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Farmland abandonment in Rio de Janeiro State, Brazil: underlying, proximate causes, and predisposing factors

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Pedro Ivo Bastos de Castro

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Referent: Prof Dr. Sven Lautenbach

Korreferent: Prof. Dr.-Ing. Theo Kötter

Korreferentin: Prof. Dr.-Ing. Ribana Roscher

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Abstract

Along the RJ-196 road, where imperial palm trees stand near the ruins of old sugar mills and dirty pastures, the landscape tells a story of change: a story of agricultural abandonment. These abandoned sugarcane fields are the focus of this thesis, which explores the issue of land abandonment in Rio de Janeiro. The transformation of these once-thriving agricultural lands into degraded pastures reflects a broader trend with important consequences for food security, the economy, and the environment. This thesis examines two key aspects: first, it analyzes the agricultural abandonment in Rio de Janeiro through an established theoretical framework in land-use science; second, it engages with existing studies based on this framework to broaden the discussion. The research focuses on three main categories: underlying and proximate causes, predisposing factors of abandonment, and its occurrence in Northern Rio de Janeiro, where the phenomenon is particularly evident. The study employs several methodologies to map and analyze the temporal and spatial extent of abandoned farmland. These are structured into four steps: (i) a descriptive analysis of cropping trends and spatial patterns, (ii) a larger-scale investigation of underlying causes, (iii) spatial mapping of sugarcane abandonment, and (iv) an analysis of the proximate causes and biophysical predisposing factors contributing to this abandonment. Interrupted Time Series Analysis (ITSA) was used to test the hypothesis that policy changes—such as the end of subsidies and the closure of the IAA—played a role in the decline of the sugarcane industry and subsequent land abandonment. Additionally, mapping efforts evaluated whether existing datasets accurately represented the timing and extent of farmland abandonment, particularly for sugarcane. Generalized linear models were employed to explore the biophysical predisposing factors and proximate causes driving farmland abandonment in Rio de Janeiro. The findings reveal that the primary reason for farmland abandonment in Rio de Janeiro is the decline of sugarcane cultivation in the Norte Fluminense region. Key factors include poor infrastructure, lack of irrigation, urban and industrial development, topographic challenges, uneven rainfall, and policy reforms. This research offers critical insights into the causes and extent of agricultural abandonment in Rio de Janeiro State.

Zusammenfassung

In Rio de Janeiro, Brasilien, erstreckt sich eine Landschaft, in der Kaiserpalmen neben den Ruinen alter Zuckermühlen und degradierten Weideflächen stehen – ein deutliches Zeichen für den Wandel einer ehemals landwirtschaftlich genutzten Region. Im Mittelpunkt dieser Arbeit stehen die aufgegebenen Zuckerrohr-Ackerbauflächen, die das Phänomen der Aufgabe des Ackerbaus im Bundesstaat Rio de Janeiro beleuchten. Der Rückgang dieser Flächen hat erhebliche Auswirkungen auf die Ernährungssicherheit, die Wirtschaft und die Umwelt. Die Arbeit untersucht zwei wesentliche Aspekte: Erstens wird die Aufgabe des Ackerbaus in Rio de Janeiro durch ein bewährtes theoretisches Rahmenwerk der Landnutzungswissenschaft analysiert. Zweitens werden bestehende Studien einbezogen, um die wissenschaftliche Diskussion zu erweitern und zu vertiefen. Der Forschungsschwerpunkt liegt auf drei Hauptkategorien: zugrundeliegende und unmittelbare Ursachen, begünstigende Faktoren sowie das Auftreten dieses Phänomens im Norden von Rio de Janeiro, wo es besonders stark ausgeprägt ist. Zur Untersuchung wurden verschiedene Methoden eingesetzt, um das zeitliche und räumliche Ausmaß der Aufgabe des Ackerbaus zu erfassen und zu analysieren. Diese Analyse gliedert sich in vier Schritte: (i) eine deskriptive Analyse der Anbautrends und räumlichen Muster, (ii) eine umfassende Untersuchung der zugrundeliegenden Ursachen, (iii) die räumliche Kartierung der Zuckerrohraufgabe und (iv) eine Analyse der unmittelbaren Ursachen sowie der biophysikalischen begünstigenden Faktoren. Um die Hypothese zu testen, dass politische Maßnahmen – wie das Ende von Subventionen und die Schließung des IAA – zum Niedergang der Zuckerrohrindustrie und zur anschließenden Aufgabe landwirtschaftlicher Flächen führten, wurde die Methode der Interrupted Time Series Analysis (ITSA) angewandt. Zudem wurde untersucht, inwieweit bestehende Datensätze den Zeitpunkt und das Ausmaß der Flächenstilllegung, insbesondere bei Zuckerrohrfeldern, präzise abbilden können. Generalisierte lineare Modelle wurden genutzt, um die biophysikalischen begünstigenden Faktoren und unmittelbaren Ursachen der Flächenaufgabe in Rio de Janeiro zu untersuchen. Die Ergebnisse zeigen, dass der Hauptgrund für die Aufgabe des Ackerbaus in Rio de Janeiro der Rückgang des Zuckerrohranbaus in der Region Norte Fluminense ist. Zu den ausschlaggebenden Faktoren zählen schlechte Infrastruktur, fehlende Bewässerung, städtische und industrielle Entwicklungen, topografische Herausforderungen, unregelmäßige Niederschläge und agrarpolitische Reformen. Diese Arbeit liefert wesentliche Erkenntnisse über die Ursachen und das Ausmaß der landwirtschaftlichen Flächenstilllegung im Bundesstaat Rio de Janeiro.

Dedication

To my mom and dad, who, despite not having much formal education, understood its value and fostered it throughout my life. And especially to my son Valentim, who made me a better person and brought real joy to my life.

Declaration / Erklärung

I hereby declare that I am the author of this Ph.D. Thesis, and I have not used sources other than those listed in the bibliography and identified as references. I further declare that this dissertation is part of a cumulative Ph.D. Thesis, in which I am the leading author of all the articles.

Hiermit erkläre ich, dass ich die vorliegende Promotionsarbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt have. Außerdem erkläre ich, dass ich nicht bereits anderweitig versucht habe, diese Dissertation ohne Erfolg einzureichen oder mich einer Doktorprüfung zu unterziehen. Ich erkläre ebenso, dass ich die Hilfe von gewerblichen Promotionsberatern bzw. -vermittlern weder bisher in Anspruch genommen habe, noch künftig in Anspruch nehmen werde.

Contents

1

Introduction

1.1 Land Use Science

Throughout history, humankind has continually transformed natural spaces to meet their needs. Different societies have emerged, each bringing different practices and ways of interacting with the environment. From the earliest, less intrusive forms of interaction to the verge of environmental depredation, humanity has left diverse marks across the globe, reflecting its journey towards a massive presence and a source of disruption.

As societies have developed and increasingly modernized, the drive for knowledge and technological progress has boosted us towards a more globally linked world. This development, while marking advances in various fields, has also led to an increased impact on the environment. Systematizing and documenting this impact has become crucial to understanding the consequences of human activities on our planet. Scientific advances, in particular, have played a key role in shedding light on the intricate dynamics of the human-nature relationship, providing the basis for a deeper understanding of our influence on the environment.

In this context, Land Change Science (LCS) has been established as an interdisciplinary field that studies how humans interact with and shape landscapes to meet their needs (Meyfroidt et al. 2016). Explicitly focused on understanding the causes and effects of land changes at various scales (H. Geist et al. 2006), LCS encompasses shifts in both land use and management — the purposes and activities through which humans influence the land — and changes in land cover — the physical properties of vegetation and the land surface.

Land cover, such as forests, agriculture, or urban areas, is often identifiable through satellite imagery, whereas discerning specific land use activities requires a more comprehensive analysis. For instance, satellite imagery allows for the identification of broad land cover categories such as agriculture or urban areas, whereas pinpointing specific land use activities, like agricultural practices over certain crop areas or whether an urban area is used for residential development or as a business hub, often requires more detailed spatial analysis and ground truthing.

LCS, therefore, systematizes knowledge about human-nature interaction and can guide us toward sustainable approaches, making it crucial for making informed decisions. This ensures a better understanding of using natural spaces and more rational management plans.

Land use and land cover changes (LULCC) are of major concern in LCS. They refer to human-induced modifications in the biophysical attributes of the earth's surface, as well as the human purpose or intent applied to these attributes (Lambin, Turner, et al. 2001). LULCCs, such as agriculture expansion, urbanization, deforestation, farmland abandonment, and afforestation, are associated with numerous causes.

LULCC can have significant implications for global land systems. On the one hand, LULCCs such as deforestation, urbanization, agricultural expansion, and farmland abandonment can have widespread consequences on the environment, society, and the economy, impacting crucial issues such as food security (Ramankutty, Foley, and Olejniczak 2008; Tilman, Balzer, et al. 2011; Foley, Ramankutty, et al. 2011), ecosystem services (Pan et al. 2013; Deng et al. 2016), climate regulation, and freshwater resources (Foley, Defries, et al. 2005; Vörösmarty et al. 2010; M.C. C Hansen et al. 2013; Newbold et al. 2015; McGill 2015).

On the other hand, LULCC related to forest transitions, as afforestation resulting from farmland abandonment, can help alleviate the adverse effects of LULCC by absorbing carbon, improving soil quality, and supporting biodiversity (Bell, Terrer, et al. 2021; Deng et al. 2016). Therefore, studying and monitoring LULCC is critical for understanding changes' causes and impacts and developing strategies to manage and mitigate their adverse effects.

1.2 Theoretical Framework of LULCC

The study of LULCCs can be a challenging and multifaceted area of research, encompassing a variety of causes and consequences that have far-reaching effects on global systems. Such a complex field of research might benefit conceptual frameworks that help to systematically analyze and explain the complex and interconnected factors driving land-use change globally.

The theoretical framework of underlying and proximate causes of global land changes (H. J. Geist and Lambin 2002) provides a valuable tool for understanding the manifold drivers of land-use change and developing effective strategies to manage and mitigate its negative impacts. This framework is divided into two main categories: underlying and proximate causes. Underlying causes are systemic factors and fundamental social processes that shape human-environment interactions and influence the demand for land use, such as broad economic shocks or policy interventions. Proximate causes are human activities or immediate actions at the local level that directly result in land use change, such as agricultural expansion, infrastructure development, urbanization, and forest degradation.

The framework also considers other biophysical, climatic, and geographical factors that will help to shape specific land changes in diverse geographical contexts (Meyfroidt et al. 2016; H. Geist et al. 2006). In descriptive studies, these mediating factors might be referred to as contributory causes or pre-disposing factors, whereas in quantitative studies, they may also be named spatial determinants (Meyfroidt et al. 2016).

This existing framework recognizes that proximate causes of land-use change are frequently interlinked and influenced by their pre-disposing factors and underlying causes. Addressing these manifold and interconnect layers of drivers is crucial for managing and mitigating the adverse effects of LULCC (H. J. Geist and Lambin 2002; Meyfroidt et al. 2016). For instance, addressing the underlying causes of population growth and economic development can help curtail the demand for land use. Similarly, encouraging sustainable agricultural practices and reducing the demand for forest products can help alleviate the pressure for agricultural expansion and deforestation.

The framework of underlying and proximate causes of global land changes provides a comprehensive approach to understanding the drivers of LULCCs. By systematically addressing the underlying causes of global land changes, it is possible to advance the knowledge and contribute to improving management and mitigating the negative impacts of LULCCs. Continuing research and applying this framework can enable a path to a more sustainable future.

1.3 Farmland abandonment

Building on the theoretical framework of LULCC, the analysis of farmland abandonment will benefit from focusing on the three key categories: underlying drivers, predisposing factors, and proximate causes. This structured approach is crucial for developing effective land-use policies and sustainable management practices (Lambin, Turner, et al. 2001; Foley, Defries, et al. 2005; Verburg, Steeg, et al. 2009; Baumann et al. 2011; Griffiths, Müller, et al. 2013; Meyfroidt et al. 2016; Liu et al. 2016).

Farmland abandonment occurs due to a broad range of underlying drivers, proximate causes, and predisposing factors in diverse environmental and socio-economic contexts around the globe (Müller, Leitão, and Sikor 2013) (Fig. 1.1). Underlying drivers refer to broader systemic factors that shape human-environment interactions and affect the demand for arable land. These include policy interventions such as state policies restricting traditional practices or the withdrawal of agricultural subsidies (Lambin, Turner, et al. 2001; Kuemmerle et al. 2008; Baumann et al. 2011; Alexander V Prishchepov et al. 2012; Griffiths, Müller, et al. 2013; Renwick et al. 2013; Zhang, X. Li, and Song 2014), economic shocks (Kuemmerle et al. 2008; Baumann et al. 2011; Hostert et al. 2011), and demographic changes (Zhou, Koomen, and Ke 2020).

Predisposing factors, such as natural and human-driven disasters (Hostert et al. 2011), alongside local geo/biophysical conditions like topographical challenges, weather and climate variations, and poor soil quality (Díaz et al. 2011; Chaudhary et al. 2020), play a crucial role in influencing natural and geo-environmental ecosystems. These factors increase the likelihood of abandonment by impacting biodiversity, water sources, surface runoff, and solar radiation (Chaudhary et al. 2020).

Proximate causes involve farmers' immediate actions or decisions directly contributing to farmland abandonment. Examples include ceasing agricultural activities due to soil degradation (Díaz et al. 2011), declining agricultural productivity, changes in market conditions, and geo-locational features like proximity to market outlets and accessibility (Xie, P. Wang, and Yao 2014; Chaudhary et al. 2020).

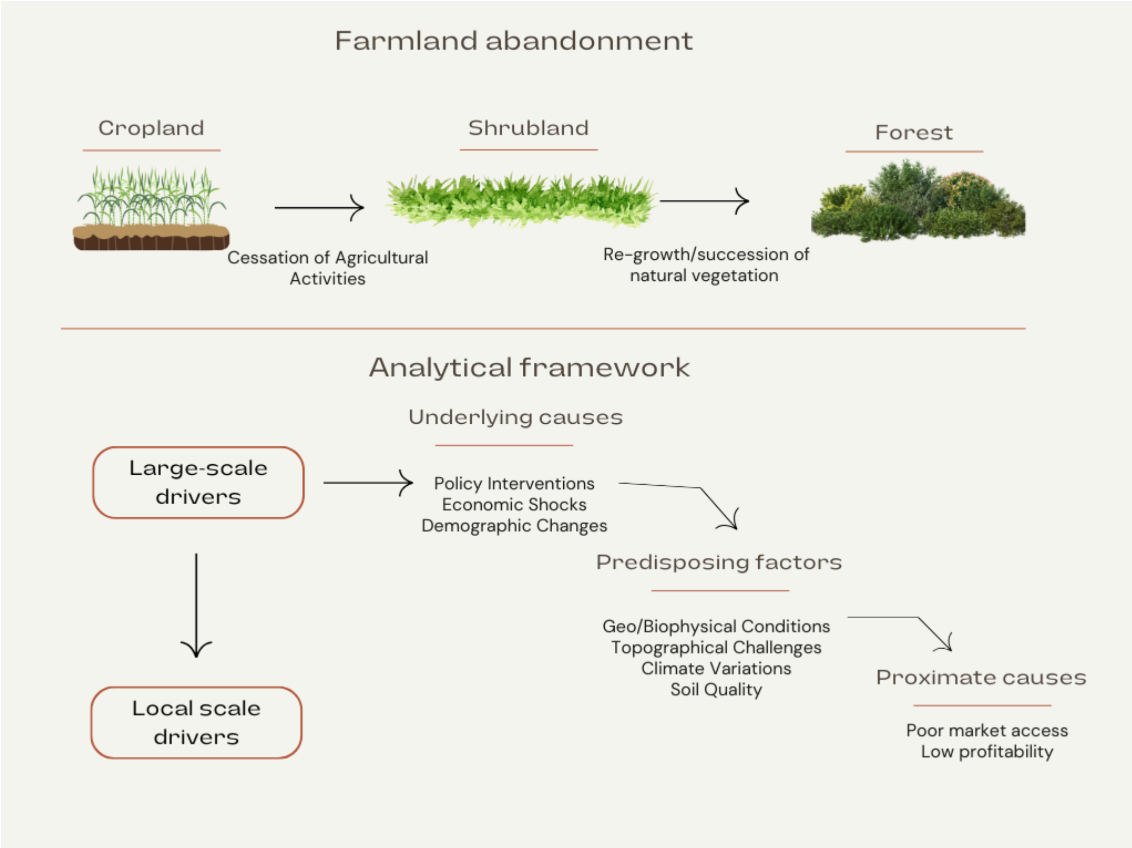

Figure 1.1: Schematic representation of farmland abandonment process and analytical framework

Over the last decade, farmland abandonment has gained attention in the LULCC literature, as it is becoming increasingly clear that it is a widespread, complex phenomenon with manifold impacts. Farmland abandonment typically occurs when a farmer decides to stop cultivating the land (Baxter and Calvert 2017) due to these underlying, proximate, and predisposing factors. The abandoned land is left idle, enabling natural succession processes to take over (Lobao and Meyer 2001; FAO 2006; Keenleyside and G. Tucker 2010).

The farmland abandonment process is of considerable relevance because the existence of abandoned fields produces both positive and negative effects on the environment and society. On the one hand, farmland abandonment can negatively impact food security (Zheng et al. 2023), energy production (Keenleyside and G. Tucker 2010), soil erosion (Lasanta et al. 1995), greenhouse gas emissions (Novara et al. 2017; Bell, Terrer, et al. 2021), and loss of cultural heritage (Gellrich and Zimmermann 2007; Ruskule et al. 2013). On the other hand, it can also lead to beneficial outcomes such as soil carbon sequestration through secondary succession (Vesterdal, Ritter, and Gundersen 2002; Keenleyside and G. Tucker 2010; Ruskule et al. 2013; S. Li and X. Li 2017; Novara et al. 2017; Bell, Terrer, et al. 2021).

Despite extensive research on farmland abandonment, only a handful of studies have utilized the theoretical framework of underlying and proximate causes for a systematic analysis (Chaudhary et al. 2020). This points to a general lack of studies with a common conceptual basis. While many studies have explored factors contributing to farmland abandonment, they have often used fuzzy terminology such as "drivers" or "spatial determinants," limiting comparative analysis.

Challenges to finding common grounds for interpreting and analyzing causal relationships associated with farmland abandonment have been previously identified and discussed (Meyfroidt et al. 2016). There is a general need for a more consistent use of standard terminology and a solid conceptual framework. This will inform the development of effective land-use policies and sustainable management practices.

1.4 Farmland abandonment in Rio de Janeiro

Rio de Janeiro State in Brazil has a long farming history, dating back to 1545. By 1565, the state started cropping sugarcane to export cachaça and sugar to Portugal. Rio de Janeiro became a significant player in the sugarcane sector by continuously expanding its sugarcane areas. By the first half of the 20th century, Rio de Janeiro State was the second-largest sugarcane producer in Brazil, with Pernambuco State leading the production. An example of Rio de Janeiro's pioneersims in the sugarcane sector was the Quissama Central Sugarmill, the first central sugar mill in Brazil (Azevedo 2002).

Significant transformation in the Brazilian agriculture sector during the second half of the century adversely affected the sugarcane industry in Rio de Janeiro and other traditional producers like Pernambuco. So by the 1940s, São Paulo emerged as the leading sugarcane producer and has since maintained this position (Smiderle 2010; Azevedo 2002). As a result, the State of Rio de Janeiro and other traditional producers gradually lost their dominant role in the sugarcane sector. The ruins of the Quissama Central Sugarmill, once the symbol of Rio de Janeiro's prominence, represent a landmark of its decay (Fig. 1.2).

Figure 1.2: The ruins of Quissama Central Sugarmill symbolize the decay of the sugarcane sector in Rio de Janeiro.

From 1980 to 2020, the cultivated areas in Rio de Janeiro State have significantly decreased by approximately 70%, primarily due to the decline in sugarcane farming

(IBGE 2021). This trend has resulted in the loss of many hectares of previously cultivated land, impacting the livelihoods of thousands of residents. The decline in cultivated areas is strongly linked to the decrease in sugarcane farming, a prevalent practice in Rio de Janeiro for a long time.

Cultivated areas in Rio de Janeiro have undergone accelerated marginalization, a significant shift from the gradual trend observed since the 1940s. This turning point is attributed to changes in intervention mechanisms in the alcohol and sugar sector, which have affected the state's primary agricultural product, sugarcane. As per grey literature sources Azevedo 2002; Alentejano 2006; Smiderle 2010, this has led to the abandonment of sugarcane farming. However, the events that marked this transition and the underlying drivers, contributory/ predisposing factors, and proximate causes of farmland abandonment remain largely unquantified and not fully understood.

1.5 Knowledge gaps

The alarming loss of cultivated areas reveals the decline of sugarcane cultivation in Rio de Janeiro. Studies targeting the mapping and quantifying of these recent events are needed. The causes of farmland abandonment in Rio de Janeiro remain unclear, emphasizing the importance of identifying the proximate causes, underlying drivers, and contributory factors and developing quantitative techniques to evaluate their influence in the case study context (Plieninger et al. 2016).

There is also a need to use existing conceptual frameworks and standard terminology in LCS to make scientific communications of findings more efficient and enable a better understanding of the farmland abandonment phenomenon. A more efficient and cohesive use of terminology might enable better engagement and contribute to advances in developing effective land-use policies and sustainable management practices.

This research uses quantitative methods to address the causes of farmland abandonment in Rio de Janeiro to support decision-makers and practitioners in land-use policies and sustainable management. It also incorporates the theoretical framework by H. J. Geist and Lambin 2002 and adapted by Chaudhary et al. 2020 to provide a structured, systematic contribution to LCS.

1.6 Objectives and research questions

The two overarching goals of this thesis are i) to characterize the farmland abandonment in Rio de Janeiro State and assess its spatial and temporal extension and ii) to identify proximate, pre-disposing, and underlying causes of farmland abandonment in Rio de Janeiro.

The choice of Rio de Janeiro State as a case study is given by the evidence presented in statistical annual reports from non-governmental organizations and political debates that indicate a process of farmland abandonment. This case study is particularly relevant due to the significance of Rio de Janeiro's economy at the national level and the fact that the root causes of farmland abandonment can be traced back to Brazil's national development process, thus providing valuable insights into land-use changes across the country. Furthermore, this study aims to contribute to a better understanding of the causal relationships associated with farmland abandonment, which is still a poorly understood phenomenon. To achieve this goal, research questions I-IV were formulated to comprehensively investigate the case of farmland abandonment in Rio de Janeiro.

Research Question I: *what are the main characteristics of farmland abandonment in Rio de Janeiro?*

Hypothesis: The extensive history of sugarcane production in Rio de Janeiro and the documented decline of the sugarcane industry suggest that crop losses in sugarcane cultivation associated with the industry breakdown have incurred farmland abandonment in Rio de Janeiro, particularly in the Norte Fluminense region, which has been identified as a significant hotspot for farmland abandonment in the literature. Therefore, farmland abandonment here is expected to be mostly chracterized by the loss of sugarcane crops in the Norte Fluminense.

The literature highlights the well-established tradition of sugarcane cultivation in Rio de Janeiro, which has been a significant economic driver for the region for many years. However, recent reports indicate that the sugarcane industry in the area has experienced a considerable downturn, leading to concerns about the long-term viability of agricultural activities in the region.

Given this context, it is reasonable to consider that sugarcane crop losses may be regarded as the proximate cause of farmland abandonment in Rio de Janeiro. This hypothesis is particularly relevant in the Norte Fluminense region, identified as a hotspot of farmland abandonment in the literature. That premise of the relationship between sugarcane crop losses and farmland abandonment in this region will guide the remaining research question, which are more specific to the particularities of the sugarcane sector.

Research Question II: *do the currently available datasets allow an accurate assessment of the time and extent of the farmland abandonment in Rio de Janeiro State?*

Hypothesis: Agricultural censuses and annuaries, cadastre data, and historical maps often fail to estimate the spatial extent of land use events because they are typically distributed in an aggregated format. In Rio de Janeiro, the datasets can support exploratory analysis, identify hotspots and the most affected crops, and access public policy impacts. Still, they present severe limitations in accurately assessing farmland abandonment areas and their explicit location.

Due to its limitations, it is necessary to employ Remote Sensing data. Landsat imagery is crucial to understanding farmland abandonment in Rio de Janeiro due to its long-term availability (approx. 40 years) and adequate spectral resolution. The use of time series change detection methods and long-term Landsat imagery will enable the accurate map and temporal assessment of single crop abandonment trends (in this context related to sugarcane), overcoming the limitations observed in the recently available agricultural censuses or annuaries. Research Question II addresses a common issue observed by land-use changes study cases and is also related to the first overarching goal outlined above.

Research Question III: *What are the underlying causes of farmland abandonment in Rio de Janeiro?*

Hypothesis: Policy interventions are a recognized potential cause of farmland abandonment in Rio de Janeiro, but quantifying their impact poses a challenge. While Interrupted Time-series Analysis (ITSA) has been employed in the literature to evaluate the effects of policy implementation on health indicators, such as mortality rates (Linden 2015; Linden 2017; Linden 2018a), their use in the field of Land Use Science has not been reported.

The use of ITSA methods over statistical annual datasets may reveal the underlying causes of farmland abandonment in Rio de Janeiro, enabling quantification and providing numerical evidence of the role played by policy interventions in the breakdown of the sugarcane industry and the abandonment of formerly cultivated areas. This adverse impact was triggered by the withdrawal of subsidies and the closure of the Institute of Sugar and Alcohol (IAA) in the agriculture sector in Rio de Janeiro.

Research Question IV: *What are the pre-disposing and proximate causes of farmland abandonment in Rio de Janeiro?*

Hypothesis: Given that sugarcane abandonment in the Norte Fluminense region is identified as the main characteristic of farmland abandonment in Rio de Janeiro State, it is crucial to tackle specific factors influencing the sugarcane sector in the state. This research question aims to tie these remaining knots.

Firstly, the proximate causes of sugarcane abandonment are closely linked to infrastructure. Geographical and proximity factors, including distance to roads, water sources, and market outlets, serve as proxy variables for assessing the impact of infrastructure. Secondly, predisposing causes of sugarcane abandonment may be attributed to insufficient precipitation and the challenges posed by steep topography. To test this hypothesis, the research employs a standard statistical approach, utilizing generalized linear methods to identify and quantify the relationship between these local drivers and crop abandonment. The model also incorporates measures to account for spatial autocorrelation in the residuals.

The specific objectives of this thesis are:

1. Based on existing agriculture data, identify which agricultural changes have a direct influence on farmland abandonment in Rio de Janeiro and if any spatial patterns are observable. (RQ I)
2. Test different methods to accurately classify the abandoned crops and access the spatial and temporal extension of the abandonment events (RQ II).
3. Identify, analyze, and quantify the relationship between policy interventions and farmland abandonment in Rio de Janeiro (RQ III).
4. Assess the geographical and biophysical variables associated with farmland abandonment in Rio de Janeiro State through statistical modeling (RQ IV).

