Nitrogen Demand and Agro-Environmental Efficiency in Brazilian Cereal Production

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NITROGEN DEMAND AND AGRO-ENVIRONMENTAL EFFICIENCY IN BRAZILIAN CEREAL PRODUCTION[1]

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Date: 06/30/2021

Abstract.

This paper aims to analyze the main factors that explain the demand for synthetic nitrogen fertilizers in Brazil, as well as the efficiency of their use. In addition, the research sought to relate the use of fertilizers with nitrous oxide (N2O) emissions. Demand was estimated using the two-stage least squares method (2SLS). Nitrogen use efficiency (NUE) was calculated using an agri-environmental index. The results indicated that demand is positively affected by price of cereal, cereal production and the quantity of fertilizers used in the past harvest. The increasing and inadequate rates of fertilizer use have resulted in agro-environmental inefficiency, that is, a decrease in NUE and an increase in N2O emissions. Public policies that guarantee more agricultural technical assistance and rational alternative forms of nitrogen use could contribute to optimizing the synthetic doses applied in production, minimizing negative environmental effects, without generating economic losses to farmers and Brazilian agricultural production.

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[1] This work was carried out with the financial support of the Coordenação de Aperfeiçoamento Pessoal de Nível Superior (CAPES), Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ).

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1. INTRODUCTION

Global environmental changes have been intensifying, being more expressive in relation to climate change (Huffman et al., 2018). At the same time, there is population growth and its effects on food demand (Tilman et al., 2011; Ray et al., 2013; Zhang et al., 2017; Travassos et al., 2020). By 2050, the global population is expected to approach 10 billion people, with food demand 70% higher than the current demand (United Nations - UN, 2019). The increase in food demand tends to be asymmetric among regions, being more expressive in developing countries, notably in the poorest (Crist et al., 2017). In addition to population growth, one in nine people still suffers from food insecurity and inequality worldwide (Food and Agricultural Organization - FAO, 2018). This food demand context, linked to climate change, will lead to higher levels of global inequalities in food consumption (FAO, 2018).

To meet the growing global demand for food, fibers and energy are necessary to intensify world agricultural systems (Ainsworth et al., 2008). This intensification has been held mainly with industrialized inputs (Pires et al., 2015), such as agrochemicals, with an emphasis on nitrogen fertilizers (Lassaletta et al., 2016). The global demand for nitrogen fertilizers in agriculture increased by 34% between 2002 and 2016 alone (FAO, 2018). Furthermore, the global demand for chemical fertilizers in 2030 is estimated to be 69 million tons, 67% of which will be nitrogenated fertilizers (Tenkorang and Deboer, 2008; Pires et al., 2015).

Nitrogen is the most required nutrient by plants, but in most cases, it has low use efficiency (Zhang et al., 2017). At inadequate doses, nitrogen can cause several environmental problems, such as greenhouse gas (GHG) emissions, mainly nitrous oxide (N2O), contamination of soil and aquatic ecosystems by leaching, increased risk of erosion and imbalance in ecosystems and depletion of natural resources (Pires et al., 2015; Clark and Tilman, 2017). Economic impacts are also possible with increased production costs, such as investment in pest and disease control due to the increased incidence in plants with higher nitrogen content (Van Raij, 1991).

Increasing the efficiency of agricultural inputs can reduce the negative environmental impacts of agriculture (Clark and Tilman, 2017). Therefore, analyzing the behavior of demand for nitrogen may help in understanding the process of choosing the product by farmers. The identification of the demand and the nitrogen use efficiency (NUE) allowed us to answer questions such as: does the NUE in cereal production differ in time between the Brazilian regions? What are the factors that most impact the demand for nitrogen fertilizers in cereal production in Brazil? These are important issues in the current context of global environmental and climate change and for which the literature in Brazil, at the regional level, is still quite incipient.

The excess and inappropriate use of nitrogen corresponds to a great risk to the environment and health (Oenema et al., 2015). Therefore, knowing the efficiency of nitrogen use has the potential to contribute to the “climate smart agriculture” system pointed out by the United Nations as agricultural strategies to ensure sustainable food security under climate change (FAO, 2018).

Therefore, given these issues, the present study aimed to understand the main factors that explain the demand for synthetic nitrogen fertilizer in Brazil and to analyze the NUE in cereal production. The paper also aims to analyze nitrogen use in Brazilian states and regions, indicating its relationship with production/planted area and the environmental effects in terms of GHG emissions resulting from nitrogen use in the period of 1994 to 2018.

These issues are extremely important in the Brazilian context, since the country is considered the fourth largest consumer of fertilizers, with approximately 6% of global demand, behind the United States, China and India (Atlas Do Agronegócio, 2018). Brazilian consumption of nitrogen fertilizers in cereal production from 1994 to 2018 increased by 59%. Cereal production responded to this increase in the use of inputs, with an average growth of 56% for the same period. The dose of fertilizers applied in the period was responsible, in part, for this increase in production, since the agricultural area used for the production of cereals grew only 4%. In addition, nitrous oxide accounted for 9% of gross emissions and 12% of Brazilian GHG emissions in 2016 (SEEG, 2018).

