STOCKHOLM SCHOOL OF ECONOMICS
Department of Economics
5350 Master's thesis in economics
Academic year 2021–2022

Global Effect of the EU Food Carbon Tax on Food Industries and Products: Case Study of Brazil

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Abstract. Several researchers suggest an introduction of a food carbon tax in EU to reduce food emissions following the European Green Deal, but taking into account food international trade, such action in EU could raise global food prices and results in possible decline in food production in some regions, thus reduce people's welfare, which is not in line with the global Sustainable Development Goals. Given that existing studies mainly focus on the local environmental, social, and economic effects of a carbon tax, our paper takes a further step by studying the possible global effect of the EU food carbon tax on food industries and products with Brazil as a case. By generating multi-regional Input-Output model in the food international trade scenario for both industrial and products level, we find that although at the industrial level, Brazil's final demand for final goods of agriculture, fishing, and food processing industries decrease, and domestic outputs decline by 47%, 88% and 84%, respectively, after the EU food carbon tax, at the product level, effect on Brazil's domestic demand and output is highly insignificant, even that most food products experienced a global short-run price rises. Hence, Brazil does not need to be overly concerned that an EU food carbon tax will cause serious social impacts in its region through the food sector.

Keywords: Carbon tax, Food Policy, International trade, Input Output

JEL: Q17, Q18, C67

Supervisor: Julius Andersson
Date submitted: May 31, 2022
Date examined: May 23, 2022
Discussant: Tamar den Besten
Examiner: Magnus Johannesson

Acknowledgement

We would like to express our sincere thanks to our supervisor Julius Andersson, who has always been supportive of our research process, providing us with helpful advice on our analytical method, and helping us improve our writing style.

We would also like to thank our peer Mara Balasa for her suggestions on the structure of our thesis and her support of our data search process, which greatly contributed to our research.

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1 Introduction

In the context of globalization, carbon tax at the national or regional level can not only have local environmental, social and economic impacts, but may also have impacts on external regions. Environmental, social, and economic problems, such as pollution, poverty, and inefficient market, caused by persistent changes in the climate states, which refers to climate change, due to greenhouse gas emissions (GHGe) that can last for decades or longer are long-term problems for human beings to solve (Fawzy et al., 2020). In addition to the well-known global warming problem, climate change can also lead to an increase in extreme weather events, more disasters, more diseases, and threats to food and water security (Cattaneo et al., 2020). We, as human beings, have an inescapable responsibility for climate change. According to Knutson et al. (2017), humans may have contributed 93%-123% of the observed global mean temperature increases from 1951-2010, and the results show high confidence that more than half of those increases since 1951 is likely due to human activities' effects on climate. Although climate change is a global issue, it is almost impossible to create a climate policy that is globally appropriate as national governments only have the power to address the negative externalities of pollutants within their own borders (Seddon et al., 2020). However, one good thing is that at the local level, more than 170 countries have implemented laws and policies, such as carbon tax, aim at mitigating climate change (Schmidt and Fleig, 2018; Nachmany et al., 2019).

Around the global, the EU region has done well in emissions abatement, reducing its emissions by almost 35% from 1979 to 2020 (Global Carbon Project, 2021), and it also proposed a European Green Deal in 2020, with the main ambition to make the EU carbon neutral by 2050 (Siddi, 2020). However, climate policies have long focused main attention on the energy sector, which ranks first in terms of greenhouse gas emissions (Hannah Ritchie and Rosado, 2020), but greenhouse gas emissions from food cannot be ignored either. In a global way, it accounts for up to 26% of total emissions, making it the second-largest emitter after the energy sector (Poore and Nemecek, 2018). In order for the EU to achieve the main carbon neutrality goal of the European Green Deal and the side goal of improving food sustainability within its region, a report by an environmental research group CE Delft (2020) advises that the EU could add a meat carbon tax policy to the European Green Deal, and suggests that it can not only reduce 120 million tonnes greenhouse gas emissions a year, but also reduce meat consumption, especially beef consumption, in the EU, leading people in the EU to a healthier diet. In addition, Leite Pinto (2021)'s study also shows that in a short-term, the meat carbon tax in EU can reduce at least 3% of EU's total emissions, as well as provide EU about 32 billion EUR revenues per year for financing its transition process to sustainable food production, and these positive impacts are more significant when the carbon tax is applied to all animal products. A study on the impacts of introducing a carbon tax on meat and dairy products in Sweden also shows that it can reduce not only greenhouse gas emissions but also nitrogen and phosphorus for about 12% from the livestock sector, and beef is the main product that cause effects (Säll and Gren, 2015).

Although the carbon tax policy, when levied on sectors like fossil fuels and food, is considered to be effective in reducing emissions (Elkins and Baker, 2001), it also has a major drawback of being regressive, meaning that groups with different incomes can be affected differently, with low incomes bear a heavier burden caused by the price increase of necessities like gasoline and food than the high incomes (Grainger and Kolstad, 2010). For example, in developed country like Denmark, a carbon tax on households and industries tend to cause undesirable distributional effects (Wier et al., 2005), and similar results are found in the study on Brazil, a developing country, where Moz-Christofoletti and Pereda (2021) find that if Brazil imposes an economy-wide carbon tax on households, it will cause welfare losses in the short-term especially on the poor. A case study on Mexico also shows that if Mexico sets a carbon policy that includes methane and nitrous oxide, the greenhouse gases mainly emit by agriculture and food sectors, under regulation, then the rise of food prices will increase poverty in Mexico in a serious way, although it is an effective way to reduce emissions (Renner, 2018). That is, carbon tax policies that are good for the environment may be harmful to human utility and welfare, especially on the low income group, which is contrary to some of the Sustainable Development Goals (SDGs) set up by the United Nations General Assembly (UN-GA) (UN, 2019) since according to the 17 Sustainable Development Goals, fighting climate change is not human's only sustainable needs, we also want to achieve goals like no poverty, zero hunger, reduced inequality, and so on (UN, 2019).

However, based on our research, we found that the majority of studies are about the local environmental, social, and economic impacts of carbon tax implementation, but we take into account that in today's globalization world of prevailing international trade, the impact of a rise in the price of essential goods in a country or region due to a carbon tax on necessities may also have the potential to affect external regions. Therefore, the innovation of this paper is that we study the possible impact of the EU implementation of a food carbon tax on Brazil's food industry and food products. We think that the impact can be caused not only by directly affecting Brazil trade with EU, but also by the EU's impact on global food prices. We choose Brazil as a case because of the EU's main food trading partners, UK, US, China, and Brazil, Brazil had the lowest GDP (World Bank, 2020) and food security index (Economist Impact, 2021) in 2015-2019, so we think if the EU imposes a carbon tax on food, the effects may be more important for Brazil. The input-output analysis method allows us to study those possible effects through inter-regional and inter-sector relationships, as well as conduct long-term simulation as time grows. Our base year calibration is based on data of food industries and food products demand, supply, and trade in 2018. By generating multi-regional input-output models at industrial level and product level, we study the distributional impact of the EU food carbon tax on Brazil's food industries and food products respectively. At the industrial level, we look at three food industries, which are agriculture, hunting and forestry industry, fishing and aquaculture industry, and manufacture of food products, beverages and tobacco products industry. We compare output of these three industries over a one-year time span before and after the implementation of food carbon tax in EU, and we find that output in all these three industries in Brazil fell after EU's food carbon tax. To examine whether the declines in these food industries' outputs mean that the outputs of certain affected food products also decrease, we then go a step further with our product level analysis, where we conduct a 7-year simulation study on 6 food products, which are beef, pork, poultry meat, cheese, coffee, and vegetables. According to Poore and Nemecek (2018), all foods except vegetables are products with high carbon emissions per unit, which means they tend to be the most affected food products, but we introduced vegetables as one of the products in our study to see if demand and supply in Brazil would be more in favor of vegetables after an emission based food carbon tax in EU, since in general, the CO_2 equivalents emissions from vegetables are almost negligible. Based on the results of our 7-year simulation, we find that all products we studied experienced a global short-term rise in prices following EU's food carbon tax shock, but prices for most products fell afterward, and for all the products we studied, their price gradually approached a new relatively stable level 3 to 4 years after the shock, and the new price value is higher than the price value in the base year. As for outputs in Brazil, in all six products we studied, the total output of products other than coffee, the one whose annual output decrease by about 0.5-0.6 million tons, continue to show an upward trend over our simulation time, and the trends are very similar to the pre-tax growth trends, even that the EU carbon tax on food caused an increase in the price of the six products we studied. Although at the industrial level, the EU food carbon tax has resulted in a reduction in the output of the three food-related industries in Brazil, at the product level, the outputs of the six food products in Brazil we studied have not been seriously affected by the EU's food carbon tax. Therefore, from a social impact perspective, the EU carbon tax on food does not appear to have a significant impact on food supply and thus food availability in Brazil, so seems Brazil does not need to be overly concerned that an EU food carbon tax will cause serious social impacts in its region through the food sector.

In the next Section, we provided a brief summary of the local environmental, social, and economic effects of a carbon tax found in past studies and research. Then in Section 3, we explained some of the important terminologies that are discussed in this paper. In Section 4, we did a descriptive analysis to explain the reasons for choosing Brazil as our case. We generated input-output models for industrial level and product level analyses in Section 5, respectively, and presented our results and discussion in Section 6. Then in Section 7, we talked about limitations of this paper and proposed suggestions for future research. Section 8 concluded.

2 Environmental, Social, and Economic Effects of Carbon Tax

A carbon tax is a tax on greenhouse gas emissions from the production of goods and services. An increase in the stock of greenhouse gases in the atmosphere cause climate change, and climate change can damage the environment and affect human health, which therefore is presented as a negative externality that makes the market fails to deliver Pareto-efficiency (Andrew, 2008). The role of carbon tax is therefore to internalize the negative externality of climate change, and guide the market to become efficient (Dinan, 2013). Finland was the first country in the EU region, and also in the world, to introduce a carbon tax in 1990, with 1.12 EUR (1.41 USD) per tonne of CO_2 (Poterba, 1991). Since then, other countries around the world have introduced carbon taxes. By 2019, 25 countries around the world have implemented carbon tax policies, of which 8 belong to the EU-27 region (Ramstein et al., 2019). Sweden currently has the highest carbon tax in the world. In 2020, the carbon tax rate in Sweden stands for 116 EUR (137 USD) per tonne of carbon emissions (Sterner, 2020), and as for results, Sweden has decreased its greenhouse gas emissions by 27% between 1991 and 2018 (Global Carbon Project, 2021).

Greenhouse gas emissions (GHGe) from food should not be underestimated. From a global perspective, food emissions account for 26% of total emissions, making it the second-highest-emitting sector after the energy sector (Poore and Nemecek, 2018). Hedenus et al. (2014) showed that reducing emissions from the agri-food sector can be achieved mainly in the following two ways: (1) Improve technology; (2) Change consumption behavior, where the first one is for the supply-side, and the second one is for the demand-side. In Wirsenius et al. (2011)'s research, by examining the postcarbon tax changes in consumption of different food, in land use, and in corresponding greenhouse gas emissions, they found that by setting up a greenhouse gas emissions based carbon tax of 60 EUR per ton of CO_2 equivalents on animal food products within the EU, the agricultural emissions in the EU could be reduced by around 32 million tons of CO_2 equivalents. Similarly, in Edjabou and Smed (2013)'s case study of Denmark, they found that a carbon tax on 23 food items could reduce emissions by at least 2.3%-8.8% and at most 10.4%-19.4%. García-Muros et al. (2017) also found in their case study on Spain using a demand system model that food tax can reduce emissions.

In addition to reducing emissions, food carbon taxes can also change consumer behavior and improve people's health by taxing environmentally unfriendly and unhealthy foods (Springmann et al., 2016). In fact, countries like Denmark (Smed, 2012), Hungary (Cabrera Escobar et al., 2013) and France (Berardi et al., 2016) have already implemented relevant "fat tax" of "sugar tax" aimed at food. Taking Denmark as an example, Smed et al. (2016) found that the Danish tax on saturated fat in October 2011 reduced consumption of saturated fat in Denmark by an average of 4%-5%. In a meta-analysis of 9 articles, 6 from the United States, 1 from Mexico, 1 from Brazil, and 1 from France, Cabrera Escobar et al. (2013) also showed that by adding greenhouse emissions based tax on sugar-sweetened beverages can help reduce obesity and overweight.

However, carbon tax, especially strict carbon tax that is too expensive or involve too many types of greenhouse gases (i.e. involve not only carbon dioxide but also methane, nitrous oxide, water vapor, and so on) may not suitable in all countries. For example, Renner (2018)'s study using the case of Mexico found that strengthening carbon policy through including methane and nitrous oxide, the greenhouse gases mainly from food industries, in carbon tax would lead to higher food prices, and thus serious increases in poverty. In Moz-Christofoletti and Pereda (2021)'s study, they find that an economy-wide carbon tax on households in Brazil will cause welfare losses in the short-run especially on the low incomes. Hasegawa et al. (2018), using a multi-model assessment of the combined effects of climate change and mitigation actions on food, also concluded that if the same stringent carbon policy was implemented across all sectors globally by 2050, the global hunger problem and food consumption pattern would be worse, and these negative impacts could outweigh the positive impacts on the environment, especially in the low-income regions such as South Asia and Sub-Saharan Africa.

From our findings, most studies still focus on the local environmental, social and economic impacts of a carbon tax on a country or region, but we consider that under the current situation of active international trade, the impact of the increase in the price of certain products caused by the carbon tax in some countries or regions can spread to other countries or regions. The novelty of this paper is therefore a cross-regional study of the impact of a carbon tax on food, which, in this paper, is the possible impacts of the EU food carbon tax on Brazil's food-related industries and certain food products, and we think that the impacts may come from two channels, one is directly affecting Brazil's food sector through the food trade between Brazil and the EU, and the other is indirectly affecting Brazil's food sector by affecting global food prices.

3 Terminology Explanation

In this section, we briefly explain some of the main terms mentioned in this paper before proceeding with the analysis process, as a background for the subsequent sections in this paper.

