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Original Article

Nitrogen demand and agro-environmental efficiency in Brazilian cereal production

Demanda de nitrogênio e eficiência agro-ambiental na produção brasileira de cereais

E. A. Santos[a]*, D. A. Cunha[a] and G. F. Travassos[a]

[a]Universidade Federal de Viçosa – UFV, Departamento de Economia Rural, Viçosa, MG, Brasil

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 (N_2O) 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 of nitrogen fertilizers is positively affected by the price of cereal, cereal production and the number of fertilizers used in the past harvest. The calculated NUE presented an average value of 53% in the 1994-2018 period, indicating inefficient use of N. Emissions from nitrogen fertilization grew 59% for the same period. The increasing and / or inadequate rates of fertilizer use have resulted in agro-environmental inefficiency, that is, a decrease in NUE and an increase in N_2O 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 adverse environmental effects without generating economic losses to farmers and Brazilian agricultural production.

Keywords: efficiency, nitrous oxide emissions, fertilizer demand, nitrogen.

Resumo

Este trabalho tem como objetivo analisar os principais fatores que explicam a demanda por fertilizantes nitrogenados sintéticos no Brasil, bem como a eficiência de seu uso. Além disso, a pesquisa buscou relacionar o uso de fertilizantes com as emissões de óxido nitroso (N_2O). A demanda foi estimada usando o método dos Mínimos Quadrados em dois Estágios (MQ2E). A eficiência do uso de nitrogênio (EUN) foi calculada por meio de um índice agroambiental. Os resultados indicaram que a demanda de fertilizantes nitrogenados é afetada positivamente pelo preço do cereal, pela produção do cereal e pela quantidade de fertilizantes utilizados na safra passada. A EUN calculada apresentou valor médio de 53% no período 1994-2018, indicando uso ineficiente de N. As emissões da adubação nitrogenada cresceram 59% no mesmo período. Os índices crescentes e/ou inadequados de uso de fertilizantes têm resultado em ineficiência agroambiental, ou seja, diminuição da EUN e aumento das emissões de N_2O. Políticas públicas que garantam mais assistência técnica agropecuária e formas alternativas e racionais de uso do nitrogênio poderiam contribuir para otimizar as doses sintéticas aplicadas na produção, minimizando os efeitos ambientais adversos, sem gerar prejuízos econômicos aos agricultores e à produção agrícola brasileira.

Palavras-chave: eficiência, emissões de óxido nitroso, demanda de fertilizantes, nitrogênio.

1. Introduction

Global environmental changes have been intensifying, becoming more expressive about climate change (Huffman et al., 2018). At the same time, there is population growth and its effects on food demand (Ray et al., 2013; Zhang et al., 2017; Travassos et al., 2020; van Dijk et al., 2021). By 2050, the global population is expected to approach 10 billion people, with food demand 70% higher than the current demand (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 (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 mainly with industrialized inputs (Pires et al., 2015), such as agrochemicals, emphasizing on nitrogen fertilizers (Lassaletta et al., 2016; Hussain et al., 2022). The global demand for nitrogen fertilizers in agriculture increased by 34% between 2002 and 2016 alone (FAO, 2018). Furthermore, the global demand for chemical

*e-mail: elizangelasantosufv@gmail.com
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fertilizers in 2030 is estimated to be 69 million tons, 67% of which will be nitrogenated fertilizers (Tenkorang and Lowenberg-DeBoer, 2009; Pires et al., 2015).

Brazil is considered the fourth largest consumer of fertilizers, with approximately 6% of global demand, behind the United States, China, and India (Farias et al., 2020). 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 to produce cereals grew only 4%. In addition, nitrous oxide accounted for 9% of gross emissions and 12% of Brazilian GHG emissions in 2016 (SEEG, 2018). It is important to emphasize that Brazil is among the largest global cereal producers and GHG emitters, along with China, the United States and India (Yu et al., 2019; Jalles, 2022).

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 (N_2O), 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 (Skendžić et al., 2021).

