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Fertilizer Logistics in Brazil: Application of a Mixed-Integer Programming Mathematical Model for Optimal Mixer Locations

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Abstract: *Background:* Brazil is one of the largest consumers of fertilizers and is highly dependent on the international market to meet its demand for agricultural production inputs. The complexity of the fertilizer supply chain motivated us to carry out this study on redesigning the fertilizer logistics chain and evaluate strategies for reducing logistics costs by redesigning the fertilizer mixing network in Brazil, a country that is heavily dependent on imported fertilizers for agriculture. *Methods:* We introduce a multi-product mixed-integer linear programming optimization model encompassing the logistics network, from import ports to mixing factories and agricultural fertilizer supply centers. This model includes logistics infrastructure and taxes, accounting for greenhouse gas emissions (specifically carbon dioxide) in fertilizer logistics. *Results:* The results indicate that expanding the port capacity for fertilizer importation can significantly reduce logistics costs and greenhouse gas emissions by up to 22.5%, decreasing by 23.9% compared to the baseline. We also observed that removing taxes on fertilizer importation can reduce logistics costs by approximately 11%, but it increases greenhouse gas emissions by 2.25% due to increased reliance on road transport. We identified 15 highly resilient regions for establishing mixing factories, evaluated various scenarios and determined the importance of these locations in optimizing the fertilizer supply network in the country. Moreover, the results suggest a significant potential to enhance the role of Brazil's Northern Arc region in fertilizer import flows. *Conclusions:* Public policies and private initiatives could be directed toward encouraging the establishment of mixing factories in the identified regions and increasing transport capacity in the Northern Arc region. Improving the logistical conditions of the fertilizer network would contribute to food security by reducing the costs of essential inputs in food production and promoting sustainability by reducing greenhouse gas emissions.

Keywords: fertilizers; logistics; mixers; optimal location; mathematical programming

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1. Introduction

The considerable growth of the global population has led to a major increase in food consumption. For food production to increase in line with population growth, there must be higher productivity, with soil fertilization representing an important factor in this regard. The fertilizer market grew by almost 345% from 1993 to 2019, which promoted agricultural productivity gains in Brazil [1].

The volume of fertilizers delivered to Brazil in 2019 exceeded 36 million tons, which placed the country as the fourth largest consumer of fertilizers in the world. Brazil represents around 8.3% of the global market of nutrient consumption, with the first position occupied by China (24%), followed by India (14.6%) and the United States (10.3%) [2].

Fertilizers have been the driving force behind the evolution of Brazilian agriculture since the 1960s [3]. The aim at that time was to improve the agricultural sector's contribution to the national economy, as the strategy until then had been solely to expand land without increasing productivity or investing in research. Thus, the State played a significant role in expanding the fertilizer market, promoting its use and attracting foreign companies that specialized in this sector. Grain production in Brazil grew by 350% between 1993 and 2019, while the planted area only increased by 77% during this period, representing a 98% improvement in agricultural productivity for this crop [4]. Among other factors, the use of fertilizers was essential in achieving these gains, with a reported 345% increase in fertilizer deliveries during the abovementioned period [1]. Agribusiness accounted for 21.4% of the Brazilian Gross Domestic Product in 2019 [5].

Despite the high growth rate of demand for fertilizers in Brazil, internal production has not increased at the same pace, resulting in a large difference between supply and demand for this input. Over the years, this has generated great dependence on fertilizer imports. If public policies in Brazil do not provide incentives for the growth of the country's fertilizer industry, it is estimated that by 2035, Brazil will import more than 85% of its fertilizers (Farias et al., 2020) [6]. To meet the increased demand for food, it is essential to pursue the path of increasing agricultural productivity, including the efficient use of inputs, such as fertilizers (Abideen, 2021) [7].

High import levels have facilitated an operation known as return freight to reduce fertilizer transportation costs. Return freight or backhauling is an operation where the delivery vehicle carries a secondary load compatible with the transport equipment, avoiding empty returns to the loading site [8]. In Brazil, the fertilizer sector extensively uses return freight, benefiting from the country's status as a major grain exporter (soybeans and corn) and fertilizer importer. This market practice effectively lowers transportation costs for fertilizers, especially during periods of high grain export when fertilizer return freight is more readily available in port regions [8]. Return freight significantly impacts routes that connect fertilizer mixing centers, ports and grain production areas by reducing transportation costs. Lima et al. (2016) [9] highlight that the routes from the Santos port region to the Midwest grain production region are especially beneficial, offering substantial economic advantages for fertilizer freights.

High external dependency and logistics problems are the key factors that contribute to the high costs of fertilizers in Brazil [10]. This study demonstrated that the costs of transportation increased by 21.1% for urea, 15.4% for monoammonium phosphate (MAP) and 22.2% for potassium chloride (KCl). Considering port costs, demurrage (fines for delays in the period between the arrival and departure of the ship in the port operation) and the merchant shipping fee (AFRMM), these percentages reach 40.1, 29.3 and 42.2%, respectively, which puts fertilizer consumers at a great disadvantage.

The concentration of fertilizer imports also leads to bottlenecks in logistics operations, causing congestion and the excessive use of ports at certain times of the year. Santos and Paranaguá are the only ports responsible for interconnecting almost 60% of the fertilizer transport network from supplier countries to consumers [11]. These problems incur extra port-related costs in the logistics chain [10].

The fertilizer sector is part of an extremely complex production chain, where several products considered raw materials may generate a very large diversity of fertilizer combinations, known as mixtures. This happens because each crop and each type of soil presents distinct nutrient requirements for plant development. Among the main nutrients, the basic foundation of a fertilizer formula comprises nitrogen, phosphorus and potassium (NPK). Thus, this market requires mixing factories, which are responsible for aggregating the raw materials and mixing them into commercial formulas that will be used in agriculture.

In the literature, several fertilizer supply chain management applications use quantitative tools. Rabbani et al. (2022) [12], using a mathematical model and a multi-objective, multi-product approach, evaluated the management of the phosphorus supply chain under an environment of uncertainties while considering economic, social and environmental factors. Benhamou et al. (2020) [13] utilized a quadratic programming model formulation to assess the economic efficiency of reverse mixing to customize fertilizer mass. Siswanto et al. (2018) [14] used a discrete event simulation approach to evaluate the effects of disruptions and develop mitigation solutions against such disturbances in the maritime transport distribution system of fertilizers in Indonesia. Santoro and Ronconi (2011) [15] modeled the transport and storage of potassium chloride for the fertilizer industry in Brazil using a mixed-integer linear programming model.

Regarding the application of models for choosing the location of fertilizer factories or mixing facilities, Wilson and Shakya (2023) [16], for example, evaluated the risks of expanding nitrogen fertilizer factories in North America, including spatial competition, in a scenario of increased price volatility in the post-COVID period, using a stochastic optimization model. In Brazil, Carvalho (2009) [17] and Alencar (2017) [18] performed specific studies for this sector using mathematical optimization models. Many of these location problems, especially those involving multiple choices, are solved by mixed-integer programming (MIP), which determines the best location points using a binary variable [19–21].

Although the main purpose of these models is to choose the location of installations, they also assist in decisions on network projects; in other words, they are used for problems in determining the routing of flows by the network based on cost or level of service. For this purpose, location models include source, destination and hub nodes, with knowledge of network topology as a key decision-making factor for modeling real problems [21].

Location problems are an important research area since finding a solution to these problems can lead to a decrease in the number of transport links between source and destination nodes. Furthermore, it can reduce general transportation costs, consolidating traffic flows from multiple sources and enabling transfers to hubs with multiple destinations [20].

According to Shang et al. (2021) [22], location problems occur in strategic planning for several cargo delivery systems, including multimodal transport and distribution in modeling problems. Although cost minimization is the primary goal, some competitive markets demand that the factor "service level" be considered, with the goal of guaranteeing delivery and decreasing the delivery time of goods.

This article evaluates strategies for reducing logistics costs by redesigning the fertilizer mixing network in Brazil, a country that is heavily dependent on imported fertilizers for agriculture. We introduce a multi-product mixed-integer linear programming optimization model encompassing the logistics network, from import ports to mixing factories and agricultural fertilizer supply centers. This model includes logistics infrastructure and taxes, accounting for greenhouse gas emissions (specifically carbon dioxide) in fertilizer logistics. We assess various scenarios to determine their impact on reducing logistics costs and CO_2 emissions. Additionally, we identify regions where mixing factories can be more resilient in response to changes in these scenarios.

2. Materials and Methods

2.1. Transport Network and Premises

The first step of this work was to define the transport network to be used in the mathematical modeling of fertilizer logistics. With the mixer representing one of the important links in this work, fertilizer logistics can be divided into two groups of flows, namely, (i) inbound flows, referring to the supply of the mixers, and (ii) outbound flows, referring to the delivery of the final product to the consumer.

In general, fertilizers can reach mixers in three ways: (i) by road, with the source in the port; (ii) by a multimodal system, with the source in the port; and (iii) by road, with the source in national factories. A diagram of the fertilizer logistics chain can be observed in Figure 1.

Still, regarding the transport network, an important premise considered was the obligation for fertilizer to pass through a mixer before arriving at the destination. Although these flows exist in practice, the lack of official data on this link in the chain and the need to estimate the capacities of installed mixers were the reasons for adopting this characteristic. Therefore, it is also worth highlighting the option of using mixed-integer programming, where the model itself will indicate the optimal places for mixers.

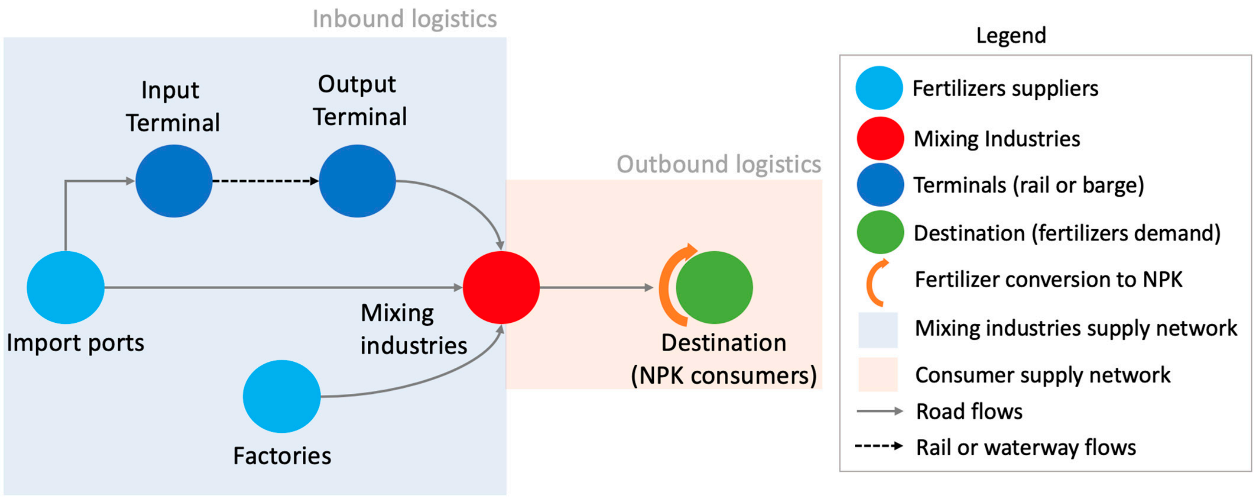

Figure 1. Logistics network considered for this work.