3.1 European Green Deal

The European Green Deal is a series of policies approved by the European Commission in 2020, such as assessing the climate merits of each existing laws, introducing new legislation on biodiversity, agriculture, and so on, with the main aim of making the EU carbon neutral by 2050 (Siddi, 2020). In the past 40 years, the EU has performed well in reducing emissions. Although the EU's carbon dioxide emissions are still as high as 2.60 million tons in 2020, the EU's annual carbon dioxide emissions has been declining in a volatile trend since it reached 4.11 million tons in 1979 (Global Carbon Project, 2021), that is, a reduction of more than 35%. While in addition, the EU still would like to go further, according to the European Green Deal (2020), with a reduction target of 50%-55% for 2030 compared with 1990 levels (Siddi, 2020). As mentioned before, the EU also wants to pay efforts on sustainable industry, building innovation, sustainable agriculture, biodiversity, sustainable finance, and so on, within their region, but the main purpose of these policies still is to support their work on achieving carbon neutrality by 2050.

3.2 Sustainable Development Goals (SDGs)

The Sustainable Development Goals are 17 ambitions set up by the United Nations General Assembly (UN-GA) in 2015 to make the world a better and more sustainable place, and are aimed to be achieved by 2030 (UN, 2019). It is worth noting that sustainable development is not only about reducing emissions to combat climate change, but also about increasing people's utility, which, in other words, about creating positive social impacts. In addition to the climate action of Goal 13 (Gupta and Vegelin, 2016), 5 of the other 16 goals are directly related to people's consumption and health, such as no poverty in Goal 1, zero hunger in Goal 2 (Gil et al., 2019), clean water and sanitation in Goal 6 (Weststrate et al., 2019), and reduced inequality in Goal 10 (UN, 2019). That is to say, the importance of ensuring people's utility improvement in terms of food, health, sanitation, and equality, is as important as dealing with climate problems.

3.3 Food Security

Food security is the assessment of the availability of food and the ability of all individuals to get access to it (McDonald, 2010). According to IFPRI (2020) and based on the definition proposed by the Committee on World Food Security (CFS), perfectly food security means that all people, at all times, have fully access to get food that meets their personal preferences and ensures their nutrition needs to live an active and healthy life. Majorly there are four pillars, according to FAO (2009), to identifying food security, which are availability, access, utilization, and stability.

3.4 Greenhouse Gas Emissions of Food Products

According to Poore and Nemecek (2018), greenhouse gas emissions of food products consist of emissions from different parts of their supply chain, which includes land use change, farm, animal feed, processing, transport, retail, and packaging. In this case, for different food products, their emissions may mainly come from different parts of the supply chain. For example, emissions of beef are mainly from farm, but emissions of pork are mainly from land use change and processing. The main greenhouse gas emitted by food products, in addition to carbon dioxide, is methane, but when measuring greenhouse gases of food products, all greenhouse gases are counted as CO_2-equivalents. Therefore, a carbon tax on food products is based on the CO_2-equivalents emissions per kilogram of that food. In general, animal meat and animal products emit more than vegetables. For example, 60 kg of CO_2-equivalents are emitted per kg of beef, 21 kg of CO_2-equivalents are emitted per kg of cheese, while most vegetables emit only around 0.4 kg of CO_2-equivalents per kilogram, almost negligible compared to the emissions of animal meat and animal products.

4 Descriptive Analysis

We think that the impact of the EU food carbon tax on Brazil's food sector is not only directly through trade, but also indirectly through the effects on global food prices. In order to investigate the extent to which EU's carbon tax on food products may causes impacts on the food-related industries and on the food products in Brazil, in this section, we firstly provide a descriptive analysis of the trends of EU agri-food products international trade between 2015 and 2019, the most recent 5 years before the Covid-19 pandemic (Ciotti et al., 2020). Secondly, we illustrate the importance of EU agri-food products trade in the global agri-food trade market in that past 5 years, by comparing it with other top exporters and importers in the world. Thirdly, we compare the economic performance and food security index of Brazil, one of EU's main trading partners not only during but also before and after that 5-year period (European Commission, 2021, 2015), and several other major EU trading partners between 2015 and 2019 to illustrate the reasons for choosing Brazil as the case. Finally, we investigate on the trade relationship trend between EU and Brazil in 2015-2019. We choose the period 2015-2019 because the Covid-19 pandemic has caused a shock to the international trade markets. Although trade rebounded sharply in 2021 after a sharp decline in 2020, according to OECD (2022), the impact on trade was highly heterogeneous, with trade in industrial products, for example, falling while trade in medical supplies and household goods rose, and those kinds of heterogeneous impact are greater than in any year in the past two decades, and serious imbalances between trading partners and products still remain until the end of 2021. Therefore, data for 2020 and beyond may affect the assessment process of the EU's importance in agri-food products trade, and the investigation process of EU's trade trend with the key partners in agri-food trading. Apart from that, another thing to consider is Brexit in early 2020 (Proctor and Boffey, 2021). Before Brexit, the UK was one of the major net importers of EU-28 member countries, so the UK's departure makes the EU-27 region a bigger exporter but a smaller importer (Matthews, 2021). In the subsequent analysis process, the EU refers to the EU-27 region, and the data are all updated according to the EU-27 region.

4.1 EU Trade in Agri-Food Products, 2015-2019

According to Eurostat (2022), between 2015 and 2019, both the EU's import and export of agri-food products with the extra-EU region increased, as showed in Figure 1, with a much more higher increase in export than increase in import, and overall a greater export value compare with import value. The export value in 2015 was about 157 billion Euro, and this value got to exceed 182 billion Euro in 2019. When it comes to import, the value got to grow from around 131 billion Euro to around 143 billion Euro, an increase of almost 1.1 times.

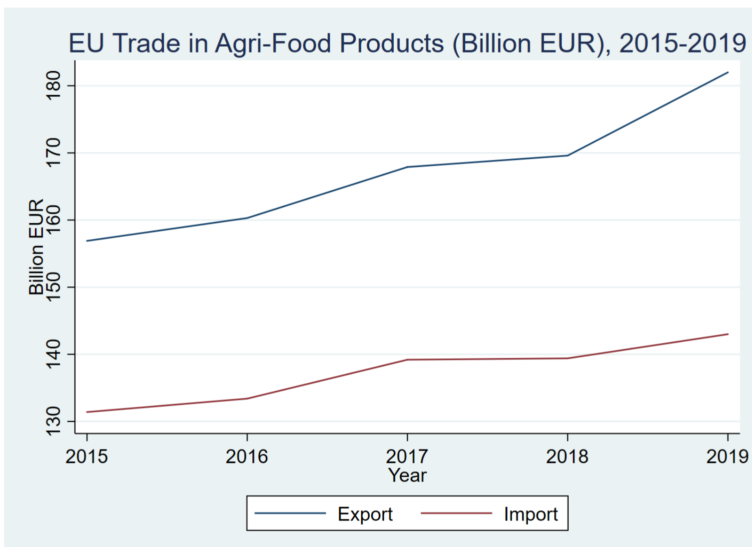

Figure 1: EU Trade in Agri-Food Products (Billion EUR), 2015-2019

The agri-food products can be roughly divided into four categories, which are animal products, vegetable products, fats and oils, and foodstuffs, according to Eurostat (2022). The detailed information about the products that are contained in those four different categories is available in Appendix A. Through descriptive analysis of the trade trends of those four roughly categorized products, we find that for each product category, their trade value is trending upwards over time, although different products may be imported or exported in larger quantities. The corresponding results for each product category are respectively shown in Figure 2, Figure 3, Figure 4, and Figure 5.

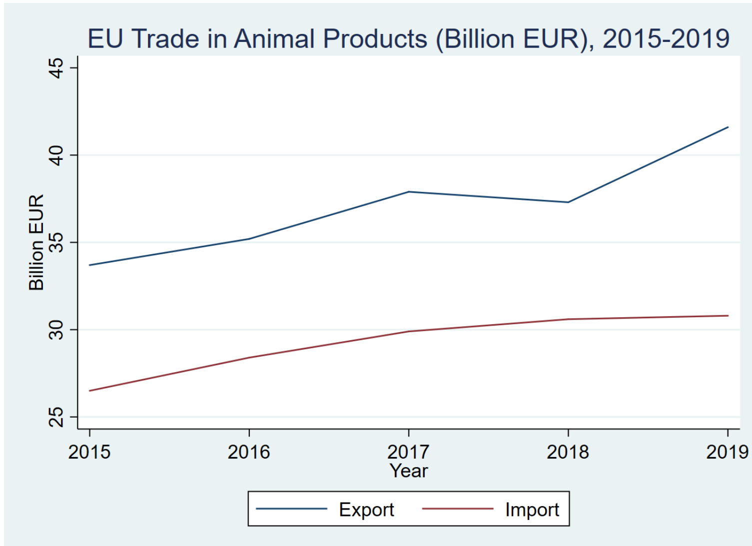

Figure 2: EU Trade in Animal Products (Billion EUR), 2015-2019

As can be seen from Figure 2, both the EU's imports and exports of animal products have increased from 2015 to 2019, but the increase rate of imports has shown a decreasing trend, while exports have shown a more obvious growth during that 5-year period. As previously mentioned in section 3, and according to Poore and Nemecek (2018), the greenhouse gas emissions (GHGe) caused by animal products tend to be larger, so we think that if the EU imposes a carbon-based tax on agri-food products, it can have a large impact on global food prices, given their large amount of exports in animal products.

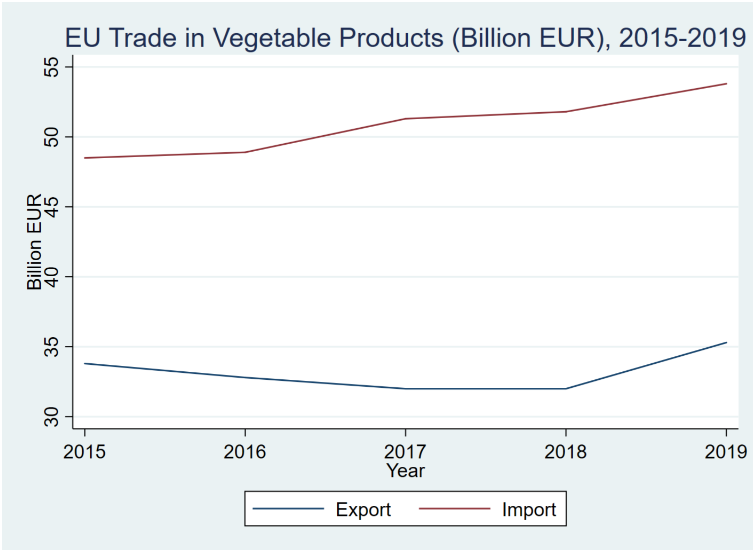

Figure 3: EU Trade in Vegetable Products (Billion EUR), 2015-2019

As for vegetable products, Figure 3 shows that the EU's main direction of vegetable products trade is import, while the export volume is much smaller than the import, and the export even shows a decreasing trend from 2015 to 2018.

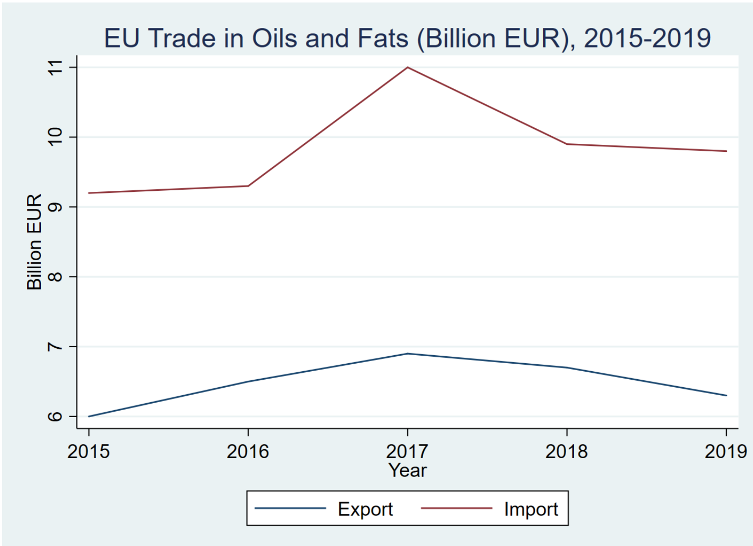

Figure 4: EU Trade in Oils and Fats (Billion EUR), 2015-2019

The EU's trade in oils and fats is relatively small, as shown in Figure 4. During 2015-2019, imports only fluctuated between 9-11 billion EUR and exports only fluctuated between 6-7 billion EUR. Excluding the sudden increase in imports and exports in 2017, the volume of international trade in oils and fats of EU is relatively stable.

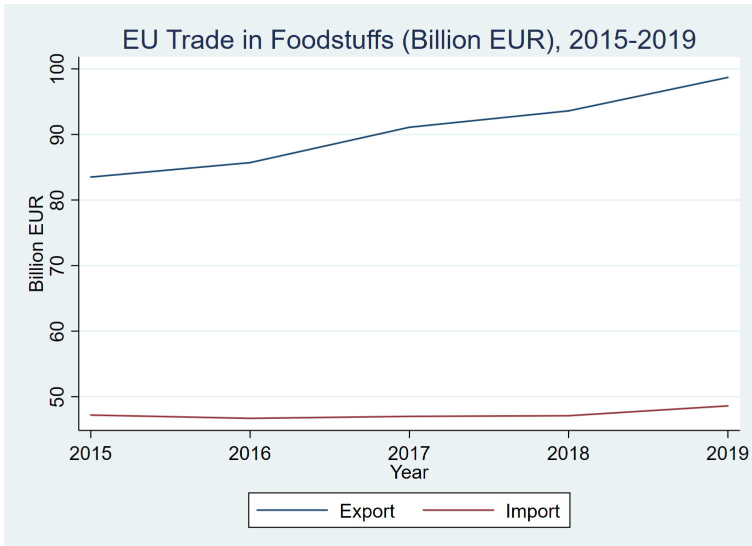

Figure 5: EU Trade in Foodstuffs (Billion EUR), 2015-2019

As can be seen from Figure 5, the EU's export in foodstuffs have always been large in that past 5-year period, with more than 80 billion EUR in 2015, and showing a steady increasing trend with an almost 20 billion EUR growth. Imports, however, are relatively small, with less than 50 billion EUR and no significant change during the 2015-2019 period.

