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# Nitrogen use (in)efficiency and cereal production in Brazil: current trends and forecasts

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*Here, we provide an analysis to understand the evolution of cereal production and consumption of nitrogen (N) fertilizers in Brazil and to correlate N use efficiency (NUE), greenhouse gas (GHG) emissions and economic and environmental losses. Our results showed that the increased consumption of N fertilizers is associated with a large decrease in NUE in recent years.* $CO_2eq$ *emissions from N fertilization for cereal production were approximately 12 times higher in 2011 compared to 1970. The projected N fertilizer forecasts are 2.09 and 2.37 million ton for 2015 and 2023, respectively. An increase of 0.02% per year in the projected NUE was predicted for the same time period. In a hypothetical scenario, a 2.39% increase in cereal NUE would lead to USD 21 million savings in N fertilizer costs. Thus, increases in NUE rates would lead not only to agronomic and environmental benefits but also to economic improvement.*

Keywords: Nitrogen, Forecast, Fertilizer Demand, Brazil, Greenhouse Gases

JEL codes:  Q15; Q24; Q54; Q56

## 1. Introduction

Agriculture has historically been a major source of greenhouse gas (GHG) emissions into the atmosphere (Beddington et al., 2012). The Agriculture, Forestry, and Other Land Use (AFOLU) sector is responsible for just under a quarter (~10–12 Gt $CO_2$eq $yr^{-1}$) of all anthropogenic GHG emissions, mainly from deforestation and agricultural emissions from livestock, soil and nutrient management (Smith et al., 2014). According to Rosenzweig and Tubiello (2007), of all the GHGs released annually into the atmosphere by human activities, the AFOLU sector is responsible for the approximately a quarter of carbon dioxide ($CO_2$) emissions through deforestation, depletion of soil organic C, use of machinery and manufactured fertilizers; half of methane ($CH_4$) emissions via livestock and rice cultivation; and three quarters of nitrous oxide ($N_2O$) emissions through fertilizer application and animal waste management. In Brazil, agriculture and livestock accounted for one third of the gross national emissions in 2010 (MCTI, 2013).

Agricultural systems around the world have increasingly intensified with the objective of meeting the growing demand for food, feed, fuel and fiber (Ainsworth et al., 2008). According to the Food and Agriculture Organization of the United Nations projections (FAO, 2006), cereal production will increase by 60% from 2000 to 2050. Thus, the use of manufactured fertilizers will increase over the coming years to cope with these changes (Cordell et al., 2009). Recent projections indicate an increase in global fertilizer consumption of approximately 69 million ton in 2030, and the increased use of nitrogen (N) fertilizers is responsible for 67% of this value (Tenkorang and Lowenberg-Deboer, 2009). However, the excessive and irrational application of fertilizer can lead to economic and environmental negative consequences, such as high production costs, depletion of energy resources, environmental pollution and increasing GHG emissions.

Nitrogen is a critical macroelement for plant growth and development, and its availability is the major limiting factor for primary productivity in most terrestrial ecosystems (Cole et al., 2008; Lebauer and Treseder, 2008). In this sense, N fertilization is one of the most commonly widespread practices in agriculture with direct consequences on agricultural productivity. Fertilizers, manure, N fixation by legumes and rainfall deposition are the main inputs of N to soils. According to the most recent FAO data (FAOSTAT, 2014), the consumption of N fertilizers in Brazil has increased by approximately 78% in the past 20 years. This over-application can result in inefficient use and high losses of excess N to the environment, which can impact air quality, water quality, biodiversity and human health (Goulding et al., 2008). For example, nitrate ($NO_3^-$) is easily lost from agricultural areas by leaching (Puckett et al., 1999). This highly mobile form of N could lead to contamination of drinking water supplies and eutrophication of water bodies (Lowrance et al., 1997). Furthermore, high levels of $NO_3^-$ can reduce nitrogen use efficiency (NUE) because the excessive N not taken up by plants is susceptible to loss (Zhu and Chen, 2002; Ju et al., 2004).

Brazilian agriculture has achieved marked progress with regard to cereal production over the past two decades. Such an increase is the result, at least in part, from increased application of N fertilizers. Cereals, such as rice, wheat and maize, consume approximately 60% of the total N used as fertilizer and account for about one third of the total protein consumed worldwide (Alexandratos, 1995). The current world population of 7.2 billion is projected to increase by 1 billion over the next 12 years and to reach 9.6 billion by 2050 (United Nations, 2013). Therefore, recent projections have reported an estimated increase of 50 to 70% in cereal production by 2050 (FAO, 2006). If there is not an increase in nutrient use efficiency in coming years, the consumption of the fertilizers will continue to increase. Thus, there is a need to identify strategies and agricultural practices to increase NUE.

The NUE for cereal production can be defined from the interplay of the following three different approaches: *agronomic efficiency*, which is generally defined as the grain yield per unit of applied N; *environmental efficiency*, which is characterized by the possible contamination of groundwater, surface water eutrophication, ozone depletion or greenhouse effect intensification caused by the release of $N_2O$; and *economic efficiency*, which is defined by the maximization of the farmer’s income (Huggins and Pan, 1993; Raun and Johnson, 1999; Hirose, 2011). NUE is a well-known agro-environmental indicator commonly used in the agro-policy context and can be calculated as the ratio between the amount of N removed with the crop and the amount of N fertilizer applied. The index provides information about the relative utilization of additional N applied to an agricultural production system of a country or region (Johnston and Poulton, 2009). The calculated NUE for cereal production worldwide is approximately 33% (Raun and Johnson, 1999), which is far less than the 50% generally reported for crops (Hardy and Havelka, 1975; Bodirsky et al., 2012).

The permanent export of N from the field due to the harvest of both temporary and permanent crops and the N fertilization supplied to the soil are the largest sources of outflow and inflow of N in an agricultural system, respectively. Therefore, the relationship between both inflow and outflow can be used to describe the NUE in agricultural production. In a theoretical system without any loss of N to the environment, an NUE of 100% would be ideal, as the inputs would correspond exactly to the outputs. However, this is not possible in practice because agriculture operates in an open environment where there is a continuous exchange of nutrients between the soil, environment, water and air (Robertson et al., 2013).

Rational application of N fertilizer contributes to the efficient use of this mineral in agricultural systems, but it does not necessarily optimize the NUE. Thus, a conflict occurs between desirable and acceptable levels of fertilizer application to meet sustainable environmental standards. Farmers, extension technician workers, the fertilizer industry, agricultural researchers and policymakers rarely take into account issues related to what is being added to the system in comparison to what is being maintained in the system as well as what happens to the excess N in such a system. Thus, the sustainable use of N fertilization is critical not only to increase the N recovery efficiency but also to increase crop yield and reduce production costs.

Here, we demonstrate the evolution of the use of N fertilizers in Brazilian agriculture through the analysis of the seven major cereal crops (rice, oats, rye, barley, corn, sorghum, and wheat). Our study reports on the evolution of cereal production and use of N fertilizers in Brazil with respect to the efficiency of these fertilizers and their implications on GHG emissions. Studies with an emphasis on the assessment of nutrient balance over a period of time in Brazil are missing. Thus, this study will help to provide such information, which will be useful for the design of public policies that deal effectively with global environmental changes.

Interventions seeking to increase the NUE and at the same time to decrease the input of N in agricultural systems are important not only to reduce environmental risks but also to reduce the cost of agricultural production (Wang et al., 2011). Thus, the goals of this study were as follows: (i) to analyse whether the consumption of N fertilizers results in an efficient use of N in cereal production in Brazil; (ii) to investigate the influence of the losses of N as $N_2O$ emissions; (iii) to project the long-term N fertilizer demand on cereal production in Brazil; and (iv) to estimate the future projections on NUE and $N_2O$ emissions based on the calculated N fertilizer demand.

