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# NITROGEN MANAGEMENT IN BRAZIL: EMISSIONS DYNAMICS, SUSTAINABILITY, AND POLICY RESPONSES

Gisleine da Silva Cunha Zeri

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Jean Pierre Henry Balbaud Ometto, and Evandro Albiach Branco, approved in March 30, 2023.

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## BANCA Nº 054/2023, REGISTRO 139858/2018

No dia 30 de março de 2023, as 14h, por teleconferência, o(a) aluno(a) mencionado(a) acima defendeu seu trabalho final (apresentação oral seguida de arguição) perante uma Banca Examinadora, cujos membros estão listados abaixo. O(A) aluno(a) foi APROVADO(A) pela Banca Examinadora, por unanimidade, em cumprimento ao requisito exigido para obtenção do Título de Doutora em Ciência do Sistema Terrestre. O trabalho não precisa de correções.

**Título: "Nitrogen management in Brazil: emissions dynamics, sustainability, and policy responses**".

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*“Eu não sei nada sobre as grandes coisas do mundo,*

*mas sobre as pequenas eu sei menos”.*

*Manoel de Barros*

Dedico aos meus amores maiores, Marcelo e Isabel, pela leveza de suas almas, por tanto amor e companheirismo, e pelos inúmeros momentos felizes.

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(in Portuguese)

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## ABSTRACT

Nitrogen pollution is one of the most widespread and challenging problems in Brazil, being the cause of several environmental and health issues. The focus of this thesis is to investigate the underlying drivers of reactive nitrogen emissions, the sustainability of nitrogen use, and the policy responses to address the pollution problem, with the aim of contributing to improving nitrogen management in the country. To accomplish this main objective, we carried out the following activities, in which specific methods were applied for each one of them, and unique but also complementary results were obtained: (i) development of a Conceptual Framework Model to understand the complexity of N dynamics in the country, the diversity of drivers, and potential damage to environment and human health; (ii) calculation of the level of nitrogen sustainability using the Entropy Weight Method (EWM) on a set of N-related indicators, within the environmental, economic, social, and institutional subsystems, and (iii) application of the Policy Coherence Analytical Framework to show how coherent interactions are among N-related policies in Brazil and how these policies can promote the development of a potential integrated nitrogen policy approach. As an overall result, we conclude that the driving forces behind the increase in N emissions are the productive activities aimed at meeting the demand for food, energy, and housing by a rapidly growing population, leading to a weak-to-basic level of sustainability of nitrogen management in the country. Our results also indicate that political and institutional factors (e.g., good governance, regulatory quality, and political stability) are essential to prepare and implement successful responses to address the problem of nitrogen pollution in Brazil. Finally, the policy coherence analysis shows a favorable outcome, since most of the analyzed policies present positive interactions, which enables and reinforces the achievement of their objectives. An exception is the 2022 National Fertilizer Plan, considering that the absence of environmental care actions could make several other policies unfeasible. In this case, we suggest reformulating the plan with the involvement of multiple actors and stakeholders, to include environmental issues related to fertilizer production and use, as well as to avoid counteraction with other N-related policies.


Keywords: Nitrogen Management. Reactive Nitrogen. Nitrogen Pollution. Sustainability. Integrated Policy Approach.

**O MANEJO DO NITROGÊNIO NO BRASIL: DINÃMICA DAS EMISSÕES, SUSTENTABILIDADE E RESPOSTAS DAS POLÍTICAS PÚBLICAS**

## RESUMO

A poluição por nitrogênio é um dos problemas mais difundidos e desafiadores no Brasil, sendo causa de diversos problemas ambientais e de saúde. O foco desta tese é investigar os impulsionadores das emissões de nitrogênio reativo, a sustentabilidade do uso de nitrogênio e as respostas de políticas públicas, com a finalidade de contribuir para melhorar o manejo do nitrogênio no país. Para atingir este objetivo principal, realizamos as seguintes atividades, nas quais foram aplicados métodos específicos para cada uma delas, e obtidos resultados únicos, mas também complementares: (i) o desenvolvimento de um Modelo Conceitual para entender a complexidade da dinâmica do nitrogênio no país, a diversidade dos impulsionadores de emissões, e os potenciais danos ao meio ambiente e à saúde humana; (ii) o cálculo do nível de sustentabilidade do nitrogênio usando o *Entropy Weight Method* (EWM) em um conjunto de indicadores relacionados ao nitrogênio, dentro dos subsistemas ambiental, econômico, social e institucional, e (iii) a aplicação do *Policy Coherence Analytical Framework* para verificar o quão coerentes são as interações entre as políticas públicas relacionadas ao nitrogênio no Brasil e como elas podem promover o desenvolvimento de uma potencial abordagem de política integrada. Como resultado geral, concluímos que as forças motrizes por trás do aumento das emissões de nitrogênio são as atividades produtivas voltadas para atender a demanda por alimentos, energia e habitação de uma população em constante crescimento, levando a um “fraco a básico” nível de sustentabilidade do manejo do nitrogênio no país. Os resultados também indicam que fatores políticos e institucionais (por exemplo, boa governança, qualidade regulatória e estabilidade política) são essenciais para preparar e implementar respostas bem-sucedidas para enfrentar o problema da poluição por nitrogênio no Brasil. Por fim, a análise da coerência das políticas mostra um resultado favorável, uma vez que a maioria das políticas analisadas apresenta interações positivas, o que possibilita e reforça o alcance de seus objetivos. Uma exceção é o Plano Nacional de Fertilizantes de 2022, considerando que a ausência de ações ambientais em sua formulação pode impedir a implementação satisfatória de diversas outras políticas relacionadas ao controle de emissões de nitrogênio. Neste caso, sugerimos a reformulação do plano com o envolvimento de múltiplos atores e partes interessadas, para incluir as questões ambientais relacionadas à produção e uso de fertilizantes, bem como evitar a contraposição com outras políticas.

Palavras-chave: Manejo do Nitrogênio. Nitrogênio reativo. Poluição por Nitrogênio. Sustentabilidade. Abordagem de Política Integrada.

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| | |
|---|---|
| BNF | Biological Nitrogen Fixation |
| CO | Carbon monoxide |
| ENA | European Nitrogen Assessment |
| EU | European Union |
| EWM | Entropy Weight Method |
| GDP | Gross Domestic Product |
| GEF | Global Environment Facility |
| GHG | Greenhouse gases |
| HDI | Human Development Index |
| IAI | Inter-American Institute for Global Change Research |
| INA | International Nitrogen Assessment |
| INCOM | Inter-convention Nitrogen Coordination Mechanism |
| INI | International Nitrogen Initiative |
| INMS | International Nitrogen Management System |
| IPCC | Intergovernmental Panel on Climate Change |
| N | Nitrogen |
| $N_2$ | Di-nitrogen |
| $N_2O$ | Nitrous oxide |
| $NH_3$ | Ammonia |
| $NH_4^+$ | Ammonium |
| $NHO_3$ | Nitric acid |
| NO | Nitric oxide |
| $NO_2$ | Nitrogen dioxide |
| $NO_3^-$ | Nitrate |
| $NO_x$ | Nitrogen oxides |
| $N_r$ | Reactive nitrogen |
| NUE | Nitrogen Use Efficiency |
| $O_3$ | Ozone |
| OECD | Organization for Economic Cooperation and Development |
| PM | Particulate Matter |

| | |
|---|---|
| SDGs | Sustainable Development Goals |
| SDSN | Sustainable Development Solutions Network |
| $SO_2$ | Sulphur dioxide |
| UNEA | United Nations Environment Assembly |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention for Climate Change |
| US-EPA | United States Environmental Protection Agency |
| WHO | World Health Organization |

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# 1 EXECUTIVE SUMMARY

- Nitrogen is one of Brazil´s most threatening and challenging environmental problems. Although reactive nitrogen ($N_r$) has positive effects in agricultural and industrial production, excess of $N_r$ in the environment has had deleterious impacts on the environment and human health.

- The purpose of this thesis is to contribute to improving sustainable nitrogen management in Brazil by investigating the (i) underlying drivers of $N_r$ emissions, (ii) the sustainability of nitrogen use, and (iii) the adequacy of policy responses.

- Firstly, a **Conceptual Framework Model** was designed to understand the nitrogen dynamics in Brazil, the diversity of drivers, and the most influential factors behind emissions growth, as well as to support the formulation of policy responses.

- The increase in $N_r$ emissions is caused by productive activities aimed at meeting the demand for food, energy, and housing by a fast-growing population, while the design and implementation of a successful response depends entirely on political and institutional factors.

- Second, the **Entropy Weight Method** was applied to a set of nitrogen-related indicators in four subsystems: environmental, economic, social, and institutional, in order to assess the nitrogen sustainability from 2000 to 2018.

- Political stability, fertilizer consumption, population growth, and investments in water and sanitation play a key role in determining nitrogen sustainability levels in the country within each subsystem, ranging from unsustainable to desirable performance.

- Governance issues are strongly impacting actions towards nitrogen management, leading Brazil to reach only a weak-to-basic level of nitrogen sustainability in the studied period.

- Finally, the **Policy Coherence Analytical Framework** was applied to a set of current nitrogen-related policies, in order to show the coherences and incoherences of these policies and how they can impact the development of a potential integrated nitrogen policy approach.

- Most of the policies are coherent, presenting more positive than negative interactions with each other, which is very favorable to sustainable nitrogen management. However, the National Fertilizer Plan can constrain the achievement of many other N-related policies goals.

- It is recommended that constraining policies be reformulated or adapted with the involvement of different actors and stakeholders, in order to avoid conflicts with other policies and also address the socio-environmental impacts of excess nitrogen in an integrated way.

## 2 INTRODUCTION

Nitrogen (N) is one of the most important elements for life on Earth, essential for the existence of all living things: plants, animals, and microorganisms (GALLOWAY; COWLING, 2021; GRUBER; GALLOWAY, 2008). Despite its abundance in the atmosphere [about 78% of the air consists of di-nitrogen ($N_2$)], nitrogen in its reactive forms (i.e., ammonium, nitrate, nitrite, etc.) is a very scarce nutrient and is often a limiting factor for many biological processes, as $N_2$ cannot be assimilated by most organisms (ALEXANDER, 1961; CANFIELD; GLAZER; FALKOWSKI, 2010; HOLLAND, 1984). Therefore, this inert form of N must be transformed, fixed, or converted, leading to reactive nitrogen (BRAUN, 2007).

Reactive nitrogen ($N_r$) is crucial in agricultural and industrial production systems, including human nutrition, food security, and energy production (JENSEN et al., 2011). Prior to the advent of Haber-Bosch process in the early 20$^{th}$ century, which enables the large-scale production of synthetic N-fertilizers (among other industrial products), almost all the $N_r$ in the biosphere was produced and recycled by microorganisms (biological nitrogen fixation) and from non-biological processes (lightning) (GALLOWAY, 1998; REAY, 2015). The Haber-Bosch process brought enormous benefits to mankind by significantly improving agricultural systems and consequently reducing hunger and nutritional problems in many parts of the world, but it also affected the nitrogen cycle (ERISMAN et al., 2008; SMIL, 2001; STEIN; KLOTZ, 2016). Unbalanced and excessive amounts of $N_r$ stem from various man-made sources, such as intensive use of fertilizers, livestock wastes, fossil fuels combustion, biomass burning, industrial wastes, sewage disposal, and atmospheric deposition (FIELDS, 2004; FOWLER et al., 2013).

Nitrogen pollution is an ongoing problem and a huge challenge for Brazil. Emissions of reactive nitrogen have significantly increased over the last five decades in the country: from 1970 to 2021, nitrogen oxides ($NO_x$) and nitrous oxide ($N_2O$) emissions have increased by 441% and 377%, respectively (SEEG-BRAZIL, 2022). The abundance of nitrogen in the environment has been imposing dire negative effects, implying impacts on human health, air, water and soil pollution, increased marine biological activity, emission of greenhouse gases (GHG), degradation of the stratospheric ozone layer, and loss of biodiversity (DUCE et al., 2008; ERISMAN et al., 2013; TOWNSEND et al., 2003). Changes in the nitrogen cycle can harshly affect the provision, regulation, and supporting of ecosystem services, causing severe economic impacts (JACKSON; BURGER; CAVAGNARO, 2008; JONES et al., 2014), as well as undermine the achievement of the Sustainable Development Goals (SDGs) (ZHANG et al., 2015).

However, specific policies designed to address nitrogen pollution and promote sustainable nitrogen management are limited worldwide, including Brazil, in contrast to the huge diversity of $N_r$ emission sources and their potential impacts, both regionally and globally (OENEMA et al., 2011a). From what we conclude that the excess of reactive nitrogen is not only a matter of global concern due to its magnitude and complexity, but also because of the lack of established coordinated actions to reduce its negative impact on the environment (UNEP, 2014). Therefore, it is fundamental to understand the challenge of producing more food and energy and, at the same time, generating the least possible impact on the environment through an integrated policy approach (DAVIDSON et al., 2015; SUTTON et al., 2013).

### 2.1 Goals, research questions, and objectives of the thesis

Although the impact of human activities on the nitrogen cycle in Brazil has been studied by several authors, important aspects remain underexplored, such as the underlying drivers of $N_r$ emissions, the sustainability of nitrogen use, and the adequacy of policy responses. In this sense, the central goals of this thesis are to investigate these knowledge gaps and contribute to improving sustainable nitrogen management in Brazil.

In particular, this thesis aims at addressing the following research questions:

1. How are the dynamics of nitrogen emissions and how can that affect nitrogen management?

2. How sustainable is the nitrogen management in Brazil?
3. How coherent are the policy responses to address nitrogen pollution in terms of an integrated approach?

The thesis is organized around three specific objectives, each respectively addressing a research question as listed above:

1. Development of a conceptual model to understand the complexity of nitrogen dynamics, the main sources and actors of emissions, the diversity of drivers, and the underlying factors behind $N_r$ emissions.
2. Conduction of an assessment using a set of N-related indicators to determine the level of nitrogen sustainability and the relevance of these indicators towards the Sustainable Development Goals.
3. Application of an analytical framework to evaluate the coherence and level of interactions of existing N-related policies in addressing nitrogen pollution.

### 2.2 Structure of the thesis

This thesis is structured as a collection of three papers, which show how the objectives of this study were addressed:

**Chapters 1 and 2** include the Executive Summary and a brief introduction to the thesis.

**Chapter 3** presents a literature review on the anthropogenic disturbances in the nitrogen cycle, the nitrogen pollution problem in Brazil, and the challenges in nitrogen policymaking.

**Chapter 4** addresses the first research question and its respective specific objective using the Conceptual Framework Methodology. This chapter is an adapted version of the published paper "*Nitrogen emissions in Latin America: a conceptual framework of drivers, impacts, and policy responses*".

**Chapter 5** covers the second research question and its respective specific objective using the Entropy Weight Method (EWM). This chapter is an adapted version of the published paper "*How sustainable is the nitrogen management in Brazil? A sustainability assessment using the Entropy Weight Method*".

**Chapter 6** explores the third research question and its respective specific objective using the Policy Coherence Analytical Framework. This chapter is based on the submitted paper "*Nitrogen pollution in Brazil: a policy coherence analysis of current N-related regulations for a potential integrated approach*".

**Chapter 7** presents concluding remarks that synthesize the main findings and emphasize the central theme of sustainable nitrogen management in Brazil with recommendations and further steps.

# 3 THEORETICAL BACKGROUND

The objectives of this research are to understand the dynamics of nitrogen emissions, to determine the level of sustainability of nitrogen use and to assess the coherence of policy responses in addressing nitrogen pollution. Hence, it is important to start with a literature review on the importance of nitrogen for life on Earth, the impact of human activities in the nitrogen cycle, the nitrogen pollution problem in Brazil, the challenges in nitrogen policymaking, and important examples of recent initiatives on sustainable nitrogen management.

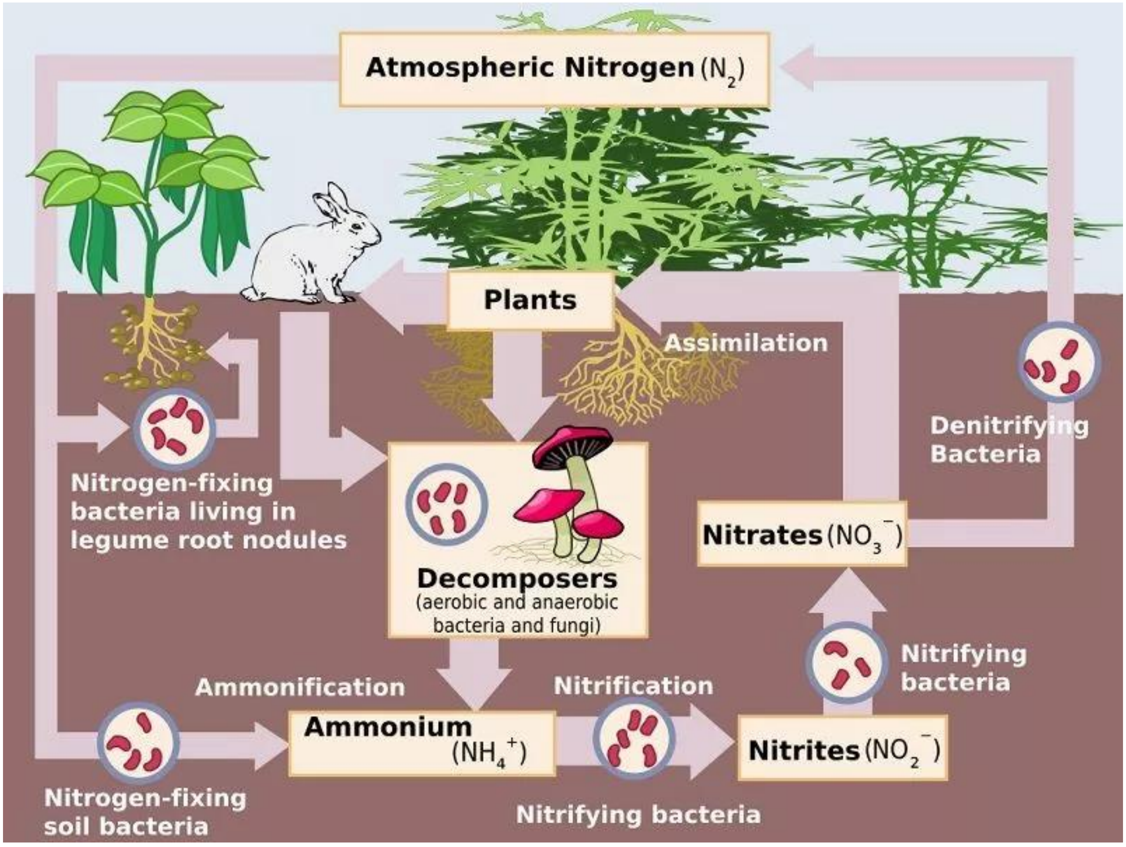
## 3.1 The nitrogen cycle

Nitrogen (N) is essential for the existence of all living beings on the planet and, although it is an abundant gas in the atmosphere (about 78% of the air we breathe), life depends on reactive nitrogen molecules for several biological processes (ALEXANDER, 1961; CANFIELD; GLAZER; FALKOWSKI, 2010; HOLLAND, 1984). Reactive nitrogen ($N_r$) is all chemical nitrogen species, except molecular di-nitrogen ($N_2$), which include inorganic reduced forms of nitrogen [e.g., ammonia ($NH_3$) and ammonium ($NH_4^+$)], inorganic oxidized forms [e.g., nitrogen oxides ($NO_x$), nitrogen dioxide ($NO_2$), nitric oxide (NO), nitric acid ($NHO_3$), nitrous oxide ($N_2O$), and nitrate ($NO_3^-$)], and organic compounds (e.g., urea, amines, and proteins) (GALLOWAY, 2003).

The input of nitrogen into the natural terrestrial ecosystem occurs from the atmosphere, through biological nitrogen fixation (BNF), which is a natural process of plant-bacteria interaction that incorporates nitrogen available in the air into the plant nutrition mechanism (BURRIS; WILSON, 1945), and also via atmospheric deposition, where the $N_r$ input takes place in gaseous, particulate, or dissolved forms; in this case, inputs are derived from ammonia volatilization, wind erosion, biomass burning and atmospheric $N_2$ fixation through electrical discharges (FOWLER et al., 2013).

The natural **nitrogen cycle** involves the following steps (Figure 3.1): to enter the terrestrial ecosystem and food chain, di-nitrogen ($N_2$) must be transformed into ammonium ($NH_4^+$) or into nitrate ($NO_3^-$), whose conversion is carried out by a biological process through of fixing bacteria (nitrification); in these new forms, nitrogen can be used by plants, by microorganisms in the terrestrial system or leach into the aquatic system; the return of nitrogen to the atmosphere (denitrification) occurs mainly in moist soils, where water makes it difficult for microorganisms to obtain oxygen; under these conditions, denitrifying bacteria will process the nitrate to obtain oxygen, leaving either $N_2O$ or $N_2$ as a by-product (HOBBS, 2000; SEINFELD; PANDIS, 2006).

Figure 3.1 – The natural nitrogen cycle.




https://biologydictionary.net/nitrogen-cycle/

Source: Biology Dictionary (2017).

For a better understanding, the various processes of the nitrogen cycle can be defined from the perspective of the organism (JAFFE, 2000): (i) **nitrogen fixation**: any process in which $N_2$ in the atmosphere reacts to form any nitrogen species, that is, nitrogen fixation is the only way nitrogen can be brought into natural systems and BNF is the enzyme-catalyzed reduction of $N_2$ to $NH_3$, $NH_4^+$ or any organic N compound; (ii) **ammonia assimilation**: $NH_3$ or $NH_4^+$ is absorbed by an organism to become part of its biomass in the form of organic N compounds; (iii) **nitrification**: the oxidation of $NH_3$ or $NH_4^+$ to $NO_2$ or $NO_3^-$ by any organism for the purpose of producing energy; (iv) **assimilatory nitrate reduction**: the reduction of $NO_3^-$ followed by uptake of the nitrogen by the organism as biomass; (v) **ammonification**: the breaking down of organic N compounds into $NH_3$ or $NH_4^+$; (vi) **denitrification**: the reduction of $NO_3^-$ to any gaseous N species, generally $N_2$ or $N_2O$.

In sum, the internal nitrogen cycle is characterized by a profusion of biochemical processes, where it acquires organic or inorganic forms; it begins with the entry of N into the soil via atmospheric deposition, continues through its internal transfer through the food chain and ends with the output of N through losses to the atmosphere or hydrosphere (gaseous emissions and leaching) (CHAPIN III; MATSON; MOONEY, 2011).

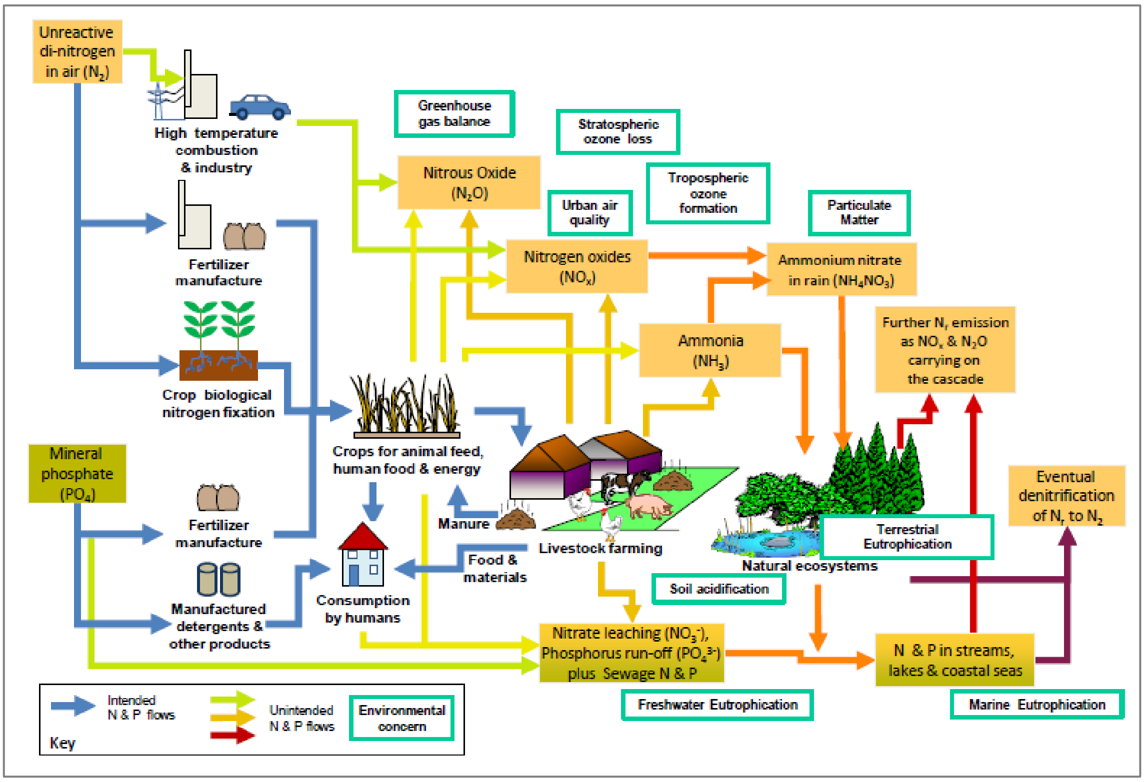
## 3.2 Anthropogenic disturbances in the nitrogen cycle

Reactive nitrogen has positive effects in agricultural and industrial production systems, including human nutrition, food security, and energy production (JENSEN et al., 2011). Basically, three types of human activities are responsible for the fixation of huge amounts of nitrogen on a daily basis: (1) the biological nitrogen fixation (BNF) through the cultivation of legumes and other crops, in order to replenish nitrogen in soils, (2) the production of $NH_3$ and $NHO_3$ mostly for fertilizers manufacturing, and (3) the production of energy by combustion of fossil fuels and biomass burning (GALLOWAY et al., 1995; JAFFE, 2000). As a result of the great intensification of these activities, the natural nitrogen cycle has been altered by humanity on an increasing scale and with diverse impacts throughout the Earth system (AYRES et al., 1994; GRUBER; GALLOWAY, 2008), as shown in Figure 3.2.