4.2 EU's Role as Agri-Food Products Exporter and Importer in Global, 2015-2019

After observing the growth trend of EU agri-food products trade between 2015-2019, we analyze the EU's role in the global agri-food products trade market. We do this by comparing the value of agri-food products export and import between the EU and other top exporters, which are United States, China, Brazil, and Canada (European Commission, 2020, 2018; Eurostat, 2017), and other top importers, which are United States, China, United Kingdom, and Japan (European Commission, 2020, 2018), between 2015 and 2019.

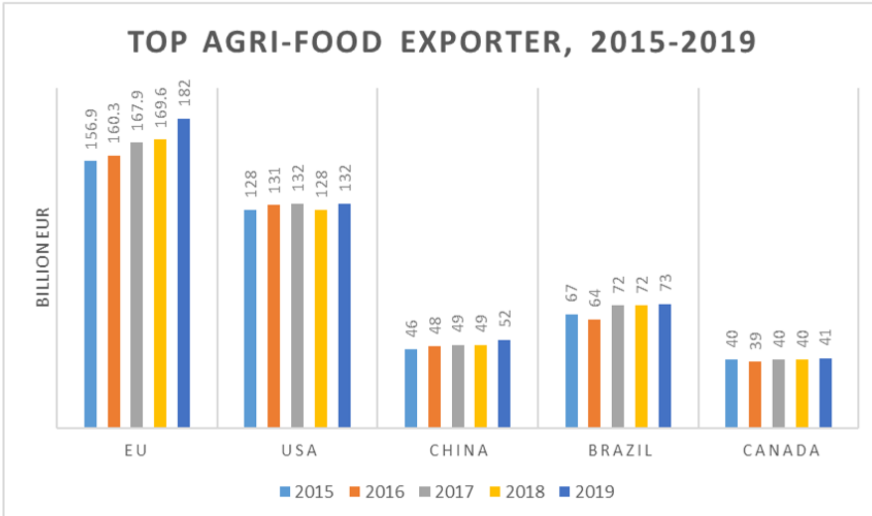

Figure 6: Top Agri-Food Exporter (Billion EUR), 2015-2019

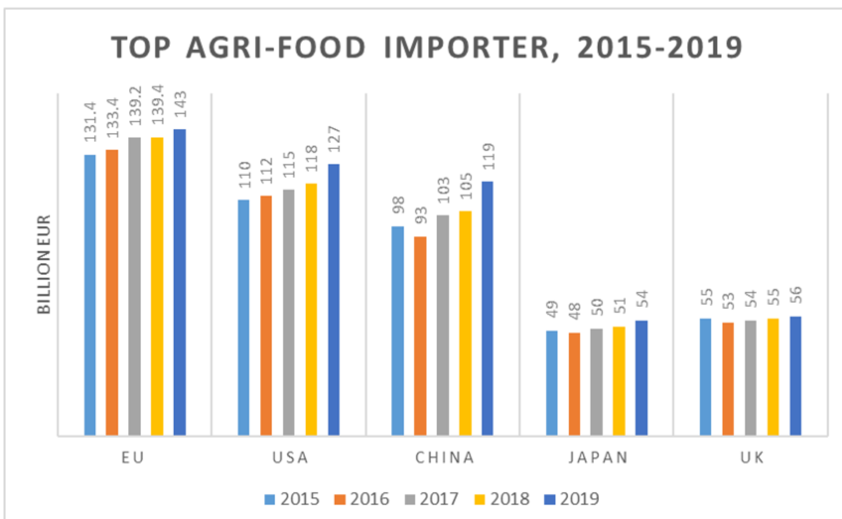

Figure 7: Top Agri-Food Importer (Billion EUR), 2015-2019

From the results in Figure 6 and Figure 7, we find that between 2015-2019, the EU was always at the leading position in the global agri-food products trade market, as the largest agri-food products exporter and importer, and the trade values were keep increasing in those five years. One thing to note here is that the trade value data for the United Kingdom (WITS, 2015, 2016, 2017, 2018, 2019) is converted from US Dollar to Euro based on the average exchange rate of the respective year, and data used for measuring the average exchange rate is presented in Table 1.

Table 1: USD to EUR Average Exchange Rate, 2015-2019

Year	USD to EUR Average Exchange Rate	Source
2015	0.9015	WITS (2015)
2016	0.9040	WITS (2016)
2017	0.8865	WITS (2017)
2018	0.8475	WITS (2018)
2019	0.8931	WITS (2019)

4.3 Real GDP and Food Security in Brazil and Other Major EU Agri-Food Products Trading Partners, 2015-2019

After adjusting EU's agri-food products trading data according to the EU-27 region, it is found that the main EU agri-food trading partners are United Kingdom, United States, China, and Brazil (Eurostat, 2017; European Commission, 2018, 2020). However, the situation of economic performance in Brazil is different than in other countries. As shown in Figure 8, during 2015-2019, Brazil has a lower real GDP compared to other countries (World Bank, 2020), so if the EU chooses to impose a carbon tax on agri-food products and thus affect extra EU regions' food price, this effect could be more important for Brazil.

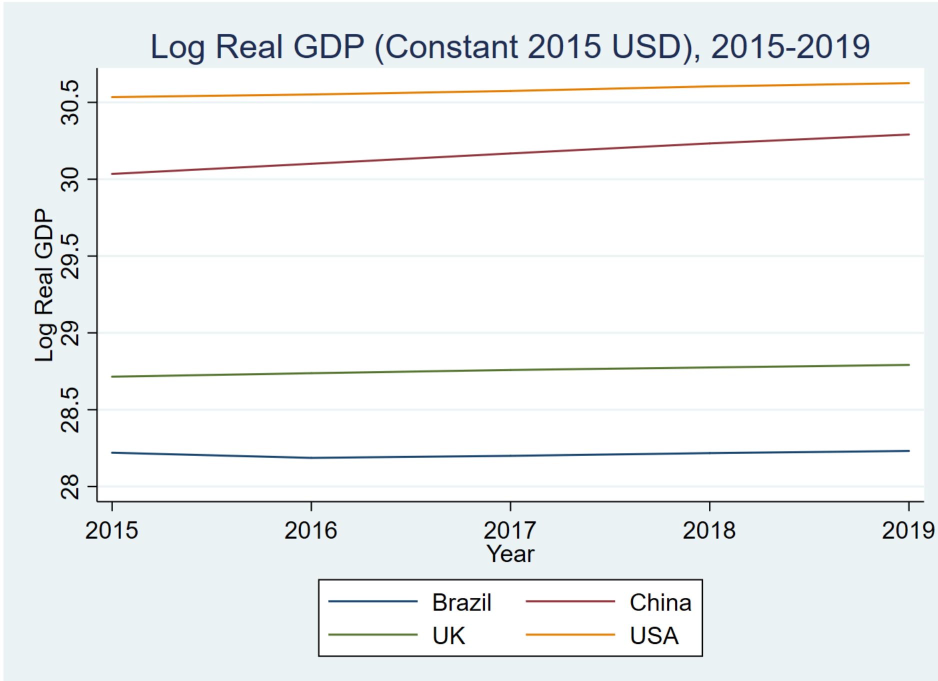

Figure 8: Log Real GDP (Constant 2015 USD), 2015-2019

The food security index is an indicator that measures a country's food security by measuring their food's quality, safety, affordability, accessibility, and sustainability, with 0 refers to the lowest security (food insecurity), and 100 refers to the highest security (Izraelov and Silber, 2019). When it comes to the food security index, as shown in Figure 9, Brazil's food security index was the lowest among all of these EU major agri-food products trading countries from 2015 to 2019, and it shows no sign of rising (Economist Impact, 2021). Therefore, we think that the impact may be more important for Brazil when the price of agri-food products is being shocked.

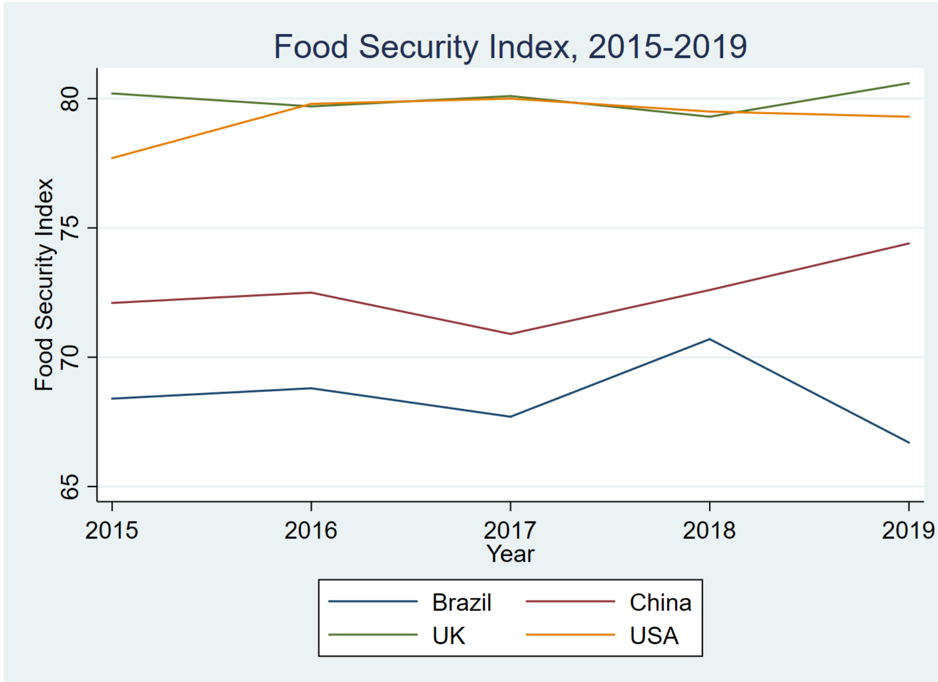

Figure 9: Food Security Index, 2015-2019

4.4 Agri-Food Products Trade Between EU and Brazil, 2015-2019

After finding that among the EU's main agri-food products trading partners, Brazil may be relatively more affected by the EU carbon tax on agri-food products, we conduct a descriptive analysis of the EU-Brazil agri-food trade relationship between 2015 and 2019 (European Commission, 2015, 2021). As can be seen from Figure 10, the imports of EU from Brazil are much larger than exports to Brazil, but from the perspective of changing, the EU's imports from Brazil are relatively stable, while exports have overall shown a very slightly increasing trend in those past five years. If EU impose a carbon tax on their agri-food products and therefore causes the price of agri-food products sold by them rises, we think there is a potential for EU imports from Brazil to increase, but exports to Brazil may decrease.

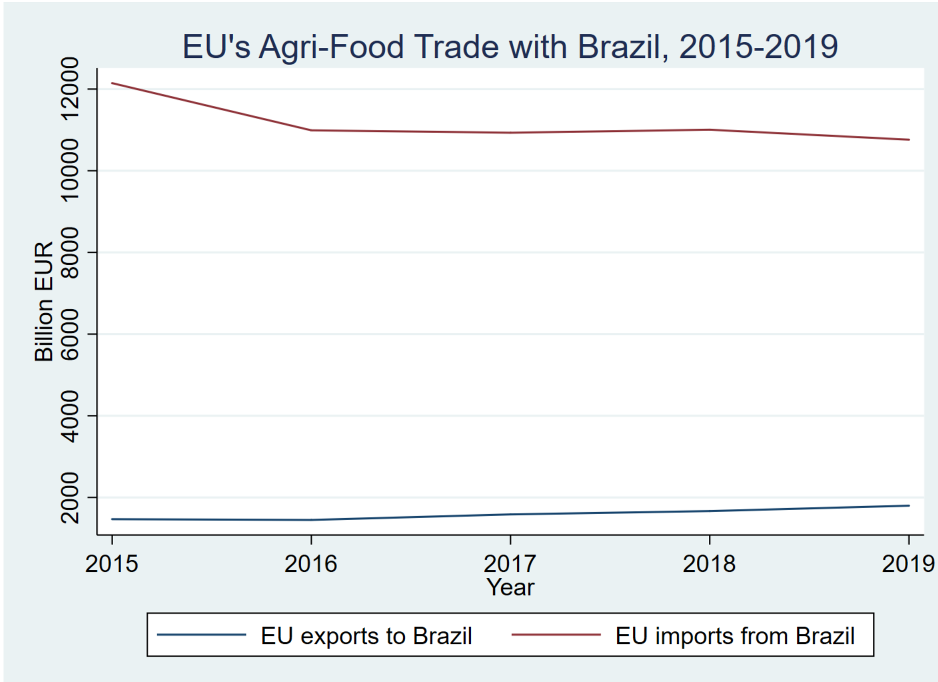

Figure 10: EU's Agri-Food Trade with Brazil (Billion EUR), 2015-2019

Again, it should be noticed that the trade value data of Brazil with EU-27 for 2015 is measured by subtracting Brazil's agri-food products trade with the United Kingdom from those with the EU-28, which is done by converting United Kingdom's agri-food products trade value with Brazil from US Dollar to Euro (WITS, 2015) based on the average exchange rate in 2015, and then subtract it from Brazil's agri-food products trade value with EU-28 that is measured in Euro (WITS, 2015), and data used for measuring that average exchange rate was previously showed in Table 1.

5 Methodology

5.1 Input-Output Analysis and Input-Output Model

In order to study the effect of the EU food carbon tax on Brazil's food industries and several food products through the inter-regional relationship not only directly through their bilateral trade but also indirectly through the impacts on global food prices, as well as simulate the long-term effect trends as time grows, we choose to use the input-output analysis method. It is a quantitative analysis method that can be used to study the interdependence or interrelationship between different sectors such as products, industries, and regions, so as to find the equilibrium conditions between supply and demand. In other words, input-output analysis is an innovative technique for explaining the general equilibrium of the economy (Ten Raa, 2009). According to Koutsoyiannis (1979), inputs refers to goods and services that are purchased as raw materials or resources for the production process by a firm, industry, or region, and outputs refers to goods and services that are sold out by them. Thus, inputs can also be thought of as costs to a firm, industry, or region, while outputs are revenues to them.