There are several NUE studies worldwide (Johnston and Poulton, 2009; Fixen et al., 2014; Du et al., 2019; Tôsto et al., 2019), which differ among cultures, field studies and methodologies. In the case of Brazil, several studies have analyzed the NUE (Silva et al., 2014a; Silva et al., 2014b; Arenhardt et al., 2015) but for specific cultures and regions at a technical level. Pires et al. (2015) calculated the NUE for Brazil but disregarded regional heterogeneities. It is important to highlight that the Brazilian regions production differ from each other due to the types of soils that retain different amounts of nitrogen, as well as cultures demanding different fertilizer applications. In addition, the adoption of agricultural practices to minimize nitrogen use applications must be differentiated since the characteristics of climate and agricultural production are regionally different.

Therefore, studying nitrogen demand and efficiency in a disaggregated manner may contribute to well-designed policies for sustainable agricultural intensification and CSA, thereby reducing, or at least mitigating, the future environmental impacts of agriculture in Brazil. Analyzing the temporal and spatial evolution of NUE, as well as their effects of use in terms of GHG emissions, will allow a better understanding of environmental implications, contributing to actions aimed at regional asymmetries in Brazil. Identifying agricultural strategies and practices to optimize efficiency in the use of nitrogen will provide less consumption of nitrogen fertilizers by Brazilian farmers, making production more sustainable, economically and environmentally.

In addition to this introduction, the study is divided into methodological procedures, indicating the path taken to fulfill the research objectives; the analysis of the main results found; discussions concerning the interpretation of these results and, finally, the main conclusions of the study.

2. METHODOLOGY

2.1 Fertilizer demand

The input demand model considered initially is presented in equation (1):

$$N = F(P_N, P_C, P_P, P_K) \qquad (1)$$

where N is the quantity demanded for nitrogen fertilizer, which is a function of the nitrogen price (P_N), cereal price (P_C) and the prices of phosphorus and potassium (P_P and P_K, respectively), complementary inputs.

In addition to the variables present in equation 1, the demand forecast model proposed by FAO (2000) and Tenkorang and DeBoer (2008) establishes that there is a correlation between the present use of nitrogen and the future production of cereals, since the amount of input acquired is directly related to the quantity of cereals who intend to produce in the future.

We emphasize that farmers' decisions are also affected by the economic conditions to which they are subjected. As a result, different locations vary in their respective agricultural incomes. Therefore, we expect that regions with higher levels of agricultural GDP will have farmers with better financial conditions to demand inputs for production.

Thus, the demand for fertilizers represented in (1) is rewritten as:

$$Q_N^D = F(P_N, P_C, P_P, P_K, Y, F_{t-1}, GDP_A) \qquad (2)$$

where Q_N^D is the quantity demanded for nitrogen fertilizer, depending on P_N own price, P_C cereal price, P_P phosphorus-based fertilizer price, P_K potassium-based fertilizer price, Y cereal production, F_{t-1} amount of nitrogen fertilizer used in the past and GDP_A the farmer's income measured in agricultural GDP.

Considering these specificities, the nitrogen demand equation is rewritten according to equation (3):

$$lnN_{it} = \alpha_{0it} + \alpha_{1it}lnP_{Nit} + \alpha_{2it}lnP_{Cit} + \alpha_{3it}lnP_{Pit} + \alpha_{4it}lnP_{Kit} + \alpha_{5it}lnN_{it-1} + \alpha_{6it}lny_{it} + \alpha_{7it}lnGDP_{Ait} + \varepsilon_{it} \qquad (3)$$

where P_N is the nitrogen fertilizer price, P_C is a cereal price index, P_P is the phosphorus price, P_K is the potassium price, N_{t-1} are nitrogen fertilizers used in year *t-1*, y_t is the ceral production in year *t*, GDP_A is the agricultural GDP and ε_{it} is the error term. We expect that the coefficients α_2, α_5, α_6 and

α_7 have a positive effect and that α_1, α_3 and α_4 have a negative effect on nitrogen demand (FAO, 2000; Tenkorang and DeBoer, 2008).

For the development of the cereal price index, we followed the proposition of Saraiva et al. (2020):

$$Ip_c = \sum_{j=1}^{n} q_{ij} p_{ij} / \sum q_{ij} \overline{p_j} \tag{4}$$

where i are the Brazilian states; j are the 7 cereals considered (Rice, Oats, Rye, Barley, Corn, Sorghum and Wheat), q_{ij} is the quantity produced of cereal j in state i, p_{ij} is the price of cereal j in state i and $\overline{p_j}$ is the average price of product j in Brazil.