Such alterations began with the advent of agriculture, about 10,000 years ago, through the cultivation of leguminous plants to naturally fix the nitrogen in the soil (WILSON; BURRIS, 1947). However, this change in the nitrogen cycle was intensified at the beginning of the last century with the emergence of the Haber-

Bosch process[1], which enabled the manufacturing of nitrogen fertilizers on an industrial scale, and brought enormous benefits to humanity: the improvement of agricultural systems allowed the increase of the food production and livestock intensification which, consequently, reduced hunger and nutritional problems in many parts of the world (ERISMAN et al., 2008, 2015; SMIL, 2001; SUTTON et al., 2011d). Over the same time period, the use of fossil fuel has dramatically increased due to the economic development and energy sector expansion, especially in the industrial and transport subsectors, and is now a major source of $N_r$ in both developed and developing countries (JAFFE, 2000).

Figure 3.2 - Anthropogenic impacts on the nitrogen cycle.




Source: Sutton et al. (2013).

Since the Industrial Revolution, the input of nitrogen into the biosphere has increased between 78% and 115%, without an equivalent expansion in the

[1] In 1908, Fritz Haber discovered how to transform $N_2$ into ammonia through a reaction between nitrogen and hydrogen (catalyzed with iron at high pressures and temperatures); for this discovery he won the 1918 Nobel Prize in Chemistry; Carl Bosch then adapted this process for industrial use in 1913 (winning the same prize in 1931), enabling its use in various sectors, from the manufacture of chemical fertilizers to ammunition and explosives – this technique became known as the Haber-Bosch process (SMIL, 2001).

magnitude of sinks to remove such a surplus (SCHLESINGER, 2009). This accumulation of $N_r$ in ecosystems has been causing numerous and interconnected threats to the environment and human health, in a cascade effect. The **nitrogen cascade**, introduced by GALLOWAY et al., (2003), refers to the ability of a single N atom (in its reactive form) to easily transform into different species, with distinct impacts on the environment. For example, a nitrogen atom present in the fertilizer applied in an agricultural field could first be volatilized as $NH_3$, which is a precursor of several fine particulate matter constituents, highly harmful to human health; this same atom could subsequently, through precipitation and oxidation, be transformed into $NO_3^-$ and eutrophicate surface waters, impacting the water quality; finally, $NO_3^-$ could be denitrified into $N_2O$ and be emitted to the atmosphere, where it would contribute to the greenhouse gases concentration in the atmosphere and to the depletion of the ozone layer.

Despite some uncertainties, about half of the globally fixed nitrogen are from anthropogenic sources, with three-quarters coming from cultivated soils of nitrogen-fixing crops and application of N-fertilizers, other 10% is from industrial raw-material production, and the remaining 15% is the result of energy combustion (FOWLER et al., 2013). In consequence, losses of nitrogen in the environment are exceeding safe boundaries and reaching a level difficult to reverse, as demonstrated by DE VRIES et al., (2013) following the concept of **planetary boundaries** (ROCKSTRÖM et al., 2009a, 2009b)[2].

Excessive amounts of $N_r$ stem from various man-made sources, such as inefficient use of fertilizers, fossil fuels combustion, biomass burning, livestock wastes, industrial wastes, sewage disposal, and atmospheric deposition (FIELDS, 2004; FOWLER et al., 2013). This excess nitrogen has had dire

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[2] Planetary boundaries refer to a level of human interference in Earth's biophysical processes beyond which harmful impacts increase dramatically, perhaps irreversibly. There are nine planetary boundaries and include: (1) climate change, (2) biodiversity loss, (3) biogeochemical fluxes (nitrogen and phosphorus cycles), (4) stratospheric ozone depletion, (5) ocean acidification, (6) land-use changes, (7) global freshwater use, (8) chemical pollution, and (9) atmospheric aerosol loading. According to the study, the boundaries in three systems have already been exceeded (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) (ROCKSTRÖM et al., 2009a, 2009b).

negative effects, implying impacts on human health, air, water and soil pollution, increased marine biological activity, emissions of greenhouse gases (GHG), degradation of the stratospheric ozone layer, loss of biodiversity, and weakening of ecosystems and their services (DUCE et al., 2008; ERISMAN et al., 2013; MOSIER; SYERS; FRENEY, 2004; TOWNSEND et al., 2003; VITOUSEK et al., 1997). Social and economic costs and consequences of $N_r$ pollution are associated with high and rising expenses for health care, treatment of drinking water and wastewater, restoration of damaged aquatic systems, investments to implement agricultural best management practices, unemployment and loss of revenue related to lowering in fishing and ecotourism industries, just to cite a few examples (KATZ, 2020).

The five key threats of excessive release of nitrogen into the environment are known by the acronym WAGES, that is, **W**ater quality, **A**ir quality, **G**reenhouse gas balance and ozone layer, **E**cosystems and biodiversity, and **S**oil quality (SUTTON et al., 2011a). These environmental issues, adverse impacts, $N_r$ species, and activities involved are summarized in Table 3.1.

Table 3.1 – Key threats of excessive release of nitrogen into the environment.

| Key threats | Adverse impacts | Main form of $N_r$ involved | Main activities |
|---|---|---|---|
| **W**ater quality | Water pollution from sewage discharge (VAN DRECHT et al., 2009); N loads to surface waters causing eutrophication and hypoxia (BREITBURG et al., 2009); $NO_3^-$ contamination (POWLSON et al., 2008; WARD et al., 2005); Atmospheric deposition causing shifts in primary producer communities in aquatic systems (DUPRE et al., 2010); Impacts on the provision of fresh water, fishery, recreation, etc. | Nitrate ($NO_3^-$) | Agriculture, urban and industrial sewage, atmospheric deposition |

continue

Table 3.1 – Continuation.

| | | | |
|---|---|---|---|
| **A**ir quality | Air pollution due to $NO_x$ emissions from industrial and combustion sources and $NH_3$ from agriculture (SRIVASTAVA et al., 2005); $NO_x$ and $NH_3$ as a precursor of particulate matter (DELUCCHI, 2003) causing respiratory diseases (TOWNSEND et al., 2003). | Nitrogen oxides ($NO_x$) | Burning fossil fuels and, to a lesser degree, biomass (the latter due to slash-and-burn agriculture) |
| | | Ammonia ($NH_3$) | Agriculture (volatilization following spreading of livestock manure or urea fertilizer) |
| | | Particulate matter | Formed in the atmosphere from precursors $NO_x$ and $NH_3$ |
| | | Ground-level ozone | Formed in photochemical processes from precursor $NO_x$ |
| **G**HG balance and ozone layer | Climate change and global warming due to GHG emissions ($N_2O$) (TIAN et al., 2020); Stratospheric ozone impacts (RAVISHANKARA; DANIEL; PORTMANN, 2009); $N_2O$ release from biofuels production (CRUTZEN et al., 2008). | Nitrous oxide ($N_2O$) | Agriculture and, to a lesser degree, burning fossil fuels and biomass, industrial processes, atmospheric deposition and sewage |

continue

Table 3.1 – Conclusion.

| | | | |
|---|---|---|---|
| **E**cosystems and biodiversity | Nitrogen deposition impacting on species richness, both on plant (SOONS et al., 2017) and animal communities (NIJSSEN; WALLISDEVRIES; SIEPEL, 2017) that are not adapted to an excess of nitrogen, causing biodiversity decline in terrestrial ecosystems (WALLISDEVRIES; BOBBINK, 2017). | Ammonia ($NH_3$) and ammonium ($NH_4^+$)<br><br>Nitrate ($NO_3^-$) and organic nitrogen | Agriculture (volatilization following spreading of livestock manure or urea fertilizer)<br><br>Agriculture, urban and industrial sewage, atmospheric deposition |
| **S**oil quality | Impact of excess nitrogen fertilization on the tropospheric ozone layer (CRUTZEN; EHHALT, 1977); soil acidification (SCHRODER et al., 2011); N leaching to groundwater (HANSEN et al., 2017); N deposition threatening terrestrial biodiversity (PAYNE et al., 2017), causing shifts in primary producer communities in terrestrial systems (DUPRE et al., 2010), and change of species and increase of invasive species (BOBBINK et al., 2010); Impacts on food production and supply (SMIL, 2009). | Ammonium ($NH_4^+$), nitrate ($NO_3^-$) and organic nitrogen | Agriculture and, to a lesser degree, atmospheric deposition |

Source: OECD (2018b).

The excessive use of nitrogen has far-reaching and complex effects, not only posing risks to human health and environment, but also threatening efforts to achieve the Paris Agreement Targets on Climate Change (UNFCCC, 2015), the Aichi Biodiversity Targets (specifically Target 8: pollution from excess nutrients, primarily nitrogen and phosphorus) (UNEP/CBD, 2010), and the Sustainable Development Goals (UN, 2015), considering that all these international instruments somewhat include nitrogen concerns in their scope, even though not explicitly. Additionally, as the resilience of ecosystems to excess nitrogen nor the effects of nitrogen loading on different ecosystem services are not yet fully understood, it is important to emphasize the need for rigorous monitoring of $N_r$ emissions and sustainable nitrogen management (OECD, 2018b).

### 3.2.1 The role of agriculture

The rapid growth of the world population since the last century has resulted in an increase in human activities related to the production of food and energy, which only became possible through the massive adoption of synthetic N-fertilizers, developed in the first decade of the 1900s, via the Haber-Bosch process (ERISMAN et al., 2008, 2015). Agricultural activities are the main global sources of anthropogenic $N_r$, especially nitrous oxide ($N_2O$), ammonia ($NH_3$), and nitrate ($NO_3^-$) (OITA et al., 2016; SUTTON et al., 2011d; TIAN et al., 2020).

The use of fertilizers remains a priority for the agriculture sector, since it serves to supplement the natural soil nutrient supply, compensate for the nutrients loss, and improve unfavorable or maintain good soil conditions, hence increasing productivity and quality of products (ISHERWOOD, 1998). However, excessive or improper fertilizer utilization can lead to a sort of environmental problems (see Table 3.1), with deleterious implications on human health (SAVCI, 2012).

Although global consumption of N-fertilizers has increased exponentially over the last half-century, and it is expected to continue growing (IFA, 2020), their use varies significantly across the world: while some countries with access to nitrogen have been excessively increasing their emissions due to production, consumption, and transport of agricultural products (OITA et al., 2016), in other regions the scarcity and/or difficulty in accessing inputs are obstacles to maintaining soil fertility, in addition to irrigation and climate problems (MUELLER et al., 2012; VITOUSEK et al., 2009).

Synthetic fertilizers contain large amounts of fixed nitrogen, mostly in the form of ammonia ($NH_3$), ammonium ($NH_4^+$) or nitrate ($NO_3^-$) (BOSWELL; MEISINGER; CASE, 2015). When applied to a field, part of the $N_r$ is consumed as a nutrient by crops, but a significant amount is not absorbed by biomass (ISHERWOOD, 1998). Instead the lost nitrogen can end up in the atmosphere (the soil microbial processes of nitrification and denitrification result in conversion of this added N to $N_2O$, which is released back into the atmosphere from the soil surface) (REAY et al., 2012), or it can be leached from the soil and enter into waterways either above ground (lakes, streams, rivers, or ocean) or into surface waters, leading to potentially detrimental concentrations of nitrate that can cause $NO_3^-$ toxicity and eutrophication (JAFFE, 2000).

The expansion of croplands and livestock [(which can also excrete $N_r$ into the soil (OENEMA, 2006)] associated with massive growth of fertilizer application is among the most impactful human actions in the global nitrogen cycle (WANG et al., 2017). The meta-analysis conducted by HAN; WALTER; DRINKWATER, (2017) pointed out that $N_2O$ emissions increase exponentially when fertilizer application exceeded plant uptake. For that reason, the utilization of a metric to measures que ideal quantity of nitrogen taken up by plants to growth is the foremost importance, namely the **nitrogen use efficiency** (NUE). The NUE consists of the relationship between agricultural productivity and the amount of nitrogen available in the soil or applied to it and can be classified into two components: (1) plants efficiency in N absorption and (2) the efficiency in the use of this absorbed nitrogen (MOLL; KAMPRATH; JACKSON, 1982).

Although strategies for increasing NUE have been studied around the world, including through the genetic improvement of plant species (XU; FAN; MILLER, 2012), it is estimated that the global use of nitrogen is extremely inefficient, with more than 80% of anthropogenic $N_r$ lost to the environment (SUTTON et al., 2013). Thus, improving nitrogen use efficiency would be essential to address three of today's main environmental challenges: (i) food security, (ii) sustainability, and (iii) climate change, considering that nitrogen inputs are crucial to the global food production system and, at the same time, an important source of local and regional pollution (HOULTON et al., 2019; KANTER; ZHANG; HOWARD, 2016; ZHANG et al., 2015).

### 3.3 The nitrogen pollution problem in Brazil

Nitrogen emissions vary geographically within the country and are mostly associated to large-scale conversion of native forests into areas of pasture and agricultural land in the North (Amazon biome) (MARTINELLI et al., 2012; MAZZETTO; BARNEZE, 2016; OMETTO; AGUIAR; MARTINELLI, 2011), land-use and land cover changes (natural biome to pasture and cropland) in the Northeast (Caatinga biome) (RIBEIRO et al., 2016), vigorous agricultural intensification, with regional production accounting for around 70% of the national total (cotton, soy, meat, and sugar cane), in the Midwest (which includes a large part of the Cerrado) (GOMES et al., 2019), and inefficient use of N-fertilizers in South and Southeast (Atlantic Forest biome) (TÔSTO et al., 2019; ZANATTA et al., 2010). Additionally, sewage and lack of sanitation due to disorderly urbanization (BUSTAMANTE et al., 2015) and burning of fossil fuels from road transport (MOTHÉ et al., 2014) are also important sources of $N_r$ spread throughout the country.

Excess $N_r$ can cause widespread pollution through various pathways between different environmental media (soil, water, and air). For example, the intensification of agriculture in Brazil determined a significant increase in the consumption of N-fertilizers [an increase of almost 1,700% in 2019 compared to 1970 (SEEG-BRAZIL, 2022)]. As more fertilizers are used, excess nutrients accumulate in agricultural fields and are transported (through leaching, runoff, erosion, or gaseous losses) to surrounding environment (FOLLETT; HATFIELD, 2001). In consequence, the transport and flows of $N_r$ from agricultural to natural ecosystems bring about groundwater pollution through the expansion of sugarcane for ethanol production (GALDOS et al., 2022; MARTINELLI; FILOSO, 2008) and by horticultural systems in karst areas (FRITZSONS; MANTOVANI; ROSA FILHO, 2011), as well as atmospheric emissions from cereals production (e.g., rice, wheat, corn) (PIRES et al., 2015). Although soybeans cultivation requires less N-fertilizers, since this plant is a legume and has high BNF rates (ALVES; BODDEY; URQUIAGA, 2003), the massive expansion of soybeans production in Brazil is causing a substantial increase in

$N_r$ through their production chain, which includes deforestation, land-use change, cultivation cycles (i.e., a second grain harvest), road transportation of the grains, storage and industrial processes, among other production losses (RAUSCH et al., 2019; REZENDE et al., 2021; SUN et al., 2018).

Many other environmental and health impacts caused by excess $N_r$ can be observed on several fronts. Important examples are (i) nitrogen dry deposition [direct transfer of gaseous or particulate species to the surfaces without precipitation (SEINFELD; PANDIS, 2006)], related to road transport, waste management, and industrial activities, are affecting biodiversity hotspots, as the Atlantic Forest located in São Paulo state (SOUZA et al., 2020); (ii) discharges of untreated domestic sewage in rivers and streams are changing the chemical composition of aquatic bodies, causing acidification and eutrophication, affecting drinking water quality and supply, endangering fish, macroinvertebrates, and other aquatic organisms, as well as bringing health concerns and economic impacts for riverine populations (COUCEIRO et al., 2007; MARA, 2013; MARTINELLI et al., 1999; OMETTO et al., 2000); and (iii) exposure to high concentrations of nitrogen oxides ($NO_x$) emitted by burning fossil fuels, especially in urban areas, is correlated with respiratory diseases, different types of cancer, premature deaths, and is also impacting on children´s development and mortality displacement in elderly population (CÉSAR; CARVALHO JUNIOR.; NASCIMENTO, 2015; COSTA et al., 2017; DA ROCHA et al., 2022; LUMINATI et al., 2022).

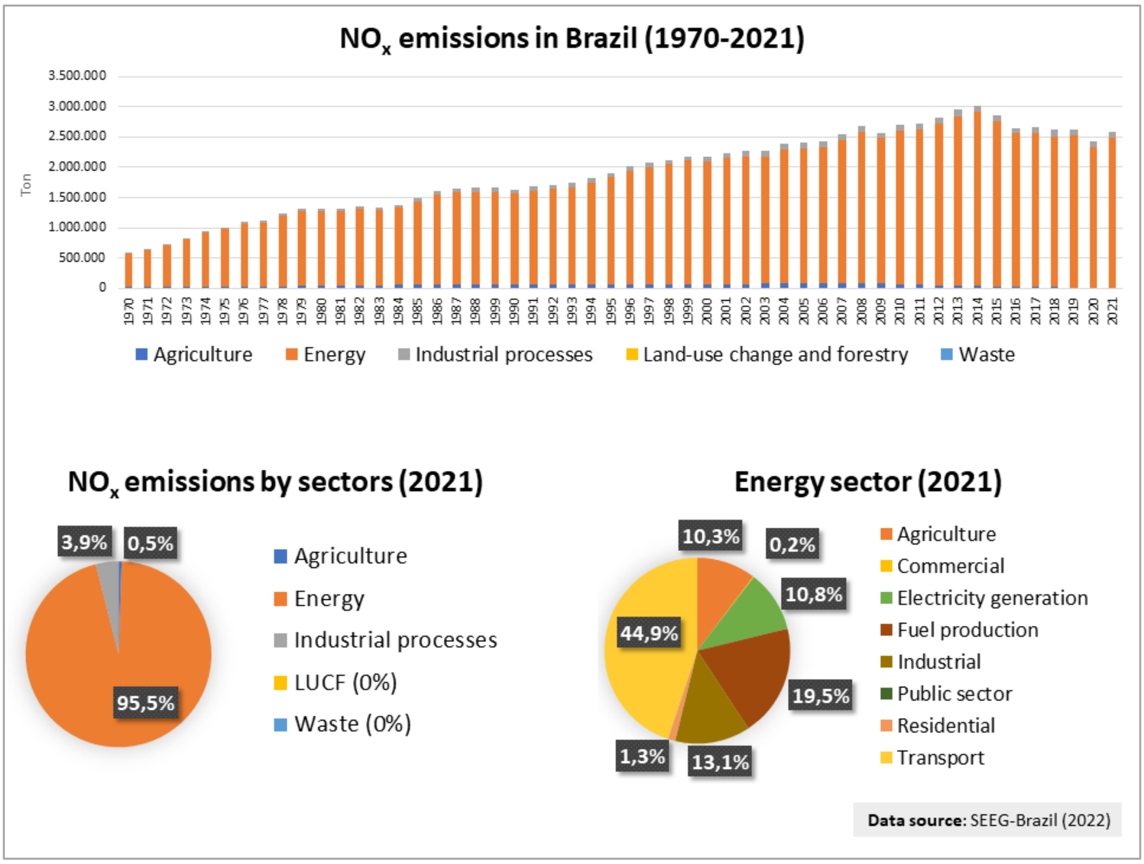
Changes in the nitrogen cycle in Brazil are predominantly associated with anthropogenic activities, rather than natural processes (FILOSO et al., 2006; MRE; MCTIC, 2019), contributing to a significant increase in $N_r$ emissions over the last five decades: nitrogen oxides ($NO_x$) and nitrous oxides ($N_2O$) emissions grew 441% and 377%, respectively, from 1970 to 2021 (DE AZEVEDO et al., 2018; SEEG-BRAZIL, 2022).

### 3.3.1 Emissions of nitrogen oxides ($NO_x$)

Nitrogen oxides ($NO_x$), the sum of nitric oxide (NO) and nitrogen dioxide ($NO_2$), are a significant air pollutant which provoke serious environmental impacts and harmful effects to human health, from respiratory diseases to heart attacks (VALLERO, 2008). These gases are released during combustion, under conditions of elevated temperature and pressure; therefore, power generating plants and vehicular combustion, which use fossil fuels, are major $NO_x$ emitters (STERN et al., 1973). $NO_x$ emissions also contribute to the formation of secondary pollutants, that is, pollutants formed in the atmosphere, such as ozone ($O_3$) and particulate matter (PM) (SEINFELD; PANDIS, 2006).

$NO_x$ emissions in Brazil is rising sharply over the years (Figure 3.3), especially through the ENERGY sector (95.5% of total $NO_x$ emissions in 2021) – mostly from transport, fuel production, and industrial subsectors (DE AZEVEDO et al., 2018; MCTIC, 2020; SEEG-BRAZIL, 2022). Indeed, the growth of $NO_x$ emissions is the result of increasing rate of energy consumption, via the combustion of fossil fuels to boost economic development and support urbanization (MCTIC, 2017, 2020). As consequence, air pollution and associated health problems increased substantially, notably in densely populated regions (CÉSAR; CARVALHO JUNIOR.; NASCIMENTO, 2015; SANTANA et al., 2020).

Figure 3.3 – $NO_x$ emissions in Brazil (1970-2021).



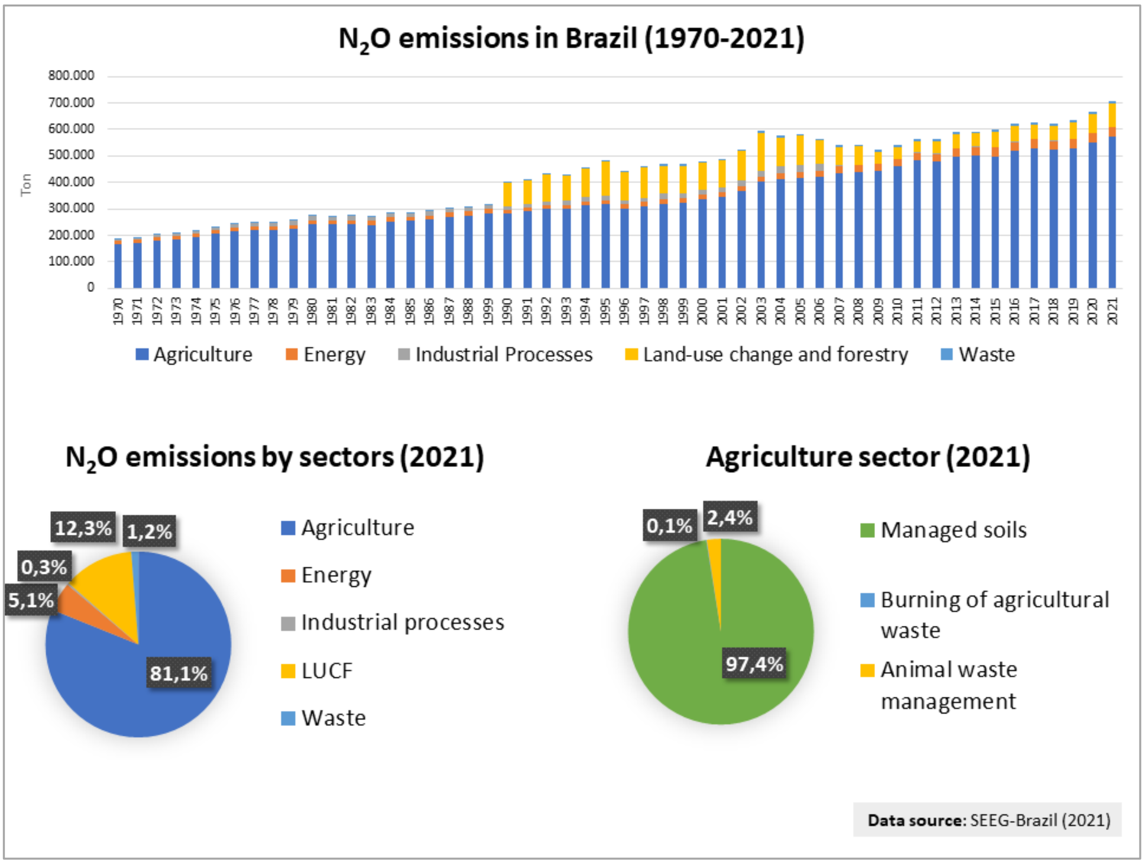

Source: Prepared by the author.