The first input-output model was proposed by Wassily Leontief in 1937 (Ten Raa, 2009). In an input-output model, an economy is structured as a set of interconnected sectors that both produce (i.e. as suppliers of inputs) and consume (i.e. as consumers of outputs) goods and services in the process of production, and therefore create flows between different sectors. That is, goods or services produced by one sector can flow to other sectors, as their inputs (Ebiefung and Kostreva, 1993).

The basic Leontief input-output model is set in the case of a static open economy, under the assumption that each involved sector produces only one homogeneous product and that no two products are produced jointly, which means that no two products are produced at the same time by a single production process (Dietzenbacher and Lahr, 2004). The basic Leontief input-output model takes the form

$$\mathbf{X} = A\mathbf{X} + \mathbf{F_d} \tag{1}$$

where $\mathbf{X}$ is a one column vector that represents the total output of different involved sectors, and $\mathbf{F_d}$ is a one column vector that represents the final demand (sometimes called final output), which can include consumption, investment and exports net of imports, of the goods and services that are produced by different sectors. In other words, $\mathbf{F_d}$ is the part of output that goes to the consumers. As for A, it is a symmetric matrix, called the input-output coefficient matrix, that records all the information about the flow of goods and services between different involved sectors, where all the elements a_{ij} in the A matrix represents the units or values needed from sector i for sector j to produce one unit or value of output. By multiplying the A matrix and the $\mathbf{X}$ vector together, the result represents the intermediate demand (sometimes called intermediate output) of the goods and services, which is the part of output that goes to all the different involved sectors (Nikaido, 1960).

When using the input-output model for analysis, the input-output coefficient matrix A and the final demand vector $\mathbf{F_d}$ are known, so we can use this model to study the output $\mathbf{X}$ that different sectors need to produce in order to meet a given final demand (i.e. final output) under a certain inter-sector relationship, which is measured by A. By re-arranging equation (1), the vector of total output can be solved by the following equation

$$\mathbf{X} = (I - A)^{-1}\mathbf{F_d} \tag{2}$$

where $(I-A)^{-1}$ is the Leontief inverse matrix, and if the matrix $(I-A)$ satisfies the Hawkins–Simon condition, which means that all the principal minors of $(I - A)$ are positive, then there exists a unique non-negative result for $\mathbf{X}$, the vector of total output (Nikaido, 1960).

The input-output analysis method can be helpful for studying both the general and chain effect on the economy caused by shocks on different involved sectors, and the linear form of the input-output model brings the advantages of convenient and rapid calculation, as well as flexibility to analyze the effect of changes in final demand (i.e. final output) (Miernyk, 2020). In addition, by setting a time index on the basic input-output model and introducing output inventory, the usefulness of the model can be extended to long-term dynamic studies (Barker and Santos, 2010). By linking different regions' input-output models together, the usefulness of the model can be extended to investigate the impacts of inter-regional relationship (Temurshoev, 2010). The usefulness of the model can also be extended to the investigation of emissions, employment, and wage flows between different sectors by including environmental vectors (Pan and Kraines, 2001), employment vectors, or income vectors (Bekhet, 2011) in the model. Based on these advantages, input-output analysis and input-output model have been frequently applied to assess and investigate the inter-regional and inter-industry dependencies and changes in output patterns that may be caused by certain policies. For example, to examine a energy, water, and food (EWF) relationship-based policy making approach to solve the EWF security (EWF-s) challenges, Vats et al. (2021) developed an EMF-extended input-output model, using India as a case study, and found that EWF relationship-oriented policy not only produces co-benefits in the long-term EWF outcomes improvement, but also causes significant improvement in economic, social, and environmental outcomes. To study the changes in carbon dioxide emissions embodied in the trade between China and US, Du et al. (2011) applied input-output analysis method and found out that intermediate input structure plays an important role in driving embodied CO_2 emissions higher during 2002-2007, and therefore suggested that China should introduce emission responsibilities allocation framework, improve energy efficiency, and improve the structure of intermediate input. Nevertheless, there are also arguments stating that input-output analysis and input-output model have drawbacks. For example, there is argument that the constancy of coefficient assumption is unrealistic, and the assumption of the proportional increase of inputs due to the increase of outputs causes limitation (Vollenweider, 1975). In addition, the lack of valid data can also be a major problem in input-output analysis, since the information on the flow between different sectors' inputs and outputs may take up to 5-7 years to be collected, and there is still no uniform statistical standard for different countries and regions (Rueda-Cantuche et al., 2020).

5.2 Model Setup: Multi-Regional Input-Output (MRIO) Model

On the basis of Leontief's inter-regional monetary Input-Output model, we generated our multi-regional input-output models for industrial level and product level cases, respectively. As previously mentioned, we think that the impact of the EU food carbon tax on Brazil's food sector is not only direct through their bilateral trade, but also indirectly through the effects on global food prices. Using the industrial-level model, we conduct a simple one-year forecast to compare the outputs of food-related industries in Brazil before and after the implementation of EU food carbon tax, as a first glance of the overall impact of EU food carbon tax on food industries in Brazil. Then to examine if outputs of the affected food products follow the same pattern in the changes of outputs of the food industries, using the product-level model, we conduct a seven-year simulation to observe the impact of the EU food carbon tax on several food products in Brazil. Specific details about the model settings are as follows.

5.2.1 Industrial Level Model

Sector Structure

The food industry include upstream industry like agriculture industry and downstream industry like manufacturing industry (Earle, 1997). The upstream industry mainly produces intermediate crops such as soybeans as inputs for the downstream industry, which will be then processed into feeds for livestock. In the industrial level model, we study on three food-related industries, which are agriculture, hunting and forestry industry, fishing and aquaculture industry, and manufacture of food products, beverages and tobacco products industry, in three regions, EU, Brazil, and the Rest of the World (ROW). Products produced by one industry can flow to the same or different domestic or foreign industries as intermediate demand, or as final demand for household, government, and non-profit institution consumption, investment, inventory, and export. In words, the output of an industry can be used for the following three purposes: (1) For its own production as an intermediate input; (2) Flow into another industry as an intermediate input, including domestic industries and foreign industries; (3) For the final use as a final good, including domestic and foreign final use. Moreover, the price of the goods and services from the same sector in each different region is assumed to be homogeneous.

Shock

We consider the implementation of food carbon tax in EU as a shock in the industrial level model. Given that food carbon tax is based on greenhouse gas emissions (GHGe), shocks are heterogeneous for food industries with different emissions, and we think then through international trade, the shock caused by the EU carbon tax on food can spread to the extra EU regions.

Imports and Exports

Imports and exports are measured in monetary terms in our model. In the industrial level model, we assume that the inter-sector flow of the imported goods and services plays an important part in a region's intermediate demand. Hence, we consider imports to be used by a region as both intermediate demand for production inputs and final demand for consumption or exports.

Total Demand

Total demand is also measured in monetary terms in our paper. The total demand is composed of the intermediate demand, which performs as inputs for own or other sectors, and the final demand, which includes demand from households, government, investors, and non-domestic customers.

- **Intermediate demand**

  The intermediate demand is defined as the demand of inputs for a particular intermediate sector. The standard assumption is that intermediate inputs are used in a fixed proportion to the output of a given sector (Vollenweider, 1975).

The inputs from sector i to a particular intermediate sector j at time t can be expressed by:

$$O_{ij,t} = a_{ij} X_{i,t}$$

where $X_{i,t}$ is the output of domestic sector i at time t, $O_{ij,t}$ is the intermediate demand of domestic sector j from sector i at time t, and a_{ij} measures the units or values needed from sector i for sector j to produce one unit or value of output.

Therefore, the aggregated intermediate demand of domestic sector i at time t can be written as

$$O_{i,t} = \sum_{j=1}^{n} a_{ij} X_{i,t} \tag{3}$$

and the aggregated intermediate demand of all domestic sectors in region r at time t can be written as

$$O_t^r = A^r X_t^r \tag{4}$$

where O_t^r represents region r's intermediate demand of all domestic sectors, X_t^r represents region r's output of all domestic sectors, and A^r is region r's input-output coefficient matrix with elements a_{ij} contain all the information about the flow of goods and services between different domestic sectors.

- **Final demand**

  Final demand consists of domestic final demand and foreign final demand for final products, where domestic final demand consists of demands from the consumers, investors, non-profit institutions, and government, and foreign final demand includes final products exported to external regions. In equation form, the final demand of region r at time t can be written as

$$F_t^r = F_{d,t}^r + F_{m,t}^r \tag{5}$$

  where $F_{d,t}^r$ is the domestic final demand of region r at time t, and $F_{m,t}^r$ is the foreign final demand of region r at time t.

By adding up the intermediate demand O_t^r and the final demand F_t^r, the total demand D_t^r of region r at time t in an open economy can be written as

$$D_t^r = O_t^r + F_t^r \tag{6}$$

and by plugging equation (4) and equation (5) in equation (6), the total demand is

$$D_t^r = A^r X_t^r + F_{d,t}^r + F_{m,t}^r \tag{7}$$

Equilibrium

Domestically, the total supply in region r at time t is considered to include both imports and domestic output, and under equilibrium condition, total supply equals total demand, which therefore gives us the balance equation of region r at time t as

$$M_t^r + X_t^r = A^r X_t^r + F_{d,t}^r + F_{m,t}^r \tag{8}$$

where M_t^r represents region r's imports at time t, and the rest of the variables are defined as previous mentioned.

We then further extend the model to a multi-region input-output model that includes inter-regional relationships using an aggregated system by not tracking imports explicitly, since imports to region r from region s are exports from region s to region r. The multi-region model is therefore:

$$X_t = AX_t + F_{d,t} + F_{m,t} \tag{9}$$

and in our three-region analysis that contains Brazil, EU, and the rest of the world (ROW), the output vector X_t takes the form

$$X_t = \begin{bmatrix} X_t^{BRA} \\ X_t^{EU} \\ X_t^{ROW} \end{bmatrix} \tag{10}$$

where X_t^{BRA}, X_t^{EU}, and X_t^{ROW} represents Brazil, EU, and ROW's domestic outputs, respectively.

As for the A matrix, it records information for both domestic and inter-regional flow between different sectors, which can be expressed by

$$A = \begin{bmatrix} A^{BRA\_BRA} & A^{BRA\_EU} & A^{BRA\_ROW} \\ A^{EU\_BRA} & A^{EU\_EU} & A^{EU\_ROW} \\ A^{ROW\_BRA} & A^{ROW\_EU} & A^{ROW\_ROW} \end{bmatrix} \tag{11}$$

In this matrix, except for the three matrices A^{BRA_BRA}, A^{EU_EU}, and A^{ROW_ROW} on the diagonal that records the domestic flow information, all the other matrices record the inter-regional flow between different sectors. For example, the matrix A^{BRA_EU} shows the inputs flow from EU to Brazil. Given that there are three industries involved in our model for each region, each matrix contained in the A matrix is a 3×3 matrix, and the A matrix is therefore a 9×9 matrix.

In matrix form, the model can be expressed as

$$\begin{bmatrix} X_t^{BRA} \\ X_t^{EU} \\ X_t^{ROW} \end{bmatrix} = \begin{bmatrix} A^{BRA\_BRA} & A^{BRA\_EU} & A^{BRA\_ROW} \\ A^{EU\_BRA} & A^{EU\_EU} & A^{EU\_ROW} \\ A^{ROW\_BRA} & A^{ROW\_EU} & A^{ROW\_ROW} \end{bmatrix} \begin{bmatrix} X_t^{BRA} \\ X_t^{EU} \\ X_t^{ROW} \end{bmatrix} + \begin{bmatrix} F_{d,t}^{BRA} \\ F_{d,t}^{EU} \\ F_{d,t}^{ROW} \end{bmatrix} + \begin{bmatrix} F_{m,t}^{BRA} \\ F_{m,t}^{EU} \\ F_{m,t}^{ROW} \end{bmatrix} \tag{12}$$

5.2.2 Product Level Model

Sector Structure

In the product level model, we study on six sectors in Brazil, and each is responsible for the production of one kind of food product. Similar to the model setting at the industrial level, the output of one sector can be used for the following three purposes: (1) For its own production as an intermediate input; (2) Flow into another domestic sector as an intermediate input; (3) For the final use as a final good, including both domestic and foreign final use.

Shock

As in the model setting at the industrial level, we consider the implementation of food carbon tax in EU as a shock. Since a food carbon tax is greenhouse gas emissions-based, we think shocks are heterogeneous for different food products with different emissions. Through international trade, the shock caused by the EU carbon tax on food can spread to the extra EU regions.

Imports and Exports

Unlike the industrial level model setting, in the product level model, we assume that the amount of imported products used for intermediate demand is negligible. Thus, all Brazil's imports are used for the final demand including domestic consumption and exports.

Total Demand

- **Intermediate Demand**

  The intermediate demand formula for the industrial level model still applies in the product level model, so Brazil's intermediate demand is

  $$O_t = A^{BRA} X_t \tag{13}$$

  where O_t is Brazil's intermediate demand of all domestic sectors at time t, X_t is the Brazil's total outputs of all domestic sectors, and A^{BRA} is Brazil's product level input-output coefficient matrix with elements a_{ij} that records all the information about the flow of goods and services between different domestic sectors.

- **Final Demand**

  In the product level model, final demand F_t is set to include domestic consumption demand and foreign final demand (i.e. exports), and we have distinguished exports to the EU and to the rest of the world, which therefore results in the equation

  $$F_t = F_{d,t} + F_{EU,t} + F_{ROW,t} \tag{14}$$

where $F_{d,t}$ is Brazil's domestic final demand at time t, $F_{EU,t}$ is Brazil's exports to EU at time t, and $F_{ROW,t}$ is Brazil's exports to the rest of the world at time t.