## 2. Methodology

### *2.1. Calculation of nitrogen use efficiency (NUE)*

The balance of N inputs/outputs in an agricultural system over time is a valuable parameter to understand the long-term fate of fertilizer-derived N in the plant-soil-water system and its impact on the environment. In this study, NUE was calculated using an output/input ratio according to the methodology proposed by Raun and Johnson (1999). The index was calculated for Brazil between 1970 and 2011. Furthermore, NUE was estimated for the coming years (2015 to 2023) adopting the calculated long-term N fertilizer demand data (see Calculation of long-term N fertilizer demand of cereal production). Although legumes such as beans and soybeans are very demanding on N, they were left out of our analysis because the current recommendation for these crops in Brazil is the use of biological inoculant without supplementation of N fertilizers. Assuming that the main cereal crops of Brazilian agricultural production are rice, oats, rye, barley, corn, sorghum and wheat, the NUE was calculated using the following equation:

$$NUE = \left[ \left( N_G - N_R \right) / N_C \right].100 \tag{1}$$

where $N_C$ is the consumption of N fertilizer (in ton) for cereal production, which corresponds to 53% of total consumed N fertilizers for Latin America according to Dobermann (2006). This value corresponds to an estimated share of cereal N use of total N consumption, calculated as weighted average of country-specific estimates of fertilizer use by crops (IFA, 2002). Weights were proportional to N use by countries. We considered as $N_C$ the sum of N fertilizer consumption of the seven crops above mentioned; $N_G$ is the cereal grain N removal calculated using the proportion of N in each cereal crop and the respective cereal production (in ton). In this case, the values of N (in g $kg^{-1}$) for each crop are as follows: rice (12.3 g $kg^{-1}$), oat (19.3 g $kg^{-1}$), rye (22.1 g $kg^{-1}$), barley (20.2 g $kg^{-1}$), maize (12.6 g $kg^{-1}$), sorghum (19.2 g $kg^{-1}$) and wheat (21.3 g $kg^{-1}$) according to Tkachuk (1977); and $N_R$ is the N removed in cereals coming from the soil and that is deposited by rainfall, which corresponds to 50% of the N removed in the cereal grains

($N_R = N_G$ x 0.5) according to Keeney (1982).

### *2.2. Calculation of GHG emissions from cereal production*

To estimate GHG emissions related to N fertilization in cereal production, we adopted the methodology proposed by De Klein et al. (2006) with some modification. $N_2O$ is produced naturally in soils through the processes of nitrification and denitrification. One of the main controlling factors in this reaction is the availability of N in the soil. This methodology estimates $N_2O$ emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilizers). The emissions of $N_2O$ occur through both a direct (i.e., directly from the soils to which the N is added/released) and indirect pathway (i.e., following volatilization of ammonia – $NH_3$ and $NO_x$ from managed soils and after leaching and runoff of N, mainly as $NO_3^-$, from managed soils), and the emissions of $N_2O$ resulting from both pathways are estimated separately. Both direct and indirect emissions rates were calculated for Brazil between 1970 and 2011. In addition, both emission rates were estimated for the coming years (2015 to 2023) adopting the calculated long-term N fertilizer demand data (see Calculation of long-term N fertilizer demand of cereal production).

Direct $N_2O$ emission from N inputs was calculated according to the following equation:

$$N_2O_{direct_{Ninputs}} = FS_N . EF_1 . CF_{N2O-N/N2O} \qquad (2)$$

where $FS_N$ is the amount of N synthetic fertilizer applied to soils (kg N year$^{-1}$); $EF_1$ is the emission factor for $N_2O$ emissions from N inputs, such as kg $N_2O$-N (kg N input)$^{-1}$, i.e., the amount of $N_2O$ emitted per kg of applied N ($EF_1 = 0.01$) (De Klein et al., 2006); $CF_{N2O\text{-}N/N2O}$ is a dimensionless conversion factor to convert the emissions from kg $N_2O$-N to kg $N_2O$ gas ($CF_{N2O\text{-}N/N2O} = 1.571$) (De Klein et al., 2006).

In addition, indirect $N_2O$ emission from N inputs was calculated according to the following equations:

$$N_20_{indirect_{Ninputs}} = N_2O_{(ATD)} + N_2O_{(L/R)} \qquad (3)$$

$$N_2O_{(ATD)} = FS_N . Frac_{GASF} . EF_2 . CF_{N2O-N/N2O} \qquad (3a)$$

$$N_2O_{(L/R)} = FS_N . Frac_{LEACH-(H)} . EF_3 . CF_{N20-N/N20} \qquad \text{(3b)}$$

where $N_2O_{(ATD)}$ is explained by equation 3a and represents the amount of $N_2O$ produced from atmospheric deposition of N volatilized from managed soils (kg $N_2O$–N $yr^{-1}$); $N_2O_{(L/R)}$ is explained by equation 3b and represents the amount of $N_2O$ produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs (kg $N_2O$–N $yr^{-1}$); $EF_2$ is the emission factor for $N_2O$ emissions from atmospheric deposition of N on soils and water surfaces [kg N–$N_2O$ (kg $NH_3$–N + $NO_x$–N volatilized)$^{-1}$] ($EF_2 = 0.01$) (De Klein et al., 2006); $EF_3$ is the emission factor for $N_2O$ emissions from N leaching and runoff [kg $N_2O$–N (kg N leached and runoff)$^{-1}$] ($EF_3 = 0.0075$) (De Klein et al., 2006); $Frac_{GASF}$ is the fraction of synthetic fertilizer N that volatilizes as $NH_3$ and $NO_x$ [kg N volatilized (kg of N applied)$^{-1}$] ($Frac_{GASF} = 0.1$) (De Klein et al., 2006); and $Frac_{LEACH-(H)}$ is the fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff [kg N (kg of N additions)$^{-1}$] ($Frac_{LEACH-(H)} = 0.3$) (De Klein et al., 2006).

Finally, we opted for display the GHG emission results in $CO_2$ equivalent ($CO_2$eq). The conversion from $N_2O$ to $CO_2$ equivalent ($CO_2$eq) emissions is through the global warming potential for each GHG and it is a commonly adopted measure. GWP is commonly defined as the cumulative radiative forcing both direct and indirect effects integrated over a period of time from the emission of a unit mass of gas relative to some reference (Forster et al., 2007). The $CO_2$eq emission related to N fertilization in cereal production was calculated according to the following equation:

$$CO_2eq = \left( N_2O_{direct_{Ninputs}} + N_2O_{indirect_{Ninputs}} \right) . CF_{N2O/CO2} . C \qquad \text{(4)}$$

where $CF_{N2O/CO2}$ is a dimensionless factor to convert $N_2O$ to $CO_2$eq, i.e., GWP for $N_2O$ over a 100-year time horizon is 310; and $C$ is a factor to convert the emissions from kg $C_2O$ to Gg $C_2O$ (1000 t = Gg).

## *2.3. Calculation of long-term N fertilizer demand of cereal production*

The growing world population will likely require more intensive agricultural crop production. Higher productivity will, in turn, increase the demand for agricultural inputs, such as fertilizers (FAO, 2000). Here, we calculated the amount of N fertilizer needed to support FAO-OECD projections of cereal production in Brazil from 2014 to 2023 according to a casual model based on agronomic relationships proposed by Tenkorang and Lowenberg-DeBoer (2009).

According to Fildes and Allen (2001), casual models are useful when projections of the exogenous variables are available, such as production and cultivated area. Previous simulations have demonstrated the correlation between fertilizer requirement forecast and past fertilizer status as well as past and future crop production based on agronomic relationships as follows (FAO, 2000; Tenkorang and Lowenberg-Deboer, 2009):

$$F_t = F_{t-1} + \left(Y_t - Y_{t-1}\right) / \left(Y_{t-1} / F_{t-1}\right) \quad (5)$$

where $F$ is the unadjusted N fertilizer application rate; $Y$ is the output; and $t$ is a time index. According to FAO (2000), “in the absence of known crop production functions, future fertilizer application rates and nutrient use efficiencies were estimated by first quantifying the relationship between production and total fertilizer application rates”. Following the studies of FAO (2000) and Tenkorang and Lowenberg-DeBoer (2009), we demonstrated that the relationship predictable to exist between actual N fertilizer use and (1) previous year’s N fertilizer use is positive; (2) expected crop production is positive; and (3) previous year’s crop production is negative. Relationship (1) shapes the persistence of N fertilizer consumption patterns over time. In this sense, strong N fertilizer-consuming countries may continue to consume more and use rates in low N fertilizer consuming regions tend to shift only gradually over time. In addition, relationship (2) associates higher N fertilizer to more crops output whereas relationship (3) suggests the ‘a good year is followed by a bad year’ crop output pattern in certain poor areas.

Thus, due to availability of historical, current and projected data of the needed variables, the following N fertilizer demand model was adopted:

$$FN_t = \alpha_0 + \beta_1 Y_t + \beta_2 Y_{t-1} + \beta_3 FN_{t-1} + \varepsilon_t \quad (6)$$

where $FN_t$ is the amount of N fertilizers used in year $t$; $Y_t$ is total cereal crop output in year $t$; and $Y_{t-1}$ is the total cereal crop output of year $t - 1$.

Similar to the model performed by Tenkorang and Lowenberg-DeBoer (2009), the last three years (2009-2011) were prearranged as out-of-sample data so that the forecasting power of the model could be validated. The predicted model was used to estimate N fertilizer amounts for the retained years, and these amounts were then compared with their current quantities using mean absolute percentage error (MAPE). Finally, re-estimation was performed using the whole sample, and the estimated model was used to forecast N fertilizer demands from 2014 to 2023 based on the projected cereal output. Furthermore, a variance inflation factor (VIF) was calculated to assess problems caused by multicollinearity, which is a common feature when projected crop output is included in regression models. A Durbin Watson modified statistical test (DWh) was also performed to evaluate the potential problems of autocorrelation.