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

The excess and inappropriate use of nitrogen poses a significant risk to the environment and health (Oenema et al., 2015; Osti et al., 2017). Therefore, knowing the efficiency of nitrogen use can contribute to the "Climate Smart Agriculture" (CSA) system pointed out by the United Nations as an agricultural strategy to ensure sustainable food security under climate change (FAO, 2018).

Several NUE studies worldwide (Fixen et al., 2015; Du et al., 2019; Tôsto et al., 2019), differ among crops, 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 crops and regions at a technical level. Pires et al. (2015) calculated the NUE for Brazil but disregarded regional heterogeneities. It is essential to highlight that the Brazilian region's production differs from each other due to the types of soils that retain different amounts of nitrogen and crops demanding different fertilizer applications. In addition, adopting agricultural practices to minimize nitrogen use applications must be differentiated since climate and agricultural production characteristics are regionally different.

Study nitrogen demand and efficiency in a disaggregated manner may contribute to well-designed policies for sustainable agricultural intensification, 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.

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.

2. Material and Methods

2.1. Fertilizer demand

The input demand model considered initially is presented in Equation 1:

$$N = F\left(P_N, P_C, P_P, P_K\right) \tag{1}$$

Where N is the quantity demanded nitrogen fertilizer, which is a function of the nitrogen price per tons (P_N), cereal price per kg (P_C) and the prices per tons 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 Lowenberg-DeBoer (2009) establishes that there is a correlation between the present use of nitrogen and the expected production of cereals, since the amount of input acquired is directly related to the number of cereals who intend to produce in the future.

We emphasize that farmers' decisions are also affected by the economic conditions they are subjected to. As a result, different locations vary in their respective agricultural incomes. Therefore, 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 Equation 1 is rewritten as Equation 2:

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

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:

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

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 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 Lowenberg-DeBoer, 2009).

For the development of the cereal price Index (Ip_c), we followed the proposition of Saraiva et al. (2020) Equation 4:

$$Ip_c = \sum_{j=1}^{n} q_{ij} p_{ij} / \Sigma q_{ij} \overline{p_j} \quad (4)$$

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) Equation 5:

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

Where N_C is application of synthetic nitrogen fertilizers in cereal production, N_G is the total nitrogen present in the cereal grain and N_R is the nitrogen present in the cereal grain from natural 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 by each cereal by the concentration of nitrogen in the plant. 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. (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) (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 valuable 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) (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 Klein et al. (2006) and Pires et al. (2015), in which N_2O emissions occur directly and indirectly, as shown in Equations 6-7:

$$N_2O_{ED} = N_{FERT} \times EF_1 \times 1.571 \times 310 \quad (6)$$

$$N_2O_{ED} = N_{FERT} \times EF_2 \times 1.571 \times 310 \quad (7)$$

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 (Klein et al., 2006). EF_2 refers to the indirect N_2O emission factor, constituting approximately 0.4% of the applied nitrogen fertilizer (Pires et al., 2015). 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 (Klein et al., 2006; Pires et al., 2015).

The variable referring to the number of synthetic nitrogen fertilizers used in cereal production was estimated using weights, represent the share of the area planted for

each cereal about 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 to approximate the value of nutrients added in each crop, which was unknown in the study period. In addition, this estimation is essential since many states may require more or fewer fertilizers, depending on the area for each crop produced.

2.4. Analysis and data source

The variable quantity of cereals produced was analyzed taking into account the total quantity produced by all 7 cereals considered in this study, in tons, for each year from 2014 to 2018, by Brazilian state. Regarding the variable "produced area", this refers to the total area planted by all cereals considered by year and by Brazilian state from 1994 to 2018 in hectares. The amount of fertilizers refers to the amount of N, P2O5 and K2O fertilizers delivered to the consumer in tons by Brazilian state from 1994 to 2018. The agricultural GDP variable was analyzed from 2014 to 2018 by Brazilian state in thousand R$. The input prices variable refers to the average prices of N, P2O5 and K2O fertilizers per ton per state between 2014 and 2018. The crop price variable corresponds to the price received by products for each type of cereal between 2014 and 2018. Variables referring to the price of inputs and prices of crops for the states and years when not available in the database were calculated by averaging the neighboring states of the specific year.

