creation. This is in line with the local development goals, which include improving social development by establishing sustainable biofuel production (AGROPOLO, 2016). In our case, considering the direct effects in feedstock sectors alone, the sugarcane-ATJ, the eucalyptus-FT, and the macauba-HEFA chains would contribute to regional development by creating 2976–12,398, 2337–9,736, and 4563–19,011 jobs, respectively, and by adding US$24–102 million, 19–80 million, and 37–156 million to GDP, respectively (as shown in Fig. 2). Furthermore, it is not only the location of the biomass fields which matters,

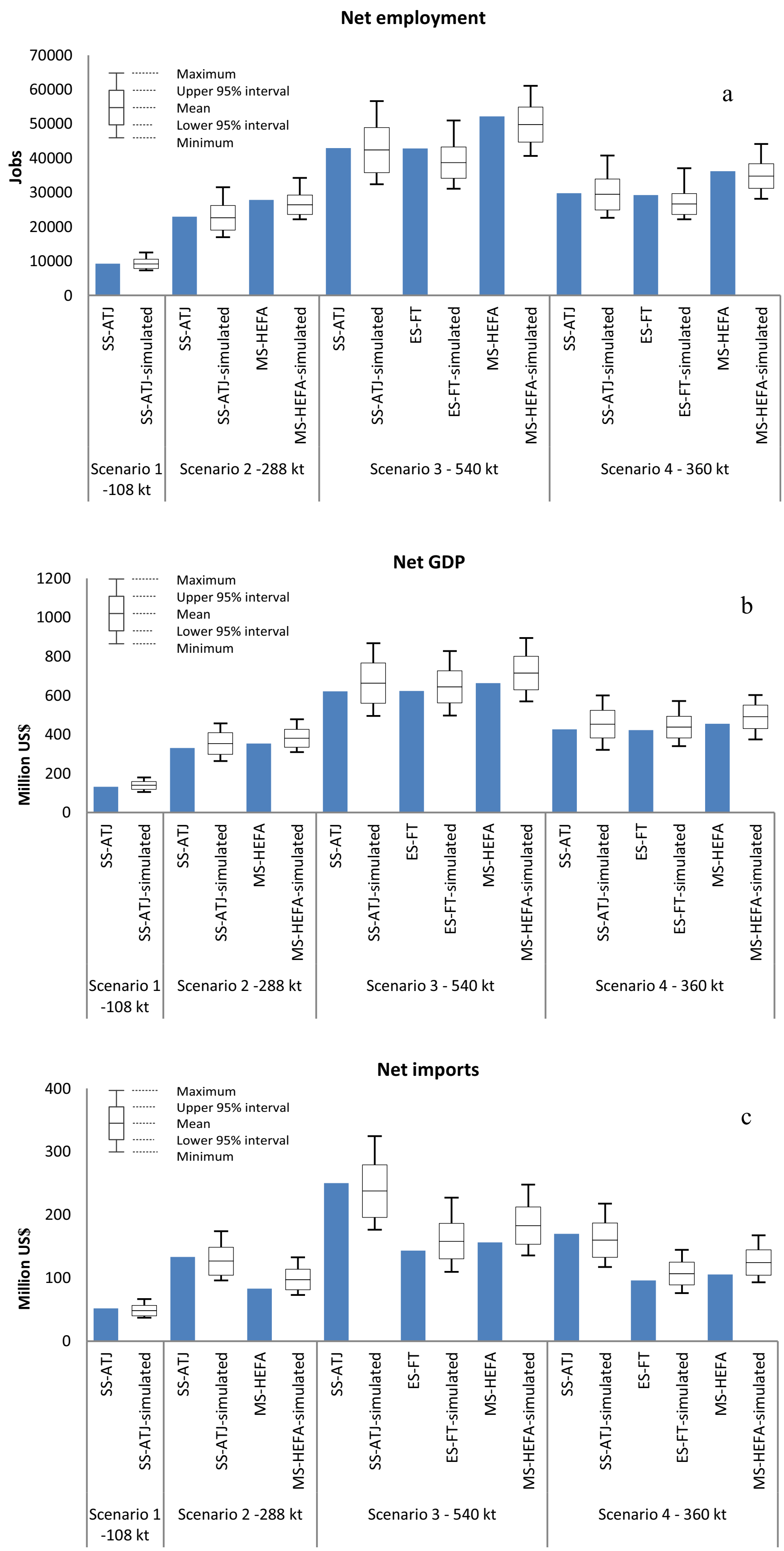

Fig. 4. Comparison between the deterministic outcomes and the simulated outcomes of net effects on (a) employment, (b) GDP, and (c) imports (SS: sugarcane-based supply chain, ES: eucalyptus-based supply chain, and MS: macauba-based supply chain).