### *2.4. Calculation of savings in N fertilizer costs*

After calculation of the NUE along the time series, we estimated the potential N fertilizer savings (ton) per year for each 1% increase in NUE under constant agricultural production (Raun and Johnson, 1999). In addition, we calculated the potential N fertilizer savings (ton) assuming a geometric growth rate (GGR) estimated from the NUE in the 41 years considered in this study (1970-2011). The GGR was estimated from the following regression:

$$\ln Y = \alpha + \beta t + \varepsilon \qquad (7)$$

where *t* is the trend variable; and $GGR = \left[ anti\log\left(\beta\right) - 1 \right].100$.

We then calculated the value of N fertilizer savings (in USD) based on the average price of three N fertilizers (i.e., urea, ammonium nitrate and ammonium sulfate) in 2014 for the nine major cereal producing states in Brazil.

### *2.5. Data*

The Brazilian annual total consumption of N fertilizer (in ton), cereal production (for rice, oats, rye, barley, corn, sorghum and wheat, in ton), and cultivated land with cereals (in hectare) from 1970 to 2011 were obtained from the FAOSTAT (2014) website. Furthermore, the projected data of Brazilian cereal output and cultivated land for cereals from 2014 to 2023 was obtained from the OECD-FAO Agricultural Outlook database. The average price of N fertilizers (urea, ammonium nitrate and ammonium sulfate) for the nine major cereal producing states in Brazil (i.e., Rio Grande do Sul, Paraná, Mato Grosso, Goiás, Santa Catarina, Mato Grosso do Sul, São Paulo and Minas Gerais) in 2014 was obtained from the Companhia Nacional de Abastecimento (CONAB). All statistical procedures were performed using Stata 12 software (StataCorp LP, College Station, TX, USA).

## 3. Results and Discussion

### *3.1. Current and historical NUE trends*

In Brazil, the consumption of N fertilizer for cereal production increased by 78% in the past 20 years. In contrast, the area cultivating major cereals in Brazil did not change significantly during the same time period. Accordingly, the use of N fertilizers per unit area increased suggesting a greater agricultural intensification. In this case, intensification was considered as an increase in the amount of external inputs (N fertilizers). Moreover, the expansion of agricultural land was neglected in the analysis of cereal production at least in the assessed period of time. However, agricultural intensification also comes at a cost to the environment. Thus, our study aimed to evaluate how this intensification was translated or not in efficiency as well as the consequences of the possible lack of efficiency.

First, we calculated the NUE for cereal production between 1970 and 2011 using an output/input ratio (Fig. 1). A decrease in the NUE of approximately 74% was observed with a decreasing rate of 2.39% per year. Although no economic loss was recorded, it is noteworthy that the increasing use of N fertilizers was not translated in efficiency. Such inefficient use of N fertilizers is likely related to environmental losses, mainly due to the open nature of an agricultural system (Robertson et al., 2013).

*Figure 1*

The world cereal grain NUE is estimated to be 33% (Raun and Johnson, 1999). The same authors reported a cereal NUE of 29% in developing countries. In comparison, the cereal NUE calculated for Brazil in 2011 was 27% (Fig. 1), while the remainder pollutes the air and ecosystems, thereby indicating that the country is below the NUE limit values for cereal production systems. Denitrification, volatilization and leaching are among the possible causes for the low NUE values found for Brazil, and these issues usually reflect irrational and unsustainable agricultural practices. Studies have reported that cereal plants release N, mainly as NH3, from their tissues after anthesis (Daigger et al., 1976; Harper et al., 1987; Francis et al., 1993). Additionally, when N fertilizers are applied at rates in excess of those required for maximum yields in cereal crops, $NO_3^-$ leaching can be significant (Olson and Swallow, 1984; Raun and Johnson, 1999).

In field studies with coffee in Brazil, average $^{15}$N fertilizer recovery at harvest was 34% in the first cropping year and 47% in the second year (Fenilli et al., 2007). Moreover, total $^{15}$N fertilizer recovery was 36% for the 3-yr-old 'Valencia' orange trees and 52% for the 'Lisbon' lemon trees (Boaretto et al., 2010). In addition, the average amount of $^{15}$N fertilizer recovered by sugarcane under Brazilian field conditions was 20% near the harvesting stage (Vieira et al., 2015). The remainder is stored in soil organic matter pools, immobilized in the soil or lost from the cropping system. Taken together, these results emphasized a low N recovery in Brazilian field conditions compared to crops other than cereals.

Another relevant factor with regard to low NUE is the complacency of farmers. Depending on the source of fertilizer adopted, N costs are approximately USD 0.42 kg$^{-1}$. This affordable price compared to per capita income of Brazilian farmers (~USD 12,500.00) is therefore likely to explain the over-application of N fertilizer. Moreover, high efficiency should not be prioritized at the expense of productivity. According to the law of diminishing returns, it is well known that the increases in productivity tend to be smaller with the increase of N amounts resulting in lower gained efficiencies (Holmes and Aldrich, 1957).

Finally, it is important to emphasize that, based on current fertilizer use and production rates, a 1% increase in NUE for cereal production would lead to a 21419.86 ton savings in N fertilizer use accounting for USD 9 million savings in N fertilizer costs. Furthermore, assuming the estimated geometric rate (NUE decrease rate over the period 1970-2011), a 2.39% increase in NUE would lead to a 50531.25 ton savings in N fertilizer accounting for USD 21 million savings in N fertilizer expenditure. In comparison, Raun and Johnson (1999) reported that a 1% increase in the efficiency of N use for grain production worldwide would lead to USD 234 million savings. Taken together, these results indicated that increases in NUE rates would lead not only to agronomic and environmental benefits but also to economic improvement for farmers.

### *3.2. GHG emissions related to N fertilization from cereal production in Brazil*

Based on the premise that agriculture is a major source of GHG emissions, we estimated the GHG emissions related to N fertilization from cereal production in Brazil from 1970 to 2011. Fig. 2 shows a dramatic increase of $CO_2$eq emissions from cereal crops by approximately 12 times between 1970 and 2011. The agricultural sector is dominated by $CH_4$ emissions from livestock due to both enteric fermentation and manure. Furthermore, $N_2O$ direct (from grazed grassland) and indirect (by N atmospheric deposition and leaching) emissions are responsible for a large amount of total agricultural GHG emissions (Rosenzweig and Tubiello, 2007). Atmospheric emissions may occur as nitrogen dioxide ($NO_2$), nitric oxide (NO), nitrogen gas ($N_2$), $N_2O$ or $NH_3$, and water bodies receive inputs of $NO_3^-$ and dissolved organic N by leaching and runoff (Pinder et al., 2013). Moreover, the manufacturing processes of N fertilizers are responsible for part of the direct emissions of $CO_2$ to the atmosphere (Robertson et al., 2013).

*Figure 2*

$N_2O$ is not a reactive gas in the troposphere, but it is a potent non-$CO_2$ GHG. On a molar basis, $N_2O$ is approximately 300 times more potent than $CO_2$ (Forster et al., 2007). The atmospheric concentration of $N_2O$ has increased by approximately 18% since the pre-industrial period (Houghton et al., 2001). This increase has contributed to approximately 6% of total GHGs that drive climate change (Forster et al., 2007). Moreover, approximately 80% of $N_2O$ added to the atmosphere annually by human activities is derived from agriculture. More specifically, approximately 60, 30 and 10% of these emissions come from agricultural land, animal waste management and burning agricultural green waste, respectively (Houghton et al., 2001; Robertson, 2004). Thus, $N_2O$ is an important target for compensation projects, which may be included in *cap and trade* markets due to high returns associated with $N_2O$ emission mitigation (Robertson et al., 2013).

Several field experiments have shown that the amount of N fertilizer applied is the strongest indicator of $N_2O$ fluxes in major cropping systems (McSwiney and Robertson, 2005; Stehfest and Bouwman, 2006; Jarecki et al., 2009; Hoben et al., 2011; Linquist et al., 2012). In addition to the amount of N applied, the $N_2O$ flow can also be influenced by the N fertilizer formulation and application timing as well as by the agronomic practices that determine N availability in the soil, such as tillage and waste management (Robertson et al., 2013). Recent studies have reported that approximately 0.5-3% of N applied to cultivated soils is emitted as $N_2O$ to the atmosphere (Stehfest and Bouwman, 2006; Linquist et al., 2012). Nevertheless, the emission rates can be even higher if the level of N fertilization exceeds crop demand (McSwiney and Robertson, 2005; Jarecki et al., 2009; Hoben et al., 2011).

