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The Environmental Impacts caused by Agricultural Frontiers in Emerging Countries: The case of the MATOPIBA Region, Brazil

DOCTORAL DISSERTATION
(Summary)

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Contents

Abstract

The literature states that the advance of intensive agricultural production on the environment, known as the agricultural frontiers, is spreading mainly among emerging countries, due to lower production costs, flexible environmental regulations, soil fertility, and a favorable climate, among others. As a way of analyzing how environmental impacts are being generated and intensified, this dissertation presents a study of Brazil's newest agricultural frontier, Matopiba. The Matopiba region covers four states in the North and Northeast of Brazil and, although it comprises a large area of the Cerrado Biome, the region has gained considerable global importance due mainly to the production of soybeans and corn. Methodologically, this study used Descriptive Analysis, a Systematic Literature Review (SLR), and two empirical studies: Canonical Correlation Analysis (CCA) and System Dynamics Modeling (SDM). With the main objective of analyzing whether the Matopiba region of Brazil is a prominent topic in the world literature on agricultural frontiers and the environment in emerging countries, SLR showed that most of the world literature is concentrated in Brazil, but in the Amazon rainforest, indicating that studies on the Cerrado biome and the Matopiba region are still mainly concentrated among Brazilian researchers and are written in Portuguese. To analyze the environmental conditions generated by the agricultural frontier in Matopiba, CCA showed that there is a relationship between economic aggregates and environmental impacts in the region, with agricultural GDP having the highest canonical correlation with deforestation and one of the highest with CO_2 emissions. In addition, the CCA showed that agricultural production has a positive relationship with environmental impacts in Matopiba, with soybean and corn production, respectively, being the most polluting in the region. Intending to predict how long the available natural resources will sustain intensive agricultural production on Matopiba's agricultural frontier, the SDM showed that, as the agricultural area increases, native vegetation in areas with high and medium agricultural suitability is expected to be extinct within 20 years if no sustainable agricultural measures are implemented in the region. The results of these studies, among other findings, deepen the discussion on the environment and agricultural frontiers in emerging countries, contribute to the orientation of environmental public policies in Matopiba, and present a formulation of System Dynamics Modeling on agriculture and the environment that can serve as a basis for studies in other emerging countries.

Keywords: Agricultural Production. Environment. Brazilian Cerrado.

1. Introduction

1.1. Research Background

Agricultural frontiers, defined here as an expression indicating the advance of intensive agricultural production over the environment, are spreading mainly among emerging countries. Problems such as increased emissions of polluting gases, increased rates of deforestation, water pollution, and loss of animal biodiversity, among others, are the result of unsustainable agricultural production in these countries (Avagyan, 2021, 2017 and 2010; Adegbeye et al., 2020). Another problem is the increased use of fertilizers and pesticides, observed mainly in Latin America and Southeast Asia (Avagyan, 2018; Schreinemachers and Tipraqsa, 2012).

The Matopiba region, the main focus of this study, is Brazil's most recent agricultural frontier. With an area of around 73 million hectares and a population of 6.2 million (IBGE, 2022), Matopiba covers four states in the north and northeast of Brazil (**Ma**ranhão, **To**cantins, **Pi**auí, and **Ba**hia), which comprise a large part of the Cerrado biome and a small part of Brazil's Caatinga biome.

The region is experiencing enormous economic growth, driven mainly by soybean and corn production (De Oliveira, Raposo, & Garcia 2024; Dos Reis et al., 2024; Loayza et. al, 2023; Nunes, Campelo Filho, & Benini, 2023). In 2021, soybean production was 16 million tons and corn production was 7.4 million tons in Matopiba, making the region responsible for almost 15% of total soybean production and almost 9% of total corn production in Brazil (IBGE, 2022). This has given Matopiba considerable global importance in grain production.

However, the advance of Matopiba's agricultural frontier has mainly been at the expense of the natural resources available in the region (Araújo et al., 2024; Evangelista & Pereira, 2024; De Sampaio Melo, Júnior, & de Espindola, 2024; Da Silva Arruda et al., 2024; Siqueira et al., 2024; Agostinho et al., 2023; De Oliveira Aparecido et al., 2023; De Souza et al., 2023; Ferreira, 2023; Loayza et. al, 2023; Santos et al., 2023). More than 12 million hectares of natural vegetation in the Brazilian Cerrado were converted into agricultural areas between 2000 and 2022 (MAPBiomas, 2023). In addition, in 2019 alone, almost 41 million tons of polluting gases (CO_2 GWP-AR5) were emitted from agriculture in the region (SEEG, 2020).

1.2 Research Questions and Hypotheses

Against this backdrop, we have the following research questions and their respective hypotheses:

RQ1: Is the Matopiba region in Brazil a hot topic in the global literature on agricultural frontiers and the environment in emerging countries?

RQ 1.1: Are some emerging countries/regions more prominent in studies on agricultural frontiers and the environment?

H1: Despite the growing number of studies on the Matopiba region in Brazil, it is still not as prominent in the global literature on agricultural frontiers and the environment, since most of this research is concentrated among Brazilian researchers and is written in Portuguese.

RQ2: How can we systematize the literature on agricultural frontiers and the environment in emerging countries?

RQ 2.1: Are there any similarities between research on agricultural frontiers and the environment in emerging countries?

H2: Emerging countries are very diverse, but I believe there is some similarity between the research that emphasizes the relationship between agricultural frontiers and the environment in these countries. These studies essentially seek to measure the environmental impacts promoted by intensive agriculture, as well as to analyze more sustainable agricultural public policies and technologies.

RQ3. Is there any relationship between the economic aggregates and the environmental impacts generated on Matopiba's agricultural frontier?

RQ 3.1. Which economic aggregate contributes the most to environmental impacts in the Matopiba region?

H3: There is a relationship between economic aggregates and environmental impacts in the Matopiba region, with the agricultural sector contributing the most to environmental degradation.

RQ4. Is agricultural production in Matopiba related to the environmental impacts generated in the region?

RQ 4.1. Which crops contribute most to environmental impacts in Matopiba's agricultural frontier?

H4: Agricultural production has a relationship with environmental impacts in Matopiba, with soybean and corn production contributing the most to environmental degradation in the region.

RQ5: How soon will the native vegetation be exhausted in the agriculturally suitable areas of Matopiba?

H5: Matopiba's native vegetation is expected to be extinct in the agriculturally suitable areas within 20 years if current intensive agricultural production continues and no environmental intervention is implemented in the region.

1.3 Main Research Motivations

Concern about the environmental impacts of Matopiba's agricultural frontier is no coincidence and is gaining great repercussions. Although the Cerrado is important for global agricultural production, it is also home to many of the planet's endemic species and is one of Latin America's most important sources of fresh water. A worrying fact is that recovering the vegetation of the Cerrado biome is not simple, as the biome is more than 45 million years old (in a quick comparison, the Amazon is only 3,000 years old).

At first, I realized that, despite Matopiba's agricultural and environmental importance, this region has not yet "gained" worldwide repercussions when compared to the Amazon Region, for example. Therefore, the first motivation for this study is to verify whether the Matopiba region in Brazil is a prominent topic in the global literature on agricultural frontiers and the environment. This analysis will help to visualize a possible and important gap in the global literature on agricultural frontiers and the environment in emerging countries.