1.7 Structure of this Thesis

This thesis is structured into four remaining chapters (Chapters 2-5). Each chapter relates to one of the specific objectives outlined above. Chapter 2 focused on identifying agricultural-related changes that proximately caused farmland abandonment in Rio de Janeiro (objective 1). Chapter 2 used statistical agricultural annuaries data from 1991 to 2013 to assess information on cultivated areas, identify trends in different crops, and access municipalities most affected by the loss of cultivated areas. Chapter 3 applied Interrupted Time-series analysis to assess and quantify the impact of policy interventions and economic shocks on farmland abandonment in Rio de Janeiro (objective 3). Chapter 4 used Landsat imagery and applied remote sensing methods to map sugarcane abandonment and accurately assess its temporal patterns, overcoming the limitations observed in the agricultural censuses or annuaries (objective 2). Chapter 5 used spatial statistical modeling to access the biophysical and other geographical factors contributing to sugarcane abandonment in Rio de Janeiro (objective 4).

Chapter 2 was written as a standalone manuscript to be published in an International peer-reviewed Book Chapter. Chapters 3 – 5 were written as standalone manuscripts to be published in international peer-reviewed Journals:

Chapter 2: Castro, P., Pedroso, R., Lautenbach, S., Villanueva, O.M.B., Vicens, R., 2019. Spatial Patterns of Farmland Abandonment in Rio de Janeiro State, in: Nehren, U., Schlueter, S., Raedig, C., Sattler, D., Hissa, H. (Eds.), Strategies and Tools for a Sustainable Rural Rio de Janeiro. pp. 69–85. https://doi.org/10.1007/978-3-319-89644-1_6

Chapter 3: Castro, P.; Pedroso, R. Lautenbach, S.; Vicens, R. Farmland Abandonment in Rio de Janeiro: underlying and contributory causes of an announced development. Land Use Policy. Vol. 95. June 2020. https://doi.org/10.1016/j.landusepol.2020.104633.

Chapter 4: Castro, P. I. B., Yin, H., Teixera Junior, P. D., Lacerda, E., Pedroso, R., Lautenbach, S., Vicens, R. S. (2022). Sugarcane abandonment mapping in Rio de Janeiro state Brazil. Remote Sensing of Environment, 280, 113194. https://doi.org/10.1016/j.rse.2022.113194.

Chapter 5: Castro, P., Lautenbach, S., Pedroso, R., Vicens, R. (2023). Predisposing Factors of Sugarcane Abandonment in Rio de Janeiro: Exploring Policy Implications. Under Review in Land Use Policy.

The complete list of peer-reviewed publications and scientific contributions can be found in the list of publications at the end of this thesis. In the end, a summary chapter will bring the main findings together and present the prospects for future research.

2

Spatial Patterns of Farmland Abandonment in Rio de Janeiro State

Book Chapter published as: *Castro, P., Pedroso, R., Lautenbach, S., Villanueva, O.M.B., Vicens, R., 2019. Spatial Patterns of Farmland Abandonment in Rio de Janeiro State, in: Nehren, U., Schlueter, S., Raedig, C., Sattler, D., Hissa, H. (Eds.), Strategies and Tools for a Sustainable Rural Rio de Janeiro. pp. 69-85. https://doi.org/10.1007/978-3-319-89644-1_6*

Abstract

While land use change in Brazil is characterized by strong cropland expansion, the federal state of Rio de Janeiro, located in Southeast Brazil, shows an opposite trend: a significant amount of cropland has been abandoned. The temporal and spatial distribution of farmland abandonment in Rio de Janeiro state was analyzed at the municipal level from 1991 to 2013. Developments differ strongly between the different regions. The Norte Fluminense region, which holds the highest share of cropping area in the state, showed the highest cropland abandonment. This decrease was mainly due to a reduction of the areas used for the cultivation of banana, maize, and sugarcane. In the Baixadas and Metropolitan Regions, the reduction of areas for orange plantations played an important role while the reduction of areas for coffee production was important for mountainous areas. Another transition seems to be the substitution of sugarcane cultivation with pineapple cultivation. Areas for coconut crop production increased mainly in the Quissamã municipality. Areas for manioc crop production remained stable throughout the analysis. The patterns identified in this paper will provide an important background for the policymakers in implementing spatially explicit plans for the agricultural sector.

keywords: farmland abandonment, agricultural dynamics, spatial analysis, time-series analysis.

2.1 Introduction

Farmland abandonment is a process in which croplands are no longer maintained. The abandoned croplands are either used to keep livestock or are left unmanaged which allows a natural succession; sometimes they make also place for plantations (FAO 2006; Keenleyside and G. Tucker 2010; Lambin and Meyfroidt 2010; Rudel, L. Schneider, and Uriarte 2010). Typically, this process is a result of agricultural intensification associated with the abandonment of marginal areas (Baumann et al. 2011; Hostert et al. 2011). One immediate cause for farmland abandonment is the low viability for smallholders, underlined mostly by agricultural policies (Aide and R. Grau 2004; Keenleyside and G. Tucker 2010; Renwick et al. 2013; Terres et al. 2015).

Farmland abandonment takes place in different geographical regions and is triggered by different geopolitical developments (Munroe et al. 2013). In Europe, it is particularly evident in Eastern Europe, southern Scandinavia, and in mountain regions (Baumann et al. 2011; Hostert et al. 2011; Grinand et al. 2013; Munroe et al. 2013; Alexander V. Prishchepov et al. 2013; Estel et al. 2015). Examples of cropland abandonment in Latin America can be found in western Honduras (Southworth and C. Tucker 2001), northern Argentina (Izquierdo and H. R. Grau 2009) and southern Chile (Díaz et al. 2011).

This study focuses on farmland abandonment in the Rio the Janeiro State in southeast Brazil. The agricultural activity in Rio de Janeiro State is characterized by the production of sugarcane, banana, coffee, manioc, maize, and orange, which account for more than 90% of the cultivated areas (IBGE 2017). The definition of farmland used there includes orchards and plantation used for fruit production and excludes animal husbandry.

From 1988 to 2016, the state lost 70% of its areas used for crop cultivation. The developments in Rio de Janeiro State are in sharp contrast with the nationwide agriculture expansion. This national trend contributed to maintaining Brazil as one of the leading producers and exporters of agricultural commodities worldwide (Gasques, Filho, and Navarro 2010; Maranhão R. 2015) - however, at the cost of biodiversity, especially in the Cerrado and Amazon biomes (Brannstrom et al. 2008; INPE 2017).

2.2 Relevant Policies

Environmental policies play an important role in the farmland abandonment and forest recovering (García-Barrios et al. 2009; Renwick et al. 2013). In Brazil, the Forest act (Federal act. 12,651/2012), the private nature reserves act (RPPN) (Federal act. 5,746/2006), and the Payment for Ecosystem Services (PES) act (Federal act. 12,512/2011) addressed essential issues related to environmental protection at a national level.

The Forest act (Federal act. 12,651/2012) promoted the Environmental Rural Cadaster (CAR) that aims to create spatial database regarding the land uses in the farms for monitoring and promoting an environmentally friendly management. The Federal law 5,746/2006 regulated and promoted the private natural reserves (RPPN), and the Federal law 12,512/2011 implemented the Payment for Ecosystem

Services (PES) at national level.

Those policies encourage the recovering of natural habitats and create income to the farmers either through nature-oriented tourism or PES. However, these policies are still at the implementation level, i.e. their effects can currently not be sufficiently evaluated. Some study cases related to the implementation of those policies will be discussed in more detail in chapter Guzman, and May and Noriega of this book.

The substantial reductions in agricultural areas in Rio the Janeiro State might be at least partially due to government policies. Therefore, since 2000, the State's government implemented several state-level acts aiming to foster different spheres of agriculture production for re-establishing the balance between the various economic activities in Rio de Janeiro.

The State law 34,335/2003 aimed to promote the cultivation of ornamental and medicinal plants by providing differentiated credit. The State law 34,015/2003 intended to strengthen the organic agriculture, stimulating the already existent productions as well as promoting the establishment of new ones. The State law 26,278/2000, also known as the Frutificar program, increased the offer of credits and projects for fruits production in the Norte and Noroeste Fluminense Administrative Regions.

Understanding the patterns and driving factors of farmland abandonment is essential due to its different socio-economic and environmental impacts (Foley, Defries, et al. 2005; Grinand et al. 2013). Farmland abandonment is clearly associated with socio-economic consequences. In Rio de Janeiro, the agricultural activity is the main source of income of approximately 170 thousand inhabitants (IBGE 2010; IBGE 2017), cropland abandonment is likely to lead to increasing unemployment rates in rural regions or migration to cities (Aide and R. Grau 2004).

When based on crop genetic engineering, those previous intensive crop areas become dependent on genetically modified species, generating substantial environmental and socio-economic impacts (Mcafee 2005). Areas with past agriculture intensification show reduced capacity for a recovery of the original vegetation (Cramer, Hobbs, and Standish 2008). Abandoned croplands converted into grassland have led to increasing runoff rates in other regions (Lasanta et al. 1995; Algeet-Abarquero et al. 2015) and posed threats to ecological high value species inhabiting croplands (Katayama et al. 2015; Zakkak et al. 2015).

In order to understand consequences of current and future developments it is essential to identify drivers of change. Within its scope, this chapter uses administrative data to understand the spatial distribution of farmland abandonment in Rio de Janeiro. The objective is to identify the regions where farmland abandonment is most critical and to identify the crop types that are most affected by farmland abandonment. Those results will be used to set up a research design for an econometric analysis to identify the driving factors for farmland abandonment in Rio de Janeiro State. Furthermore, the spatial pattern identified in this study establishes the basis for the assessment of the effects of public policies in Rio de Janeiro state.

2.3 Materials and Methods

2.3.1 Study Site

Located in southeast Brazil, Rio de Janeiro state (Figure 2.1) is the second biggest economy in the country, with a share of 11% in the national gross domestic product (GDP). The state is the fourth most populated in the country with nearly 16 million inhabitants. Its population density is only surpassed by the Federal District (IBGE 2011).

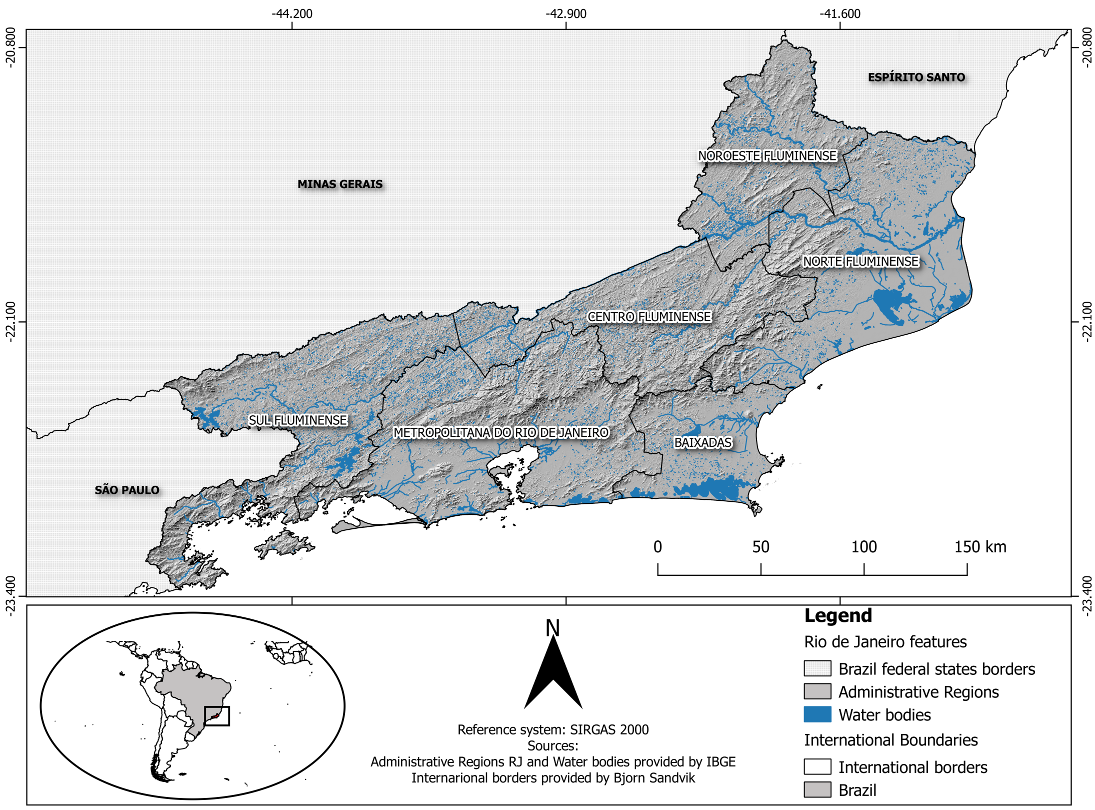

Figure 2.1: Meso-regions of Rio de Janeiro State.

The economy of the state is based on the services sector, which accounts for 69% of the state GDP (CEPERJ 2017). The importance of agricultural activities has been continuously decreasing: the share of the agricultural production of the federal state GDP has decreased from 0.4% in 2002 to 0.26% in 2015 (CEPERJ 2017). The share of the livestock activity has also decreased from 0.2% to 0.17% (CEPERJ 2017).

In Rio de Janeiro State there is evidence for a rural-out movement: while the urban population is increasing, rural areas are characterized by an opposite trend. From 1991 to 2010 the number of inhabitants in Rio de Janeiro state grew by 36%, from 9.5 million to 12.9 million (IBGE 2011). In the meantime, the rural population decreased by 5%, from 470,222 to 447,694 (IBGE 2011).

2.3.2 Environmental factors of land use change

It is well documented that steep topographic conditions play a substantial role regarding farmland abandonment and subsequent forest transitions in Southeast Brazil (R. F. d. Silva, Batistella, and Emilio F. Moran 2016; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017). In Rio de Janeiro, the most likely direct consequence is the conversion from crop farms to low-maintenance activities such as cattle raising. In Argentina, for example, this trend occurs differently. In its northern parts, livestock activity is not common in highlands because the cattle raising activity relies on extensively flat areas (Izquierdo and H. R. Grau 2009).

Topographic conditions are also seen as an important driving factor in farmland abandonment in other parts of the world. In the Swiss mountains, soil and topographic conditions associated with an under-developed road infrastructure triggered substantial farmland abandonment, mostly impacting landscapes of traditional agriculture as well as the habitats of high ecological value species (Gellrich and Zimmermann 2007).

2.3.3 Methods and data

In order to assess changes in cropland areas in Rio de Janeiro Federal State, the authors used the agricultural production per municipality (PAM) survey, from the Brazilian Institute of Geography and Statistics (IBGE). Since 1988 the PAM has been providing annual data per municipality about the cultivated area, harvested area, crop yields, and production values for 29 different temporary crop types and 33 permanent crop types (IBGE 2002).

The time series of each of the main crops in the Rio de Janeiro State was analyzed to uncover specific temporal and spatial dynamics. The eight crops with the largest cropland share in the federal state were selected: sugarcane, bananas, coffee, manioc, maize, oranges, coconuts, and pineapples. For the analysis of spatial pattern, administrative statistics were linked to the Rio de Janeiro Federal state municipality administrative divisions. After 1991 some municipalities were split into two or more new municipalities (see table 2.1), leading to an increase from 70 to 92 municipalities in Rio de Janeiro Federal State (IBGE 2017). In order to allow a proper analysis, only the pre-1991 municipalities were used. For municipalities that were split after 1991, the areas were aggregated for the pre-1991 municipalities.

The analysis of the spatial pattern of each crop considering the cultivated areas per municipality was done for 1991, 2000 and 2013. The selection of a starting period from 1991 intended to match the tabular results with the oldest spatial data containing the municipality boundary available. The year 2000 was selected because it was the time where several agricultural policies were implemented. The final year of 2013 was selected to observe the possible impacts of those policies since their implementation. The information on the amount of livestock was analyzed as well. The information on livestock was obtained through the livestock production per municipality (PPM). Pasture was not considered in the definition of farmland because the data for pasture was not available for the period of analysis.

Information about pasture uses was obtained by the IBGE agricultural census, which covers a different period, from 1975 to 2006. In this survey, the information was provided only at a federal state level. The agricultural census considered crop farms and husbandry farms, denominated agriculture establishments. This concept of farm differs from the one it is included on the farmland abandonment in this chapter, which considers only crop farms. Bearing in mind that limitation, the agricultural census data was used only to evaluate if the abandoned farms are being converted into areas for cattle raising.

2.4 Results

Cropland areas (excluding livestock activities) in Rio de Janeiro federal state decreased by 301,906 hectares (70%) from 1988 to 2016 (IBGE 2017). This development was in sharp contrast to the national trends (Figure 2.2), where crop areas have increased by around 20 million hectares from 1988 to 2016 (IBGE 2017). The amount of livestock also decreased in the federal state of Rio de Janeiro. The figures show a 15% reduction from 1974 to 2015 (IBGE 2017).

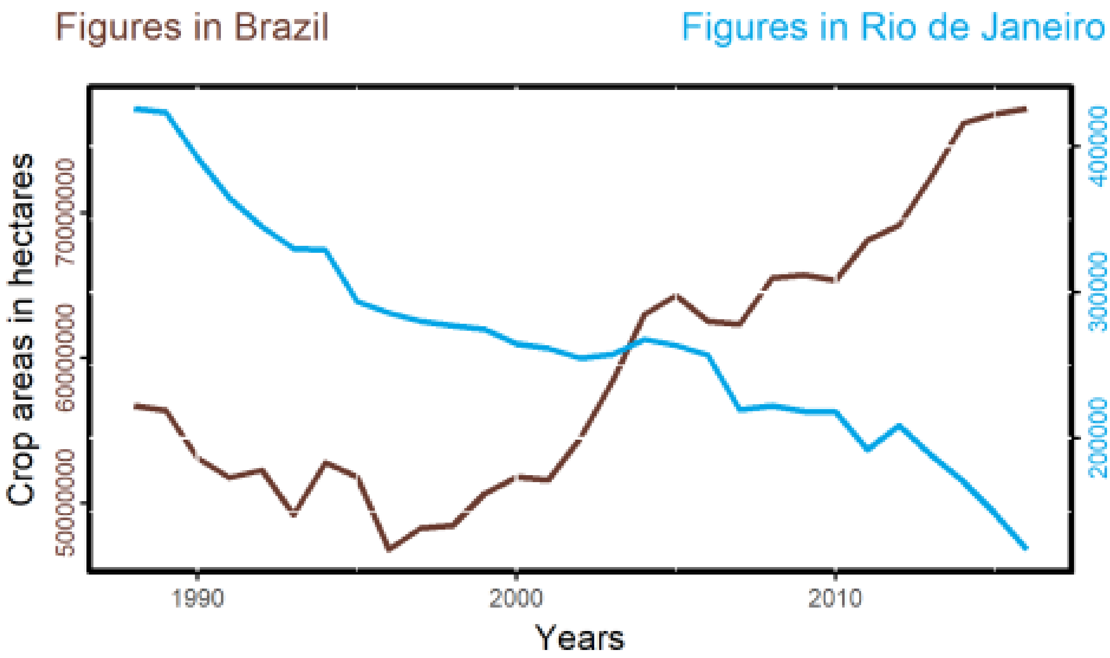

Figure 2.2: Trends of cultivated areas in Rio de Janeiro are in contrast with the trends in Brazil.

The total area of agricultural establishments (crop farms and husbandry farms) in Rio de Janeiro decreased from 3,181,385 ha to 2,059,462 ha, from 1980 to 2006 (IBGE 2009). In 1980, pasture accounted for the biggest share within the establishments with 1,744,614 ha, i.e. 54% of the total area. Despite having the biggest absolute loss of 454,252 ha from 1980 to 2006, pasture still accounted for the highest share in the establishments. In 2006, the pasture uses accounted for 63% of the uses within the establishments. Meanwhile, the share of crops decreased from 19% to 14%.

In 2013, pineapples, bananas, coffee, sugarcane, coconut, oranges, manioc, and maize accounted for 92.91% of the cultivated areas in Rio de Janeiro State (Figure 2.3),. From those, sugarcane accounted for 57%, followed by bananas (11%), coffee (7%), manioc (7%), maize 3%, coconuts (2%), oranges (2%), and pineapples (2%). Areas used to cultivate traditional crops decreased during the study period while

Table 2.1: Municipalities subdivisions in Rio de Janeiro state from 1980 to 2013.

1980	1991	2013
Resende	Resende	Resende
		Porto Real
	Itatiaia	Itatiaia
Barra Mansa	Barra Mansa	Quatis
		Barra Mansa
Piraí	Piraí	Pinheiral
		Piraí
Itaguaí	Itaguaí	Itaguaí
		Seropédica
Nova Iguaçu	Nova Iguaçu	Nova Iguaçu
		Queimados
		Japeri
		Mesquita
		Belford Roxo
Vassouras	Vassouras	Paty do Alferes
		Vassouras
Três rios	Três rios	Areal
		Três Rios
		Comendador Levy Gasparian
Magé	Magé	Guapimirim
		Magé
Itaboraí	Itaboraí	Tanguá
		Itaboraí
Petrópolis	Petrópolis	Petrópolis
	São José do Vale do Rio Preto	São José do Vale do Rio Preto
Cabo Frio	Cabo Frio	Cabo Frio
		Arraial do Cabo
		Armação dos Búzios
São Pedro da Aldeia	São Pedro da Aldeia	São Pedro da Aldeia
		Iguaba Grande
Casimiro de Abreu	Casimiro de Abreu	Casimiro de Abreu
		Rio das Ostras
Cordeiro	Cordeiro	Cordeiro
		Macuco
Macaé	Macaé	Macaé
		Carapebus
	Quissama	Quissama
Santo Antônio de Pádua	Santo Antônio de Pádua	Santo Antônio de Pádua
		Aperibé
Cambuci	Cambuci	São José de Ubá
		Cambuci
Natividade	Natividade	Natividade
		Varre e Sai
Campos dos Goytacazes	Campos dos Goytacazes	Campos dos Goytacazes
	Italva	Italva
		Cardoso Moreira
São João da Barra	São João da Barra	São João da Barra
		São Francisco do Itabapoana

fruit production increased, especially from the 2000's.

The areas used to cultivate sugarcane, bananas, maize, and oranges showed a clear decrease over time. The areas used to farm manioc were relatively stable with periods of oscillation. The areas used to cultivate coffee showed a sharp decrease at the beginning of the 90's but recovered in the following decade. Coconuts and pineapples showed a strong increase in cultivated areas, especially during the 2000's.

The spatial patterns for the different crops in Rio de Janeiro State are shown in (Figure 2.4 and Figure 2.5). Cultivated areas for sugarcane were concentrated in the Norte Fluminense region (Figure 2.4),. The municipalities of Quissamã (13,000 ha), São João da Barra (23,200 ha), and Campos de dos Goytacazes (56,650 ha) hosted most of the cultivated sugarcane area of the state. Although most sugarcane cultivation areas kept concentrated in the Norte Fluminense, the cultivated areas were reduced by 45% in the Federal State and by 46% in the Norte Fluminense Region between 1991 and 2013. The municipalities with the highest reduction were Itaocara, São Fidélis, Macaé and Conceição de Macabu; they are also characterized as areas with extensive pasture occupation.

Besides sugarcane, maize, bananas, and oranges showed a remarkable reduction in cultivated areas. Maize reduction occurred along its main occupation area in the Paraíba do Sul River Basin, which also includes the Centro Fluminense and the Noroeste Fluminense. The abandonment occurred in the mountainous areas of the State.

The cultivation of oranges was concentrated in the Macacu River basin, which includes the Metropolitan and the Baixadas Region. This is where the strongest decrease in cultivated areas happened. The bananas production was spread along the Federal State mostly southwards of the mountain ridge due to a more humid climate. The reduction of bananas acreages was strongest in the Norte Fluminense Region.

Manioc cultivation areas were spread across the federal state. The spatial pattern was fundamentally different from sugarcane. Approximately 81% of the manioc crop production in the state was focused in the Norte Fluminense (42%) and the Metropolitana Region (39%). Between 1991 and 2000 the cultivated areas for manioc in the Rio de Janeiro state showed a slight reduction from 13,307 to 12,948 hectares, which represents a 3% decrease in cultivated area. In the period from 2000 to 2013, the cultivated area of manioc increased slightly by 1%.

From 1991 to 2013, areas used to cultivate coffee decreased by 24% (Figure 2.4). The period from 1991 to 2000 faced an important reduction of 7,921 ha (45%). From 2000 to 2013 about 3,727 ha of coffee partially recovered. Coffee production occupied the headwaters of the PBSB, in the mountainous landscapes located in the Sul, Centro, and the Noroeste Fluminense. From 1991 to 2000, there was a withdrawal of the traditional coffee plantations in the municipality of Valença, in the Sul Fluminense Region. The municipality lost 1,446 of its initial 1,450 ha. During the following period from 2000 to 2013 coffee crop production migrated towards the Muriaé River Basin, in the Noroeste Fluminense Region.

The areas used to cultivate pineapples were concentrated in the Norte Fluminense Region (Figure 2.5). The city of São João da Barra, in the Norte Fluminense, hosted 91% of the cultivated areas. Land use to cultivate pineapples increased between 1991 and 2000 at a rate of 66% and between 2000 and 2013 at a rate of 434%. In total,

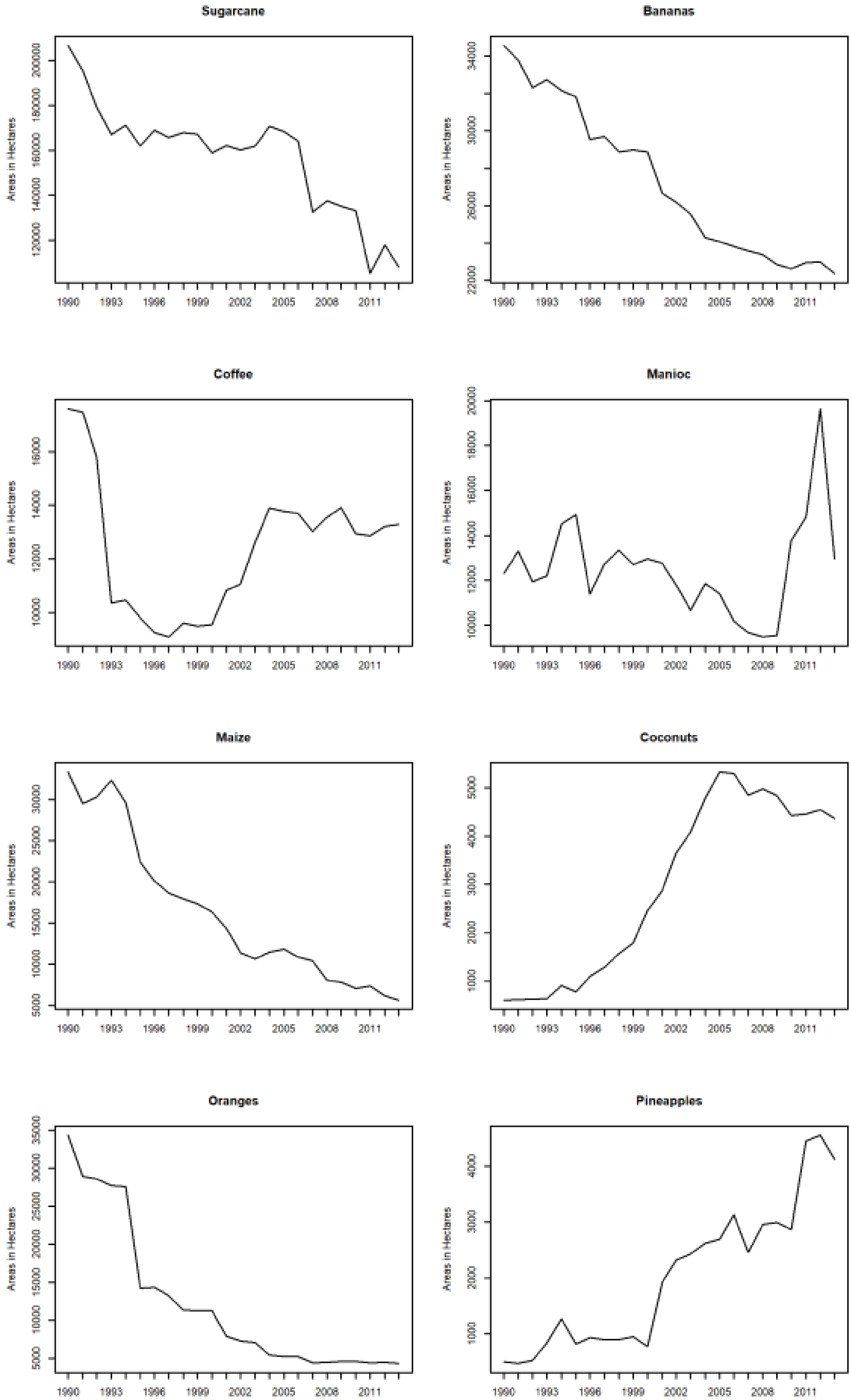

Figure 2.3: Trends of cultivated areas of different crops in Rio de Janeiro.

the pineapple area boomed by 784%, starting in 1991 with 466 ha and reaching 4,121 ha in 2013.