Fig. 2 shows that the emission related to N fertilization from cereal production reached a value of approximately 10 million ton of $CO_2$eq in 2010. In comparison, agricultural and livestock activities were responsible for the emission of 437 million ton of $CO_2$eq in the same year in Brazil, and $N_2O$ contributed 161 million ton of $CO_2$eq, i.e., approximately 37% of total emissions from the agricultural sector (MCTI, 2013). Moreover, the application of synthetic fertilizer was responsible for both direct and indirect (atmospheric deposition + leaching) emission of 24 million ton of $CO_2$eq in 2010 in Brazil (MCTI, 2013). Our results suggest that the emission derived from N fertilization for cereal production represents 42% of the total synthetic fertilization emission contribution from the Brazilian agricultural sector.

### *3.3. Projections of long-term N fertilizer demand highlight the need to improve NUE*

To obtain the long-term N fertilizer requirement forecasts, we estimated the structural-causal model described in section Calculation of long-term N fertilizer demand of cereal production (Equation 6). The model $R^2$ was above 0.9, and the *F*-statistic was highly significant (P-level: 0.000). The CV in our structural model was 17.25 suggesting a good model fit. Only the coefficient of the lagged crop output ($Y_{t-1}$) was not significantly different from zero, and the other coefficients were statistically significant at the 1% or 5% test level when considering the White robust standard error terms. We also tested the model for the presence of multicollinearity using the variance inflation factor (VIF). According to the results, the VIF values ranged between 10.9 and 15.5. Although VIF values less than ten are desirable, O'Brien (2007) stated that a VIF up to 40 can be tolerated and does not undermine the regression analysis. It is important to highlight that there was no autocorrelation in the model. The Durbin Watson statistic (Durbin's *h* test) was not statistically significant. Table 1 shows a detailed overview of the model estimation.

*Table 1*

We also validated the model forecasting power using the mean absolute percentage error (MAPE). When comparing the actual N fertilizer consumption and the model-estimated consumption, the models tracked the historical data well (Fig. 3). The MAPE for the in-sample forecasts (1970-2008) was 12.1%. Moreover, the MAPE for the out-of-sample forecasts (2009-

2011), which are more informative and reliable (Tenkorang and Lowenberg-Deboer, 2009), was 9.6%.

*Figure 3*

The estimated causal model offered additional evidence in relation to the inefficiency of N use in Brazil and corroborated our above-mentioned results (Fig. 1). This evidence resulted from the evaluation of the elasticity of fertilizer use with respect to output (evaluated from the average output and average fertilizer use), which was calculated by the product of the output coefficient ($\beta_1$ in the Equation 6) and the ratio of average crop output ($Y_t$) to average fertilizer use ($FN_t$). The value indicates the percentage change in $FN_t$ due to a 1% change in $Y_t$. Elasticity estimated for the 1970–2011 time period was 0.65. According to Tenkorang and Lowenberg-DeBoer (2009), elasticities less than one are a good indication of nutrient drawdown, i.e., inadequate N application, indicating soil nutrient depletion. A long-term drawdown is likely to increase environmental and agricultural risks associated with low NUE and soil moisture as well as to decrease farm income capacity (Snyder, 2000).

Using the causal model, we projected N fertilizer forecasts for cereal production in Brazil. The estimated values were 2.09 million ton and 2.37 million ton for 2015 and 2023, respectively, at a rate of growth of 1.67% (Fig. 3). Several recent reports have suggested that the projected crop production increases during the next 30 years will likely require the increased use of fertilizers, particularly N (Bumb and Baanante, 1996; Dyson, 1999; Tenkorang and Lowenberg-Deboer, 2009). Based on an econometric model, Bumb and Baanante (1996) estimated that the world fertilizer demand did and will increase by 1.2% annually from 1992 to 2020. Dyson (1999) estimated that world use of mineral N will double by 2025 at a growth rate of 2.26%. According to Tenkorang and Lowenberg-DeBoer (2009), the projected global N fertilizer forecasts are 115 million ton and 137 million ton for 2015 and 2030, respectively. The same authors reported that Latin America would consume approximately 5.3 million ton of N fertilizer in 2015 (Tenkorang and Lowenberg-Deboer, 2009). In comparison, the projected N fertilizer consumption for Brazil will account for 40% of total Latin America consumption in 2015.

It is noteworthy that our baseline rate of growth for N fertilizer demand between 1970 and 2011 was 5.41% per year, and the projected rate of growth (2015-2023) will decrease to 1.67% as mentioned above. Thus, we also investigated how this trend would be translated in NUE and in possible decreases in GHG emission rates. Intriguingly, a sharp increase in the projected NUE rates was observed (Table 2). Based on the model estimated by Equation 6 and their related parameters shown in Table 1, we estimated that NUE would increase 0.02% annually from 2015 to 2023. In contrast, a decrease rate of 2.39% per year was observed between 1970 and 2011. Thus, our results highlight an optimistic scenario for cereal production in Brazil related to the efficiency of N use in coming years. This change in the NUE trend is clearly related to the lower rate of growth for N fertilizer projected by our model. In addition, this is a simulation of a more optimistic scenario, in which it is expected to increase sustainable agricultural practices with regard to the use of N. However, some caution should be used, and a more detailed dialogue should be encouraged as discussed below.

*Table 2*

Given its importance in the maintenance of soil fertility, N has been intensively studied to improve NUE from an agronomic, physiological and genetic perspective. These experimental efforts seek to reduce N loss from the soil and to improve the mechanism of absorption and N metabolism within the plant. However, studies emphasizing the *trade-off* between economic development and the impact of the use of agricultural inputs on GHG emission are scarce. Thus, it is of pivotal importance that economic policies include environmental issues in their agenda due to the relevance of such issues to agricultural productivity and food security.

More efficient use of N through improved timing, split applications, site-specific management, crop rotation, crop diversification, soil testing, biological N fixation (BNF) and improved plant traits by genetic breeding can help improve yields with the same amount or even less amounts of N fertilizers. Biological nitrification inhibition (BNI) by *Brachiaria* roots exudates represents another important strategy to improve NUE in Brazilian soils (Subbarao et al., 2006; Souza et al., 2006). The process of nitrification (i.e., the biological oxidation of $NH_4^+$ in $NO_3^-$ by bacteria of the genera *Nitrosomonas* and *Nitrobacter*) increases N leaching and atmospheric losses. It is noteworthy that for most part, Brazilian soils are well-drained and present neutral to slightly acidic reaction characteristics, which favor the prevalence of N in the $NO_3^-$ form (Tisdale et al., 1985). In this sense, nitrification inhibitors are widely used and can help reduce losses of N in soil that would otherwise be used by crops. These characteristics reinforce the relevance of using *Brachiaria* as a BNI tool in Brazilian soils, especially in crop rotation strategies.

In this sense, the adoption of agricultural practices that enable increased NUE to replace conventional practices should be highly encouraged. For example, for an improved NUE, farmers can reduce N fertilization to levels that still provide satisfactory yields (Médici et al., 2004). In addition, there is a lag between the release of N applied and its uptake by plants. In general, after the application of N to soil, its availability decreases over time, but the crop requirement increases. Thus, N fertilizer applied at the correct time maximizes the effect of N and minimizes potential environmental losses (Robertson et al., 2013).

Additionally, the development of cultivars with high agronomic NUE is an economically viable option to ensure higher productivity in agricultural systems with a low use of inputs (Sinebo et al., 2004; Anbessa et al., 2009; Sylvester-Bradley and Kindred, 2009). Thus, further efforts are needed to enhance the selection of plants with high rates of NUE, which is something that is often not considered a priority by plant breeders (Raun and Johnson, 1999). Ongoing investment in plant breeding research and development is vital to ensure continued advances to obtain cultivars that efficiently use the available N sources, thus reducing farm costs and associated losses.

Several N management practices to improve NUE of agricultural systems are already available and require only appropriate support to adopt. Such strategies should be prioritized, and more rational methods of N fertilizer application should be developed to avoid excessive fertilization including the following practices: *i*) fertilizer placement as it affects its availability for crop uptake in addition to its susceptibility to soil transformations; *ii*) rate or amount of N fertilizer applied, as this affects the amount of GHGs emitted more than any other factor; *iii*) fertilizer timing, which represents a major challenge for efficient fertilizer management and is aimed at synchronizing soil N availability with crop N demand; and *iv*) N fertilizer formulation and additives (Robertson et al., 2013). For example, controlled release fertilizers (CRFs) enhance the efficiency of N uptake and minimize losses to the environment, and they represent a feasible alternative to conventional practices. However, the acceptance of CRFs by farmers remains limited worldwide due to lack of experience with the technique and its high relative cost (Medina et al., 2008; Zhao et al., 2013).