By adding up Brazil's intermediate demand O_t and final demand F_t, and plugging in equation (13) and (14), Brazil's total demand D_t at time t is

$$D_t = A^{BRA}X_t + F_{d,t} + F_{EU,t} + F_{ROW,t} \tag{15}$$

Equilibrium

At the product level, Brazil's total supply at time t is considered to include imports from the EU $M_{EU,t}$, imports from the rest of the world $M_{ROW,t}$, and its domestic output. By equalizing total supply and total demand, Brazil's equilibrium formula in product level can be written as

$$M_{EU,t} + M_{ROW,t} + X_t = A^{BRA}X_t + F_{d,t} + F_{EU,t} + F_{ROW,t} \tag{16}$$

In this setting, X_t is a 6×1 vector of Brazil's domestic output of all the six products we study on, which takes the form

$$X_t = \begin{bmatrix} X_t^1 \\ X_t^2 \\ \vdots \\ X_t^6 \end{bmatrix} \tag{17}$$

and the input-output coefficient matrix A^{BRA} here is a 6×6 matrix that implies the domestic inputs flow between the production sector of different food products. The A^{BRA} matrix takes the form

$$A^{BRA} = \begin{bmatrix} a_{11} & \cdots & a_{16} \\ \vdots & \ddots & \vdots \\ a_{61} & \cdots & a_{66} \end{bmatrix} \tag{18}$$

Hence, the model in matrix form can be expressed as

$$\begin{bmatrix} M_{EU,t}^1 \\ M_{EU,t}^2 \\ \vdots \\ M_{EU,t}^6 \end{bmatrix} + \begin{bmatrix} M_{ROW,t}^1 \\ M_{ROW,t}^2 \\ \vdots \\ M_{ROW,t}^6 \end{bmatrix} + \begin{bmatrix} X_t^1 \\ X_t^2 \\ \vdots \\ X_t^6 \end{bmatrix} = \begin{bmatrix} a_{11} & \cdots & a_{16} \\ \vdots & \ddots & \vdots \\ a_{61} & \cdots & a_{66} \end{bmatrix} \begin{bmatrix} X_t^1 \\ X_t^2 \\ \vdots \\ X_t^6 \end{bmatrix} + \begin{bmatrix} F_{d,t}^1 \\ F_{d,t}^2 \\ \vdots \\ F_{d,t}^6 \end{bmatrix} + \begin{bmatrix} F_{EU,t}^1 \\ F_{EU,t}^2 \\ \vdots \\ F_{EU,t}^6 \end{bmatrix} + \begin{bmatrix} F_{ROW,t}^1 \\ F_{ROW,t}^2 \\ \vdots \\ F_{ROW,t}^6 \end{bmatrix} \tag{19}$$

5.3 Calibration

After generating the industrial level model and the product level model, we calibrated the input-output coefficient matrix for those two models separately using 2018 as the base year.

5.3.1 Industrial Level Input-Output Coefficient Matrix

To obtain the industrial level multi-regional input-output coefficient matrix, we remake the 2018 inter-country input-output (ICIO) tables created by OECD (2021) by unifying all countries except Brazil and the EU into a region called the rest of the world (ROW), from where we know the sector-to-sector relationship in food production between different industries. By selecting the industries we want to study, we obtain the 9×9 input-output coefficient matrix for intermediate demand in the base year and assume it to be constant over our simulation time. The result is shown in Table 2.

Table 2: Industrial Level Input-Output Coefficient Matrix

		Brazil			EU			ROW		
		Agriculture	Fishing	Processing	Agriculture	Fishing	Processing	Agriculture	Fishing	Processing
Brazil	Agriculture	8.5E-02	6.9E-04	6.3E-01	5.5E-03	1.5E-05	3.2E-02	8.8E-02	3.0E-03	1.5E-01
	Fishing	5.5E-02	8.6E-02	7.7E-01	5.2E-04	1.6E-05	3.0E-03	7.4E-03	1.9E-03	7.3E-02
	Processing	1.5E-01	2.5E-03	6.8E-01	5.8E-03	9.6E-05	2.5E-02	3.9E-02	6.2E-03	8.8E-02
EU	Agriculture	5.2E-05	5.4E-07	2.8E-04	2.3E-01	6.0E-04	7.3E-01	1.1E-02	1.6E-04	2.5E-02
	Fishing	2.3E-05	3.4E-05	2.9E-04	8.5E-03	1.4E-01	7.2E-01	1.8E-03	9.1E-03	1.2E-01
	Processing	1.5E-04	2.2E-06	9.9E-04	1.6E-01	3.7E-03	7.6E-01	1.9E-02	2.8E-03	5.0E-02
ROW	Agriculture	7.3E-05	6.5E-07	4.3E-04	2.1E-03	1.3E-05	8.6E-03	3.6E-01	8.9E-03	6.2E-01
	Fishing	1.8E-05	2.7E-05	2.2E-04	1.2E-04	1.2E-03	1.2E-02	2.1E-02	2.3E-01	7.3E-01
	Processing	1.1E-04	1.7E-06	5.0E-04	2.8E-03	6.1E-05	1.2E-02	2.8E-01	4.0E-02	6.6E-01

The input-output coefficient matrix shows the composition of the use of inputs from different regions and industries in the production of a sector. The coefficient refers to ratios of input from each sector to total inputs from all sectors. For example, for agriculture, hunting, and forestry sector of Brazil to produce one unit of product, it requires 0.08513 units of agriculture products, 0.05504 units of fishing products, 0.14985 units of processed food products from Brazil, 0.00005 units of agriculture products, 0.00002 units of fishing products, 0.00015 units of processed food products from EU, and 0.00007 units of agriculture products, 0.00002units of fishing products, 0.00011 units of processed food products from ROW.

5.3.2 Product Level Input-Output Coefficient Matrix

To obtain the product level input-output coefficient matrix, we firstly applied Heijungs and de Koning (2019)'s method under the industry technology assumption, an assumption assumes that "all products produced by an industry are produced with the same input structure" (OECD, 2001), to derive the Input–Output Table (IOT) from a pair of 2018 Supply–Use tables (SUTs) generated by Brazilian Institute of Geography and Statistics (2019).

The input-output coefficient matrix of Brazil is presented as follows.

Table 3: Product Level Input-Output Coefficient Matrix

	Beef	Cheese	Coffee	Pork	Poultry meat	Vegetables
Beef	0.012994	0.011764	0.001213	0.015292	0.013771	0.001234
Cheese	0.016902	0.015136	0.004084	0.020027	0.018107	0.004016
Coffee	0.000005	0.000012	0.000553	0.000014	0.000021	0.000523
Pork	0.011204	0.009995	0.000004	0.013232	0.011928	0.000102
Poultry meat	0.009653	0.00861	0.000082	0.011398	0.010293	0.00016
Vegetables	0.000437	0.000464	0.005222	0.000599	0.000609	0.005052

5.4 Forecast Exogenous Variables

5.4.1 Industrial Level Model

Final Demand

Due to the lack of reliable data, we cannot come up with specific estimates for the changes in demand at the industry level. Therefore, based on the existing literature on the impact of food tax on demand and the carbon emissions of different industries, we assume corresponding percent for the change of final demand. In the product level, we will product more precise forecast of demand.

Empirical literature shows that the increase in price resulting from the introduction of a tax on food products is associated with a decrease in demand. Research by Ecorys (2014) found that demand for cooking oils, butter and margarine decreased by 5.5%, 5.5%, and 8.2% respectively in 2012 after they implement the tax on saturated fat in Denmark. Other kinds of food taxes also make the demand decrease between 0.4% to 11.2%. Furthermore, the decrease in demand is generally proportionally smaller than the increase in price. On average, a 1% increase in price is related with a 0.6% decrease in demand for food products .

Based on the global emissions data published by the World Resources Institute (Mengpin Ge and Vigna, 2020), approximately 20% of emissions come form agri-food related sectors. In detail, agriculture, hunting, and forestry sector accounts for 18.4%, manufacturing of tobacco products and food processing sector accounts for 1%, and fishing and aquaculture sector accounts for 1.7%. Thus agriculture, hunting, and forestry sector needs to pay the most carbon tax, then fishing and aquaculture sector and manufacturing of tobacco products and food processing sector.

Based on the literature of effects of food tax on demand and price and carbon emissions of these industries, we assume the carbon tax will cause a reduction of 11.04%, 1.02% and 0.6% respectively of these three sectors for the final demand and total imports of EU. Firstly forecasting the demand in the next period without carbon taxes using time series data, then calculating the final demand from the assumed decrease percentage, we obtain the forecast final demand for the three industries of EU, Brazil and rest of world, as shown in Table 4 below.

Table 4: Industry Level Final Demand

		t	t+1	Growth Rate
Brazil	Agriculture, hunting, forestry	46174.23	45938.17628	-0.511%
	Fishing and aquaculture	5757.206	5757.127597	-0.001%
	Food products, beverages and tobacco	136541.9	136522.1727	-0.014%
EU	Agriculture, hunting, forestry	2102285	1870192.313	-11.040%
	Fishing and aquaculture	256583.9	253966.7144	-1.020%
	Food products, beverages and tobacco	4119993	4095273.421	-0.600%
ROW	Agriculture, hunting, forestry	1902969	1900685.014	-0.120%
	Fishing and aquaculture	250584.9	250551.0434	-0.014%
	Food products, beverages and tobacco	3438193	3437824.883	-0.011%

5.4.2 Product Level Model

Carbon Tax

Since Finland first introduced a carbon tax in 1990, 18 EU countries have successively implemented carbon tax policies. Carbon tax rates of EU range from $0.08 per ton of carbon emissions in Poland to $137 in Sweden (World Bank, 2022). When calculating the carbon tax of different industries and products, we base on the carbon tax rate data from World Bank (2022). We set our carbon tax rate of EU countries at $42.49 per ton of CO2 equivalent, which is the average of current tax rate of these 18 countries. To control the effects of carbon price policy of other countries, carbon tax of Brazil and rest of world is assumed to be zero. Moreover, the carbon tax rate is assumed to be constant in our 7-year simulation period. Using the average current carbon tax rate of EU countries, we calculate the carbon tax on different food products base on carbon footprint data from Hannah Ritchie and Rosado (2020). Carbon emissions per kilogram and calculated carbon tax rate for different kinds of food products are shown as follows.

Table 5: Carbon Emission and Carbon Tax for Food Products

	Emissions (kg CO2/kg)	Tax (USD/kg)
Beef	60	2.5374
Cheese	21	0.88809
Coffee	17	0.71893
Pork	7	0.29603
Poultry	6	0.25374
Vegetable	0.4	0.016916

According to data from OECD/FAO (2021), the pre-tax price in base year 2018 and calculated after-tax consumer price on food products of EU is shown in Table 6 below. The increase of price for different kinds of food products varies from 0.1% to 65%. Since beef has the most emissions, the price of beef is most affected. Beef price increases approximately $2500 per tonne after the implementation of carbon tax on food products, while vegetables price only rises around \$17 per tonne.

Table 6: Pre-tax and After-tax Price for Food Products

Unit: USD/Tonne	Pre-tax Price	After-tax price
Beef	3931	6468.4
Cheese	3648	4536.09
Coffee	2593	3311.93
Pork	1965	2261.03
Poultry	1552	1805.74
Vegetable	1623	1639.916

Price

When forecasting the price of different food products, we use price data from OECD/FAO (2021) and trade data from FAO (2021) in 2018. Taking into account the impact of the price of food products imported from the EU on the local price, we use weighted average functions to calculate the average price in Brazil and the rest of the world (ROW) based on the import price and the import share of their total supply. As for the EU, we assume after the food carbon tax is added, its food prices rise and then remain the same.

Our assumption is that the economy starts at $t = 0$, with the same global unit food price for all participants, EU, Brazil, and ROW, which means that at $t = 0$, the unit price of a food product is subject to the following condition

$$P_{EU,t=0} = P_{BRA,t=0} = P_{ROW,t=0} = P_{t=0} \tag{20}$$

We assume that the EU implements a food carbon tax at $t = 1$ and then we forecast prices for 7 periods.

Since we assume that food prices in the EU rise and then remain the same after the food carbon tax implementation, the price of a food product from EU at $t = 1, 2, ..., 7$ will be

$$P_{EU,tax} = P_{t=0} + \tau \tag{21}$$

where $P_{t=0}$ is the pre-tax unit price of a food product, and τ is the unit food carbon tax put on that food product.

For Brazil and ROW, we assume that at $t = 1, 2, ..., 7$, their food prices are affected by the prices of imported food products, and therefore we choose to use weighted average functions to calculate the average price of their food products at $t = 1, 2, ..., 7$. As for the weights, we assume that their weights in each period are derived by referring to the proportion of imports and domestic output to total supply in the previous period. Therefore, price of a food product from Brazil at $t = 1, 2, ..., 7$

can be expressed by

$$\begin{aligned}P_{BRA,t} =& \frac{Import_{EU,t-1}}{Import_{EU,t-1} + Import_{ROW,t-1} + X_{BRA,t-1}} * P_{EU,tax} \\ &+ \frac{Import_{ROW,t-1}}{Import_{EU,t-1} + Import_{ROW,t-1} + X_{BRA,t-1}} * P_{ROW,t} \\ &+ \frac{X_{BRA,t-1}}{Import_{EU,t-1} + Import_{ROW,t-1} + X_{BRA,t-1}} * P_{t=0}\end{aligned} \tag{22}$$

where $X_{BRA,t-1}$ represents Brazil's total output of a food product.

Similarly, the price of a food product from ROW at $t = 1, 2, ..., 7$ can be expressed by

$$\begin{aligned}P_{ROW,t} =& \frac{Import_{EU,t-1}}{Import_{EU,t-1} + Import_{BRA,t-1} + X_{ROW,t-1}} * P_{EU,tax} \\ &+ \frac{Import_{BRA,t-1}}{Import_{EU,t-1} + Import_{BRA,t-1} + X_{ROW,t-1}} * P_{BRA,t} \\ &+ \frac{X_{ROW,t-1}}{Import_{EU,t-1} + Import_{BRA,t-1} + X_{ROW,t-1}} * P_{t=0}\end{aligned} \tag{23}$$

where $X_{ROW,t-1}$ represents ROW's total output of a food product.