It is also important to highlight that the flows of the basic raw materials, which are especially present in the supply of national factories (and can even be performed by rail transport), were not considered. Therefore, the logistic network proposed for the model considers the logistics of the supply and distribution of only simple fertilizers. For these types of products, the rail network is currently not used to supply mixers to national factories.

Another important premise is related to the greater complexity of the fertilizer production chain, which undergoes a series of transformations compared to the logistics chain. This means that supply (production and import) and demand data are not compatible. Thus, for a more precise calculation of the quantities of fertilizers transported, the data on demand were treated as NPK. Therefore, to equalize the supply and demand data, a conversion factor (CF) was proposed for the model, which basically converts each type of fertilizer into the concentrations of the three main nutrients present.

Regarding data structuring, this work has a national scope, considering the country to be divided into 137 mesoregions as presented by IBGE (2018) [4]. To facilitate the calculation of transport costs between the nodes of the transport network, centroid municipalities representing each mesoregion were defined. For ports and factories, the municipalities of locations were considered from data from MDIC (2018) [23] and ABISOLO (2018) [24], respectively. Data on the input and output terminals for rail transport were obtained from ANTT (2020) [25], whereas for the waterway mode, the data from ANTAQ (2020) [26] were used.

On the other hand, the centroids of the mixers and final destinations were defined based on the volume of the agricultural production of temporary crops from the Municipal Agricultural Production (PAM) data published by IBGE (2018) [4]. Thus, the municipality with the highest production in a mesoregion was considered the destination (consumption) centroid, while the second largest producer was considered the mixer centroid. It is worth highlighting that, in the cases of mesoregions that possess fertilizer importing ports, the municipality where the port is located was used as the centroid of the mixer to make the model more in line with reality. Figure 2 shows the division of Brazil into mesoregions, as well as the centroids used for each node of the logistic network.

Brazil's Northern Arc system consists of ports located in the north and northeast regions of Brazil, particularly the ports of Porto Velho (RO), Manaus (MA), Miritituba (PA), Santarém (PA), Barcarena (PA), Santana (AP) and São Luís (MA). This logistical corridor was proposed as an alternative to alleviate the continuous exhaustion of the capacities of the ports in the south and southeast regions, in addition to the high costs associated with maritime operations in these regions [27]. Despite facing transportation infrastructure issues, Brazil's Northern Arc system has significantly increased its share in

Brazilian exports in recent years [28]. Recent scientific studies indicate that this logistical corridor is important for the flow of grain production from the Brazilian Cerrado, bringing economic, social and logistical advantages [27]. However, it is notable that investment in logistics and port development in this region will significantly increase the competitiveness of Brazilian products in the international market.

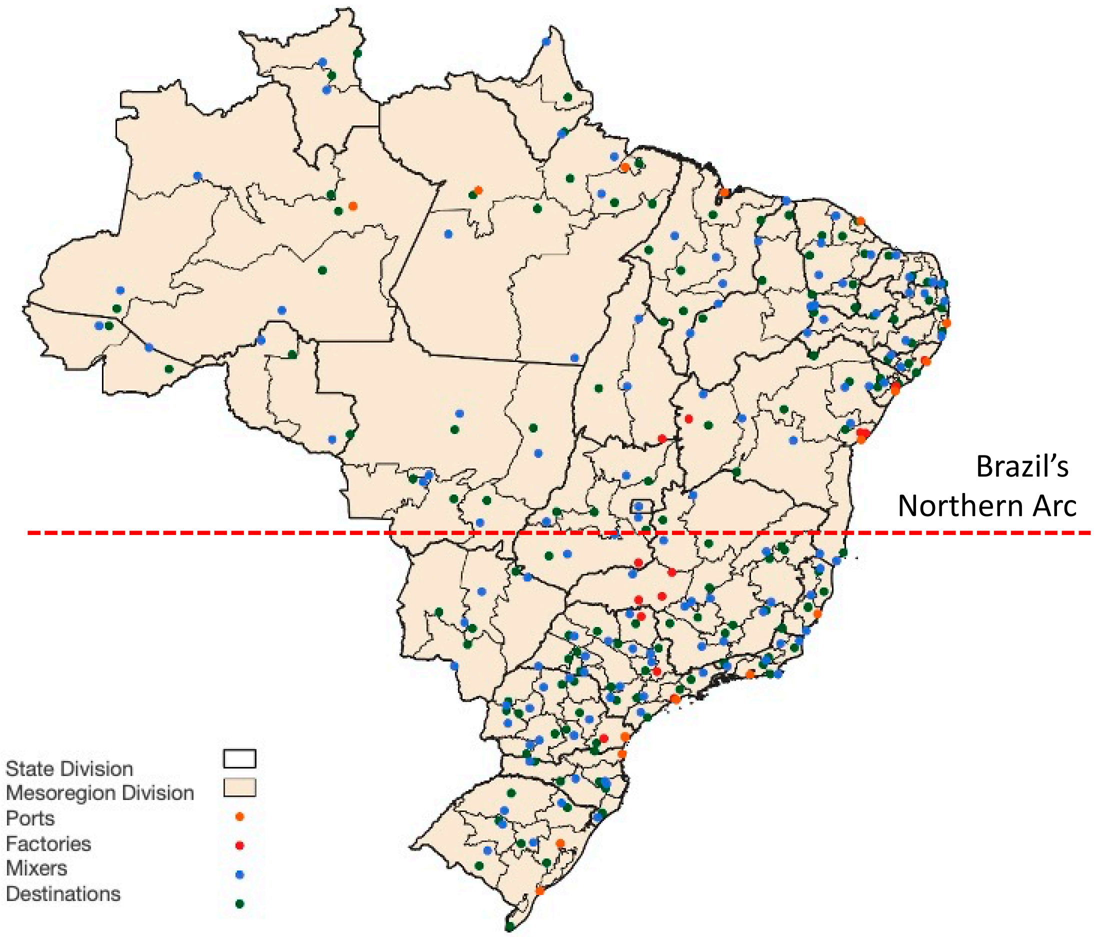

Figure 2. Municipalities considered centroids for fertilizer demand, mixture and sources.

The last important premise is related to the calculation of logistics costs. As explored in the literature review, taxes, specifically on operations relating to the circulation of goods and provisions of Interstate and Intermunicipal Transport and Communication Services ("ICMS"), will be incorporated into the mathematical modeling as a logistics cost. Regarding state tax, each federation unit adopts a different rule for charging it, especially import tax. An important characteristic is the requirement of industrialization in a state for the product not to be taxed at the time of import. Thus, it was necessary to consider all possible combinations, including the source, mixer and final destination, as parameters of the mathematical model.

Finally, it is important to highlight that the year 2018 was used as a reference for all parameters used in the mathematical model. This year was chosen based on the availability of information since it was difficult to obtain recent data for some parameters. Additionally, the economic changes caused by the COVID-19 pandemic caused major alterations in the historical pattern of the data, which could lead to distortions in the results compared to the real scenario.

2.2. Proposed Mathematical Model

Based on the premises discussed above, a mixed-integer programming model was chosen, aiming to minimize the total logistics costs of the fertilizer transport chain. Given the aims of this work, a single-period mathematical model was employed, where it was possible to analyze the results more strategically, not considering operational restrictions and limits.

The details of the information that will be used in the mathematical model are described below, with definitions of the sets, parameters, and variables.

The sets are:

O : ports (offer);
F : fertilizers factories (offer);
M : mixers (centroids);
D : demand for fertilizers (centroids);
P : type of fertilizer;
I : nutrients (N, P, K);
E : inbound trans-shipment terminal;
S : output trans-shipment terminal.

The parameters are:

CR_{OMD} : total road costs of port O, mixed in M and distributed to D, USD/ton;
CRF_{FMD} : total road costs of factory M, mixed in M and distributed to D, USD/ton;
CM_{OESMD} : total intermodal costs of leaving port O and passing through terminals E and S, mixed in M and distributed to D, USD/ton;
A_{OP} : volume imported at port O for each type of fertilizer P, tons;
B_{FP} : production capacity of factory F for each type of fertilizer P, tons;
C_E : capacity of input terminal E, tons;
DEM_{DI} : demand for fertilizers in consumer D for each nutrient I, tons;
FC_{PI} : fertilizer conversion factor from fertilizer type P to nutrient I, %;
C : fixed cost linked to the opening of a mixer, USD/ton;
MIN : minimum volume to open a mixing unit, tons;
ER_{OMD} : road CO_2 emission coefficient for transportation from port O, mixed in M and distributed to D, in tons of CO_2 equivalent per ton of fertilizers transported;
ERM_{FMD} : road CO_2 emission coefficient for transportation from factory F, mixed in M and distributed to D, in tons of CO_2 equivalent per ton of fertilizers transported;
EM_{OESMD} : intermodal emission coefficient of leaving port O and passing through terminals E and S, mixed in M and distributed to D, in tons of CO_2 equivalent per ton of fertilizers transported.

The decision variables are:

VR_{OMDP} : road volume transported from port O, mixed in M and distributed to D, for fertilizer type P, tons;
VRM_{FMDP} : road volume transported from factory F, mixed in M and distributed to D, for fertilizer type P, tons;
VM_{OESMDP} : multimodal volume transported from port O and passing through terminals E and S, mixed in M and distributed to D, for fertilizer type P, tons;
GHG_I : CO_2 emissions per nutrient I in fertilizer logistics, tons;
GHG_{TOTAL} : total CO_2 emissions in fertilizer logistics, tons;
GHG_{inert} : CO_2 emissions from the inert weight of fertilizers (excluding nitrogen, phosphorus and potassium) in fertilizer logistics, tons;
BM_M : Binary decision variable for optimal location.

$$\begin{cases} 1, & \text{if mixer M must be chosen} \\ 0, & \text{otherwise} \end{cases}$$

The objective function:

$$\text{Minimize Total Cost (CT)} = \left(\begin{array}{c} \sum_{O=1}^{17}\sum_{M=1}^{137}\sum_{D=1}^{137}\sum_{P=1}^{13} VR_{OMDP}CR_{OMD} + \sum_{F=1}^{17}\sum_{M=1}^{137}\sum_{D=1}^{137}\sum_{P=1}^{13} VRM_{FMDP}CRF_{FMD} \\ + \sum_{O=1}^{17}\sum_{E=1}^{9}\sum_{S=1}^{9}\sum_{M=1}^{137}\sum_{D=1}^{137}\sum_{P=1}^{13} VM_{OESMDP}CM_{OESMD} + C\sum_{M=1}^{137} BM_M \end{array} \right) \quad (1)$$