### 3.3.2 Emissions of nitrous oxides ($N_2O$)

Nitrous oxide ($N_2O$) is the result of microbial transformations of nitrogen in soil and water, where two main processes contribute to its emissions: nitrification and denitrification (BUTTERBACH-BAHL et al., 2013). $N_2O$ has been attracting a considerable interest for being a long-lived potent greenhouse gas (GHG) with a warming potential 298 times that of carbon dioxide (SEINFELD; PANDIS, 2006), besides being the most important depleting substance of stratospheric ozone (RAVISHANKARA; DANIEL; PORTMANN, 2009). According to the recent Intergovernmental Panel on Climate Change Working Group 1 Report (IPCC, 2021), it is unequivocal that emissions of nitrous oxide, carbon dioxide, and methane from human activities are the main drivers of increases in atmospheric GHG concentrations since the pre-industrial period. However, a deeper discussion to reduce $N_2O$ emissions was sidelined at the Glasgow

Climate Change Conference – COP26 (MASOOD; TOLLEFSON, 2021), nor mentioned in the Glasgow Climate Pact (UNFCCC, 2021).

Figure 3.4 – $N_2O$ emissions in Brazil (1970-2021).



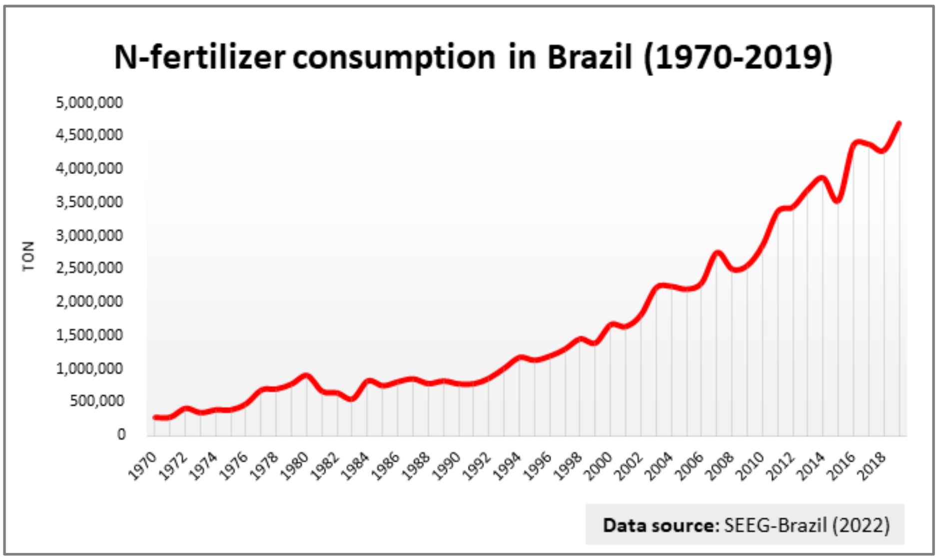

Source: Prepared by the author.

Most of the $N_2O$ emissions in Brazil come from the AGRICULTURE sector, accounting for 81.1% of total emissions in 2021 (Figure 3.4), mainly related to the quantity and quality of agricultural production, the types and amount of fertilizers used in agricultural soil management, and the size of the cattle population (DE AZEVEDO et al., 2018; MCTIC, 2020; SEEG-BRAZIL, 2022). Within the agriculture sector, emissions via managed agricultural soils contributed to 97.4% of the total in 2021. $N_2O$ emissions from agricultural soils occur *directly* (by the addition of synthetic fertilizers and manure to the soil, by the cultivation of N-fixing plants, by the incorporation in the soil of crop residues, and by the mineralization of nitrogen associated with the cultivation of organic soils) or *indirectly* (fraction of nitrogen added to soils as fertilizers, which is volatilized as ammonia or nitrogen oxides and deposited in soils, and also by leaching) (MCTIC, 2020).

Another $N_r$ species directly related to the agriculture sector and produced in large quantities in the country is ammonia ($NH_3$), but emissions data are not available on the platforms consulted (SEGG-Brazil). Ammonia serves as a raw material for the manufacture of urea, the main nitrogen fertilizer used in Brazil, and for the production of nitric acid, intermediate in the production of fertilizer ammonium nitrate and explosive ammonium nitrate (ISHERWOOD, 1998; MCTIC, 2016). Fertilizers (organic or mineral) are used in agriculture to complement the natural availability of nutrients in the soil, to compensate the decrease in nutrients resulting from crop removal, soil leaching or gaseous elimination, and to improving, maintaining or restoring soil conditions (LAPIDO-LOUREIRO; MELAMED; FIGUEIREDO NETO, 2009). Nitrogen mineral fertilizers are an essential component for increasing agricultural production in Brazil and worldwide, despite being subject to various losses that cause environmental damage (MALAVOLTA; MORAES, 2009; MOSIER; SYERS; FRENEY, 2004). These losses occur because part of the applied inputs is incorporated into plants and soil, part volatilizes in the form of $NO_x$ and $NH_3$, and part is emitted in the form of $N_2O$ (WILSON; BURRIS, 1947). The percentage of these losses varies according to the type and soil moisture, environmental temperatures, fertilizer application methods, among other variables (TASCA et al., 2011).

A close and positive relation of crop production and fertilizer use has been observed in Brazil in recent years, which might indicate that there is still room for increase in the use of synthetic fertilizer in the country (FAO, 2004). The consumption of synthetic nitrogen fertilizers in Brazil has been growing substantially over the years (Figure 3.5): in 2019, consumption was 4,691,273 tons of N-fertilizers, an increase of 1,698% compared to 1970 (SEEG-BRAZIL, 2022). As more fertilizers are used, excess nutrients accumulate in agricultural fields and are transported (through leaching, runoff, erosion, or gaseous losses) to surrounding environment (FOLLETT; HATFIELD, 2001). Therefore, excessive or improper fertilizer utilization can lead to several environmental problems as, for instance, the release of GHG into the atmosphere, air pollution, eutrophication of waterways (which, in turn, can lead to harmful algal blooms), and water contamination, with deleterious implications on human health (MOSIER; SYERS; FRENEY, 2004; SAVCI, 2012). Unsustainable use of N-fertilizers can result in increased production costs, depletion of energy resources, impacts on air, water, biodiversity, and human health quality and, consequently, cause serious economic and environmental damages in Brazil (PIRES et al., 2015).

Figure 3.5 – N-fertilizer consumption in Brazil (1970-2019).




Source: Prepared by the author.

Despite the potential damage caused, Isherwood (1998) demonstrated in long-term field experiments that interrupting the use of N-fertilizers could have an immediate impact on the production of several crops, causing a progressive drop in productivity, insofar as soil nutrient reserves run out. Such situation would also aggravate food security problems, both in terms of quality and quantity. Spiertz (2009) points out that the solution to this dilemma (food security versus environmental damage) would be the adequate and efficient use of N-fertilizers through a transition to sustainable agriculture, maximization of ecological processes, investments in technology, among other measures supported by public policies and specific regulations.

### 3.4 Challenges in nitrogen policymaking

Nitrogen is a vital resource for all organisms, thus crucial to food and energy securities (JENSEN et al., 2011), but at the same time, a dangerous pollutant that has multiple sources, pathways, and impacts (COMPTON et al., 2011; TOWNSEND et al., 2003; WATANABE; ORTEGA, 2011). Potential solutions and strategies to address the nitrogen dilemma – *not too much, not too little, just enough* – would involve improving technical and managerial measures for specific sectors (i.e., agriculture, energy, industry, transport, and sewage), as well as introducing behavioral changes concerning societal consumption patterns (GALLOWAY et al., 2008; OENEMA et al., 2011a). Examples of key actions to improve nitrogen management are presented in Table 3.2.

Table 3.2 – Examples of actions to improve nitrogen management.

| Sectors | Challenges | Actions |
|---|---|---|
| Agriculture | Agriculture is a key economic sector in Brazil, and it is by far the largest emitter of $N_2O$ (Figure 3.4), among other $N_r$ species ($NH_3$ and $NO_3^-$), and also the largest N-fertilizer user (Figure 3.5). | Improving nitrogen use efficiency (NUE) in crop production (TILMAN et al., 2002; TÔSTO et al., 2019).<br><br>Improving nitrogen use efficiency (NUE) in livestock production (OLIVEIRA et al., 2022; VAN DER HOEK, 1998).<br><br>Improving biological nitrogen fixation (BNF) in agricultural systems (REIS et al., 2020).<br><br>Increasing the use of animal manure as fertilizers (PRADO et al., 2022). |
| Energy | The energy sector is by far the largest emitter of $NO_x$, especially in the industry and transport subsectors (Figure 3.3), due to the combustion of fossil fuels to boost economic development and support urbanization. | Adopting low-$NO_x$ combustion technologies (SAITEJA et al., 2022).<br><br>Increasing energy-use efficiency and adoption of renewable energy sources (PEHNT, 2006). |

continue

Table 3.2 – Conclusion.

| | | |
|---|---|---|
| Sewage | Lack of basic infrastructure for sewage treatment and disposal systems causes the release of waste in aquatic systems (mostly $NH_3$ and $NO_3^-$). | Recycling nitrogen from wastewater systems through biological practices (bacteria) that convert ammonia to di-nitrogen (HOLMES; DANG; SMITH, 2019). |
| Societal consumption patters | Unsustainable consumption patterns influence the increase of anthropogenic $N_r$ emissions | Changes in population dietary patterns by lowering animal protein consumption (LASSALETTA et al., 2016; WESTHOEK et al., 2015).<br><br>Reducing emissions through energy and transport savings (OENEMA et al., 2011a).<br><br>Adopting a low N-footprint in the production and consumption of food and energy (COSTA LEITE et al., 2020; LEACH et al., 2012) |

Source: Prepared by the author.

Although these examples of actions are likely to be successful in improving nitrogen management, they would require tremendous efforts to be implemented (including political interventions), which would affect the nitrogen cycle and the production and consumption of food and energy (ABROL et al., 2012; OENEMA, 2019; SUTTON et al., 2013). The great challenge is that these potential measures need not only to ensure the population's food and energy security, but also not be extremely burdensome for specific sectors, groups and/or areas.

However, policies designed to address nitrogen pollution and promote sustainable nitrogen management are limited worldwide, including Brazil, in contrast to the immense variety of emissions sources and potential impacts at local, regional, and global scales (OENEMA et al., 2011a). In general, existing N-related policies are fragmented among different $N_r$ species, therefore an integrated approach would encourage to consider the synergies and trade-offs between benefits and threats of $N_r$ use (SUTTON et al., 2019a). Besides, joined-up measures for nitrogen management would allow quantifying the social cost of nitrogen pollution, hence designing more efficient policies (ERISMAN et al., 2001; VAN GRINSVEN et al., 2013).

According to Mosier et al. (2001), the development of sound policies for nitrogen management involves several challenges: the first and most important is that nitrogen use is closely linked to essential human needs, that is, the supply of food and energy; the second is the issue of *cause and effect*, that is, sources and sinks are often separated due to the great mobility of species (they move through air and water, crossing geographic and political boundaries); third is that while the impacts of excess nitrogen also occur at regional and global scales, existing policies are implemented only at the local level; and, finally, is the fact that changes in the nitrogen cycle are interactive with other global changes, which affect policy development and management at both regional and global levels. Another major challenge would be to increase public and institutional awareness of the benefits and threats of nitrogen, in order to create an essential basis for the development of proper actions and increase effectiveness in policy formulation and implementation (REAY et al., 2011).

Furthermore, it is essential to consider that the unique and ephemeral nature of the various $N_r$ species is an immense challenge for policy-makers, given the need not only to define at which point in the N cascade to intervene (WOIWODE, 2006), but also to consider it as a whole by developing measures to avoid an offsetting effect, that is, accentuating emissions of a pollutant in a given area, while managing its attenuation in another (KANTER, 2014). Not least, gathering reliable information on how different productive activities influence nitrogen footprints[3] can support action plans consistent with health

[3] According to GALLOWAY et al., (2014), the nitrogen footprint is defined as the total amount of $N_r$ released into the environment as a result of an entity's consumption patterns. There are several tools for calculating the N- footprint, which consider the country where people live, the products they consume, among other details of each individual's routine. These tools provide a framework for decision making about resources use and possible tradeoffs, with the aim of decreasing consumer contributions to N-related problems.

and environmental sustainability targets (GALLOWAY et al., 2014; LEACH et al., 2012, 2016).

Kanter, (2014) indicates that, in strategic terms, global nitrogen management policies present different and, to some extent, conflicting perspectives: (i) *top-down approach*, considering the need for a single and comprehensive international agreement, either within an existing structure or a new exclusivity treaty, due to the regional and planetary characteristics of nitrogen impacts (SUTTON et al., 2013; WOIWODE, 2006); and (ii) a *bottom-up approach*, which suggests that policies should start at the local level, given the enormous diversity among countries, especially with regard to agricultural management (HOWARTH, 2005; KRONVANG et al., 2008). Both approaches have advantages and disadvantages: while the top-down has been heavily criticized for being insensitive to local conditions, the bottom-up is considered indifferent to the issue that local actions can exacerbate regional problems (CASH et al., 2006). However, regardless of the approach to be adopted, several authors uphold the inclusion of the nitrogen pollution problem in a broad and comprehensive global agenda of discussion (OENEMA et al., 2011a; REAY et al., 2011; SUTTON et al., 2019a), which would result in the establishment of a technical-scientific panel, similar to the Intergovernmental Panel on Climate Change – IPCC (HOULTON et al., 2019), or an Inter-convention Nitrogen Coordination Mechanism (SUTTON et al., 2021).

To sum up, an integrated policy approach should consider not only the multiple benefits and impacts of nitrogen use, but also interactions with other element cycles (phosphorus and carbon cycles, for instance) and alignment with existing environmental frameworks (e.g., the United Nations Framework, the Convention on Biological Diversity, and the 2030 Agenda for Sustainable Development). Sutton et al. (2019a) suggests that achieving sustainable nitrogen management depends on local and regional actions supported by global intergovernmental guidelines.

### 3.4.1 Recent global initiatives on sustainable nitrogen management

Nitrogen management has somehow attracted the attention of scholars and policy-makers, with a view to maintaining the benefits of nitrogen use, while minimizing threats to the environment (KANTER et al., 2020a, 2020b; MOSIER et al., 2001; OECD, 2018b; TOWNSEND; PALM, 2009). Therefore, despite all the challenges, many efforts have been recently contributing to scientific advancement and the debate over integrated policies for reducing nitrogen pollution, both at local and global levels (SUTTON et al., 2020). Important examples of these initiatives include:

- **The International Nitrogen Initiative (INI)**: an international program, set up in 2003, which aims to optimize the beneficial role of nitrogen in sustainable food production and minimize its negative effects on human health and the environment resulting from food and energy production (https://initrogen.org/). The INI is coordinated by a Steering Committee and six regional centers, representing Africa, Europe, Latin America, North America, South Asia, and East Asia. Besides, the INI holds an international conference every three years to discuss ideas and exchange knowledge on nitrogen issues. The last INI Conference was held in Berlin, Germany, in 2021, and the key output of the conference was the *Berlin Declaration on Sustainable Nitrogen Management for the Sustainable Development Goals* (INI, 2021).

- **Regional nitrogen assessments**: in general, regional assessments provide a detailed overview of issues and challenges related to nitrogen use and overuse, through a review of current scientific knowledge regarding nitrogen sources and impacts, as basis for potential policy responses. Examples of regional assessments are the European Nitrogen Assessment (SUTTON et al., 2011b), the United States Nitrogen Assessment (SUDDICK et al., 2013), the California Nitrogen Assessment (TOMICH, 2016), the Indian Nitrogen Assessment (ABROL et al., 2017), and the Pakistani Nitrogen Assessment (AZIZ et al., 2022). The International Nitrogen Assessment (INA) report is currently under preparation and will be published in 2023. The INA will provide a synthesis of emerging findings on nitrogen, comprising twenty-nine chapters into five parts: (a) the global nitrogen challenge, (b) foundations for assessing the nitrogen cycle, (c) global integrated assessment across the nitrogen cycle, (d) nitrogen challenges and opportunities for key world regions, and (e) grasping the future challenge [4].

- **The International Nitrogen Management System (INMS)**: the INMS is a science-policy support process that brings together people, information, approaches, indicators, cost-benefit analysis, regional demonstration, etc., as a basis to support governments and others through international nitrogen policy processes (SUTTON et al., 2020). The INMS was established in 2016 and its activities have financial support from the Global Environment Facility (GEF), among other partners through the "Towards INMS" project (https://www.inms.international/). In addition to many other nitrogen-related activities, the INMS is also responsible for the establishment of the "Inter-convention Nitrogen Coordination Mechanism (INCOM)" as an intergovernmental mechanism for coordination of nitrogen policies on the existing platforms and networks, under the auspices of the United Nations Environment Programme (UNEP). The INCOM aims to promote synergies through cooperation between other multi-lateral environmental agreements (Air Convention, Framework Convention on Climate Change, Convention on Biological Diversity, among others) and United Nations organizations (Food and Agriculture Organization, World Health Organization, World Meteorological Organization, etc.), thereby stepping up progress towards nitrogen challenges (SUTTON et al., 2021).

[4] The International Nitrogen Assessment (INA) will be published by Cambridge University Press in 2023. The author is coauthoring three INA chapters: Part A, Chapter 2 (Nitrogen, environment and sustainable development), Part A, Chapter 4 (Nitrogen in current national and international policies), and Part D, Chapter 20 (Assessment of nitrogen flows, impacts, and solutions in Latin America). Additional information at: https://www.inms.international/international-nitrogen-assessment/open-call-peer-review.

- **Regional projects (Latin America)**: as in other regions of the world (Africa, Asia, Europe, and North America), Latin American countries are also engaged in technical-scientific cooperation projects, aiming to improve knowledge about the nitrogen cycle in the region, producing new data on nitrogen budget and nutrient management, and support the formulation of public policies. Examples are the *Nitrogen cycling in Latin America: driver, impacts, and vulnerabilities (Nnet)* that established a scientific cooperation network across Argentina, Bolivia, Brazil, Chile, Mexico, and Venezuela (NNET PROJECT, 2016; OMETTO et al., 2020a) from 2013 to 2018, supported by the Inter-American Institute for Global Change Research (IAI), and the *Latin America Demonstration Site – La Plata Basin* (Argentina, Bolivia, Brazil, Paraguay, and Uruguay) in the scope of the INMS, that aims at designing common methodology and conducting regional demos to refine $N_r$ assessments, and improve understanding of N cycle.

In response to the many initiatives to increase the relevance of nitrogen in the scientific and political spheres, a major breakthrough took place during the closing plenary session of the *Fourth Session of the United Nations Environment Assembly (UNEA)* of the United Nations Environment Program (UNEP), held on March 15, 2019, when delegates adopted the Resolution UNEP/EA.4/L.16 (UNITED NATIONS, 2019), which calls for a coordinated and collaborative approach to sustainable nitrogen management. The Resolution recognizes the multiple threats and adverse effects of anthropogenic $N_r$ and highlights ways to improve its management. It also supports the exploration of options for better management of the global nitrogen cycle to achieve the goals of sustainable development, through the exchange of methodologies, management practices, guidance documents, and emerging technologies for recovery of nitrogen recycling and other nutrients.

Following the powers of the Resolution, in October 2019 the UNEP launched a global campaign for the sustainable nitrogen management. Entitled “Nitrogen for Life”, under the leadership of the Sri Lankan president, the campaign generated the "Colombo Declaration for Sustainable Management of Nitrogen"[5] (UNEP, 2019a), and a "Roadmap for Action on Sustainable Nitrogen Management 2020-2022", with the aim of preparing the bases to halve nitrogen waste by 2030 (UNEP, 2019b). In parallel, SUTTON et al., (2019b) published the Manifesto for Science in Action, which aims to disseminate the efficient nitrogen management as a central theme for sustainable development, as well as producing evidence to support government officials, public policy-makers, and decision-makers in developing appropriate measures for local problems. The Manifesto claims that reducing the inefficiency of nitrogen use to reach the Sustainable Development Goals is an extremely ambitious target, but possible through simultaneous science-based actions in various productive sectors, towards the production and consumption of food, as well as the energy, wastewater, and transportation systems.

To proceed with the above-mentioned Roadmap for Action on Sustainable Nitrogen Management, an international workshop was held in Paris, France (May 18-20, 2022)[6], bringing together an international and interdisciplinary group of academics, stakeholders, and policy experts to discuss current policies and measures to address nitrogen pollution in different parts of the world and propose a coherent approach for developing national action plans for sustainable nitrogen management. Deliverables expected from the Paris Workshop include a 'Guidance Document for National Action Plans' to improve nitrogen management and to guide the various policy processes among countries associated with the Colombo Declaration, and a Policy Brief to report experiences from efforts to address the multiple impacts of nitrogen compounds in the human environment, both to be released in middle 2023.

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[5] Additional information about the Colombo Declaration can be found at: https://www.inms.international/colombo-declaration/colombo-declaration

[6] The "Developing Roadmaps for Sustainable Nitrogen Workshop – Paris Workshop" was a collaboration between the International Nitrogen Initiative (INMS), the Organization for Economic Cooperation and Development (OECD), and the Institute of Advanced Studies in Paris, France. The author attended the Paris Workshop and gave a talk about Brazil's policies to limit nitrogen pollution. Additional information at: https://www.paris-iea.fr/en/events/developing-roadmaps-for-sustainable-nitrogen-management-2.

## 4 THE DYNAMICS OF NITROGEN EMISSIONS IN BRAZIL[7]

In this chapter, we address the research question number one of the thesis: "*How are the dynamics of nitrogen emissions and how can that affect nitrogen management?",* raised in Section 2.1. For that, we develop a conceptual framework model to understand the complexity of nitrogen dynamics in Brazil, the diversity of drivers, and potential harms to environment and human health. This study also aims to support the formulation of adequate mechanisms to deal with the adverse impacts while increasing the benefits of nitrogen use. The main findings show that the increase in nitrogen emissions is due to demand drivers (demand for food, energy, and housing, connected with socioeconomic factors), while preparing and implementing a successful response to solve the problem of nitrogen pollution depends entirely on structural drivers (political and institutional factors). We highlight the crucial role of political decision and institutional forcefulness in the design and implementation of appropriate policy instruments to deal with the duality of nitrogen use.

### 4.1 Links between productive activities and nitrogen emissions

Human activities have been triggering substantial changes in the nitrogen cycle in Brazil, involving excess of $N_r$ species in the soil, water bodies, and atmosphere, bringing detrimental impacts on the environment and human health (AUSTIN et al., 2013; FILOSO et al., 2006). The driving forces behind these anthropogenic actions are the activities engendered to meet the high demands for food, energy, and housing by a fast-growing population, such as agriculture and livestock, biomass burning, biofuels production, industrial and transport sectors, and urbanization. In the next paragraphs, some of the socioeconomic impacts of unsustainable nitrogen management is presented for each of these activities.

[7] This chapter is an adapted version of the paper: CUNHA-ZERI, GISLEINE; OMETTO, JEAN. ***Nitrogen emissions in Latin America: A conceptual framework of drivers, impacts, and policy responses.*** ENVIRONMENTAL DEVELOPMENT, v. 38, p. 100605, 2021. https://doi.org/10.1016/j.envdev.2020.100605

- **Agriculture and livestock**: Agribusiness is of paramount importance to Brazil, since agriculture and pasture occupies 41% of its land area (around 351.2 million hectares) (IBGE, 2019), employs 38% of the labor force, and accounts for about 40% of the volume of domestic exports (KURESKI; MOREIRA; VEIGA, 2020). This performance makes the country one of the world´s largest producers and exporters of agricultural commodities (FAO, 2018) and one of the largest $N_2O$ emitters, along with the United States, China, and India, which together account for 46% of global emissions (OITA et al., 2016). The agriculture and livestock sectors are among the main economic actors in Brazil (FAO, 2021). In fact, agricultural production and trade were important instruments to face the 2008 global economic and financial chaos, more effectively than other sectors (FAO, 2014; IMF, 2016). Notwithstanding the worldwide COVID-19 pandemic outbreak, that spawned a global economic crisis (IMF, 2020), agribusiness in Brazil has had positive prospects and is thriving despite the sanitation and economic situation (USTINOVA; WOODY, 2020).