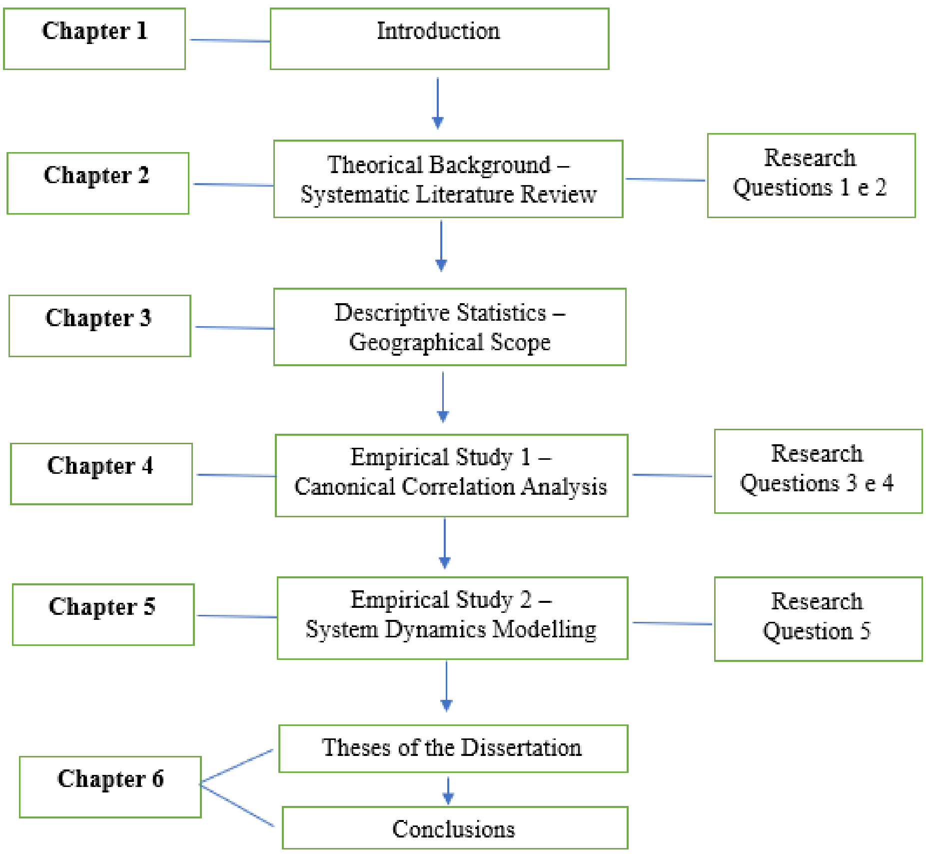
When relating to agricultural production and the environment in Matopiba, I realized that there are no studies that verify which crops are considered the most polluting or least sustainable in the region. Therefore, my second motivation was to fill this gap and formulate, using machine learning techniques, an analysis of environmental conditioning between crops. It is believed that this information will serve as a basis for formulating or encouraging sustainable agricultural policies.

Another concern that motivated this study was to find out how much time "we have left" to try to reverse or minimize the process of extinction of the Cerrado Biome present in Matopiba. With the help of System Dynamics Modeling, the complexity of the dynamic relationship between the main crops and natural resources in Matopiba can be verified and, from there, measures can be proposed to help make agricultural production more sustainable.

1.4. Structure of the Doctoral Dissertation

This dissertation is divided into six chapters, as shown in Figure 1. *Chapter 1* introduces the study. *Chapter 2* provides theoretical background. *Chapter* 3 provides the descriptive statistics. *Chapters 4* and *5* are the empirical studies of this dissertation. *Chapter 6* presents the theses of the dissertation, as well as the limitations and contributions to future research.

Figure 1: Structure of the Doctoral Dissertation



Source: Own Elaboration.

2. Literature Review: Agricultural Frontiers and Environment in Emerging Countries

To analyze and measure the environmental impacts of intensive agricultural production in emerging countries, it is necessary to consider the disparities and specificities of each region. Thus, this chapter[1] presents a Systematic Literature Review (SLR) of the main studies on the environmental impacts of agricultural frontiers in emerging countries from 1993 to 2022. To do that, the analysis initially included 14,366 scientific articles from a wide range of subjects in the social and natural sciences, available in the Web of Science (Clarivate Analytics), Google Scholar, and ScienceDirect (Elsevier) databases.

2.1 Key Studies by Country/Region

This section offers an overview of significant research conducted in emerging countries, highlighting the primary concerns of the authors in each region. Brazil, known as a global biodiversity hotspot, has been a focal point for studies on the environmental impacts of intensive agricultural production, especially in the Amazon Rainforest (Rodrigues et al., 2009; Pacheco, 2009; Macedo et al., 2012; Schiesari et al., 2013; Verburg et al., 2014; Ochoa-Quintero et al., 2015; Nobre et al., 2016).

In addition to studies on the Amazon, a few articles analyzed other Brazilian biomes of global importance, such as the Cerrado and the Atlantic Forest. With the implementation of the inclusion and exclusion criteria for this SLR (scientific articles ONLY written in English, published between 1993 and 2022, and with citation number greater than 50), only 3 articles dealt with the Brazilian Cerrado or the Matopiba region in Brazil. However, before the English language exclusion criterion was implemented, 98 articles considered to have a high impact factor dealt with the issue of the agricultural frontier and the environment in the Matopiba region. This shows that research on the Brazilian Cerrado or the Matopiba region is still at a local level, i.e. it is mainly concentrated among Brazilian researchers and is written in Portuguese.

Table 1 presents some of the literature on agricultural frontiers and the environment in other emerging countries and regions published from 2013 to 2022.

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[1] Chapter 2 is partly based on my systematic review article entitled "Agricultural Frontiers and Environment: A Systematic Literature Review and Research Agenda for Emerging Countries", carried out in 2022 and published in the Journal "Environment, Development and Sustainability" in 2023 (Sales, 2023).

Table 1: Reputable articles on Agricultural Frontiers and the Environment from 2013 to 2022

Reference	Study area	Approach / Issue	Contributions
Volante et al. (2016)	Argentina	Preservation or regeneration policies	The "Native Forest Law" was enacted to regulate the deforestation process; nonetheless, it proved insufficient to prevent the land from changing due to deforestation.
Deng and Gibson (2019)	China	Socioeconomic Factors	While eco-efficiency is better in developed city areas, land productivity is concentrated in cities located far from the provincial or economic center. Thus, sustainable agricultural output requires timely management of trade-offs between agricultural productivity and urbanization.
Horion et al. (2016)	Eurasia	General Approach	The collapse of the Soviet Union, the abandonment of farmland, and human influences (more salinization, increased grazing intensity, and altered irrigation techniques) have all contributed to a decline in rainfall use efficiency.
Athreya et al. (2013)	India	Biodiversity	Although a wide range of wild carnivores can be found on human-dominated agricultural land, the absence of other wild animals and wild herbivore prey suggests that agriculture has caused human intervention in native ecosystems.
Carlson et al. (2013)	Indonesia	Greenhouse gas emissions	Between 2000 and 2010, the country's 47% intact forest destruction was fueled by intensive palm oil development. According to projections, the growth of plantations in Kalimantan alone would be responsible for about 20% of Indonesia's CO_2 emissions in 2020 if this course was continued.
Busch et al. (2015)	Indonesia	Preservation or regeneration policies	The nation's rates of deforestation have increased because of concessions for oil palm plantations and logging operations in recently approved regions. The implementation of a carbon pricing program or broadening the moratorium to include not just existing concessions but also regions outside of concessions and protected areas would have prevented this.
Graesser et al. (2015)	Latin America	Land use	In Latin America, between 2001 and 2013, new agriculture and grassland displaced forests by 17% and 57%, respectively.
Meyfroidt et al. (2016)	Russia and Ukraine	Preservation or regeneration policies	After 2000, areas with a younger workforce and a growing rural population saw greater recultivation and less abandonment of crops. Just 8.5 million hectares (Mha) of the 47.3 million Mha of farmed land that was abandoned in 2009 may be used for agriculture with no cost to the environment and few socioeconomic limitations.
Jewitt et al. (2015)	South Africa	General Approach	Between 2005 and 2011, the primary factors contributing to the loss of 7.6% of KwaZulu-Natal's natural habitat were mining, dams, agriculture, and forestry plantations. Additionally, the residual biodiversity in these places or those nearby is negatively impacted by the anthropogenically altered land covers, including secondary vegetation.
Fehlenberg et al. (2017)	South America	Deforestation	Livestock in Argentina, Bolivia, and Paraguay was strongly linked to deforestation. However, soy farming in Argentina may have contributed indirectly to deforestation in Bolivia and Paraguay, as it was the only direct cause of deforestation in the Argentine Chaco.

Source: Own Elaboration.

2.2 The Connections between Agricultural Frontiers and the Environment

The literature review has concentrated on measuring the effects of intensive farming on remaining natural resources, along with analyzing more sustainable agricultural public policies and methodology. Consequently, the interaction between agricultural expansion and the environment in Emerging Countries will be explored in two distinct approaches: the Extended Industrial Agriculture Focus, which involves the literature's emphasis on measuring, analyzing, and interpreting the impacts on natural resources (including water, soil, air, wildlife, and plants) caused by the growth of agricultural activities; and the Socio-Economic-Ecological Focus, which examines how local socioeconomic factors and public policies influence population behaviors in the context of environmental and agricultural frontier interactions.