The variables related to the price of cereals, price of fertilizers and agricultural GDP were deflated using the General Price Index - Internal Availability (IGP-DI), which was chosen based on the specialized literature (Profeta and Braga, 2011). The prices of fertilizers N, P and K used were ammonium sulfate, single superphosphate and potassium chloride, respectively.

2.2 Nitrogen use efficiency (NUE)

The NUE indicator considered in this research was based on the balance of nutrients, adapted according to the methodology proposed by Raun and Johnson (1999):

$$EUN = \left[\frac{(N_G - N_R)}{N_C}\right] \times 100 \tag{5}$$

where N_C is the application of nitrogen fertilizers for cereal production, N_G is the removal of nitrogen from the cereal grain and N_R is the nitrogen removed by cereals from natural soil fertilization.

The application of nitrogen fertilizers (N_C) corresponded to the amount applied in tons for each cereal crop in each state and region in the period 1994 - 2018. The removal of nitrogen from the grain (N_G) in g/kg was calculated by multiplying the quantity produced of each cereal by the concentration of nitrogen in the culture. The nitrogen concentration values are different for each cereal crop. The crops considered in this study were rice, oats, rye, barley, corn, sorghum and wheat, with the following concentration values: 12.3 g/kg; 19.3 g/kg; 22.1 g/kg; 20.2 g/kg; 12.6 g/kg; 19.2 g/kg; 21.3 g/kg. (Tkachuk, 1977; Pires et al., 2015). Nitrogen from natural fertilization (N_R) was considered according to the literature, which corresponds, on average, to 50% of the amount of nitrogen taken up in the grain (N_G) (Lara Cabezas et al., 2005).

When measured by the balance of nutrients, the NUE corresponds to an agri-environmental efficiency indicator, which plays a key role in policy management analysis (Oenema et al., 2015). This is because part of the nitrogen applied and not absorbed by the grain will tend to become lost to the environment. According to Casarin (2015), if i) NUE > 1: N is being removed more than applied, with possible environmental effects of depleting soil fertility; ii) NUE < 1: N is being applied more than removed, indicating that the non-removed N may be stored in the soil and/or flowing through the environment; and iii) NUE = 1: the amount of nutrient applied is equal to that removed, and in no biological system will this situation occur.

This study considered agroenvironmental NUE based on the balance of outgoing/incoming nutrients, which for agricultural production systems depends on the type of crop, the capacity to remove N in the grain and nitrogen fertilization in the soil. This agri-environmental index provides useful information on the relative use of the additional synthetic nitrogen fertilizer applied, that is, if the excessive application is turning into losses for the environment (Oenema et al., 2015).

2.3 Greenhouse gas emissions

The inappropriate and/or excessive use of nitrogen can generate adverse impacts on the environment, including the release of nitrous oxide (N_2O), which is a greenhouse gas (GHG) (De Klein et al., 2006). In the case of cereals, N_2O emissions resulting from the use of nitrogen fertilizers were estimated following the methodology proposed by De Klein et al. (2006), Crutzen et al. (2008) and Pires et al. (2015), in which N_2O emissions occur directly and indirectly, as shown in equations (6 and 7):

$$N_2O_{ED} = N_{FERT} \times EF_1 \times 1{,}571 \times 310 \tag{6}$$

$$N_2O_{EI} = N_{FERT} \times EF_2 \times 1{,}571 \times 310 \tag{7}$$

Where N_{FERT} is the amount of synthetic nitrogen fertilizer applied, EF_1 is the direct N_2O emission factor, which corresponded to 1% of the total nitrogen fertilizer applied in cereal production (De Klein et al., 2006). EF_2 refers to the indirect N_2O emission factor, constituting approximately 0.4% of the applied nitrogen fertilizer (Crutzen et al., 2008). The values of 1,571 and 310 added in these equations refer to the conversion factor from N_2O-N to N_2O and from N_2O to CO_2, respectively, analyzing the global warming potential of N_2O over time (De Klein et al., 2006; Pires et al., 2015).

The variable referring to the amount of synthetic nitrogen fertilizers used in cereal production was estimated by means of weights, which represent the share of the area planted for each cereal in relation to the area planted with all temporary crops in each year and state. Subsequently, the weights were multiplied by the amount of nitrogen delivered to the producer (variable available). This calculation was performed as a way of approximating the true value of nutrient added in each culture, which is unknown in the period of the study. In addition, this estimation is important since many states may require more or less fertilizers, depending on the area for each crop produced.

2.4 Data source

We used databases from different sources: (i) *Sistema IBGE de Recuperação Automática* (SIDRA) for quantity produced of cereals, area produced of cereals and state agricultural GDP; (ii) *Anuário Estatístico do Setor de fertilizantes* 1994 – 2018 of the *Nacional para difusão de Adubos – ANDA* for quantity of fertilizers N, P, K delivered to the consumer; and (iii) Companhia Nacional de Abastecimento (CONAB) for inputs price N, P and K and cereal prices.