- **Biomass burning**: biomass burning is frequently used as land clearing method for livestock and agricultural activities (PIVELLO, 2011). Such a practice, however, causes negative impacts by increasing GHG emissions (i.e., $N_2O$), among other gases (including $NO_x$), which affect both nitrogen and carbon cycles (CASTELLANOS; BOERSMA; VAN DER WERF, 2014; CRUTZEN et al., 2016; WEITZ et al., 1998). Biomass burning has been associated with deforestation, and it is undoubtedly an important source of global $N_2O$ emissions (CHUVIECO et al., 2008; KELLER et al., 1993). Biomass burning is a source of $N_2O$ during the fire and increases soil emissions afterwards by fertilizing the soil through N mineralization (SKIBA; SMITH, 2000). Additionally, these large amounts of nitrogen compounds are transferred from land to the atmosphere, and then redistributed regionally (TREBS et al., 2006).

- **Biofuels production**: in the last decades, Brazil has been focusing on bioethanol production from sugarcane and more recently experiencing the use of soybeans for biodiesel production, which are alternative markets for agricultural commodities (JANSSEN; RUTZ, 2011; MARTINELLI; FILOSO, 2008). Biofuels can replace fossil fuels and contribute to meet the world´s energy needs and to decrease GHG and other pollutants emissions (JANSSEN; RUTZ, 2011; MILLER, 2010), as well as generate extra income through international biofuel market expansion (JANSSEN; RUTZ, 2011). Nevertheless, even in allegedly sustainable cultures that require low input of N-fertilizer, like sugarcane plantation, there is a range of problems (BALDANI et al., 2002; CABRAL et al., 2020). The common practice of burning sugarcane residues has significant environmental implications, such as the high temperature at the soil surface that causes volatilization of soil nutrients (including nitrogen) and the release of organic contaminants into the atmosphere (TAVARES et al., 2018). The sustainability of biofuels production is very controversial, due to its effects on GHG emissions, deforestation, biodiversity, water use, and food security (BAILIS et al., 2014; RENZAHO; KAMARA; TOOLE, 2017; SOLOMON; BAILIS, 2014; VERDADE; PIÑA; ROSALINO, 2015). An example is the European Union (EU), which has been questioning the sustainability of Brazilian ethanol, due to the government's decision to allow the expansion of sugarcane in the Amazon biome, which can hinder the ratification of the EU-Mercosur trade agreement (FOLLADOR et al., 2021). Finally, since the first-generation biofuels in Brazil are food based, the growth in demand for biofuels may put upward pressure on domestic and global food prices (FAO, 2018; TO; GRAFTON, 2015).

- **Industrial and transport sectors**: many studies have shown the significant relationship between economic growth and energy consumption, as well as the enhancing dependence on fossil fuels to generate energy to the industrial and transport sectors (CHANG; SORUCO CARBALLO, 2011; HANIF, 2017; SHEINBAUM; RUÍZ;

OZAWA, 2011; ZILIO; RECALDE, 2011). Rapid and rampant urbanization has also increased demands for transportation, public and domestic utilities, and other services (GURJAR et al., 2008; HANIF, 2017). As a result, the combustion of fossil fuels to foster economic growth and support urbanization has increased air pollution by emitting GHGs and other toxic substances [sulphur dioxide ($SO_2$), carbon monoxide (CO), particulate matters (PM), and nitrogen oxides ($NO_x$)] (HANIF, 2017). As seen in Figure 3.3 (Section 3.3.1), the transport sector has the largest share of energy use in Brazil, consequently emissions from on-road transportation are rising pollution levels and bringing associated health risks, especially in densely populated areas (BELL et al., 2006, 2011; D'ANGIOLA et al., 2010). An aggravating factor is that emissions can significantly impact on a regional scale, through the long-range transport of air pollutants (BUTLER; LAWRENCE, 2009).

- **Urbanization**: the total population of Brazil is the largest in Latin America and an estimated 87% resided in urban settlements in 2018, particularly concentrated in megacities as São Paulo, with more than 20 million inhabitants, and megacities under development, like Rio de Janeiro (UN, 2018a, 2019a). Updated projections show that the population of Brazil will increase by 7.7% from 212 million in 2020 to nearly 229 million in 2050 (UN, 2019a), and will have more than 90% of its population residing in urban areas (UN, 2018b). The dramatic transition from rural to urban housing has been accompanied by a series of problems, such as poor living conditions, escalating violence and crime, social and political struggles (ANGOTTI, 2013). In addition, the lack of basic infrastructure for sewage treatment and disposal systems causes the release of waste in aquatic systems (AUSTIN et al., 2013; BUSTAMANTE et al., 2015). The pollution of water bodies results in severe problems related to nutrient enrichment (nitrogen and phosphorus), eutrophication, acidification, and biodiversity loss (GOMEZ-OLIVAN, 2019; VITOUSEK et al., 1997), impairing trophic interactions (DANIEL et al., 2002;

OMETTO et al., 2000) and affecting water resources of an entire region (BUSTAMANTE et al., 2015; WATANABE et al., 2012).

## 4.2 A conceptual framework of nitrogen emissions drivers

The lack of specific information on the nitrogen cycle in Latin America in general, and in Brazil in particular, is a critical impediment to provide a proper evaluation and projection on how human activities are altering nitrogen pools and turnover at regional and global levels (OMETTO et al., 2020b). To address these issues, the key drivers of changes in the nitrogen cycle must be well comprehended in an integrated way, especially the role of political and institutional factors in providing and implementing sound mechanisms to solve the problem (or if they are a part of the problem).

Considering this knowledge gap, a conceptual framework of nitrogen emissions drivers was developed to depict the complexity of nitrogen dynamics in Brazil, the diversity of drivers, and impacts and risks on the environment and human health. The objectives were to (i) evaluate the significance of socioeconomic factors as a key driver for demanding food, energy, and housing, hence increasing emissions; (ii) discuss the crucial role of political decisions and institutional forcefulness in providing and implementing appropriate mechanisms to deal with the duality of nitrogen use (benefits and costs), and (iii) provide a visual panorama that communicates at a glance the nitrogen situation not only for nitrogen scientists, but especially for decision and policy-makers, and also for a more general public.

### 4.2.1 Methodology

Conceptual frameworks support the development of qualitative research when existing theories are not applicable or are insufficient to understand specific scientific issues (RAVITCH; CARL, 2015). Their elaboration is essential to present a visual and logical structure, where each element and/or variable is well defined, shows clear interactions between them, and influences each other (ADOM; HUSSEIN; AGYEM, 2018; MILES; HUBERMAN; SALDANA, 2014). A great advantage of building a conceptual framework is to organize and guide a research topic from its inception to its completion by situating the problem within multiple contexts (RAVITCH; RIGGAN, 2016). In contrast, its limitation is the need of specific literature and/or further empirical work to validate the information containing in the framework, because it is not possible to extract definitive responses just by designing it, even though its formulation can generate knowledge and integrative understanding of the topic (RAVITCH; CARL, 2015; RAVITCH; RIGGAN, 2016).

To develop a conceptual framework of nitrogen emissions drivers, the methodological structures proposed by Miles and Huberman (1994), Ravitch and Carl (2015), and Ravitch and Riggan (2016) were followed, where: (i) the construction of a conceptual framework involves the elaboration of a diagram, in order to clearly contextualize the elements/variables to the research topic; (ii) the potential interactions between the elements/variables are shown by arrows; and (iii) the concepts that define the elements/variables are searched through a wide literature review, established theories, and, when necessary, research datasets. Additionally, this work follows the Fisher and Buglear (2010) methodology which suggest that the details of the diagrammatic representation of the conceptual model must also be expressed in writing, to facilitate its understanding by thoroughly explaining the relationships between the elements/variables and, consequently, contributing to the elucidation of the proposed scientific issues.

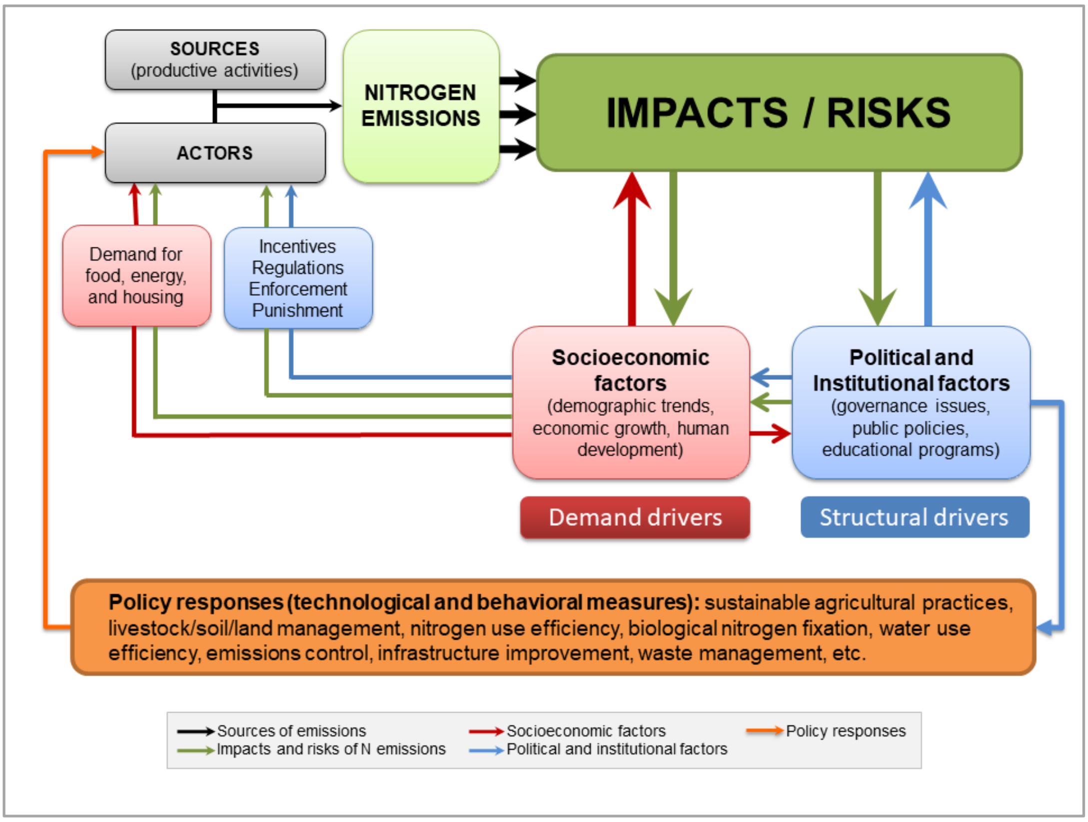
General examples of conceptual frameworks are the models designed for understanding the factors of deforestation in tropical countries (HEROLD et al., 2008) and for the operationalization of ecosystem services in the context of social change (POTSCHIN-YOUNG et al., 2018). Model applications for nitrogen issues are found in the reports prepared by the United States Environmental Protection Agency (US-EPA) (EPA, 2011), the European Nitrogen Assessment (ENA) (SUTTON et al., 2011b), and the Indian Nitrogen Assessment (ABROL et al., 2017). In both US-EPA and ENA the diagrams are adaptations of the nitrogen cascade (GALLOWAY et al., 2003). In the US-EPA report, it was developed to provide a context for considering nitrogen-related issues and ecosystem effects in the US, while in the ENA it highlights the raised flows of nitrogen and their multiple impacts under anthropogenic influences (SUTTON et al., 2011c, 2011a). Additionally, the ENA offers another conceptual framework for developing and analyzing integrated approaches to $N_r$ management in Europe (OENEMA et al., 2011a). Although the US-EPA and ENA reports and frameworks have provided useful insights for designing a $N_r$ assessment for India (RUDEK; ANEJA; ABROL, 2017), the Indian conceptual models are focused on the ecological approach to nitrogen management in horticulture systems (GANESHAMURTHY et al., 2017), for depicting the nitrogen biogeochemical process in the mangrove ecosystem (PRIYA et al., 2017), and for explaining the nitrogen cycle under the agroforestry system (RAM et al., 2017). Finally, an analogous framework for China is presented by Gu et al. (2015), that describes the nitrogen cycle in coupled human and natural systems, and among many Chinese subsystems.

### 4.2.2 Model description

According to the conceptual framework presented in Figure 4.1, the **impacts** and **risks** are related to the environmental and human health problems resulted from the excess of **nitrogen emissions** in ecosystems (ERISMAN et al., 2013; TOWNSEND et al., 2003), as well as the imposed social costs of nitrogen, which can be estimated through the monetary value of damages caused by an incremental increase in nitrogen emissions (BRINK et al., 2011; KEELER et al., 2016). The **sources** of nitrogen emissions are primarily linked to productive activities (black arrows), corresponding to agriculture and livestock, biomass burning, biofuels production, industrial and transport sectors, and urbanization (see Section 4.1).

These productive activities are conducted by the **actors**, which are not only the instruments of changes, but they are specifically the main recipients of the benefits and adverse impacts and risks of uncontrolled emissions (green arrows). At any rate, the actors are attending their own (and/or a third part) demand for food, energy, and housing, which are depending upon the **socioeconomic factors**. These factors refer to *demographic trends* [intense population growth in Brazil over the past few years and the projection of continuous increase for the coming decades (UN, 2018b)]; *economic growth* [the strong relationship between economic growth and energy consumption, leading to environmental degradation (PABLO-ROMERO; DE JESÚS, 2016; ZILIO; RECALDE, 2011)]; *human development* [related to how countries are addressing basic human needs, although inequality, poverty, illiteracy, and poor living conditions are still present in Brazil, putting pressure on the natural environment (UN, 2019b)]. Socioeconomic factors affect human activities also at the regional level (AUSTIN; PIÑEIRO; GONZALEZ-POLO, 2006), specially to attend the market pressure for food production, which is an opportunity to alleviate poverty in rural areas (MORALES et al., 2003; SOUSA et al., 2019). Therefore, the socioeconomic factors are considered the **demand drivers**, which promote a direct and potent effect on increasing nitrogen emissions (red arrows), through modifying the natural ecosystems for food, energy production, and urbanization.

Figure 4.1 – Conceptual framework of nitrogen emissions drivers.




Source: Prepared by the author.

The actors´ behavior is likewise influenced by **political and institutional factors** through *incentives* (tax breaks, tax exemptions, subsidies), *regulations* (laws, directives, deregulation, treaties), *enforcement* (compliance with a law, rule, or obligation), and *punishment* (fines, license revocation, probation). For instance, a certain government offers subsidies to encourage crop plantations for biofuels production, under some specific directives for restricting deforestation and biomass burning to increase the extent of agricultural land, or for limiting the amount of N-fertilizer use, or for controlling nitrogen emissions; the non-compliance with those regulations can incur in fines, or license revocation, to the perpetrator; on the other hand, lack of enforcement and punishment can favor bad behavior. These elements may decrease or induce the nitrogen emissions depending on the governance issues, public policies, and educational programs. For that reason, they are considered the **structural drivers**, which influence the intensity of nitrogen emissions (blue arrows) by underlyingly acting upon the actors´ motivation for engaging in unsustainable productive activities that negatively impact on the nitrogen cycle. Previous studies have emphasized the huge influence of government and institutional quality on environmental protection (BARBIER; DAMANIA; LÉONARD, 2005; BARRETT et al., 2001; KAUFMANN, 1997; SMITH et al., 2003), which implies that a country with good governance systems works to build capable, efficient, open, inclusive, and accountable institutions that are able to efficiently protect its natural resources, through well-designed environmental policies and educational programs for nature conservation. Unfortunately, Brazil has been experiencing prominent levels of political corruption (TRANSPARENCY INTERNATIONAL, 2019) and presenting medium-to-low scores of governance indicators over the years (namely, control of corruption, government effectiveness, political stability and absence of violence, regulatory quality, rule of law, and voice and accountability) (KAUFMANN; KRAAY, 2022). These indicators demonstrate governmental and institutional capabilities of a country to pursue a good and fair policy system. For instance, a successful nitrogen policy would rely upon the ‘regulatory quality’ and ‘government effectiveness’ indicators, which conjointly reflect the ability of the government to formulate and implement sound policies and regulations, and the credibility of commitment to such policies.

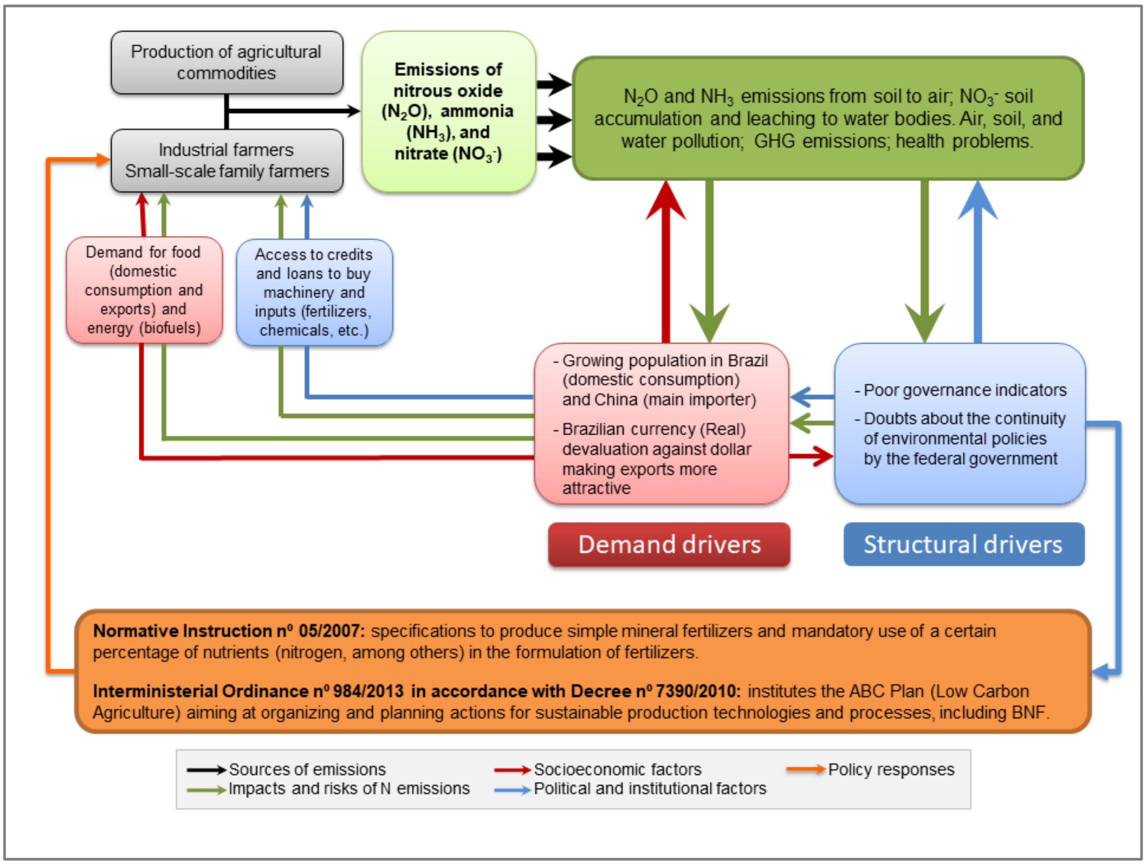
Interactions exist between demand and structural drivers, since some policies and incentives can also influence socioeconomic aspects, especially those concerning demographic trends and economic development. Besides, both socioeconomic and political and institutional factors are feedback by the intensity of impacts and risks of growing emissions (green arrows) in a very dynamic interchange. Both the demand and structural drivers influence the actors´ behavior (and are mutually influenced) and, therefore, determine whether nitrogen leaks to the environment are balanced or exceeding safe boundaries, as suggested by DE VRIES et al., (2013).

The conceptual model also emphasizes the crucial role of political decisions and institutional forcefulness in providing and implementing appropriate mechanisms to deal with the impacts and risks associated with nitrogen emissions. Such mechanisms are related to the **policy responses** designed to appropriately deal with the whole ‘benefits versus costs’ situation of nitrogen use (orange arrows) and are causally linked to the actors. Some examples are the technological and behavioral measures for sustainable agricultural practices, soil and land management, nitrogen use efficiency, biological nitrogen fixation, water use efficiency, waste management, among many others. These policy responses for nitrogen management will guide the actors' actions and reactions by influencing their choices to engage in sustainable (or unsustainable) productive activities. The justification of governmental policies is to decrease emissions to levels at which negative impacts and risks do not outweigh the benefits (MOSIER et al., 2001). In other words, the ultimate objective of policies and measures is maximizing the efficiency of nitrogen use, while limiting its adverse impacts on human health and environment. General solutions, however, could be particularly challenging because $N_r$ generates profits and costs on multiple scales, from local to global, and there are countless interlinks between these scales (SUTTON et al., 2019a).

### 4.2.3 Application of the conceptual model in the agriculture sector

In this section, the agriculture sector is used as an example to fill the conceptual framework for nitrogen emissions drivers in Brazil. According to Figure 4.2, **sources** of emissions are related to the production of agricultural commodities by industrial farmers and small-to-medium-scale family farmers (often organized into cooperatives or associations) (ARIAS et al., 2017), which are the **actors**. The improvement of crop and pasture productivity depends heavily on the use of synthetic N-fertilizers; however, the inefficient use of fertilizers can lead to **$N_r$ emissions**, especially nitrous oxide ($N_2O$), ammonia ($NH_3$), and nitrate ($NO_3^-$). The **impacts and risks** include the $N_2O$ and $NH_3$ emissions from soil to air, and $NO_3^-$ soil accumulation and leaching to water bodies, causing air, soil, and water pollution, GHG emissions, and health problems (respiratory diseases, for instance).

Figure 4.2 – Conceptual framework applied to the agriculture sector.




Source: Prepared by the author.

**Demand drivers** are characterized by high demand for food (to attend domestic consumption and exports) and energy (through crops plantations for biofuels production). They are the main actor´s motivations, which are driven by a growing population in Brazil and in China, the largest commodities importer (FAOSTAT, 2020). Other aspect that has favored export performance is the Brazilian currency (Real) devaluation against dollar (USTINOVA; WOODY, 2020). The central challenge is the **structural drivers**, since Brazil has historically scored medium to low governance indicators (KAUFMANN; KRAAY, 2022) and that can undermine the government´s ability to provide an effective policy system. In addition, the government elected for the 2019-2022 period raised doubts about the continuity of environmental protection policies and science and technology investments, whose interruption had the potential to bring unpredictable consequences in the short and long terms, in economic, social, and environmental terms (ESCOBAR, 2019; NOBRE, 2019; PEREIRA et al., 2019; TOLLEFSON, 2019).

Two examples are listed as **policy responses**: (i) specifications for fertilizers production, packaging and labelling, and (ii) the institution of the Brazilian Plan for Low Carbon Emission in Agriculture (ABC Plan), which is a credit initiative that provides low-interest loans to farmers who want to implement a set of sustainable agriculture practices, including biological nitrogen fixation (BNF). The policy for fertilizers specifications regulates only the production processes, but do not present instructions or stablish limits for utilization. It can be classified as a commerce policy, intended only to implement regulations of nitrogen commercial and trade activities (KANTER et al., 2020b). Hence, such policy is useless concerning nitrogen use efficiency and emissions control. In relation to the ABC Plan, the first technical report informed that almost 10 million hectares were cultivated using BNF from 2010 to 2016, corresponding to 181% of reaching the proposed target for the period (MAPA, 2018). It is important to mention that the ABC Plan´s goal is to increase farm productivity on existing agricultural land as a strategy to constrain cultivation expansion over forests (WEST; FEARNSIDE, 2021). However, the Global Forest Resources Assessment has repeatedly pointed to Brazil as the country that reported the greatest forest loss, and consequent conversion of deforested areas to agriculture (FAO, 2016, 2020). This land-use change may jeopardize the potential positive results from the ABC Plan by increasing GHG emissions directly through deforestation and nitrogen compounds later through the agricultural sector, whose production intensification (soy, sugarcane, and maize, for example) requires a more intense fertilizer utilization (LAPOLA et al., 2013; MARTINELLI et al., 2010). In fact, the consumption of synthetic N-fertilizers in Brazil has been growing dramatically over the years, as seen in Figure 3.5 (Section 3.3.2). These examples of policies in Brazil highlight the importance of integrated approaches for sustainable nitrogen management (OENEMA et al., 2011a). Some other potential action towards integrating management approaches would be to institute mechanisms to restrain illegal land grabbing, improve land tenure system, promote proper policies to regulate fertilizers utilization, and enforce investments in BNF research and implementation strategy.