2.2.1 Extended Industrial Agriculture Focus

Several studies have shown significant environmental impacts resulting from the expansion of agricultural frontiers in emerging countries. Research with *Extended Industrial Agriculture Focus* has examined these impacts on a wide range of natural resources, including land, fauna, flora, air, and water. To do this, the researchers used argumentative/narrative text, satellite-based maps, and linear, probabilistic, and simulation models as the main methodologies.

The term "environment" is broad and subjective, leading some researchers to address multiple natural resources in a single study. Data revealed that studies analyzing two natural resources primarily focus on the environmental impact of agricultural production on land use or flora (deforestation) along with another resource.

2.2.2 Socio-Economic-Ecological Focus

To analyze the literature with a Socio-Economic-Ecological focus, the authors presented data on the environmental impacts caused by agricultural frontiers, with an emphasis on listing possible solutions for preservation and regeneration, in addition to examining how socioeconomic factors can influence environmental degradation. The discussion first addresses potential solutions to environmental issues and then considers the impact of socioeconomic aspects.

3. Matopiba: Brazil's Newest Agricultural Frontier

This chapter, descriptive and informative, aims to summarize the socio-economic and environmental characteristics of the Matopiba region in Brazil. The analysis was based on data provided by Brazilian institutes and projects.

3.1 Developmental Aspects

With an area of around 73 million hectares and a population of 6.2 million (IBGE, 2022), Matopiba is a region in the north and northeast of Brazil that encompasses four states: Maranhão (33% of the total area of this region), Tocantins (38%), Piauí (11%) and Bahia (18%), comprising 337 municipalities divided into 31 geographical micro-regions. In addition, Matopiba encompasses around 324,326 agricultural establishments occupying an area of approximately 36 million ha, as well as 781 agrarian reform settlements and quilombola areas (approximately 14 million ha), 46 ecological conservation units (8.4 million ha), and 35 indigenous lands (4.2 million ha) (Miranda, 2015).

According to the Regional, Urban and Environmental Bulletin developed by IPEA (Pereira, Porcionato, & Castro, 2018), Matopiba has been undergoing socio-economic transformations because of the expansion of intensive agriculture, in which social indicators, such as the Municipal Human Development Index (MHDI) and the Social Vulnerability Index (SVI), have shown trends of social improvement in Matopiba since the 2000s.

Between 2000 and 2021, the Matopiba region had a gross GDP growth rate of 1,419%, going from 10.6 billion reais in 2000 to 150.9 billion reais in 2021. Taking taxes into account, this growth is 1460%, from a current GDP of 11.3 billion in 2000 to 166 billion reais in 2021. The region's great economic growth has been driven mainly by agriculture and the goods and services sector (IBGE, 2022).

Agricultural production in Matopiba grew by 387% between 2000 and 2021, from 8.4 million tons in 2000 to 32.5 million tons in 2021. With an increase of 725%, soybean production went from 2.2 million tons in 2000 to 16 million tons in 2021. This growth has made soybean the main agricultural crop in Matopiba and one of the most important in Brazil, accounting for almost 15% of Brazil's total soybean production. Corn production increased from 1.3 million tons in 2000 to 7.4 million tons in 2021 (an increase of 560%). Currently, corn production represents 22% of

Matopiba's total production, and, together with soybeans, it is the region's main agricultural crop (71% of total agricultural production) (IBGE, 2022).

The progress of farming in Matopiba can also be seen when looking at the history of land cover in the region. Farming areas jumped from 16 million hectares in 2000 to 25.2 million in 2021. This increase was due to the intensive growth of pasture and agricultural areas. Pastureland increased by another 5 million hectares between 2000 and 2021 in Matopiba. The area devoted to agriculture grew by 381% in the same period, from 1.5 million hectares in 2000 to over 5.8 million in 2021, mainly due to the large production of soybeans and corn in the region (IBGE, 2022).

3.2 Environmental Aspects

In addition to an enormous animal biodiversity, Matopiba encompasses a diversity of endemic plants of global importance. However, around 12 million hectares of native vegetation were lost between 2000 and 2022. Native vegetation covered an area of around 53 million hectares in 2000 in Matopiba, while in 2022 this area was 41 million. Around 502,000 hectares of native vegetation are cleared every year in the region.

Data from MapBiomas (2024) shows that farming was responsible for 99.5% of the conversion of native vegetation between 2000 and 2022. Other factors, such as mining, urbanized areas, and aquaculture, had little influence, together accounting for just 0.5%. The conversion of vegetation into pasture amounted to 5.5 million hectares, which represents 50% of all vegetation converted in Matopiba between 2000 and 2022. Agriculture comes next, with a converted area of 3.45 million (31% of the total conversion).

In addition to the deforestation of native vegetation, the rates of carbon dioxide emissions from farming have also been increasing in Matopiba. Data from the Gas Emission Estimation System - Brazil (SEEG, 2020) shows that CO_2 emissions from farming increased by around 15 million tons (GWP-AR5) between 2000 and 2019. CO_2 emissions from farming increased from 25.7 million tons in 2000 to 40.6 million in 2019. Total CO_2 emissions in 2019 were just over 85.7 million tons, which means that farming is responsible for 47% of total CO_2 emissions in the region.

4. Verification of Environmental Conditions in the Matopiba Region

This chapter aims to use machine learning techniques to develop two statistical models to analyze the environmental conditions generated by the agricultural frontier in the region.

Canonical Correlation Analysis (CCA) was used to verify the relationship and magnitude of dependence between environmental impacts, economic growth, and agricultural production in Matopiba. This statistical technique of the machine learning approach was chosen because of the possibility of finding a linear combination in each set of variables that maximizes the relationship between one or more dependent and independent variables.

4.1 The Machine Learning Method

CCA is the general multivariate analysis model that uses metric and non-metric variables as dependent and independent variables. While multiple regression analysis involves one metric dependent variable and several independent variables, canonical correlation analysis relates a set of several dependent variables Y (metric and non-metric) to a set of several independent variables X (metric and non-metric) (Hair et al., 2009).

Models Specification

Model 1 consists of analyzing the canonical correlation between environmental and economic growth variables, which serves as the basis for proving Hypothesis 3 of this study. The analysis will be carried out in two stages: First, the relationship of dependence between environmental issues and the economic aggregates of GDP is initially verified. Second, if there is a significant correlation, an attempt is made to identify the relative contribution of the economic aggregates to explaining environmental impacts in Matopiba. Model 1 is described in the equation:

$$\propto_1 Y_1 + \propto_2 Y_2 = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

Where:

Y_1 represents CO_2 Total Emissions,

Y_2 is the Deforestation in the region,

X_1 represents Gross Value Added in Agriculture,

X_2 is the Gross Value Added in Industry,

X_3 is the Gross Value Added of Services and Administration,

$\propto$ are the correlation coefficients for each canonical dependent variable of Model 1,

β are the correlation coefficients for each canonical independent variable of Model 1.

Model 2 aims to analyze the canonical correlation between environmental and agricultural production variables, which serves as the basis for proving Hypothesis 4. The analysis is also carried out in two stages: Initially, the dependency relationship between environmental variables and the production of the main crops in Matopiba is verified. Secondly, the aim is to identify the contribution of each agricultural crop to environmental impacts in the region. Model 2 is described in the equation:

$$\propto_1 Y_1 + \propto_2 Y_2 = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$$

Where:

Y_1 represents CO_2 Agricultural Emissions,

Y_2 is the Deforestation in the region,

X_1 represents the Quantity Produced of sugar cane,

X_2 is the Quantity Produced of corn,

X_3 is the Quantity Produced of soybeans,

X_4 represents the Quantity Produced of rice,

$\propto$ are the correlation coefficients for each canonical dependent variable of Model 2,

β are the correlation coefficients for each canonical independent variable of Model 2.

In addition to the availability of databases, the environmental variables in Model 1 (deforestation of native vegetation and total CO_2 emissions) were chosen because these are the main environmental problems faced in the Matopiba region in recent years. For Model 2, CO_2 emissions exclusive to the agricultural sector were used to determine which of the region's main crops (sugar cane, corn, soy, and rice) are the most polluting. The choice of all the variables that make up CCA Models 1 and 2 was based on the data and information presented in Chapter 3. The analyses of both models used the 31 micro-regions of Matopiba as a sample.

4.2 Results of the Canonical Correlation Analysis

This section presents the results of the Canonical Correlation Analysis between Environmental Impacts and Economic Growth (Model 1), as well as between Environmental Impacts and Agricultural Production (Model 2). For both models, the assumptions of Normality, Linearity, and Multicollinearity were checked and met.