3. RESULTS

3.1 Demand for Nitrogen Fertilizers

Table 1 shows the results for the estimation of the demand for nitrogen fertilizers.

Table 1 - Estimation of demand for nitrogen by 2SLS.

Variable	Coefficient	Variable	Coefficient
$LnPn$	-0.2586 (0.2380)	lnN_{t-1}	0.9344*** (0.0322)
$LnPc$	0.2674** (0.1189)	lny_t	0.0812*** (0.0306)
$LnPp$	-0.1574 (0.1348)	$lnGDP_A$	0.0055 (0.0297)
$LnPk$	0.0078 (0.2608)	*Constant*	2.3792 (1.9191)

Note: According to the Sargan test, the instruments are valid; the Hausman test indicated that the variables are exogenous; standard errors in parentheses; ***p<1%, **p<5%.

The results indicate that the estimated coefficients for the variables *cereal production* (y_t), cereal price index (P_C) and the amount of nitrogen demand lagged by one year (N_{t-1}) were statistically significant. The coefficients of these variables showed the expected signs, indicating a positive effect on nitrogen demand. The results showed that the increase of 1% in the quantity produced of cereals would affect the amount of fertilizers consumed by 0.08%; the 1% increase in the expected cereal price would lead to an increase of 0.26% in the quantity demanded for the input; and for the lagged amount of nitrogen, the variation of 1% would increase the amount of fertilizers consumed by 0.93%. As the equations were estimated in logarithmic form, the coefficients can be interpreted as elasticities. Therefore, the results indicated that the amount of nitrogen demanded is inelastic to these variables.

3.2 Nitrogen use efficiency (NUE)

As shown in Figure 1, the NUE in cereal production in Brazil had an average value of 53%, with a decrease of 0.23% per year between 1994 and 2018. The Northeast region presented an average NUE value of 38%, with a rate of decrease of 2.01% per year; the Southeast region reached a value of 27% in the average NUE, with annual growth of 1.25%; and the South and Midwest regions obtained an average NUE of 73% and 84% and a decrease of 1.20% and 1.25% per year, respectively.

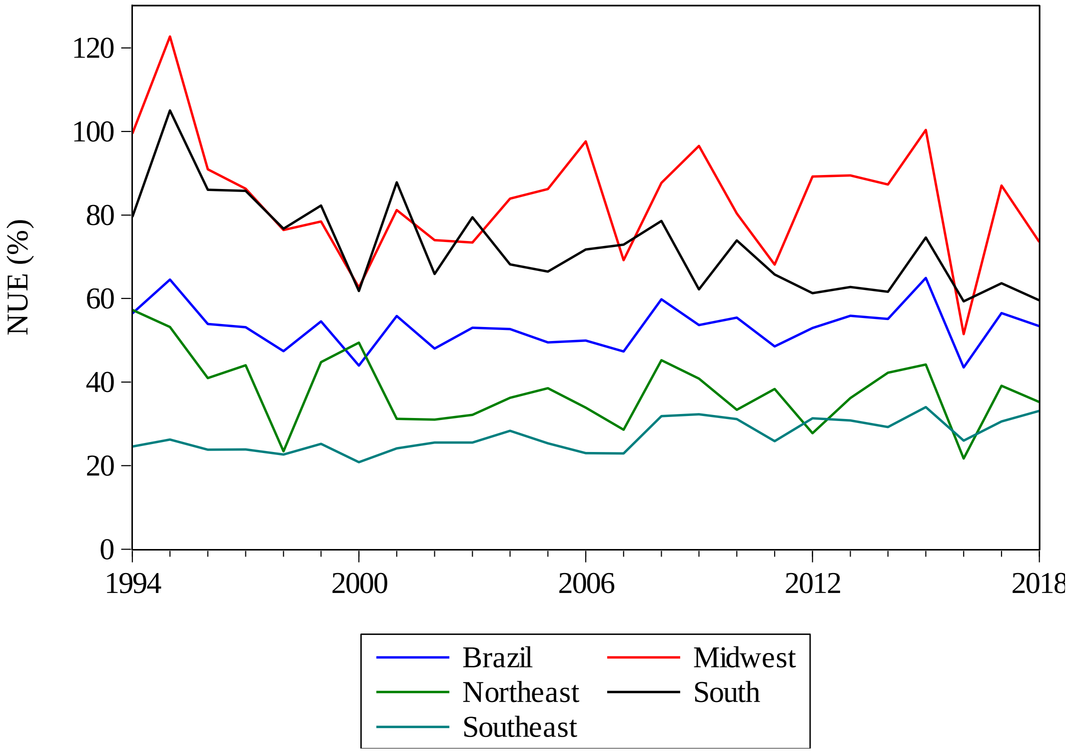

Fig. 1. Evolution of the NUE in Brazil and in the main regions

From 1994 to 2018, the consumption of nitrogen fertilizers in Brazilian cereal production increased 59%. The area cultivated with the main cereals (rice, oats, rye, barley, corn, sorghum and wheat) expanded by only 4% in the same period. This caused the annual nitrogen dose (kg/ha) applied to these crops in Brazil to increase from 25.17 kg/ha to 58.54 kg/ha. Cereal production in Brazil responded to this increase in the use of fertilizers; however, it did not exceed a 56% increase in the same period.