The agricultural sector is of key importance for the economy of the whole country, accounting for about 24% of Brazil´s Gross Domestic Product (GDP) (CASTRO, 2019). It is also the country's main source of $N_r$ emissions (see Figure 3.4, Section 3.3.2). Although some argue that agriculture productivity can continue to grow in Brazil without depleting natural resources nor further increasing emissions (ARIAS et al., 2017; STABILE et al., 2020), things seemed to be heading in the opposite direction due to a series of changes to Brazilian environmental policies, bringing both environmental and economic consequences (ARRUDA; CANDIDO; FONSECA, 2019; RAJÃO et al., 2020).

Even though population growth can be correlated with the increase of nitrogen emissions (GALLOWAY; LEVY; KASIBHATLA, 1994; SMIL, 1997), the conceptual model suggests that the structural drivers (political and institutional factors) play an underlying role in influencing $N_r$ emissions and their impacts and risks. That is, the structural drivers in Brazil shape the effect of other factors (demographic trends, economic features, laws, enforcement, etc.) without being explicit itself. In consequence, whether population pressure is considered the definitive cause of the enhancement of emissions, it may induce to misguided policy interventions, assuming that demographic trends and human development are also influenced by government institutions and their governance condition. Therefore, the example of Brazil shows that the increase in $N_r$ emissions is due to demand drivers, while preparing and implementing a successful response to solve the nitrogen pollution problem depends entirely on the structural drivers (more specifically good governance and regulatory quality).

### 4.3 Conclusions

Anthropogenic nitrogen emissions in Brazil come mainly from the expansion of N-fertilizer utilization to attend the high demand and trade of agricultural commodities and biofuels production, intense biomass burning to clear land for agriculture, rising consumption of fossil fuels and other oil-based products by the industrial and transport sectors, and uncontrolled urban sprawls leading to sewage and sanitation issues.

The driving forces behind these actions are the productive activities carried out to meet the high demands for food, energy, and housing by a fast-growing population. Although changes in the population´s dietary patterns can be an effective measure not only to curb $N_r$ emissions, but also GHG emissions (LASSALETTA et al., 2016; WESTHOEK et al., 2015), these results show that solely aiming at population issues may lead to an ineffective policy mechanism, because the diagnosis might be incomplete. The main outcome of the conceptual framework (and its application to the Brazilian agriculture sector) is that the structural drivers play an underlying role both in the $N_r$ emissions (through perverse incentives) and in the formulation and effectiveness of measures to solve the problem.

Poor governance and weak political institutions in Brazil pose a challenge to the sustainable nitrogen management, significantly impacting on the development and the attainment of the public policies objectives in many spheres. Additionally, the country has recently been facing economic and political turmoil

(IMF, 2016; WORLD BANK, 2019) and a crisis spread across several areas, including environmental conservation, indigenous peoples' rights, public health, public security, freedom of expression, among many others (HUMAN RIGHTS WATCH, 2021; MAGNUSSON et al., 2018), which worsen an already complex circumstance. Designing and implementing mechanisms to curb excess nitrogen losses requires governmental and institutional capabilities, and evidences show that this would be a tremendous challenge for Brazil.

The number of policy instruments specifically focused on nitrogen is limited worldwide, in contrast with the huge diversity in $N_r$ sources and pathways. Even though many governmental measures aimed at decreasing $N_r$ emissions have been developed in Europe, many of these policies are usually centered on individual compounds from specific sectors, rather than an integrated approach where the focus is not only on abating emissions but on the nitrogen cycle and its intertwined nature with human dimensions and societal demands (OENEMA et al., 2011b). Moreover, many agricultural policies (especially in the developing countries) support the production and consumption of nitrogen (commerce and pro-N policies), reinforcing the importance of food production over environmental protection (KANTER et al., 2020b). In this way, raising public and institutional awareness of nitrogen issues has the potential to provide an essential basis to develop concrete actions and increase the efficacy of future integrated nitrogen policies (REAY et al., 2011).

At large, Brazil has reported general measures and mechanisms to deal with nitrogen in their National Communications to the United Nations Framework Convention for Climate Change (UNFCCC, 2018), but essentially as a greenhouse gas ($N_2O$). Focus is on lower concentrations on specific bodies (air, water, soil) to below critical levels based on regulatory references from international agencies, like the World Health Organization (WHO). Thus, theoretical and empirical bases of policy measures related to $N_r$ emissions are still small or inexistent, even for Europe and North America (OENEMA et al., 2011b). On the bright side, even though instruments to integrate the measures and contemplate the complex dynamics of the nitrogen cycle are not yet implemented or fully available, global actions are emerging to mobilize potential solutions for nitrogen pollution, as the *Guidance Document on Integrated Sustainable Nitrogen Management* (UN, 2021) and the *National Nitrogen Target for Germany* (GEUPEL et al., 2021).

In this sense, the application of the conceptual framework by individual countries may assist policy-makers in determining each of the aspects that culminate in the consequences of unsustainable nitrogen use, that is, precisely identifying the actors, what are the main productive activities, which demand and structural drivers most influence the behavior of the actors, whether there are any policy instruments available, and so forth. As a result, the model output may provide more complete and detailed information that enable faster and more effective responses towards sustainable nitrogen practices.

# 5 NITROGEN SUSTAINABILITY IN BRAZIL[8]

In this chapter, we address the research question number two of the thesis: "*How sustainable is the nitrogen management in Brazil?",* raised in Section 2.1. For that, we conduct an assessment of nitrogen sustainability in Brazil from 2000 to 2018 applying the Entropy Weight Method (EWM) to a set of nitrogen-related indicators within four subsystems: environmental, economic, social, and institutional. The EWM is an objective and unbiased weighting method, based on the entropy coefficient expressed in a series of statistical steps, that determines the weight of each indicator according to the information provided by themselves and, therefore, avoids negative influences of subjective factors. Our research objectives are to determine an overall Nitrogen Sustainability Index and discuss the relevance of indicators linked to the main anthropogenic sources of nitrogen pollution. By our analysis, the following indicators play a key role in determining nitrogen sustainability levels in the country: political stability, fertilizer consumption, population growth, and investments in water and sanitation. Our findings suggest that political and institutional concerns are greatly impacting sustainable actions towards nitrogen management, leading Brazil to reach only a weak-to-basic level of sustainability in the studied period. We highlight that neglecting the problems caused by the unsustainable nitrogen management can increase environmental, economic, and social issues, and jeopardize the achievement of the Sustainable Development Goals.

## 5.1 Nitrogen and the sustainable development goals

A society is considered sustainable when human and environmental conditions are satisfactory or continuously improving, that is, when there is a harmonious and balanced relationship between human beings and the environment without compromising the development of future generations (UNITED NATIONS, 2015a). Following this guideline, the United Nations member countries adopted

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[8] This chapter is an adapted version of the paper: CUNHA-ZERI, GISLEINE; GUIDOLINI, JANAINA F.; BRANCO, EVANDRO A.; OMETTO, JEAN. ***How sustainable is the nitrogen management in Brazil? A sustainability assessment using the Entropy Weight Method.*** JOURNAL OF ENVIRONMENTAL MANAGEMENT, v. 316, p. 115330, 2022. https://doi.org/10.1016/j.jenvman.2022.115330

the 2030 Agenda for Sustainable Development in September 2015 (UNITED NATIONS, 2015b), which includes the Sustainable Development Goals (SDGs). The SDGs are seventeen interlinked and multidisciplinary goals and 169 targets that aim to steer the world towards a sustainable and resilient path and are balanced on the three pillars of sustainable development: economic, social, and environmental (UNITED NATIONS, 2015a).

Considering the anthropogenic disturbance in the global nitrogen cycle (GALLOWAY, 1998; GALLOWAY et al., 2008), which is causing multiple forms of pollution and impacts from local to global scales (SUTTON et al., 2019a), it is vital to explore options for better use of nitrogen in line with the SDGs. The sustainability of nitrogen management depends on balancing the 'benefits *versus* costs' situation of its use, that is, optimizing the beneficial effects and, at the same time, neutralizing or reducing the negative impacts of excess reactive nitrogen ($N_r$) on the environment and human health (LEIP et al., 2014; MOSIER et al., 2001; ZHANG et al., 2015).

Although not expressly mentioned in any SDGs, which may be the result of scientific and political fragmentation in relation to $N_r$ (KANTER; ZHANG; HOWARD, 2016; SUTTON et al., 2019b), nitrogen is extremely relevant to many sustainability indicators. Sustainable nitrogen management has the potential to **directly** contribute to achieve the following SDGs, as stressed in Figure 5.1 (including a brief description and strength of these relations): SDG-2 (zero hunger), SDG-3 (good health and well-being), SGD-6 (clean water and sanitation), SDG-7 (affordable and clean energy), SDG-9 (industry, innovation and infrastructure), SDG-11 (sustainable cities and communities), SGD-12 (responsible consumption and production), SDG-13 (climate action), SDG-14 (life below water), and SDG-15 (life on land). The role of nitrogen varies significantly, between excess and scarcity, making it **indirectly** relevant to other SDGs: SDG-1 (no poverty), SDG-4 (quality education), SDG-5 (gender equality), SDG-8 (decent work and economic growth), SDG-10 (reduced inequalities), SDG-16 (peace, justice, and strong institutions), and SDG-17 (partnerships for the goals).

The relevance of the nitrogen within the perspectives of the SDGs reinforces the need to develop an integrated approach to improve the efficiency of nitrogen use. Examples include technological innovations, socioeconomic concerns, political interventions, and behavioral changes, which would affect the nitrogen cycle and, consequently, the production and consumption of food and energy (ABROL et al., 2012; OENEMA, 2019; SUTTON et al., 2013).

Figure 5.1 – Sustainable nitrogen management and the SDGs.


Relationship between sustainable nitrogen management and the Sustainable Development Goals (SDGs).
Source: Prepared by the author.

Anthropogenic nitrogen emissions have been rising sharply over the past five decades in Brazil, mostly from the agriculture and energy sectors (DE AZEVEDO et al., 2018), which are related to the advance of country´s economic activity (MCTIC, 2017, 2020). In consequence, the 2022 Sustainable Global Rank launched by the Sustainable Development Solutions Network (SDSN) pointed out that Brazil´s overall performance ranked 72.8 (best 100), placing the country in the 53$^{rd}$ position of 163 (SACHS et al., 2022). This low score indicates that the country may face significant challenges in achieving sustainable nitrogen use, which consequently may also affect the achievement of the SDGs.

In this context, the goal of this study is to assess the condition of nitrogen sustainability in Brazil, over almost two decades (2000–2018), considering the main sources of nitrogen pollution linked to the agriculture and energy sectors. For this, we estimate the relevance of each nitrogen-related indicator in each of the four subsystems (environmental, economic, social, institutional), as well as the weight of each subsystem in the global outcome, that is, the Nitrogen Sustainability Index. The significance of this study is to support governments, policy-makers, and civil society organizations to develop sustainable nitrogen roadmaps to halve nitrogen waste by 2030, as outlined in the Colombo Declaration on Sustainable Nitrogen Management (UNEP, 2019a, 2019b) in implementing the United National Environment Assembly (UNEA) resolution on Sustainable Nitrogen Management (UNEP, 2019c).

## 5.2 Material and methods

### 5.2.1 Indicators selection

The construction of the database for this study followed objective criteria, guided by the OECD (2008), considering the availability of data for the same period for all indicators and, more importantly, according to a theoretical framework based on sustainable nitrogen management (UNECE, 2021). Indicators are grouped into four subsystems – environmental, economic, social, institutional – considering the main dimensions that represent the pillar of sustainability and allowing their analysis in an integrated manner (UNCSD, 2001). As described in Table 5.1, we compiled secondary data for thirty-one indicators at the national level for the period 2000-2018 from official sources (i.e., Food and Agriculture Organization, International Fertilizer Association, Climate Data Explores, SEEG-Brazil, Brazilian Institute of Geography and Statistics, International Energy Agency, The World Bank, National Traffic Department, and United Nations Development Programme).

The selection of indicators for each subsystem was based on the relationship between sustainable nitrogen management and the SDGs and connected with productive activities to meet people's demand for food, water, and housing, which are the main drivers of excess of $N_r$ emissions in Brazil, and their associated impacts and risks (CUNHA-ZERI; OMETTO, 2021). For instance, the environmental subsystem includes agricultural information (land used for cultivation and fertilizer consumption), GHG emissions, and $N_r$ emissions. Hence the goals that most relate to these activities are SDG-2 (NUE for agricultural production) and SGD-13 (reduction of $N_r$ emissions to mitigate climate change). In the economic subsystem, SDG-7 (clean energy production to reduce N-footprint) and SDG-12 (changing consumption patterns to decrease N pollution) are more often related to the indicators selected. SDG-3 (nitrogen pollution control for health improvement) and SDG-10 (equitable access to ecosystem services) are linked with many indicators in the social subsystem. Finally, all indicators in the institutional subsystems are related to SDG-13 (sustainability and climate actions through emission reduction), SDG-16 (global cooperation to tackle nitrogen challenges) and SDG-17 (encouraging partnerships through an international nitrogen convention). Other N-related SDGs connected with each selected indicator are shown in the third column of Table 5.1.

Table 5.1 – List of indicators, N-related SDGs, and desirable trends.

| INDICATORS | | N-related SDGs | Desirable trends |
|---|---|---|---|
| | **ENVIRONMENTAL SUBSYSTEM** | | |
| AG-L | Agricultural land (1000 ha) | 2, 15 | - |
| FERT | Fertilizer consumption (1000 tonnes) | 2, 4, 13, 15 | - |
| GHG-AG | GHG emissions (except $N_2O$) – Agriculture sector (Mt CO2e) | 2, 13 | - |
| GHG-EN | GHG emissions (except $N_2O$) – Energy sector (Mt CO2e) | 7, 13 | - |
| N2O | Nitrous oxide ($N_2O$) emissions (all sectors) (Ton) | 2, 3, 6, 13 | - |
| NOx | Nitrogen oxides ($NO_x$) emissions (all sectors) (Ton) | 3, 7, 9, 11 | - |
| | **ECONOMIC SUBSYSTEM** | | |
| AG-GDP | Agriculture sector contribution to GDP (annual %) | 1, 2 | - |
| ENC | Energy consumption (kiloton of oil equivalent) | 7, 12 | - |
| ENS-F | Energy supply – fossil fuels (kiloton of oil equivalent) | 7, 12, 13 | - |
| ENS-R | Energy supply – renewables (kiloton of oil equivalent) | 7, 12, 13 | + |
| EXP | Exports of goods and services (current USD) | 8, 9 | + |
| GDP | Gross Domestic Product (GDP) per capita (current USD) | 1, 10 | + |
| GINI | GINI index (index: 0 to 100) | 1, 10 | - |
| IND-GDP | Industry sector contribution to GDP (annual %) | 8, 9 | + |
| INV-EN | Investment in energy (current USD) | 7, 13 | + |
| INV-WS | Investment in water and sanitation (current USD) | 6, 14 | + |
| VEH | Vehicle fleet (units) | 7, 11, 13 | - |
| | **SOCIAL SUBSYSTEM** | | |
| AC-WS | Access to safely managed drinking water services (% population) | 3, 6, 10 | + |
| AC-EL | Access to electricity (% of population) | 7, 10 | + |
| AC-SS | Access to safely managed sanitation services (% population) | 3, 6, 10 | + |
| H-GDP | Health expenditure (% of GDP) | 3, 10 | + |
| HDI | Human Development Index (HDI) (index) | 4, 5, 10 | + |
| POP | Population growth (annual %) | 1, 3, 4, 6, 10, 12 | - |
| UNP | Unemployment rate (% of total labor force) | 8, 10 | - |
| U-POP | Urban population (% of total population) | 11, 12 | - |
| | **INSTITUTIONAL SUBSYSTEM** | | |
| CC | Control of corruption (estimates from -2.5 to 2.5) | 13, 16, 17 | + |
| GE | Government effectiveness (estimates from -2.5 to 2.5) | 13, 16, 17 | + |
| PS | Political stability (estimates from -2.5 to 2.5) | 13, 16, 17 | + |
| RQ | Regulatory quality (estimates from -2.5 to 2.5) | 13, 16, 17 | + |
| RL | Rule of law (estimates from -2.5 to 2.5) | 13, 16, 17 | + |
| VA | Voice and accountability (estimates from -2.5 to 2.5) | 13, 16, 17 | + |

Source: Prepared by the author.

The fourth column of Table 5.1 shows "desirable trends", which mean the probability of a given indicator achieving (or not achieving) sustainability. For example, the positive trend (+) of the indicator '*energy supply – renewables'* implies that the more energy produced by renewable sources, the greater its contribution to the total energy supply, and the lower the emission of $NO_x$ (and other pollutants) from the burning of fossil fuels. Consequently, a positive trend is a way to achieve sustainability when it is on an upward trend, otherwise it compromises the level of sustainability (the higher the better; the lower the worse). A negative trend (-) represents exactly the opposite (i.e., the indicator '*energy supply – fossil fuels*'), that is, the higher the worse; the lower the better.

### 5.2.2 The entropy weight method

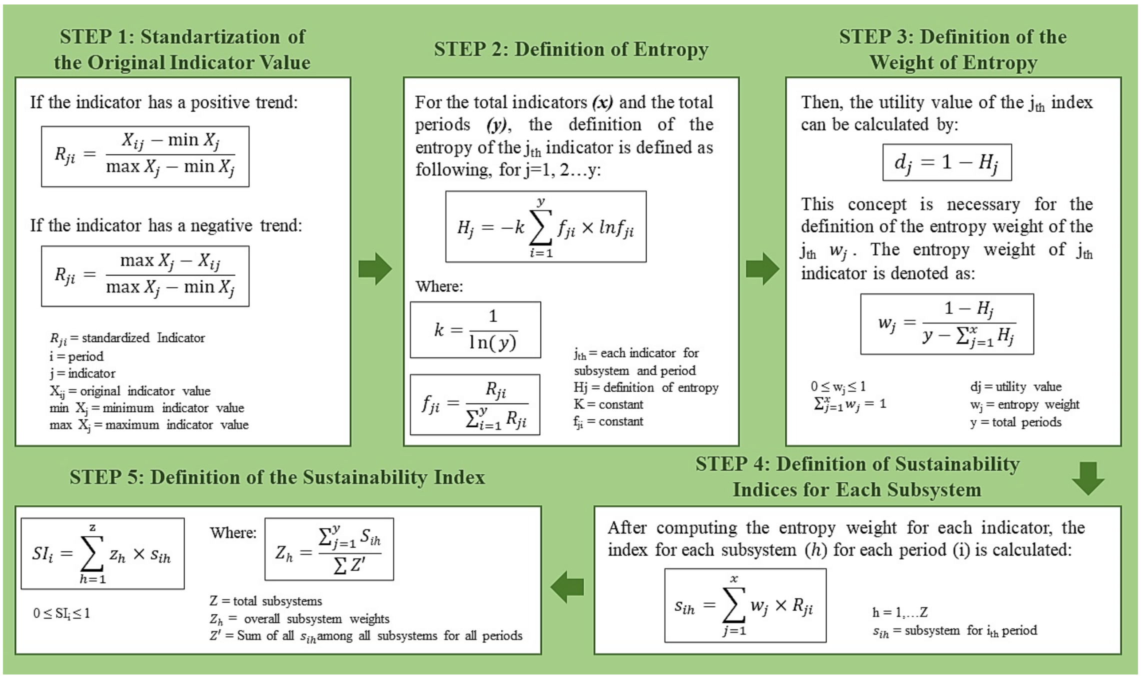
Entropy is a concept of thermodynamics that is associated with a state of disorder, randomness, or uncertainty of a system; therefore, a minimum production of entropy can be the sustainability benchmark (ADDISCOTT, 1995). Indeed, based on the Georgescu-Roegen (1971) principles, we use low entropy energy and matter from the surrounding natural environment (i.e., soil, reactive nitrogen, etc.) to produce consumption goods (i.e., crops, plants, etc.), and later discards high entropy wastes and dissipated heat back into the environment (nitrous oxide, ammonia, nitrate, etc.).

In this way, considering the inherent complexity of assessing sustainability, which requires integrating all dimensions (environmental, economic, social, institutional) and their respective indicators in a tangible manner (MUNDA, 2005), the objectivity of the Entropy Weight Method (EWM) makes it suitable for sustainability analysis by generating more realistic results. The EWM is an unbiased weighting method, based on entropy coefficient developed by Shannon (1948), which is expressed in a series of statistical steps (see Figure 5.2) to determine the weight of indicators according to the information provided by themselves and, therefore, avoiding negative influences of subjective factors and resulting in more applicable findings. That is, the lower the entropy is, the more information an indicator provides, and the higher the weight of that indicator. Thus, the EWM can avert the subjectivity of weight setting, being an objective alternative in comparison with other methods (as the Analytic Hierarchy Process and the Additive Ratio Assessment, for instance). Therefore, the EWM has been extensively and successfully applied in many environmental and sustainability studies, such as overall sustainability of countries (TOUMI; LE GALLO; BEN REJEB, 2017), transportation development system (LI; ZHAO; SUO, 2014), soil fertility (SU; ZHU, 2012), water quality (LIU et al., 2010; SAHOO et al., 2017), basic sanitation systems (GUIDOLINI et al., 2020), natural disasters (YE et al., 2011), forest ecological security (LU et al., 2020), evaluation of ecological environmental performance (CAO; BIAN, 2021), emissions rights for particulate matter (GUO et al., 2021), and environmental vulnerability (ZHANG et al., 2014; ZHAO et al., 2018).

On the other hand, the results presented in this assessment are restricted to its methodology, meaning that generalizations to different periods and to other work scales are not possible. Furthermore, in order to carry out spatio-temporal analyzes based on this study, it is necessary to use the same system of indicators for a national scale and time period for all indicators. Another shortcoming is that the relevance of an indicator cannot be determined solely on account of its weight, thus, to overcome this limitation, we contextualize and analyze each result based on a literature review on nitrogen emissions in Brazil.

The methodological steps for calculating the nitrogen sustainability in Brazil using the EWM are the following: (i) *standardization of the original indicator value* – due to the differences among the indicators in subsystems, measures, and potential effects on sustainability, as well as the positive and negative trends; (ii) *definition of entropy* – for the total of indicators and periods ($j_{th}$ indicator); (iii) *definition of the weight of entropy* – by computing the utility of the $j_{th}$ indicator and then determine its entropy weight; (iv) *definition of sustainability indices for each subsystem* – after calculating the entropy weight for each indicator, the sustainability index of each subsystem (environmental, economic, social, institutional) is determined; (v) *definition of the sustainability index* – definition of an overall sustainability level per year, that is, the sustainability index (SI). The flowchart (Figure 5.2) displays the sequence of steps and equations performed to calculate the Nitrogen Sustainability Index.

Figure 5.2 – Methodological steps of Entropy Weight Method (EWM).




Methodological steps to calculate the nitrogen sustainability in Brazil using the EWM. Source: Adapted from Guidolini et al. (2020).

The dataset for this assessment, including data description, data sources, references, and all calculations using the EWM, among other information, can be accessed at: https://data.mendeley.com/datasets/k5vxsz5rsf/2 (CUNHA-ZERI et al., 2021).

## 5.3 Results and discussion

The set of these four subsystems are important to reflect sustainability through social improvement, institutional strengthening, economic prosperity, and the maintenance of environmental integrity. The application of the EWM enables the identification of the weight of each indicator and the weight of each subsystem (Table 5.2), which serves to determine the relative importance of the indicator and for a better understanding of the different levels of impact on the outcome.