Subject to:

$$\sum_{M=1}^{137}\sum_{D=1}^{137} VR_{OMDP} + \sum_{E=1}^{17}\sum_{S=1}^{9}\sum_{M=1}^{137}\sum_{D=1}^{137} VM_{OESMDP} = A_{OP} \qquad \forall O, P \quad (2)$$

$$\sum_{M=1}^{137}\sum_{D=1}^{137} VRM_{FMDP} \leq B_{FP} \qquad \forall M, P \quad (3)$$

$$\sum_{O=1}^{17}\sum_{S=1}^{9}\sum_{D=1}^{137}\sum_{M=1}^{137}\sum_{P=1}^{13} VM_{OESMD} \leq C_E \qquad \forall E \quad (4)$$

$$\left(\begin{array}{c} \sum_{O=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13} VR_{OMDP}FC_{PI} + \sum_{F=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13} VRM_{FMDP}FC_{PI} \\ + \sum_{O=1}^{17}\sum_{E=1}^{9}\sum_{S=1}^{9}\sum_{M=1}^{137}\sum_{P=1}^{13} VM_{OESMDP}FC_{PI} \end{array} \right) \geq DEM_{DI} \qquad \forall D, I \quad (5)$$

$$\left(\begin{array}{c} \sum_{O=1}^{17}\sum_{D=1}^{137}\sum_{P=1}^{13} VR_{OMDP} + \sum_{F=1}^{17}\sum_{D=1}^{137}\sum_{P=1}^{13} VRM_{FMDP} \\ + \sum_{O=1}^{17}\sum_{E=1}^{9}\sum_{S=1}^{9}\sum_{D=1}^{137}\sum_{P=1}^{13} VM_{OESMDP} \end{array} \right) \geq \text{MIN } BM_M \qquad \forall M \quad (6)$$

$$GHG_I = \left(\begin{array}{c} \sum_{O=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} ER_{OMD}VR_{OMDP}FC_{PI} + \\ \sum_{F=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} ERM_{FMD}VRM_{FMDP}FC_{PI} + \\ \sum_{O=1}^{17}\sum_{E=1}^{9}\sum_{S=1}^{9}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} EM_{OESMD}VM_{OESMDP}FC_{PI} \end{array} \right) \quad \forall\ I \quad (7)$$

$$GHG_{TOTAL} = \left(\begin{array}{c} \sum_{O=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} ER_{OMD}VR_{OMDP} + \\ \sum_{F=1}^{17}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} ERM_{FMD}VRM_{FMDP} + \\ \sum_{O=1}^{17}\sum_{E=1}^{9}\sum_{S=1}^{9}\sum_{M=1}^{137}\sum_{P=1}^{13}\sum_{D=1}^{137} EM_{OESMD}VM_{OESMDP} \end{array} \right) \quad (8)$$

$$GHG_{inert} = GHG_{TOTAL} - \sum_{I=1}^{3} GHG_I \quad (9)$$

Regarding the previously presented expressions, Equation (1) aims to minimize the total logistic cost. This equation sums up the transportation costs of inbound logistic flows (importation or from the factory to the fertilizer mixing factories), the transportation costs of outbound logistic flows (from the mixing factories to the fertilizer-consuming regions) and the construction costs of the mixing factories, with consideration of the binary decision variable of setting up the fertilizer mixing factory. Equation (2) ensures that the sum of the inbound logistic flows of fertilizers from national factories matches the supply they offer for each raw material. Inequality 3 restricts the importation of fertilizers at each port, considering different raw materials. Inequality 4 limits the intermodal transport capacity for each terminal, basing the maximum volume on the availability of each infrastructure. Inequality 5 establishes a minimum supply of nutrients (N, P and K) in consumer regions, which the outbound logistic flows from the mixing factories must meet, including a conversion factor for various fertilizers based on nitrogen, phosphorus and potassium content. Inequality 6 dictates the minimum capacity for a mixing factory when chosen for installation, incorporating a binary variable linked to the factory's minimum capacity. Equation (7) calculates greenhouse gas emissions from the volumes transported in each transport flow and mode, applying the CO_2 emission coefficient for each nutrient (N, P and K) and factoring in the conversion of fertilizers to nutrients. Equation (8) computes the total greenhouse gas emissions. Lastly, Equation (9) calculates the CO_2 emissions from the inert load, which accounts for emissions not originating from nitrogen, phosphorus and potassium.

For each analysis scenario (detailed in the subsequent sections), we obtained the optimal solution of the formulated mathematical optimization model by processing the model through the General Algebraic Modeling System (GAMS) software [29], using the solver CPLEX. Furthermore, processing occurred in an ordinary computational environment, using a notebook with Intel Core i5 processor with 8 GB of RAM memory. For each scenario analyzed, there was a different processing time, which varied between 2 and 10 h. The relative gap was set to be less than or equal to 0.3%.

2.3. Parameters and Data Sources

To define the simple fertilizers considered, the Mercosur Common Nomenclature (NCM) classification was used, which considers 37 different types of organic and synthetic fertilizers. From the import data obtained by MDIC (2018) [23], the fertilizers were grouped into 13 types based on their NPK concentration [30]. Table 1 shows a list of the fertilizers that were considered, as well as the concentration of each nutrient (conversion factor).

Table 1. Fertilizers considered and concentration of each nutrient.

Nutrient/Fertilizer	ID	N	P	K
Potassium chloride (KCl)	1	0%	0%	60%
Di-ammonium phosphate (DAP)	2	18%	45%	0%
NPK formulas	3	16%	15%	15%
Monoammonium phosphate (MAP)	4	10%	52%	0%
Ammonium nitrate	5	33%	0%	0%
Nitrocalcium	6	20%	0%	0%
Others	7	13%	5%	11%
Other fertilizers with N and P	8	9%	3%	1%
Others with nitrogen	9	13%	4%	4%
Ammonium sulfate	10	20%	0%	0%
Simple superphosphate	11	0%	18%	0%
Triple superphosphate	12	0%	44%	0%
Urea	13	45%	0%	0%

Fertilizer import data were obtained from MDIC (2018) [23], as previously mentioned. The data referring to the year 2018 indicated 17 fertilizer importing ports, totaling just over 29.3 million tons, which were grouped according to the 13 types of fertilizers already presented.

For the fertilizer sources in the factories, the data source employed was the ABISOLO Yearbook (2018) [24], which presents a survey of the national fertilizer factories per nutrient. From these data, the pieces of information were aggregated according to the municipality where each factory was located, adopting the total sum of production capacity for each type of fertilizer considered.

Fertilizer demand from the consumer centers was also calculated based on the data from ANDA (2018) [1] and IBGE (2018) [4]. Specifically, the fertilizer delivery index in NPK per state was used, with the planted area of the main crops in each microregion being the proxy used to calculate regionalized demand. Figure 3 shows the graphic distribution of fertilizer demand in Brazil per microregion.

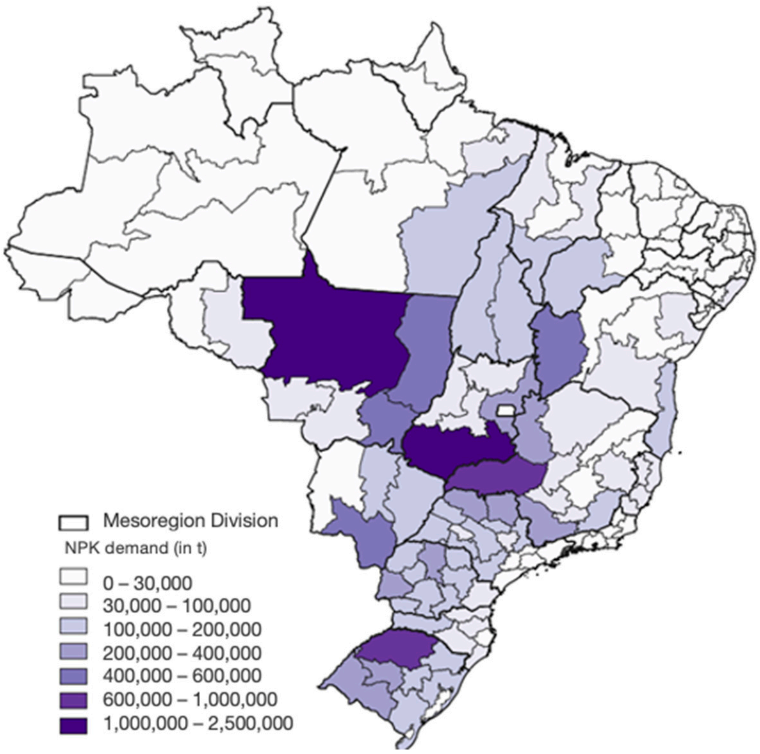

Figure 3. Distribution of nitrogen, phosphorus and potassium (NPK) demand per mesoregion in 2018.

The volumes transported in the intermodal infrastructures were obtained by employing the statistics of ANTT (2020) [25] for the rail mode and of ANTAQ (2020) [26] for the waterway mode. In both modes, the handled volumes of each terminal in the year 2018 were considered.

Regarding the total logistics costs adopted, represented in the mathematical model by CR, CRF and CM, they can be calculated from the following equation:

$$CT = CP + CI + CO + I \quad (10)$$

where:

CT: total cost associated with the transport flow;
CP: port cost;
CI: inbound cost (mixer supply flow);
CO: outbound cost (flow of distribution for consumption);
I: taxes.

It is important to consider that the port cost is equal to zero for flows originating in the factories. Inbound costs can refer to the cost of a single road freight traveling to a mixer or the sum of two road freights and an intermodal freight in the case of rail or waterway flows. On the other hand, the outbound cost refers to a single road freight traveling between the mixer and the final destination.

For port costs, a questionnaire was distributed to five companies in Brazil that import fertilizers, aiming to understand what these costs mean and the differences among the ports. In this sense, in the port costs adopted, the following were included: (a) foremanship (removal of the fertilizer from the ship and internal movement in the port to a warehouse); (b) storage; (c) AFRMM (Mercantile Marine Fee and Taxes); (d) demurrage (fine charged for delay in unloading a ship). Thus, for each port, the mean value collected for each agent of the sector was adopted.

To obtain the road freight values, the Freight Information System was used (SIFRECA, 2019) [31]. From this information, a database was constructed with the annual means of all existing fertilizer routes in the year 2018, totaling 2451 data points on source, destination, distance and shipping cost. Thus, two simple regression models were constructed to estimate the freight values among the points considered in the mathematical model. As demonstrated by Rocha and Caixeta-Filho (2018) [32], freight prices have a very strong relationship with distance, in addition to presenting logarithmic or linear behaviors, depending on the distance range of a route. Equations (11) and (12) represent the logarithmic and linear relationships between freight and distance and were used to estimate the costs of transportation in this work.

$$Y = e^{a}X^{b} \tag{11}$$

$$Y = aX + b \tag{12}$$

where:

Y: estimated value of the freight of fertilizers (in USD/t);
X: road distance of the route (in km);
a: angular coefficient (or slope);
b: linear coefficient (or intercept).

Furthermore, fertilizer freights tend to present different behaviors depending on the transport corridor of a route [9]. Based on this characteristic, regionalization among the routes present in SIFRECA was conducted in order to differentiate freight curves between ports and the regions of origin of the products. In summary, seven equations were obtained (regionalization) from freights for the fertilizer import routes, as well as eleven equations for the routes of internal distribution of the input.

Regarding the use of the freight curve expressed in the regression equations, a "cut-off distance" was established, with the logarithmic equation applied when the distance was smaller in relation to the "cut-off distance" and the linear equation when it was larger. The "cut-off distance" was defined by the meeting of the linear and logarithmic curves.

In both equations obtained in the regression (8 and 9), the road distances were applied to the routes of the corresponding movement corridor. All distances were obtained from Google Maps (2020) [33].

The intermodal freights (water and rail) were calculated based on the road freight. For the rail freight, a 30% discount was used in relation to the same origin–destination of the road freight, whereas for the waterway freight, a 60% discount was applied. This application of discounts on road freight is a common market practice adopted by Brazilian railway and waterway concessionaires when setting prices [34].

Based on the state rules, there is a need to know the complete flow of the fertilizer until delivery for final consumption for ICMS calculation. It is worth highlighting that there is no clear understanding of taxation for the state of Amapá; thus, we employed the same rule used by Roraima as a premise. The average prices used for the calculation were USD 205.80 for simple fertilizers (before mixing) and USD 291.30 for fertilizers that were already mixed [1].

The reference exchange rate adopted was BRL 5.15 per USD.