3.3 Greenhouse gas emissions

There was a continuous growth in emissions from the use of nitrogen fertilizers in all regions of the country. From 1994 to 2018, emissions grew on average 59% in the country (Figure 2). Emissions related to the application of synthetic nitrogen fertilizers in cereal production reached values close to 8.7 million tons of CO2eq. in 2018. Regionally, this growth was 92% in the North, 88% in the Midwest, 58% in the Northeast, 52% in the South, and 16% in the Southeast region. The annual geometric growth was 10.9% in the North, 9.27% for the Midwest, 3.63% for the Northeast, 3.09% for the South and 0.73% for the Southeast region. For Brazil, the geometric growth rate was 3.74% per year.

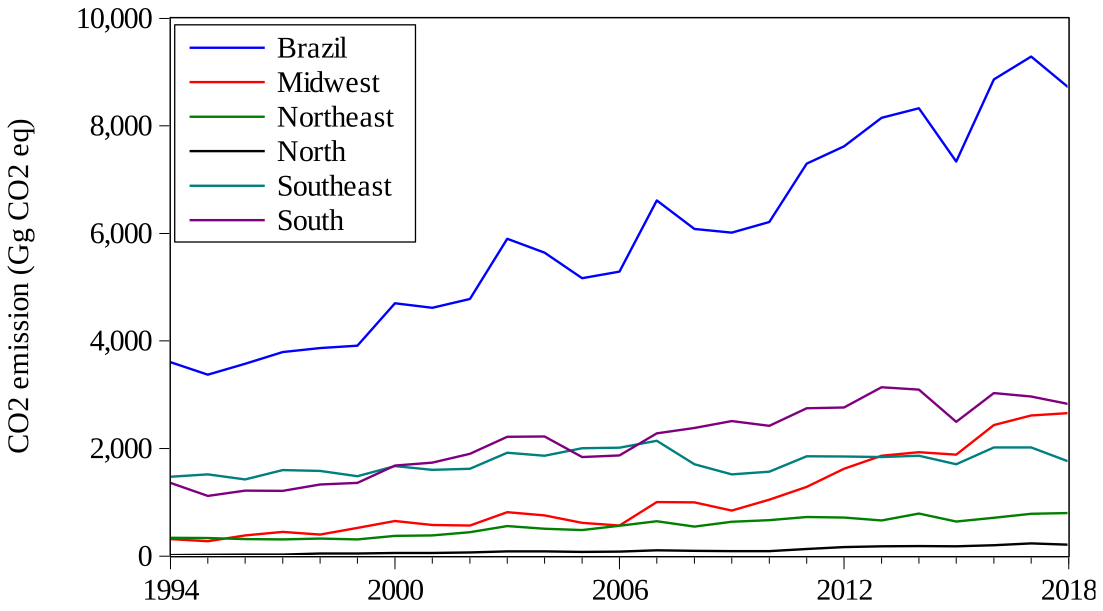

Fig. 2. Evolution of greenhouse gas emissions from synthetic nitrogen fertilization in cereal production between 1994 and 2018
Note: N2O emissions have been converted to Gg CO_2 eq (1 unit of Gg is equivalent to 1000 tons).

In terms of participation, Figure 3 shows the percentage contribution of different regions and states in Brazil to the average CO2eq emission in the period derived from nitrogen fertilization for cereal production. There is a greater contribution from the South region, followed by the Southeast and Midwest regions. The states with the highest emissions were Minas Gerais, Rio Grande do Sul and Paraná, with contributions greater than 15% of total emissions.