Table 5.2 – Weight of subsystems and weight of indicators for each subsystem (ranked from highest to lowest weight) and desirable trends.

| Weight of INSTITUTIONAL subsystem: 0.3259 | | | |
|---|---|---|---|
| PS | Political stability | 0.3223 | + |
| CC | Control of corruption | 0.2332 | + |
| RQ | Regulatory quality | 0.1771 | + |
| GE | Government effectiveness | 0.1338 | + |
| RL | Rule of Law | 0.1175 | + |
| VA | Voice and accountability | 0.0162 | + |
| **Weight of ENVIRONMENTAL subsystem: 0.2518** | | | |
| FERT | Fertilizer consumption | 0.4768 | - |
| GHG-EN | GHG emissions – energy | 0.2554 | - |
| NOx | NOx emissions | 0.1229 | - |
| N2O | N2O emissions | 0.0929 | - |
| GHG-AG | GHG emissions – agriculture | 0.0478 | - |
| AG-L | Agricultural land | 0.0042 | - |
| **Weight of SOCIAL subsystem: 0.2455** | | | |
| POP | Population growth | 0.3897 | - |
| UNP | Unemployment rate | 0.3704 | - |
| AC-SS | Access to sanitation services | 0.1176 | + |
| H-GDP | Health expenditure | 0.0750 | + |
| AC-WS | Access to drinking water | 0.0210 | + |
| U-POP | Urban population | 0.0101 | - |
| HDI | Human Development Index | 0.0100 | + |
| AC-EL | Access to electricity | 0.0063 | + |
| **Weight of ECONOMIC subsystem: 0.1768** | | | |
| INV-WS | Investment in water & sanitation | 0.4337 | + |
| INV-EN | Investment in energy | 0.1561 | + |
| GINI | GINI | 0.1026 | - |
| EXP | Exports of goods and services | 0.0942 | + |
| VEH | Vehicle fleet | 0.0900 | - |
| ENS-R | Energy supply (renewables) | 0.0337 | + |
| ENC | Energy consumption | 0.0329 | - |
| AG-GDP | Agriculture contribution to GDP | 0.0247 | - |
| ENS-F | Energy supply (fossil fuels) | 0.0180 | - |
| IND-GDP | Industry contribution to GDP | 0.0137 | + |
| GDP | GDP per capita | 0.0004 | + |

Source: Prepared by the author.

Following the methodology, the next step after calculating the weights of indicators and weights of subsystems is to determine the sustainability index of each subsystem and, finally, compute the overall sustainability index. These resulting indices express the situation and trends of nitrogen sustainability in Brazil over the years, which can be evaluated through the five levels of sustainability defined by Prescott-Allen (1996, 2001), included at the bottom of

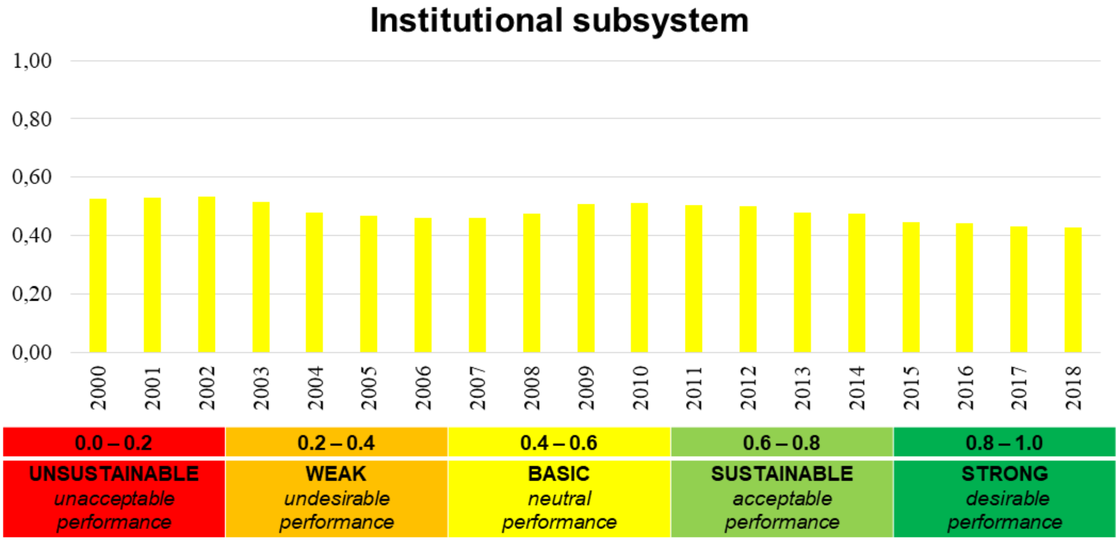
Figures 5.3 to 5.7. The results of applying the EWM for each subsystem are discussed separately in the next subsections, finalizing with the overall result of nitrogen sustainability. The order of presentation of the subsystems is according to their weight resulting from the application of the method.

### 5.3.1 Institutional subsystem

The institutional subsystem is intended to measure the quality of both institutional framework (legal and policy instruments) and institutional capacity (human, scientific, technological, organizational, and resource capabilities), both of which encourage and support sustainable development (UNCSD, 2001). Therefore, good governance is a key theme within this subsystem, since it is an essential condition for social stability, security, peace, human rights, and long-term sustainable development. Our analysis is based on the World Bank six dimensions of governance (KAUFMANN; KRAAY, 2022; WORLD BANK, 2021a), as described in Table 5.1. The sustainability levels of this dimension can be visualized in Figure 5.3, noting that it reached only the basic level over the period 2000 to 2018.

Our results point out that *political stability* has the greatest weight within this subsystem, but although its desirable trend is positive (the higher the better), the data follow a very unfavorable downward trajectory. The effect of political instability and poor governance on environmental degradation has long been observed (BARRETT et al., 2001; DIDIA, 1997; SMITH et al., 2003), implying that institutional constraints affect the government´s ability to efficiently design and implement sustainability and climate actions (SDG-13). Regrettably, Brazil has been presenting medium-to-low scores of governance indicators over the years, including low level of political stability (KAUFMANN; KRAAY, 2022), which may jeopardize the efforts aimed at promoting inclusive societies and institutions, as well as global cooperation (SDG-16) and partnerships (SDG-17), which are vital for building effective actions to address widespread nitrogen issues.

Figure 5.3 – The sustainability levels of the institutional subsystem.



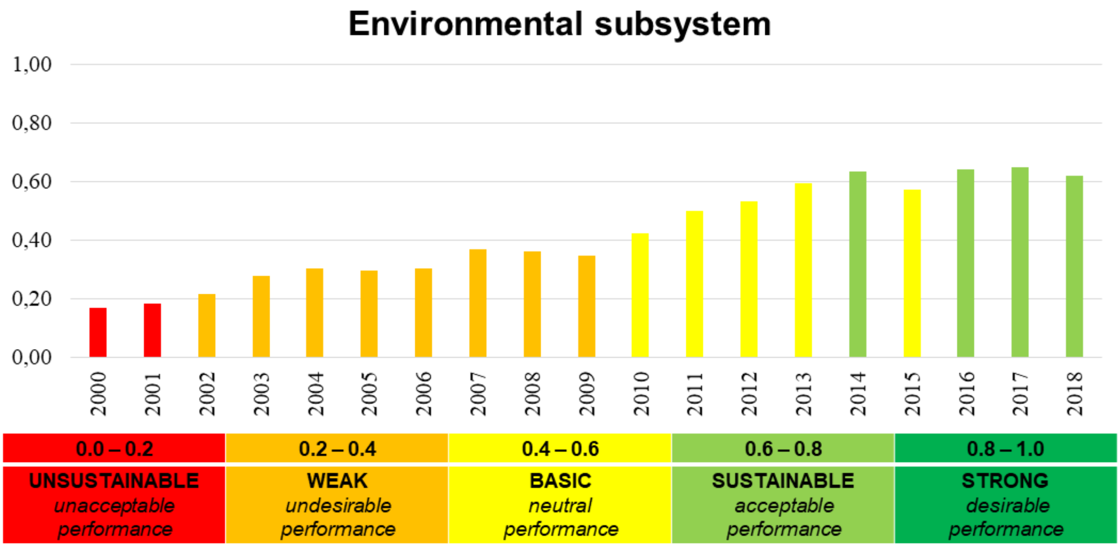

The sustainability levels of the institutional subsystem showed basic performance throughout the period from 2000 to 2018.
Source: Prepared by the author.

The former Brazilian government (2019-2022) discontinued several biodiversity monitoring and conservation programmes, in addition to the dismantling of environmental institutions, and imposed deep cuts in science and technology funding, compromising local and global sustainability and climate actions (BARBOSA; ALVES; GRELLE, 2021). Instability of political and institutional systems can have disastrous and long-lasting economic, social, and environmental consequences (MAGNUSSON et al., 2018), including lowering the overall level of nitrogen sustainability in the country.

### 5.3.2 Environmental subsystem

The environmental dimension measures how a set of indicators can impact the atmosphere, land, water, and biodiversity, which could be long-term, regional or global, and irreversible for future generations, with important consequences to the economic and social dimensions (UNCSD, 2001). The levels of sustainability of the environmental subsystem have varied over the years, going from unsustainable in the early 2000s to sustainable from 2014 onwards (Figure 5.4). However, it is necessary to observe whether this sustainability trend will continue in the coming years, especially given the persistent occurrences of fire and deforestation in Brazil´s forests and wetlands (MEGA, 2020; SILVA et al., 2021), causing ecosystems stress and higher emissions (GATTI et al., 2021).

Figure 5.4 – The sustainability levels of the environmental subsystem.




The sustainability levels of the environmental subsystem ranged from unsustainable in 2000 and 2001 to sustainable in 2014 and 2016–2018, with weak and basic performances in between.
Source: Prepared by the author.

The results pointed out that *fertilizer consumption* is of great relevance for sustainable nitrogen management in Brazil, since this indicator has a negative trend towards sustainability (the lower the better) but is presenting an opposite direction. Agriculture is a key economic sector in the country, indicating that the already high demand for N-fertilizers may continue to grow, in order to attend both domestic consumption and exports of agricultural commodities and biofuels (OECD/FAO, 2019). Besides that, current agricultural policies tend to encourage the use of nitrogen to sustain food production at the expense of preserving the environment (KANTER et al., 2020b). The intense expansion of croplands and livestock [(which can also excrete $N_r$ into the soil (OENEMA, 2006)] associated with massive growth of fertilizer application is among the most impactful human actions in the global nitrogen cycle (WANG et al., 2017), especially when fertilizer application exceeds plant uptake, leading to an exponential increase in $N_2O$ emissions (HAN; WALTER; DRINKWATER, 2017) (SDGs 13 and 15).

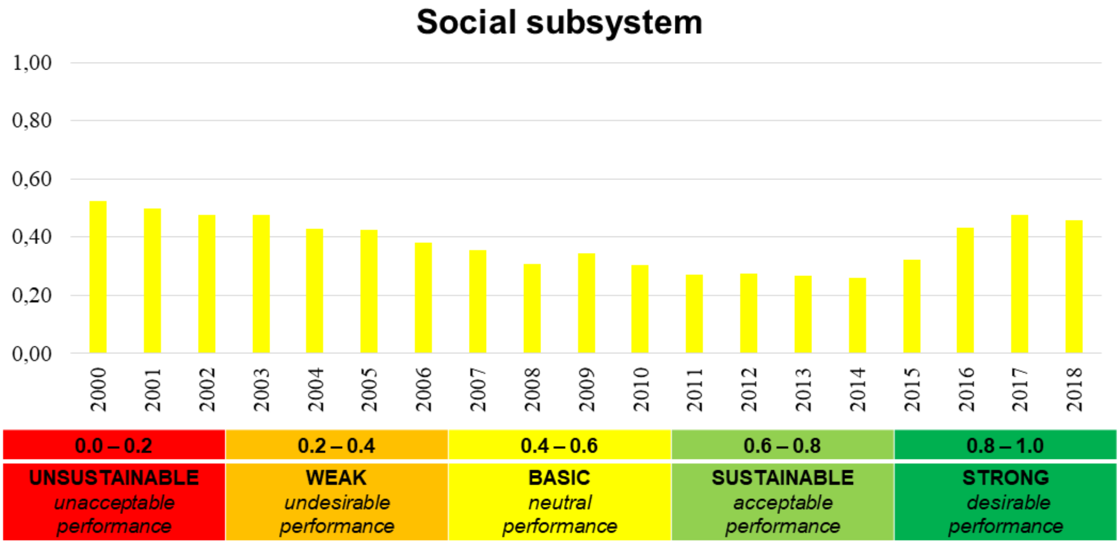
For those reasons, the concept of Nitrogen Use Efficiency (NUE), which consists of the relationship between agricultural productivity and the amount of nitrogen available in the soil or applied to it (MOLL; KAMPRATH; JACKSON, 1982), is of foremost importance to boost sustainable agriculture in Brazil (SDG-2). Unfortunately, NUE is very uneven within the country: while some regions present good NUE values, most of the agricultural areas have poor performance (TÔSTO et al., 2019). In addition to this, the analysis conducted by Pires et al. (2015) shows that in recent years there has been a massive decrease in NUE directly related to the increase consumption of N-fertilizers. These findings reinforce the importance of fertilizer consumption (and its efficient use) in the level of nitrogen sustainability in Brazil.

Considering that NUE is a tool accepted worldwide, it has been suggested as an indicator to assess progress towards the SDGs (SDSN, 2015; ZHANG; DAVIDSON, 2019). Different approaches have been proposed to encourage NUE and support agricultural policy development all around the world (ERISMAN et al., 2018; HUTCHINGS et al., 2020; SHARMA; BALI, 2017). In Brazil, a good start would be a strategic communication policy to raise awareness and educate farmers not only about better fertilizer management practices, but especially about the relationship between their activity and nitrogen pollution (SDG-4).

### 5.3.3 Social subsystem

The social subsystem indicators are related to key themes as population, equity, health, education, and access to basic public services (UNCSD, 2001). The sustainability levels of the social dimension are depicted in Figure 5.5. Regarding the weight of the indicators, the results show that *population growth* deserves special attention to assess nitrogen sustainability in Brazil. Population is an important benchmarking for sustainable development due to its interrelationship between people´s consumption needs and the pressure on the environment (UNCSD, 2001).

Figure 5.5 – The sustainability levels of the social subsystem.




The sustainability levels of the social subsystem showed basic performance throughout the period from 2000 to 2018.
Source: Prepared by the author.

The total population of Brazil is the largest in Latin America and an estimated 87% resided in urban areas in 2018, particularly concentrated in megacities as São Paulo, with more than 20 million inhabitants, and emerging megacities, like Rio de Janeiro (UN, 2019a). Updated projections show that the population of Brazil will increase by 7.7% from 212 million in 2020 to nearly 229 million in 2050 (UN, 2019a), and will have more than 90% of their population living in urban areas (UN, 2018b). Population migration from rural to urban areas is accompanied by a series of problems, such as poor living conditions, escalating violence and crime, social and political struggles, and environmental degradation (ANGOTTI, 2013). This process results in limited and uneven access to basic services – such as health care (SDG-3), education (SDG-4), and sanitation (SDG-6), among others – and to ecosystem services (drinking water, clean air, etc.) (SDG-10), thus begetting more poverty in a never-ending cycle (SGD-1).

Many authors correlate the increase in $N_r$ emissions with the high demand for food and energy by an expanding population (GALLOWAY et al., 2017; SMIL, 1997; VAN BEEK et al., 2010). An option to address this problem would be to change population´s dietary behavior (SDG-12) by decreasing consumption of animal products (meat, dairy, eggs) and adopting a more plant-based diet (AIKING; ERISMAN, 2021; SUTTON et al., 2013). Nevertheless, population pressure should not be considered the ultimate cause of rising $N_r$ emissions, since activities that results in nitrogen pollution are also influenced by political and institutional factors (CUNHA-ZERI; OMETTO, 2021).

Although total population in Brazil is expected to grow in the coming years (UN, 2019a), population growth rate has been decreasing in the last two decades (WORLD BANK, 2021b). Stable levels of fertility can lead to a positive impact on quality of life and, consequently, lower pressure on the environment (UNCSD, 2001). However, Brazil has been experiencing a profound social, economic, health, political, and institutional crisis in recent years (BURKI, 2021; VÉRAS DE OLIVEIRA, 2019), which can impair the country to consistently improving its sustainability levels.

### 5.3.4 Economic subsystem

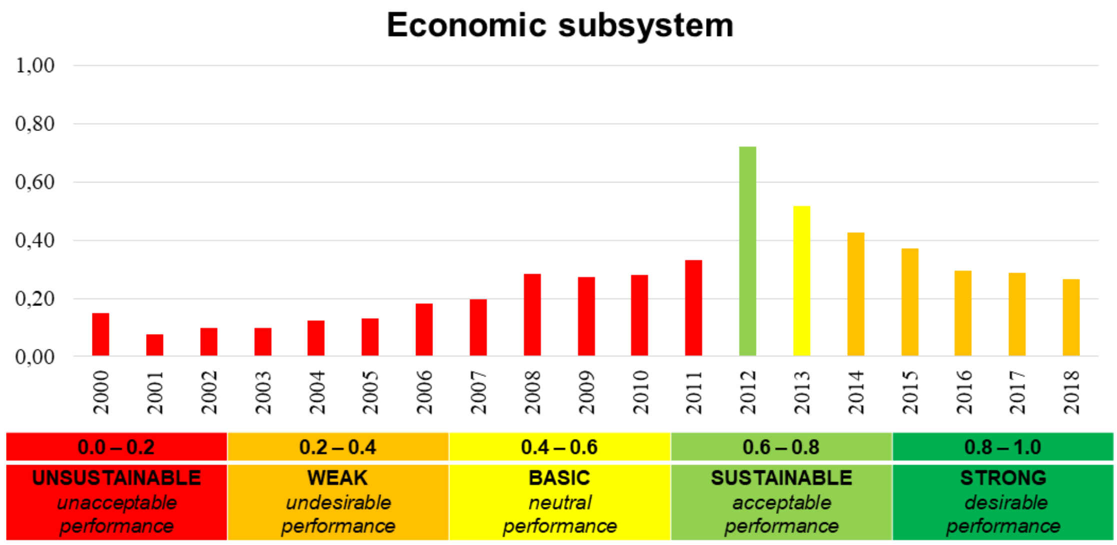
The economic subsystem indicators cover information related to the economic structure and performance, as well as the consumption and production patterns of a nation (UNCSD, 2001). The sustainability levels of the economic dimension shown in Figure 5.6 indicate that a decade of unsustainability was suddenly surpassed by a sustainable performance (in 2012, see below), which unfortunately did no hold up and fell to a weak level in the following years.

The results of the weight of the indicators reveal that *investment in water and sanitation* are the most relevant concerning nitrogen management in this dimension, representing a positive trend towards sustainability. Investment in water and sanitation refers to commitments to infrastructure projects to serve the public (WORLD BANK, 2021b). Such projects include the removal of contaminants from wastewater from domestic and industrial sewage and deliver an environmentally safe treated effluent (SDG-6).

The lack of basic infrastructure for sewage treatment and disposal systems leads to the release of waste in water bodies, affecting the quality of aquatic resources and water supply of an entire region (BUSTAMANTE et al., 2015)

(SDG-14). The discharge of untreated sewage into surface water results in serious problems related to nutrient enrichment (nitrogen and phosphorus), acidification, eutrophication, and loss of biodiversity, which bring environmental and human health concerns (VITOUSEK et al., 1997). In particular, the nitrogen enrichment can impact species affluence, while increasing other unwanted organisms more resistant to pollution (OMETTO et al., 2000), as well as cause alteration of the nitrogen cycle (MARTINELLI et al., 2006). These alterations not only provoke chemical changes in the composition of aquatic bodies, but also economic effects on the riverside dwellers who make their living from there (MARTINELLI et al., 1999).

Figure 5.6 – The sustainability levels of the economic subsystem.




The sustainability levels of the economic subsystem ranged from unsustainable (2000–2011) to sustainable (2012) but dropped to basic (2013) and weak (2014–2018) performances in subsequent years.

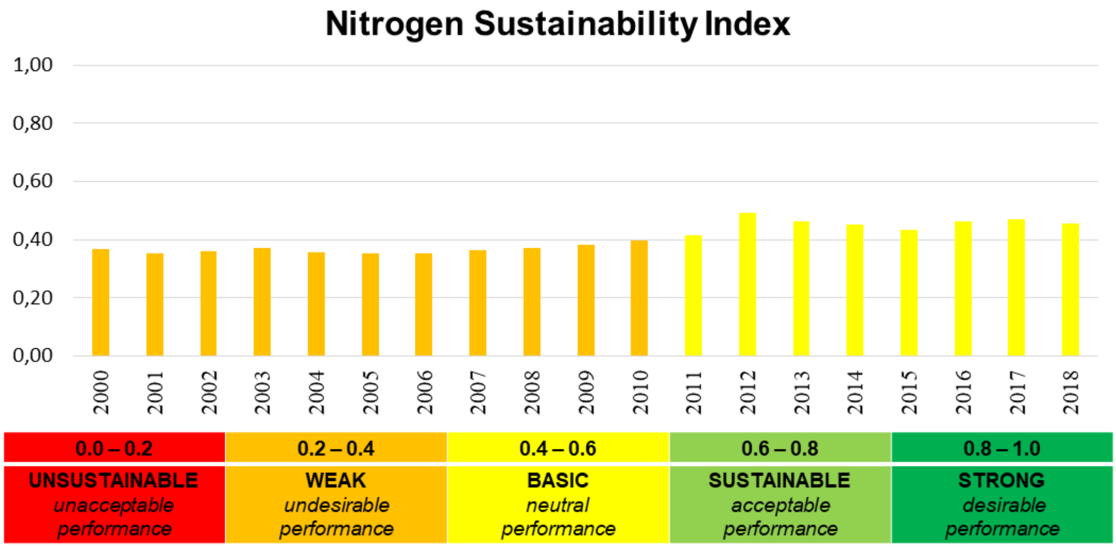
Source: Prepared by the author.

It is interesting to note that in 2012 there was a peak in investments in water and sanitation in Brazil (almost 18.5 times the average for previous years since 2000), which was a very optimistic increment to infrastructure development, and also influenced the sustainability levels of the economic dimension (Figure 5.6). This increase in financial resources came from the Growth Acceleration Program (PAC, in portuguese), launched by the government in 2007 and expanded from 2011 to 2014, whose second phase aimed at economic growth in Brazil with investments in the areas of sanitation, housing, water resources, energy, and transport (JARDIM; SILVA, 2015; RODRIGUES; SANTOS; FARONI, 2018). However, after this huge increase in investment, the amount was considerably reduced in the following years, reaching the lowest value of the entire historical series in 2018 and affecting the overall nitrogen sustainability level. Nonetheless, this financial inflow was not enough to expand access in the country, since only 46.8% of its population was using safely managed sanitation services in 2018 (FAOSTAT, 2021).

### 5.3.5 Overall outcome of nitrogen sustainability

The weight of each indicator and the weight of each subsystem were statistically calculated through the application of the Entropy Weight Method to the four subsystems; thereafter, an overall Nitrogen Sustainability Index was determined with the aim of assessing the level of nitrogen sustainability in Brazil. The outcome shows a weak-to-basic performance for the period from 2000 to 2018 (Figure 5.7).

Figure 5.7 – The overall Nitrogen Sustainability Index.




The overall Nitrogen Sustainability Index ranged from weak (2000–2010) to basic (2011–2018) performance in the period.
Source: Prepared by the author.

Our results reveal that the institutional subsystem has the greater weight in the overall sustainability index. This suggests that political instability and institutional concerns are strongly impacting actions toward nitrogen management in Brazil. Poor governance restricts the ability of a government to implement measures in all dimensions (GÜNEY, 2017). Thus, answering the question “how sustainable is the nitrogen management in Brazil?“, the situation is as follows: the economic pressure to produce livestock products and agricultural commodities (SDG-2), in order to attend an intense domestic and international demand for food and animal protein (SDG-12), has led to intense land-use change (forest to pasture/farmland conversion) and enhancing fertilizer consumption, which result in increasing $N_r$ emissions (SDGs 13 and 15) and all their negative effects on human health and the environment (SDGs 3 and 14). Additionally, the lack of government commitment (SDGs 16 and 17) can impair investments in basic services to the population, such as health care (SDG-3), education (SDG-4), and sanitation infrastructure (SDG-6), reinforcing poverty (SDG-1) and inequality standards (SDG-10).

It should be noted that due to the stabilization of the sustainability levels after reaching its peak in 2012, it is not possible to state that the country is on a pathway to higher levels of sustainability in the coming years. Besides, in a post-pandemic scenario, economic and social inequalities may increase in countries that already present such a pattern, bringing a setback in the achievement of sustainability in several areas and dimensions (UNDP/UNICEF/UNESCO/PAHO, 2021).

## 5.4 Conclusions

The weak-to-basic level of sustainability of nitrogen management in Brazil has far-reaching and complex effects in environmental, social, and economic spheres, in addition to threatening efforts to achieve the Sustainable Development Goals (SDGs), as well as other international agreements, as the Paris Agreement Targets on Climate Change, and the Aichi Biodiversity Targets. The results present here draws out important institutional and political implications, that should be considered when developing sustainable nitrogen roadmaps to halve nitrogen waste by 2030, as defined by the 2019 Colombo Declaration on Sustainable Nitrogen Management. Therefore, the comprehensiveness of this study may contribute to (i) stimulate societies to debate the trade-offs between costs and benefits of nitrogen use, (ii) provide insights to raise people's awareness of the impact of their food and energy choices, and (iii) support societies to claim and actively participate in the elaboration of effective policies to solve the problem of nitrogen pollution.