Generally, any practice that increases NUE is expected to reduce GHG emissions because N absorbed by the plant is not available to soil processes that drive N emissions at least in the short term (Robertson et al., 2013). For example, good N management practices, such as crop rotation, have been shown to decrease $N_2O$ emissions (Adviento-Borbe et al., 2007; Snyder et al., 2007). However, decreases in our projected $CO_2$eq emissions were not observed alongside NUE increases. We estimated a value of $CO_2$eq emission 25% higher in 2023 (~15 million ton of $CO_2$eq) in comparison to 2011 (~12 million ton of $CO_2$eq). Our results corroborated that practices improving NUE do not always reduce GHG emissions (Robertson et al., 2013). For example, different N fertilizer formulations or additives can result in different $N_2O$ emissions despite presumed NUE effects. In addition, banded fertilizer placement can increase NUE but also increase $N_2O$ emissions. In general, NUE is an important parameter, but it is not enough by itself to decrease GHG emissions (Robertson et al., 2013).

In this sense, specific policies that stimulate sustainable agriculture practices that mitigate GHG emissions are needed. As the world population grows and the demand for agricultural commodities increases, sectorial plans to mitigate GHG emissions can contribute significantly to achieve the international goals for the reduction of future global emissions and the stabilization of atmospheric concentrations within safe levels (Jones and Sands, 2013).

Brazil became an international example regarding mitigation plans once it voluntarily committed to reduce its GHG emissions in 2009. The Brazilian Government launched the National Climate Change Plan (NCCP), which has the goal of reducing GHG emissions by 36.1 to 38.9% by 2020 considering a baseline scenario. The estimated reduction is approximately one billion ton of $CO_2$eq (Brasil, 2008). In the context of the Brazilian NCCP, the so-called Low-Carbon Agriculture (ABC) program provides resources and incentives for farmers who adopt sustainable agricultural practices (e.g., no-till systems, degraded pastureland rehabilitation, integrated crop-livestock-forestry systems, planted forests, BNF, and animal waste management).

Our future projections of NUE and N fertilizer demand (Fig. 3) are likely to indicate long-term benefits of the Brazilian NCCP. Increases in adoption of agricultural practices, such as no-till systems or crop rotation/diversification should contribute to decreases in N fertilizer demand growth rate and to increases in NUE in coming years. No-till cultivation improves soil structure and enhances the nutrient retention of plants (Soares-Filho et al., 2012). When we take into consideration the Brazilian agricultural production as a whole, N input through BNF, a microbiological process that converts atmospheric N into a plant-usable form can help to maintain soil N reserves and substitute for N fertilizer to attain large crop yields (Peoples and Craswell, 1992; Bohlool et al., 1992). However, Brazilian farmers remain skeptical of the ability of the ABC program to reduce agricultural carbon emissions (Angelo, 2012). In this context, it is of pivotal importance that the ABC program is strictly enforced (Lapola et al., 2014).

Although some optimism can be encouraged from our forecasting results, we should highlight that Brazil has not yet reached a point at which it is possible to reduce the use of N fertilizers without compromising cereals yield. More importantly, we found a continuous increase of temporal yield in relation to N fertilizer use, and those increases are likely to persist in estimated forecasts (Fig. 4). A typical N response curve based on field or greenhouse studies shows that applying N gives a large increase in yield but applying too much can reduce yield due to salinity damages, specific nutrient toxicities, and other factors (Bodirsky and Muller, 2014; Lassaleta et al., 2014; Nelson et al., 2014). However, this does not happen on a daily basis on the farm because farmers typically don’t apply those high rates, unless it is an unintentional mistake. Finally, our results emphasized a country-level temporal trajectory of a high environmental footprint and the need for specific policies aimed at reducing the unsustainable N fertilizer consumption.

*Figure 4*

One of the main challenges of modern agriculture is coping with the increasing world population on one hand and the magnitude of food production on the other hand. Some recent works point to Brazil one of the main food suppliers worldwide in the coming years (Nelson et al., 2014). In this sense, the relationship between cereals yield and N fertilization is not only of interest to understand NUE, but also helps to stimulate and formulate policies to increase NUE and reduce N input into the agricultural systems (Bodirsky and Muller, 2014; Lassaleta et al., 2014). In addition to those already-mentioned strategies to improve agronomic practices (Medina et al., 2008; Robertson et al., 2013; Zhao et al., 2013; Nelson et al., 2014), an increased NUE can be obtained by demand-side mitigation measures, such as a reduction of household waste and less consumption of livestock-based products (Bodirsky and Muller, 2014). Furthermore, it is noteworthy that economic instruments like taxes on N fertilizers should be associated with investments into Research and Development that effectively stimulate improvements in agronomic techniques to ensure a rational N use.

## 4. Conclusions

Our study aimed to investigate the relationship between the evolution in cereal production (rice, oats, rye, barley, corn, sorghum and wheat) and the use of N fertilizers in Brazil with respect to the efficiency of these fertilizers and their implications for producing GHG emissions. We evaluated the N use efficiency (NUE), the contribution of N fertilization to GHG emissions, and the long-term N fertilizer demand for cereal production in Brazil in addition to future projections of the association between NUE and GHG emissions.

We observed a decrease in NUE of approximately 74% between 1970 and 2011. As a consequence, the inefficient use of N fertilizers is directly related to environmental losses, such as GHG emissions, mainly $N_2O$. Our results suggest that the emissions derived from N fertilization in cereal production represents 42% of the total synthetic fertilization emissions contribution from the Brazilian agricultural sector in 2010. Based on current fertilizer use and production rates, a 2.39% hypothetical increase in NUE would lead to a 50531.25 ton savings in N fertilizer accounting for USD 21 million savings in N fertilizer expenditure.

However, it is noteworthy that low values of NUE do not mean that all N not in grain is lost. Fertilization of lower quality soils, along with the increased addition of organic matter, can result in increased soil organic carbon and nitrogen. This process is likely not responsible for retaining most of the unaccounted N, but it should not be ignored in our analyses. Further studies are required in order to clarify the importance of NUE in lower quality soils.

Based on predicted scenario of the increase in N fertilizer consumption in coming years, our results indicated that increases in NUE rates would lead not only to agronomic and environmental benefits but also to economic improvement. However, these improvements can only be achieved through the adoption of sustainable practices that help to maximize NUE and encourage the rational use of agricultural inputs.

In summary, our suggestions for a pathway to NUE improvement in Brazil are as follows: *i*) the adoption of agricultural practices that enable increased NUE (e.g., crop rotation, no-till systems, BNI and BNF) in order to replace conventional unsustainable agricultural practices; *ii*) the development of cultivars with high agronomic NUE through genetic breeding, which efficiently utilize available N sources, thereby reducing farm costs and associated losses; *iii*) the use of more rational methods of N fertilizer application in the field to avoid excessive fertilization; and *iv)* the adoption of demand-side measures aimed to reduce household waste and animal products consumption. Some of these opportunities are already available today, but many others require more empirical and theoretical research to be confirmed as potential strategies. These opportunities all require effective incentives to become a reality in practice. Thus, it is of pivotal importance that economic policies include environmental issues in their agenda based upon the relevance of such issues in agricultural productivity and food security.

## References

Adviento-Borbe MAA, Haddix ML, Binder DL, Walters DT, Dobermann A. Soil greenhouse gas fluxes and global warming potential in four high-yielding maize systems. Glob. Change Biol. 2007; 13: 1972-1988.

Ainsworth EA, Rogers A, Leakey DB. Targets for crop biotechnology in a future high-$CO_2$ and high-$O_3$ world. Plant Physiol. 2008; 147: 13-19.

Alexandratos N. World agriculture: Towards 2010 – An FAO study. New York: Wiley; 1995.

Anbessa Y, Juskiw P, Good A, Nyachiro J, Helm J. Genetic variability in nitrogen use efficiency of spring barley. Crop Sci. 49: 2009; 1259-1269.

Angelo C. Brazil's fund for low-carbon agriculture lies fallow. Nature 2012 Aug 2. doi: 10.1038/nature.2012.11111

Beddington JR, Asaduzzaman M, Clark ME, Fernández Bremauntz A, Guillou MD, Howlett DJB, et al. What Next for Agriculture After Durban? Science 2012; 335: 289-290.

Boaretto RM, Junior DM, Quaggio JA, Cantarella H, Trivelin PCO. Nitrogen-15 uptake and distribution in two citrus species. In: Gilkes R, Prakongkep, editors. Soil Solutions for a Changing World; 2010 Aug 1-6; Brisbane, Australia. Available from: http://soilscienceaustralia.com.au/19th-world-congress-of-soil-science

Bodirsky BL, Müller C. Robust relationship between yields and nitrogen inputs indicates three ways to reduce nitrogen pollution. Environ. Res. Lett. 2014; 9: 111005.