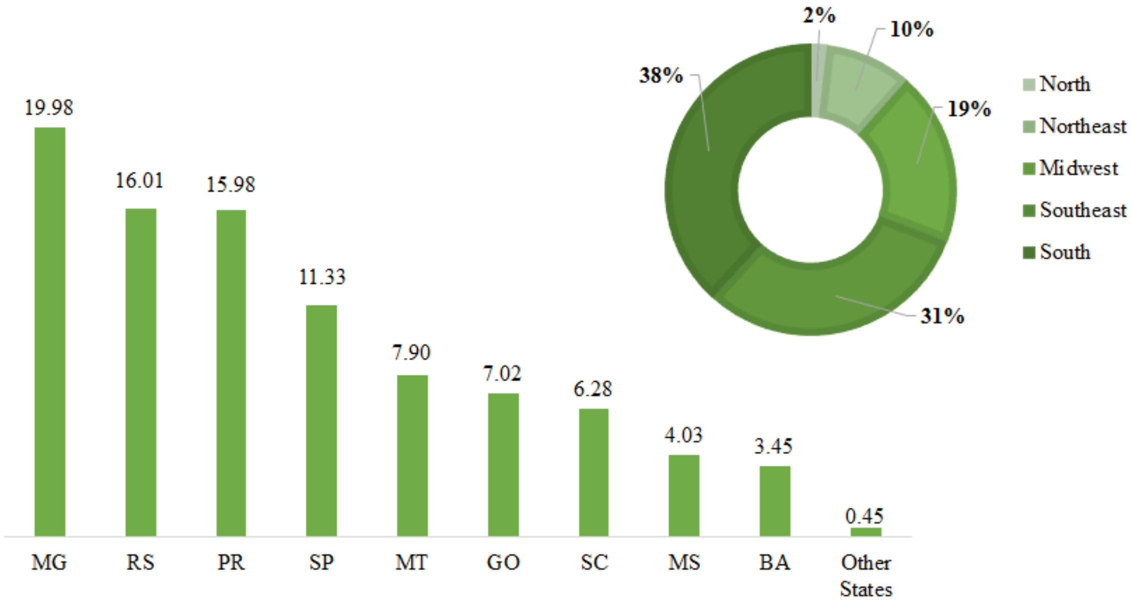

Fig. 3. Percentage average contribution of regions and states in Brazil to CO2eq emissions from nitrogen fertilization for cereal production in the period 1994-2018 (%)

4. DISCUSSION

4.1 Nitrogen demand and farmers' inertia

Brazil is among the largest cereal producers in the world, along with China, the United States and India (FAO, 2018). At the same time, the increased consumption of nitrogen fertilizers for the production of these crops makes Brazil the fourth country that most consumed nitrogen fertilizers in the world in agriculture in 2017 (FAOSTAT, 2019), even with agricultural areas with potential for expansion. One of the main factors that explains the increase in the use of nitrogen fertilizers is the expansion of corn cultivation in the double cropping system, in consortium with soy, increasing the need for nutrients (Pires et al., 2015; Jankowski et al., 2018).

The positive relationship between cereal production and the amount of nitrogen demanded suggests that Brazilian farmers tend to consume increasing amounts of synthetic nitrogen fertilizers in the hope of obtaining ever higher yields. Similar results were found in the literature (Tenkorang and Deboer, 2008; Acheampong and Dicks, 2012; Pires et al., 2015). The elasticity of fertilizer use in relation to cereal production of less than one unit demonstrated that the quantities of fertilizers are inelastic to cereal production, indicating that there is an inadequate application of nitrogen fertilizers (Tenkorang and Deboer, 2008).

The inadequate application of fertilizers, both in greater and lesser quantities, impairs the process of assimilation of plants, affecting the production of cereals. On the other hand, to obtain growth in production, the farmer adds even more nutrients, ignoring the “Law of Diminishing Returns”. As in most production processes, the use of a given input is subject to the aforementioned "law" (Holmes and Aldrich, 1957), and agricultural production tends to decrease if there is an increasing and excessive addition of just one input. In addition, most farmers are unable to predict harvest yield due to uncontrollable characteristics, so the addition of inputs will always be the maximum judged by them.

For the cereal price variable, a positive relationship was observed with the demand for fertilizers, which is in line with other results in the literature (Acheampong and Dicks, 2012; Leonard, 2014). This shows that farmers take into account the price of cereals when consuming fertilizers, which is certainly associated with the expected economic return. In general, when the cereal price increases considerably, farmers change from legume-cereal rotation to continuous cultivation of cereal, which makes it possible to obtain short-term returns.

We emphasize that in many regions, the price of nitrogen fertilizer is relatively cheaper than the crop price, which leads farmers to apply more fertilizers than necessary (Cai et al., 2014). Therefore, as long as the cereal market continues to appreciate, the greater the incentive to produce more and, consequently, greater demand for input and the possibility of inefficient use. For example, Cai et al. (2014) simulated a 50% increase in the price of nitrogen fertilizer and, at the same time, in the corn price, and observed that the change in the cereal price has a greater impact on the application of nitrogen than the increase in the fertilizer price.

Regarding the importance of the lagged amount of nitrogen variable, this can be explained by the farmers' inertia regarding the past use of nitrogen. Many farmers tend to stay on the same trajectory of using fertilizers in the hope of achieving equal or greater gains. Additionally, most farmers do not have access to information and technology. In addition, countries with high fertilizer consumption may continue to consume more, and consumption rates in areas of low fertilizer use tend to change slowly over time (Tenkorang and Deboer, 2008). We emphasize that there are times when the producer invests in soil fertilization in a given year for fear that the next year does not have financial resources to purchase such inputs. In this way, nutrients may be stored in the soil during periods of financial scarcity. Concomitantly, as Brazil still has available areas, growth in the use of fertilizers is expected to supply the need for nutrients in the soil.