This study considered the following CO_2 emission parameters: 36.27 g of CO_2 equivalent per ton-kilometer in road transportation, 16.28 g of CO_2 equivalent per ton-kilometer in rail transportation, and 3.46 g of CO_2 equivalent per ton-kilometer in waterway transportation.

Finally, an estimate of the fixed cost linked to the binary variable of the opening of a mixer (C) was not performed, considering a negligible value (USD 1) for the composition of the mathematical model. This choice was made before establishing the goal of indiscriminately evaluating the main places for the mixture of fertilizers in Brazil, disregarding the factor of implementation feasibility.

2.4. Analyzed Scenarios

From the mathematical model discussed in this chapter, several scenarios will be constructed in which we expect to obtain answers to the specific objectives already presented in this work. The analysis of scenarios will be evaluated based on alterations in the equations of the mathematical model proposed or in the parameters of restriction costs, as summarized in Table 2.

Table 2. Characteristics of the analyzed scenarios.

Scenarios	Characteristics/Alterations
C1	Base scenario
C2	Full tax exemption
C3	Unrestricted import capacity
C4	New intermodal logistics solutions/increase in the current capacity
C5	Expansion of fertilizer demand

For C2, an alteration occurred in the cost regarding tax, which was zero for all existing flows in the model. The aim of this scenario was to evaluate the impact of ICMS taxation in the fertilizer logistics chain. In C3, the aim was to evaluate the fertilizer logistics chain without restrictions regarding the import volume in Brazilian ports and types of fertilizers. Regarding C4, the main purpose was to simulate alterations in the fertilizer logistics chain with the inclusion of new projected intermodal infrastructures (Rondonópolis–Santos, Santarém–Itaituba, Santos–Rio Verde and São Luís–Palmeirante), as well as the rise in the capacity of the current infrastructures.

For C5, besides obtaining information on the new intermodal infrastructures mentioned, the main goal was to analyze a scenario of expansion in fertilizer demand for 10 years. For this, data on the projection of the agricultural production area from the agribusiness projection report, released by MAPA (2018) [35], were used. Thus, the values of the parameter DEM_{DI} were readjusted according to the percentage of the rise in the agricultural production area of the nine main products that are associated with the consumption of fertilizers, reflecting an 18.3% increase in fertilizer demand.

3. Results

3.1. Logistics Costs of the Fertilizer Production Chain

An important parameter of the mathematical model is the logistics costs incurred in the fertilizer production chain. From the results obtained in each scenario, it was possible to identify the contribution of each of the four components that constitute the total logistics cost considered in the mathematical modeling. Figure 4 summarizes, in a stratified way, the composition of logistics costs in each scenario analyzed.

The optimal results obtained from the mathematical model show that the port costs have a high representation compared to the total logistics costs of the transport network considered. In Scenarios 1, 2 and 4, where there were restrictions equal to the import volumes, port costs totaled around USD 356.85 million. On the other hand, in C3, when there were no restrictions on the imported volumes, port costs dropped to around USD 281.71 million, which indicates a change in the allocation of the flows to ports that have a lower associated cost. In C5, which considers the expansion in fertilizer demand, there is an increase of 22.2% in port costs, reaching around USD 435 million. This shows that the Brazilian dependency on imports will cause port costs to rise considerably with the increase in the demand for fertilizers.

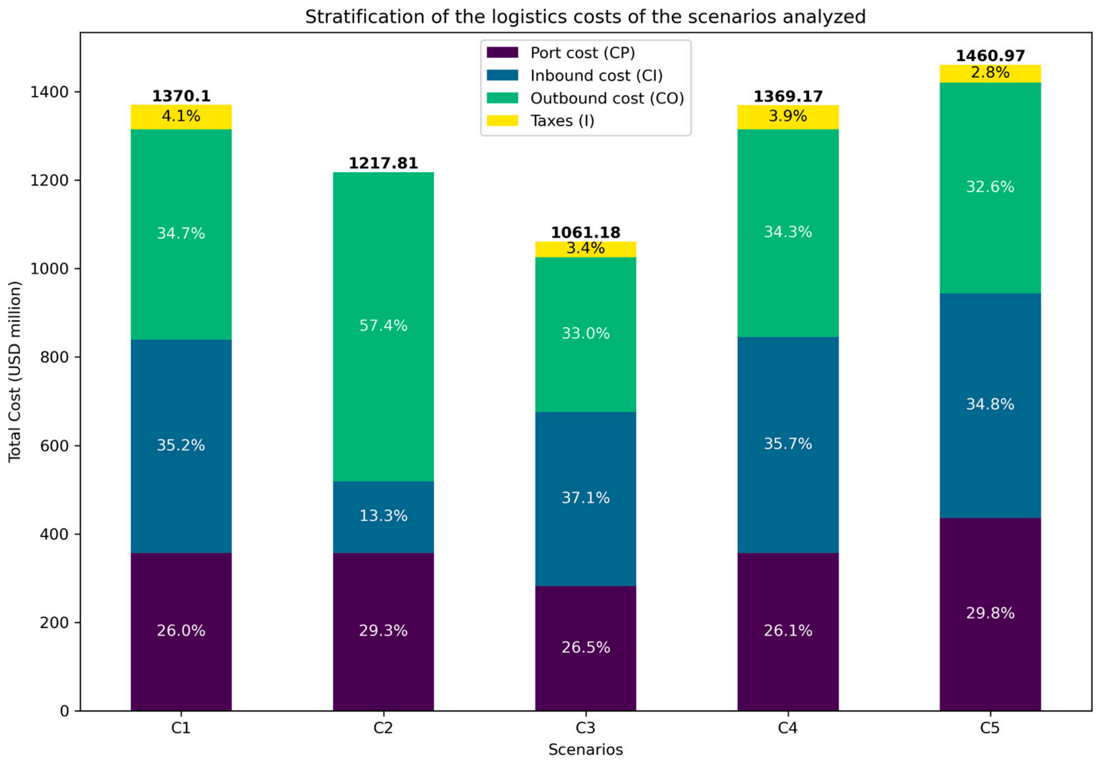

Figure 4. Stratification of the logistics costs for each scenario analyzed.

When the representation of the port costs was analyzed, Scenarios 1, 3 and 4 indicated that these costs correspond to between 26 and 26.5% of the total logistics costs. In C2, a scenario where taxes are set to zero, there was an increase in the representation of port costs (29.3%). This increase is associated with a reduction in the total logistics costs (USD 1.21 billion), where the optimum result shows better allocation of flows when taxes are set to zero. In C5, in addition to a rise in the total port cost, there is an increase in representation compared to the scenarios with import restrictions, providing further evidence of the Brazilian dependency on imports.

Regarding the optics of the costs of taxes, it was verified that they do not constitute a large portion of the total logistics costs, representing around 0.29% in C1, 0.18% in C3, 0.28% in C4 and 0.21% in C5. This shows that the strategy used in the fertilizer sector to reduce logistics costs is associated with the use of routes that do not have taxation associated with ICMS. Comparing the total logistics costs of C1 and of C2, for instance, a reduction of 12.5% is observed, decreasing from USD 1.37 billion to 1.21 billion. In other words, the taxation of the fertilizer logistics chain has a great impact on the design of the transport network, which justifies considering that this type of cost is also a logistics cost.

It is also interesting to highlight that the tax issue considerably modifies the stratification of transport costs, with the costs associated with outbound transport being the main component of the total cost (57.4%). Compared to the other scenarios, this cost represents between 32.6 and 34.7% of the total logistics costs. Regarding the inbound costs, the opposite is true; in other words, they have a much lower representation (13.3%) in relation to the other scenarios (between 34.8 and 35.7%). This shows the large impact of taxation on the fertilizer logistics chain.

The results also show a great reduction in total cost in C3 when there are no restrictions on fertilizer import. In this scenario, a reduction of almost 26% was observed in the total volume of fertilizers transported to meet the demand of NPK. In this sense, it is highlighted that the preference for the transport of more concentrated fertilizers has a great impact on the logistics costs, with a reduction of 22.5% in the total cost per demand.

In Scenarios 4 and 5, when increases in capacity and new infrastructures for intermodality are considered, there is a reduction in the logistics costs to meet the demand. In C4, the reduction is very low, around 0.1% in relation to C1. On the other hand, in C5, the cost is reduced to USD 80.42/t, almost 10% less in relation to C1. This situation shows that the expansion of intermodality tends to generate logistics gains only in the future with growth in the demand for fertilizers.

3.2. Greenhouse Gas Emissions in Fertilizer Logistics

Figure 5 quantifies greenhouse gas emissions in fertilizer logistics across various scenarios, explicitly focusing on CO_2-equivalent emissions. The analysis categorizes carbon dioxide emissions based on the types of nutrients consumed, including nitrogen (N), phosphorus (P) and potassium (K), and the inert weight, i.e., the part of the fertilizer not containing N, P or K.

In the baseline scenario, C1, the logistics processes emitted 975,000 tons of CO_2, with transportation of the inert weight contributing to 50% of these emissions. Scenario 3 showed the lowest emission levels, achieving a 23.9% reduction compared to the baseline scenario.

Figure 6 explores the relationship between total CO_2 emissions and logistical costs in each scenario. The scenario that redesigns the fertilizer mixing factory network to minimize logistical costs also reduces carbon dioxide emissions, thanks to the unrestricted port capacity for fertilizer importation. A key observation in Scenario 2, which introduces tax exemption for fertilizers, is that it leads to an 11.1% cost reduction. However, this scenario also causes a 2.25% increase in CO_2 emissions, as the tax exemption boosts the use of more polluting road transportation.

Scenario 4, focusing on expanding the railway and waterway networks, does not reduce costs compared to the baseline scenario, C1. However, it leads to a 23.9% decrease in carbon dioxide emissions by promoting lower-polluting modes of transport.

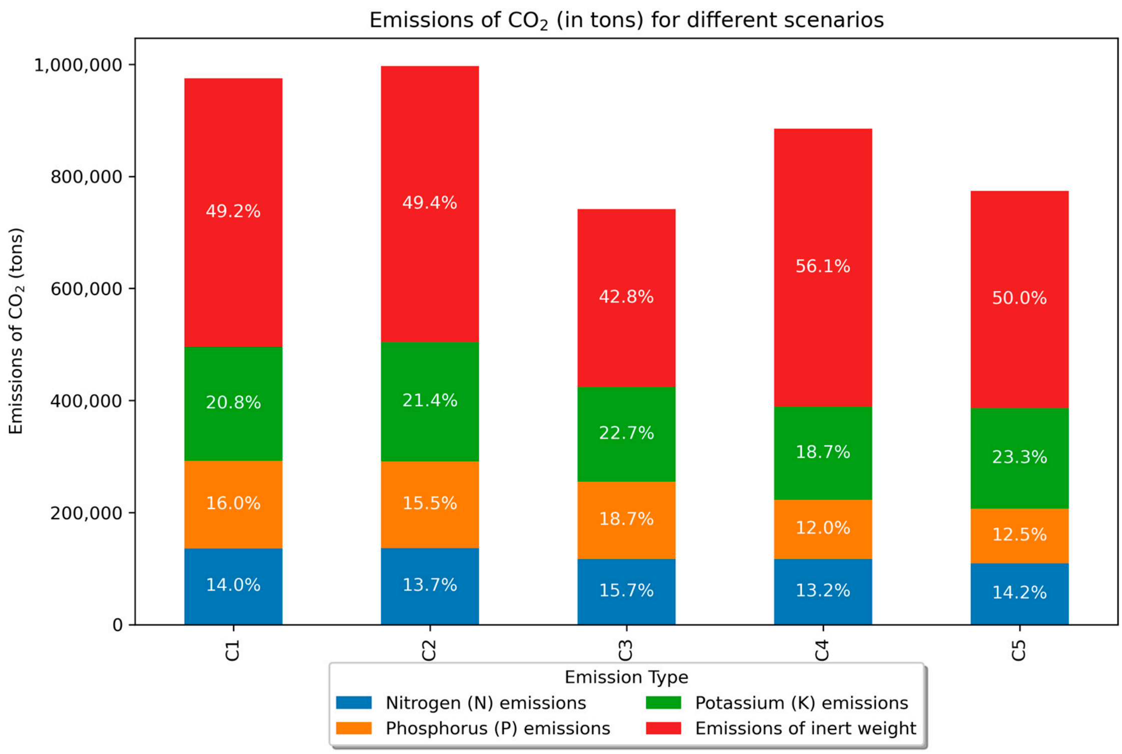

Figure 5. CO_2 emissions by scenario and nutrient.