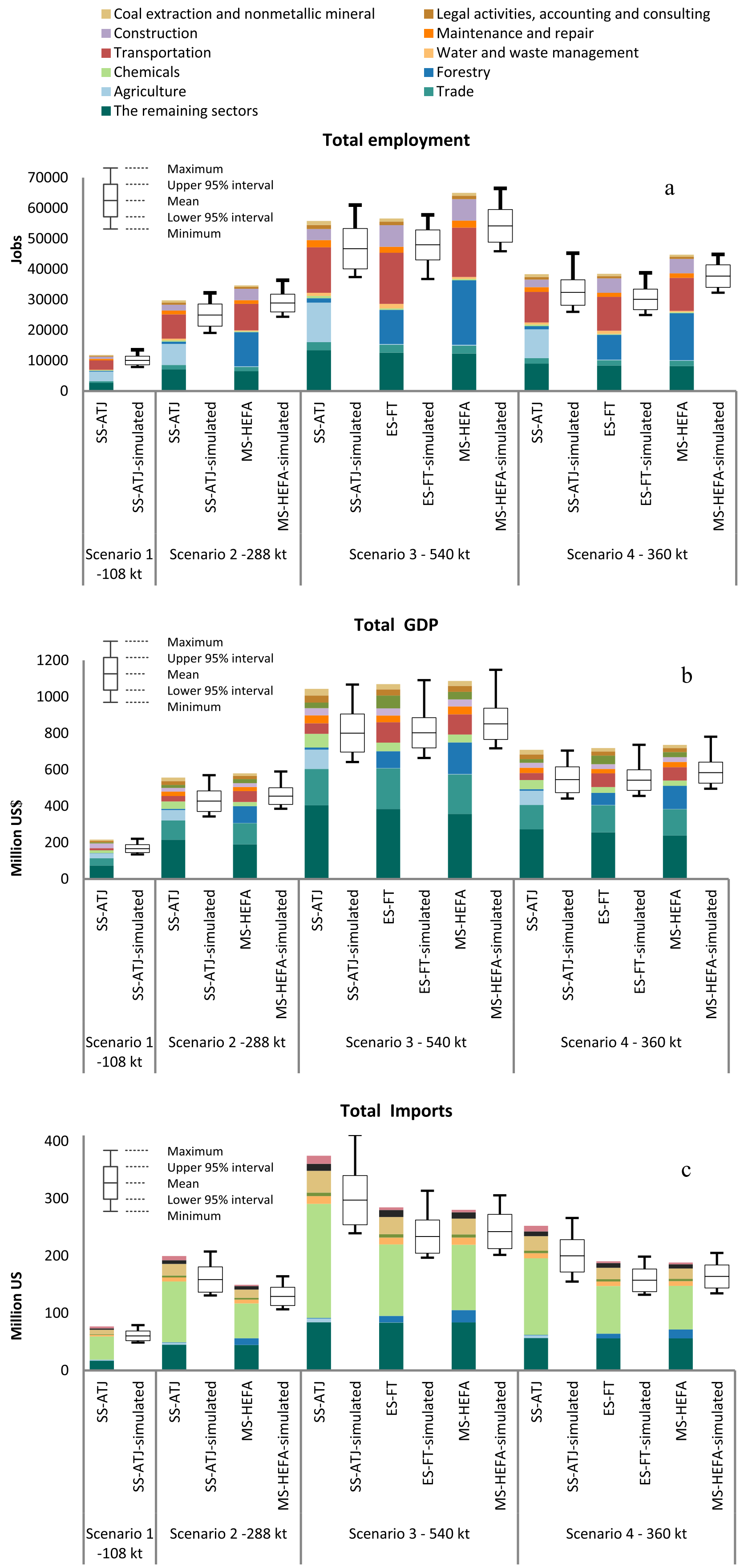

Fig. 5. Comparison between the deterministic outcomes and the stochastic outcomes of total effects on (a) employment, (b) GDP, and (c) imports (SS: sugarcane-based supply chain, ES: eucalyptus-based supply chain, and MS: macauba-based supply chain).

regional economic structures and characteristics also play a part (Brinkman et al., 2018; Martínez et al., 2013). All three supply chains we studied result in more indirect than direct effects on employment and GDP. So if sectors providing intermediate inputs for aviation biofuel are mostly located outside the actual region of biofuel production, interregional economic activities will be stimulated. On the other hand, if the aim is to retain as many of the socioeconomic benefits as possible within the region of production, policy incentives will be required to expand local sectors in order to increase regional economic independence.

In the scenarios we studied, the macauba-HEFA chain is associated with relatively high employment and GDP effects, and with low import effects. The underlying assumption here is that the macauba-based supply chain will have the same production capacity as the relatively more established sugarcane and eucalyptus supply chains in Brazil. This assumption is based on the favorable position of macauba as a promising feedstock for biofuel production. Despite its great potential, it remains uncertain whether a sustainable and mature macauba supply chain will be in place by 2050. The cultivation of macauba is currently being promoted by supportive programs in the Minas Gerais region (AGROPOLO, 2016; Evaristo et al., 2016). The continuity of such programs will play an essential role in the development of macauba-based biofuel supply chains.

To mitigate the negative impact of replacing fossil aviation fuel with biofuel on trade balance, one solution worth considering is the integration of bio-chemicals production within the biorefinery. This would help reduce dependency on imported chemical products, and potentially generate additional value. Current demand for aviation fuel in Brazil is not entirely met by domestic production. In fact, about 25% of the aviation fuel consumed in Brazil is imported (ANP, 2018). Hence, establishing domestic aviation