4.2 Low and decreasing NUE values, inefficient use and high nitrogen losses

The intensification of land use that occurred in the production of cereals due to the increasing use of nitrogen fertilizers resulted in a decrease in agro-environmental NUE in Brazil and in the major regions. The average NUE for cereal production in Brazil calculated was 53%, higher than those found by Pires et al. (2015) and lower than those found by Casarin (2015). According to Oenema et al. (2015), desirable NUE values should vary between 50-90%, indicating satisfactory use of N; however, the definition of target values involves the type of agricultural system, soil and climate. For Latin America, the minimum desirable average NUE is 60% (Tôsto et al., 2019), so the values found here were lower.

Low and decreasing NUE values, as identified in this research, in addition to indicating inefficient use of this resource, point to high nitrogen losses, since part of the nitrogen not removed flows into the environment (Sutton et al., 2011; Oenema et al., 2015). Excessive applications of nitrogen fertilizers lead to environmental problems, such as water eutrophication, loss of biodiversity, global warming and stratospheric ozone depletion (Sutton et al., 2011; Rutting, et al., 2018). On the other hand, limited access to nitrogen, or very high NUE, leads to reduced yields and insufficient food supplies, indicating depletion of resources, that is, depletion of soil nitrogen, leading to degradation, erosion and nutrient poverty (Oenema et al., 2015; Rutting et al., 2018).

In areas of high profitability, there are usually excessive applications of synthetic nitrogen fertilizers (Sutton et al., 2011). On the other hand, as in very poor rural areas and with inefficient logistics (Africa, for example), the farmer's income is low, and the application of nitrogen fertilizers is not favored, which results in soil mining (Oenema et al., 2015). Therefore, when analyzing the results at the regional level, we can see that both the excessive application and the absence of synthetic fertilization resulted in inefficient use. This statement can be exemplified in the results from the Northeast region in Brazil, which consumed on average 23 kg/ha of fertilizer, compared to those in the Southeast region, which used approximately 96 kg/ha. Both regions had the lowest average NUE values. This range of N addition values producing equal use inefficiency can mean soil degradation in the Northeast region through nitrogen mining and excessive losses to the environment, including emission of polluting gases, in the Southeast (Moss, 2007).

In relation to the South and Midwest regions, which had the highest values of average NUE, the result can be explained, in part, by the excellent productivity achieved in the period. Although the values of average productivity in the Southeast are close to those in the South and Midwest, this region did not obtain better NUE values due to the high values of annual nitrogen dose per area and the low participation in national cereal production (not exceeding 12% in the 2018 harvest).

The way in which fertilizers are applied can also interfere with NUE, since it can cause salinization in the seeds (Debruin and Butzen, 2015). Late nitrogen application can lead to low development and low productivity. Therefore, applying fertilizer at the time when the plant needs it most and in the indicated amount is one of the viable ways to achieve ideal NUE (Broch et al., 2012). On the other hand, the fragmentation of nitrogen fertilizer makes the practice of costly post-planting fertilization (Costa et al., 2013). Alternatives such as biological nitrogen fixation (BNF), which is technically well used in Brazil in soybean crops, can be an excellent source of N for cereals, increasing NUE, since it allows less application of N in crop rotation.

In general terms, previous research has identified that in certain types of soils, synthetic nitrogen fertilizer can be reduced by up to 50% of the applied rates without sacrificing cereal agricultural production (Du et al., 2019). Numerous studies have sought to identify practices to improve NUE, seeking better synchronization between nitrogen supply and demand by the plant, including harvesting techniques, ideal application rate, time and method (Sahar et al., 2012; Du et al., 2019).

4.3 The growing use of nitrogen fertilizers and GHG emissions

Due to the increasing nitrogen use in the Brazilian production of cereals, part of the losses of this macro element to the environment were translated into GHG emissions, particularly nitrous oxide (N2O) (which in this research was converted into CO2eq.). Brazil is considered the seventh largest GHG emitter in the world, contributing 3.4% of total emissions (SEEG, 2018), ranking third considering only emissions from agriculture (SEEG, 2018). World agriculture contributes approximately 80% of N2O emitted to the atmosphere annually by human activities (Robertson, 2004; Pires et al., 2015).

The decrease in the NUE and the growth in emissions in the evaluated period is explained, in part, by the agricultural intensification that occurred in Brazil in the period 1994-2018. The growing use of synthetic nitrogen fertilizers has meant inefficiency in their use in agricultural cereal production, resulting in environmental losses and GHG emissions to the atmosphere. In general, there was an increase in N2O and NO emissions following the application rates of nitrogen fertilizers in agricultural production (Zhang et al., 2016). This was because the high rates of nitrogen application stimulated the nitrification process and/or denitrification.