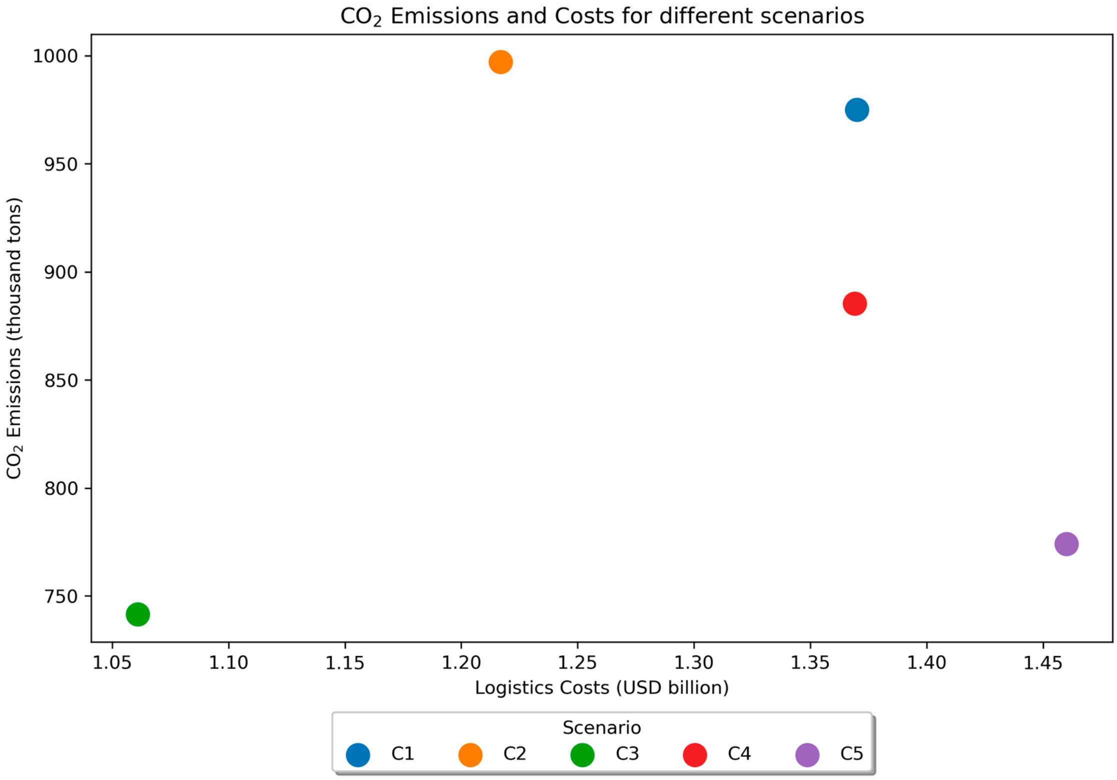

Figure 6. Relationship between logistic costs and CO_2 emissions by scenario.

Finally, Scenario 5, which involves the expansion of fertilizer demand, port capacity and the railway and waterway networks, shows a 6.63% cost increase due to the higher fertilizer demand considered in the modeling. Nonetheless, this scenario achieves a 20.6% reduction in CO_2 emissions compared to the baseline, thanks to the more efficient use of transportation infrastructures, especially port infrastructures.

3.3. Transport Flows of Fertilizer

An important decision variable that resulted from the mathematical model refers to the location of the mixers. With the lack of official data on this link in the chain, this section aims to present the optimal locations of mixer factories for the analyzed scenario, as well as an estimate of their production capacities.

Figures 7 and 8 graphically demonstrate all inbound and outbound transport flows, respectively, as well as the locations of the mixers obtained from the results of each scenario. It is worth highlighting that when there are no transport flows leaving from or arriving at a certain point, this indicates a proprietary supply flow.

Regarding the locations of the mixers, port regions are found to be ideal in all analyzed scenarios, which can be explained by their close proximity to the sources of fertilizers in import flows. The locations of national factories are also determining factors in the locations of the mixers, with emphasis on the mesoregions Sul Goiano and Triângulo Mineiro. Intermodal output terminals are also proven to be ideal places for the location of the factories.

A decisive issue regarding the location of mixing factories concerns taxation. With the imposed tax rules, the mathematical model aims to always allocate a mixer to states that do not have fertilizer importing ports, such as Goiás, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Tocantins and Piauí. With a minimum restriction of mixing capacity of 300 thousand tons, states that present low consumption of fertilizers are rarely considered ideal places for the location of mixers, as is the case for regions in the north and northeast.

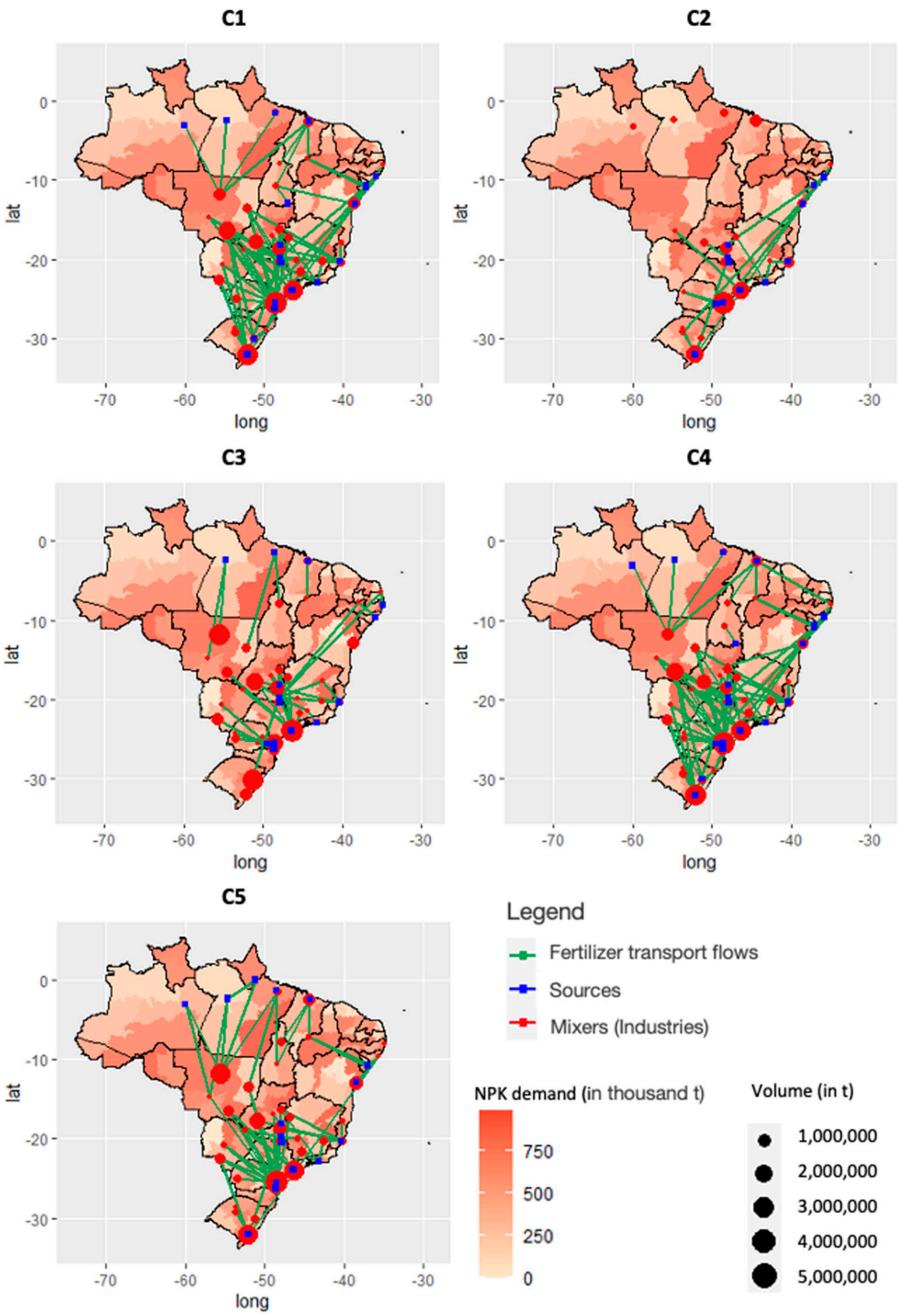

Figure 7. Inbound flows for each scenario analyzed.

Regarding exemption from taxation, C2 presents the greatest alteration in the profile of the mixer location. The results show that there is an even greater concentration of mixers in port regions, negating the need for their location inland for ICMS taxation. Only Goiás, Minas Gerais and Mato Grosso can be considered candidates for the location of mixers because of the proximity of national factories, yet they present large reductions in capacity compared to the other scenarios.