An even stronger increase of 600% was observed for the areas used to cultivate coconuts with a 297% increase between 1991 and 2000. The municipality of Quissamã, in the Norte Fluminense, pushed this growth with an increase of 1,391 ha of cultivated areas from 1991 to 2013 (Figure 2.5). From the 240,836 hectares of areas used as cultivated land that was lost in Rio de Janeiro between 1991 and 2013, sugarcane accounted for 87,348 hectares (34%). Coconuts and pineapples were the crops that had the highest increase in cultivated areas - 3,751, and 3,655 ha respectively.

The figures in Rio de Janeiro show that the reduction of sugarcane crop production of 87,348 ha was considerably higher than the increase of area used to cultivate pineapples (3,655 ha). Considering also the 3,751 ha increase in land used to cultivate coconuts, the sum of both crops does not reach 10% of the decrease of cultivated areas for sugarcane. Despite the crop substitution from sugarcane to pineapples or coconuts in some farms on São João da Barra, the figures reinforce that most of the sugarcane fields are being abandoned.

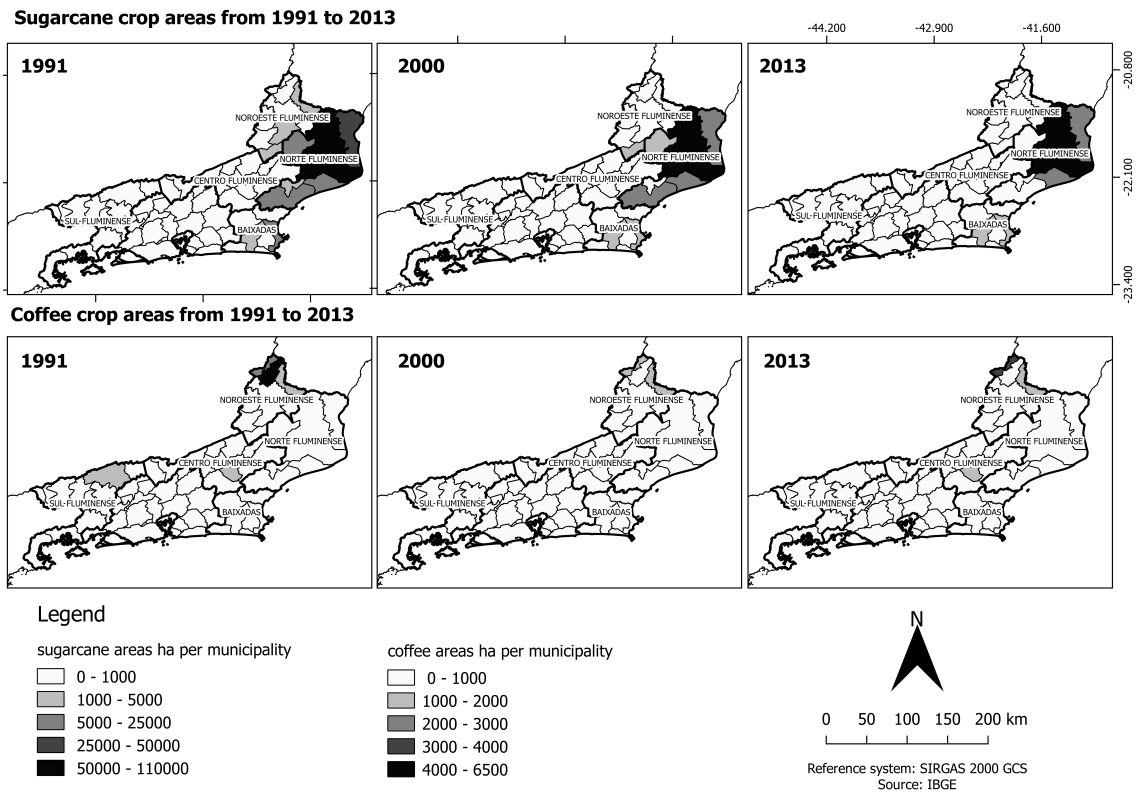

Figure 2.4: trends of cultivated areas of different crops in Rio de Janeiro.

Sugarcane holds 57% of the cultivated areas in Rio de Janeiro State. From those sugarcane areas, 85% are concentrated in the Norte Fluminense. Therefore, the farmland abandonment observed in Rio de Janeiro State was pushed mostly by sugarcane and took place mainly in the Norte Fluminense Region.

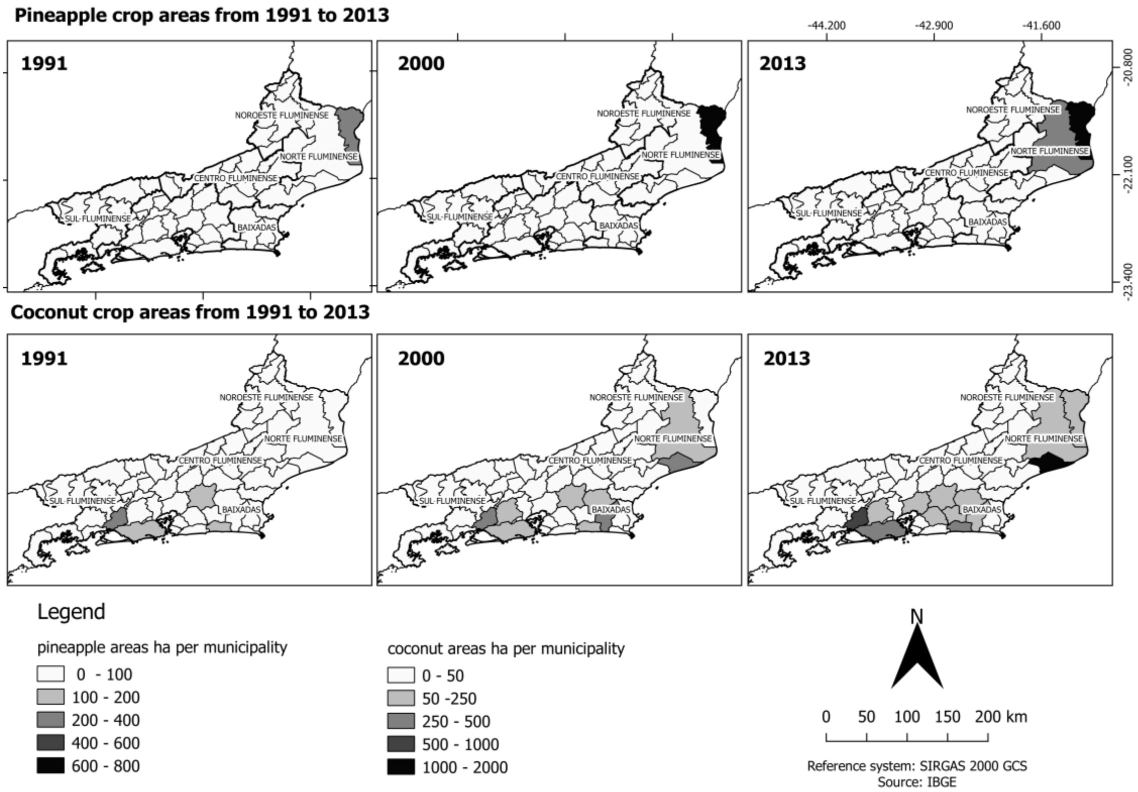

Figure 2.5: trends of cultivated areas of different crops in Rio de Janeiro.

2.5 Discussion

The open access policy from IBGE and its wide range of data originated from its various survey programs provide essential information for research. The survey program agriculture production per municipality considers temporary and permanent crops. The PAM did not provide information regarding livestock activities in its survey. For livestock activity, IBGE has another survey: livestock production per municipality (PPM), providing only data for the amount of livestock, but not for the size of pasture areas.

For pasture uses, data from the agricultural census was considered; it provided data at the federal state's level only. The agricultural census considered both animal crop farms and husbandry farms. The census showed the total areas of farms decreased. However, the share of pastures had increased within the remaining farms. This means while some farms were abandoned, others switched from crop to livestock activities.

Despite its advantages, the main disadvantage of the PAM data is its limited spatial resolution that does not allow an analysis at the sub-municipal scale. Moreover, PAM itself does not provide elements to explain the driving factors for changes in agricultural areas. Other socio-economic factors such as demographic and production factors, e.g. the value of production, labor, fertilizers, and transportation costs, and environmental factors should be incorporated in the analysis to understand at which level the policies reduced or aggravated the current farmland abandonment process. Nonetheless, the agriculture production per municipality data allowed the understanding of the patterns of agriculture production in Rio de Janeiro State.

The production of maize seems to be affected by the steep topography of the region. The abandonment is associated with the high-cost maintenance of the farm activity in those regions. Farmlands might be converted into extensive grassland for cattle raising or simply abandoned in those areas. (Alentejano 2006).

Coffee, which occupies mainly the headwaters of the PSRB, became more concentrated in the Noroeste Fluminense. The trend in Rio de Janeiro followed a nationwide trend, which appears to be related to price fluctuations in the international market, especially after the fall of the International Coffee Agreement (ICA) (Jarvis 2005; Mehta and Chavas 2008; Russell, Mohan, and Banerjee 2012).

The ICA, established in 1979, created quotes for export and importing country members as well as mechanisms to control prices fluctuations. The objective was to offer guarantees and protect the local producers (Jarvis 2005). In 1989, the ICA fell apart, leading to a more competitive market. Outside of this shield, some countries became more susceptible to price fluctuations (Russell et al. 2012).

From 1987 to 1995 the coffee farm-gate prices in Brazil were particularly low. Fluctuations mainly impacted those coffee producers who failed to increase either productivity or quality (Mehta and Chavas 2008). The impact of the price fluctuations on those farmers could be a reason for the decrease in coffee production in the case study region.

Possible impacts of Frutificar (State act. 26,278/2000) can be seen in the Campos dos Goytacazes (D. Bahiense 2014; N. Bahiense, D. Souza, and Ponciano 2015). The municipality located in the Norte Fluminense Region shows an intriguing development. Areas used for the cultivation of pineapples decreased by 13% between 1991 and 2000. Between 2001 and 2013 the production area trend reverted with an increase of 508%, from 57 to 290 hectares. This boom matched the start of the Frutificar program.

The increase in areas for the cultivation of pineapples was followed by a decrease in sugarcane-cultivated areas, which suggests a crop substitution in the São João da Barra. The availability of new pineapple varieties with a shorter phenological cycle and, thereby, increased productivity enabled this substitution. Nonetheless, the increase in areas for the cultivation of pineapples and the decrease for sugarcane was not balanced.

The high labor cost and a small farm size structure, non-suitable for mechanization, may have affected the sugarcane farms. Nevertheless, sugarcane still has the biggest share in the crop areas on the state. Besides, sugarcane still accounts for 85% of the areas cultivated in the Norte Fluminense, which indicates the absence of any fundamental transformation in the spatial distribution of the sugarcane in Rio de Janeiro (N. Bahiense, D. Souza, and Ponciano 2015).

In the Norte Fluminense Region, the topography is known to be suitable for crop production due to the Paraíba do Sul River Basin extensive floodplain. However, the past overuse of soil resources might have created a dependency on fertilizers, seeds, and machinery to make the farm activity profitable. Despite the increasing importance of pineapples, the figures indicate that the state-level acts aiming to promote fruits production (State act. 26,278/2000), flowers production (State act. 34,335/2003), and organic agriculture (State act. 34,015/2003) could not avoid an evident loss of cropland in Rio de Janeiro Federal State. The Frutificar Program (State act. 26,278/2000) might have reduced the impact of farmland abandonment by promoting pineapples and coconuts (D. Bahiense 2014; N. Bahiense, D. Souza, and Ponciano 2015). Nonetheless, the effects are locally restricted to the Norte Fluminense.

Low crop productivity led to land fragmentation and conversion to low-maintenance extensive grassland occupation in the federal state of Rio de Janeiro. In some cases, those abandoned croplands were converted to pasture for raising cattle in extensive areas. In other cases, those areas might were simply converted to fallow lands, for speculation purposes (Alentejano 2006). The most affected area was the Norte Fluminense region.

2.6 Conclusions

Agriculture in Rio de Janeiro showed a diverging trend from the rest of Brazil. The importance of agricultural production in the Rio de Janeiro state decreased during the study period. The Norte Fluminense Region, which holds the highest share of cropping areas in the state, also showed the highest crop area reduction. The decrease of bananas, maize, and sugarcane had a dominant impact on farmland abandonment in the Norte Fluminense Region.

Cultivated areas of oranges and coffee also decreased. Oranges were mainly produced in the Baixadas and Metropolitan regions and coffee mainly in mountainous areas. In the latter, low-cost maintenance could have been a trigger factor for switching from crop to grassland. Croplands were either converted to pasture for raising the cattle in extensive areas, or simply converted to fallow land, for speculation purposes.

The increase in the area used to cultivate pineapples accompanied by a shrinkage in sugarcane-cultivated fields in the Norte Fluminense Region indicates a crop substitution in the Region. Areas for coconut crop production also increased in the federal state, pushed mainly by the Quissamã municipality. From 2000 to 2013 incentives for fruits such as pineapples and coconuts might have triggered a substitution of crops, avoiding an even more extensive farmland abandonment. The trends in fruits crops matched with the period of implementation of the Frutificar program (State act. 26,278/2000), suggesting the program had a positive impact on the production of fruits in Rio de Janeiro State, particularly in the Norte Fluminense.

In this exploratory research, a general description of the agricultural sector in Rio de Janeiro State was performed. The patterns of spatial distribution were described, and the trend of the most important crops was identified. Within the analysis, it was possible to observe interrupted trends in the time series probably associated with farmland abandonment. Throughout the spatial distribution, it was possible to observe where the farmland abandonment was most prominent. This analysis could be used as a basis to develop an econometric model to identify the factors that drive and trigger farmland abandonment in Rio de Janeiro State.

3

Farmland abandonment in Rio de Janeiro: underlying and contributory causes of an announced development

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Abstract

Farmland abandonment is a widespread process with mixed socio-economic and environmental consequences. Farmland abandonment in Rio de Janeiro State is mainly instigated by the sugarcane industry crisis. The sugarcane crisis in Rio de Janeiro State affected traditional livelihoods and altered the environment and economy in the Norte Fluminense region (eastern part of Rio de Janeiro State). Therefore, it is essential to understand the underlying forces and contributory causes of farmland abandonment in Rio de Janeiro. We hypothesized that since the 1970s, macroeconomic and agricultural reforms mediated by economic shocks had driven the farmland abandonment in Rio de Janeiro State. We applied an interrupted time-series analysis over sugarcane harvest areas, relating the years of policy reforms and economic shocks to the trends in sugarcane harvest areas. The results suggest that the removal of agricultural subsidies, macroeconomic reforms, and elimination of the supply quota in the sugar mills have prompted competition and favored high-input agroindustry. Meanwhile, the labor force migration to the higher-paying oil Industry exacerbated the farmland abandonment rates for the smallholders of Rio de Janeiro State. This paper offers a valuable contribution to scientists and policymakers by providing an overview of the outcomes of the policies implemented and how they contributed to shaping the socio-economic dynamics in Rio de Janeiro State.

keywords: farmland abandonment, land-use change, underlying and contributory causes, synthetic control group estimation, interrupted time series analysis

3.1 Introduction

Farmland abandonment is a widespread process whereby the farmers decide to no longer manage their lands (FAO 2006; Keenleyside and G. Tucker 2010; Lambin and Meyfroidt 2010; Rudel, L. Schneider, and Uriarte 2010). The process of farmland abandonment can be characterized as a livelihood strategy (Lobao and Meyer 2001). After the abandonment, the natural succession process is expected to carry on the transition to shrubland, and ultimately to forest (Verburg and Overmars 2009). Farmland abandonment may generate negative socio-economic and environmental consequences; however, in some contexts, it may also provide opportunities for restoration of non-agricultural habitats (Keenleyside and G. Tucker 2010).

Farmland abandonment derives from a combination of factors and varies among geographic regions (Foley, Defries, et al. 2005; Griffiths, Müller, et al. 2013; Lambin, Turner, et al. 2001). The causes of farmland abandonment in many geographic regions are not yet well understood (Baumann et al. 2011; Alexander V. Prishchepov et al. 2013). Brazil is one of the particularly interesting cases in which causal explanations of farmland abandonment are yet to be analyzed.

Although Brazil is one of the top agricultural producers and a traditional commodities exporter, many of its States experienced severe consequences of the recent modernization processes that followed the green revolution (Gasques, Filho, and Navarro 2010). Among those States is Rio de Janeiro, a traditional sugarcane producer that faced a continuous loss of relevance in the national sugarcane and alcohol sector (Azevedo 2002; Smiderle 2010). The abandonment of extensive lands appears as evidence of the decadence of the sugarcane sector in Rio de Janeiro, which reflected on also the agriculture sector as a whole.

The recent agricultural developments in Rio de Janeiro State have been analyzed from different perspectives, describing the events unfolding the Brazilian macroeconomic policies (Azevedo 2002; Smiderle 2010) and analyzing changes in the agriculture areas (Alentejano 2006; Pedro Castro et al. 2019) or the role of state-level policies in promoting the substitution of traditional crops such as sugarcane and cassava for pineapples (N. Bahiense, D. Souza, and Ponciano 2015). The literature also revealed the role of economic shocks related to the discovery of oil resources, which generated local employment and investment opportunities in the oil industry (T. J. Trebat and N. M. Trebat 2012).

Published literature has not quantitatively related specific policy reforms and economic shocks to concrete structural breaks in the agricultural production of Rio de Janeiro State. To close this gap, we applied Interrupted Time Series Analysis (ITSA) to the temporal development of sugarcane production in Rio de Janeiro State (1974-2017). We analyzed the effects of the Pro-Alcohol Program in 1975, the reforms of the rural credit system starting in 1985, the Collor Plans I and II and the first oil boom in 1990, the Real Plan ("Plano Real") stabilizing the economy after 1995, and implementation of the Growth Acceleration Program (PAC) immediately following the second oil boom in the Santos Basin after 2006.

3.2 Background

Farmland abandonment can have mixed environmental and socio-economic effects. Farmland abandonment may lead to increasing connectivity between non-agricultural habitats and stimulate a subsequent restoration of these habitats (Cramer, Hobbs, and Standish 2008; Katayama et al. 2015; Keenleyside and G. Tucker 2010; Ruskule et al. 2013), also increasing the stock of soil organic carbon (Novara et al. 2017). Restoration is nevertheless moderated by local conditions such as climate, history of cultivation, and remaining uses of abandoned plots for recreational activities (Cramer, Hobbs, and Standish 2008; Gellrich, Baur, et al. 2008; Zanden et al. 2017; Verburg and Overmars 2009). Notwithstanding, farmland abandonment may be harmful to high-value species in farming ecosystems (Gellrich and Zimmermann 2007; Katayama et al. 2015; Keenleyside and G. Tucker 2010; Zakkak et al. 2015), also increasing the runoff when the areas remain bare, especially in steep and mountainous regions (Lasanta et al. 1995). Abandoned areas might as well become more vulnerable to invasive species and fire (Cramer, Hobbs, and Standish 2008; Munroe et al. 2013; Zanden et al. 2017).

Loss of traditional landscapes and the displacement of rural livelihoods are also linked to farmland abandonment (Gellrich and Zimmermann 2007; Munroe et al. 2013). The rural-out migration associated with farmland abandonment also tends to increase pressures in urban centers, resulting in inadequate housing conditions (slums), rising unemployment rates, aggravation of poverty, and violence (Maddox, 1960; Torres, 2011). Rural-out migration can also increase per capita consumption rates. Consumption of urban citizens is estimated to be approximately double that of rural citizens from similar income groups (Hoornweg, Bhada-Tata, and C. Kennedy 2013). The urban population tends to consume high amounts of animal protein, refined fats, refined sugars, alcohols, and oils as well as prepackaged meals and fast food (Kearney 2010; Seto and Ramankutty 2016; Tilman and Clark 2014).

Causal relationships leading to farmland abandonment are complex. The literature distinguished between underlying and proximate causes (H. J. Geist and Lambin 2002), while also reflecting upon the variety of terms used in land use science (Meyfroidt et al. 2016). The use of terms such as contributory causes and moderating factors is also worth considering. Contributory causes will appear in the literature as additional causes, therefore not determinant for a land-use change to occur. Meanwhile, moderating factors have a more influential role, such as maximizing or minimizing the impacts of underlying causes (Meyfroidt et al. 2016).

Environmental conditions appear as moderating factors for farmland abandonment in a variety of studies. Topographic constraints (e.g., Estel et al. 2015; Izquierdo and H. R. Grau 2009; Müller, Leitão, and Sikor 2013; Raj Khanal and Watanabe 2006) and poor soil conditions (e.g., Díaz et al. 2011) are among the most common moderating factors for farmland abandonment in Latin America, Asia, and Europe. In several cases in Latin America and Europe, the land is abandoned partially because of its low productivity and high management costs, which pushes farmers to adopt a more intensive use in areas with better soil conditions (Díaz et al. 2011; Hostert et al. 2011; Izquierdo and H. R. Grau 2009; Southworth and C. Tucker 2001). This is especially problematic because it can lead to a spatial concentration of ecological-harmful activities (Munroe et al. 2013).

Social and economic factors also work as moderating factors of farmland abandonment. Abandonment in both European and Latin American countries has been triggered by Farmland ownership fragmentation (Müller and Munroe 2008; Sklenicka 2016), and lack of infrastructure (Gellrich and Zimmermann 2007; Díaz et al. 2011). Several studies identified the low price of staple crops and the cultural and economic attraction of urban centers as moderating factors for farmland abandonment in Latin America (Aide and R. Grau 2004; García-Barrios et al. 2009). In Eastern European countries, the political and economic instability after the fall of the Iron Curtain (Baumann et al. 2011; Griffiths, Müller, et al. 2013; Hostert et al. 2011; Alexander V. Prishchepov et al. 2013), and events of industrial contamination (Hostert et al. 2011) also contributed to farmland abandonment. In the USA and China, a shortage of farming labor force due to the increasing opportunities in the growing industrial sector worked as a moderating factor of farmland abandonment (Maddox 1960; Xie, P. Wang, and Yao 2014). In China, the recent rapid urbanization was also a moderating factor of farmland abandonment (S. Li and X. Li 2017). Despite often enjoying the spotlight of the explanandum of causes of land-use changes, moderating factors (either environmental or socioeconomic) do not operate in isolation. Instead, moderating factors are linked to underlying causes.

Underlying causes are understood as large scale influence factors underlying profound societal transformations (H. J. Geist and Lambin 2002). Policymakers' decisions are underlying causes of farmland abandonment (García-Barrios et al. 2009; H. J. Geist and Lambin 2002; Lobao and Meyer 2001; Müller and Munroe 2008; Renwick et al. 2013). In the EU, the Common Agricultural Policy (CAP) - the European agricultural and trade policy reform on land-use - was expected to exacerbate farmland abandonment (Renwick et al. 2013). In the USA and Latin America, the policies benefiting large farm enterprises in the agro-industry increased inequalities between farmers and caused farmland abandonment of smallholders as a side effect (García-Barrios et al. 2009; Lobao and Meyer 2001). Rural-out migration and environmental policies also caused farmland abandonment by smallholders in Latin America, which concurrently contributed to reducing the rates of forest loss (García-Barrios et al. 2009; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017; R. F. d. Silva, Batistella, and Emilio F. Moran 2016).

Several studies have documented the effects of policy interventions as underlying causes of agricultural land changes in Brazil (Bastos and Moraes 2014; Chaddad et al. 2006; Coelho 2001; Helfand and De Rezende 2004; Martinelli, Naylor, et al. 2010). Even though all Brazilian Federal States were exposed to the same several policy reforms implemented since the 70s, the induced land-use changes differed considerably across states. The development in Rio de Janeiro State is an exception in that agricultural production is decreasing in contrast to the national trend: the federal state lost 73% of the cultivated areas during the last thirty years (IBGE 2018b). Circa 70% of the agricultural areas in Rio de Janeiro State were abandoned, with partial substitution of pineapples and coconuts by other staple crops (Alentejano 2006; N. Bahiense, D. Souza, and Ponciano 2015; Pedro Castro et al. 2019). The abandonment of cultivated land in Rio de Janeiro has been spatially concentrated: the most affected Region has been the Norte Fluminense, and sugarcane has been the most affected crop until now (Pedro Castro et al. 2019).

3.3 Materials and methods

3.3.1 Study site

In its regional analysis, the Brazilian Institute of Geography and Statistics (IBGE) subdivides Rio de Janeiro State into six Meso-regions: Noroeste Fluminense, Norte Fluminense, Centro Fluminense, Baixadas, Metropolitana, and Sul Fluminense. The Metropolitana region, which includes the federal state capital Rio de Janeiro City, has a population of approximately 12.6 million inhabitants, accounting for 78% of the state's population (IBGE 2011). Of these 12.6 million, only 150,000 live in rural areas. In absolute terms, the Metropolitan region has the largest rural community in the state, being followed by the Norte Fluminense region, which has around 100,000 rural residents.

Agricultural activity in Rio de Janeiro State is characterized by the production of sugarcane, bananas, coffee, cassavas, maize, pineapples, coconuts, and oranges, which account for more than 90% of the cultivated areas (IBGE 2018a), and cattle raising, predominantly for meat production (IBGE 2018c). Sugarcane is the most important crop in Rio de Janeiro State, covering 48% of the total cultivated areas (IBGE 2017). Medium and small farms dominate the production of sugarcane in Rio de Janeiro State: smallholding accounts for 61% of the number of farmlands, other small-scale farms for a further 28%. Together, these groups represent 41% of the total farmland areas in the state (INCRA 2016).