We used databases from different sources: (i) *Sistema IBGE de Recuperação Automática* – SIDRA (SIDRA, 2018) for quantity produced of cereals (2014 to 2018), area produced of cereals (1994 to 2018) and state agricultural GDP (2014 to 2018) ; (ii) *Anuário Estatístico do Setor de fertilizantes* 1994 – 2018 of the *Associação Nacional para Difusão de Adubos – ANDA* (ANDA, 2018) for quantity of fertilizers N, P, K delivered to the consumer; and (iii) Companhia Nacional de Abastecimento – CONAB (CONAB, 2018) for inputs price N, P and K and cereal prices (2014 to 2018).

3. Results

3.1. Demand for nitrogen fertilizers

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

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 at 1% over the demand for nitrogen fertilizers. 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.

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

Variable	Coefficient	Variable	Coefficient
LnPn	-0.2586	lnN_{t-1}	0.9344***
	-0.238		-0.0322
LnPc	0.2674**	lny_t	0.0812***
	-0.1189		-0.0306
LnPp	-0.1574	$lnGDP_A$	0.0055
	-0.1348		-0.0297
LnPk	0.0078	*Constant*	2.3792
	-0.2608		-1.9191
Number of obs	108		
R-squared	0.9911		
Mean VIF	4.08		

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%.

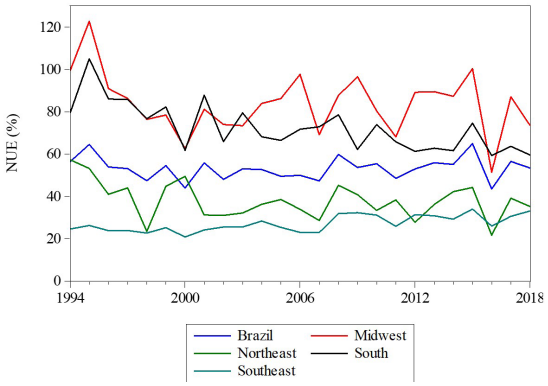

Figure 1. Evolution of the NUE in Brazil and in the main regions. **Note:** For the evolution of the NUE, the results and discussion for the North region were not considered, as the participation of this region in the national production of cereals is extremely low, which resulted in outliers, which could lead to inconsistent and mistaken interpretations.

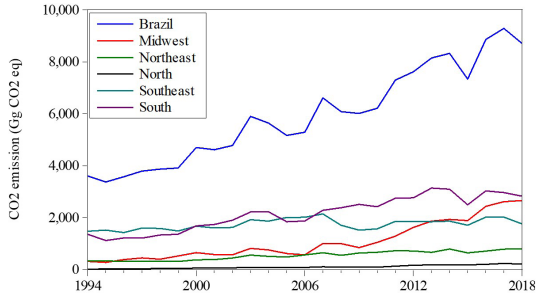

Figure 2. Evolution of greenhouse gas emissions from synthetic nitrogen fertilization in cereal production between 1994 and 2018. **Note:** N_2O emissions have been converted to Gg CO_2 eq (1 unit of Gg is equivalent to 1000 tons).

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 using nitrogen fertilizers in all regions of the country. From 1994 to 2018, the country's emissions grew on average by 59% (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. 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. The most significant contributions to the average CO2eq emission from nitrogen fertilization for cereal production come from the South region, the Southeast, and Midwest.

4. Discussion

4.1. Nitrogen demand and farmers' inertia

One of the main factors that explain the increase in 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 consume increasing amounts of synthetic nitrogen fertilizers to obtain ever higher yields. Similar results were found in the literature (Tenkorang and Lowenberg-DeBoer, 2009; Pires et al., 2015). The elasticity of fertilizer use concerning cereal production of less than one unit demonstrated that the quantities of fertilizers are inelastic to cereal production, indicating an inadequate application of nitrogen fertilizers (Tenkorang and Lowenberg-DeBoer, 2009).