biofuel production could have a positive effect on energy security. Furthermore, if the Brazilian aviation biofuel industry manages to grow in a sustainable way, it has the potential to make the country a vital player in the international market by exporting “cleaner” fuel to nations with stringent emissions regulations and scarce biomass resources.

4. Limitations

4.1. Scenarios

Scenario analysis has been used in this study to depict the possible futures of aviation biofuel development in Brazil. These constructed scenarios were useful in providing a plausible basis for the quantification of socioeconomic effects. However, they do not rule out the possibility of other alternative futures for aviation biofuel with different production volumes or feedstocks. For example, used cooking oil and municipal wastes are also seen as promising feedstocks, which opens up the possibility of a scenario involving waste-based aviation biofuel production. The challenge in this case, however, is the limited availability of the feedstocks for large-scale production, not to mention the competition for feedstock with biodiesel production (Hileman and Stratton, 2014). On the other hand, aviation biofuel produced from oil crops via the HEFA pathway might be less advantageous than other options when life cycle GHG emissions are borne in mind (de Jong et al., 2017). Since the macauba-HEFA chain seems to be associated with the greatest socioeconomic benefits, a trade-off becomes apparent once more aspects are taken into consideration.

Secondly, due to the lack of published data on future demand for aviation biofuel in particular, the projected demand shock for each scenario was based on the trajectory formulated by the WEC (2016). These projections are, however, rather conservative when compared with the ambitious emission-related targets set for the aviation sector. Even in “The Grand Leap” scenario, where the projected demand for aviation biofuel is the highest, only 15% of the fuel needs are covered by biofuel. But taking into account the current state of technological development, the political environment, and sustainability concerns associated with biofuel expansion, we have estimated the demands for aviation biofuel based on scientific literature rather than wild guesses.