Sugarcane cultivation is concentrated at the coastal tablelands and fluvial and fluvial-lacustrine plains in the Norte Fluminense, situated mostly on the Counties of Campos dos Goytacazes, São Francisco de Itabapoana, and Quissamã (IBGE 2018a) (figure 3.1). Coastal tablelands are landforms slightly dissected with large surfaces characterized by low hills alternating with shallow valleys (Dantas 2000). Coastal tablelands are typically known to facilitate the technological management of the farmland. The more technical implementation is limited only by the constraints to the mechanization in areas with uneven topography and moderated water availability. Nevertheless, the soils in these landforms exhibit low natural fertility, which in many cases results from high aluminum saturation. Those soil conditions call for controlled management based on techniques for land conservation and require a significant level of investment (Carvalho Filho et al. 2000).

Temperatures vary along the different regions of the state. Together with the Metropolitan Region, the Norte Fluminense region shows the highest annual temperatures, ranging from 26°C during winter to 33.5°C in the summer (W. L. Silva and Dereczynski 2014). Precipitation in the Norte Fluminense region is approximately 1000 mm/year, the lowest among Rio de Janeiro's Meso-regions (Davis and Naghettini 2000).

3.3.2 Policy reforms and economic shocks at the national level

Government policies specific to the agricultural sector date back to the 30s, when the government created the Institute of Alcohol and Sugar (IAA). From that period on, the growth of the sector was continually fueled by several other interventions (Coelho 2001). From 1963 to 1972, several important measures were implemented, focusing on stimulating the sugarcane industry. The most prominent were: the establishment

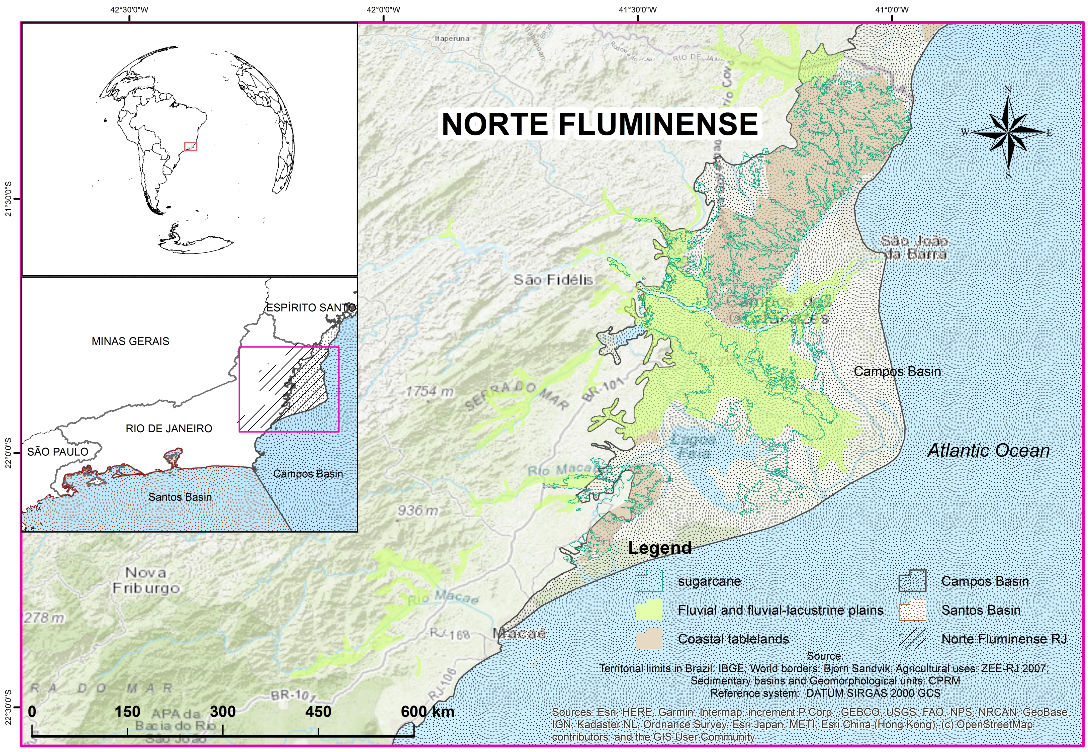

Figure 3.1: Case study region: sugarcane croplands in Rio de Janeiro State stretch across coastal tablelands, fluvial and fluvial-lacustrine plains. The highest concentration of sugarcane is in the East, in the Norte Fluminense region.

of the National System of Rural Credit (SNCR), the implementation of the Policy of Minimum Prices Guarantee (PGPM), the expansion of the IAA's assignments together with several additional incentives for the expansion of the sugar and alcohol industry. These reforms mentioned above increased national production and reduced imports. Nonetheless, the Oil crisis in 1973 hit the Brazilian economy hard, which at the time mainly relied on oil imports. The Brazilian government immediately responded by creating the National Fuel Alcohol Program (Pro-Alcohol) in 1975, which aimed to reduce the Brazilian dependency on oil imports by promoting alcohol production and consumption as a substitute for gasoline (Coelho 2001; Pupim de Oliveira 2002).

However, in 1982, national budget and inflation pressures forced the government to reduce subsidies and the availability of cheap credits. This initiated a profound reform of the rural economy that culminated with the complete removal of subsidies for the rural sector in 1985 (Coelho 2001; Azevedo 2002).

In 1990, important policy reforms were implemented with the Collor Plans I and II. The Collor Plan I was an unsuccessful attempt to control the rising of the prices and monetary depreciation. The Collor Plan II followed one year later with more measures to control inflation, such as raising interest rates to very high levels hoping in this way to support the currency and control inflation (Coelho 2001; Helfand and De Rezende 2004). A crucial point of these reforms was the shutting down of the IAA, which included the removal of the supply quota per sugar mill at the national level, elimination of production limits per sugar mill, and led to

Table 3.1: Important policy reforms and economic shocks from 1977 to 2006

Year	Event
1977	Oil crisis and establishment of the Pro-Alcohol Program
1986	Removal of subsidies in the rural credit system in the framework of national macroeconomic reforms
1990	Collor Plan I and II (and the shutting down of the IAA) and discovery of oil reserves in the Campos Basin
1995	Real Plan (consolidation of macroeconomic reforms – stabilization policies)
2006	Discovery of oil reserves under the pre-salt layer in Santos Basin, Southeastern Brazil and the subsequent implementation of the Growth Acceleration Program (PAC)

increased competition in the sugar sector. These measures set up an economic transition period, uncovering the low productivity and comparative disadvantages of sugarcane production in Rio de Janeiro State (Coelho 2001; Azevedo 2002). The year 1990 also marked out what we considered the first oil boom in Rio de Janeiro State: the discovery of giant oil fields in the Campos Basin.

What followed was a difficult period for both the sugarcane sector in Rio de Janeiro State and the Brazilian economy in general, with several disastrous fiscal and monetary interventions. It was only from 1993 to 1995 that the government managed to finally stabilize the economy with the Real Plan (Coelho 2001; Helfand and De Rezende 2004). The Real Plan was aimed at controlling the country's hyperinflation. A new currency called the Real was introduced alongside high-interest rates and a series of fiscal reforms, also in the rural sector, which successfully restricted the government's expenditure. The program worked, meaning that inflation, as well as other important macroeconomic problems, were finally under control (Coelho 2001).

In July 2005, The Brazilian National Oil Company (Petrobrás) found oil reserves under the deep-water oil fields (also known as pre-salt) in the Paraty Field, Santos Basin, southeast Brazil. After the discovery of oil under the pre-salt layer, the Brazilian National Oil Company decided to invest in new exploitation fields. In 2006, Petrobrás found significant oil reserves in the Tupi Field, Santos Basin. The Tupi was estimated to yield between five and eight Billions barrels of oil and natural gas. A substantial increase in investments in the oil sector followed the pre-salt discovery as the government implemented the Growth Acceleration Program (PAC), which also outlined investments in the infrastructure and social welfare.

3.3.3 Data

This study used data from the IBGE's Agricultural census (CEAGRO) and Agricultural Production per Municipality (PAM). The CEAGRO data was used to calculate the net change in each land use and estimate the total area that can be classified as farmland abandonment. The agricultural census has been conducted at 5-year or 10-year intervals since 1970 and provides a range of agricultural data at different administrative levels in Brazil. The classification used by the agricultural census changed between 2006 and 2017. Therefore, we adapted the classification of the 2017 survey to the previous land use classification: forest, temporary crops , permanent crop, natural grassland, cultivated grassland, forestry, and others (including constructed areas, artificial lakes, and dams).

The PAM time-series of harvest areas for the sugarcane crop in Rio de Janeiro State from 1974 to 2017 was used to analyze the effects of policy interventions and economic shocks. Since 1974, the PAM releases annual data for agriculture production (harvest, cultivated area, amount produced) at the county level. The PAM data is derived from an analysis of data collected at municipal level followed by a discussion panel with stakeholders from the agricultural sector (Counties' agricultural bureaus, Counties' environmental protection bureaus, farmers, processors, distributors). Due to its comprehensive method of collection and the frequency of updates, the PAM data was considered more reliable for this study.

Harvest area was selected as the indicator for the analysis because it had been recently updated, including annual information at Rio de Janeiro State level from 1974 to 2017, separated per crop type. All other variables had data only from 1988 to 2017.

3.3.4 Interrupted time-series analysis (ITSA)

Interrupted time series analysis is used to investigate the effect of an intervention or shock on the level and trend of a time series (Crosbie 1993; Linden 2015). In this study, the outcome variable was the harvest area of sugarcane in Rio de Janeiro State from 1974 to 2017.

The ITSA method has been mainly used and developed in health-related studies (Bernal, Cummins, and Gasparrini 2017; Statistics 2013) but has been applied in other fields of public policy intervention analysis (e.g., Lott and Mustard 2008; Muller 2004). This study used an ordinary least squares (OLS) formulation of ITSA considering temporal autocorrelation in the error term (Equation 3.1). In our case, a single group ITSA specification is used because control groups were not available (Linden 2015; McKnight, McKean, and Huitema 2000).

$$y_t = \beta_0 + \beta_1 T_1 + \beta_2 X_2 + \beta_3 X_t T_t + ...\mu_t \tag{3.1}$$

where T_t is the elapsed time since the beginning of the analysis; X_t is a dummy variable indicating the intervention period (preintervention 0, post-intervention 1). The coefficient β_0 represents the intercept or the starting level of the outcome variable, β_1 indicates the trend of the outcome variable before the first intervention, and β_2 shows the change in the level of the outcome immediately following the intervention. The coefficient β_3 represents the difference between the pre-intervention and post-intervention trends of the outcome variable. $X_t T_t$ is an interaction term for assessing the trend changes. The sum $\beta_1 + \beta_3$ would represent the new slope after the intervention period. Additional interventions or shocks can be included for testing by adding the corresponding X_n and $X_n T_n$ variables to the model. The error term u_t was assumed to follow a pth order autoregressive process AR(p) (Equation 3.2):

$$\mu_t = \rho_1 \mu_{t-1} + \rho_2 \mu_{t-1} + \rho_p \mu_{t-p} ... + \epsilon_t \tag{3.2}$$

where $\epsilon_t \simeq WN(0, \sigma^2)$. The model was estimated using Newey-West standard errors (Linden 2015; Baum and Schaffer 2015) and tested for temporal autocorrelation in the residuals following the general Cumby-Huizinga test for autocorrelation in time series for a lag size of up to six.

The following ITSA model specification was used:

$$
\begin{aligned}
y_t = \beta_0 + \beta_1 T_1 + \beta_2 X_{1977} + \beta_3 X_{1977} T_t + \beta_4 X_{1985} + \beta_5 X_{1985} T_t + \beta_6 X_{1990} + \\
\beta_7 X_{1990} T_t + \beta_8 X_{1995} + \beta_9 X_{1995} T_t + \beta_1 0 X_{2006} + \beta_1 1 X_{2006} T_t + \mu_t
\end{aligned}
\tag{3.3}
$$

3.3.5 Multi-group interrupted time-series analysis with a single intervention

To dissociate the effects of confounding drivers (i.e., economic shocks related to the oil boom from policy interventions) for a certain period, we applied the ITSA multi-group analysis (Linden 2018b). Equation 3.4 describes the ITSA multi-group model:

$$
y_t = \beta_0 + \beta_1 T_t + \beta_2 X_t + \beta_3 X_t T_t + \beta_4 Z + \beta_5 Z T_t + \beta_6 Z X_t + \beta_7 Z X_t T_t ... \mu_t \tag{3.4}
$$

where β_0 refers to the intercept; β_1 represents the slope before the intervention; β_2 refers to the change in level in the period immediately following intervention initiation (compared with counterfactual); and β_3 represents the difference between preintervention and postintervention slopes. The multiple groups include: β_4, the difference in the level between treatment and control before the intervention; β_5 , the difference in the slope between treatment and control before the intervention; β_6, the difference in the level between treatment and control in the period immediately following intervention initiation; and β_7, the difference between treatment and control in the slope after initiation of the intervention compared with preintervention (Linden 2015).

For the ITSA multi-group analysis, we ran a model selecting a control group (i.e., States) that presented non-significant differences between the pre-intervention trends regarding the intervention group, i.e., Rio de Janeiro State. By non-significant differences, we consider p-values higher than 0.10 on both β_4 and β_5 (Linden 2015). Due to the differences in agricultural production among the States in Brazil, a comparable group could not be found by using the automatic method ITSA MATCH for searching States following the p-value higher than 0.10 criteria (Linden 2018b).

Instead, we applied the Synthetic control method (SYNTH) to estimate a control group for the comparative analysis and combined the results of the SYNTH in the multiple-group ITSA analysis (Abadie, Diamond, Hainmueller, et al. 2010a; Linden 2018b). We selected several covariates to improve the estimation of the synthetic control group. The variables used in the SYNTH analysis were the MSWEP 2.2 precipitation data aggregated per federal state from 1974 to 2018, the number of trucks used in the farms, the labor force employed in the farming activities, and pasture land area in hectares. The last three variables were obtained from the Agricultural Census.

The definition of the States to be used in the synthetic control approach follow the criteria for selecting traditional sugarcane producers in similar environmental conditions as Rio de Janeiro. In that sense, we selected the Northeastern Brazilian States, which developed their agriculture production over the coastal tablelands and fluvial floodplains, just as Rio de Janeiro State. The States selected were: Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, and Recife. For running the synthetic control method, we used the Stata package SYNTH (Abadie, Diamond, Hainmueller, et al. 2010a).

The output of the SYNTH analysis was used as the input for the multi-group ITSA. Rio de Janeiro State was defined as an intervention group and the synthetic control output as the control group. Regarding the intervention periods, we ran the multi-groups ITSA for a single intervention period in 1990, when both the Collor Plans and the oil boom occurred.

Equation 3.5 describes the multiple groups ITSA for a single intervention period in 1990:

$$\begin{split} y_t = \beta_0 + \beta_1 T_t + \beta_2 X_{1990} + \beta_3 X_t T_{1990} + \beta_4 Z + \\ \beta_5 Z T_t + \beta_6 Z X_{1990} + \beta_7 Z X_t T_{1990} ... \mu_t \end{split} \tag{3.5}$$

To dissociate the effects of confounding drivers for the intervention period 2006 (i.e., the second oil boom and the Growth Acceleration Program), we applied the same method of combined SYNTH and multi-group ITSA. The synthetic control group was estimated using the same covariates of the previous analysis. For estimating the synthetic control group, we selected the States of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, which were not exposed to the second oil boom.

Equation 3.6 describes the multiple groups ITSA for a single intervention period in 2006:

$$\begin{split} y_t = \beta_0 + \beta_1 T_t + \beta_2 X_{2006} + \beta_3 X_t T_{2006} + \beta_4 Z + \\ \beta_5 Z T_t + \beta_6 Z X_{2006} + \beta_7 Z X_t T_{2006} ... \mu_t \end{split} \tag{3.6}$$

3.4 Results

3.4.1 Changes in agricultural uses from 1970 to 2017

Using the CEAGRO data, we estimated that agricultural areas have decreased by 945,285 ha in Rio de Janeiro State from 1970 to 2017 (Figure 3.2). Temporary and permanent crops decreased by 439,724 ha over this period. Approximately 45% of losses on managed land consisted of cropland abandonment. Forestry and reforestation areas increased by 16,898 ha, and 4,395 ha, respectively. An interesting aspect was the nearly complete substitution between natural and cultivated pasture land. Cultivated pasture lands increased by 519,026 ha in Rio de Janeiro State, while natural pasture areas decreased by 673,099 ha. Taken together, pasture lands (cultivated and natural) showed a net decrease of 154,073 ha. Land under other uses (constructed sites, artificial lakes, household areas) decreased by 370,781 ha.

3.4.2 Interrupted time-series analysis over sugarcane harvest areas

The ITSA identified significant interruptions for sugarcane harvest areas for the years 1977, 1986, 1990, 1995, and 2006 (Figure 3.3, Table 3.2). The starting level

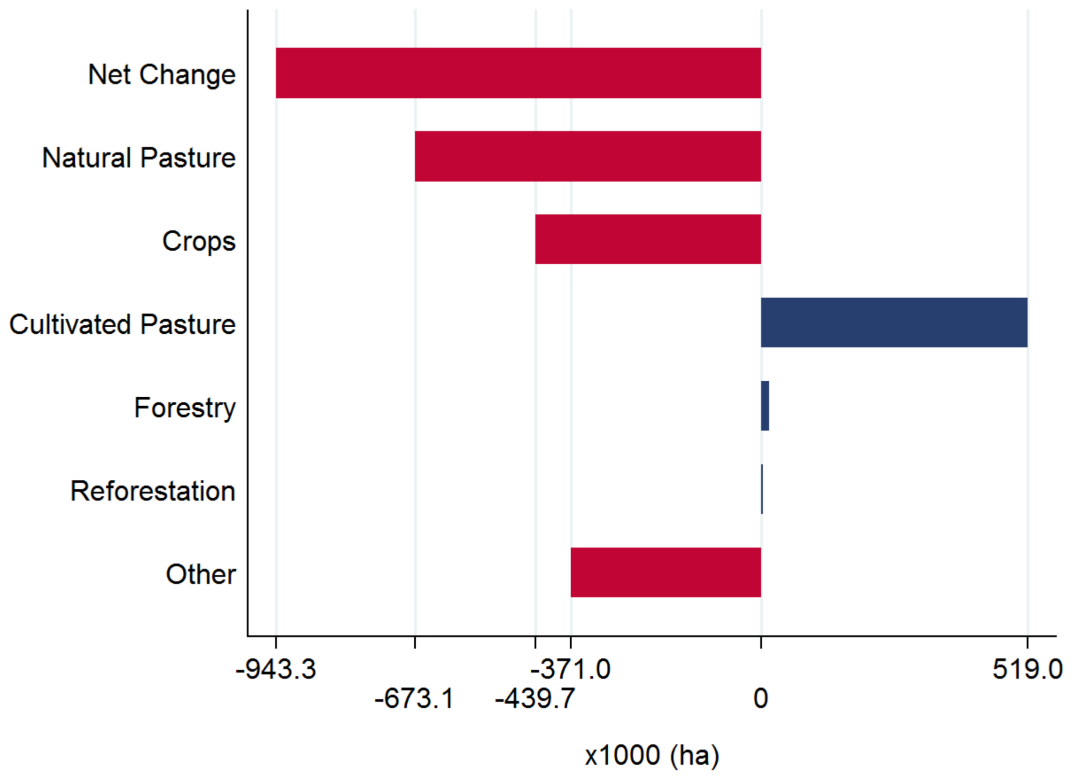

Figure 3.2: Changes in the land use of agricultural establishments in Rio de Janeiro State from 1970 to 2017 according to the agricultural census.

of sugarcane acreage in Rio de Janeiro State was estimated at 162,600 ha ($\beta_0 : p = 10^{-9}$), with sugarcane acreage decreasing until 1977 by 157.5 ha per year ($\beta_1 : p = 0.001$). Two years after the Pro-Alcohol Program was implemented in 1975, there was a 21,600 ha delayed effect ("step-change") in the acreage level in sugarcane ($\beta_2 : p = 10^{-9}$). The post-intervention development of sugarcane acreage showed an increasing trend after 1977. The significant increase of 3,700 ha per year ($\beta_1+\beta_3 : p = 10^{-9}$) was potentially a positive effect of the Pro-Alcohol Program. The difference to the pre-intervention period trend (before 1977) was 3,880 ha per year ($\beta_3 : p = 10^{-9}$).

There was no significant immediate increase in the level of sugarcane acreage following the consolidation of the rural credit rationalization and new structuring of the rural credit sector in 1986 ($\beta_4 : p = 0.182$). The difference to the pre-intervention period trend (before 1986) was estimated as - 3,419 ha per year ($\beta_5 : p = 0.004$). The non-significant trend (horizontal line) after 1986 is presumably linked to the contractive policies of the 1980s ($\beta_1 + \beta_3 + \beta_5 : p = 0.632$).

A significant immediate decrease of 21,800 ha sugarcane acreage followed the macroeconomic opening (Collor Plans I and II), and the shutting down of the IAA in 1990 ($\beta_6 : p = 10^{-9}$). The effect was an annual decrease in sugarcane acreage of -10,500 ha per year ($\beta_1 + \beta_3 + \beta_5 + \beta_7 : p = 10^{-9}$). The difference to the pre-shock trend was estimated as -10,800 ha per year($\beta_7 : p = 10^{-9}$).

The Real Plan from in 1995 appears to have led to a stabilization of the level of sugarcane area as the slope is non-significantly different from zero for this period ($\beta_1 + \beta_3 + \beta_5 + \beta_7 + \beta_9 : p = 0.826$). The discovery of the pre-salt oil reserves in

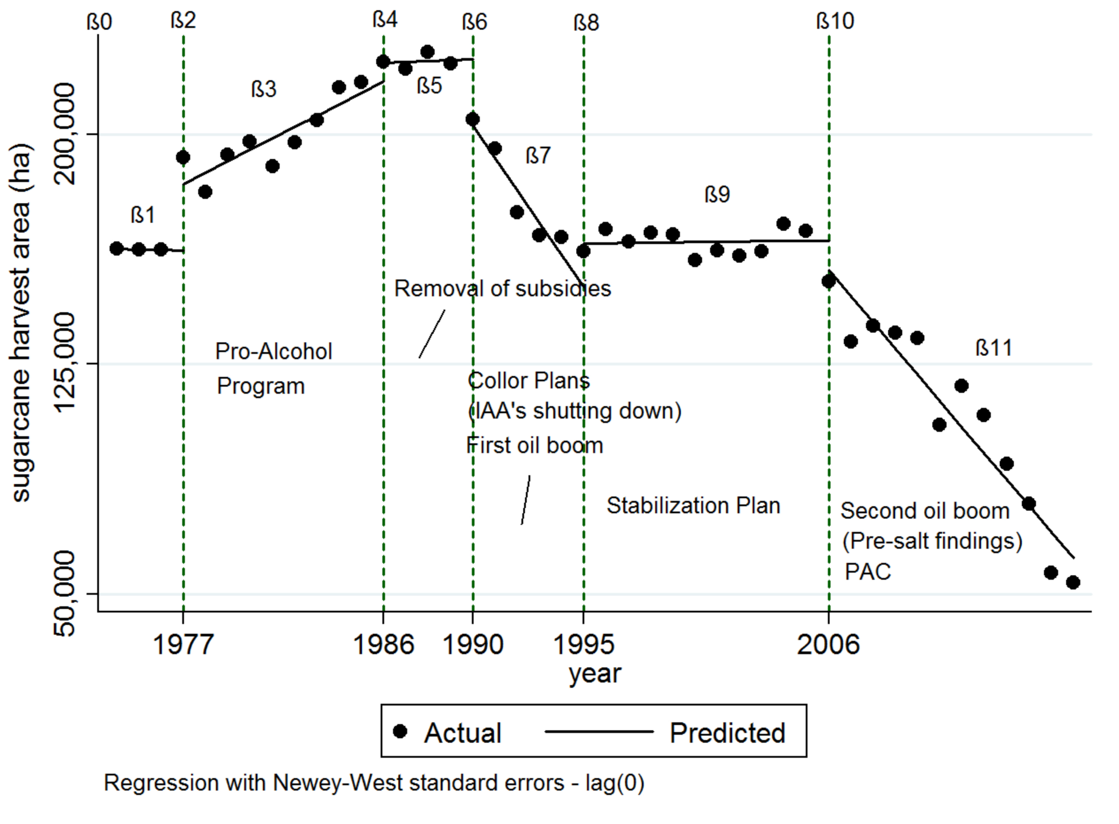

Figure 3.3: Time-series plot of sugarcane harvest areas is indicating the intervention periods and economic shocks.

2006 corresponds to a strong decrease of about 8,500 ha per year ($\beta_1 + \beta_3 + \beta_5 + \beta_7 + \beta_9 + \beta_1 1 : p = 10^{-9}$). The differences between sugarcane acreage trends before and after this event was estimated as -8,663 ha ($(\beta_1 1) : p = 10^{-9}$).

The null hypothesis of the absence of temporal autocorrelation in the residuals of the ITA could not be rejected ($p = 10^(- 9)$). Therefore, the ITSA model was carried out without fitting the AR process to the residuals.

3.4.3 Multi-group interrupted time-series analysis over sugarcane harvest areas

Multi-group single intervention 1990

The ITSA identified significant interruptions for sugarcane harvested areas after the year 1990 (Table 3.3, Figure 3.4). The result $\beta_3 - p = 10^{-9}$ demonstrates significant differences between the trends before and after the introduction of the Collor Plans. The differences corresponded to an annual reduction of $7,780$ ha. The non-significant differences between the treatment and control groups before 1990 ($\beta_4 - p = 0.979$) and the non-significant difference between the slopes of treatment and control groups before 1990 ($\beta_5 - p = 0.992$) indicate that both groups are comparable in terms of ITSA multi-group analysis. The selection of the intervention period 1990 aimed to isolate the effects of the oil boom and the Collor Plans by comparing to traditional sugarcane producer States that did not experience to the oil boom (Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, and Recife) with Rio de

Table 3.2: Regression coefficients, standard errors, and p-values of the estimated ITSA model.

Model parameters	**Years/Period**	**Coefficient**	**SE**	**p**
β_0	1974	$162,588.0$	66.5	10^{-9}
β_1	1974 – 1977	-157.5	43.5	0.001
β_2	1977	$21,633.3$	$5,025.5$	10^{-9}
β_3	1977 – 1986	$3,879.7$	897.1	10^{-9}
β_4	1986	$5,973.9$	$4,375.8$	0.182
β_5	1986 – 1990	$-3,418.9$	$1,094.2$	0.004
β_6	1990	$-21,800.5$	$3,783.9$	10^{-9}
β_7	1990 – 1995	$-10,815.9$	$1,720.1$	10^{-9}
β_8	1995	$14,279.3$	$6,740.0$	0.042
β_9	1995 – 2006	$10,602.5$	$1,652.4$	10^{-9}
β_{10}	2006	$-9,752.4$	$6,422.8$	0.139
β_{11}	2006 – 2017	$-8,632.8$	968.1	10^{-9}
$\beta_1 + \beta_3$	1974 – 1977	$3,722.2$	896.0	10^{-9}
$\beta_1 + \beta_3 + \beta_5$	1986 – 1990	303.3	628.0	0.632
$\beta_1 + \beta_3 + \beta_5 + \beta_7$	1990 – 1995	$-10,500.0$	$1,601.3$	10^{-9}
$\beta_1 + \beta_3 + \beta_5 + \beta_7 + \beta_9$	1995 – 2006	89.9	407.5	0.826
$\beta_1+\beta_3+\beta_5+\beta_7+\beta_9+\beta_{11}$	2006 – 2017	$-8,540.0$	878.2	10^{-9}
Model parameters:	**obs = 44**	$F(11,32) = 390.36$	**Prob.** $> F = 10^{-9}$	lags(0)

Janeiro State, which was the subject of the oil boom. The result $\beta_6 - p = 0.043$ suggested there were significant differences between treatment and control after 1990; however, the result $\beta_7 - p = 0.169$ showed that the differences in both slopes were non-significant.