By combining equations (20), (21), (22), and (23), the values of $P_{EU,tax}$, $P_{BRA,t}$, and $P_{ROW,t}$ are all solvable.

Quantity

In order to obtain the quantity demanded change after the introduction of EU food carbon tax, we use the method from Wirsenius et al. (2011) to estimate the effects of a food carbon tax on the quantity demanded of different food products. They provide a way to gain relative change in demand using a function of relative changes in the prices of food products and their own- and cross-price elasticities of demand. Estimated value of own- and cross-price elasticities between animal food are also based on the work of Wirsenius et al. (2011). Moreover, cross-price elasticities between vegetables and other food products are assumed to be zero.

$$Q_i^{Tax} = Q_i^{Ref} \prod_{j=1} \left[\frac{P_j^{Tax}}{P_j^{Ref}} \right]^{\boldsymbol{\varepsilon_{ij}}} \tag{24}$$

where
Q_i^{Tax} is the after-tax total quantity demanded of food product i
Q_i^{Ref} is the pre-tax total quantity demanded of food product i
P_j^{Tax} is the after-tax unit price of product j
P_j^{Ref} is the pre-tax unit price of product j
$\boldsymbol{\varepsilon_{ij}}$ is the own- and cross-price elasticities of demand

In order to forecast the pre-tax quantity demand of consumption, exports and imports, we use consumption data of past years comes from Our World in Data (2020) and trade data of past years from FAO (2021), and make the forecast through time series forecast tools in R, where we assume population and income are fixed through our simulation period.

We include both own- and cross-price elasticity of demand into our after-tax forecast. Own price elasticity measures the percentage change in the quantity demanded of a good when the price of the good changes, and cross price elasticity is used to measure the responsiveness of the quantity demanded for one product when the price of another product changes. Previous scholars often use two ways to determine the cross price elasticity. Some scholars assume the cross-price elasticity to be zero(Holmes, 1989), that is, if the price of meat increases, the demand for the vegetarian diet is assumed to be unchanged. Other scholars believe the cross price elasticity between different kinds of food products is not zero(Andreyeva et al., 2010). Considering there are complementary and substitute relationships between different categories of food products, we assume the cross-price elasticity not to be zero in our study. According to Wirsenius et al. (2011) and Anderson et al. (1997), based on the data of EU countries, the estimated own- and cross- price elasticities between beef, pork, poultry, cheese, coffee and vegetables are presented below.

Table 7: Estimated own- and cross- price elasticity

	Beef	Cheese	Coffee	Pork	Poultry	Vegetable
Beef	-1.3	-0.05	0	0.3	0.3	0
Cheese	-0.03	-0.5	0	-0.03	-0.02	0
Coffee	0	0	0.25	0	0	0
Pork	0.3	-0.04	0	-0.8	0.3	0
Poultry	0.6	-0.04	0	0.5	-1	0
Vegetable	0	0	0	0	0	0

6 Simulation Results and Discussion

An important part of input-output model is that it enables to forecast one variable with other variables using balance equations. Solving the model requires two steps. Firstly, forecast most variables exogenously or use an equation to specify their relationship with other variables. Secondly, the last variable can be solved in terms of the rest based on balance equation.

6.1 Industrial Level Model

In the industrial level, the equilibrium formula can be written as

$$X_t = AX_t + F_{d,t} + F_{m,t} \tag{25}$$

Given that the final demand is assumed to be exogenous, the output of the domestic economy for an arbitrary demand in time period $t+1$ is

$$X_{t+1} = (I - A)^{-1}(F_{d,t+1} + F_{m,t+1}) \tag{26}$$

Final demand is comprised of the domestic demand and exports demand. We apply the same shocks to exports demand $F^r_{i,t+1}$ and domestic final demand $F^r_{d,t+1}$. On the one hand, the carbon tax of EU will have direct effects on the price of food products produced in the EU, which in turn affects domestic demand and exports. On the other hand, due to the change of demand for food products in the EU, it indirectly affects the imports from other countries. Thus the final use demands affected by the EU carbon tax include EU domestic demand $F^{EU}_{d,t+1}$, EU export to Brazil $F^{EU}_{m_{BRA},t+1}$, EU export to rest of world $F^{EU}_{m_{ROW},t+1}$, EU import from Brazil $F^{BRA}_{m_{EU},t+1}$ and EU import from rest of world $F^{BRA}_{m_{ROW},t+1}$.

Using the industrial level input output coefficient matrix and assumed demand, we obtain the output in the next year. The effects of carbon tax on different regions' food industries output are shown in Table 8 below. All sectors from Brazil and rest of the world have less outputs after the implementation of carbon tax. Fishing and aquaculture sector of Brazil suffers most, then is the manufacturing of tobacco products and food processing sector of Brazil. One of the factors leading to the closeness of changes in production of these two sectors could be the close linkage of their inputs of production. As shown in the technology matrix, for the manufacturing of tobacco products and food processing sector of Brazil to produce one unit product, it requires 0.77245 units of domestic fishing and aquaculture products. Thus the domestic output of fishing and aquaculture sector is associated with the output of food processing sector in Brazil.

The output of sectors in EU show interesting changes. The agriculture, hunting and forestry sector of EU product more even though the total final demand decreases by more than 10 percent. It adds nearly 431 billion in output, while the fishing sector adds nearly 10 billion and the food processing sector decrease around 34 billion. It implies that the intermediate demand of agriculture sector and fishing sector increase rapidly after the introduction of carbon tax on food products. Conversely, production in the food processing sector has decreased. Unlike the other two sectors, most inputs in the EU food processing sector come from domestic sources. It requires 0.72865 units of agriculture products, 0.7183 fishing products and 0.76384 processed food products to make one unit product. Its large demand for other two domestic sectors could help account for the increase intermediate demand of those two.

Table 8: Industry Level Outputs

		Output		
		t	t+1	Growth Rate
Brazil	Agriculture, hunting, forestry	124913.7575	66208.47848	-47%
	Fishing and aquaculture	6814.441476	838.109031	-88%
	Food products, beverages and tobacco	169148.4417	26829.10332	-84%
EU	Agriculture, hunting, forestry	520904.8656	951924.5895	83%
	Fishing and aquaculture	15878.98909	25747.81486	62%
	Food products, beverages and tobacco	1142295.732	796524.3467	-30%
ROW	Agriculture, hunting, forestry	4331213.006	1699515.929	-61%
	Fishing and aquaculture	424543.2593	147430.0388	-65%
	Food products, beverages and tobacco	4450404.76	789385.99	-82%

6.2 Product Level Model

After finding the effects of EU carbon tax on global food industries, we concentrate on the effects on the specific products of Brazil. By using the price elasticity of demand, we obtain the total domestic and foreign demand of next period. In addition, we have the data of input-output coefficient matrix. Then we can solve the output using balance equations. Given that the final demand is assumed to be exogenous, the output of the domestic economy for an arbitrary demand in time period $t+1$ is

$$X_{t+1} = (I - A)^{-1}(F_{d,t+1} + F_{m,t+1} - M_{t+1}) \tag{27}$$

6.2.1 Price

To observe the effects, we firstly take a look at the food prices. The forecast values of food product price in Brazil and rest of world are shown as follows. We can see from the results that a tax introduction is followed by prices increasing for most products in Brazil and rest of world in the short run. Overall, food price in rest of world rise more than Brazil. More than half products' price in rest of world increases by more than \$10 per ton, while in Brazil most products' price only increase less than \$1 per ton. The sharp rise in food price of rest of world is related to their dependence on trade with the EU. The rest of world import a larger share of food products from the EU than Brazil does. From a dynamic perspective, food price in Brazil and other countries show similar trends. The price of some products like vegetables continue to increase slightly after the introduction of carbon tax, while the price of some products fluctuates in the short run and keep steady from three or four years later, such as beef, cheese and poultry.

Among various food products, the price of cheese increase most, followed by beef and coffee. Cheese price in the rest of world increases by nearly \$100 per ton in 7 years and in Brazil rises by around \$4 per ton. The pork and poultry price only slightly increases, while the vegetables price is almost unchanged. On the one hand, the results prove again that prices of food products that are more reliant on EU imports are more affected by EU carbon tax. In the base year, Brazil import 3051 ton cheese from EU while only import 556 ton pork and 12 ton poultry. On the other hand, the various impacts on different categories of food products is correlated with their carbon emission and tax need to pay. Brazil hardly imports beef from the EU, however, since the price of beef in EU rises a lot due to the high carbon tax, it affects EU beef export to other countries and further affect the global beef price.

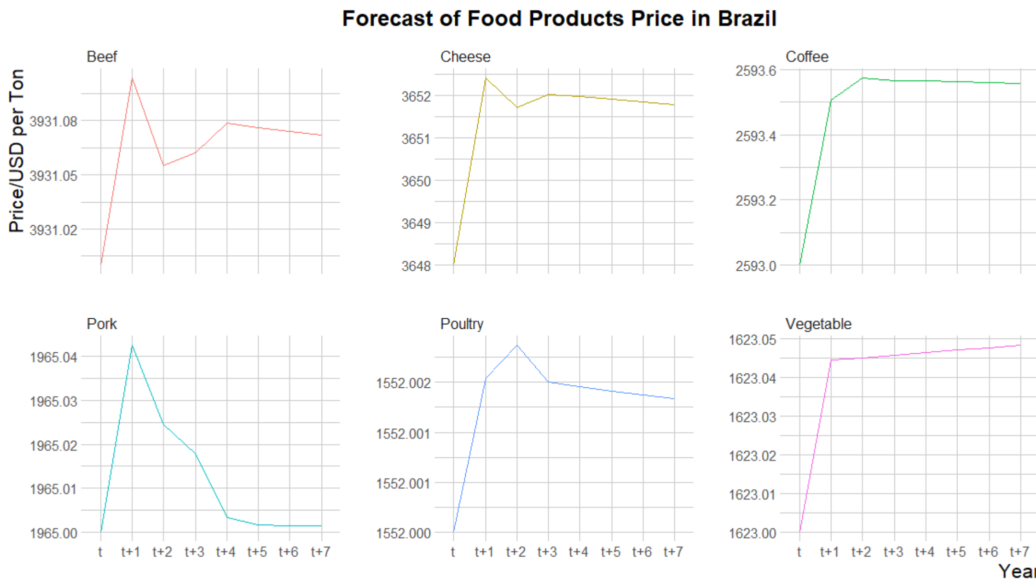

Figure 11: Forecast of Food Products Price in Brazil

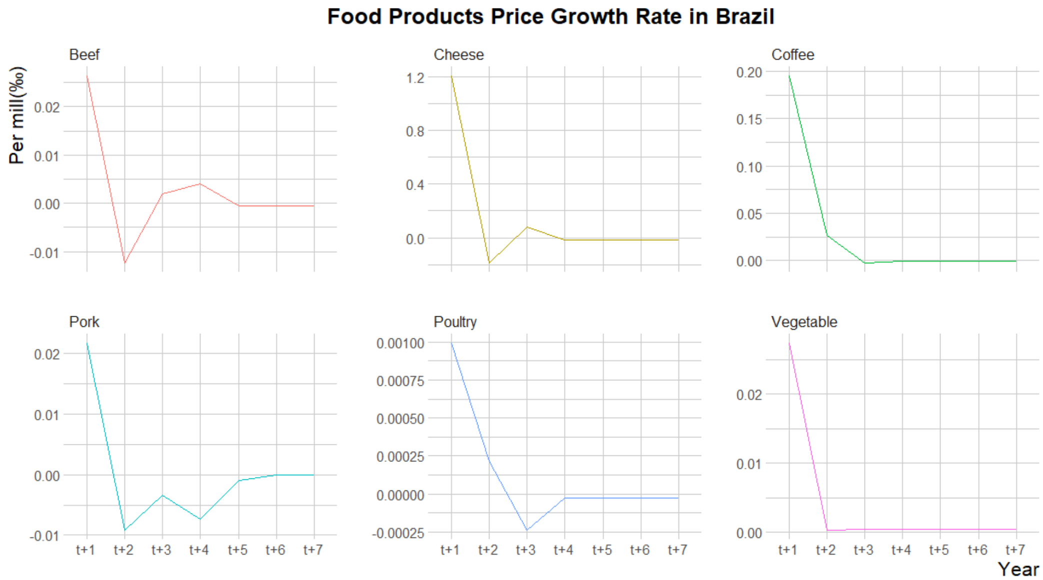

Figure 12: Food Products Price Growth in Brazil

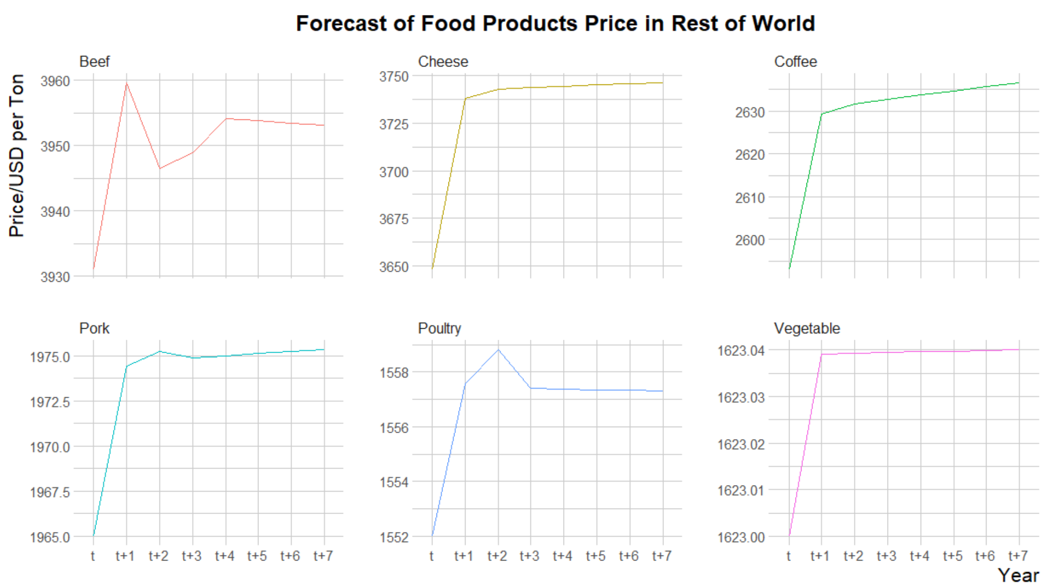

Figure 13: Forecast of Food Products Price in Rest of World

Figure 14: Food Products Price Growth in Rest of World

6.2.2 Consumption

Figure 15 displays the forecast of Brazil's domestic food product consumption. For most products, there is little impact of carbon tax on Brazil's domestic consumption demand. For all products except for coffee, the consumption increases at a steady rate. In terms of coffee, we note there is a rapid rise on consumption in the first year after implementing the carbon tax on food, and there is a small gap between the pre-tax consumption and after-tax consumption. Interestingly, since the second year after the introduction of carbon tax, the consumption of coffee reaches a long-term steady state.