4.2.1 CCA Between Environmental Impacts and Economic Growth

The four significance tests showed statistically significant results at a level of 0.05 for Model 1, with Wilks' $\lambda = 0.21237$ ($F = 10.13962$; $p < 0.01$). Thus, there is probably a relationship between the economic aggregates of GDP and environmental impacts in Matopiba.

The effect size of the model was 0.78763, i.e. the proportion of variance shared between the two sets of variables in the two canonical functions is 78.76%. Taken together, the results (so far) indicate that the entire model is statistically significant and can be considered to have a large effect size (> 0.70).

The results of the dimension reduction analysis also show that the complete model 1 (all the roots of the canonical function) is statistically significant (Wilks' $\lambda = 0.21237$, $F = 10.13962$, $p < 0.01$). As a result, the three analyses (significance tests, size effects, and dimension reduction) show that there is a large and significant canonical relationship between environmental impacts and the economic aggregates of GDP in the Matopiba region.

The next step was to identify the relative contribution/effect of each GDP aggregate on environmental impacts. Analysis of the eigenvalues showed that the relationship between the variables is captured by the first and second functions in the canonical model. According to the results of the Squared Canonical Correlations (Sq. Cor) presented in Table 2, the first function explained 63.91% of the variation within its function (Sq. Cor = 0.63912), and the second function explained 41.15% (Sq. Cor = 0.41152) of the variation within its function, which means that they should be retained for interpretation.

Table 2: Eigenvalues and Canonical Correlations of Model 1

Roots	Eigenvalues	Percentage	Cumulative Percentage	Canonical Correlations	**Squared Canonical correlations (Sq. Cor)**
1	1.77098	71.691	71.691	0.79945	**0.63912**
2	0.69930	28.308	100	0.64150	**0.41152**

Source: Own Elaboration.

The magnitude of the Standardized Canonical Coefficients represents their relative contribution to the two canonical functions, but this is particularly unstable in the presence of multicollinearity. Although the assumption of the absence of multicollinearity has been met in both models, it is safer to interpret the Structural Canonical Correlations (Ho, 2013).

Looking at the coefficients of the Structural Canonical Correlations in Table 3, deforestation was the most significant dependent variable (0.71493) for the first canonical function and is directly associated with the Gross Value Added of Agriculture (0.54243). This means that an increase in Agricultural GDP positively affects deforestation in the Matopiba region.

Table 3: CCA between Environmental Impacts and Economic Growth

		Standardized Canonical Coefficients		**Structural Canonical Correlations**	
Dependent Variables (Environmental Impacts)		1º	2º	1º	2º
Y_1	CO_2 Total Emissions	- 0.73943	**0.75608**	- 0.42851	**0.90354**
Y_2	Deforestation	**0.95554**	0.45317	**0.71493**	0.69919
Independent Variables (GDP Economic Aggregates)					
X_1	Agricultural GDP	0.87158	0.61500	**0.54243**	**0.83996**
X_2	Industrial GDP	**- 1.11867**	**0.69941**	-0.40234	**0.85548**
X_3	Services GDP	0.27471	- 0.14035	-0.12641	0.81871

Source: Own Elaboration.

The second canonical function has CO_2 emissions as the most powerful dependent variable, with 0.90354. Analyzing the coefficients of the structural canonical correlations, it was observed that the Gross Value Added of Industry (0.85548) and Agriculture (0.83996) have greater canonical weights (positive relationship) for CO_2 emissions in Matopiba. The results of the structural canonical correlations in Model 1 indicate that there is a canonical relationship between environmental impacts and the economic aggregates of GDP in Matopiba, with agricultural GDP being the largest contributor to deforestation and one of the largest to the CO_2 emissions in the region.

4.2.2 CCA Between Environmental Impacts and Agricultural Production

The four significance tests and the results of the dimensional reduction analysis were also statistically significant for Model 2 (significance level = 0.05). With Wilks' $\lambda = 0.14909$ ($F = 21.95816$; $p < 0.01$), the null hypothesis that there is no relationship between the two sets of latent variables can be rejected.

The effect size of model 2 was also high, with a proportion of shared variance in the canonical functions of 85.09% (0.85091). This indicates that there is a relationship (strong) between agricultural production and environmental impacts in Matopiba.

According to the results of the eigenvalues and squared canonical correlations presented in Table 4, two canonical functions will also be interpreted in Model 2. The first canonical function explained 92.76% of the variation within its function (Sq. Cor = 0.92768), and the second function explained 32.12% (Sq. Cor = 0.32121).

Table 4: Eigenvalues and Canonical Correlations of Model 2

Roots	Eigenvalues	Percentage	Cumulative Percentage	Canonical Correlations	**Squared Canonical correlations (Sq. Cor)**
1	12.82682	96.44199	96.44199	0.96316	**0.92768**
2	0.47322	3.55801	100	0.56676	**0.32121**

Source: Own Elaboration.

As shown in Table 5, the first canonical function has CO_2 agricultural emissions as the strongest dependent variable (0.99078), with the greatest contribution from soybean and corn productions (0.65165 and 0.46621, respectively). Deforestation was the strongest dependent variable in the second canonical function (0.82464), indicating that soybean (0.78706) and corn (0.75353) productions are also the most responsible for deforestation in the region.

Table 5: CCA Between Environmental Impacts and Agricultural Production

		Standardized Canonical Coefficients		**Structural Canonical Correlations**	
Dependent Variables (Environmental Degradation)		1º	2º	1º	2º
Y_1	CO_2 Agricultural Emissions	**1.11374**	- 0.76397	**0.99078**	0.13545
Y_2	Deforestation	- 0.18294	**1.33814**	0.56566	**0.82464**
Independent Variables (Agricultural Production)					
X_1	Sugar Cane	0.33859	- 0.42799	0.28445	- 0.38664
X_2	Corn	0.08057	0.39142	**0.46621**	**0.75353**
X_3	Soybeans	**0.55343**	**0.43643**	**0.65165**	**0.78706**
X_4	Rice	**0.76432**	**- 0.44181**	0.41204	- 0.46357

Source: Own Elaboration.

The results of the canonical analysis showed that soy is the crop that generates the most deforestation of native vegetation and CO_2 emissions in Matopiba, closely followed by corn production, in other words, soybean and corn production are the main contributors to environmental impacts in the region. These results are also consistent with the descriptive analysis presented in Chapter 3.

5. Prediction of Environmental Conditions in the Matopiba Region

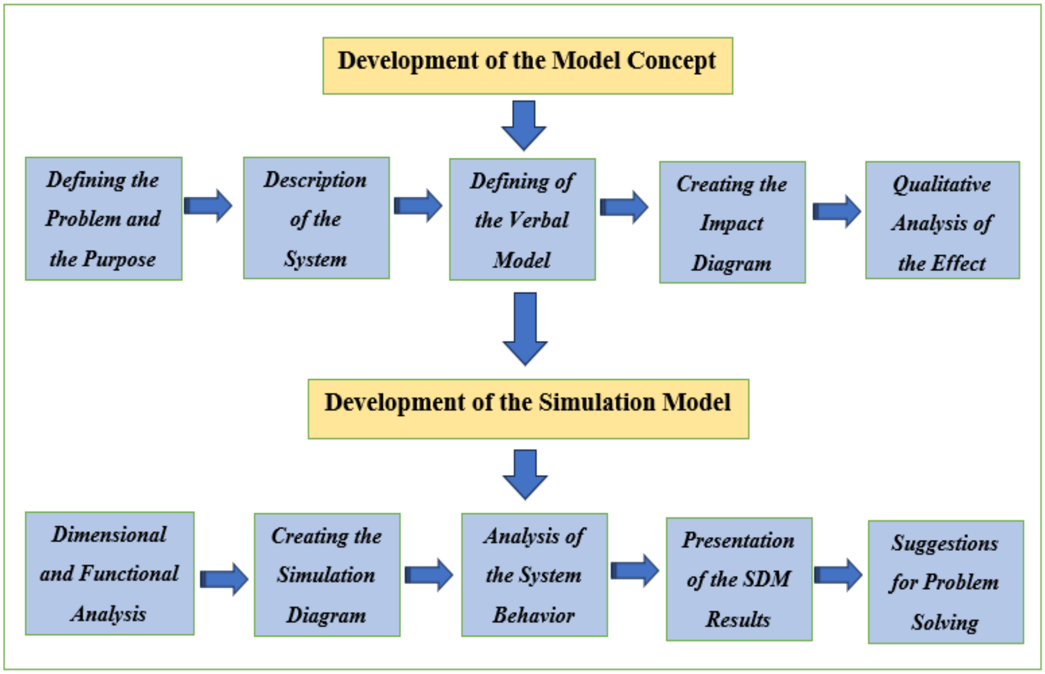
This chapter aims to use System Dynamics Modeling (SDM) to predict the future of Matopiba regarding available natural resources (land suitable for agriculture and native vegetation) and intensive agricultural production. From there, measures will be discussed to try to contain or slow down the process of environmental depletion in the region.