Multi-group single intervention 2006

The combined approach of SYNTH and multi-group ITSA identified significant interruptions for sugarcane harvested areas after the year 2006 (Table 3.4, Figure 3.5). The analysis for the intervention period 2006 aimed to isolate the effects of the second oil boom and the Growth Acceleration Program by comparing Rio de Janeiro State to traditional sugarcane producer States that were not exposed to the oil boom (Piauí, Ceará, Rio Grande do Norte, Paraíba, and Pernambuco). The result $\beta_3 - p = 10^{-9}$ shows significant differences between the trends before and after 2006, corresponding to an annual reduction of 5,016 ha. The non-significant differences between the treatment and control groups before 2006 ($\beta_4 - p = 0.357$) and the non-significant difference between the slopes of treatment and control groups before 2006 ($\beta_5 - p = 0.286$) indicates that both groups are comparable in terms of ITSA multi-group analysis. The result $\beta_6) - p = 0.374$ suggested there were no significant differences between treatment and control immediately after 2006, however, the result $\beta_7 - p = 0.056$ showed that the differences in both slopes were significant.

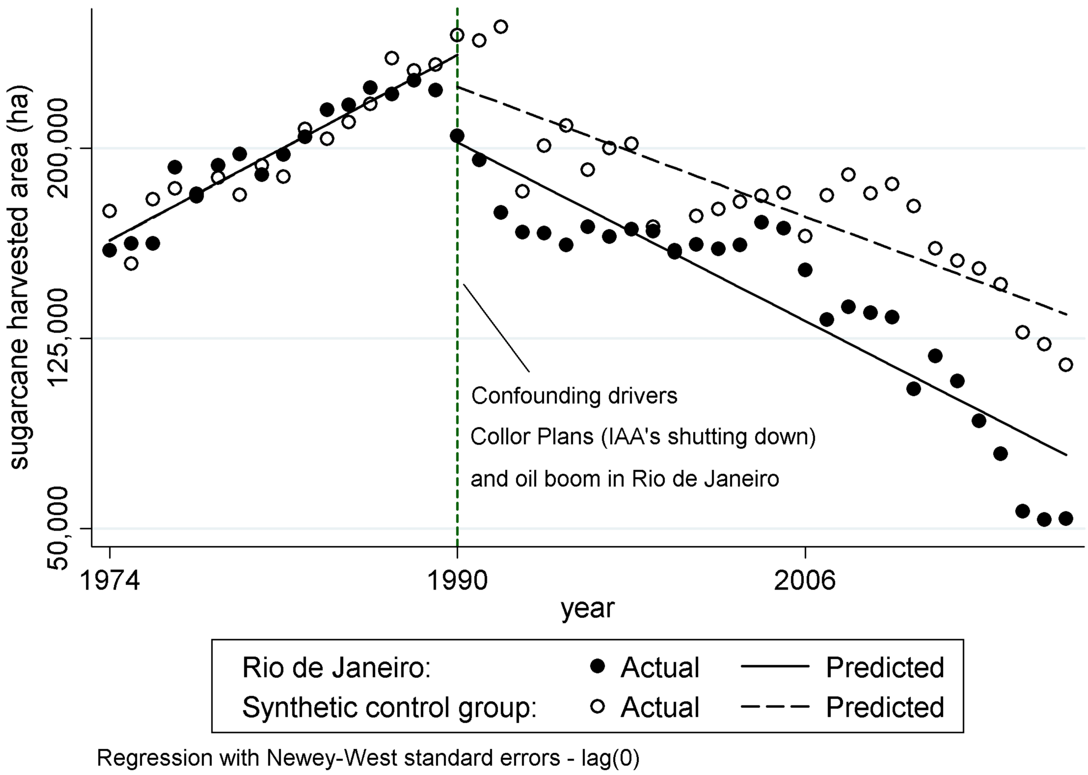

Figure 3.4: Multi-group comparison between Rio de Janeiro State and the average of other traditional sugarcane producer States of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, and Recife after 1990.

3.5 Discussion

Approximately one million hectares of farmland were abandoned in Rio de Janeiro State from 1975 to 2017. The findings of this paper reinforce the thesis of farmland abandonment pointed out in a previous study using data of cultivated areas in the municipalities in Rio de Janeiro State (Pedro Castro et al. 2019). The authors identified the Norte Fluminense as the most affected region and the sugarcane as the crop with the highest share in the loss of cultivated areas in the last decades. Approximately half of the cultivated areas' losses in the state are related to the sugarcane losses (IBGE 2018a). The data provided by the IBGE suggests that those abandoned crops are becoming part of what IBGE characterize as non-agricultural establishments (which might characterize the migration to second residences or becoming state land). In the field, we observed that degraded grassland occupied previous sugarcane fields. The evidence constitutes of abandoned sugar mills surrounded by degraded meadows with some extensive cattle ranching, which we believe is a mechanism some farmers use for occupying unproductive land, as previously addressed by (Alentejano 2006).

The ITSA model analyzed the breaks in the harvest areas of sugarcane in Rio de Janeiro State concerning relevant policy reforms and economic shocks during the study period. Our findings indicate that the Pro-Alcohol program introduced in 1977 had a positive outcome in the sugarcane harvest areas in Rio de Janeiro State. The positive trend in sugarcane harvest areas from 1977 to 1986 shows the

Table 3.3: Regression coefficients, standard errors, and p-values of the estimated multi-group ITSA model after 1990.

Model parameters	Years/Period	Coefficient	SE	p
β_0	1977	$163,474.9$	$4,651.2$	10^{-9}
β_1	slope before 1990	$4,577.1$	474.7	10^{-9}
β_2	change after 1990	$-12,535.4$	$8,495.4$	0.144
β_3	diff. before 1990 and after 1990 slopes	$-7,780.3$	638.7	10^{-9}
β_4	diff. between treatment and control before 1990	162.9	$6,098.5$	0.979
β_5	slopes diff. between treatment and control before 1990	-6.1	618.3	0.992
β_6	diff. between treatment and control after 1990	$-21,989.6$	$10,696.2$	0.043
β_7	slopes diff. between treatment and control after 1990	$-1,192.9$	860.1	0.169
$\beta_1 + \beta_4 + \beta_2 + \beta_6$	treated	$-4.40e+03$	418.1	10^{-9}
$\beta_1 + \beta_2$	controls	$-3.20e+03$	427.4	10^{-9}
$\beta_4 + \beta_4$	difference	$-1.20e+03$	597.0	0.0482
Model parameters:	**obs = 90**	$F(7,82) = 101.77$	**Prob.** $> F = 10^{-9}$	lags(0)

role of the Pro-Alcohol program boosting the production of sugarcane in Rio de Janeiro State, which is in line with previous studies (Coelho 2001; Azevedo 2002; Helfand,S.; Rezende 2003; Martinelli, Garrett, et al. 2011; Pupim de Oliveira 2002; Rico, Mercedes, and Sauer 2010). The effect lasted until 1986 at the time the credit sector restrictive reforms culminated. This suggests that the removal of subsidies had a strong impact on the sugarcane production in Rio de Janeiro, paving the way for the decay of the industry the years after. This is in line with previous arguments presented by Coelho 2001 and Azevedo 2002.

The period starting in 1990 is characterized by a strong negative break in the level of production in sugarcane harvest areas in Rio de Janeiro State. This structural break coincides with the implementation of the macroeconomic reforms of the Collor Plans I and II, released in 1990 and 1991. The Collor Plans were unsuccessful attempts to control the rising of the prices and monetary depreciation (Coelho 2001; Helfand,S.; Rezende 2003). The plans included new interest rate indexation rules for rural credit, the removal of transportation subsidies still foreseen in the PGPM, and the shutting down of the IAA in 1990.

The shutting down of the IAA has set an end to the supplying quota per sugar-mill at the national level, further exposing the sugarcane industry in the Norte

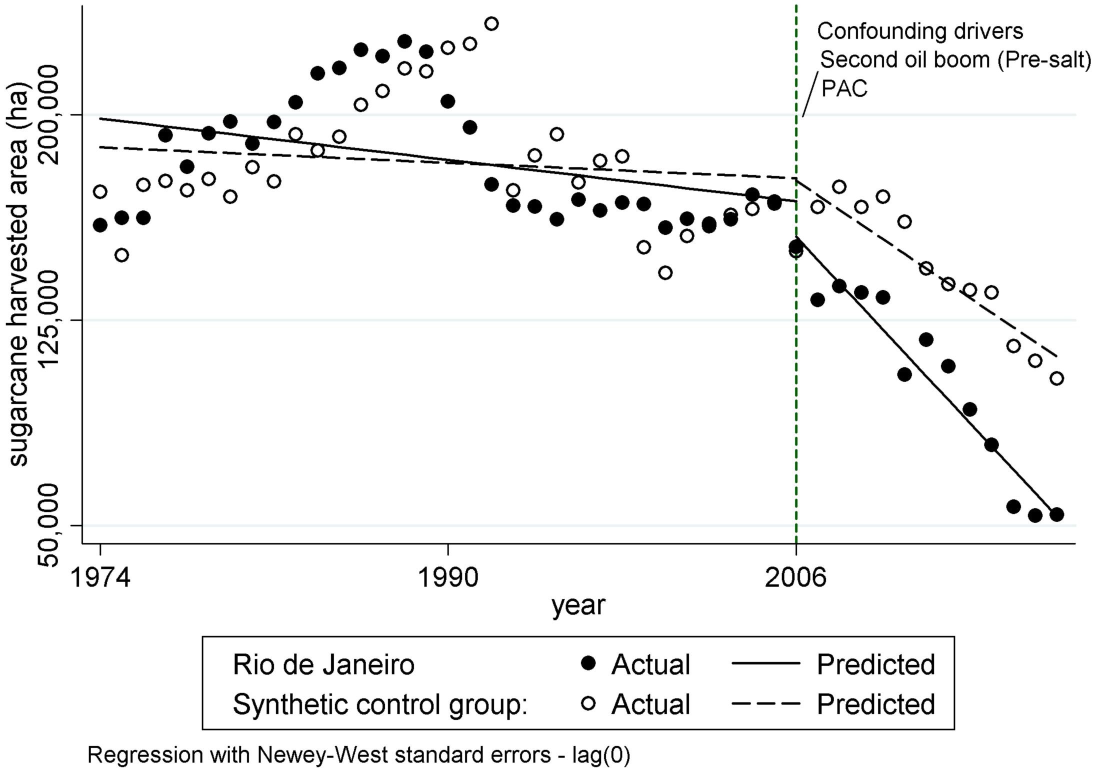

Figure 3.5: Multi-group comparison between Rio de Janeiro State and the average of other traditional sugarcane producer States of Piauí, Ceará, Rio Grande do Norte, Paraíba, and Pernambuco after 2006.

Fluminense to stronger competitors such as São Paulo, Paraná, Mato Grosso, Minas Gerais, and Goiás. Azevedo 2002 have previously addressed the effects of the elimination of the supply quota per sugar mill in intensifying the competition in the sugarcane industry and its role in exposing the weaknesses of the sugarcane sector in Rio de Janeiro State. These are seen as underlying causes of the sugarcane crisis from 1990 to 1995 (Coelho 2001; Helfand,S.; Rezende 2003).

Nevertheless, it is difficult to relate the structural break of 1990 in sugarcane production only to the Collor Plans. As referred by Linden 2017, the most common threat to the validity of single group ITSA modeling is the possibility that some other event also contributed to the observed effect in the time series, limiting the ability to draw causal inferences. There is another very important development that difficults the inference of the causes of the decay of sugarcane production after 1990 using a single ITSA analysis: the boom in the oil industry in the Norte Fluminense. This boom was sowed a decade earlier with the discovery of two large oil reserves in the Campos Basin offshore, the Albacora in 1984 and the Marlim in 1985. Alone from 1989 to 1990, there was an increase of 38% in the annual oil production, as reported by the National Oil Agency (ANP). T. J. Trebat and N. M. Trebat 2012 refer that the oil discoveries have gradually increased the oil supply for the industrial sector, inducing investments in Rio de Janeiro State's oil industry.

The oil boom in the Norte Fluminense also meant that several municipalities would benefit from royalties, which became their primary source of revenue (Piquet, Tavares, and Pessôa 2017). Policy reforms in the oil sector (law 7,453/1985, and

Table 3.4: Regression coefficients, standard errors, and p-values of the estimated multi-group ITSA model after 2006.

Model parameters	Years/Period	Coefficient	SE	p
β_0	1977	$188,105.2$	$7,014.0$	10^{-9}
β_1	slope before 2006	-351.4	380.9	0.359
β_2	change after 2006	-865.0	11416.2	0.940
β_3	diff. before 2006 and after 2006 slopes	$-5,015.8$	$1,096.6$	10^{-9}
β_4	diff. between treatment and control before 2006	$10,485.9$	$11,315.7$	0.357
β_5	slopes diff. between treatment and control before 2006	-590.8	549.9	0.286
β_6	diff. between treatment and control after 2006	$-12,085.1$	$13,518.6$	0.374
β_7	slopes diff. between treatment and control after 2006	$-2,558.6$	$1,321.0$	0.056
$\beta_1+\beta_4+\beta_2+\beta_6$	treated	$-8.52e+03$	620.7	10^{-9}
$\beta_1+\beta_2$	controls	$-5.37e+03$	1028.3	10^{-9}
$\beta_4+\beta_4$	difference	$-3.15e+03$	1201.1	0.010
Model parameters:	**obs = 90**	$F(7,82) = 101.77$	**Prob.** $> F = 10^{-9}$	lags(0)

law 9,478/1997) extended the list of municipalities that benefited with the royalties' payments. Those policies shifted the economic-basis of several municipalities of the Norte Fluminense region, including Campos dos Goytacazes, Carapebus, Macaé, Quissamã e São João da Barra. Those municipalities changed from an agrarian-based economy to an oil-dependent economy. The growing job offer related to the development of the oil industry in the Norte Fluminense also attracted a wave of workers from other areas, resulting in rapid industrialization and potential aggravation of social problems. That is because the demand for the highly qualified labor force and the massive economic returns of oil-related projects tend to set higher wages than in the other activities, potentially attracting the labor force from other sectors (Lewis 1984).

The rural population in the Norte Fluminense dropped from $127,230$ to $100,835$ from 1991 to 2010 (IBGE 2011). In Macaé, the urban population changed drastically: 88% in 1991 to 98% in 2010. In Campos, the urban population in 1991 was 83%, and in 2010 was 90% (IBGE 2011). The increase of the urban population in Macaé was somewhat radical: from $70,079$ urban citizens in 1991 to $102,545$ urban citizens in 2010 (IBGE 2010). Cases of rapid urbanization following the farmland abandonment, such as the observed in Rio de Janeiro State, also took place in China

(S. Li and X. Li 2017).

Notwithstanding, Piquet, Tavares, and Pessôa 2017 suggested that the oil industry in the Norte Fluminense did not absorb the local labor force. Accordingly, the low skilled workers in the region were not eligible for occupying job positions in the oil sector, which had to import high-educated workers from elsewhere. The workers without many years of formal education were absorbed by supporting activities, such as civil construction and services.

The combined approach of SYNTH and multi-group ITSA showed which of the co-founding drivers identified for 1990 (i.e., the oil boom and Collor Plans) played an underlying role in the sugarcane industry breakdown in Rio de Janeiro State and the consecutive farmland abandonment. Despite the oil boom in Rio de Janeiro State, no differences in the trends were observed among the groups. The results showed that the oil boom was not determinant for the breaks in agriculture trends in Rio de Janeiro State. The oil boom was, therefore, an additional cause. The impact of the Collor Plan in the trends sugarcane harvested areas in Rio de Janeiro State and the synthetic control group (formed by the States of Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, and Recife) is visible through the significant differences before and after the Collor Plans $\beta_3 - p = 10^{-9}$), which demonstrates the impact of the policy interventions as an underlying cause of the sugarcane crisis in those traditional sugarcane producers.

The fact the sugarcane is the base of the agriculture production in Rio de Janeiro State puts in evidence the role of the policy interventions as an underlying cause of the breakdown of the sugar industry and following farmland abandonment in Rio de Janeiro State. The impact of the Collor Plans is visible from 1989 to 1995, when eight sugar-mills ceased their activities in the Norte Fluminense region: Santa Maria (1989), Outeiro (1992), Santo Amaro (1994), Baixa Grande (1994), São João (1995), Cambaíba (1995), Queimado (1995) (Azevedo 2002; Smiderle 2010).

A period of macroeconomic stabilization that followed the introduction of the Real Plan in 1995 was also reflected in the sugarcane industry, which remained stable until 2006. After 2006, another oil boom took place in Rio de Janeiro State (T. J. Trebat and N. M. Trebat 2012). The second oil boom started after the discovery of the deep-water oil fields (pre-salt) in the Santos Basin, southeast Brazil in 2006. A substantial increase in government investments in the energy sector followed the findings in the Santos Basin in 2006. Those investments occur under the umbrella of the Growth Acceleration Program (PAC), which consisted of a national policy encompassing investments in the energy sector, infrastructure, and social welfare.

The occurrence of the second oil boom in 2006 and the following implementation of the PAC in 2007 also limits the capacity of stabilizing the causal inferences regarding the breaks in the sugarcane harvested areas. The comparative analysis between Rio de Janeiro State and the synthetic group composed of sugarcane producers that were not subject to the oil boom in 2006 puts some light in those relationships.

Even though both groups benefited from the investments of the PAC, the occurrence of the second oil boom maximized the investments in Rio de Janeiro State, creating an element of differentiation between Rio de Janeiro State and the synthetic control group.Although the immediate differences between Rio de Janeiro State and the synthetic group of sugarcane producers immediately after 2006 ($\beta_6 - p = 0.374$) were non-significant, the differences in the slopes 2006 ($\beta_7 - p = 0.056$) indicated that the existence of the second oil boom added an element of differentiation between the sugarcane harvested areas of Rio de Janeiro State and the synthetic group over the years.

Despite its marginal level of significance, the coefficient (β_7)indicates that the differences in the trends between both groups might illustrate the role of the second oil boom in maximizing the impacts of PAC in 2007. The PAC program prompted massive investments in the energy sector, infrastructure, social welfare. The higher demand for the labor force for the infrastructure projects attracted workers from the rural to the civil construction and the oil sector. From 2006 until 2012, the population employed in the oil sector in Rio de Janeiro State increased by 91%, jumping from 6,299 to 12,045 (IBGE 2018c). Meanwhile, the population employed in the sugarcane related activities decreased by 11% (IBGE 2018c).

The implementation of the PAC played an underlying role in the decreasing trend of sugarcane harvested areas as it promoted investments in infrastructure and social welfare, attracting the labor force with few years of formal education to the civil construction. The investments in urbanization projects in Macaé amounted to circa 12 million Brazilian Reais from 2007 to 2010. The implementation of the PAC explains the migration of the labor force from the rural sector to the services and construction sector after 2006.

Meanwhile, the second oil boom played a mediating role in the decreasing trend of the sugarcane harvested areas in Rio de Janeiro State by enhancing the impacts related to the PAC. As part of the energy sector, the oil industry took advantage of the massive government investments in the scope of the PAC. From 2007 to 2010, the investments of the PAC in the oil sector exclusively in Rio de Janeiro State amounted to $54,187.2$ million Brazilian Reais.

The economic developments explain the migration of a part of the labor force from the sugarcane sector to civil construction and services associated that followed this second economic shock (T. J. Trebat and N. M. Trebat 2012). Since 2006 three other sugar mills stopped their activities: Cupim (2006), Barcelos (2009), and Santa Cruz (2010). Only three sugar-mills are still working in the region (Coagro, Sapucaia, and Paraíso) (Smiderle 2010).

Our study has shown that several national policies acted as underlying causes of the agricultural sector, removing protection of the sugarcane sector in Rio de Janeiro State, and exposing Rio de Janeiro's sugarcane industry to the competition with other state producers. The results illustrated the effects of those policies on the breakdown of the principal agricultural industry of the state. The study also shows that economic shocks played a different role over the years. The first oil boom did not play a determinant role in the breakdown of the sugarcane industry in the state in 1990, acting instead as an additional cause. The second oil boom enhanced the effects of the PAC, allowing massive investments in the energy sector in Rio de Janeiro State. The economic shock that took place after 2006 acted as a mediating factor for farmland abandonment in Rio de Janeiro State.

3.6 Conclusions

The CEAGRO data showed 945,000 hectares of net farmland abandonment in Rio de Janeiro State, mostly occurring in sugarcane areas in the Norte Fluminense region of Rio de Janeiro. The ITSA analysis was implemented to investigate the correspondence between policy interventions and economic shocks with the abandonment of sugarcane farming activities. In this study, we analyzed the correspondence of policy interventions and their effects in harvested areas of sugarcane throughout an ITSA analysis. Furthermore, we investigated how the discovery of oil in the Campos Basin and the Santos Basin impacted the farmland abandonment. Through the combination of synthetic control group estimation and multi-group ITSA analysis, we compared Rio de Janeiro State with groups composed by States characterized as traditional sugarcane producers that also presented the same pre-intervention trends found in Rio de Janeiro State. Both groups were an object of the national policy intervention, but only Rio de Janeiro State was subject to the oil booms. With the Multi-group ITSA analysis, we found out that the first boom in the oil sector added elements for the socio-economic transformations in the region but did not play an underlying role in the farmland abandonment in Rio de Janeiro state. We also found out that the second oil boom had a more prominent role in the farmland abandonment in Rio de Janeiro State by augmenting the investments of the PAC and attracting labor force from rural to urban areas.

The study puts a spotlight on the underlying role of the policy interventions impacting the region's economic development and people's livelihoods. Although the study also addresses how the local realities add elements to social dynamics, it concludes that those elements materialized on the booms in the oil industry played different roles according to their temporal contexts. While the first oil boom represented an additional element of alterations on social dynamics upon which it is worth reflecting, the second oil boom took advantage of the context to potentialize the drainage of the labor force from the rural to the urban areas caused by the implementation of the PAC. The study case on farmland abandonment in Rio de Janeiro State puts in evidence the underlying role of the policy interventions in Rio de Janeiro's farmland abandonment.

3.7 Acknowledgements

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4

Sugarcane abandonment mapping in Rio de Janeiro state Brazil

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Abstract

The mapping of sugarcane plantations and their changes is relevant to the economy and the environment, notably due to sugarcane's interface in the biofuel industry through ethanol. The necessary mapping of sugarcane crop changes is especially challenging when plantation occurs under smallholders' land ownership structures used for heterogeneous crop management. We evaluated two approaches to address this challenge with the example of sugarcane abandonment in the Norte Fluminense Region, Northeastern Rio de Janeiro State, Brazil. The region is characterized by a large share of smallholders. We trained a random forest classifier for sugarcane for 2018 based on all available Landsat imagery. Based on the concept of temporal generalization, we applied the classifier trained in 2018 for the period from 1986 until 2020. The resulting annual sugarcane probability maps were used as input for two abandonment mapping methods: LandtrendR and muti-temporal cropland abandonment mapping. The performance of both approaches was evaluated based on a stratified sampling approach. We detected three distinct trajectories for sugarcane farmland: i) permanently abandoned sugarcane, ii) fallow sugarcane, and iii) and stable sugarcane. The multi-temporal cropland abandonment mapping performed better for the sugarcane abandonment class (F1= 0.84) than the LandtrendR approach (F1= 0.21). The LandtrendR results revealed a higher omission (PA= 0.12) in mapping the sugarcane abandonment class. For the multi-temporal cropland abandonment mapping, we found that 66% (67,353 ha) of the stable sugarcane areas were abandoned between 1990 and 2016. The highest abandonment rates occurred between 1990 and 1994 and between 2010 and 2016. The spatial distribution of abandonment was heterogeneous. The earliest abandonment was concentrated in the northern part of the study area. The most recent abandonment was more extensive in the southern part of the study site. Our results highlight the advantages and challenges of using Landsat time series to map sugarcane abandonment in a heterogeneous management system. Our results also highlight the spatially and temporal heterogeneous pattern of sugarcane abandonment in the region and provide the necessary database for subsequent studies to identify underlying and proximate causes for the abandonment.

keywords: cropland abandonment, sugarcane, multi-temporal cropland abandonment mapping, LandtrendR, Land Use Land Cover Change, temporal generalization, Brazil, Landsat.

4.1 Introduction

Cropland abandonment refers to land once used as agricultural cropland that no longer serves this purpose (Baxter and Calvert 2017). Cropland abandonment does not strictly imply idle land because the abandoned crop might become a new active use, such as pasture or urban sites. However, abandoned croplands might also be left entirely unmanaged in some cases, allowing natural succession to take over. The management's pulling out might occur gradually by an initial reduction of farming intensity or abruptly due to different driving forces Keenleyside and G. Tucker 2010.

Cropland abandonment results from policies, regional socio-economic, and environmental factors (Ustaoglu and Collier 2018). The main causes and the direct and indirect implications of cropland abandonment vary between geographic regions. For example, drastic economic and political changes due to the breakdown of the former USSR triggered the abandonment of extensive lands in the former block member states Kuemmerle et al. 2008. Also, sector-specific policy interventions underlined cropland abandonment in Southeastern Brazil R. F. d. Silva, Batistella, and Emilio F. Moran 2016; P. Castro et al. 2020. Various socio-economic factors contributed to cropland abandonment in Japan (Su, Okahashi, and Chen 2018), China (Xie, P. Wang, and Yao 2014), Nepal (Rai et al. 2019), Russia (Alexander V. Prishchepov et al. 2013), Ukraine (Baumann et al. 2011), Slovakia (Pazúr et al. 2014), Albania (Müller and Munroe 2008), Spain (Zaragozí et al. 2012; Vidal-Macua, Zabala, et al. 2018), and Brazil (R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017). Cost-related factors such as poor infrastructure and distance to markets were important drivers of cropland abandonment in Brazil (Laue and Arima 2016) and Chile (Díaz et al. 2011). Topographical constraints played an important role in cropland abandonment in Switzerland (Gellrich and Zimmermann 2007) and Eastern Europe (Baumann et al. 2011; Pazúr et al. 2014; Estel et al. 2015; Kolecka et al. 2017).

Cropland abandonment outcomes are manifold. They vary from severe socio-economic and environmental consequences to opportunities for conservation and potential ecological benefits (Young et al. 2005). For example, reported negative environmental impacts of cropland abandonment included the growing risk of forest fires (Moreira, Rego, and Ferreira 2001) and the loss of high- ecological-value species (Katayama et al. 2015). Potentially productive abandoned areas can threaten food sovereignty (Meyfroidt et al. 2016). Cropland abandonment can also imply loss of rural livelihoods (Gellrich and Zimmermann 2007) and rapid urbanization (Xie, P. Wang, and Yao 2014). However, cropland abandonment can bring positive impacts as well. For example, forest restoration linked to forest succession on the abandoned plots has a positive impact on the carbon cycle (Cramer, Hobbs, and Standish 2008; R. F. d. Silva, Batistella, and Emilio F. Moran 2016; Kolecka et al. 2017) as well as on soil and water quality (Díaz et al. 2011). It is therefore important to monitor cropland abandonment to understand its drivers and consequences.