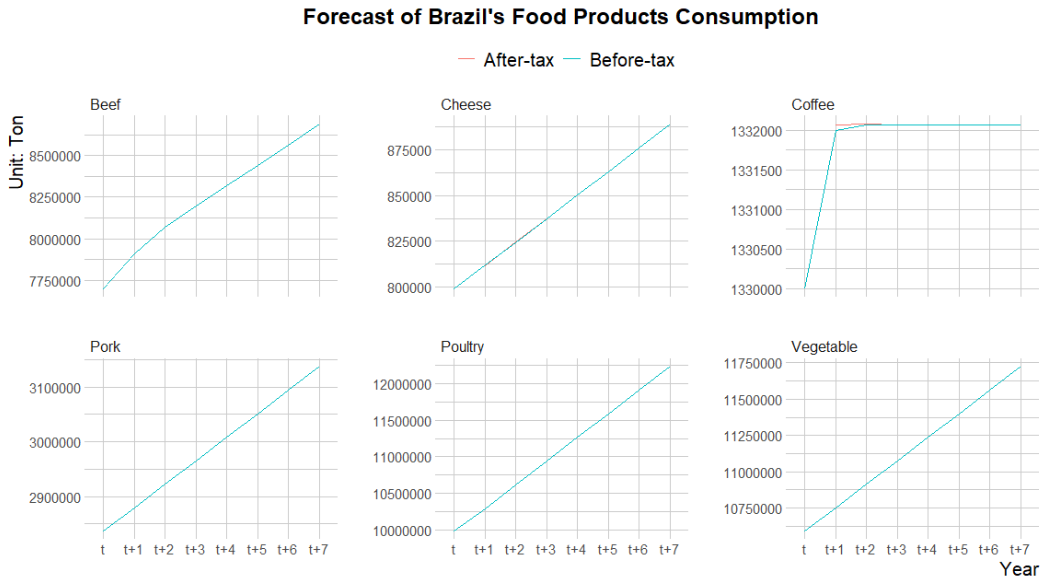

Figure 15: Forecast of Brazil's Food Products Consumption

6.2.3 Import from and Export to EU

Brazil's food import and export forecasts after the implementation of carbon tax are presented in Figure 16 and Figure 17 below. The import and export show various trends for different categories of food products. Compared with exports, Brazil's import from EU is more affected. Among Brazil's all import products, beef, cheese and coffee are affected most by the shock. Compared with the base year, imports of beef, coffee and pork fall off, while imports of cheese and poultry rise. However, compared with the before-tax forecast, Brazil import more coffee, pork and poultry after tax and import less beef and cheese. On the one hand, the decrease of imports for beef and cheese can be attributed to the high carbon tax on these two products, whose carbon emissions are the highest too. On the other hand, the demand change of different food products is related to their own- and cross-price elasticity. For substitute products, an increase in the price of a product will lead to an increase in the demand for its competing product. Given that cross-price elasticities between beef and pork or poultry are both positive, keeping all other factors constant, an increase in beef price in EU is related to an increase of demand of pork and poultry. Furthermore, the cross-price elasticities between cheese and beef, pork, poultry are all negative. Thus, the demand of beef, pork and poultry will decrease after the rise of cheese price. Under the combined effect of various food price changes, positive impact outweighs the negative impact for pork and poultry, while negative impact outweighs the positive impact for beef and cheese.

By looking more closely at Figure 16, we observe the trends and magnitudes of the change in imports of these products vary. Brazil's import of vegetables grows most among all products. Brazil imports approximately 6000 ton more vegetables in seven years, while only imports 5 more ton poultry. In terms of trends, there is a continued growth in Brazil's import demand for vegetables. The imports of cheese and poultry also increase, but in a different way. They rise rapidly in the first two years and stay steady in the long run. Imports of beef, coffee and pork show opposite trends. Brazil's beef and coffee imports from EU decline rapidly after the shock, then stabilize a few years later.

For Brazil's export to EU, we note coffee is the only product that is greatly affected by the carbon tax. Brazil's coffee exports to EU surge in the first year after the implementation of carbon tax. For the third year, it returns to the steady state. There is little gap between the before-tax export and after-tax export for other products. Furthermore, as can be observed in Figure 16 and 17, there is a big difference between the trend directions of import and export for different products. It is interesting to find that for pork, poultry and vegetables, both import and export change in the same direction after the shock, while beef, cheese and coffee show opposite trends in import and export.

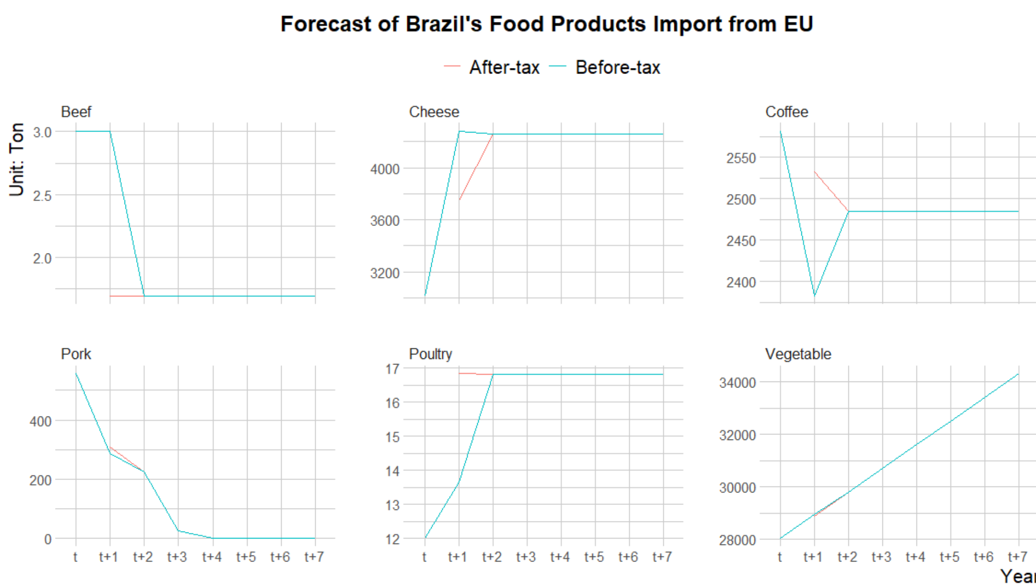

Figure 16: Forecast of Brazil's Food Products Import from EU

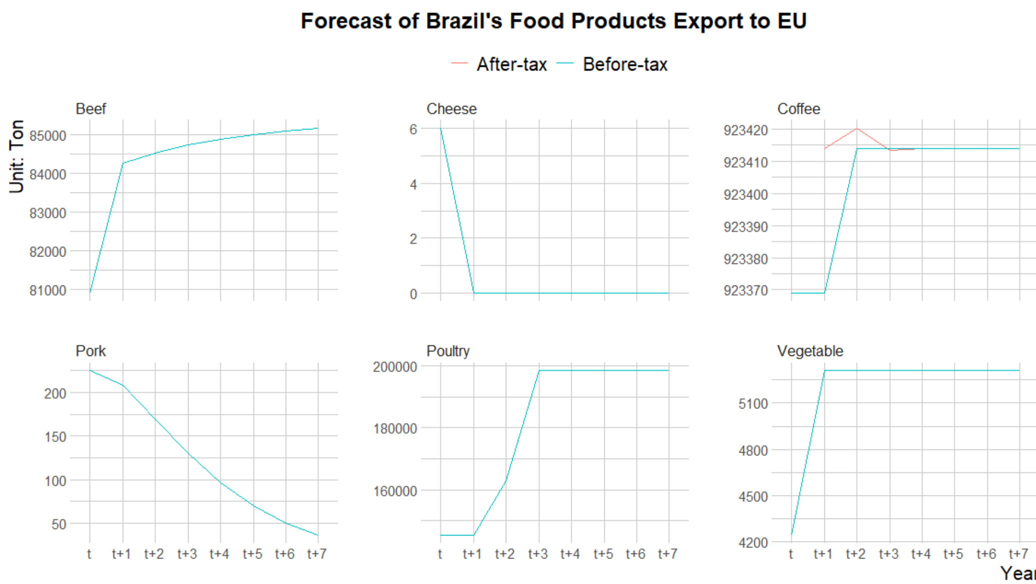

Figure 17: Forecast of Brazil's Food Products Export to EU

6.2.4 Final Demand

Figure 18 and Figure 19 present the final demand and its growth rate of Brazil. It is obvious that there is almost no gap between the pre-tax and after-tax final demand, which equals the sum of consumption and total exports minus total imports. The final demand of all products show increasing trends in the following years. However, the growth rate is various among different categories of food products. After the carbon tax is implemented, the growth rate of final demand for beef, pork and vegetables gradually declines, while that of cheese and poultry increases first and drop then. The growth of final demand for coffee stays at a low rate. Overall, the final demand of all products grows steadily, and poultry sees the most growth. In sum, the food carbon tax of EU does not have significant effects on Brazil's food products final demand.

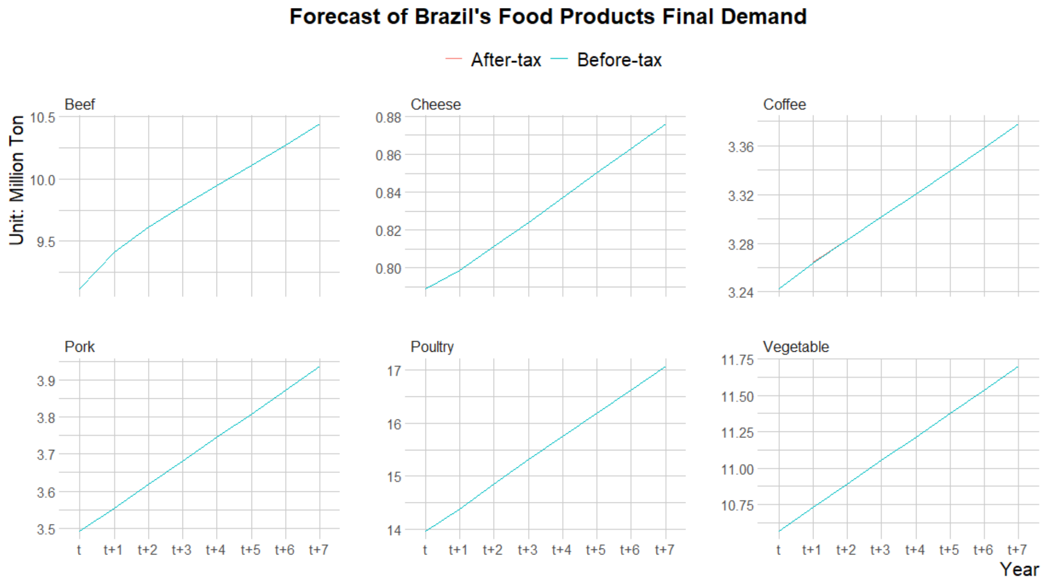

Figure 18: Forecast of Brazil's Food Products Final Demand

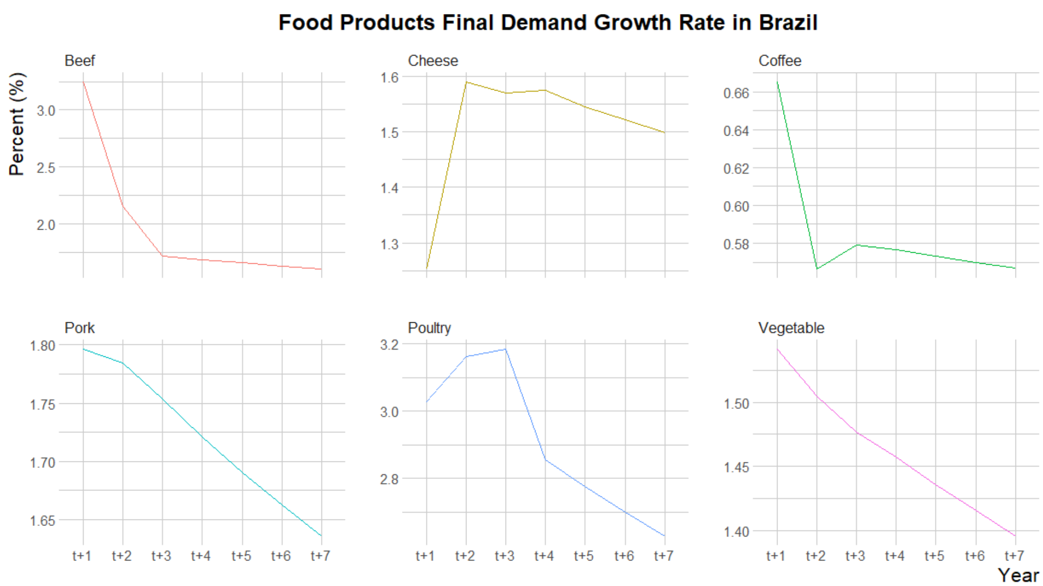

Figure 19: Food Products Final Demand Growth Rate in Brazil

6.2.5 Output

Using the balance equation of IO model, the output of the domestic economy in time period $t+1$ is

$$X_{t+1} = (I - A)^{-1}(F_{d,t+1} + F_{m,t+1} - M_{t+1}) \tag{28}$$

As shown in Figure 20 below, there is little difference between the pre-tax output and after-tax output in Brazil. In the first year after the implementation of carbon tax, outputs of beef, cheese, coffee and pork show small fluctuations, while outputs of poultry and vegetables increase steadily. The output of poultry is most affected by the carbon tax. Brazil's domestic poultry output rises by more than 4 million tons in the following 7 years. The outputs of beef and vegetables both increase by approximately 1 million ton. Coffee is the only product whose output decreases after the implementation of carbon tax. Taking the final demand growth of all products into consideration, the decreasing output of coffee in the first year can be attributed to the decrease of intermediate demand. Since the production of all other products do not require a lot of coffee inputs, the drop of intermediate demand of itself contributes to the decreasing outputs.