5.1 The System Dynamics Modeling Methodology

In summary, System Dynamics Modeling (SDM) focuses on integrating physical processes, information flows, and management policies with the dynamics of the variables of interest. The totality of these relationships constitutes the “structure” of the system, in which “dynamic behaviors” are generated over time. The main objective of the SDM is to understand the creation of the dynamics of interest (how and why) to seek out and propose management policies for the situation analyzed (Saysel, Barlas, and Yenigün, 2002).

With some similarity to other modeling approaches, the SDM application process consists of developing the model concept and developing the simulation model. This application process will be the schedule for interpreting the results of this study.

Figure 2: The Process of the System Dynamics Modeling Building



Source: Own Elaboration, based on Banks et al. (2013).

5.2 Development of the SDM Concept for Matopiba

Definition of the Problem and Justification for the Model

As discussed in Chapters 3 and 4, farming grew by 158% from 2000 to 2021, mainly due to the increase in pasture areas and soybean and corn production in the region. Consequently, the annual demand for land is also increasing, with more than 475,000 hectares of new land needed annually for farming in Matopiba, where approximately 203,000 hectares are required for agriculture, 184,000 for pastures, 79,000 for mosaic areas and 12,100 hectares on average per year for forest plantations. However, the Solidaridad Brasil study (Brasil, 2021) showed that Matopiba has only 6.6 million hectares of pasture suitable for agriculture, of which 4 million hectares are degraded pasture. In addition, the relative area of native vegetation with high and medium agricultural suitability and no slope restriction is around 7.5 million hectares (Rudorff et al., 2015). Therefore, the major challenge facing Matopiba's agricultural frontier today is to balance intensive agricultural production with the environment, in other words, to maintain production using the minimum area of native vegetation.

The following questions then arise: how long will the available natural resources (suitable land and native vegetation) support intensive agricultural production in Matopiba? What measures can be taken to try to contain or slow down the process of environmental depletion in the region? To answer these questions, the main objective of this chapter is to develop system dynamics modeling to predict the future of Brazil's newest agricultural frontier (Matopiba). To do this, we will look at the "lifetime" of the region's environmental resources without any action being taken to intensive agricultural production and, from there, propose (appropriate) solutions to this problem. The justification for the SDM is based on the importance of environmental and agricultural production of Matopiba for the world, while at the same time serving as a base model for other studies that address the environmental impacts of agricultural frontiers, especially in emerging countries.

Description of the System Components

The SDM for Matopiba consists of two *Stocks*: Native Vegetation Availability and Virgin Land Demand Availability. These subsystems are the main components of the model and have their values defined by input and output *Flows*. These two stocks were chosen due to the data and analyses presented in Chapters 3 and 4 of this dissertation, which show the direct relationship between agricultural production, increased demand for land, and environmental impacts (mainly deforestation of native vegetation).

Dynamic Variables are usually functions of constants and stocks that represent a state of the model and can assign themselves the result of a calculation or operation. This model has 24 dynamic variables, 21 of which are used to analyze the demand for farming land in Matopiba, 1 variable represents agricultural deforestation, 1 to analyze the impact of land demand on agricultural deforestation, and 1 dynamic variable to analyze other impacts on agricultural deforestation.

The *Parameters* represent some characteristics of the modeled object statically, i.e. it is a constant in a single simulation and is changed only when it is necessary to adjust the model's behavior. There are 23 parameters in the SDM for Matopiba, 20 of which are used as constants in the analysis of agricultural land demand, 1 represents the (constant) change in the forest plantation area, 1 constant to measure the impact of land demand on agricultural deforestation, and 1 parameter to represent non-agricultural deforestation.

It should be noted that soybeans and corn were the only crops used to construct parameters and dynamic variables for the demand for agricultural land since these are the most polluting and influential crops on Matopiba's agricultural frontier (discussed in Chapters 3 and 4).

Definition of the Verbal Simulation Model

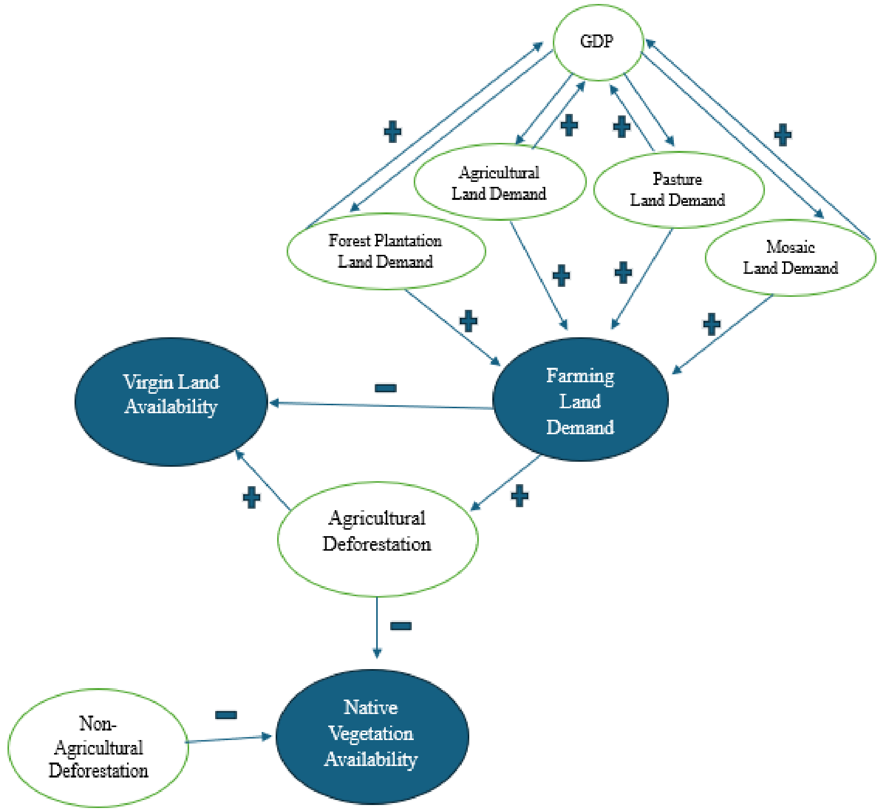
The relationships formed from SDM for Matopiba are as follows:

- Native Vegetation Availability is reduced by Agricultural Deforestation.
- Native Vegetation Availability is reduced by Non-Agricultural Deforestation.
- Agricultural Deforestation is driven by Farming Land Demand.
- Agricultural Deforestation is driven by Other Agricultural Factors.
- Virgin Land Availability is driven by Agricultural Deforestation.
- Virgin Land Availability is reduced by Farming Land Demand.
- Farming Land Demand is driven by Agricultural Land Demand.
- Farming Land Demand is driven by Pasture Land Demand.
- Farming Land Demand is driven by Mosaic Land Demand.
- Farming Land Demand is driven by Forest Plantation Land Demand.
- Agricultural Land Demand is driven by GDP.
- Pasture Land Demand is driven by GDP.
- Mosaic Land Demand is driven by GDP.
- GDP is driven by Agricultural Land Demand.
- GDP is driven by Pasture Land Demand.
- GDP is stimulated by Mosaic Land Demand.

Creation of the Model's Impact Diagram

As the basis of the simulation model, Figure 3 shows the Impact Diagram of the variables that make up the SDM for Matopiba.

Figure 3: The Impact Diagram of the SDM for Matopiba



Source: Own Elaboration.

Qualitative Analysis of the Impact Structure

As seen in the SDM Impact Diagram for Matopiba, the region's native vegetation is reduced by agricultural deforestation which, in turn, increases the area of land used mainly for agriculture. The use of land for agriculture leads to economic growth in the region (represented here by GDP) and this economic growth increasingly encourages demand for land, resulting in agricultural deforestation and, consequently, the reduction of native vegetation. This is the agricultural-environmental cycle that has been taking place in Matopiba in recent years.