Thirdly, to account for the potential competition for biomass resources attributed to aviation biofuel production, we included feedstock price fluctuations. It was assumed that feedstock prices were driven up when aviation biofuel industry competes for biomass with other biobased industries. However, this is rather a simplified assumption. The actual effects of biomass competition and further land competition effects require more in-depth analysis in order to reveal the actual mechanisms involved.

4.2. IO analysis

For each feedstock, the availability of information and data differs. Specifically, there is a lack of data on actual current production of macauba. Consequently, data regarding the macauba-HEFA chain was derived from recent techno-economic evaluations reported in literature on aviation biofuel production using macauba feedstock. Hence, the calculations provided for the macauba-HEFA chain should not be considered as absolute results. Rather, they should be seen as a proxy for the way macauba-based aviation biofuel might develop in the foreseeable futures. Further studies with field data would contribute to a more accurate analysis of this chain.

As described in Section 2.5, a stochastic simulation was performed to address the uncertainties of IO analysis. The historical trend could shed light on the structural changes to the macroeconomy over time. However, it remains unclear whether such trends are representative for the emerging “biojet” sector, which features radical and advanced technologies. Nevertheless, the stochastic simulation approach has been helpful in providing a deeper understanding of the robustness of IO analysis. In this study, the stochastic simulation was performed around the uncertainties of the technical coefficients, excluding other variables (e.g., employment, GDP, and imports coefficients) which might further affect the robustness and the overall uncertainty of the results. To better understand uncertainty and improve IO analysis, uncertainties stemming from all variables should be further investigated in future studies.

5. Conclusions

The objective of this study was to assess the socioeconomic effects of aviation biofuel development on employment, GDP, and trade balance. This was achieved by applying a scenarios-based IO analysis, taking Brazil as an example. All the scenarios presented result in significant socioeconomic effects on employment and GDP. In terms of employment, depending on the scenario concerned either about 11,850, 29,800–34,500, 55,800–65,000, or 38,400–44,700 jobs are created to cover, respectively, 3%, 8%, 15%, or 10% of the demand for aviation fuel in Brazil. Under each scenario, the macauba-HEFA chain has the greatest positive effects on employment, creating 16–17% more jobs than the sugarcane-ATJ chain and 15–16% more than the eucalyptus-FT chain. The production of aviation biofuel contributes about US$220 million, US$560–580 million, US$1040-1090 million, or US$710–740 million to Brazil's GDP annually, in Scenario 1, 2, 3, or 4, respectively. In this regard, the macauba-HEFA chain also outperforms the other two by 3–4% (sugarcane-ATJ) and 1–2% (eucalyptus-FT). The effects on trade balance, on the other hand, reveal different trends. To fulfill demands for aviation biofuel, imports worth approximately US$80 million, US$150–200 million, US$280–370 million, or US$190–250 million are needed in Scenarios 1, 2, 3, or 4, respectively. The sugarcane-ATJ chain results in the largest import effects, 31–32% higher than those for the eucalyptus-FT chain and 33–34% higher than those for the macauba-HEFA chain.

Aviation biofuel production shows large positive net socioeconomic effects on employment and GDP, whereas some of the fossil sectors are negatively affected. Despite the relatively modest scales of these negative effects, efforts such as professional training for new jobs or reaching agreements to re-allocate labor to aviation biofuel-related sectors are desirable, in order to rebalance the displaced socioeconomic benefits in those sectors.

Overall, the macauba-HEFA chain (with the greatest effects on employment and GDP, and the least effects on imports) seems to be the most favorable option considering the scenarios studied, despite the uncertainty associated with its establishment. In this regard, regional policies to stimulate economic activities related to the "biojet" sector, especially the production of macauba feedstock, could be helpful to lower the risks and eventually to achieve the desired level of socioeconomic benefits.

Acknowledgements

This work was carried out within the BE-Basic R&D Program, which was granted an FES subsidy by the Dutch Ministry of Economic Affairs. The authors would like to thank Dr. Arjan de Koning for his helpful comments on the IO analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.05.145.

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