Satellite-based approaches provide adequate means to map cropland areas accurately and, consequently, cropland abandonment. Aggregated data on agricultural production published by local statistical bureaus do not properly identify cropland abandonment as they lack spatial resolution (Pedro Castro et al. 2019). Availability of consistent, long-term time series with high temporal resolution is beneficial for detecting cropland abandonment. Landsat has been frequently used for spatial-temporal mapping of cropland abandonment, specifically in areas dominated by tilled crops in different regions in the world (Yin, Alexander V. Prishchepov, et al. 2018; Grădinaru, Kienast, and Psomas 2019; Yin, Brandão, et al. 2020; Natalia Kolecka 2021). Other studies used MODIS NDVI time series products to map cropland abandonment at large scales (Alcantara et al. 2012; Estel et al. 2015). However, studies based on MODIS are restricted to periods after 2000 due to the availability of MODIS data. Compared to MODIS, Landsat images offer advantages to cropland abandonment mapping in study regions characterized by smallholding structure mainly due to Landsat's higher spatial resolution and the over 40-year continuous imagery acquisition (Matthew C. Hansen and Loveland 2012; Irons, Dwyer, and Barsi 2012; Zhu, Wulder, et al. 2019). Sentinel-2 imagery provides higher resolution than Landsat but is only available after June 2015; therefore, covering only a limited time window.

Trajectory-based change detection methods are suitable for detecting and monitoring cropland abandonment based on satellite image time series (Yin, Alexander V. Prishchepov, et al. 2018). The methods encompass several techniques, including decomposing the temporal trajectory of spectral values into segments and fitting the segments by parametric functions (R. E. Kennedy, Cohen, and Schroeder 2007; Verbesselt et al. 2010), as well as the identification of expected - on the basis of benchmark studies- temporal patterns in the entire trajectory of long-term satellite data (Zhu and Woodcock 2014; Maus et al. 2019). Some examples of methods used in this context are the Breaks For Additive Seasonal and Trend (BFAST) (Verbesselt et al. 2010), the Continuous Change Detection and Classification (CCDC) (Zhu and Woodcock 2014), the dtwSat or Time-Weighted Dynamic Time Warping for Satellite Image Time Series Analysis ((Maus et al. 2019), and the LandtrendR (R. E. Kennedy, Yang, and Cohen 2010; R. E. Kennedy, Yang, Gorelick, et al. 2018; Yin, Alexander V. Prishchepov, et al. 2018). In addition, the use of spatio-temporal metrics from multi-spectral bands and/or spectral indices such as the NDVI, EVI, NDMI (Gao 1996), BSI (Sanne Diek, Fabio Fornallaz, and Michael E. Schaepman and Rogier de Jong 2017), or tasseled cap (Eric P. Crist 1985) has also been proven advantageous in mapping cropland abandonment in various spatio-temporal contexts (Schmidt et al. 2016; Yin, Alexander V. Prishchepov, et al. 2018; Yin, Brandão, et al. 2020).

In addition to the mapping of cropland abandonment, there is a need to map abandonment of specific crop types. This is important as driving factors for abandonment can be assumed to differ between crop types as well as the environmental and socio-economic impacts of abandonment. Such focused analysis can be assumed to be of special importance for economically relevant crops such as sugarcane, which produces more than half of the world's supply of sugar and is used as input for a wide range of products, including bio-fuel through ethanol (OECD, Food, and United Nations 2021)). Mapping sugarcane abandonment implies the ability to monitor annual sugarcane crops accurately. Although new approaches using deep learning architectures have proved applicable for accurate large-scale crop mapping (Kussul et al. 2017; Zhong, Hu, et al. 2019; Xu et al. 2020; Poortinga et al. 2021), the use of the supervised classifiers Support Vector Machine (SVM), and Random Forest remains consolidated in the remote sensing-based crop mapping literature (Schmidt et al. 2016; Santos Luciano, Picoli, Rocha, Franco, et al. 2018; Santos Luciano, Picoli, Rocha, Duft, et al. 2019S). The Random Forests (RF) classifier applied to satellite imagery is well suited for sugarcane mapping in various spatio-temporal contexts (Santos Luciano, Picoli, Rocha, Franco, et al. 2018; Santos Luciano, Picoli, Rocha, Duft, et al. 2019; Jiang et al. 2019; M. Wang et al. 2019). Yet, mapping the abandonment of sugarcane crops encompasses many challenges. One of these challenges is that the growth period differs strongly depending on the variety and the management practice used. In addition, sugarcane might be followed by a fallow period. This can both lead to a complex temporal pattern that needs to be considered in classification and validation.

Temporal or within-scene generalization is essential to avoid labor-intensive year-by-year training data collection for multi-temporal crop mapping (Zhong, Gong, and Biging 2014). Temporal generalization means assessing classifier transferability to multiple years., i.e., when a classifier built from signatures derived from one image is applied to other images derived on different dates (Woodcock et al. 2001; Pax-Lenney et al. 2001). Temporal generalization has been frequently assessed in forest change monitoring, where significant spectral differences between forest and non-forest facilitate the application (Woodcock et al. 2001; Pax-Lenney et al. 2001). Temporal generalization has also been assessed for specific crop types such as wheat and soybean (Zhong, Gong, and Biging 2014) and for the monitoring of large sugarcane areas (Santos Luciano, Picoli, Rocha, Franco, et al. 2018; Santos Luciano, Picoli, Rocha, Duft, et al. 2019).

Temporal generalization in the sugarcane mapping implies that the classifier is sensitive to interannual variability of sugarcane growth (Santos Luciano, Picoli, Rocha, Franco, et al. 2018). For that, a few requirements need to be met. First, the temporal generalization of sugarcane mapping requires comprehensive predictor datasets extracted from the satellite images, including many years of reference and satellite data (Santos Luciano, Picoli, Rocha, Franco, et al. 2018). The Landsat imagery time coverage and recurrence period allow gathering of many years of reference satellite data for building a set of predictors that comprises the interannual variability of sugarcane growth (Zhu, Wulder, et al. 2019). Second, it is necessary to assure a consistent spectral response of the modeled land cover types across the years. Normalizing satellite image time series enables a consistent spectral response throughout the years (Pax-Lenney et al. 2001). Third, to train a classifier collected training data needs to capture unique spectral signatures for sugarcane crops for a reference year. Training data collection for sugarcane crop mapping is challenging, especially in regions where sugarcane crop-pasture management predominates. Sugarcane is a grass crop (family Poaceae or Gramineae) (Burton and Couch 2021) and is particularly difficult to differentiate from natural grassland used for cattle ranching due to their phenological and spectral similarities (Schmidt et al. 2016). The identification of unambiguous - phenology-based - sugarcane training data is crucial to building a classifier capable of distinguishing highly confounding land cover types such as sugarcane from natural grassland.

Sugarcane is one of the most important commodities in Brazil. The country dominates the global sugarcane market with a share of 40.5% of the world's global sugarcane exports in 2019 (OEC 2019). São Paulo, Minas Gerais, Goiás, Paraná, Mato Grosso, and Mato Grosso do Sul States (de- nominated Center-South Economic Region by IBGE) account for 91% of the sugarcane production in Brazil (IBGE 2021). The agricultural production data in the center-south of Brazil showed an expansion of 62% and 59% of cultivated areas and production between 2000 and 2019 (IBGE 2021).

While the Center-South of Brazil witnessed an expansion of sugarcane, other traditional sugarcane production regions in northeastern and southeastern Brazil showed a critical reduction (**Supp. 4.10**). For example, in northeast Brazil, the traditional sugarcane producers Bahia, Pernambuco, and Paraíba showed a decrease of 26% of their sugarcane cultivated areas and 5% of their yield between 2000 and 2019 (IBGE 2021). The Norte Fluminense, another traditional sugarcane production region in the northeastern part of Rio de Janeiro State, southeast Brazil, also showed a substantial decrease of 76% in sugarcane production between 2000 and 2020 (IBGE 2021). Sugarcane accounted for more than 70% of the decline in crop areas in Rio de Janeiro and 92% in the Norte Fluminense Region between 1990 and 2020 (IBGE 2021). Although other crops such as pineapple and coconut increased their cultivated area, the extent of their expansion is small and covers less than 5% of the lost area of sugarcane (IBGE 2021).

National statistical annuaries provide evidence of the abandonment of sugarcane areas; however, detailed information on the location and timing of abandonment are missing, which constraints a proper identification of sugarcane abandoned areas (Yin, Brandão, et al. 2020). The nationwide satellite-based Land Use Land Cover mapping initiative Mapbiomas (C. M. Souza et al. 2020) also has limitations in the sugarcane mapping, notably in regions characterized by smallholder farming. Mapbiomas classifies sugarcane areas in traditional sugarcane smallholder regions as a mosaic of mixed cropland and grassland/pasture. Sugarcane mapping in southeastern Brazil mainly focused on detecting extensive fields in key state producers and investigating their relationship with the sugar and ethanol industry (Aguiar et al. 2011; Vieira and Santos 2012; Rudorff, Luciana, et al. 2005; Rudorff, Aguiar, et al. 2010). The literature also provides examples of annual sugarcane crop mapping in the Norte Fluminense Region, Northeastern Rio de Janeiro (Mendonca et al. 2011; Barbosa et al. 2020). Despite the abandonment of sugarcane fields in the Norte Fluminense Region has been reported (Azevedo 2002; Smiderle 2010; Pedro Castro et al. 2019; P. Castro et al. 2020), very little is known about the timing and location of abandonment.

In Rio de Janeiro, we hypothesize that cropland abandonment refers to sugarcane plots that changed to a non-crop type, mostly being replaced by grassland in a natural succession process characteristic of former farms that lost their function. Given that: i) cropland abandonment in Rio de Janeiro refers to sugarcane replaced by grassland and; ii) the currently nationwide statistical annuaries and satellite-based mapping initiatives fail to separate sugarcane from pasture and other crops in some of the traditional sugarcane regions (e.g., Rio de Janeiro), it is essential to map sugarcane accurately to understand the process of cropland abandonment in Rio de Janeiro.

Therefore, the analysis presented here focuses on the multi-temporal mapping of abandoned sugarcane plantations in the Norte Fluminense Region, using long-term time-series Landsat imagery. Our goals are threefold: (1) to assess classifier generalization in producing consistent annual sugarcane crop maps between 1986 and 2020; (2) to test two different approaches to map the location and timing of sugarcane abandonment using annual sugarcane maps; (3) to assess the spatio-temporal extent of the sugarcane abandonment process in the Norte Fluminense region.

4.2 Data and Methods

4.2.1 Study Site

We mapped sugarcane abandoned areas in the Norte Fluminense Region IBGE 1990, Northeastern Rio de Janeiro State (4.1). The region shows the highest annual temperatures in Rio de Janeiro State, ranging from 26° C during winter to 33.5° C in the summer (W. L. Silva and Dereczynski 2014). Precipitation is approximately 1000 mm/year, the lowest among the federal state's regions (Davis and Naghettini 2000). On the one hand, high temperatures throughout the whole year and especially in the summer create suitable conditions for sugarcane farming. On the other hand, the low precipitation during winter negatively affects sugarcane production and increases its costs (Azevedo 2002).

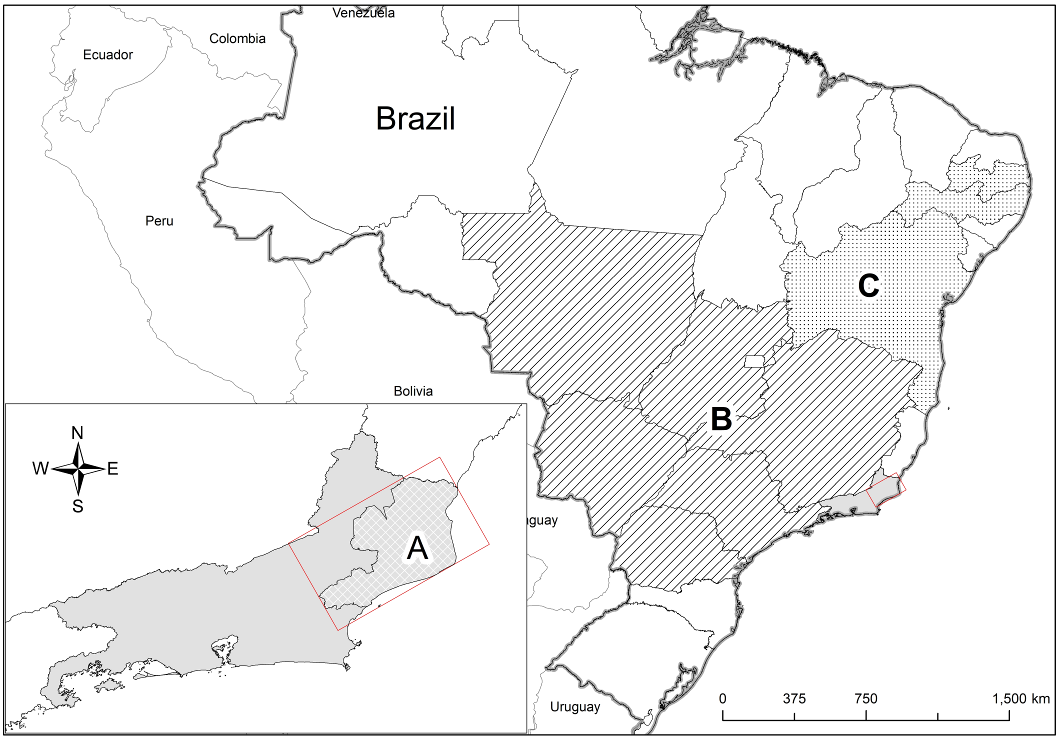

Figure 4.1: A. Norte Fluminense Region, Northeastern Rio de Janeiro State. B. Center-South States represent the modernized sugarcane production region. C. Northeastern Brazil traditional sugarcane producer states.

Sugarcane is a semi-perennial crop whereby harvest cycles can last up to 6 years by replanting the sections of the stalk of immature cane (known as seed cane). In intensive sugarcane management, successive annual sugarcane harvests result in a gradual yield loss shrinking its economically profitable. Farmers usually let the area fallow for up to three years or temporarily change the management to a leguminous due to its capacity to fix nitrogenous to the soils (Vieira and Santos 2012; P. Castro 12th of March, 2021).That management practice aims to recover soil's natural fertility and allow continuity in sugarcane production.

Sugarcane remained Norte Fluminense's most extensive crop for the reference year 2020, holding a 74% share of cultivated areas, followed by cassava (13%) and pineapple (8%) (IBGE 2021). The agricultural census in 2017 showed that small-holders primarily owned land in the Norte Fluminense: circa 89% of the farms were smaller than 50 ha ((**Supp. 4.11**)).

In Rio de Janeiro State, planting rows have circa 1.8 m spacing. Most of the production is labor-intensive (non-mechanized), slash and burn practices still occur, and plague and herbicides are applied for herb control (P. Castro 12th of March, 2021). While some farmers in the region use fallow periods, most farmers cultivated sugarcane either in a 12-month ("plantio de quente") or an 18-month cycle (**Supp. 4.12**). The 12-month sugarcane cultivation pattern was used on around 30% of the cultivated areas (P. Castro 12th of March, 2021), while most producers grew sugarcane in an 18-month cycle. In the 12-month sugarcane management, the planting typically occurs between August and October. In the 18-month cycle, planting usually occurs between January and March, and harvest happens between July and September the following year (Vieira and Santos 2012; P. Castro 12th of March, 2021).

4.2.2 Methods and data

Our approach consisted of the following steps (c.f.**Fig. 4.2**):

1. Normalization of imagery from different Landsat sensors available in Google Earth Engine using the coefficients from Roy et al. 2016;
2. creation of spatio-temporal metrics from the normalized Landsat imagery as previously done by Yin, Brandão, et al. 2020;
3. building a training set of sugarcane/non-sugarcane for the reference year 2018;
4. training of the random forest classifier (Breiman 2001) for mapping sugarcane and non-sugarcane in our study region to the reference year 2018;
5. make use of our classifier to extend the temporal frequency of our mapping and produce annual sugarcane maps from 1986 to 2020
6. use our annual sugarcane classification outputs to test two different methods for mapping sugarcane abandonment: a trajectory-based LandtrendR algorithm and a pixel-based multi-temporal cropland abandonment mapping approach.

The out-of-bag (OOB) error estimate is often used to evaluate the accuracy of a random forest. However, the OOB can overestimate the true prediction error depending on the choices of random forest parameters (Janitza and Hornung 2018).

Considering this limitation of the OOB, we used an error-adjusted stratified estimator to access both our annual sugarcane mapping and sugarcane abandonment maps accuracies and calculated the mapped areas (Stehman 2014; Olofsson, Foody, Stehman, et al. 2013; Olofsson, Foody, Herold, et al. 2014). We performed our analysis in Google's Earth Engine (Gorelick et al. 2017).

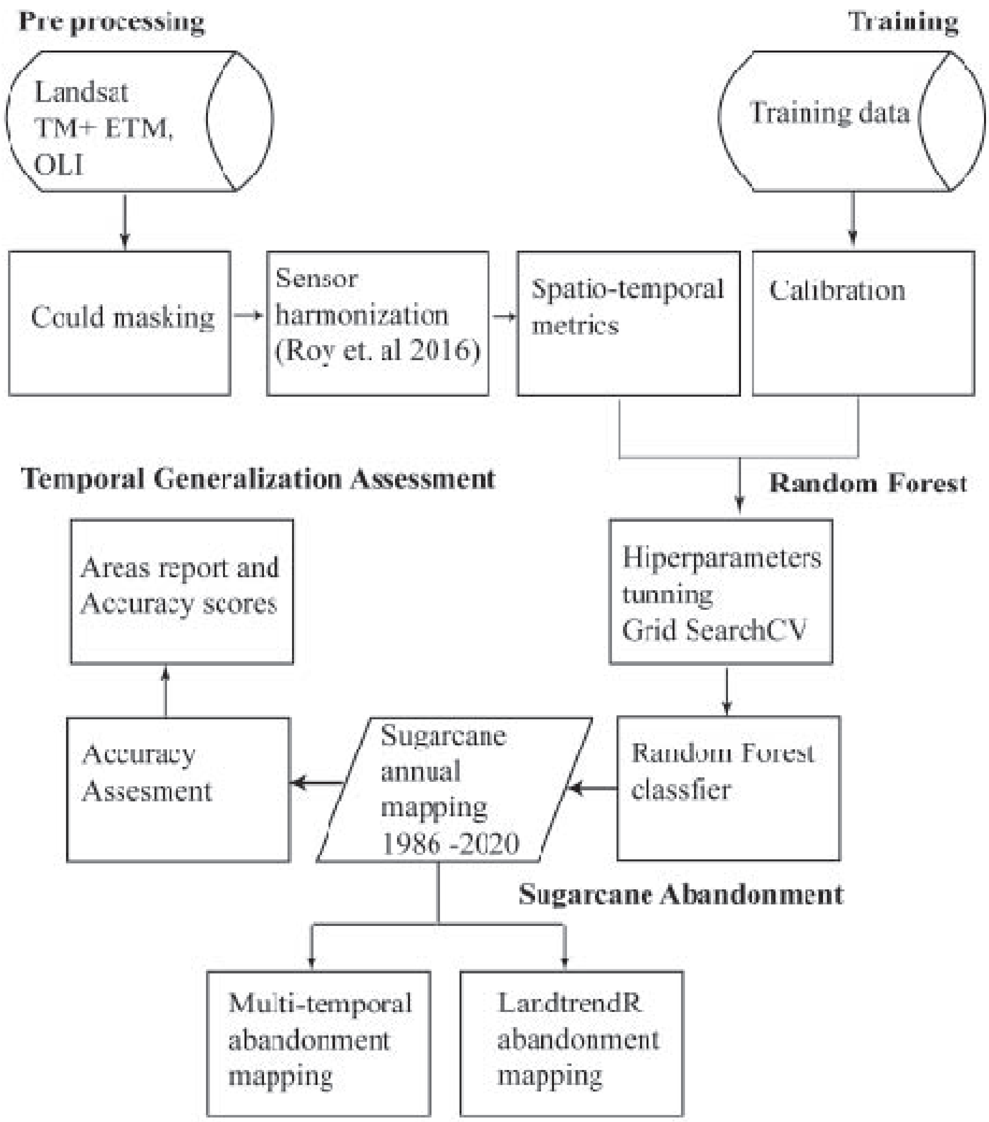

Figure 4.2: Flow diagram of the analysis.

Data processing

We analyzed Landsat Tier 1 surface reflectance available for our study region in Google Earth Engine from 1986 to 2018 (**Fig. 4.3**). The Landsat data we used were atmospherically corrected by the USGS using LEDAPS (Masek et al. 2006) and LaSRC (Vermote et al. 2016). We used the quality flags in the quality assessment band to exclude clouds and shadows. The coefficients from (Roy et al. 2016) were then applied to normalize the Landsat imagery by harmonizing the OLI reflectance to the predecessors TM and ETM+ sensors. The use of normalized imagery across time allowed the temporal generalization further on (Woodcock et al. 2001; Pax-

Lenney et al. 2001).

Next, we produced annual spatial-temporal metrics from the Landsat collections to capture the dynamics of sugarcane crops in our study region. For calculating the spatial-temporal metrics for a certain year, we considered a +/- 1 year imagery period (Yin, Brandão, et al. 2020) and calculated the median, standard deviation, and the 5, 10, 30, 70, 90, and 98 percentile from of the following indices and spectral bands: blue, green, red, NIR, SWIR and SWIR-2 bands, BSI, NDVI, NBR, EVI, NDMI, as well as the Tasseled Cap transformation bands Brightness, Greenness, Wetness. This led to 112 summary statistics for the year in focus.

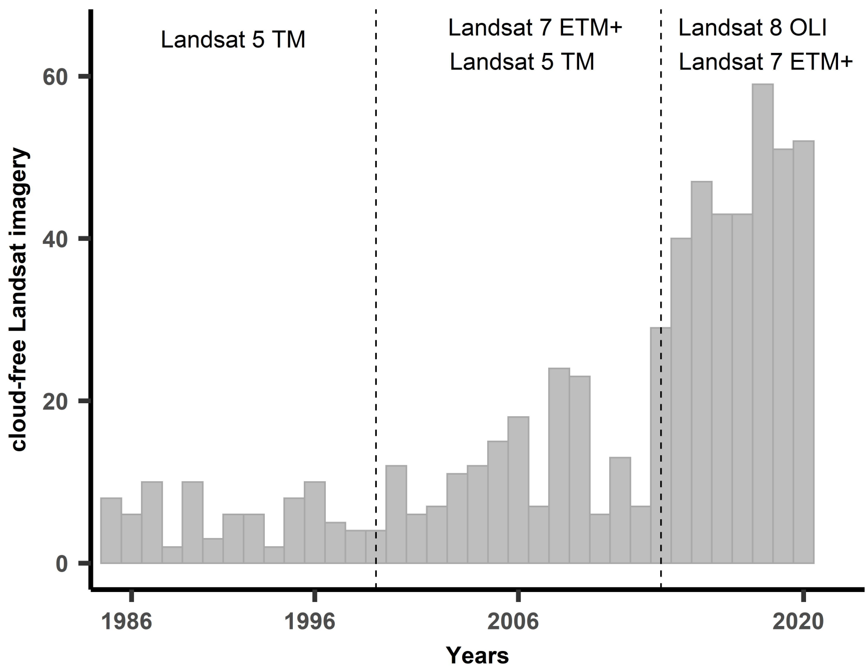

Figure 4.3: Amount of cloud-free Landsat images per year for the case study region. Image availability increased after 1999 due to the start of the Landsat 7 ETM+ operation.

Training samples calibration

We generated a set of training samples that included i) sugarcane sample points collected in the field in 2018 with a Garmin GPS device and ii) samples of several land-use types relevant for our study region. The latter was obtained by visual interpretation using high-resolution imagery from Google Earth. Each sample point corresponds to a pixel on the Landsat imagery. We ran a pre-classification (sugarcane x non-sugarcane) using our initial set of samples and performed a sensitivity analysis to determine whether our sugarcane classified areas corresponded to the cadaster of sugarcane farms provided by the ASFLUCAN (Norte Fluminense's Association of Sugarcane Producers). ASFLUCAN records the geographical limits of the farms that produce sugarcane for the association's sugar mills. The cadaster is updated yearly, and we obtained the register of associated farmers that grew sugarcane from 2015 until 2018. After the sensitivity analysis, we visually inspected all the sugarcane sample points to select those with unambiguous sugarcane signatures (i.e., sample points that fit into a typical sugarcane description for a reference crop year). We used the works of Rudorff, Luciana, et al. 2005; Rudorff, Aguiar, et al. 2010; Aguiar et al. 2011; Vieira and Santos 2012 as baseline studies to assist us in the interpretation of usual sugarcane patterns in southeastern Brazil, helping us to determine whether a sample point fits into a typical sugarcane pattern. We considered only the two sugarcane patterns typically observed in the producing regions in southeast Brazil (Rudorff, Luciana, et al. 2005; Rudorff, Aguiar, et al. 2010; Aguiar et al. 2011; Vieira and Santos 2012) that follow a 12- and an 18-month period with a 12 and 6-month development phase.

The sugarcane plant fields were characterized by a growing trend in NDVI values during the development of the plants. After a short period of constant values, the NDVI dropped sharply due to the harvest between July and September (**Fig. 4.4**). We also used the BSI values to assist that interpretation. Conversely to the NDVI, BSI time-series showed high values during the post-harvest period (between July and September) and lower values during the plant development period (**Fig. 4.4**).

These patterns in the time series of the spectral indices were used along with the typical sugarcane appearance in natural color compositions (light green with a relatively smooth texture) to identify additional sugarcane sample points. The visual search for sugarcane fields was based on high-resolution images on Google Earth. For the temporal pattern analysis in the spectral indices, we used the Time Series Viewer that includes Landsat and Sentinel-2 imagery (Yin, Brandão, et al. 2020). We selected our imagery collection for periods ranging from the first of January 2017 until the thirty-first of May 2020, so we were able to identify the pattern of a crop period 2017-2018 map to sugarcane areas for our reference year 2018. We visually inspected the time series of NDVI and BSI indices built from the Landsat TM, ETM+, and OLI and the Sentinel 2 sensors. This led to a calibrated sample size of $n = 962$ ($sugarcane = 262$, and $non - sugarcane = 700$).

Sugarcane annual mapping

For our reference classification 2018, we used Landsat imagery from the first of January of 2017-1-01 to the thirty-first of December of 2019 (2018 +/- 1 year). Then, we trained a random forest classifier on the 112 summary statistics for our study region. We applied a grid search using cross-validation (kernel 5x5) to support the choice of hyperparameters for our random forest model. Our analysis showed 12 randomly sampled variables as candidates at each split (mtry) and 50 trees as the best choice. The classifier was then applied to the rest of the time series from 1986 to 2020, resulting in annual sugarcane classifications.

Sugarcane annual map validation

We validated our annual sugarcane map using a random disproportional stratified sampling (Olofsson, Foody, Herold, et al. 2014). We used in our sample design parameters of anticipated user's accuracies (UA) of 0.95 and a target standard error of 0.02. We applied disproportional allocation to ensure we had enough samples to assess classes with limited coverage (Olofsson, Foody, Herold, et al. 2014). Next, we randomly selected 120 pixels equally split between the strata sugarcane and non-sugarcane.