Future developments of this study involve the inclusion of more recent data (from 2019 onwards) and other indicators that reflect current trends (e.g., ammonia emissions, food and energy production, consumption, and exports, among others, which were not included here due to lack of data), especially given the potential global impacts of recent events (i.e., COVID 19 pandemic and Eastern Europe conflict) on the production and commercialization of fertilizers and non-renewable energy.

Finally, finding the balance between the benefits and negative impacts of nitrogen to achieve its sustainable management poses an immense challenge for Brazil. It will not only involve technological innovations for energy efficiency, infrastructure for sewage treatment and disposal, improving management practices in agriculture, and willingness to change ingrained consumption patterns, but especially reversing its political and institutional issues, in order to design and implement measures that promote the sustainable nitrogen management in an integrated way.

# 6 POLICY COHERENCE ANALYSIS OF CURRENT N-POLICIES[9]

In this chapter, we address the research question number three of the thesis: "*How coherent are the policy responses to address nitrogen pollution in terms of an integrated approach?",* raised in Section 2.1. For that, we assess a set of current nitrogen-related policies in Brazil by applying the Policy Coherence Analytical Framework, in order to show the coherences and incoherences of these policies and how they can affect the development of a potential integrated nitrogen policy approach. Although there are some constraining policies, which can limit the achievement of the objectives of other policies, in general, our findings show a very favorable outcome, since most of the analyzed policies present positive interactions, capable of enabling and reinforcing their policy objectives. This policy coherence is essential to allow integration between nitrogen policies and minimizing the risk of unintended impacts in other areas. For a future integrated nitrogen policy approach, we recommend that these constraining policies be updated, adapted or reformulated in order to include concrete actions that promote sustainable nitrogen management and avoid clashing with other N-related policies.

## 6.1 The importance of policy coherence in dealing with public problems

Nitrogen pollution is a global public problem that, despite its relevance to the Sustainable Development Goals (SDGs) (see Figure 5.1, Section 5.1), still lacks wide visibility and coordinated governance, which would be essential for effective actions (SUTTON et al., 2021). As a general definition, public problems are situations of an economic, social, cultural, or environmental nature, which may arise in a small locality, state, country, or even globally, that affect a considerable number of people and have to be resolved through a government action program (SECCHI, 2014). More specifically, Gusfield (1984) asserts that a situation becomes a public problem when it acquires a 'societal'

[9] This chapter is based on the paper submitted to SCIENCE OF THE TOTAL ENVIRONMENT (under review), entitled ***Nitrogen pollution in Brazil: a policy coherence analysis of current nitrogen-related regulations for a potential integrated approach***, authors CUNHA-ZERI, GISLEINE; BRANCO, EVANDRO A., OMETTO, JEAN.

dimension, turning into a matter of conflict, controversy, and debate in the public arena, which needs to be addressed through collective action by public authorities, institutions, and/or social movements. Public problems can arise in endless ways and have different stakeholders; thus, they require distinct, but coordinated policy responses (such as regulations, subsidies, quotas, and laws) at the local, national, or international level (PETERS, 2005, 2018). Usually, public problems do not have a clear 'ownership' (who owns this problem and who should solve it?) nor unique and indisputable solutions, therefore, a prominent level of creativity and coordination is required to design and implement policies that satisfy those affected by such problems (GUSFIELD, 1984; NOVECK, 2021).

Indeed, nitrogen pollution is a serious public problem in Brazil and remains a major unresolved challenge: emissions of reactive nitrogen ($N_r$) have significantly increased over the last decades (SEEG-BRAZIL, 2022), caused mainly by productive activities aimed at meeting the demand for food, energy, and housing by a fast-growing population (CUNHA-ZERI; OMETTO, 2021), leading to a weak-to-basic level of sustainability of nitrogen management in the country (CUNHA-ZERI et al., 2022). Notwithstanding, it is important to emphasize that nitrogen use is crucial to national and global food security, as the country is one of the largest producers and exporters of agricultural commodities in the world (FAO, 2021). In this sense, ensuring food security for billions of people without crossing planetary boundaries requires huge incentives for the efficient use of nitrogen in agriculture integrated with mitigation measures for non-agricultural nitrogen sources (SCHULTE-UEBBING et al., 2022).

Developing integrated measures to address the public problem of nitrogen would involve not only focusing on curbing emissions, but also on the nitrogen cycle and its intertwined nature with human dimensions and societal demands, in connection with the water-food-energy-ecosystems nexus (ERISMAN et al., 2001; OENEMA et al., 2011a; SUTTON et al., 2021). Therefore, an integrated nitrogen policy approach should consider multiple sinks (e.g., air, soil, water) and sectors (e.g., agriculture, energy, industry, transport, waste), in order to promote synergies and limit the risk of pollution swapping (KANTER et al., 2020b), which occurs when a measure introduced to reduce one pollutant results in the increase of another, different pollutant (STEVENS; QUINTON, 2009). Ideally, such policy integration should include measures to reduce the levels of emissions and undesirable effects of nitrogen, while facilitating economic development in sectors that rely on nitrogen use, as the agriculture sector, for instance (HEER; ROOZEN; MAAS, 2017).

At present, there are no specific, exclusive, or integrated measures to address nitrogen pollution in Brazil, however, several current policies have included some nitrogen concerns in their regulations (see Table 6.1). It is interesting to note how the controversial nature of nitrogen use (benefits versus costs) influences policy goals: while some of the existing policies aim to support nitrogen consumption (i.e., fertilizers production and commercialization), others intend to reduce emissions to limit negative impacts (i.e., financial incentives to expand biological nitrogen fixation to replace the use of N-fertilizers). Additionally, these listed nitrogen-related policies cut across various interministerial departments and government representatives, with different interests and focus on sectors linked to their own demands, which can lead to lack of coordination and/or fragmented policy responses (YANG et al., 2022). Thus, policy coherence and interministerial coordination are necessary to ensure that progress achieved under one measure contributes to the success of others, as well as minimizing the risk of unintended nitrogen impacts in other areas. For instance, mitigation measures to curb nitrous oxides ($N_2O$) from agriculture conducted by the Ministry of Agriculture might contribute to policies for reducing of greenhouse gases (GHG) led by the Ministry of the Environment.

Policy coherence is defined by the Organization for Economic Cooperation and Development (OECD) as “*the systematic promotion of mutually reinforcing policy action across government departments and agencies creating synergies towards achieving the defined objective*” (JONES, 2002). Promoting policy coherence is of utmost importance for nitrogen management, since it can allow policy integration and reduce potential conflicts between them (OECD, 2018b). Indeed, enhancing coherence across nitrogen policies is one of the activities to be conducted by the Inter-convention Nitrogen Coordination Mechanism (INCOM), as proposed by the 2019 Colombo Declaration on Sustainable Nitrogen Management (UNEP, 2019a) (see Section 3.4.1). In this way, the Policy Coherence Analytical Framework applied in this study is an important qualitative tool capable of closely examining current policies, in order to identify their inconsistencies and the possibility of contradicting or constraining each other, in addition to supporting the design of a potential integrated policy approach to address nitrogen pollution in Brazil, as outlined in the 2019 UNEP Resolution on Sustainable Nitrogen Management (UNEP, 2019c).

## 6.2 Material and methods

### 6.2.1 The policy coherence analytical framework

The policy coherence methodology allow us to visualize the coherence of nitrogen management regulations through the interactions (positive or negative) between them and, therefore, identify preferences and biases, as well as suggesting more sound instruments to be developed, considering the interactions between the economic, social, and environmental spheres that surround sustainable nitrogen management.

The global acceptance of policy coherence analysis as a substantive assessment method has resulted in numerous qualitative studies in several areas, such as the implementation, achievement, and interactions between the Sustainable Development Goals (COLLSTE; PEDERCINI; CORNELL, 2017; COSCIEME; MORTENSEN; DONOHUE, 2021; KOFF; CHALLENGER; PORTILLO, 2020; NILSSON; GRIGGS; VISBECK, 2016; OECD, 2018a), the impact of agriculture and climate policies on food systems and food security (BROOKS, 2014; HIDALGO; NUNN; BEAZLEY, 2021; MUSCAT et al., 2021), the sustainability transitions and biogas production (HUTTUNEN; KIVIMAA; VIRKAMÄKI, 2014; KANDA et al., 2022), the analysis of agriculture, climate, and forestry policies to avoid conflicting incentives in relation to land-use and land-allocation (CARTER et al., 2018; HARAHAP; SILVEIRA; KHATIWADA, 2017), the effects of subsidies policies on fisheries management (MALLORY, 2016), and renewable energy policies in relation to international GHG mitigation targets (FRAUNDORFER; RABITZ, 2020), among others.

In this work, we follow the analytical framework proposed by Nilsson et al. (2012) and Nilsson, Griggs, and Visbeck (2016), using a seven-point scoring system (Figure 6.1), where positive interactions receive scores of +1 (enabling), +2 (reinforcing), or +3 (indivisible), negative interactions are scored as -1 (constraining), -2 (counteracting), or -3 (cancelling), and neutral score (0) is assigned when no significant positive or negative interactions occur between targets. This scale of interactions allows the identification of potential synergies between policy instruments (when one policy reinforce the achievement of another) and the trade-offs that should properly be managed (when policies cancel each other), thus highlighting priorities for potential integrated policies.

Figure 6.1 – Policy Coherence Scale of Interactions.

| **Policy Coherence Scale of Interactions** | | | | | | |
|---|---|---|---|---|---|---|
| **Cancelling** | **Counteracting** | **Constraining** | **Consistent** | **Enabling** | **Reinforcing** | **Indivisible** |
| **-3** | **-2** | **-1** | **0** | **+1** | **+2** | **+3** |
| Makes it impossible to reach another goal | Clashes with another goal | Limits options on another goal | No significant positive or negative interactions | Creates conditions that further another goal | Aids the achievement of another goal | Inextricably linked to the achievement of another goal |

Source*:* Nilsson, Griggs, and Visbeck (2016).

The magnitude of the score, either positive or negative, indicates of how a given policy influences another. For instance, policies that promote the sustainable use of N-fertilizers in agriculture creates conditions to decrease the release of $N_r$ emissions to the atmosphere. In this case, a positive score represents an 'enabling' interaction, where achieving one goal facilitates reaching the other. An example of negative interaction is when a certain policy encourages N-fertilizer use (i.e., tax reduction), in order to boost agricultural productivity, but ends up undermining measures aimed at reducing soil emissions.

For this analysis, we also considered the four constraints assumed by Nilsson et al., (2016) when applying the scale, which are: (i) if interactions among policies are reversible or not, (ii) if interactions go in both directions, (iii) the strength of the interactions, and (iv) the probability of an interaction actually happening or just being a possibility. On the other hand, we do not examine geographic, technological, and governance disparities, which would avoid dangerous generalizations, as we are analyzing national policies applied across the country.

### 6.2.2 Data collection and categorization

Considering that there are no specific, exclusive, or integrated policies to directly deal with nitrogen pollution in Brazil, we defined a series of terms related to nitrogen management (such as, air, water, and soil pollution, fertilizers, sewage and waste management, eutrophication, acidification, food security, energy, transport, fossil fuels, etc.) and to nitrogen species [all $N_r$ compounds: ammonia ($NH_3$), ammonium ($NH_4^+$), nitrogen oxides ($NO_x$), nitrogen dioxide ($NO_2$), nitric oxide (NO), nitric acid ($NHO_3$), nitrous oxide ($N_2O$), and nitrate ($NO_3^-$)], and then conducted searches on the Brazilian Legislation Portal[10]. This search was restricted to the federal level, since state and municipal regulations cannot contradict federal regulations and could result in redundancies.

The next step of our data compilation involved a careful textual analysis of thirty-nine selected documents, according to the content analysis methodology of Bengtsson (2016), with the aim of examining the content of the regulations and how they relate to the nitrogen context. Revoked policies, amendments, and documents related solely to the establishment of committees or working groups were excluded. This process resulted in nineteen nitrogen-related policies, among laws, decrees, resolutions, ordinances, and instructions. Then,

[10] Through the Legislation Portal it is possible to have access to all regulatory acts at the federal level. The search can be carried out by keyword, type of legislation, reference number, year, etc. Available at: http://www4.planalto.gov.br/legislacao/.

we followed the methodology proposed by Kanter et al. (2020) for the categorization of policies, that is, *policy category* (commerce, data & methods, economic, framework, pro-nitrogen, regulatory, and research & development), *sinks* (air, climate, ecosystems, soil, water, and multiple sinks), and *sectors* (agriculture, energy, industry, transport, waste, multiple sectors). These results are presented in Table 6.1, including a concise description of each policy, the $N_r$ species mentioned in the documents, and the actors (ministries) of each instrument. Note that the codes presented in the first column of Table 6.1 are composed of the first letter of each classification, preceded by the number of policies of each policy category (for instance, 1-FMM refers to 1$^{st}$ Framework, Multiple sink, Multiple sector; 2-FAT refers to 2$^{nd}$ Framework, Air sink, Transport sector; 1-RAM refers to 1$^{st}$ Regulatory, Air sink, Multiple sector, and so on).

Table 6.1 – Data collection and categorization of N-related policies (from oldest to newest).

| CODE | POLICY DESCRIPTION (REFERENCE Nº / YEAR) | POLICY CATEGORY | SINK | SECTOR | $N_r$ SPECIES | ACTORS |
|---|---|---|---|---|---|---|
| 1-FMM | **National Environment Plan** (Law 6938/1981) – aims at preserving, improving and recovering environmental quality throughout the country, while providing conditions for socio-economic development, national security interests and the protection of the dignity of human life. | Framework | Multiple | Multiple | Not mentioned | Interministerial |
| 2-FAT | **National Program to Control Vehicular Pollution** (Resolution 018/1986) – aims to reduce pollutant emission levels by motor vehicles to meet air quality standards, especially in urban centers, the technological development of methods and equipment for measuring pollutant emissions, enhancing public awareness of air pollution, among other measures. | Framework | Air | Transport | $NO_x$ | Ministry of Environment |
| 3-FAM | **National Air Quality Control Program** (Resolution 005/1989) – aims to limit pollutant emission levels from sources of atmospheric pollution to improve air quality, meet established standards, and not compromise air quality in non-degraded areas. | Framework | Air | Multiple | Not mentioned | Ministry of Environment |

continue

Table 6.1 – Continuation.

| | | | | | | |
|---|---|---|---|---|---|---|
| 1-RAM | **Air quality standards and regulations** (Resolution 003/1990) – aims to establish pollutant emission standards to improve air quality, being (1) primary standards: concentrations of pollutants that, if exceeded, can affect the health of the population, and (2) secondary standards: concentrations of pollutants that cause minimal impact on the well-being of the population, as well as on flora and fauna and the environment in general. | Regulatory | Air | Multiple | $NO_2$ | Ministry of Environment |
| 2-RAT | **Reduction of pollutant emissions by motor vehicles** (Law 8723/1993) – obliges motor vehicle and fuel manufacturers to take the necessary measures to reduce pollutant emission levels from products sold in the country, within the limits of pollutant emission and deadlines established in this law. | Regulatory | Air | Transport | $NO_x$ | Ministry of Environment |
| 4-FWM | **National Water Resources Plan** (Law 9433/1997) – Its objectives are: (i) guarantee to current and future generations the necessary availability of water, in quality standards suitable for use, (ii) the rational and integrated use of water resources aiming at sustainable development, and (iii) the prevention and defense against natural hydrological events or those resulting from the inappropriate use of natural resources. | Framework | Water | Multiple | Not mentioned | Ministry of Environment |

continue

Table 6.1 – Continuation.

| | | | | | | |
|---|---|---|---|---|---|---|
| 5-FEM | **National Biodiversity Plan** (Decree 4339/2002) – aims at the conservation of biodiversity and its sustainable management, guided by the following targets: (1) knowledge, (2) conservation, (3) sustainable use, (4) monitoring, evaluation, prevention and mitigation of impacts, (5) access to genetic resources and associated traditional knowledge, (6) education, public awareness, and information on biodiversity, and (7) legal and institutional strengthening for biodiversity management. | Framework | Ecosystem | Multiple | $NO_2$, $N_2O$ | Ministry of Environment |
| 1-PSA | **Tax reduction for fertilizers** (Decree 5630/2005) - reduces to zero the rates levied on imports and commercialization in the domestic market of fertilizers (in addition to pesticides and other agricultural products). | Pro-nitrogen | Soil | Agriculture | Not mentioned | Ministry of Agriculture |
| 3-RAM | **Limits for the emission of air pollutants** (Resolution 382/2006) – establishes maximum limits (according to types of pollutants and sources of pollution) for controlling the emission of atmospheric pollutants. The limits must consider environmental and geographic criteria, in addition to adopting technically and economically viable technologies to control the emission of atmospheric pollutants. | Regulatory | Air | Multiple | $NO_x$, $NH_3$ | Ministry of Environment |

continue

Table 6.1 – Continuation.

| | | | | | | |
|---|---|---|---|---|---|---|
| 4-RSM | **Agricultural use of sewage sludge** (Resolution 375/2006) – establishes criteria and procedures for the use, in agricultural areas, of sewage sludge generated in a sanitary sewage treatment plant and its derivatives, aiming at benefits to agriculture and avoiding risks to public health and the environment. | Regulatory | Soil | Multiple | $NO_3^-$, $NO_2^-$, $NH_3$ | Ministry of Environment |
| 6-FWW | **National Guidelines for Sanitation** (Law 11445/2007) –aims to promote basic sanitation, especially in areas occupied by low-income populations, in addition to (i) promoting scientific and technological development for basic sanitation, (ii) minimize environmental impacts related to the implementation of basic sanitation actions, and (iii) encourage the adoption of sanitary equipment that contribute to the reduction of water consumption, among other measures. | Framework | Water | Waste | Not mentioned | Interministerial |

continue

Table 6.1 – Continuation.

| | | | | | | |
|---|---|---|---|---|---|---|
| 7-FCM | **National Climate Change Plan** (Law 12187/2009) – aims at (i) making economic and social development compatible with the protection of the climate system, (ii) reducing anthropogenic emissions of GHGs from different sources, (iii) anthropogenic removals from sinks of GHGs (iv) promote adaptation to climate change, (v) preservation, conservation, and recovery of environmental resources, (vi) expansion of protected areas and incentives for reforestation and restoration of vegetation cover in degraded areas, among other measures. | Framework | Climate | Multiple | $N_2O$ | Interministerial |
| 1-ESA | **Institutes the Low-Carbon Agriculture Plan (ABC Plan)** (Decree 7390/2010) – establishes action plans to prevent and control deforestation in biomes and sectoral plans to mitigate and adapt to climate change. Among the activities of the ABC Plan is the expansion of biological nitrogen fixation (BNF) in 5.5 million hectares of cultivated areas, replacing the use of nitrogen fertilizers. | Economic | Soil | Agriculture | $N_2O$, $NH_3$ | Ministry of Agriculture |
| 5-RWM | **Quality of water for human consumption** (Ordinance 2914/2011) – establishes procedures for controlling and monitoring the quality of water for human consumption and potability standard. | Regulatory | Water | Multiple | $NO_3^-$, $NO_2^-$, $NH_3$ | Ministry of Health |

continue

Table 6.1 – Continuation.

| | | | | | | |
|---|---|---|---|---|---|---|
| 6-RWW | **Release of effluents in receiving water bodies** (Resolution 430/2011) – aims to establish conditions, parameters, norms and guidelines for the management of the release of effluents into receiving water bodies. Effluents from any polluting source may only be discharged directly into the receiving body as long as they comply with the conditions and standards. | Regulatory | Water | Waste | $NO_3^-$, $NO_2^-$, $NH_3$ | Ministry of Environment |
| 1-CSA | **Inspection of fertilizers production and trade** (Decree 8384/2014) – aims to establish guidelines for the inspection of the production and commercialization of fertilizers, correctives, inoculants and biofertilizers for agricultural use. | Commerce | Soil | Agriculture | $NO_3^-$, $NH_3$ | Ministry of Agriculture |
| 2-CSA | **Specifications (packaging, labelling, etc.) for fertilizers trading** (Instruction 046/2016) – establishes definitions and standards on specifications and guarantees, tolerances, registration, packaging, and labeling of mineral fertilizers for agricultural use. | Commerce | Soil | Agriculture | $NO_3^-$, $NH_3$ | Ministry of Agriculture |

continue

Table 6.1 – Conclusion.

| | | | | | | |
|---|---|---|---|---|---|---|
| 8-FCE | **National Biofuels Plan** (Law 13576/2017) – Its objectives are: (i) to contribute to meeting the commitments of the Paris Agreement under the UNFCCC, (ii) to contribute to energy efficiency and the reduction of GHG emissions in the production, marketing, and use of biofuels, (iii) expand the production and use of biofuels in the national energy matrix, with an emphasis on supply, and (iv) encourage the competitive participation of various biofuels in the national fuel market. | Framework | Climate | Energy | $N_2O$ | Ministry of Mines and Energy |
| 9-FSA | **National Fertilizer Plan** (Decree 10991/2022) – aims to increase the competitiveness of the internal fertilizer industry, reduce external dependence, and increase the participation of Brazilian agribusiness in the international market. | Framework | Soil | Agriculture | Not mentioned | Interministerial |

Source: Prepared by the author.

Classifying policies into policy categories (third column of Table 6.1) is essential to understanding their purposes and targets, and a crucial step towards the coherence analysis. Most of the policies selected for this analysis are classified as FRAMEWORK type (nine documents in total), which includes broad environmental policies that introduce national strategic plans and where N-policies might be bound. Then comes the REGULATORY policies (six documents in total), which are those that set quantifiable limits, consumption restrictions, or quality standards, and often has an enforcement mechanism. The ECONOMIC type (one document) provides financial incentives and signals to encourage enforceable and quantifiable behavioral changes related to nitrogen management. Finally, the COMMERCE policy (two documents), which regulates production, commercial and trade activities surrounding nitrogen, and the PRO-NITROGEN policy (one document), which provides incentives to increase nitrogen use, are both important types of mechanisms that influence the production and consumption of nitrogen in key areas of the country´s economy, i.e., the agriculture sector. None of the policies on this list were classified as DATA & METHODS (data collection/reporting protocols, including parameters for environmental impact assessments) or RESEARCH & DEVELOPMENT (research and development funding into nitrogen pollution effects of mitigation technologies). For a more detailed description of these policy categories see Kanter et al. (2020).

The complete dataset for this study, including the full list of selected policies, description of policy goals, links to official policy documents (in Portuguese), and results of coherence analysis, among other information, can be accessed using the following link: https://data.mendeley.com/datasets/6rj7hz4548/1 (CUNHA-ZERI; BRANCO; OMETTO, 2023).

## 6.3 Results and discussions

To conduct the policy coherence analysis, we formulated the following research question aligned with the objectives of this study: ***how are the goals of this policy contributing to the formulation of an integrated policy approach to limit nitrogen pollution in Brazil*?** Therefore, the first step was to analyze each policy individually to address the research question, considering the policy objectives, policy categories, and other information shown in Table 6.1. As initial analysis, an individual weight was assigned to each policy, according to the Nilsson´s policy coherence scale of interaction (Figure 6.1).

The second step was to assess and validate the first step´s results of the coherence analysis. For that, we conducted a focus group online session according to the methods of Stewart and Shamdasani (2015). The focus group was formed by a panel of experts, with prior knowledge on the subject to be debated (nitrogen management and/or environmental policies). It is important to highlight that the identities of experts are preserved to avoid bias and ensure the quality of the final result.

We started the focus group by explaining the objective of the study and the methodology of policy coherence. Next, we presented the initial analysis to all participants and discuss the details of the interaction between each policy until we reach a consensus. The focus group analyzed and discussed in detail all the results of the first stage of the coherence analysis, recommending specific changes in the weight of some policies in the interaction scale, as well as suggesting a detailed explanation to justify the results. As the preliminary results were validated, the final results matrix was designed, showing how the policies are distributed over the scale of interactions (Figure 6.2), that is, 01 Canceling, 01 Constraining, 03 Consistent, 03 Enabling, 06 Reinforcing, and 05 Indivisible (no policy was classified as Counteracting).

Figure 6.2 – Final results of the Policy Coherence analysis.

| How are the goals of this policy contributing to the formulation of an integrated policy approach to limit nitrogen pollution in Brazil? | | | | | | |
|---|---|---|---|---|---|---|
| CANCELLING (-3) | COUNTERACTING (-2) | CONSTRAINING (-1) | CONSISTENT (0) | ENABLING (+1) | REINFORCING (+2) | INDIVISIBLE (+3) |
| 9-FSA | | 1-PSA | 5-FEM | 1-FMM | 2-FAT | 1-RAM |
| | | | 1-CSA | 4-RSM | 3-FAM | 2-RAT |
| | | | 2-CSA | 8-FCE | 4-FWM | 3-RAM |
| | | | | | 6-FWW | 1-ESA |
| | | | | | 7-FCM | 6-RWW |
| | | | | | 5-RWM | |

Source: Prepared by the author.