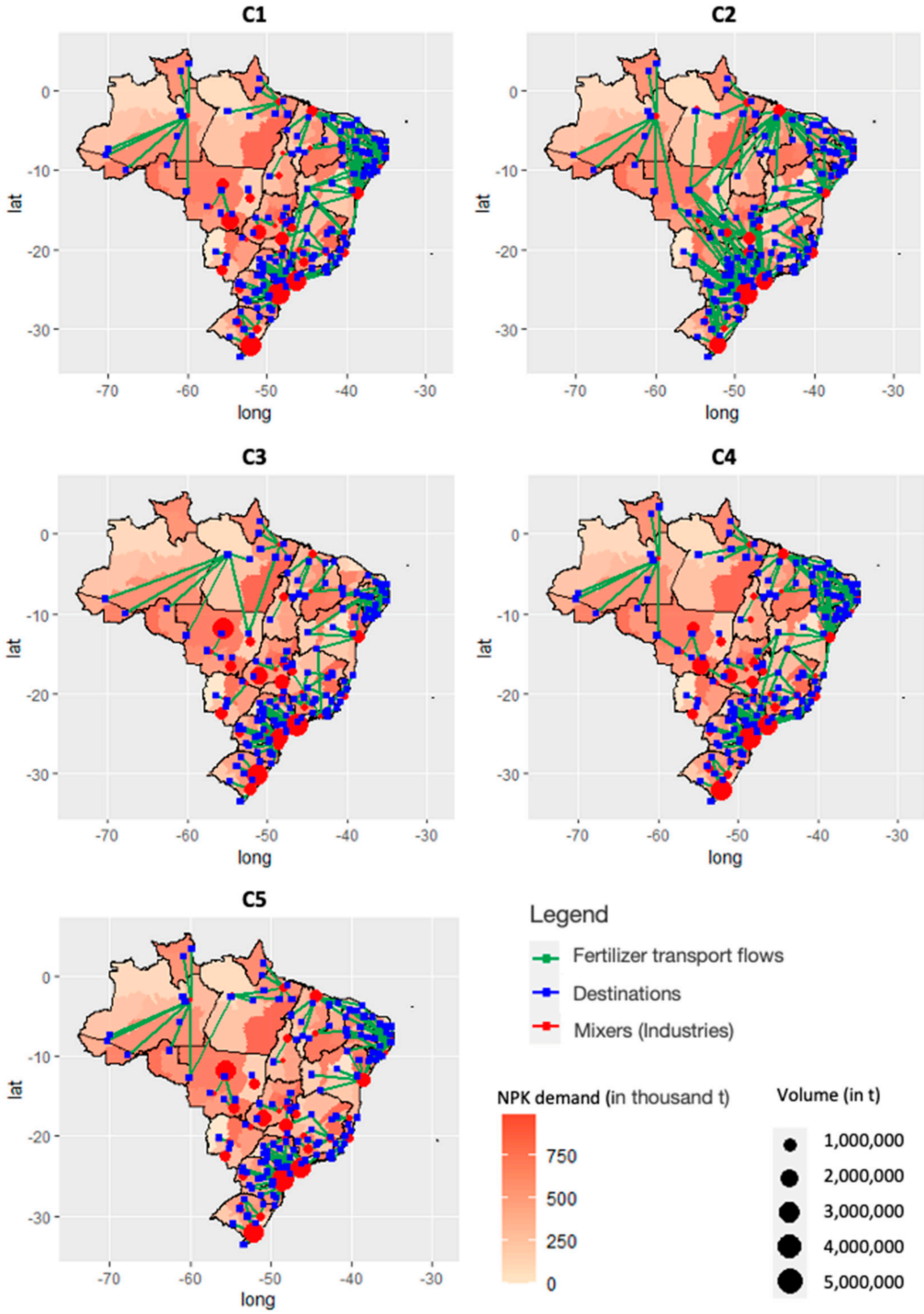

Figure 8. Outbound flows for each scenario analyzed.

Regarding port regions, the port of Paranaguá was identified as the main mixing hub in the country, totaling almost 10 million tons (an increase of 83% in relation to C1), followed by Rio Grande (5.2 million, an increase of 14%), Santos (5 million, an increase of 31%), São Francisco do Sul (2.2 million, an increase of 92%) and São Luís (2 million, an increase of 102%). On the other hand, for the inland mesoregions, the southeast of Mato Grosso was the main mixing region, with its capacity reduced from almost 2.9 million to 300 thousand tons. The south of Goiás presented a reduction of 55% in mixing capacity (920 thousand tons in C2). The north of Mato Grosso, southwest of Mato Grosso do Sul, east of Goiás, northeast of Mato Grosso and west of Paraná, which were important mixing regions in C1, had their capacities set to zero in C2. When the regions close to the factories were analyzed, Ribeirão Preto and Triângulo Mineiro were the mesoregions that exhibited the greatest increase in mixing capacity with tax exemption, with increases of 317% and 38%, respectively.

When C4 is analyzed, which incorporates an increase in capacity and new intermodal infrastructures, there are no considerable changes in the aspect of the location of mixing factories. The mixing centers are very similar to those observed in C1, with little variation in capacity. The most significant change is observed in the state of Tocantins, where in C1, there is a higher concentration of mixing capacity in the eastern Tocantins mesoregion. In C4, a higher concentration is observed in the western Tocantins mesoregion, especially because of the presence of the new corridor for rail transport for fertilizers from São Luís (MA) to Palmeirante (TO).

In C5, considering the growth in the demand for fertilizers, there are considerable changes in the design of mixing factories, especially in Mato Grosso (the main fertilizer consumer center). Of the five mesoregions that compose the state, only central–south Mato Grosso was not a candidate for mixing in any of the scenarios. Considering the other four mesoregions, the southeast of Mato Grosso was the main mixing region in C1, with a capacity of almost 2.9 million tons. The results obtained for C5 demonstrate a reduction of 65% in the mixing volume of this region, corresponding to just over 1 million tons.

The mesoregion north of Mato Grosso absorbs a large part of this volume with the loss of capacity in the southeast of Mato Grosso. In C5, this region develops a capacity close to 3.7 million tons, which represents an increase of 208% in relation to C1. This change reflects the increase in the capacity of the waterway flow from Santarém (PA) to Itaituba (PA), as well as the possibility of the expansion of fertilizer imports by the ports of the Northern Arc, according to the results of the mathematical model. Another mesoregion affected by C5 is the northeast of Mato Grosso, which presents an increase of 37% in capacity in relation to C1, increasing from 767 thousand to just over 1 million tons. In addition to the previously mentioned factors, this region will also have a large expansion in demand for fertilizers in 2028.

This expansion in demand, combined with the establishment of new infrastructures with multimodalities, must also cause alterations in the mixing capacities of other localities. The new railway corridor from Santos (SP) to Rio Verde (GO) must further consolidate the mesoregion of the south of Goiás as an ideal fertilizer mixing center. In C5, the region presents an increase of 8% in mixing capacity, which represents a volume close to 2.2 million tons.

The alternatives proposed in C5 also increase the mixing capacities for the ports of the Northern Arc in general. Belém (PA), for instance, presents an increase of 31% in relation to C1, whereas Santarém (PA) represents an important new mixing location. On the other hand, the port of São Luís has almost 1.3 million tons of mixing capacity, which represents an increase of 28% in relation to C1.

The volumes moved in each transport flow are important variables in the mathematical model that help in understanding the main inbound and outbound flows of the fertilizer logistics network. The supply flows of the mixer will be analyzed to understand the dynamics of fertilizer origin, while the supply flows at the destination will be analyzed to understand the area of influence of the mixers.

From the results obtained by the mathematical model referring to inbound flows, it is possible to infer the handled volumes originating in importing ports or national factories. Regarding the characteristics imposed on the model, the import volumes are equal in Scenarios 1, 2 and 4. Conversely, the factories present variations in all scenarios in relation to fertilizer supply.

The results of the base scenario (C1) indicate that the import flows represent around 80.2% of the entire volume that supplies the mixers, with the other 19.8% corresponding to the flows originating in the national factories. In C3, with no restrictions on import capacity, these flows represent 84.2% of the total inbound volume. In this scenario, in relation to C1, there is a considerable alteration in the import flows of Rio Grande do Sul, which leads to a greater concentration of volume in Porto Alegre (RS) than in Rio Grande (RS). As such, the volumes allocated from the factory of Rio Grande (RS) present a reduction of 93%, falling from 1.3 million to 100 thousand tons. On the other hand, C3 demonstrates an increase in imports of 21% in Santos (SP), which also favors greater production capacity in Cubatão, increasing from almost 1.1 million in C1 to 1.5 million tons in C3.

Regarding the optics of the scenario with tax exemption (C2), there is a reduction of around 3% in the volumes allocated to the factories compared to C1. In general, tax exemption, especially for fertilizer imports, disfavors the flows of national factories, especially those located in port regions. The factories located in Paranaguá (PR), for example, had a reduction in flows from 835 thousand tons to 268 thousand tons (−68%). In Cubatão (SP), the reduction was 36% (from 1.1 million to 695 thousand tons), whereas Rio Grande (RS) presented a less dramatic drop, from 1.3 to 1.2 million tons (−8%).

When the increases in capacities and new intermodal infrastructures are analyzed (C4), there are no major alterations in the profile of the mixer supply. On the other hand, with the expansion in demand projected in C5, the inbound flows originating from the factories demonstrate a steep decline, representing only 6.3% of all mixer supply flows. Thus, Brazil becomes even more dependent on imports considering these modifications, which indicates a need to increase national capacities to logistically benefit the fertilizer chain.

Regarding Scenario 5, inland factories suffer the most with the increase in the transport capacity of the intermodality. Catalão (GO), for instance, a major producer of fertilizers, presents a reduction of 64% in inbound flows compared to C1. A large part of this reduction is compensated for by the new railway route from Santos (SP) to Rio Verde (GO), which leads to much competition for supply in the state of Goiás. Conversely, the factories located in Uberaba (MG) present a reduction of 67% in the flows of fertilizer organization, decreasing from 2.2 million to almost 1 million tons, when Scenarios 5 and 1 are compared.

Regarding fertilizer import flows, in Scenarios 1, 2 and 4, when the parameters are not altered, there is a concentration of volume in the ports of the south and southeast, with emphasis on Paranaguá (PR), Rio Grande (RS), Santos (SP) and São Francisco do Sul (SC), which together represent almost 82% of the total national import of fertilizers. On the other hand, the ports of the north/northeast contribute close to 18% of fertilizer imports, with São Luís (MA), Salvador (BA) and Belém (PA) as the main ports regarding import volume.

An analysis was conducted on changes in the fertilizer import profile. In C3, with unrestricted import capacity, the contribution of the ports in the north/northeast increases to 30% in relation to scenarios C1, C2 and C4 (these scenarios displayed the same import capacity restrictions for fertilizers by port, so they are grouped together in the figure). Conversely, in C5, considering the expansion in demand and the new intermodal infrastructures, the mathematical model also tends to expand the inbound flows for the ports in the north/northeast region, representing 28% of the total volume. In Figure 9, these changes are presented in each scenario analyzed.

Upon evaluating C3, the ports in the north/northeast region that show the highest growth in the representation of imports occur in Belém (PA), which contributes 5.9% of the total volume of imported fertilizers, compared to 2.6% in C1 and Santarém (PA), whose import contribution is 14.4%, compared to 1.6% in C1. In other words, the results obtained from the mathematical model indicate that the northern and northeastern ports present competitive logistical costs, suggesting significant potential for the development of this region for fertilizer imports.

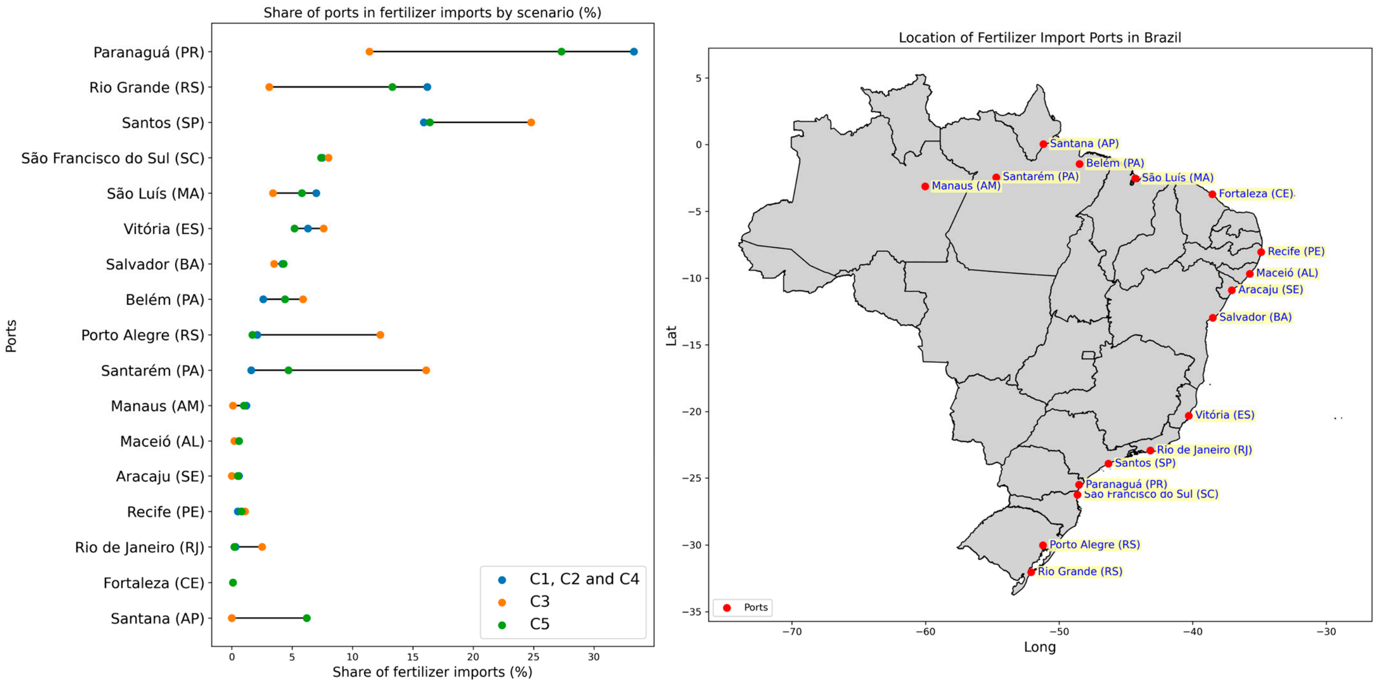

Figure 9. Contribution of fertilizer imports in each scenario and location of port imports in Brazil.