5.3 Results of the System Dynamics Modeling for the Matopiba Region

Development of the dimensional and functional analysis of the model

Table 6 summarizes the initial values or functions that make up the stocks and parameters. The references for these values were the available literature, as well as official data from the Brazilian government for the year 2020. To estimate some internal parameters (fraction), Bivariate Regression Analyses were carried out.

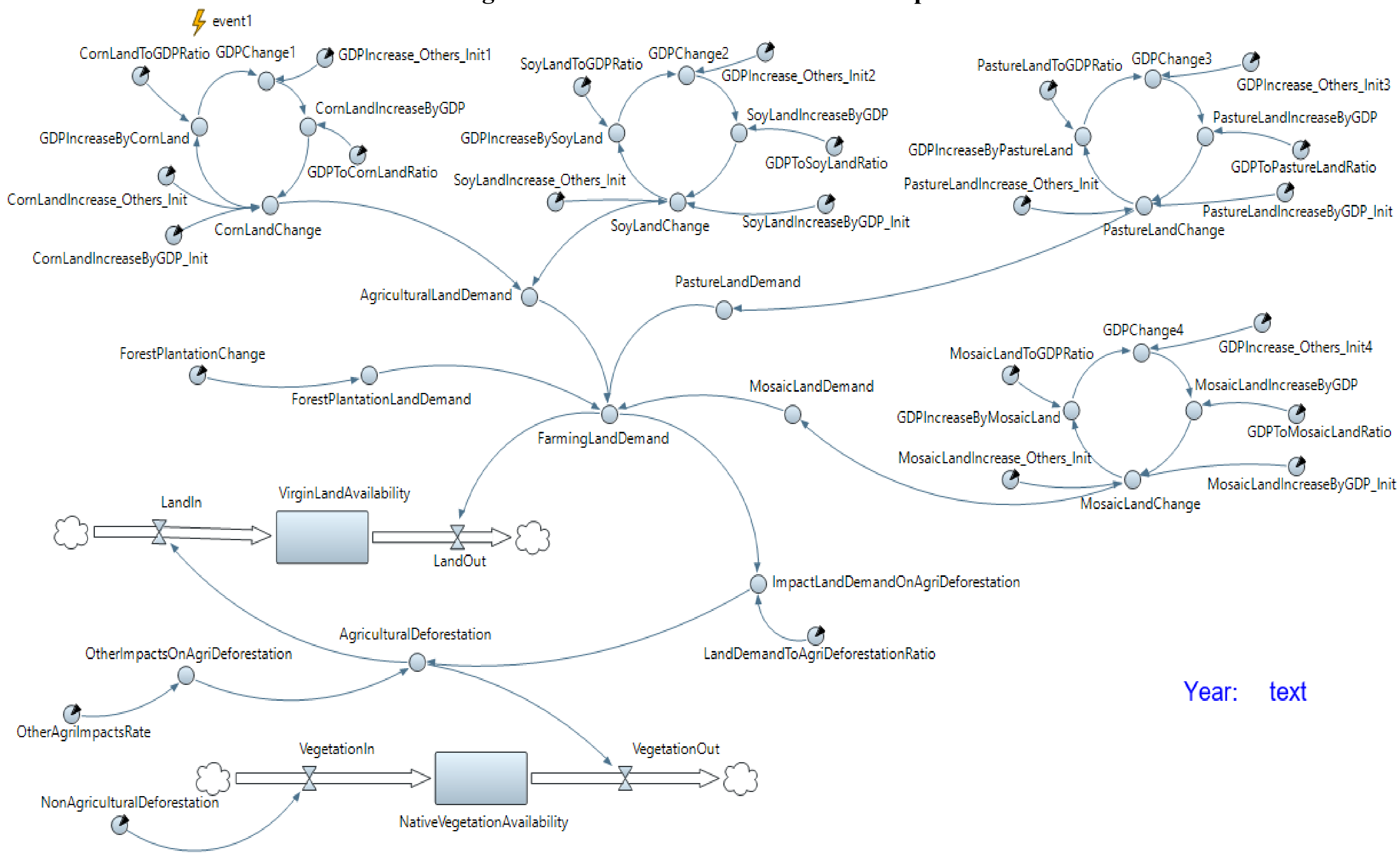
Table 6: Initial Values of Model Elements (stocks and parameters)

	Initial Value	Unit of Measurement	Source
Stocks			
NativeVegetationAvailability	7167.25	Thousand Hectares	MAPBiomas, Brazil.
VirginLandAvailability	2630.38	Thousand Hectares	MAPBiomas, Brazil.
External System Parameters (Constants)			
NonAgriculturalDeforestation	26.78	Thousand Hectares	MAPBiomas, Brazil.
OtherAgriImpactsRate	132.00	Thousand Hectares	MAPBiomas, Brazil.
ForestPlantationChange	14.51	Thousand Hectares	MAPBiomas, Brazil.
Internal System Parameters			
LandDemandToAgriDeforestationRatio	0.815	Fraction	Own parameter estimation[2].
CornLandToGDPRatio	152.738	Fraction	Own parameter estimation.
SoyLandToGDPRatio	30.968	Fraction	Own parameter estimation.
PastureLandToGDPRatio	22.284	Fraction	Own parameter estimation.
MosaicLandToGDPRatio	57.565	Fraction	Own parameter estimation.
GDPToCornLandRatio	0.00637	Fraction	Own parameter estimation.
GDPToSoyLandRatio	0.03237	Fraction	Own parameter estimation.
GDPToPastureLandRatio	0.04491	Fraction	Own parameter estimation.
GDPToMosaicLandRatio	0.01528	Fraction	Own parameter estimation.
CornLandIncreaseByGDP_Init	20.89	Thousand Hectares	MAPBiomas, Brazil.
SoyLandIncreaseByGDP_Init	196.25	Thousand Hectares	MAPBiomas, Brazil.
PastureLandIncreaseByGDP_Init	245.19	Thousand Hectares	MAPBiomas, Brazil.
MosaicLandIncreaseByGDP_Init	3.11	Thousand Hectares	MAPBiomas, Brazil.

Source: Own Elaboration.

[2] To estimate the “own parameters”, databases provided by MAPBiomas - Brazil and IBGE - Brazil were used.

Figure 4: Structure of the SDM for Matopiba



Source: Own Elaboration, based on AnyLogic output.

Analysis of the system's behavior (modeling tests)

The SDM simulation for forecasting was run from 2020 until the exhaustion of the main source of natural resources available for agricultural production in Matopiba (Availability of Native Vegetation). However, before analyzing these values, it is necessary to discuss the model's calibration and validation process, as well as the system's behavior.

Calibration Process: To verify that the parameters used in the SDM simulation are reliable, the calibration process was initially carried out, which consisted of simulating the SDM until 2020 (the year the SDM simulation for Matopiba began) and verifying that the results correspond to the real data. In the calibration process, the analysis was carried out from 2001 to 2011. In this process, the average difference between the model's simulated values and the real values of the main elements that make up the SDM (Native Vegetation Availability, Virgin Land Demand Availability, Farming Land Demand, and Agricultural Deforestation) was observed. As a result, the average difference between the real values and the simulated values in the calibration process was between -2% and 0%, thus demonstrating the strong reliability of the parameters that make up the SDM.

Validation Process: As its name suggests, the validation process aims to "validate" the parameters and initial values of the elements that make up the SDM. Once validated, these values will be used as the basis for the (future) simulation of the SDM for Matopiba. The validation process, like the calibration process, consists of simulating the SDM until 2020 and verifying whether the results correspond to the real data, however, in the validation process, the analysis was carried out from 2001 to 2020. The average difference between the model's simulated values and the actual values of the main elements that make up the model in the validation process was between 0% and 1%, thus demonstrating the strong reliability of the SDM data.

System's behavior: The behavior of the system shows the trend of the elements that make up the SDM for Matopiba from 2020 onwards. This system's behavior then reflects the continuation of the trend observed in the validation process. In the coming years (from 2020 onwards), the area of land suitable for farming is expected to increase as the region's native vegetation is depleted. This is stimulated by a growing demand for farming land and agricultural deforestation.