We assigned a reference label for the 120 selected pixels based on a visual inspec-

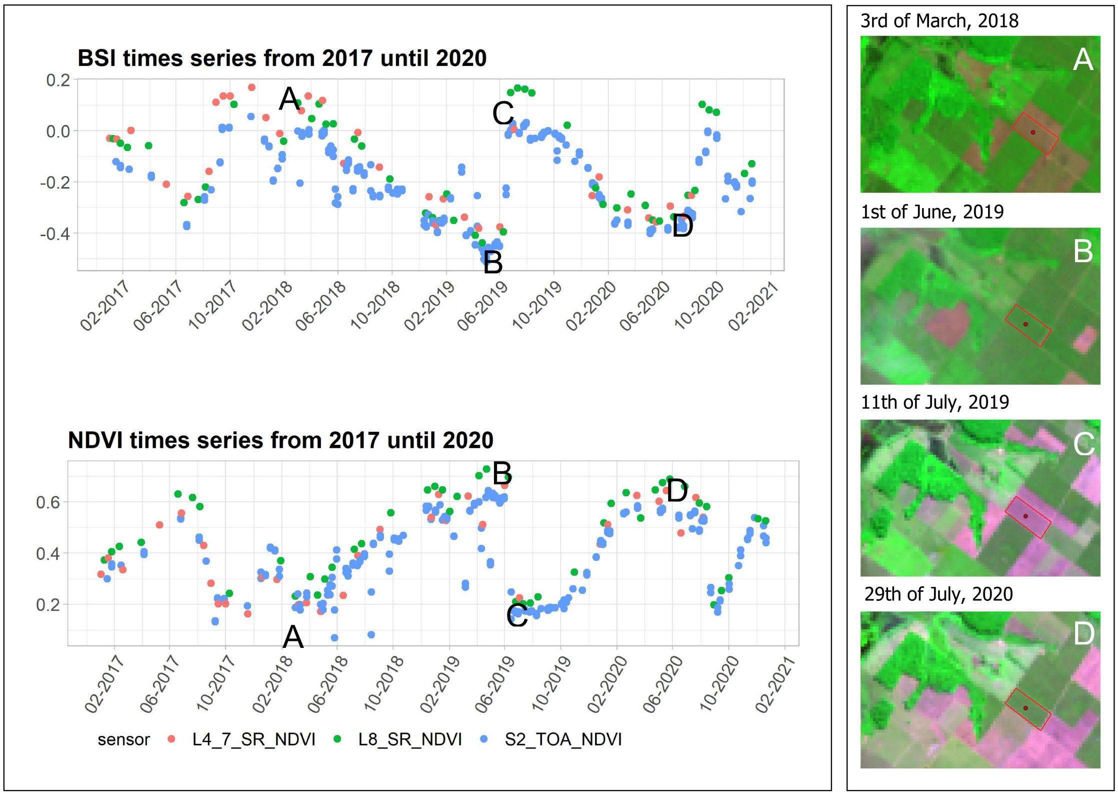

Figure 4.4: A: The Landsat image from the third of March, 2021, shows the beginning of a growing period for an 18-month sugarcane crop. B: On the first of June, 2019, the sugarcane is ready to harvest. C: The Landsat image on the eleventh of July, 2019, shows the beginning of the growing period of a 12-month crop. D: On the twenty-ninth of July 2020, the image shows the sugarcane field ready to harvest.

tion (Olofsson, Foody, Herold, et al. 2014). Two tools assisted our visual interpretation: 1) Google Earth historical imagery and 2) the time series of the spectral indices NDVI, BSI, Tasseled-Cap Brightness, Greenness, and Wetness in a Landsat Time Series Inspector Yin, Brandão, et al. 2020). No information on the mapped classes was made available to the interpreter during the validation process. After assigning the reference labels, we created a confusion matrix and calculated the producer's and user's accuracies (also known as recall and precision) and the F1 score (the harmonic mean of the precision and recall) for each sugarcane and non-sugarcane class. We also assessed the overall accuracy of our reference sugarcane map.

To assess the temporal generalization of our approach, we applied an independent validation for four selected years: 1986, 1996, 2006, and 2020. We assured a minimum 10-year interval between the validated maps and validated the classifier's transfer to years before and after the reference year. For each of the four select years, we performed a stratification (Supp. 4). We generated independent samples for validating each selected year separately (plus the reference year 2018, which also had an independent validation). The stratification for the four selected years was performed using the target SE of overall accuracy with expected users' accuracies (UA) of 0.95 and a minimum standard error of 0.02. The sampling size recommended was 119. We allocated an equal sample size of 60 for each mapped class (sugarcane and non-sugarcane) in each of the years validated. Then, we evaluated sugarcane annual mapping performance and accessed the sugarcane mapped areas across the selected years.

Sugarcane abandonment mapping

We tested two approaches for the mapping of sugarcane abandonment: (1) a pixel-based multi-temporal cropland abandonment mapping approach applied to annual binary sugarcane/non-sugarcane classifications (Yin, Brandão, et al. 2020); (2) the LandtrendR approach applied to annual sugarcane land probabilities aggregated per spatial objects (Yin, Alexander V. Prishchepov, et al. 2018). In both approaches, we distinguished the land use classes stable sugarcane crops, fallow sugarcane, and sugarcane abandonment. We used the FAO's definition of cropland abandonment to classify distinct sugarcane trajectories in the region: (1) permanent sugarcane abandonment as areas that have not been used for at least five years; (2) fallow sugarcane as areas that have been used as sugarcane again within five years, (3) stable sugarcane areas for areas that remained sugarcane along the years (FAO 2006). Non-sugarcane areas were masked out for the remainder of our analysis.

Pixel-based multi-temporal cropland abandonment mapping

The pixel-based multi-temporal cropland abandonment mapping approach was applied to annual sugarcane/non-sugarcane classifications based on the random forest classifier. For that, we produced a mask of stable sugarcane before 1990 containing pixels classified as sugarcane in at least three years between 1986 and 1989 - following the approach by (Yin, Brandão, et al. 2020).

We classified a pixel as sugarcane abandonment when a pixel inside the stable sugarcane mask was classified as non-sugarcane for at least five consecutive years. We labeled the pixel by the year of abandonment, defined as the year after the sugarcane was replaced by a different crop or natural vegetation (i.e., the first year without sugarcane of the minimum five years necessary to characterize the area as so). Sugarcane abandonment labels ranged from 1990 to 2016. The sugarcane areas that were not actively managed consecutively for <5 years were mapped as fallow, according to the definition of (FAO, 2021). Non-sugarcane areas were masked out from the analysis.

LandtrendR mapping

We used spatial segmentation to obtain temporally homogeneous geo-objects (Yin, Alexander V. Prishchepov, et al. 2018) and aggregated our annual probability classifications into the temporally homogeneous geo-objects. We applied the bottom-up multi-resolution segmentation in eCognition (Baatz and Schäpe 2000) to produce our spatial objects over Landsat images from 2017, 2007, 1997, and 1987. The multi-resolution segmentation uses a scale parameter and two homogeneity criteria to delineate objects in eCognition™. The scale parameter relates to the spatial resolution of the imagery and the size of the objects of interest. The spectral and shape homogeneity criteria refer to the weight of the spectral properties of the image and the compactness of the object extraction, respectively (Developer, 2012). We included all spectral bands and the indices NDVI, SAVI, and the tasseled cap brightness, wetness, and greenness for the segmentation. All bands were assigned equal weight, and we set values for color and shape of 0.8 and 0.2, respectively.

Next, we aggregated our sugarcane annual probability classification into these homogeneous spatial objects (geo-objects) based on the average probability of all pixels for each object. Then, we applied the temporal segmentation approach of LandtrendR over the geo-objects aggregated annual sugarcane probability collection to detect sugarcane abandonment (R. E. Kennedy, Cohen, and Schroeder 2007; R. E. Kennedy, Yang, Gorelick, et al. 2018). Each temporal segment generated by LandtrendR retains the start value, start year, end value, end year, magnitude, and duration parameters (R. E. Kennedy, Yang, Gorelick, et al. 2018).

We used these parameters to define our sugarcane abandonment classification criterion. We labeled the objects as sugarcane abandonment that changed from active sugarcane (probability value 0.5) to inactive sugarcane (probability value $<$0.5) if the inactive period was longer than five years, following the approach in Yin, Alexander V. Prishchepov, et al. 2018. If the inactive period was shorter than five years, we labeled them fallow sugarcane. Objects were labeled as stable sugarcane if sugarcane probability was higher than 0.5 and the duration was longer than 25 years. To keep the consistency and compare with the pixel-based multi-temporal cropland abandonment mapping approach, we only considered abandonment between 1990 and 2016. We applied the same masks used in the pixel-based spatial-temporal mapping.

Sugarcane abandonment mapping accuracy assessment

We validated our sugarcane abandonment maps using a stratified sample design (Olofsson, Foody, Herold, et al. 2014) using a target standard error (0.02) of the overall accuracy of specifying anticipated user's accuracies (UA) of 0.95. We ran independent validations for both our multi-temporal and Landtrendr mapping approaches. We obtained a recommended sample size of 119, considering all the stable, fallow, and abandonment strata from 1990 to 2016 in both cases. We then applied the proportional allocation criteria to produce our validation points for the multi-temporal sugarcane abandonment mapping. For our LandtrendR mapping, we used disproportional allocation criteria to ensure we obtained at least 10 validations points per stratum (Supp. 5). The validation was performed using Google Earth Pro historical imagery and Landsat Time Series Inspector by independent and experienced interpreters. Strata information was not made available to the interpreters during the validation. We then applied an error-adjusted area estimator (Stehman 2014; Olofsson, Foody, Stehman, et al. 2013) to obtain the mapped areas and the accuracy metrics. That way, we were able to compare both mapping approaches.

4.3 Results

4.3.1 Sugarcane mapping in 2018

Our random forest classifier showed an out-of-bag error estimate of 0.048 for 2018. The variables with the highest importance were the median and standard deviation of the NDMI, the standard deviation of the BSI, the 10-percentile of the tasseled cap brightness, and the 5-percentiles of the BLUE, SWIR, and NIR bands. The results for the reference sugarcane mapping for 2018 had an overall accuracy of 0.98 ± 0.031

for a 95% confidence interval based on an independent accuracy assessment. The F1 score and the user accuracy indicate a very good model performance for both sugarcane and non-sugarcane classes (c.f. Table **??**). While the producer's accuracy (PA) was very high for non-sugarcane, it indicated only good model performance for sugarcane. The share of sugarcane was estimated as 6% of the total mapped area. The sugarcane area estimation had a standard error of 0.016. This translates into a sugarcane area in 2018 of 56,884 ha.

Table 4.1: Error-adjusted area calculations and validation results of the sugarcane 2018 reference map includes class-specific scores of producer's accuracy (PA), user's accuracy (UA), and F1 score results. The overall accuracy of the 2018 sugarcane map was 0.98 ± 0.031 for a 95% confidence interval.

Property/Strata	**Sugarcane**	**Non-sugarcane**
Area proportion	0.058	0.942
Standard Error (area prop)	0.016	0.016
Area (ha)	56,884.13	918,803.58
95% Confidence Interval (CI) in ± ha	30,564.23	30,564.23
Producer's accuracy (PA)	0.727	0.996
User's accuracy (UA)	0.917	0.983
F1 score	0.84	0.99

4.3.2 Sugarcane annual mapping

Temporal generalization assessment showed that our model performed well for mapping sugarcane areas throughout the years (**Fig. 4.5**). Our annual mapping in 2020 showed an overall accuracy of 0.976 ± 0.032. Our annual mapping in 2006 had an overall accuracy of 0.890 ± 0.064. In 1996, our mapping reached overall accuracy of 0.850 ± 0.078. In 1986, the overall accuracy was 0.845 ± 0.074. Independent validation has shown that the performance decreased from 2020 to 1986 (**Fig. 4.5**). The sugarcane F1 scores were equal to 0.73, 0.81, 0.56, 0.52, 0.64, respectively in the years 2020, 2018, 2006, 1996, 1986. Mapped areas showed that the sugarcane occupation decreased from 1986 to 2020. Sugarcane crops occupied 240,939 ha in 1986. In 1996, sugarcane mapped areas were 195,160 ha, while in 2006, sugarcane occupied 142,985 ha. In contrast, our reference mapping in 2018 showed 56,884 ha, and our map in 2020 had 46,293 ha of sugarcane (**Fig. 4.5**). Non-sugarcane class presented F1 scores above 0.9 all years..

4.3.3 Sugarcane abandonment mapping

Spatio-temporal mapping of sugarcane abandonment

The pixel-based multi-temporal sugarcane abandonment mapping had an overall accuracy of 0.635 ± 0.057 for a 95% confidence interval when classifying the three main trajectories: abandoned, fallow and stable sugarcane (**Fig.4.6**). Our research design allowed us to perform error-adjusted area calculations. In terms of area proportion, 66% of the stable sugarcane areas at the beginning of our analysis were abandoned. The area estimation had a standard error of 0.039. The total sugarcane abandoned area from 1990 to 2016 is 67,353 ha (**Fig.4.6**). Sugarcane abandonment was widespread in our study region.

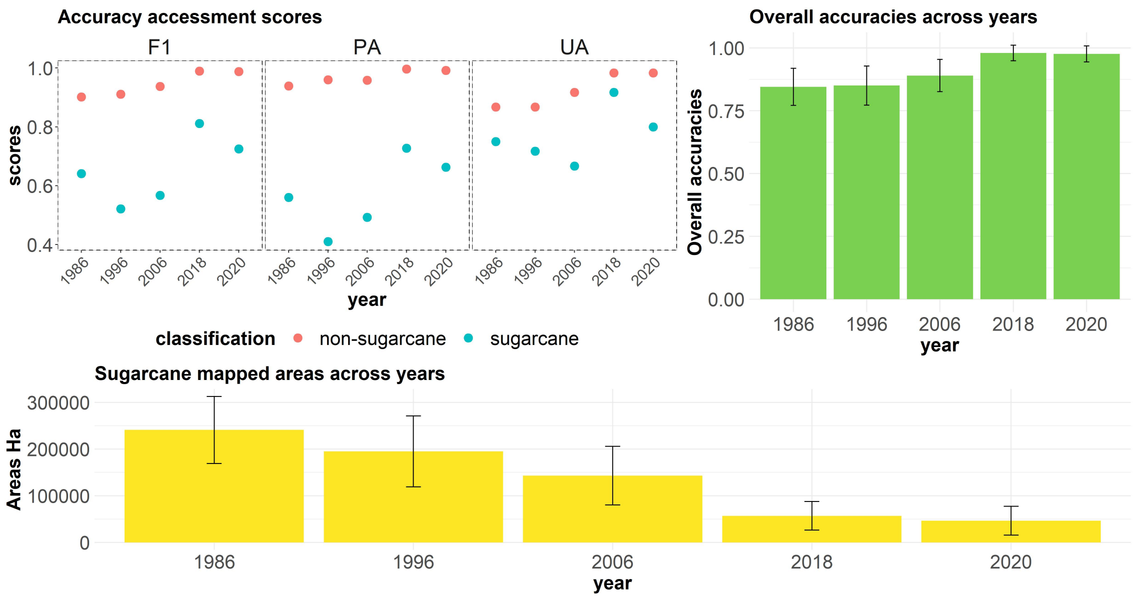

Figure 4.5: Independent validation across the years has shown that the sugarcane performance scores (F1, User' 's Accuracies (UA) , Producer' 's Accuracies (PA)) and the overall annual sugarcane mapping accuracy decreased continuously from 2020 to 1986. Sugarcane mapped areas decreased continuously from 1986 to 2020.

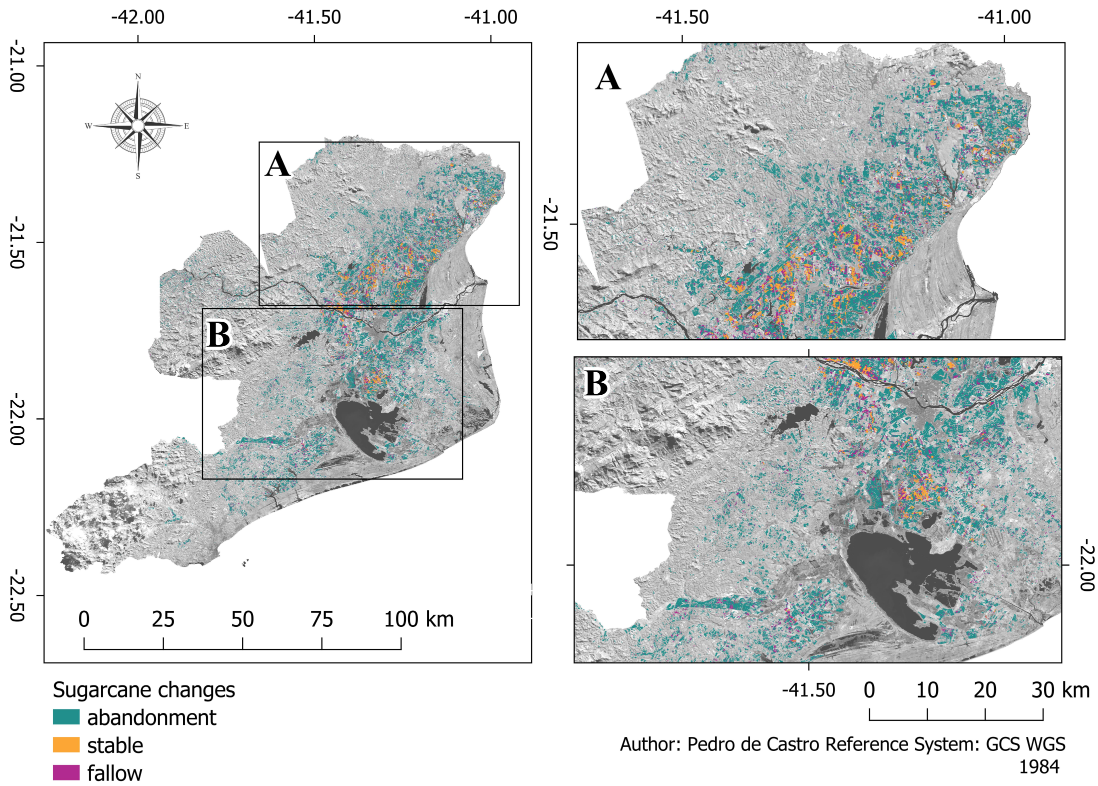

Figure 4.6: Sugarcane abandonment mapping from 1990 until 2016 by the multi-temporal sugarcane abandonment mapping. The map displays abandoned, fallow, and stable sugarcane areas and shows that since 1990 most of the sugarcane areas were abandoned.

Our classification into abandonment time had a somewhat lower overall accuracy of 0.411 ± 0.088 for a 95% confidence interval. This classification informed us that the strongest abandonment occurred between 1990 and 1994 with 20,614 ha and between 2010 and 2014 with 16,155 ha (**Fig.4.7**). The earliest abandonment occurred in the northern part of our study region, while the most recent abandonment took place in the southern part of our study region (**Fig.4.8**). The pixel-based multi-temporal sugarcane abandonment mapping results showed that abandonment between 1990 and 1994 had the highest F1 scores (0.62). The period between 1990 and 1994 also presented the highest PA with 0.75 and the highest UA with 0.53. The period between 2005 and 2009 presented the lowest PA and UA scores (0.2 and 0.154, respectively) (**Fig.4.9**).

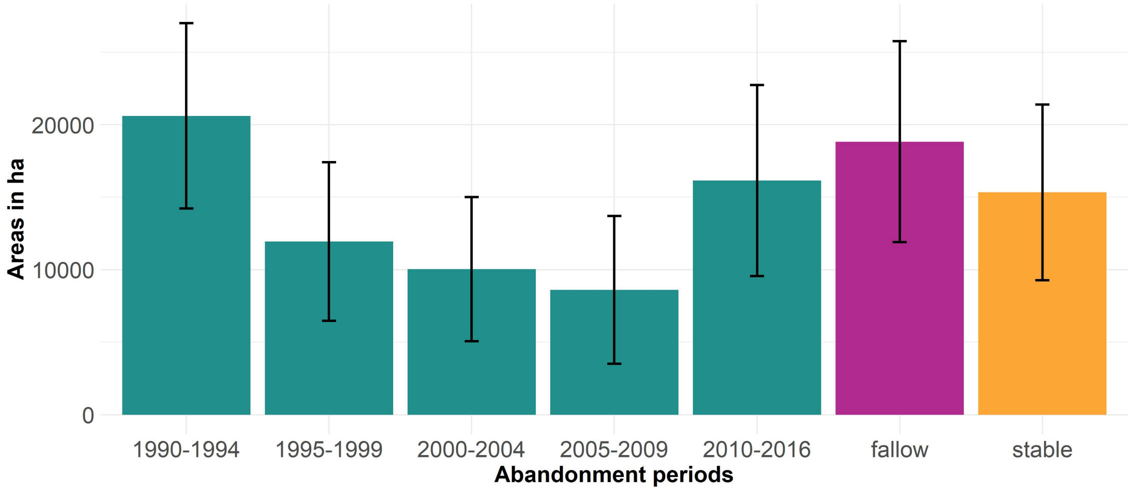

Figure 4.7: Sugarcane areas between 1990 and 2016, according to our multi-temporal sugarcane abandonment mapping. Label 1990-1994 indicates abandonment during 1990 and 1994. In addition, the amount of fallow on sugarcane fields and stable sugarcane farming areas are indicated. Note that the peaks of sugarcane abandonment occurred between 1990-1994 and between 2010 and 2016.

LandtrendR mapping of sugarcane abandonment

The results of our LandtrendR mapping showed an overall accuracy of 0.23 ± 0.088 for the classifications into three main trajectories. The validation results using unbiased estimators allowed the comparison between the multi-temporal sugarcane abandonment mapping and the LandtrendR approaches. Table 3.1 shows the F1 accuracy reports for the classification of the three main trajectories: abandoned, stable, and fallow sugarcane at both approaches.

Table 4.2: Validation results allow comparative analysis of LandtrendR and multi-temporal sugarcane abandonment mapping - the latter performed considerably better.

	Multi-temporal abandonment mapping			LandtrendR abandonment mapping		
Classification	abandoned	stable	fallow	abandoned	stable	fallow
Area proportion	0.66	0.15	0.19	0.66	0.17	0.17
SE (area prop)	0.04	0.03	0.04	0.06	0.05	0.05
Area (ha)	67,353.28	15,372.72	18,790.53	71,163.42	18,230.20	18,573.75
95% Confidence Interval (CI) in ± ha	7,702.52	6,053.83	7,092.44	11,982.98	9,591.71	9,496.98
Producer's Accuracy	0.92	0.27	0.23	0.12	0.79	0.08
User's Accuracy	0.78	0.56	0.31	0.71	0.18	0.10
F1 score	0.84	0.36	0.27	0.21	0.29	0.09
Overall Accuracy		**0.696 ± 0.078**			**0.228 ± 0.088**	

LandtrendR mapping into timing labels showed an overall accuracy of 0.2 ± 0.089

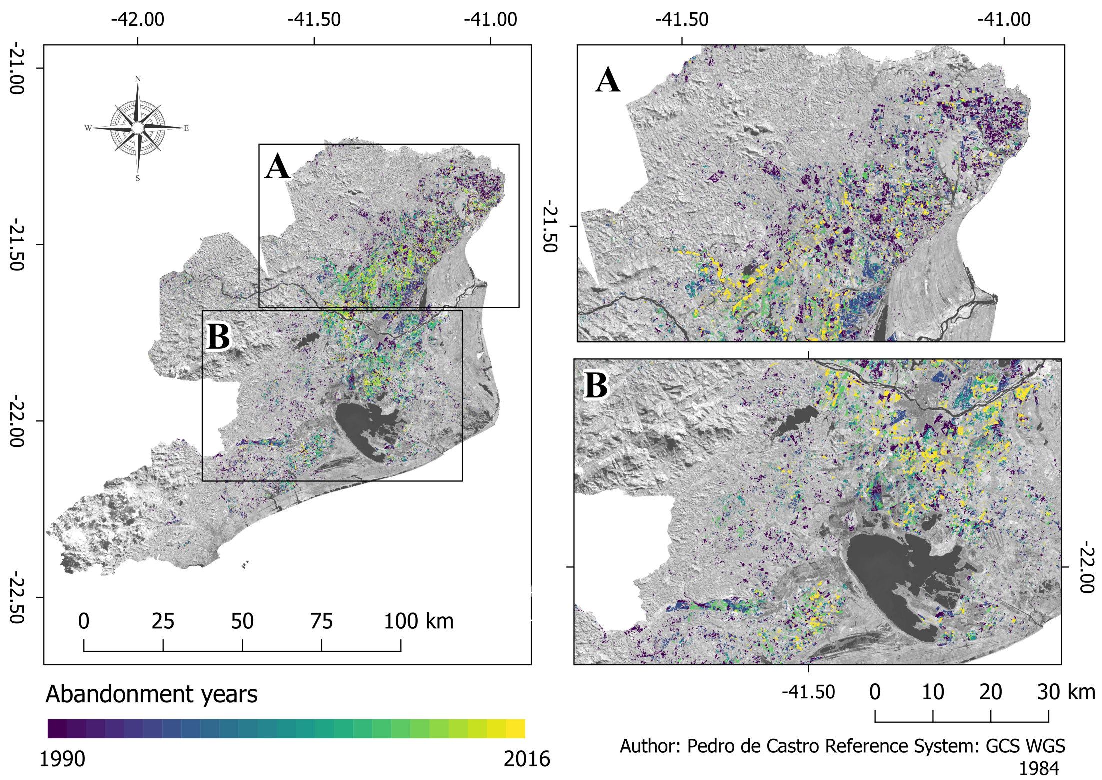

Figure 4.8: Sugarcane abandonment mapping per year from 1990 until 2016 by the multi-temporal sugarcane abandonment mapping. The earliest abandonment took place in the northern part of our study area.

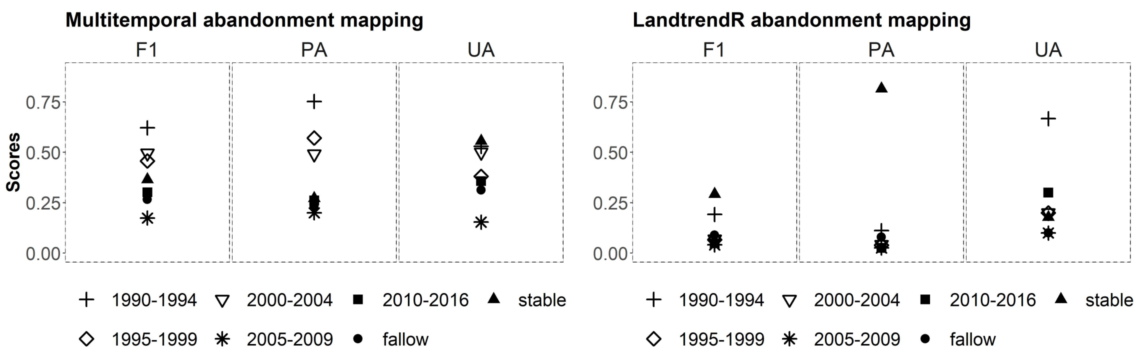

Figure 4.9: User' 's accuracies (UA), Producer' 's Accuracies (PA), and F1 score for the timing of sugarcane abandonment in the Norte Fluminense Region showed differences in performance between multi-temporal sugarcane abandonment mapping and LandtrendR approaches.

for a 95% confidence interval. The accuracies varied among the two approaches and over time (Fig.9). Stable sugarcane and sugarcane abandonment between 1990 and 1994 had the highest F1 scores (0.29 and 0.19, respectively). These were the only classes that presented F1 scores above 0.1. While the stable sugarcane class showed the highest PA (0.82), abandonment between 1990-1994 showed the highest UA with 0.67. All other periods showed PA lower than 0.1. The periods 2005-2009 and 2010-2016 presented the UA of 0.26 and 033, respectively. The remaining periods presented UA values lower than 0.2 (Fig.9).