In the next subsections, we discuss the results organized by consistent interactions, positive synergies, negative interactions, and cross-interactions between policies, ending with an overall discussion and recommendations.

### 6.3.1 Consistent interactions

Consistent or neutral interactions (score 0) mean that no positive or negative interactions were found between these policies, demonstrating their neutrality towards the research question. The policies included in this level are the following:

| | | | CONSISTENT | | | |
|---|---|---|---|---|---|---|

**5-FEM (National Biodiversity Plan)**: this policy is not primarily aimed at reducing N pollution. It is not mentioned in any other N-related policy, therefore, it does not influence the achievement of other policies. It is important to mention that, although the specific objectives of this policy are not related to nitrogen management (neutral interaction), protecting biodiversity should be included in a future integrated nitrogen policy, considering the impact of excessive nitrogen pollution on it.

**1-CSA (Inspection of fertilizer production and trade)**: this policy aims to establish guidelines for the inspection of the production (correct amount of raw material for its manufacture) and commercialization of fertilizers, among other products for agricultural use. It does not aim to reduce N pollution, nor does it have an influence on increasing $N_r$ emissions, although regulations are essential for safety and quality control in the production and commercialization of N-fertilizers.

**2-CSA (Specifications for fertilizers trading)**: this policy aims to establish specifications for the commercialization of N-fertilizers (definitions and standards on specifications and guarantees, tolerances, registration, packaging, and labeling of mineral fertilizers). It does not aim to reduce nitrogen pollution, nor does it have an influence on increasing $N_r$ emissions, although regulations are essential for safety and quality control in the production and commercialization of N-fertilizers.

### 6.3.2 Positive synergies between policies

Enabling interactions (score +1) create conditions that promote the achievement of another policy goal not initially targeted and/or refer to measures that pursue the same policy objectives through different approaches. The policies included in this level are the following:

| | | | | ENABLING | | |
|---|---|---|---|---|---|---|

**1-FMM (National Environment Plan)**: this policy is the basis of other environmental policies in the country, directly or indirectly. Hence it enables the achievement of another goals. It is not primarily aimed at reducing nitrogen pollution, but it is cited in other N-related policies (2-RAT, 4-RSM, 6-RWW).

**4-RSM (Agricultural use of sewage sludge)**: this policy aims to reduce nitrate ($NO_3^-$), nitrite ($NO_2^-$) and ammonia ($NH_3$) emissions using sewage sludge in agriculture. It is not linked to any other N-policy (only 1-FMM), but its objectives are aligned with the reduction of reactive nitrogen pursued by other policies.

**8-FCE (National Biofuels Plan)**: this policy aims to encourage the production, commercialization, and use of biofuels, in order to reduce GHG emissions and increase energy efficiency in the country. It is related to another framework policy (7-FCM), but not directly to any specific nitrogen-related policy. On the other hand, it can support the achievement of other N-policy targets by reducing $N_2O$ and $NO_x$ emissions, for instance.

Reinforcing interactions (score +2) aids the achievement of other goals not initially targeted, as well as to pursue similar goals from other policies, rather than working on cross-purposes. This type of interaction is particularly important to the formulation of an integrated nitrogen policy approach. The policies included in this level are the following:

| | | | | | REINFORCING | |
|---|---|---|---|---|---|---|

**2-FAT (National Program to Control Vehicular Pollution)**: this policy aims to reduce $NO_x$ emissions from motor vehicles (among other pollutants). It is also linked to the development of existing N-related policies (2-RAT), and it is an instrument of another framework policy (3-FAM).

**3-FAM (National Air Quality Control Program)**: this policy aims to limit pollutant emission levels to improve air quality and, although it does not mention any $N_r$ species, it does create conditions for the development of N-related policies (1-RAM, 3-RAM).

**4-FWM (National Water Resources Plan)**: this policy aims to provide access to water in quality standards suitable for use and, although it does not mention any $N_r$ species, it does create conditions for the development of N-related policies (5-RWM, 6-RWW).

**6-FWW (National Guidelines for Sanitation)**: this policy aims to minimize the environmental impacts related to the implementation and development of basic sanitation actions and, although it does not mention any $N_r$ species, it assists in the development and achievement of other N-related policies (5-RWM, 6-RWW).

**7-FCM (National Climate Change Plan)**: this policy aims to reduce anthropogenic emissions of GHG ($N_2O$ included). It also allows the development of existing N-related policies (1-ESA) and is related to another framework policy (8-FCE).

**5-RWM (Quality of water for human consumption)**: this policy aims to reduce nitrate ($NO_3$-), nitrite ($NO_2$-), and ammonia ($NH_3$) to improve water quality. It is linked to the National Water Resources Plan (4-FWM) and the National Guidelines for Sanitation (6-FWW).

Indivisible interactions (score +3) are inextricably linked to the achievement of another policy objective. They are coordinated policies or programs that pursue the same police goals and, in some cases, refer to each other. These types of policies should be included in a potential integrated nitrogen policy approach (with some adaptations and/or updates) as their objectives are effectively aligned. The policies included in this level are the following:

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | **INDIVISIBLE** |

**1-RAM (Air quality standard and regulations):** this policy aims to reduce $NO_2$ emissions (among other pollutants) to improve air quality, which is essential for sustainable nitrogen management. It is linked to the National Air Quality Program (3-FAM).

**2-RAT (Reduction of pollutant emissions by motor vehicles)**: this policy aims to reduce $NO_x$ emissions from motor vehicles (among other pollutants), essential to improve nitrogen management. It is not referenced in other N-related policies, although it is important to achieve the goals of the National Environment Plan (1-FMM) and the National Program to Control Vehicular Pollution (2-FAT).

**3-RAM (Limits for the emissions of air pollutants)**: this policy aims to reduce $NO_x$ and $NH_3$ emissions (among other pollutants, including acid nitric, and components of N-fertilizers) to improve air quality. It is linked to the National Air Quality Program (3-FAM).

**1-ESA (Low-carbon agriculture plan – ABC Plan)**: among other activities, the ABC Plan includes the expansion of biological nitrogen fixation (BNF) to replace the use of nitrogen fertilizers, hence reducing $N_2O$ and $NH_3$ emissions. This plan is related to the National Climate Change Plan (7-FCM).

**6-RWW (Release of effluents in receiving water bodies)**: this policy aims to establish guidelines for the release of effluents in water bodies, including nitrate ($NO_3$-), nitrite ($NO_2$-), and ammonia ($NH_3$). It is linked to the National Environmental Plan (1-FMM), but it does not reference other N-related policy. However, it directly contributes to the achievement of other N-policies, especially those related to water management (4-FWM, 6-FWW, 5-RWM).

### 6.3.3 Negative interactions between policies

Constraining interactions (score -1) are those that limit the implementation of policies or the achievement of policy goals through constraints at distinct levels (unintentional and indirect impacts), thus undermining policy objectives. The policy included in this level is the following:

**CONSTRAINING**

**1-PSA (Tax reduction for fertilizers)**: by reducing taxes, this policy may encourage increased use of N-fertilizers. As it does not mention any measures to control the excess of nitrogen emitted into the environment, it may hamper the achievement of other policy goals to reduce nitrogen pollution (e.g., 3-RAM, 7FCM, 1-ESA, 5-RWM, 6-RWW).

Cancelling interactions (score -3) are those that negatively impact (or make impossible to reach) the objectives of another policy due to competing goals that openly contradict each other (unintentional but direct impacts) or political rivalries between actors. These types of policies can undermine a potential integrated nitrogen policy approach. The policy included in this level is the following:

**CANCELLING**

**9-FSA (National Fertilizer Plan)**: this policy encourages the use of N-fertilizers by increasing their production and trade within the country, besides stimulating agricultural production to increase participation in the international market. As it does not mention measures to control the negative impacts of excess nitrogen in the environment, it may hamper the achievement of other policy goals to reduce nitrogen pollution (e.g., 3-RAM, 7FCM, 1-ESA, 5-RWM, 6- RWW).

### 6.3.4 Cross-interactions between policies

During the policy coherence analysis process, we realized that some policy interactions might be different if the research question is not directly related to the integrated nitrogen policy approach. In this case, exploring a cross-interaction between all policies could elucidate this query. Thus, we formulated another research question to enrich our policy coherence analysis, which is: ***how are the goals of each N-related policies interacting with each other?*** The results of this second policy coherence analysis were also validated by the focus group, similar to the first research question, and are represented in Figure 6.3.

Figure 6.3 – Final results of cross-interaction between policies.

**How are the goals of each N-related policies interacting with each other?**

CANCELLING | COUNTERACTING | CONSTRAINING | CONSISTENT | ENABLING | REINFORCING | INDIVISIBLE

| 1-FMM | 2-FAT | 3-FAM | 1-RAM | 2-RAT | 4-FWM | 5-FEM | 1-PSA | 3-RAM | 4-RSM | 6-FWW | 7-FCM | 1-ESA | 5-RWM | 6-RWW | 1-CSA | 2-CSA | 8-FCE | 9-FSA | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | +1 | +1 | +1 | +1 | +1 | +1 | -1 | +1 | +1 | +1 | +1 | +1 | +1 | +1 | 0 | 0 | +1 | -2 | 1-FMM |
| | | +3 | +3 | +3 | +2 | +1 | 0 | +3 | 0 | 0 | +2 | 0 | +2 | +1 | 0 | 0 | +2 | 0 | 2-FAT |
| | | | +3 | +3 | +2 | +1 | -1 | +3 | 0 | 0 | +2 | +1 | +2 | +1 | 0 | 0 | +2 | -2 | 3-FAM |
| | | | | +3 | +2 | +1 | -1 | +3 | 0 | 0 | +2 | 0 | +2 | +1 | 0 | 0 | +2 | -2 | 1-RAM |
| | | | | | +2 | +1 | 0 | +3 | 0 | 0 | +2 | 0 | +2 | +1 | 0 | 0 | +2 | 0 | 2-RAT |
| | | | | | | +1 | -1 | +2 | +1 | +2 | +2 | +1 | +3 | +3 | 0 | 0 | 0 | -2 | 4-FWM |
| | | | | | | | -1 | +1 | +1 | +1 | +1 | +1 | +1 | +1 | 0 | 0 | -1 | -2 | 5-FEM |
| | | | | | | | | -2 | -1 | 0 | -2 | -2 | -2 | -2 | 0 | 0 | +1 | -1 | 1-PSA |
| | | | | | | | | | 0 | 0 | +2 | 0 | +2 | 0 | 0 | 0 | +3 | -2 | 3-RAM |
| | | | | | | | | | | +3 | +2 | +1 | +2 | +2 | 0 | 0 | +2 | -1 | 4-RSM |
| | | | | | | | | | | | +2 | 0 | +3 | +3 | 0 | 0 | 0 | -1 | 6-FWW |
| | | | | | | | | | | | | +3 | +1 | +1 | 0 | 0 | +2 | -2 | 7-FCM |
| | | | | | | | | | | | | | +1 | +1 | 0 | 0 | +2 | -2 | 1-ESA |
| | | | | | | | | | | | | | | +3 | 0 | 0 | 0 | -2 | 5-RWM |
| | | | | | | | | | | | | | | | 0 | 0 | 0 | -2 | 6-RWW |
| | | | | | | | | | | | | | | | | +2 | 0 | 0 | 1-CSA |
| | | | | | | | | | | | | | | | | | 0 | 0 | 2-CSA |
| | | | | | | | | | | | | | | | | | | +2 | 8-FCE |
| | | | | | | | | | | | | | | | | | | | 9-FSA |

Source: Prepared by the author.

Results indicate that more than half of cross-interactions between all policies represent positive synergies (enabling, reinforcing, and indivisible). Not surprisingly, the positive interactions are between policies with similar sinks (air, water, climate) and goals. In other cases, although targeting different sinks and/or sectors, it is very clear how the successful implementation of one policy can be enabled or reinforced by another policy, because they pursue similar objectives. Examples are the National Biofuels Plan (8-FCE) and the Air

Pollutant Emission Limits (3-RAM), and the Agricultural Use of Sewage Sludge (4-RSM) and the National Guidelines for Sanitation (6-FWW).

Apart from the 1-CSA and 2-CSA policies, which have consistent interactions with all other policies except each other, neutral relations also occur between policies of the same sink (2-FAT, 3-FAM, 1-RAM, 2-RAT, 3-RAM – all air-related regulations) with other policies that present unrelated targets, such as the National Guidelines for Sanitation (6-FWW) and the Agricultural Use of Sewage Sludge (4-RSM). Another example of neutral interactions is all water-related regulations (4-FWM, 6-FWW, 5-RWM, 6-RWW) with the National Biofuels Plan (8-FCE).

On the other hand, the National Biodiversity Plan (5-FEM) presents a neutral interaction in the context of the integrated nitrogen policy (first research question), but in the cross-interaction framework it shows enforcing interactions with all other policies, except with 1-PSA, 8-FCE, and 9-FSA, with which it has constraining and counteracting relations.

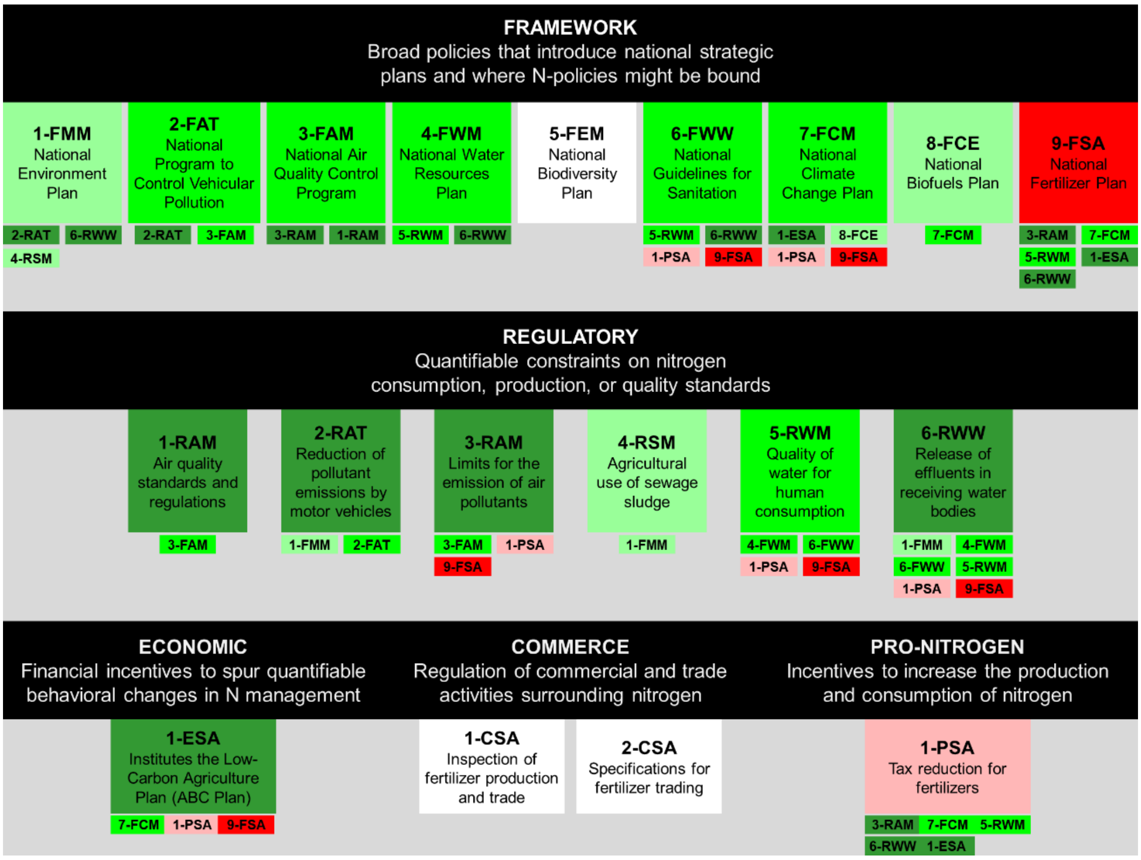
The most interesting results are related to policies that show negative interactions in the context of an integrated nitrogen policy approach, as well as constraining and counteracting relations in cross-interactions with some policies, i.e., 1-PSA (Tax Reduction for Fertilizers) and 9-FSA (National Fertilizer Plan). However, these two policies have enabling and reinforcing interactions, respectively, with 8-FCE (National Biofuels Plan), indicating that both reducing taxes on fertilizers and increasing fertilizer production in Brazil could be extremely beneficial to minimize the costs of agricultural production (including biofuel crops) and ensure food and fuel security.

### 6.3.5 Overall discussion and recommendations

To proceed with the application of the Policy Coherence Analytical Framework we elaborated two research questions: (**1**) *how are the goals of this policy contributing to the formulation of an integrated policy approach to limit nitrogen pollution in Brazil?* and (**2**) *how are the goals of each N-related policies interacting with each other?*, from now on RQ1 and RQ2, respectively. Overall, the results are very promising, since most of the analyzed policies are within the enabling, reinforcing, and indivisible clusters, meaning positive synergies, both in RQ1 and in RQ2 models.

Focusing on the RQ1 outcome, a summary of policy interactions is presented in Figure 6.4. We highlight that most nitrogen-related policies in Brazil are of the framework, regulatory, and economic categories (most with positive synergies) which, to a certain extent, are more favorable to sustainable nitrogen management, in contrast to policies that encourage nitrogen use (commerce and pro-nitrogen types).

Figure 6.4 – Summary of policy interactions (RQ1).




Source: Prepared by the author.

In this way, we suggest that it would be more feasible to adapt and/or reformulate some of these existing policies to build a potential integrated approach, rather than designing new policies from scratch (even though new policies with innovative approaches would be highly encouraged). For example, updating the acceptable levels of pollutants to improve air and water quality, among other adjustments, in addition to expanding policies to adopt the biological nitrogen fixation and the sustainable use of fertilizers (1-ESA, the ABC Plan).

It is important to mention that depending on the research question, some conflicting outcomes emerge. This is the case of policies 9-FSA and 1-PSA, which have cancelling and constraining interactions with other policies, specifically in the context of an integrated nitrogen policy approach (RQ1) but show positive (and neutral) relations with some policies in a cross-interaction model (RQ2).

The National Fertilizer Plan (9-FSA) is a very emblematic example: while it has the potential to bring many benefits to agricultural production in Brazil (ensuring food and fuel security), it also encourages nitrogen use without concrete actions to promote sustainable fertilizer management and curb nitrogen pollution. For a future integrated nitrogen policy approach, we suggest reformulating this plan to include environmental concerns and to avoid constraining, counteracting, or even canceling other N-related policies from different sinks and sectors[11].

Finally, we also suggest that actors involved in the formulation of nitrogen policies come from multiple civil society organizations and government departments (environmental, agricultural, water supply, clean energy, transportation, industry, waste management, etc.) and consider all domains of sustainability (environmental, economic, social, and institutional). This is important not only to strengthen the coherence between nitrogen policies, but also avoid conflicts with other environmental policies (climate policies, for instance) that are not primarily aimed at reducing nitrogen pollution.

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[11] The National Fertilizer Plan is among the four hundred acts of the Federal Executive Power (2019-2022) indicated by a civil society organization (https://talanoainstitute.org/) to be revised or revoked for the reconstitution of the Brazilian climate and environmental agenda (TALANOA, 2022).

### 6.4 Conclusions

We started this study by stating that in Brazil, currently, there are no specific, exclusive or integrated measures to deal with nitrogen pollution, but only some policies that somehow included nitrogen concerns in their regulations. In this sense, it would be a burdensome task for the country to develop an integrated nitrogen policy, as recommended by the 2019 UNEP Resolution on Sustainable Nitrogen Management.

Nonetheless, the results of applying the policy coherence analytical framework show us that there are more positive than negative interactions between nitrogen policies, which is very favorable to sustainable nitrogen management. In addition, to be part of a future integrated approach, cancelling or constraining policies can be reassessed, reformulated, and/or adapted to address concerns related to the socio-environmental consequences of excess nitrogen.

# 7 CONCLUDING REMARKS AND FUTURE DEVELOPMENTS

The objectives of this thesis were to investigate important aspects of nitrogen management in Brazil that were still underexplored, that is, the underlying drivers of $N_r$ emissions, the sustainability of nitrogen use, and the adequacy of policy responses to deal with nitrogen pollution in the country. To achieve these goals, we performed an extensive literature review on the anthropogenic disturbances in the nitrogen cycle, historical data on $N_r$ emissions over the last five decades (including the share of emissions by productive sectors), challenges in nitrogen policy making, and recent global initiatives on sustainable nitrogen management (Chapter 3). This review provided us with a general theoretical basis for developing the following chapters of the thesis (specific literature reviews were also performed for Chapters 4 to 6).

In Chapter 4, we developed a conceptual model to understand the complexity of nitrogen dynamics in Brazil, the diversity of drivers, and potential impacts to environment and human health. Our findings showed that the driving forces behind the increase in $N_r$ emissions are the productive activities undertaken to meet the high demands for food, energy, and housing by a rapidly growing population. Through the application of the conceptual model to the Brazilian agricultural sector, we concluded that the increase in $N_r$ emissions is due to demand drivers (influenced by socioeconomic factors), but policy responses to deal with the nitrogen pollution problem depend on the structural drivers (political and institutional factors). Considering the country's governance issues (poor regulatory quality and law enforcement, for instance), designing and implementing mechanisms to promote sustainable nitrogen management would be a huge challenge for Brazil.

In Chapter 5, we calculated the level of nitrogen sustainability from 2000 to 2018 using the Entropy Weight Method (EWM). Our results indicated that political stability, fertilizer consumption, population growth, and investments in water and sanitation are important indicators for sustainable nitrogen management in the country. More specifically, political and institutional concerns are impacting sustainable actions towards nitrogen management, leading Brazil to reach a weak-to-basic level of sustainability in the studied period. Unsustainable nitrogen management can increase environmental, economic, and social issues, and impair the achievement of the Sustainable Development Goals, as well as other international agreements, as the Paris Agreement Targets for Climate Change and the Aichi Biodiversity Targets. Considering that knowing the indicators that impact the sustainability of nitrogen management could support the formulation of more appropriate policies, we suggest that further developments of this study include updated data (from 2019 onwards) and, if possible, some important indicators that could not be contemplated due to lack of data (ammonia emissions, among others).

In Chapter 6, we applied the Policy Coherence Analytical Framework to show the interactions (neutral, positive or negative) between N-related policies in Brazil and how these policies could foster the development (or be part of) a potential integrated nitrogen policy approach. As currently there are no specific, exclusive, or integrated policies in Brazil to deal with nitrogen pollution, the initial assumption of this study was that it would be an enormous burden for the country to develop policies for this purpose, as outlined in the 2019 UNEP Resolution on Sustainable Nitrogen Management. Our findings, however, showed that most policies are coherent and have positive interactions with each other. An exception is the 2022 National Fertilizer Plan, which was assessed as cancellation policy, since its implementation without any environmental concerns could make several other policies unfeasible, especially those aimed at reducing $N_r$ emissions. In this case, we suggest reformulating the plan with the involvement of multiple actors and stakeholders, in order to include environmental issues and avoid conflicts with other N-related policies.

It is important to emphasize that even if most of the analyzed policies present positive synergies, it does not necessarily mean that curbing nitrogen pollution would be an easy task (especially given the governance issues, as pointed out in Chapters 4 and 5), but rather that Brazil has already consolidated a significant path towards the introduction of integrated nitrogen policies.

Although this thesis has contributed to the debate on nitrogen management in Brazil, there is still much to be done, especially in the context of nitrogen policies, which is an emerging and challenging subject worldwide. In this sense, a potential research agenda for future studies in the field of public policy would include (i) building a conceptual model of an ideal integrated nitrogen approach specific to Brazil, considering the complexity of nitrogen use (benefits and costs) in the country, (ii) analyzing the steps towards shaping the nitrogen policy agenda, including mapping stakeholders and political processes, identifying antagonisms and institutional limitations, and assessing the feasibility of the ideal scenario, and (iii) analyzing the strategies that affect decision-makers and mapping intervention scenarios to visualize the future state of society and the environment under influence of policies. Different methods can be adopted to conduct these studies, such as the Advocacy Coalition Framework, the Social Network Analysis, and the Multiple Streams Framework, among others.

Ultimately, the expected outcome of this research agenda would be to contribute to the discussions towards the formation of a nitrogen policy agenda (agenda-setting) in Brazil, in order to attract government attention and convert the nitrogen problem into policy commitments. In addition, it could support the development of communication and education actions to increased public and institutional awareness of both the benefits and threats of nitrogen use, with a view to fostering adherence and effectiveness of N-policies.

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