Bodirsky BL, Popp A, Weindl I, Dietrich JP, Rolinski S, Scheiffele L, et al. $N_2O$ emissions from the global agricultural nitrogen cycle – current state and future scenarios. Biogeosciences 2012; 9: 4169-4197.

Bohlool BB, Ladha JK, Garrity DP, George T. Biological nitrogen fixation for sustainable agriculture: a perspective. Plant Soil 1992; 141: 1-11.

Bumb BL, Baanante CA. The Role of Fertilizer in Sustaining Food Security and Protecting the Environment to 2020 [Internet]. Washington, DC: International Food Policy Research Institute; 1996 [cited 2014 Oct 22]. Available from: http://www.ifpri.org/publication/role-fertilizer-sustaining-food-security-and-protecting-environment-2020

Cole L, Buckland SM, Bardgett RD. Influence of disturbance and nitrogen addition on plant and soil animal diversity in grassland. Soil Biol. Biochem. 2008; 40: 505-514.

Cordell D, Drangert J-O, White S. The story of phosphorus: global food security and food for thought. Global Environ. Change 2009; 19: 292-305.

Daigger LA, Sander DH, Peterson GA. Nitrogen content of winter wheat during growth and maturation. Agron. J. 1976; 68: 815-818.

De Klein C, Novoa RSA, Ogle S, Smith KA, Rochette P, Wirth TC, et al. $N_2O$ emissions from managed soils, and $CO_2$ emissions from lime and urea application. In: Gytarsky M, Hiraishi T, Irving W, Krug T, Penman J, editors. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Geneve: International Panel on Climate Change (IPPC); 2006. pp. 4:11.1-11.54.

Dobermann AR. Nitrogen use efficiency in cereal systems. In: Turner N, Acuna T, editors. Ground breaking stuff. Proceedings of the 13th ASA Conference, 2006 Sep 10-14; Perth, Australia. Available from: http://www.regional.org.au/au/asa/2006/

Dyson T. World food trends and prospects to 2025. Proc. Natl. Acad. Sci. USA 1999; 96: 5929-5936.

Fenilli TAB, Reichardt K, Dourado-Neto D, Trivelin PCO, Favarin JL, Costa FMP, et al. Growth, development, and fertilizer-15N recovery by the coffee plant. Sci. Agri. 2007; 64: 541-547.

Fildes RA, Allen PG. Econometric forecasting: strategies and techniques. In: Armstrong JS, editor. Principles of forecasting: a handbook for researchers and practitioners. Berlin: Springer; 2001. pp. 303-362.

Food and Agriculture Organization of the United Nations – FAO. FAOSTAT; 2014. Database: FAOSTAT [Internet]. Accessed: 2014 Oct 12. Availabe: http://data.fao.org/ref/262b79ca-279c-4517-93de-ee3b7c7cb553.html?version=1.0

Food and Agriculture Organization of the United Nations – FAO. Fertilizer requirements in 2015 and 2030. Rome: FAO; 2000. [cited 2014 Oct 13]. Available from: ftp://ftp.fao.org/agl/agll/docs/barfinal.pdf

Food and Agriculture Organization of the United Nations – FAO. World Agriculture: towards 2030/2050. Rome: FAO; 2006. [cited 2014 Oct 4]. Available from: http://www.fao.org/economic/esa/esag/en/

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, et al. Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, et al, editors. Climate Change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2007. pp. 131-234.

Francis DD, Schepers JS, Vigil MF. Post-anthesis nitrogen loss from corn. Agron. J. 1993; 85: 659-663.

Goulding K, Jarvis S, Whitmore A. Optimizing nutrient management for farm systems. Phil. Trans. R. Soc. B 363: 2008; 667-680.

Hardy RWF, Havelka UD. Nitrogen fixation research: A key to world food? Science 1975; 188: 633-643.

Harper LA, Sharpe RR, Langdale GW, Giddens JE. Nitrogen cycling in a wheat crop: Soil, plant, and aerial nitrogen transport. Agron. J. 1987; 79: 965-973.

Hirose T. Nitrogen use efficiency revisited. Oecologia 2011; 166: 863-867.

Hoben JP, Gehl RJ, Millar N, Grace PR, Robertson GP. Nonlinear nitrous oxide ($N_2O$) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Glob. Change Biol. 2011; 17: 1140-1152.

Holmes W, Aldrich DTA. Nitrogenous fertilizers and the production of crops and grass. P. Nutr. Soc. 1957; 16: 9-14.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, et al, editors. Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2001.

Huggins DR, Pan WL. Nitrogen efficiency component analysis: An evaluation of cropping system differences in productivity. Agron. J. 1993; 85: 898-905.

Interministerial Committee on Climate Change. National Plan on Climate Change. Decree no. 6263 of November 21, 2007 [Internet]. Brasília: Government of Brazil; 2008. [cited 2014 Sep 20]. Available from: http://www.mma.gov.br/clima/politica-nacional-sobre-mudanca-do-clima/plano-nacional-sobre-mudanca-do-clima

International Fertilizer Industry Association – IFA. Fertilizer use by crop. Rome: IFA, IFDC, IPI, PPI, FAO; 2002. [cited 2015 Apr 15]. Available from: http://www.fertilizer.org//En/Knowledge_Resources/Library/IFA_Selection_Fertilizer_Use.aspx

Jarecki MK, Parkin TB, Chan ASK, Kaspar TC, Moorman TB, Singer JW, et al. Cover crop effects on nitrous oxide emission from a manure-treated Mollisol. Agr. Ecosyst. Environ. 2009; 134: 29-35.

Johnston AE, Poulton PR. Nitrogen in Agriculture: An Overview and Definitions of Nitrogen Use Efficiency. York: Proceedings International Fertiliser Society; 2009.

Jones C, Sands R. Impacts of agricultural productivity gains on greenhouse gas emissions: a global analysis. Am. J. Agr. Econ. 2013; 95: 1309-1316.

Ju X, Liu X, Zhang F, Roelcke M. Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China. Ambio 2004; 33: 300-305.

Keeney DR. Nitrogen management for maximum efficiency and minimum pollution. In: Stevenson FJ, editor. Nitrogen in agricultural soils. Madison: Soil Science Society of America (SSSA); 1982. pp. 605-949.

Lapola DM, Martinelli LA, Peres CA, Ometto JPHB, Ferreira ME, Nobre CA, et al. Pervasive transition of the Brazilian land-use system. Nature Clim. Change 2014; 4: 27-35.

Lassaleta L, Billen G, Grizzetti B, Anglade J, Garnier J. 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 2014; 9: 105011.

Lebauer DS, Treseder KK. Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. Ecology 2008; 89: 371-379.

Linquist B, van Groenigen KJ, Adviento-Borbe MA, Pittelkow C, van Kessel C. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob. Change Biol. 2012; 18: 194-209.

Lowrance R, Altier LS, Newbold JD, Schnabel RR, Groffman PM, Denver JM, et al. Water quality functions of riparian forest buffers in Chesapeake Bay watersheds. Environ. Manage. 1997; 21: 687-712.

McSwiney CP, Robertson GP. Non-linear response of $N_2O$ flux to incremental fertilizer addition in a continuous maize (*Zea mays* sp.) cropping system. Glob. Change Biol. 2005; 11: 1712-1719.

Médici LO, Pereira MB, Lea PJ, Azevedo RA. Diallel analysis of maize lines with contrasting responses to applied nitrogen. J. Agr. Sci. 2004; 142: 535-541.

Medina LC, Obreza TA, Sartain JB, Rouse RE. Nitrogen release patterns of a mixed controlled-release fertilizer and its components. HortTechnology 2008; 18: 475-480.

Ministério da Ciência, Tecnologia e Inovação – MCTI. Estimativas anuais de emissões de gases de efeito estufa no Brasil [Internet]. Brasília: MCTI; 2013. [cited 2014 Sep 21]. Available from: http://www.mct.gov.br/index.php/content/view/347281.html

Nelson GC, Valin H, Sands RD, Havlík P, Ahammad H, Deryng D, et al. Climate change effects on agriculture: Economic responses to biophysical shocks. Proc. Natl. Acad. Sci. USA 2014; 9: 3274-3279.

O'brien RM. A caution regarding rules of thumb for variance inflation factors. Qual. Quant. 2007; 41: 673-690.

Olson RV, Swallow CW. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 1984; 48: 583-586.

Peoples MB, Crasswell ET. Biological nitrogen fixation: Investments, expectations and actual contributions to agriculture. Plant Soil 1992; 141: 13-39.