By looking back at the technical matrix of Brazil, we observe that the production of cheese, poultry meat, pork and beef is related to each other. In order to product one unit of beef, it requires 0.013 units of beef, 0.017 units of cheese, 0.011 units of pork and 0.01 unit of poultry. To produce one unit of pork, it requires 0.015 beef, 0.02 cheese, 0.013 pork and 0.011 poultry meat. One unit of poultry meat production needs 0.014 units of beef, 0.018 units of cheese, 0.012 units of pork and 0.010 units of poultry meat. In some sense, the close relationship among the these products' production contribute to the similar trends of outputs of these products.

Figure 21 displays the after-tax output growth rate in Brazil in the following 7 years. Overall, all products' output growth rates stay at a low level. In the first year after implementation of carbon tax, among all products, cheese and has highest growth rate while coffee has the smallest rate. In the second year, growth rates of all products show small fluctuation.

As shown in Figure 22, the ratio of after-tax output to pre-tax output of different products is various. For animal food like beef, pork and poultry, the gap between after-tax output and pre-tax output gradually narrows. On the contrary, the gap for vegetables widens. For cheese and coffee, there is a small fluctuation for the ratio. Overall, the difference between after-tax output and pre-tax output is not greatly affected by the carbon tax. In most cases, the after-tax output is a little smaller than the pre-tax output. It is important that the differences in the results at the industry and product levels are not contradictory, but because of the differences in the methods we used to estimate the final demand. Furthermore, we need to emphasize that an increase in the demand for the final product does not correlate with an increase in output due to inter-sectoral flows. In the same way, output can increase even if final demand decreases.

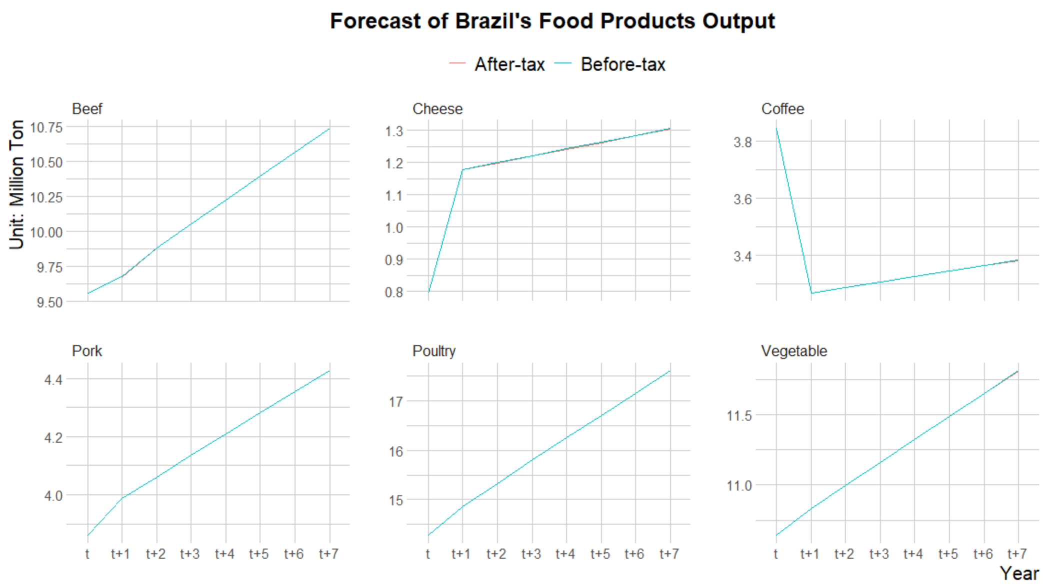

Figure 20: Forecast of Brazil's Food Products Output

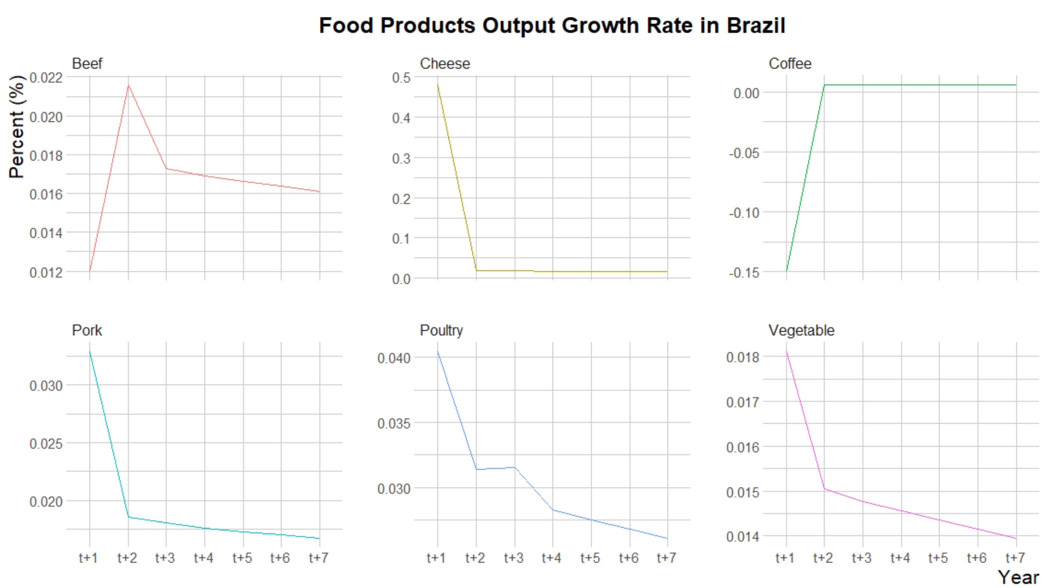

Figure 21: Food Products Output Growth in Brazil

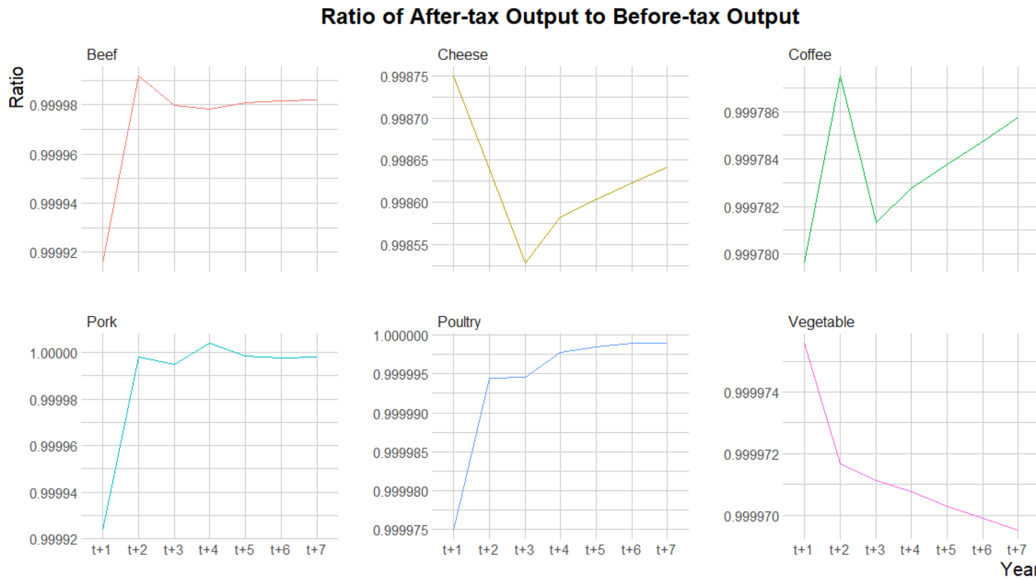

Figure 22: Ratio of After-tax Output to Before-tax Output in Brazil

7 Limitations and Further Research Suggestions

7.1 Limitations

There are several limitations of our paper, and one is the disadvantage of the input-output model. Firstly, input-output model is restricted since it only emphasizes the productive side of the economy and demand is assumed to be exogenous. Final demand is regarded as an independent variable in the input-output model. Though we use the own- and cross- price elasticity to estimate the effects of carbon tax on demand, it is hard to measure changes of the demand curve at the microeconomics level. Secondly, when we forecast the consumption demand of consumers, we do not take the change of consumer preference into consideration. Thirdly, the assumption of fixed coefficient of production ignores the possibility of inputs substitution. Since the carbon tax is envied on consumers, it is difficult to measure the factor substitution in production. Another limitation is the lack of reliable data in the industrial level, which limits the scope of our analysis. Due to the lack of industry price data, we can not come up with accurate forecast of demand. Therefore we can only assign them a value based on the existing literature and qualitative analysis. Considering the accuracy of the data, we cannot make long-term forecasts, so we only solve the model for one year.

7.2 Suggestions for Future Research

The results of our paper would provide insights regarding further research on food carbon tax. Firstly, based on our research on the impact of carbon tax on production at the industry level, there is room for further study on effects on unemployment rates, wages, etc. in the food industry. As our study shows, carbon tax has various effects on different sectors. It may lead to the labor flow between industries and sectors, possibly increase the wage of several sectors while reduce others. Moreover, we would suggest that future research also explore the effects on global food industry employment market.

Secondly, it would be important to discuss the effects of similar policies aimed at reducing greenhouse gas emissions, such as subsides on sustainable food, on the consumers' behavior. Carbon tax may encourage more consumers to purchase sustainable meat substitutes, resulting in the change of consumer preference. If future research could simulate the mixed effects of carbon tax and subsides on sustainable food, that would potentially contribute to change consumers' behavior and thus reduce the carbon emission.

Thirdly, due to the lack of reliable data, we do not obtain a long-term forecast at the industry level. If future research could identity ways to forecast the industry price, that could potentially be key to studying the long-term effects of carbon tax on both price and output of food industries. As consumer preferences change, consumption demand for carbon-intensive foods tends to decrease, which might leads to different effects of carbon tax in the long and short term.

8 Conclusion

We finally conclude that we find different effects of a food carbon tax in the EU on Brazil's production of food industries, including agriculture, hunting, and forestry industry, fishing and aquaculture industry, and manufacturing of tobacco products and food processing industry, and certain food products like beef, pork, poultry, cheese, coffee and vegetables. At the industry level, with a reduction of 0.511%, 0.002% and 0.014% respectively of these three industries, Brazil's domestic outputs decline 47%, 88% and 84%. Fishing and aquaculture industry of Brazil is most affected by the carbon tax. For agriculture, hunting, and forestry industry and fishing and aquaculture industry, production of EU increases, while production of other countries decreases. For manufacturing of tobacco products and food processing sector, there is a decrease on global production, and production of Brazil declines most. At the product level, a carbon tax on food in the EU leads to a global short-run price increase on most food products. Brazil imports fewer carbon-intensive foods like beef and cheese. However, there is little impact of carbon tax on Brazil's domestic demand or production. The final demand of all products shows increasing trends in the following seven years. All products except for coffee produces more after the implementation of carbon tax. It is important that the differences in the results at the industry and product levels are not contradictory, but because of the differences in the methods we used to estimate the final demand. By figuring out the effects of EU's food carbon tax on Brazil and rest of world, we fill the research gap on the global impact of a carbon tax. Our results provide evidence that a carbon tax on food in EU will not lead to serious negative effects in Brazil's food production, which contributes to alleviating concerns about the negative global impact of food carbon tax policies.

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9 Appendix

9.1 Agricultural-Food Products

Table 9: Agricultural Food Products by Categories

Animal Products
- Live animals
- Meat and edible meat offal
- Fish and crustaceans, molluscs and other aquatic invertebrates
- Dairy produce; birds' eggs; natural honey; edible products
- Products of animal origin, not elsewhere specified or included
Vegetable Products
- Live trees and other plants; bulbs, roots and the like; cut flowers and omamental foliage
- Edible vegetables and certain roots and tubers
- Edible fruit and nuts; peel of citrus fruits or melons
- Coffee, tea, mate and spices
- Cereals
- Products of the milling industry; malt; starches; inulin; wheat gluten
- Oil seeds and oleaginous fruits; miscellaneous grains, seeds and fruit; industrial or medicinal plants; straw and fodder
- Lac; gums, resins and other vegetable saps and extracts
- Vegetable plaiting materials; vegetable products not elsewhere specified or included
Fats and Oils
- Animal or vegetable fats and oils and their cleavage products; prepared edible fats; animal or vegetable waxes
Foodstuffs
- Preparations of meat, of fish or of crustaceans, molluscs or other aquatic invertebrates
- Sugars and sugar confectionery
- Cocoa and cocoa preperations
- Preparations of cereals, flour, starch or milk; pastrycooks' products
- Preparations of vegetables, fruit, nuts or other parts of plants
- Miscellaneous edible preparations
- Beverages, spirits and vinegar
- Residues and waste from the food industries; prepared animal fodder
- Tobacco and manufactured tobacco substitutes

[1] The agricultural food products categorizing result is based on Eurostat (2022)