With regard to Brazilian regions, we observed that the South was the one that most contributed to N2O emissions, followed by the Southeast region. However, even though the Southeast region represents a relatively low share of national cereal production, the states of São Paulo and Minas Gerais belong to this region, considered in 2017, together with Pará and Mato Grosso do Sul, the largest GHG emitters in the sum from the sectors of agriculture, energy, land use changes, industrial processes and waste (SEEG, 2018). The Midwest region, on the other hand, even with higher production than the Southeast, did not present, on average, such expressive emissions, which can be justified, in part, by the NUE that occurred in the period.

Field studies have shown that the high rates of application and/or the non-optimized use of synthetic nitrogen fertilizers are practices that promote the flow of N2O in the main agricultural productions (Jarecki et al., 2009; Hoben et al., 2011 Linquist et al., 2012). Additionally, emissions from nitrogen fertilization constitute financial losses. In Europe, the damage caused by nitrogen pollution was estimated at 70 to 320 billion euros, equivalent to 1 to 4% of the total income (Bodirsky et al., 2012). Increases in NUE in Brazil could generate savings of more than 20 million dollars in costs with nitrogen fertilizers (Pires et al., 2015). Therefore, practices that increase the NUE can contribute to reductions in GHG emissions, as well as avoiding economic losses and cost generation.

The great challenge in intensive agricultural production systems is to integrate ideal values of NUE and sustainability with expressive production and productivity in minimal lands. The efficient use of alternative forms of nitrogen is the basis for combining low environmental impact with future food security (Rutting et al., 2018). Among the alternative forms of non-synthetic nitrogen, intercropping with legumes reduces nitrogen leaching under no-till conditions (Constatin et al., 2015). The system of direct planting in legume straw is of great relevance in reducing applications of synthetic fertilizers, reducing losses, expenses and generating agricultural sustainability (Quinkenstein et al., 2012; Silva, 2016).

Minimizing the use of synthetic nitrogen fertilizers could be the most efficient option. However, Brazilian agriculture is still a major chemical dependent on input, which would compromise future food, fiber and fuel production. The reduction in fertilizer consumption in developed countries was successful due to the improvement of agricultural production technologies, such as denitrification inhibitors, polymer-coated slow release fertilizers and precision agriculture (FAO, 2018); however, such measures are still costly for Brazil.

Efficient agricultural technical assistance in the country becomes the best alternative in the current context, as it allows communication, training and service provision directly to the producer, preserving and recovering the available natural resources without impacting the gross value of production. However, only 19% of Brazilian rural establishments received adequate agricultural technical assistance (IBGE, 2018), the rest being dependent on input vendors' opinions, consuming even more fertilizers and exacerbating the pressure on natural resources. The lack of technical assistance aggravated by the low level of training of many farmers (IBGE, 2018) reflects the non-adoption of technologies and the failure to use appropriate cultural practices for rotation, consequently increasing production losses and the use of inputs (Castro, 2015).

5. CONCLUSIONS

In general, the results of this research demonstrated that the agricultural intensification that occurred in Brazil in the period 1994-2018 was related to the increase in the use of fertilizers by area, which has been translated, partially, into high CO2eq emissions in the period. The agri-environmental efficiency of nitrogen use in cereal production is distinguished temporally among Brazilian regions, but the national average is still low. The average values calculated for the NUE are below the desirable values for Latin America (Tôsto et al., 2019), which indicates that GHG reduction targets by the end of the century may be compromised. In terms of demand for nitrogen fertilizers, while the cereal prices rise, the greater the consumption of this input will be.

Increasing productivity and production based on sustainable intensification comprises one of the alternative paths for future environmental change, since the trade-off between economic growth and environmental impact will always exist, but it can be minimized. Therefore, offering efficient agricultural assistance and means for farmers to invest in sustainable agricultural intensification techniques could optimize the use of inputs, making production more economical and with less negative environmental effects. Improvements in the efficiency of nitrogen use in agricultural production are critical to meeting the challenges of humanity. Achieving food security, with the least possible environmental degradation, in a climate change environment requires not only improvement on the production side but also on all consumers. It is noteworthy that although the impacts resulting from the inefficiency of the use of nitrogen come from different or distant regions, the negative effects are felt on a global scale, compromising society as a whole.

Finally, we emphasize that for policy-making purposes, the analysis of the NUE developed here must be used together with information on productivity and production gains and crop rotation, among others collected in the field. In addition, the edaphoclimatic and economic conditions to which the regions are subjected can also impact the use of fertilizers. Therefore, this theme should be explored in future research since the agro-environmental efficiency considered here takes into account its rational use and not its availability to use. There are rich and efficient areas, but there can also be poor and efficient areas.

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