System Dynamics Modeling Results for Matopiba Region

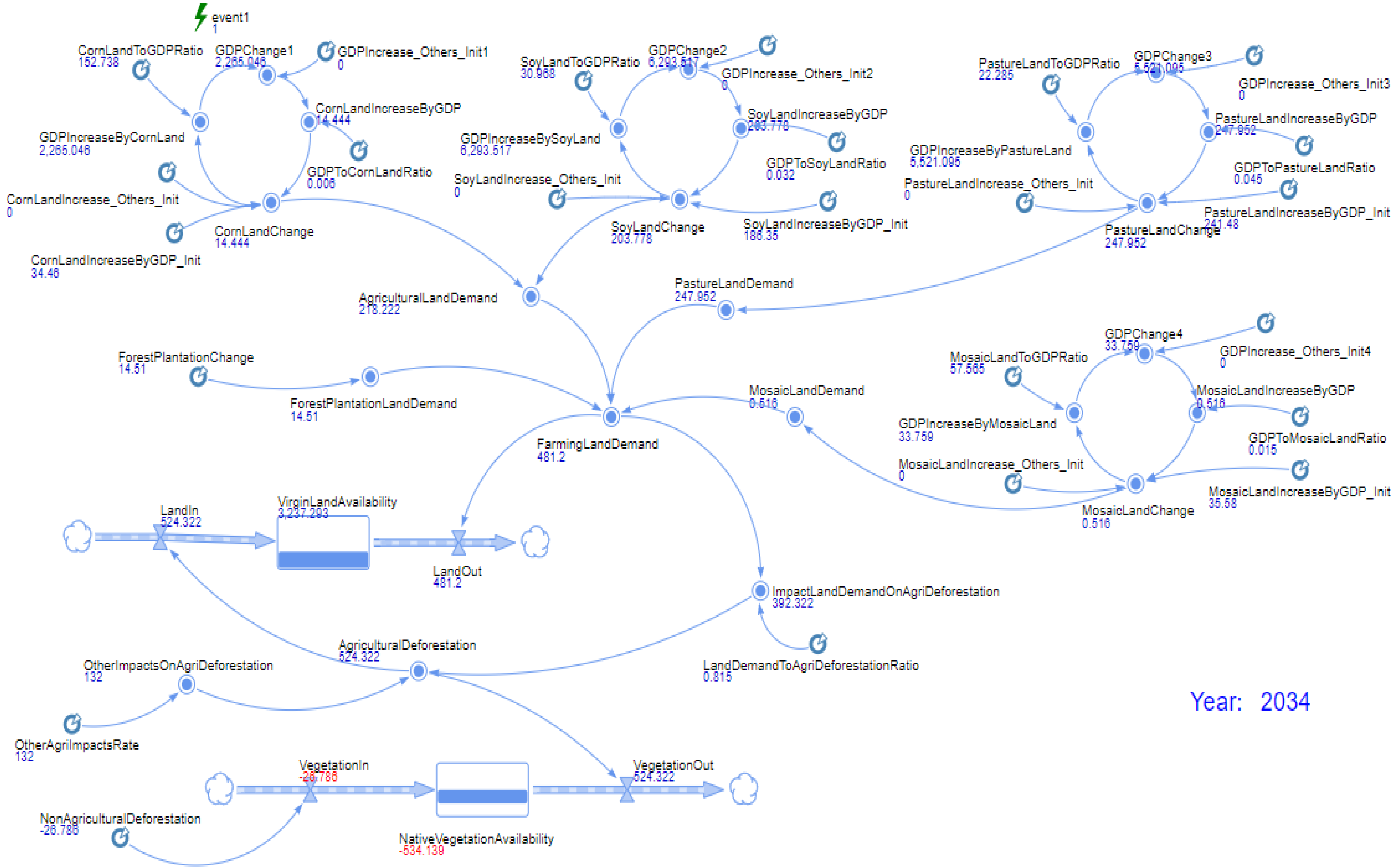
The SDM for Matopiba showed that Native vegetation in areas with high and medium agricultural suitability in Matopiba is expected to be exhausted within 20 years if no environmental intervention or policy is implemented in the region. As the analysis was carried out from the year 2020, native vegetation is expected to be extinct by around 2034.

As the area of native vegetation is the main source of intensive agricultural production, this result confirms the high environmental impact of Matopiba's agricultural frontier, as well as showing that producers and the government will have to stimulate innovative measures to try to meet the demand for land for agricultural production.

Driven mainly by the increase in the area coming from agricultural deforestation (which is expected to be around 525,000 hectares per year), the data shows that the virgin area suitable for agriculture is set to increase in 20 years. In addition, there is also an upward trend in the demand for new agricultural land (virgin land demand), which is expected to reach more than 480,000 hectares per year within 20 years.

The results also confirm that there is a high conversion cycle between agricultural areas in Matopiba, with pasture and soybean production requiring the largest percentage of new agricultural areas in the region in the coming years. Therefore, the innovative measures that will be proposed must be based on the demand for land for these two crops.

Figure 5: SDM Simulation Results for Matopiba



Source: Own Elaboration, based on AnyLogic output.

Suggestions for problem-solving

The SDM results showed that the area of native vegetation is the main source of intensive agricultural production in Matopiba, with pasture and soybean production demanding the most new areas. The problem is how to maintain production and the growing demand for agricultural land using the minimum area of native vegetation.

Measures such as tightening environmental tax legislation, environmental regeneration and reforestation policies, and the use of sustainable agricultural technologies, among others, could be useful in solving this problem. However, without ruling out the other measures mentioned, this study presents the incentive for crop-livestock-forest integration (CLFI) as a viable solution for maintaining Matopiba's agricultural frontier and the Cerrado biome at the same time.

Data from EMBRAPA (Skorupa et al., 2019) confirms that 65% of agricultural expansion in Matopiba has been due to the conversion of native forests and 35% to the conversion of pastures and other crops. As a result, the expansion of agricultural production is expected to be exhausted in native areas in the coming years, causing productive development to occur based on changes in the economic uses of the land. In addition, the study by Solidaridad Brasil (Brasil, 2021) states that Matopiba has 6.6 million hectares of pastures with agricultural aptitude, of which 4 million hectares are degraded pastures. Converting degraded pasture areas into crops through the CLFI system is therefore a viable option for expanding sustainable agricultural production in the region.

In short, the CLFI system integrates crops (agriculture), pastures (livestock), and forests in the same area and can be applied through crop rotation or succession at specific times. The CLFI system can then be configured as one of the preventive actions (political implications) for the environmental restructuring of the Cerrado Biome and the Matopiba region (Leite et al., 2024; Oliveira et al., 2024; Júnior & Figueiredo, 2023; Barbosa et al., 2022; Da Silva et al., 2021; Gontijo Neto et al., 2018; Torres, Assis & Loss, 2018; Gil, Garrett & Berger, 2016; Rangel et al., 2016; Costa et al., 2015; De Moraes et al., 2014; Garcia et al., 2013; Balbino et al., 2011; Silva et al., 2011; Vilela et al., 2011).

EMBRAPA has been developing the CLFI system in Matopiba since 2005, considering the environmental and economic specificities of each state and sub-region. According to the report (Skorupa et al., 2019), the states of Maranhão and Piauí and the western region of Bahia have the potential to expand CLFI in the current grain and livestock-producing areas. In Tocantins, the potential for expanding CLFI lies in the degraded areas.

Through the research carried out by Skorupa et al. (2019) over ten years with partner farms in the Matopiba region, an increase in the economic and productive development of the region was observed due to the increased production of corn and soybeans in CLFI systems and the generation of employment and income due to crop rotation. In addition, the report shows important results in terms of environmental regeneration (mainly of the soil) in Matopiba through the increase in water retention capacity in the soils using the CLFI system, as well as a considerable increase in the content of organic matter present in the soil. It is therefore believed that the implementation and increasing encouragement of the CLFI system represents an alternative for meeting the demand for land suitable for agriculture (mainly through the regeneration of degraded soils), as well as for more sustainable production in Matopiba.

6. Theses of the Doctoral Dissertation

6.1. Theses

This chapter presents my research theses based on the results of the Systematic Literature Review, Canonical Correlation Analyses, and System Dynamics Modeling, presented in *Chapters 2, 4,* and *5*, respectively.

Chapter 2 presented a Systematic Literature Review on agricultural frontiers and the environment in emerging countries. As well as being the main theoretical source of the dissertation, this chapter provided answers to Research Questions 1 and 2:

RQ1. Is the Matopiba region in Brazil a hot topic in the global literature on agricultural frontiers and the environment in emerging countries?

RQ1.1. Are some emerging countries/regions more prominent in studies on agricultural frontiers and the environment?