Pinder RW, Bettez ND, Bonan GB, Greaver TL, Wieder WR, Schlesinger WH, et al. Impacts of human alteration of the nitrogen cycle in the US on radiative forcing. Biogeochemistry 2013; 114: 25-40.

Puckett LJ, Cowdery TK, Lorenz DL, Stoner JD. Estimation of nitrate contamination of an agro-ecosystem outwash aquifer using a nitrogen mass-balance budget. J. Appl. Ecol. 1999; 28: 2015–2025.

Raun WR, Johnson GV. Improving Nitrogen Use Efficiency for Cereal Production. Agron. J. 1999; 91: 357-363.

Robertson GP, Bruulsema TW, Gehl RJ, Kanter D, Mauzerall DL, Rotz CA, et al. Nitrogen–climate interactions in US agriculture. Biogeochemistry 2013; 114: 41-70.

Robertson GP. Abatement of nitrous oxide, methane, and the other non-$CO_2$ greenhouse gases: the need for a systems approach. In: Field CB, Raupach MR, editors. The global carbon cycle. Washington, DC: Island Press; 2004. pp. 493-506.

Rosenzweig C, Tubiello FN. Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig. Adapt. Strategies Glob. Chang. 2007; 12: 855-873.

Sinebo W, Gretzmacher R, Edelbauer A. Genotypic variation for nitrogen use efficiency in Ethiopian barley. Field Crop. Res. 2004; 85: 43-60.

Smith P, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, et al. Agriculture, Forestry and Other Land Use (AFOLU). In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al, editors. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. pp. 812-922.

Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agr. Ecosyst. Environ. 2009; 133: 247-266.

Snyder CS. How much fertilizer does it take to raise soil test levels? Agri-Briefs. 2000; 6. Availabe: https://www.ipni.net/ppiweb/agbrief.nsf/$webindex/article=47A7A85E852569670056EC4A3057B332

Soares-Filho B, Lima L, Bowman M, Viana L. Challenges for Low-Carbon Agriculture and Forest Conservation in Brazil [Internet]. Washington, DC: Inter-American Development Bank; 2012. [cited 2014 Sep 14]. Available from: http://publications.iadb.org/handle/11319/5407

Souza LS, Velini ED, Martins D, Rosolem CA. [Allelopathic effects of *Brachiaria decumbens* on the initial development of seven crops]. Planta Daninha 2006; 24: 657-668.

Stehfest E, Bouwman L. $N_2O$ and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr. Cycl. Agroecosys. 2006; 74: 207-228.

Subbarao GV, Rondon M, Ito O, Ishikawa T, Rao IM, Nakahara K, et al. Biological nitrification inhibition (BNI) - is it a widespread phenomenon? Plant Soil 2007; 294: 5-18.

Sylvester-Bradley R, Kindred DR. Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. J. Exp. Bot. 2009; 60: 1939-1951.

Tenkorang F, Lowenberg-DeBoer J. Forecasting long-term global fertilizer demand. Nutr. Cycl. Agroecosys. 2009; 83: 233-247.

Tisdale SL, Nelson WL, Beaton JD. Soil fertility and fertilizers. New York: Macmillan Publishing Company; 1985.

Tkachuk R. Calculation of the nitrogen-to-protein conversion factor. In: Hulse JH, Rachie KO, Billingsley LW, editors. Nutritional standards and methods of evaluation for food legume breeders. Ottawa: International Development Research Centre (IDRC); 1977. pp. 78-81.

United Nations – UN. World Population Prospects: The 2012 Revision, Key Findings and Advance Tables. New York: UN; 2013. [cited 2014 Sep 16]. Avaliable from: http://esa.un.org/unpd/wpp/index.htm

Vieira-Megda MX, Mariano E, Leite JM, Franco HCJ, Vitti AC, Megda MM, et al. Contribution of fertilizer nitrogen to the total nitrogen extracted by sugarcane under Brazilian field conditions. Nutr. Cycl. Agroecosyst. 2015; 101: 241-257.

Wang RF, An DG, Hu CS, Li LH, Zhang YM, Jia YG, et al. Relationship between nitrogen uptake and use efficiency of winter wheat grown in the North China Plain. Crop Pasture Sci. 2011; 62: 504-514.

Zhao B, Dong S, Zhang J, Liu P. Effects of Controlled-Release Fertiliser on Nitrogen Use Efficiency in Summer Maize. PLoS One 2013; 8: e70569.

Zhu ZL, Chen DL. Nitrogen fertilizer use in China contributions to food production, impacts on the environment and best management strategies. Nutr. Cycl. Agroecosys. 2002; 63: 117-127.

**Table 1. Nitrogen fertilizer forecast model estimates for cereal production in Brazil.** Sample size, *N* = 41. Asterisks indicate statistically significant differences at 1% (***), 5% (**), and 10% test level (*) considering the White robust standard error terms (estimated by bootstrap – 1000 replicates). The data in brackets for the model fit are P-values.

| | *Coefficient* | *Bootstrap Std. Error* | *P-value* | *VIF* |
|---|---|---|---|---|
| Crop Output ($Y_t$) | 0.0100** | 0.0040 | 0.0130 | 11.95 |
| Lagged Crop Output ($Y_{t-1}$) | -0.0022 | 0.0043 | 0.6020 | 10.93 |
| Lagged N Fertilizers ($FN_{t-1}$) | 0.7486*** | 0.1949 | 0.0000 | 15.51 |
| Constant | -141224* | 80129.6 | 0.0780 | --- |
| *Model fit* | | | | |
| $R^2$: 0.9342; Model *CV*: 17.25 | | | | |
| *F-value*: 175.16 [0.0000] | | | | |
| *Durbin stat (DWh)*: 0.468 [0.4937] | | | | |

**Table 2. Nitrogen use efficiency (NUE) and $CO_2$eq emission related to N fertilization from cereal production forecast for Brazil from 2015 to 2023.** Estimations are based on the model estimated by Equation 6 and their related parameters shown in Table 1.

| *Year* | *NUE caculated [%]* | *$CO_2$ emissions [Gg $CO_2$eq]*[a] |
|---|---|---|
| 2015 | 37.43 | 13538.21 |
| 2016 | 37.67 | 13627.47 |
| 2017 | 38.13 | 13832.09 |
| 2018 | 38.27 | 14054.02 |
| 2019 | 38.43 | 14347.34 |
| 2020 | 38.28 | 14627.67 |
| 2021 | 37.98 | 14873.18 |
| 2022 | 37.73 | 15105.09 |
| 2023 | 37.54 | 15331.35 |
| *Mean* | 37.94 | 14370.71 |
| *Std. Dev.* | 0.361 | 653.55 |
| *CV (%)* | 0.95 | 4.55 |

[a] 1Gg = 1000 tons.

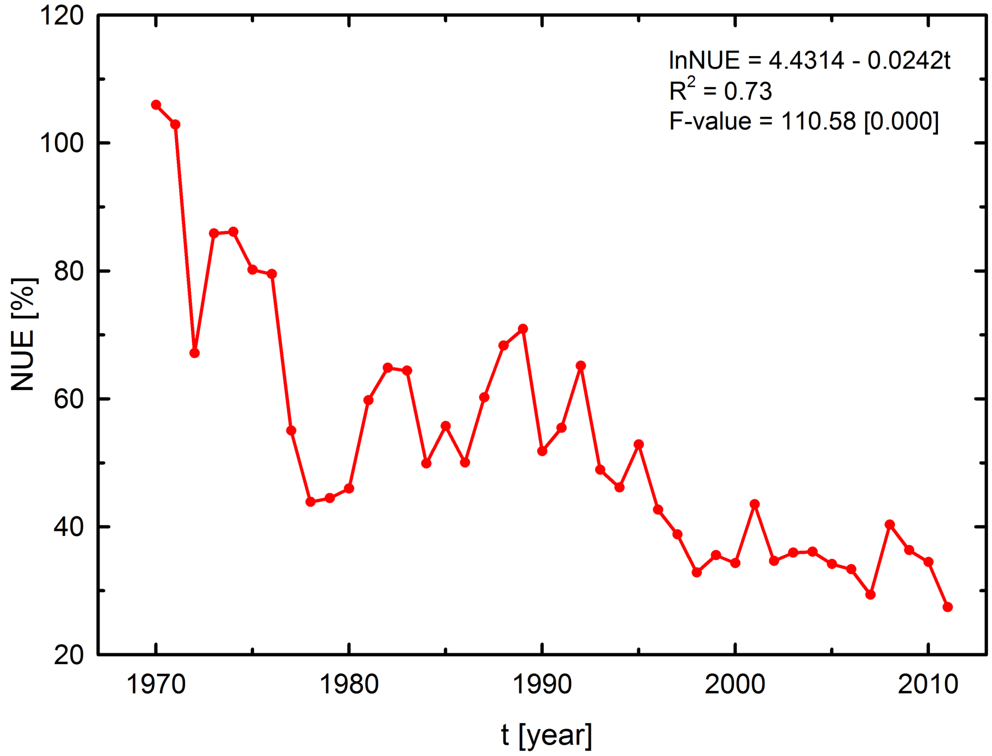

**Figure 1. Calculated nitrogen use efficiency (NUE) for Brazil, 1970-2011.** Data are shown for the seven major cereal crops (rice, oats, rye, barley, corn, sorghum, and wheat). NUE data are based on author's calculation from the estimated model (Equation 1). The geometric growth rate (GGR) was estimated from GGR = [*anti*log (β) – 1].100 where value β was estimated from the Equation 7. All coefficients were statistically significant at 1%.