When analyzing the ports of the south and southeast, the import profile changes considerably. The results of C3 demonstrate a drop to 11.4% in the import contribution of the port of Paranaguá (PR), which is currently the main importer of fertilizers. In C1, the port represented 33.3% of the total volume imported by Brazil. The port of Rio Grande (RS) is another port for which the model indicates a reduction in import contribution, reaching 3.1% in C3, compared to 16.2% in C2. On the other hand, the opportunities for the ports of the south and southeast are evidenced by Santos (SP), Porto Alegre (RS) and Vitória (ES), whose contributions in C3 are 24.8%, 12.3% and 7.6%, respectively, compared to 15.9%, 2.1% and 7% in C1.

When C5 is analyzed, the ports of the north/northeast region show a slight drop in the contribution to imports compared to C3; nonetheless, they also indicate a large growth opportunity with the expansion of agriculture and intermodal infrastructures. The new import flow originating in the municipality of Santana (AP) brings a lot of competitiveness to the supply of mixers, representing 6.2% of the volume imported by Brazil. As in C3, Belém (PA), Barcarena (PA) and Santarém (PA) also present an increase in the volume of imported fertilizer contributed, which reflects the rise in the capacity of the waterway route to Itaituba (PA).

Considering the new railway logistics corridor from São Luís (MA) to Palmeirante (TO), the port of São Luís (MA) presents an increase in its imported fertilizer contribution of 5.8%, compared to 3.4% observed in C3. The port of Salvador (BA) does not present great alterations in import volume in the analyzed scenarios.

As identified in this work, the fertilizer logistics chain exhibits high dependency on the road modality, with a low rate of utilization of intermodality in the transport network. An important characteristic of the fertilizer sector is that the intermodal infrastructures have not been designed for fertilizer operations. In this sense, the need for a flow from the port to an input terminal represents a disadvantage for the competitiveness of railway and waterway fertilizer logistics. Thus, with the results obtained, it was also possible to evaluate how each scenario will impact the fertilizer transport matrix in Brazil, as detailed in Table 3.

Table 3. Volume allocated by the mathematical model for each mode of transport and scenario.

Transportation Mode	Scenarios				
	C1	**C2**	**C3**	**C4**	**C5**
Waterway	1%	0%	1%	1%	3%
Railway	8%	2%	6%	9%	11%
Road	91%	98%	93%	90%	86%

The optimal results obtained by the model indicate that 91% of the transport flows were allocated to the road mode, 8% to the railway mode and 1% to the waterway mode in C1. In other words, only 9% of all fertilizer flows involved transport via multimodality. Compared to C2, tax exemption in the logistics chain drastically reduces the allocation of flows to the intermodal routes. The waterway flows were practically zero, while the rail flows represented only 2% of the total volume. Thus, the gains obtained by tax exemption make it practically impossible to transport fertilizers through other modalities.

Regarding C4, the expansion of capacities and the new intermodal infrastructures are enough to increase the contribution of multimodality in fertilizer transport, and only the rail flows present an increase (albeit small) in the transport matrix. Compared to C1, there is an increase of around 500 thousand tons considering the routes from Santos (SP) to Rio Verde (GO) and from São Luís (MA) to Palmeirante (TO).

On the other hand, considering the expansion in demand for fertilizers, the use of the railway and waterway routes increases more significantly. The data of C5 demonstrate that multimodality must contribute 14% of the transport of fertilizers in Brazil, compared to 9% observed in C1. This increase reflects greater use of the railway from Santos (SP) to Rio Verde (GO) and from São Luís (MA) to Palmeirante (TO). Still, the waterway route from Santarém (PA) to Itaituba (PA) boosts the use of this modality for fertilizers. The only reason the share of intermodality does not increase further is because of the lower use of the railway from Santos (SP) to Rondonópolis (MT) in this scenario.

3.4. Location of Fertilizer Mixer Factories: Capacity and Resilience

The mathematical model results also show changes in the positions of mixing factories in each scenario. Considering the tax issues of the fertilizer sector in Brazil, Figure 10 indicates a tendency for the optimal location of mixing factories to be closer to demand sites rather than to import ports, meaning that outbound flows have a shorter average transport distance compared to the supply distance for mixers.

The expansion of fertilizer demand and intermodal infrastructures (C5) leads not only to the previously presented cost reductions but also to a decrease in the average transport distance in the logistics chain by 10 km compared to C1. The increased intermodality in fertilizer transportation also results in mixing factories moving even closer to demand sites, replacing long-distance inbound road flows with rail or waterway transport.

It is notable that the most divergent scenario is the one that ignores regional tax differences (C2), where there is a strong tendency for mixing factories to be located closer to import ports. Additionally, there is a reduction in the average transport distance by 52 km, showing that the tax rules for the fertilizer sector in Brazil create inefficient transport flows from a logistics standpoint. However, tax exemption for this sector would discourage investments in intermodal infrastructures in the country, given the logistical challenges of moving mixed fertilizers through other transport modes.

Besides bringing factories closer to fertilizer import ports, tax exemption would also lead to greater concentrations than in other scenarios. Figure 11 shows that in C2, the four major optimal regions for mixer location account for over 60% of the total volume demand in Brazil. In other scenarios, the analysis shows that this concentration is close to 45%, indicating a wider distribution of factories across the national territory.

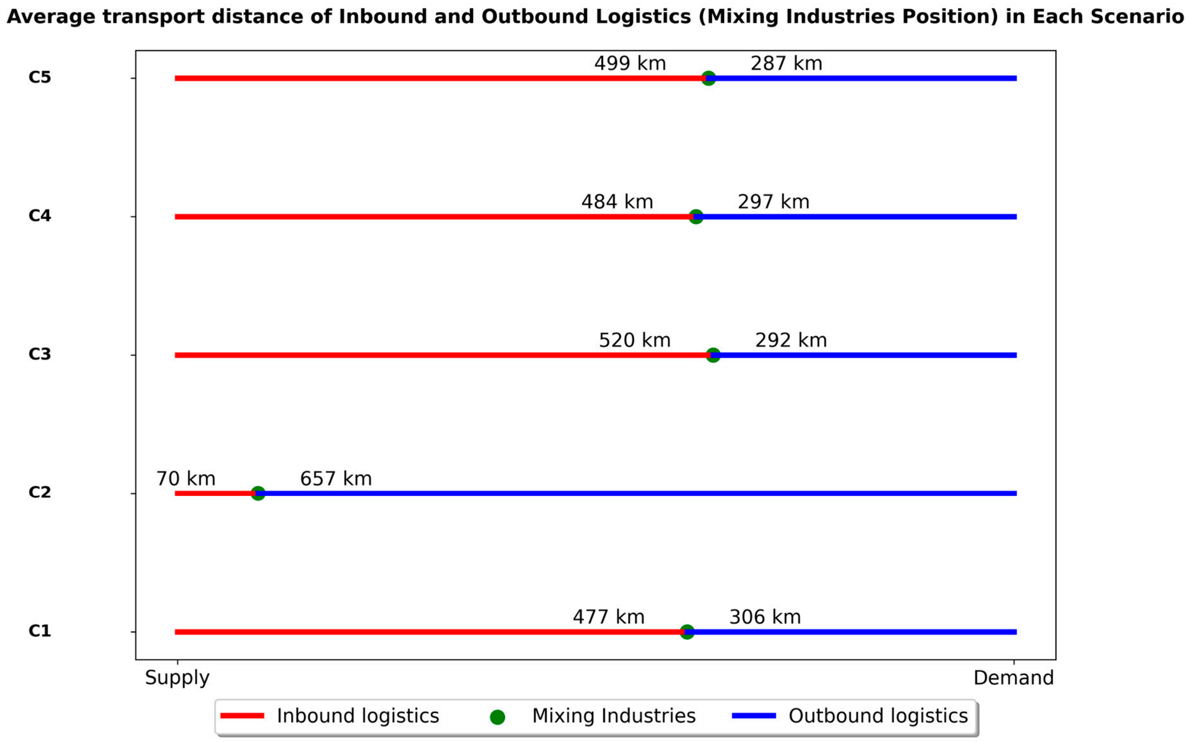

Figure 10. Average transport distances and the position of mixing factories in each scenario.

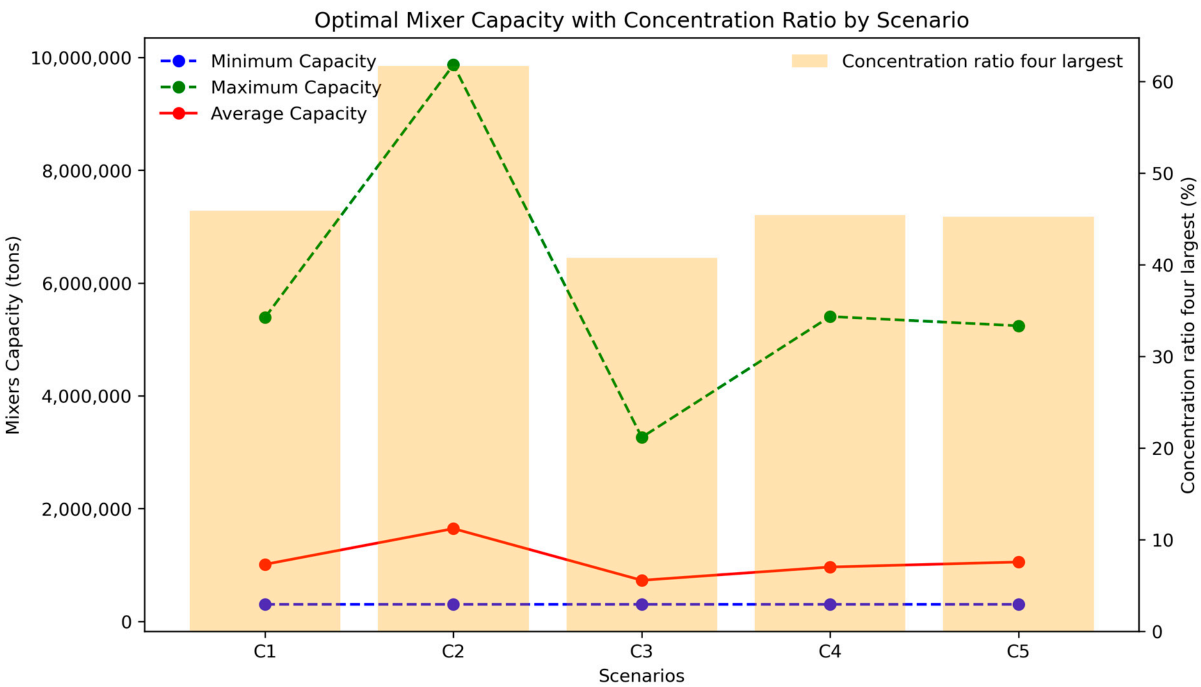

Figure 11. Concentration of mixing factories in each scenario. Minimum capacity: 300,000 tons; average capacity: 720,000 to 1,644,000 tons; maximum capacity: 3,260,000 to 9,868,900 tons.