To find out whether the Matopiba region in Brazil is an important topic in the global literature on agricultural frontiers and the environment in emerging countries, the analyses presented in subchapter 2.1 were checked. It showed that most studies on the agricultural frontier and the environment in emerging countries are concentrated in Brazil. However, this focus is especially (almost exclusively) on the Amazon rainforest. Subchapter 2.1 also showed that research on the Cerrado Biome and the Matopiba Region is still at a regional level, in which there are few studies written in English and with a high impact factor (inclusion and exclusion criteria for this study).

Thus, based on the results presented in Subchapter 2.1, **Hypothesis 1** of this study is accepted, and **Thesis 1** of this dissertation is formed:

THESIS 1

The literature on agricultural frontiers and the environment in emerging countries has focused mainly on Brazil's Amazon rainforest. Despite the growing number of studies on Brazil's Matopiba, this region has not yet been given as much prominence in the world literature on agricultural frontiers and the environment, since most of this research is concentrated among Brazilian researchers and is written in Portuguese.

To answer how we can systematize the literature on agricultural frontiers and the environment in emerging countries (RQ2), I initially checked whether there are similarities between these studies amidst the great diversity that exists between emerging countries (RQ2.1).

RQ2. How can we systematize literature on agricultural frontiers and the environment in emerging countries?
RQ2.1. Are there any similarities between research on agricultural frontiers and the environment in emerging countries?

In subchapter 2.2 (The Connections between Agricultural Frontiers and the Environment) of the Systematic Literature Review was observed that research in emerging countries has two main focuses: measuring the effects of intensive agriculture on remaining natural resources and analyzing and/or proposing more sustainable agricultural public policies and technologies. With this finding, **Hypothesis 2** of this study is accepted, and **Thesis 2** of this dissertation is formed:

THESIS 2

Despite the enormous diversity between emerging countries, the literature on agricultural frontiers and the environment in these countries is similar, as it essentially seeks to measure the environmental impacts caused by intensive agriculture, as well as analyze agricultural technologies and public policies. Thus,

these two research focuses are currently the best way to systematize the literature on agricultural frontiers and the environment in emerging countries.

Using machine learning techniques, *Chapter 4* analyzed the environmental conditions generated by Matopiba's agricultural frontier. This empirical study provided answers to Research Questions 3 and 4:

RQ3. Is there any relationship between the economic aggregates and the environmental impacts generated on Matopiba's agricultural frontier?

RQ3.1. Which economic aggregate contributes the most to environmental impacts in the Matopiba region?

To answer whether there is any relationship between the economic aggregates and the environmental impacts generated by the Matopiba agricultural frontier, subchapter 4.2.1 was checked. Subchapter 4.2.1 brought the results of the canonical correlation analysis between the economic variables (GDP aggregates) and the environmental variables (deforestation, CO_2 emissions). The analysis showed that there is a strong relationship between economic aggregates and environmental impacts in Matopiba, with agricultural GDP contributing the most to environmental degradation.

Based on these results, **Hypothesis 3** of this study is accepted, and **Thesis 3** of this dissertation is formed:

THESIS 3

There is a relationship between economic aggregates of GDP and environmental impacts in the Matopiba region of Brazil, with the agricultural sector having a positive and the highest correlation with deforestation and one of the highest magnitudes with CO_2 emissions in the region.

Subchapter 4.2.2 provided an analysis of the canonical correlation between the production of Matopiba's main crops (soybeans, corn, sugarcane, rice, etc.) and the variables that represent environmental impacts, thus providing answers to Research Question 4:

RQ4. Is agricultural production in Matopiba related to the environmental impacts generated in the region?

RQ4.1. Which crops contribute most to environmental impacts in Matopiba's agricultural frontier?

The analysis presented in Subchapter 4.2.2 showed that there is a strong relationship between agricultural production and environmental impacts in the Matopiba region, with soybean and corn production contributing the most to these impacts. Thus, Hypothesis 4 of this study is accepted, and Thesis 4 of this dissertation is formed:

THESIS 4

Agricultural production has a relationship with environmental impacts in the Matopiba region of Brazil, with soybean and corn production consecutively being the biggest contributors to deforestation and agricultural CO_2 emissions in the region.

Chapter 5 used System Dynamics Modeling (SDM) to predict the future of the Matopiba Region regarding available natural resources and intensive agricultural production. This empirical study provided the answer to Research Question 5:

RQ5: How soon will the native vegetation be exhausted in the agriculturally suitable areas of Matopiba?

Subchapter 5.3 showed that the area of native vegetation with high and medium agricultural suitability is expected to be exhausted within 20 years in Matopiba if no environmental intervention or policy is implemented in the region. This will occur due to intense agricultural production and increased demand for land. Based on these results, Hypothesis 5 of this study is accepted, and Thesis 5 of this dissertation is formed:

THESIS 5

Native vegetation in areas with high and medium agricultural suitability in Matopiba is expected to be extinct within 20 years if current intensive agricultural production continues and no environmental intervention is implemented in the region. As the SDM analysis was carried out from the year 2020, native vegetation is expected to be extinct by around 2034. This extinction of native vegetation is

associated with intensive agricultural production and increased demand for agricultural land in the region.

6.2 New and Novel Results

Firstly, the Systematic Literature Review showed that there is a certain similarity in the studies on agricultural frontiers and the environment in emerging countries, in which the authors essentially sought to measure the environmental impacts caused by intensive agriculture and evaluate public policies and the use of agricultural technologies. In addition, the SRL showed that there are still few studies on the agricultural frontier of Matopiba written in English, thus opening up an important gap to be filled in the literature on emerging countries.

Secondly, using Canonical Correlation Analyses, it was possible to verify which of the GDP aggregates and which of the main crops produced in Matopiba are directly correlated with CO_2 emission rates and the deforestation of native vegetation in the region. As well as being a pioneer in the use of Machine Learning technologies, the results of the CCA help to develop more sustainable public policies.

Through System Dynamics Modeling, it was observed that native vegetation in areas with high and medium agricultural suitability in Matopiba is expected to be extinct within 20 years, mainly due to intensive soybean production and the increased demand for agricultural land for pasture areas, as well as for soybean production. These results make a relevant contribution to the implementation of environmental actions in Matopiba, as they show the fields that should be prioritized and worked on to promote more sustainable agricultural production.

In addition to all the new results presented, this study is a pioneer in the use of a Systematic Literature Review to analyze the literature on the environment and agricultural frontiers in emerging countries; it is a pioneer in the use of Machine Learning techniques to analyze environmental and economic variables (together) for Matopiba; as well as a pioneer in the formulation of a System Dynamics Modeling on agricultural production and environmental impacts for the Brazilian Cerrado.

6.3. Study Limitations and Future Research

Firstly, the Systematic Literature Review used inclusion and exclusion criteria which, even following the guidelines of the literature, are subjective and, once used, can obscure important studies. In addition, the key terms used for the analysis may also have obscured some emerging countries or regions. Therefore, a suggestion for future research is, in addition to updating the period of analysis, to include emerging countries or regions that were not used in the study.

Secondly, for the Canonical Correlation Analysis, only the proxies for deforestation of native vegetation and CO_2 emissions were used as environmental variables. The initial idea was to use a variable that represented the reduction of drinking water in the region, believing that this inclusion would bring an important debate to Matopiba's agricultural frontier. However, no database was found that represented the reduction of drinking water. Therefore, an important suggestion is to include this variable in the analysis.

It was noted by System Dynamics Modeling that there is a tendency for agricultural deforestation to be greater than the demand for land in Matopiba in the coming years. Moved to try and discuss this issue, and I came across a report by the Climate Observatory (2023) which explains that the SAD Cerrado alert detection system has been incorporated operationally, which provides more accurate data on deforestation in the Cerrado (Matopiba). The report also provides the relevant information that deforestation in Matopiba is spreading to Legal Reserves and Permanent Protection Areas, areas that could not even be touched. From these two pieces of information, it can be deduced that the deforestation surplus in Matopiba is due to improved detection systems in the region compared to other data, as well as the fact that the data on demand for agricultural land does not include Legal Reserves and Permanent Protection Areas in the Cerrado. As this is only an assumption, it opens up a gap for future research.

Through the SDM it was also seen the dynamic connections between the environmental and economic components of Matopiba, as well as the “duration” of each of these components. However, the model did not include variables representing solutions to the problem presented. Despite mentioning that the CLFI system is one of the preventive actions (political implications) for the environmental restructuring of Matopiba and the Cerrado Biome, there was no simulation to verify the effect of this action. I, therefore, suggest including the CLFI system, or another relevant preventive action, in System Dynamics Modeling for Matopiba.

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