The inadequate application of fertilizers impairs the process of assimilation of plants, affecting the production of cereals. On the other hand, the farmer adds even more nutrients to obtain growth in production, ignoring the "Law of Diminishing Marginal Returns". As in most production processes, the use of a given input is subject to the aforementioned "law" (Holmes and Aldrich, 1957). Agricultural production tends to decrease if there is an increasing and excessive addition of just one input. In addition, most farmers cannot 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 (Leonard, 2014). This shows that farmers consider the price of cereals when consuming fertilizers, which is undoubtedly 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, if 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 more significant 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 to achieve equal or more significant gains. Additionally, most farmers need 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 Lowenberg-DeBoer, 2009). We emphasize that there are times when the farmer invests in soil fertilization each year for fear that the next year does not have financial resources to purchase such inputs. This way, nutrients may be stored in the soil during periods of financial scarcity. 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 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 accetable 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, and 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, biodiversity loss, global warming, and stratospheric ozone depletion (Sutton et al., 2011; Rütting 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; Rütting 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, in impoverished rural areas and with inefficient logistics (Africa, for example), the farmer's income coul,d be higher, 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).

Applying fertilizers 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 when the plant needs it most and in the indicated amount is one of the viable ways to achieve ideal NUE (Congreves et al., 2021). On the other hand, the fragmentation of nitrogen fertilizer makes the practice 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 agricultural cereal 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 (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 (N_2O) (which in this research was converted into CO2eq.). 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 agricultural cereal production, resulting in environmental losses and GHG emissions to the atmosphere. In general, there was an increase in N_2O and NO emissions following the application rates of nitrogen fertilizers in agricultural production (Zhang et al., 2016). This high nitrogen application rates stimulated the nitrification and denitrification processes.

Regarding Brazilian regions, we observed that the South was the one that most contributed to N_2O 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.

On the other hand, even with a high efficiency, the South region had the greatest contribution to CO2e emissions. This result may be related, in part, to its high production of cereals in the period, mainly the production of rice. In addition, according to data from the SEEG (2018) when considering cattle raising and the application of fertilizers to other crops, in addition to cereals, the Brazilian regions that contribute most to greenhouse gas emissions N2O are: the Midwest, responsible for around 50% of N2O emissions in the country, due to the strong presence of agricultural activity, with emphasis on the production of soy, corn and cattle raising, and the South region, accounting for around 25% of the country's emissions, due to agricultural activity, rice production and cattle raising.

Field studies have shown that the high rates of application and the non-optimized use of synthetic nitrogen fertilizers are practices that promote the flow of N_2O in the main agricultural productions (Trautmann et al., 2022; Fan et al., 2023; Benghzial et al., 2023). 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 and avoid economic losses and cost generation.

The great challenge in intensive agricultural production systems is 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 (Rütting et al., 2018). Among the alternative forms of non-synthetic nitrogen, intercropping with legumes reduces nitrogen leaching under no-till conditions (Constantin et al., 2015). The direct planting system in legume straw is of great relevance in reducing applications of synthetic fertilizers, reducing losses and expenses, and generating agricultural sustainability (Wang et al., 2022).

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 directly allows communication, training, and service provision 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 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. Final Remarks

In general, the results of this research demonstrated that the agricultural intensification in Brazil in 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 growing use of fertilizers in cereal production in Brazil was responsible, in part, for the emission of almost 9 million tons of CO2eq. in 2018. The average agro-environmental efficiency of nitrogen found in Brazilian cereal production was 53%, differing in time among Brazilian regions. The average values calculated for the NUE are below the desirable values for Latin America, indicating that GHG reduction targets may be compromised by the end of the century. In terms of demand for nitrogen fertilizers, the price elasticities found in this study show us that while the cereal prices rise, the greater the consumption of this input will be.

Increasing productivity and production based on sustainable intensification is one of the alternative paths for future environmental change. 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 fewer adverse 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 improvement on the production side and for all consumers. It is noteworthy that although the impacts resulting from inefficient use of nitrogen come from different or distant regions, the adverse effects are felt globally, compromising society.

Finally, we emphasize that for policy-making purposes, the analysis of the NUE developed here must be used together with information on productivity, 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 considers its rational use and not its availability. There are affluent and efficient areas, but there can also be poor and efficient areas.

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