It is important to note that the higher the concentration of mixing factories, the greater the installed capacity of the factory tends to be. Therefore, tax exemption would help some port regions already overburdened with the import and mixing of fertilizers, such as the port of Paranaguá (PR). In contrast, expanding port capacity for fertilizer unloading operations (C3) results in a lower concentration of mixing factories. It is important for relieving traditional ports and reducing logistical costs in the fertilizer chain.

The final analysis focuses on identifying the resilience of optimal locations for fertilizer mixing factories. We define location resilience as the frequency with which a region is recommended as an optimal location in the evaluated scenarios. This study analyzed five distinct scenarios, each varying in its specific characteristics. A region that emerges as an optimal location in all five scenarios is considered highly resilient to the tested changes. In contrast, regions with only one optimal location indication are classified as having low resilience, demonstrating limited viability under specific conditions.

Location resilience analysis serves as a measure of locational risk. Regions showing high resilience to the tested scenarios present a low risk of needing relocation to achieve the optimal solution.

Figure 12 illustrates the number of optimal recommendations for each region across the five evaluated scenarios. Ten regions showed just one optimal location recommendation, indicating low resilience. One region had two recommendations, six regions had three recommendations, sixteen regions had four recommendations and fifteen regions received five recommendations, showing high resilience. The regions of high resilience, receiving five recommendations, are highlighted in blue in the figure. These regions are characterized by proximity to the country's main fertilizer import ports or significant railway terminals.

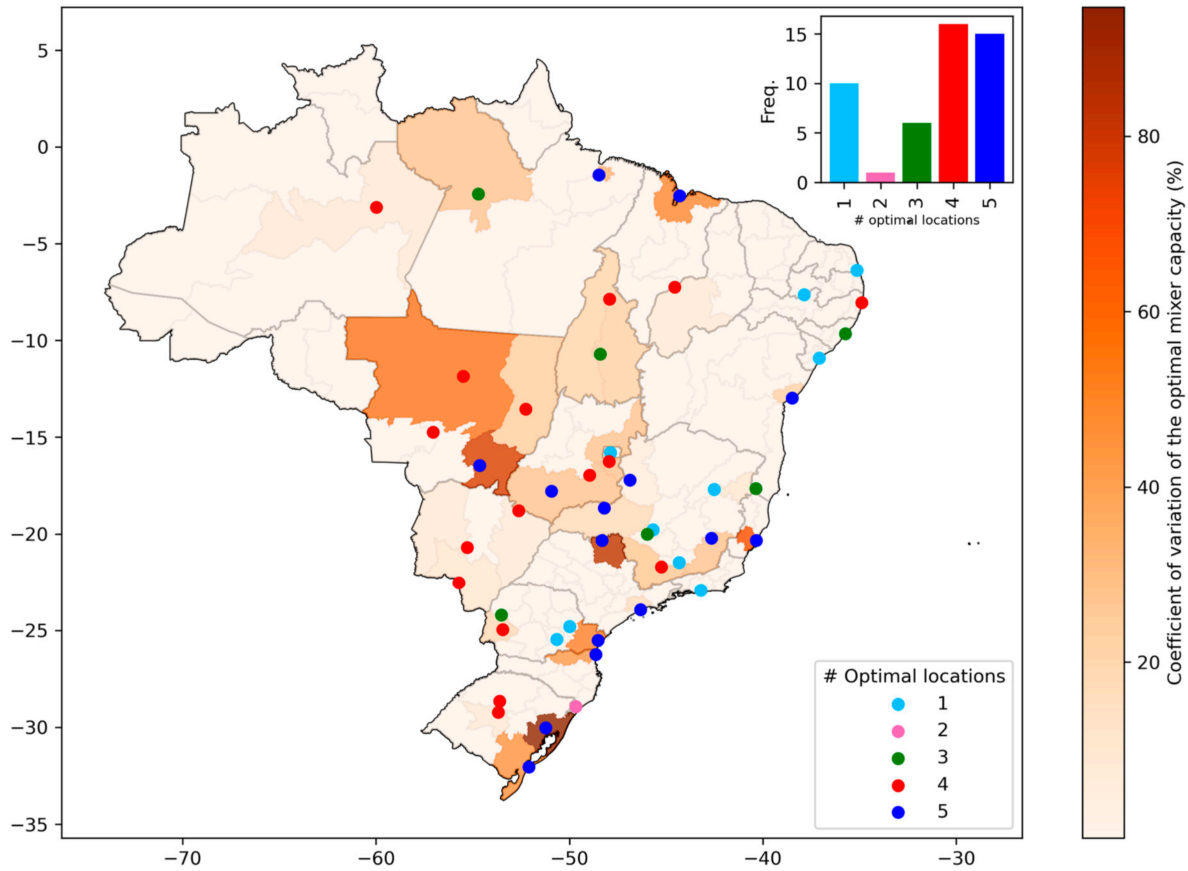

Figure 12. Map of location recommendation resilience: number of optimal recommendations per region for fertilizer mixing factories in all five tested scenarios.

Furthermore, Figure 12 presents the coefficient of variation of the optimal capacity of fertilizer mixing factories in each region, considering the five evaluated scenarios. This coefficient indicates the stability of the fertilizer mixing capacity in these regions. For example, the regions of Araguari (MG), Paracatu (MG) and the port of Santos (SP) showed high location resilience with five optimal recommendations and a coefficient of variation in mixing capacity below 20%. In contrast, the regions of Guaíra (SP), Paranaguá (PR), Porto

Alegre (RS), Rondonópolis (MT) and Vitória (ES) demonstrated high resilience but with a coefficient of variation in mixing capacity above 50%.

4. Conclusions

Of the several production chains present in the Brazilian agribusiness, the fertilizer chain is one of the most complex. Its importance, problems and lack of data motivated us to carry out this study on optimizing fertilizer logistics in Brazil using a mathematical model for choosing the location of mixing factories. Five scenarios were considered in order to address the main objectives.

The Brazilian dependency on fertilizer imports leads to very high costs for the country, evidenced in this work by the port costs. In C1, which represents the current reality of the fertilizer sector, the port costs amounted to USD 356.85 million, that is, 26% of the total logistics costs for the supply of fertilizers. With the expansion of Brazilian agriculture, it was verified in C5 that there will be an even greater increase in the dependency on imported fertilizers. Therefore, the stimulation of national production through public policies must be evaluated to reduce logistics costs and increase Brazilian competitiveness in the fertilizer sector.

The proposed mathematical model allowed for the estimation of the optimal locations of mixing factories in Brazil, as well as the calculation of their capacities. In general, mixers are concentrated in regions close to the source of the fertilizer, specifically ports and national factories. States with a high demand for fertilizers were also observed as a determining factor for the location of mixers, validating the rule of tax exemption for imports when there is industrialization within the destination of the input.

Tax exemption for fertilizer imports, analyzed in C2, promotes a series of alterations in transport flows, which makes it important to consider taxes as a logistical cost in mathematical models. Among these changes, there is a reduction of 12.5% in the total logistics costs of the chain, in addition to a greater concentration of mixers in the port regions and an increase in the outbound flows among the states. These changes indicate logistics and energy waste, which may even have associated environmental impacts. Our analysis revealed that in the scenario without fertilizer taxation, there is an increase of 2.25% in greenhouse gas emissions compared to the base scenario. On the other hand, it inhibits the national capacity of fertilizer production, in addition to reducing the rail and waterway flows. Therefore, the tax in each state must be assessed jointly with the federal government, aiming to achieve a common objective.

The importance of expanding port capacities for fertilizer importation is also apparent. Such expansion can lead to reduced logistics costs, as demonstrated in C3, resulting in the most significant reduction in greenhouse gas emissions.

The expansion of Brazilian agriculture until 2028 indicated a series of changes in the design of the fertilizer logistics chain. Through the disaggregation of fertilizer demand proposed in this work, it was possible to identify the main mesoregions that are expected to present a growth in fertilizer consumption in the future. The Mato Grosso and agricultural frontier region (Maranhão, Piauí, Tocantins and Bahia), regions with a higher observed increase in demand, must be treated as central points by professionals in the sector for the redesigning of fertilizer logistics in Brazil.

Specifically, in Mato Grosso, the main fertilizer-consuming state, C5, showed a considerable change in the profile of mixing capacities within the state. Conversely, in C1, which presented the mesoregion of the southeast of Mato Grosso as the main mixing region, C5 indicated a shift in the mixing center to the mesoregion of the north of Mato Grosso. This change is also a reflection of a higher aptitude of this new region for imports via the Northern Arc, which are more competitive.

Regarding fertilizer import flows, the results indicate substantial growth potential for the ports of the Northern Arc, with emphasis on Belém (PA), Santana (AP), Manaus (AM), Santarém (PA) and São Luís (MA). The representation of imports by the Northern Arc increases from 18% in C1, which evaluates the current conditions, to 28% in C5, which evaluates the expansion of demand and new infrastructures for fertilizer intermodality. It is concluded that investments in increasing the capacity and in the modernization of the ports of the Northern Arc are necessary to achieve logistics gains for the fertilizer transport chain.

A relevant problem in the fertilizer logistics chain lies in its transport matrix, and thus, intermodality is seldom used in this sector. C1 indicated that 91% of the fertilizer flows obtained by the mathematical model were allocated to the road modality, whereas only 9% were divided between the railways and waterways. Still, with the simulation of the increase in the current capacity and of new routes, the contribution of multimodality increased to 14% in C5. Thus, investments in infrastructures for fertilizer intermodality, especially to facilitate access to the input terminals, are essential for balancing the transport matrix and reducing fertilizer logistics costs.

Another critical aspect is the resilience of fertilizer factory locations in the evaluated scenarios. We identified 15 optimal locations, all exhibiting high resilience (with a recommendation for installation in all evaluated scenarios). Public policies could be developed to support the establishment of factories in these regions, as well as the expansion of port capacity. Improving the logistical conditions of the fertilizer network contributes to food security by reducing the costs of essential inputs in food production and promoting sustainability by reducing greenhouse gas emissions.

A limitation of this work lies in the national production of fertilizers. The proposed model aims to minimize only the logistics costs, not considering the industrial cost inherent to this link in the chain. Thus, it is suggested that future works design more appropriate models to more clearly understand public and private policies to stimulate the national production of fertilizers. It would also be interesting to perform an in-depth survey on new ore deposits in Brazil to identify possible new sources of fertilizers. Security is important in the supply chain, and new techniques have been designed to promote its application [36,37]. This theme could be explored for fertilizer logistics in future work.

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