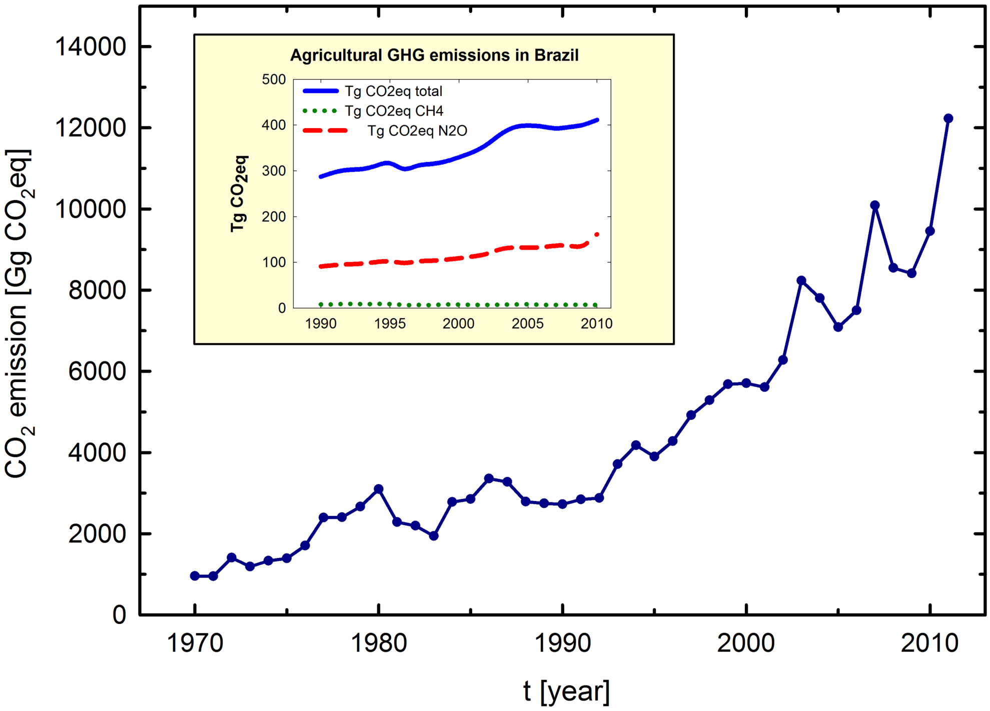

**Figure 2. $CO_2$eq emission trends related to nitrogen fertilization from cereal production for Brazil, 1970-2011.** Data of $CO_2$eq emissions (1Gg = 1000 ton) from N fertilization are based on author's calculation from the estimated model (Equations 2-4). The inset graph illustrates agricultural GHG emissions in Brazil from 1990 to 2010 according to MCTI report (2013).

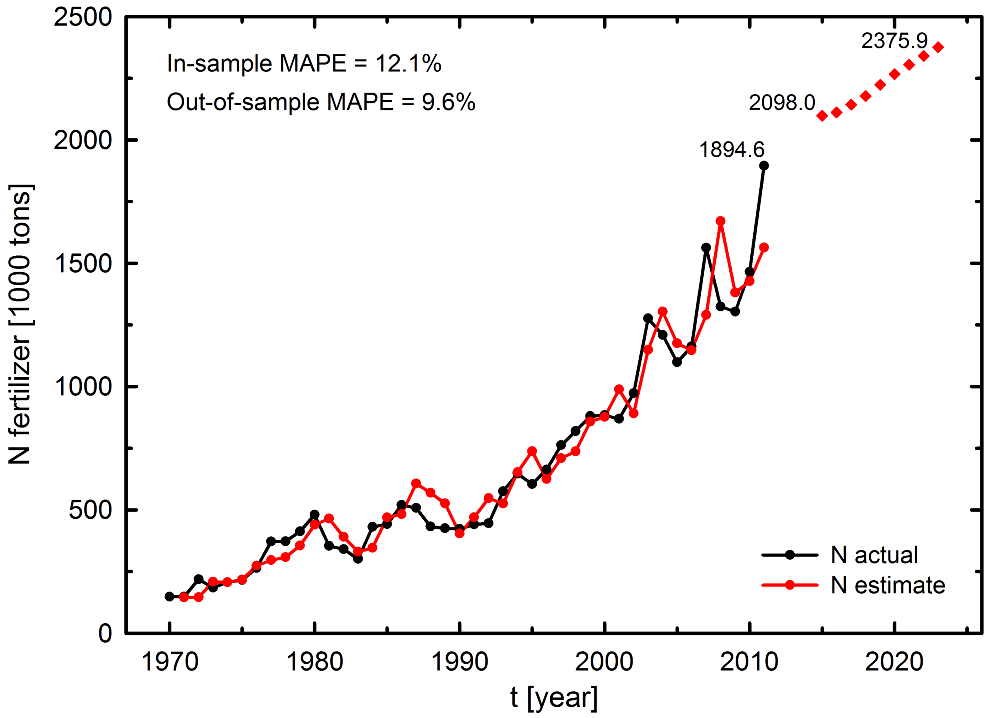

**Figure 3. Long-term nitrogen fertilizer demand for cereal production in Brazil.** Actual versus estimate forecast (1970-2011), and nitrogen fertilizer requirement forecasts for 2015 to 2023 calculated from the estimated model (Equation 6).

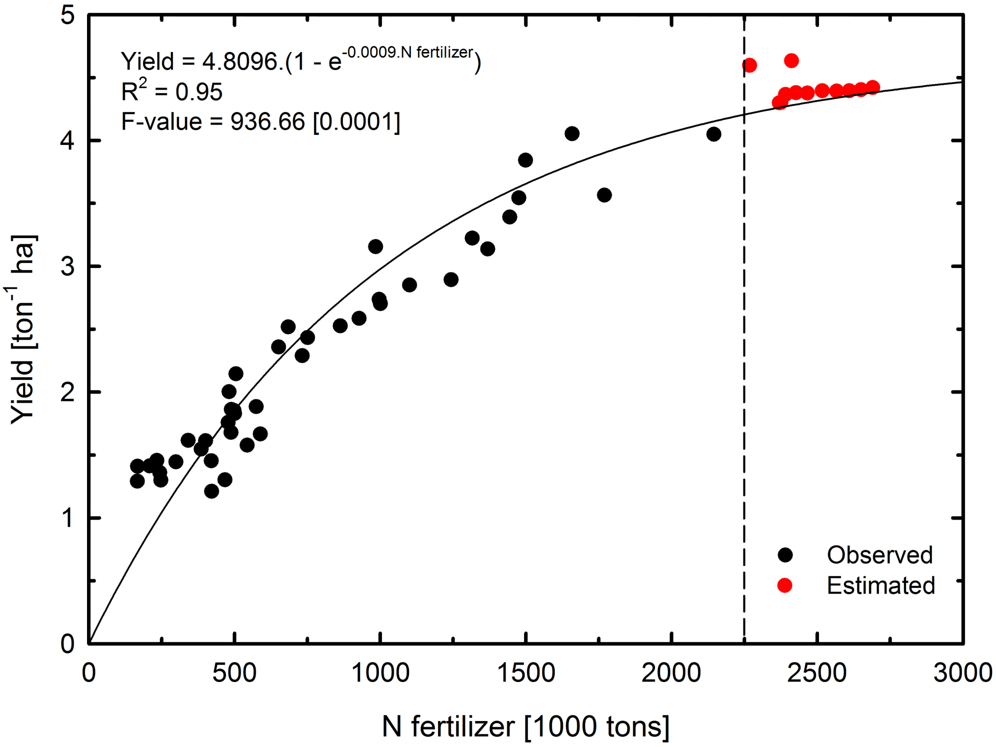

**Figure 4. Effect of nitrogen fertilizer consumption on cereal yield for Brazil, 1970-2023.** Observed (1970-2011) and estimated (2015-2023) relationships between N fertilization and yield. The trend line represents an exponential model fit. All coefficients were statistically significant at 1%.