4.4 Discussion

We applied existing methods to produce consistent sugarcane probability maps from 1986 to 2020. These annual sugarcane maps were used as input to test and compare different methods for mapping sugarcane abandonment. Using stratified random sampling and area-adjusted estimators (Stehman 2014; Olofsson, Foody, Stehman, et al. 2013; Olofsson, Foody, Herold, et al. 2014) allowed us to overcome a limitation of the out-of-bag (OOB) error estimation previously reported by Janitza and Hornung 2018. This way, we provided unbiased reports of areas and accuracies scores.

Our reference sugarcane map in 2018 - from which we generalized the classifier - produced high overall accuracy (0.98) and highly accurate class-specific results (e.g., sugarcane F1 score was 0.81). Our results were similar to the sugarcane mapping produced by the CANSAT project for the South-Central region of Brazil for the crop year 2010/2011 (Rudorff, Aguiar, et al. 2010), where Adami et al. 2012 reported overall accuracy similar to (98%). Another study on a sugarcane/ non-sugarcane classification in São Paulo reported 93.99% global accuracy (Vieira and Santos 2012). A few other studies on sugarcane crop mapping in our study region - Norte Fluminense - were found in the literature (Mendonca et al. 2011; Barbosa et al. 2020), however without an accessible mapping accuracy report. Other studies applying state-of-art deep-learning architecture U-Net reached F1 scores above 0.9 in the sugarcane mapping using high-resolution satellite images in the tropics (Poortinga et al. 2021). These results might point out the direction of future research in sugarcane annual mapping and monitoring. Yet, we did not find in our literature search studies using Deep Learn architectures to map sugarcane abandonment.

Our method achieved consistent results by generalizing a classifier trained for the reference year 2018 to multiple years (1986-2020). Temporal generalization assessment showed that we spared ourselves a time-consuming year-by-year training data collection without suffering from serious impacts on model performance. Our overall accuracy remained high between 1986 and 2020 (i.e., 0.85 to 0.98) and our sugarcane class scores ranged from F1=0.52 in 1996 to F1 =0.81 in 2018. This suggested that temporal generalization has the potential to generate temporally consistent maps for single crops. Our finding is comparable to that of (Zhong, Gong, and Biging 2014), which showed that temporal generalization could be used to map multi-year soybean and corn crops. We observed a decreasing mapping performance as the time interval to our reference classification (2018) increased. In 1986, our mapping showed F1=0.64. In 2006, performance was the weakest among the selected years (F1=0.52). Moreover, our annual sugarcane mapping results captured a previously reported decreasing trend in sugarcane crop areas in the Norte Fluminense Region (IBGE 2021).

Miss-classification in our annual sugarcane mapping might result mainly from spectral characteristics of the farming systems in the study region. The Norte Fluminense is typically in a low-intensity smallholder farmland ownership structure, whose farmers typically opt for an integrated crop pasture management system. The integrated cropland-pasture system in our study region includes sugarcane, cassava, pineapples, and pasture (Azevedo 2002; Smiderle 2010; IBGE 2021). Under cropland-pasture management conditions, mapping errors are likely to originate from spectrally mixed pixels. The spectral similarity between sugarcane and the pasture cover is likely causing mapping errors within these smallholder farmlands (Schmidt et al. 2016). Another plausible cause of classification errors could be the reduced amount of cloud-free Landsat images to compose the annual summary metrics, notably before 2013 (c.f. Fig. 2). Loss of mapping performance due to lower availability of cloud-free Landsat imagery was previously pointed out as a source of miss-classification of corn and soybeans crops mapping (Zhong, Gong, and Biging 2014). Our annual mapping accuracy assessment suggested that the lower availability of cloud-free Landsat intra-annual imagery at the beginning of the analysis period could have impacted our mapping performance due to the observed reduction in overall and sugarcane accuracy scores towards the beginning of the series. Besides, differences in sugarcane management and other climate conditions in years further apart from the reference year can generate inconsistencies in the spectral signature of the sugarcane, making it harder for model reproducibility. Despite that drawbacks, our approach developed consistent sugarcane maps over 30 years, something not observed in the literature before.

When comparing both sugarcane abandonment mapping approaches, we observed that the pixel-based multi-temporal cropland abandonment mapping performed better in mapping the sugarcane abandonment class than the LandtrendR approach. The LandtrendR results revealed higher omission in mapping the sugarcane abandonment class. The high omission by the LandtrendR approach occurred due to poor curve fitting (under-segmentation) when the LandtrendR algorithm failed to segment the probability series, showing an inability to capture the cyclical nature of sugarcane cultivation and its fallow periods. Under-segmentation also explained why the LandtrendR showed a very low omission probability for the stable sugarcane class and higher commission errors. By under-segmenting, LandtrendR created a segment of long duration, which was mapped as stable sugarcane, leading to an overestimation of stable sugarcane areas (**Supp. 4.13**). The LandtrendR showed a somewhat low commission error probabilities in sugarcane abandonment class mapping. The fallow classification performed poorly in both approaches (multi-temporal cropland abandonment mapping F1 = 0.27 vs LandtrendR F1 = 0.09).

Despite our annual sugarcane maps presenting high precision (overall accuracies > 0.85), our sugarcane abandonment maps produced somewhat lower scores. One possible explanation is that overall accuracy in the annual sugarcane maps was inflated by the high scores of the non-sugarcane class. High scores of the non-sugarcane might have slightly inflated the overall accuracy in the annual sugarcane maps. However, the sugarcane-specific scores mainly were above 0.7.

Our pixel-based multi-temporal cropland abandonment mapping results - the approach that showed the best performance - revealed that temporal generalization was suitable both for mapping annual sugarcane crop and for mapping sugarcane abandonment events in Rio de Janeiro state. In the pixel-based multi-temporal sugarcane abandonment mapping, we found accuracy levels comparable to other studies mapping tilled croplands with similar farm size characteristics. For example, Yin, Brandão, et al. 2020 found - in areas characterized by smallholders and low-intensive farms - F1 scores of 0.4. Our sugarcane abandonment F1 scores ranged from 0.17 to 0.62. Our findings were similar to those obtained in drylands (e.g., Nebraska and Shaanxi), where the F1 scores were around 0.5. Higher accuracy in mapping abandonment in tilled croplands was found in industrialized agriculture regions (F1 scores = 0.8 in Mato Grosso and 0.6 in Volgograd and Belarus)(Yin, Brandão, et al. 2020).

Through our multi-temporal cropland abandonment mapping, we were capable of accurately accessing the sugarcane abandonment figures at our study site. The 67,000 ha of sugarcane abandoned between 1990 and 2016 represented a circa 66% sugarcane abandonment rate in the Norte Fluminense Region, Rio de Janeiro, Southeastern Brazil. In terms of absolute values, our findings were similar to cropland abandonment reports in Slovakia (Pazúr et al. 2014) from 1990 until 2000. Our sugarcane abandonment rates were nevertheless somewhat higher than those observed in studies on cropland abandonment Southern Chile (Díaz et al. 2011) for the period 1985 to 2007, in Western Ukraine between 1989 and 2006 (Baumann et al. 2011), and in In Latvia (Vinogradovs et al. 2018) between 1990 and 2015. Other studies also reported cropland abandonment in the Brazilian Legal Amazon (Laue and Arima 2016), the European Russia (Alexander V. Prishchepov et al. 2013), and Polish Carpathians (Kolecka et al. 2017). Nevertheless, those studies were developed in much larger geographic extensions and different environments; therefore, they are not comparable to our study case. It is important to notice that the worldwide studies discussed focused rather on cropland abandonment, not on crop-specific cases as our sugarcane abandonment mapping did. Nevertheless, these studies served as a baseline to globally contextualize the figures on cropland abandonment with Rio de Janeiro's case, which is mainly linked to sugarcane abandonment.

The extensive abandonment of sugarcane fields our mapping showed in the Norte Fluminense Region has been previously suggested (Azevedo 2002; Alentejano 2006; Smiderle 2010; Pedro Castro et al. 2019; P. Castro et al. 2020) but only now quantified by our study. We showed the most expressive abandonment occurred between 1990 and 1994 and between 2010 and 2014. The results of our multi-temporal sugarcane abandonment are in line with what was previously observed in Rio de Janeiro State by (P. Castro et al. 2020). Through the analysis of data provided by the National Statistical Bureau (IBGE), P. Castro et al. 2020 showed that the most significant events of sugarcane abandonment in Rio de Janeiro occurred between 1990 and 1995 and after 2006 due mainly to impacts of the changes in agricultural policy and economic shocks. The shift in the agricultural policies after 1990 also drove the abandonment of smallholders in the Paraíba Valley's portion in São Paulo State, Southeastern Brazil (R. F. d. Silva, Batistella, and Emilio F. Moran 2016; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017).

The results of our multi-temporal mapping of sugarcane abandonment in the Norte Fluminense region allowed us to understand the timing and extent of cropland abandonment in Rio de Janeiro and will allow us to answer questions that were not possible to address before as, for example, what are the causes of abandonment in Rio de Janeiro State. Although the investigation of the spatial determinants of cropland abandonment in the Norte Fluminense Region is beyond the scope of this paper, we acknowledge the existence of multiple factors contributing to it. Baseline studies showed land ownership (Laue and Arima 2016), distance factors (Laue and Arima 2016; Díaz et al. 2011; Rai et al. 2019; Xie, P. Wang, and Yao 2014; Alexander V. Prishchepov et al. 2013; Pazúr et al. 2014; Gellrich and Zimmermann 2007), off-farm income (Xie, P. Wang, and Yao 2014; Su, Okahashi, and Chen 2018; Rajpar et al. 2019; Baumann et al. 2011; Kolecka et al. 2017; Vidal-Macua, Ninyerola, et al. 2018), and topography (Baumann et al. 2011; Kolecka et al. 2017; Vidal-Macua, Ninyerola, et al. 2018) are important spatial determinants of cropland abandonment in South America, Asia, and Europe. In Rio de Janeiro, we acknowledge that areas with water scarcity and administrated by farmers with other income sources are prone to abandonment. These areas are currently only being occupied by a low livestock density to justify them not being declared idle. But these areas are not serving this function anymore.

Before our study, figures on sugarcane-related changes in Rio de Janeiro were drawn upon analysis of aggregated data obtained from statistical surveys provided by Statistical bureaus. Such data provided valuable information. However, data obtained from these studies are highly dependent on the survey's respondents and secondary sources, which might be subjected to bias. Our study provided an essential contribution to further investigating spatial determinants of abandonment by producing a reliable satellite-based spatial-temporal abandonment mapping of sugarcane areas in Rio de Janeiro. The sugarcane abandonment mapping produced here will serve as a baseline to further studies aiming at a deeper understanding of the causes and consequences of cropland abandonment in Rio de Janeiro.

4.5 Conclusions

The use of normalized Landsat imagery and a training data calibration based on the search for unambiguous - phenology-based - sugarcane signature sample points is a valuable approach to avoiding time-consuming training data collection year-by-year and ensuring, at the same time, reliable sugarcane abandonment mapping results. The temporal generalization assessment showed reliable annual sugarcane crop maps. It allowed us to test different methods for mapping sugarcane abandonment in smallholder farming structure, which includes a mix of grassland and other temporary crops. We found that the pixel-based multi-temporal cropland abandonment mapping approach developed over binary annual sugarcane maps outperformed the LandtrendR approach using sugarcane land probability annual maps.

Our study added more evidence on cropland abandonment by identifying and quantifying spatial-temporal patterns of sugarcane abandonment in Rio de Janeiro. We learned that more than half of the stable sugarcane areas in 1990 were abandoned and that the sugarcane abandonment within the Norte Fluminense region spatio-temporal diverse, and the earlier and most extensive abandonment took place in the northern part of the study region. By providing a feasible and reliable methodological solution to the long-term analysis of single crops, we developed a baseline study that enables a deeper understanding of the causes and consequences of cropland abandonment in Rio de Janeiro. Our findings will provide essential information for examining the future role of sugarcane plantations on the study region's economy.

4.6 Supplementary materials

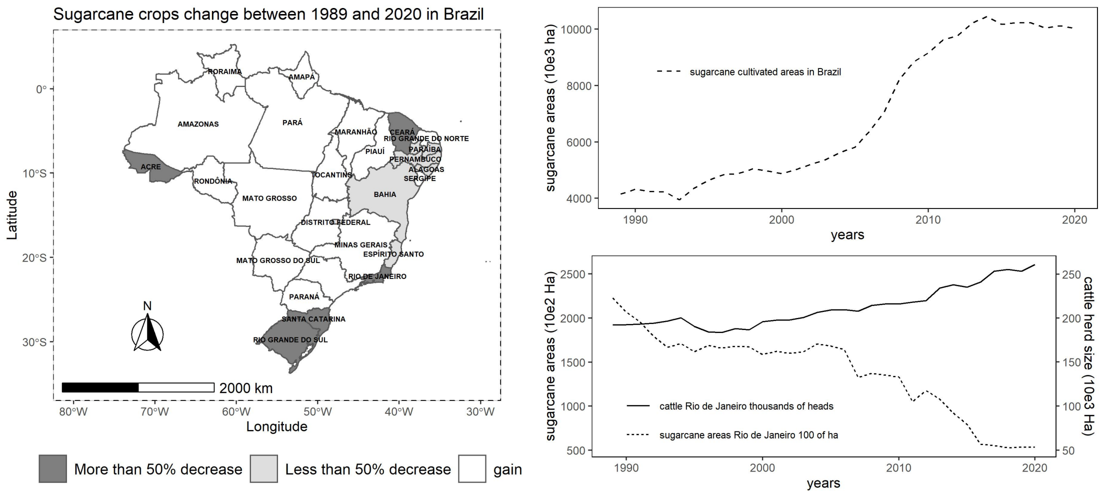

Figure 4.10: The contrast between the expanding Center-south and the declining traditional sugarcane production regions in northeastern and southeastern are characteristics of the regional agricultural development in Brazil. In Rio de Janeiro, the decreasing trend of sugarcane is associated with an increasing amount of cattle herd. Source: Municipal Agricultural Production and Livestock Research— IBGE 2019

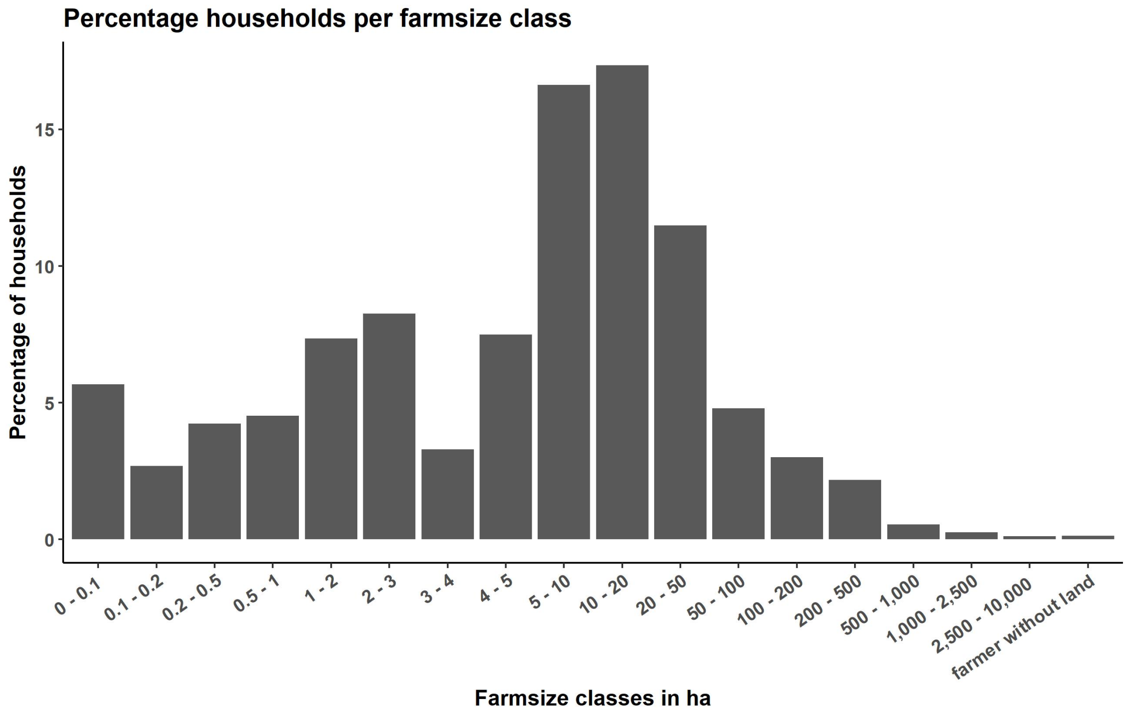

Figure 4.11: Smallholder farming predominates in the Norte Fluminense Region, where 89% of the farms were smaller than 50 ha. Source: IBGE Agricultural Census 2017 IBGE 2019)

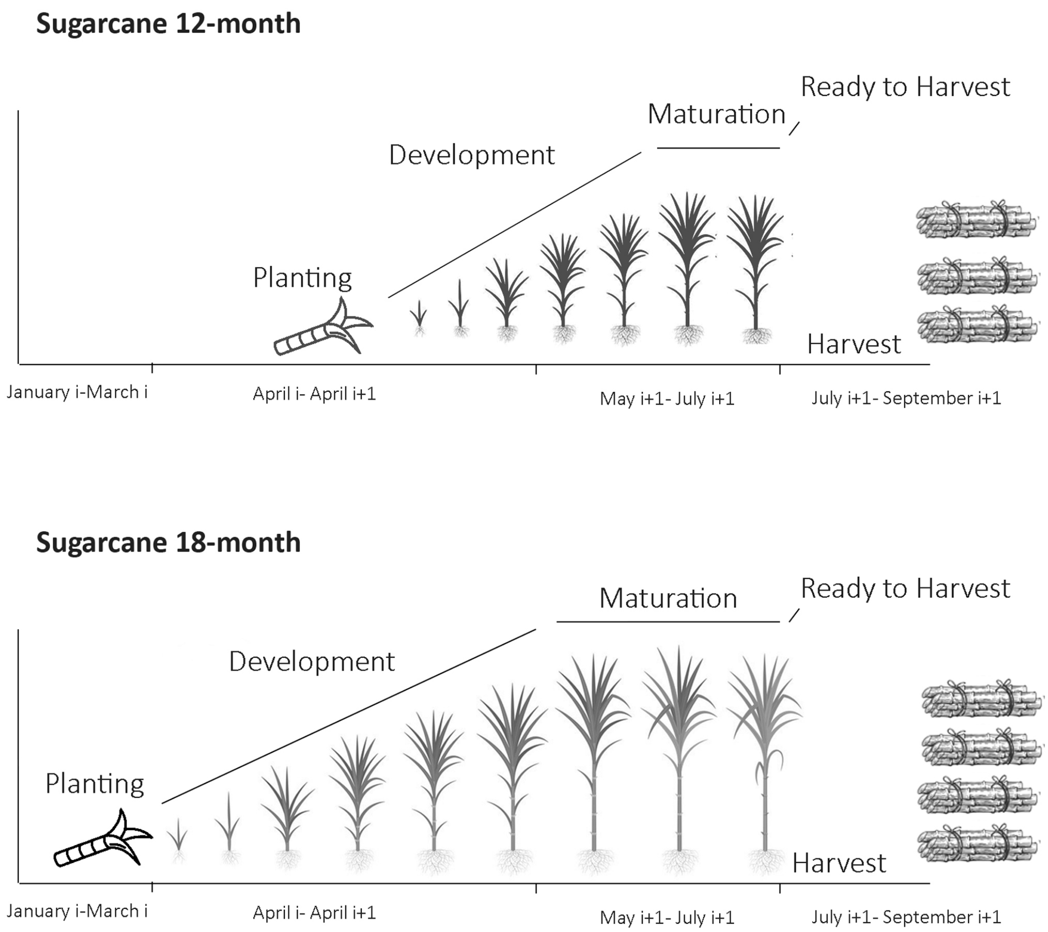

Figure 4.12: Sugarcane management schemes in the Norte Fluminense Region. Source: P. Castro 12th of March, 2021

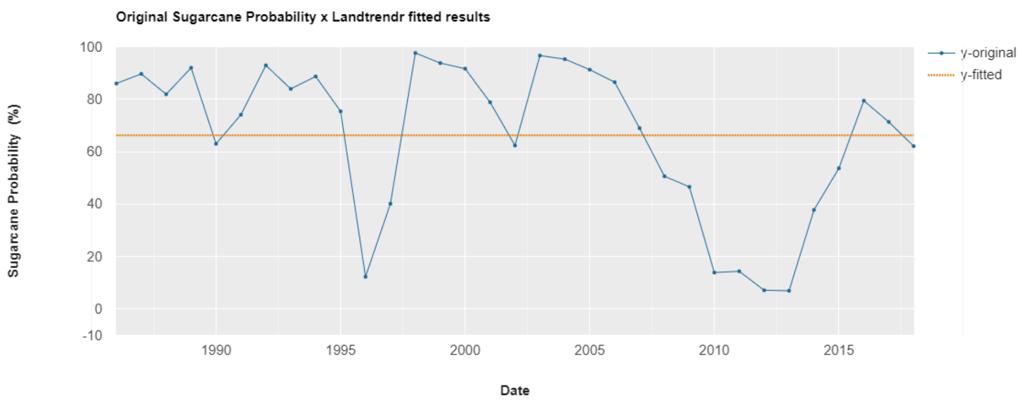

Figure 4.13: Under-segmentation in LandtrendR created a segment of long duration, mapped as stable sugarcane.

5

Predisposing Factors of Sugarcane Abandonment in Rio de Janeiro: Exploring Policy Implications

`Article submitted`

Abstract

Cropland abandonment is an agricultural land use change with notable socioeconomic and environmental implications. Previously managed fields are no longer cultivated and undergo natural succession. Biophysical, socioeconomic, and institutional factors that drive cropland abandonment differ between regions across the globe. In Brazil, Rio de Janeiro State has been showing a strong loss of cropland areas since the end of the 1980s. Especially sugarcane fields have become abandoned. This study used a spatial regression approach (spatial eigenvector mapping) to unveil the influence of biophysical and distance/cost-related factors on sugarcane abandonment in Rio de Janeiro. The results showed that both average precipitation and precipitation variability strongly influenced the amount of sugarcane abandonment: areas with higher precipitation variability and lower average precipitations in wet and dry seasons were more susceptible to abandonment. Sugarcane abandonment occurred mainly in steep areas outside the coastal tablelands. Access to markets, such as the road network distance to active sugarmills, also showed a significant positive relationship with sugarcane abandonment. Interestingly, the presence of protected areas - as a legal constraint - and Euclidean distance to roads and river channels were not significantly associated with sugarcane abandonment in our study region. The study sheds light on the impact of water scarcity on the sugarcane farming development in the Norte Fluminense region.

keywords: Sugarcane abandonment, Land-use change, Statistical modeling, Spatial Eigenvector Mapping, Policy decisions, Brazil.

5.1 Introduction

Cropland abandonment describes the discontinuation of agricultural activities on previously cultivated land. To distinguish abandoned cropland from fallow, a minimum of five years that the land has not been farmed and regrowth of natural vegetation has been used (Baxter and Calvert 2017; FAO 2006).

Cropland abandonment is a widespread agricultural land use change with mixed implications (Bell, Raymond, et al. 2023; Daskalova and Kamp 2023). On the one hand, abandoned croplands can contribute to carbon accumulation and thereby aid in climate change mitigation (Silver, Ostertag, and Lugo 2000; Bell, Terrer, et al. 2021). On the other hand, cropland abandonment might have adverse effects, potentially compromising food security and increasing pressure on natural ecosystems. With a projected global population of 8.5 billion by 2030 (UN-DESA 2019) and potential declines in crop yields due to climate change (Jägermeyr et al. 2021), there is a growing need to increase our understanding of the available arable land and ways to farm the land most efficiently (Fayet et al. 2022). Additionally, cropland abandonment negatively impacts smallholders and their livelihoods (Gellrich and Zimmermann 2007; Munroe et al. 2013; Daskalova and Kamp 2023).

In recent years, cropland abandonment literature has flourished and shed light on occurrences in various parts of the world. Affected regions include the European Union, Post-Soviet Europe, Latin America, and Asian countries (Gellrich and Zimmermann 2007; Kuemmerle et al. 2008; Díaz et al. 2011; Hostert et al. 2011; Baumann et al. 2011; Corbelle-Rico and Crecente-Maseda 2014; Pazúr et al. 2014; Xie, P. Wang, and Yao 2014; Laue and Arima 2016; Vinogradovs et al. 2018; Zavalloni et al. 2021; Y. Li et al. 2021; Castillo et al. 2021). The analytical framework by H. J. Geist and Lambin 2002 - further adapted by Chaudhary et al. 2020 - provides a basis for a systematic analysis of the causes of cropland abandonment. The framework proposes that underlying and proximate causes are mediated by biophysical predisposing factors, ultimately leading to cropland abandonment.

Underlying causes operate indirectly from a remote distance and/or act at the regional or global scale. They might consist of a mixture of policy/institutional, cultural, technological, demographic, or economic factors (H. J. Geist and Lambin 2002; Chaudhary et al. 2020). Proximate causes refer to human-induced local conditions(H. J. Geist and Lambin 2002; Chaudhary et al. 2020). Predisposing factors are biophysical and distance/cost-related local conditions moderating and underpinning cropland abandonment across different regions (H. J. Geist and Lambin 2002).

The prevalent use of fuzzy terms such as "drivers", "driving forces", and "trigger factors" in the literature (Meyfroidt et al. 2016) limits the identification of an adequate linkage between the study cases results to the existing conceptual basis. That is particularly evident regarding the proximate causes, which require adequate study of local actors' direct decisions.

Despite that, several studies established the link between observed land use change and the conceptual basis. García-Barrios et al. 2009 reported rural out-migration and policies strongly favoring high-input, industry-based agriculture as underlying causes for smallholder farmland abandonment in Mexico. Renwick et al. 2013 identified policy interventions - such as the Common Agricultural Policy (CAP) and environmental regulations - as underlying causes of farmland abandonment in many EU countries.

More often, studies reported the combination of predisposing local factors such as climate, topography, and geographical-related attributes moderating cropland abandonment across various regions. For example, precipitation variability followed by periodic and prolonged droughts has led to abandoning cropland in regions with rain-fed agriculture in the Legal Amazon in Brazil (Laue and Arima 2016).

Steep topography - which limits mechanized agriculture and hampers productivity growth - has been related to marginalization and abandonment (Strijker 2005). The hilly and mountainous terrain was linked to cropland abandonment in studies in South America and across Europe (Gellrich and Zimmermann 2007; Baumann et al. 2011; Díaz et al. 2011; Corbelle-Rico and Crecente-Maseda 2014; Pazúr et al. 2014; Laue and Arima 2016; Vinogradovs et al. 2018). Market access limitations - expressed by distances to roads, villages, or towns - have been identified as proximate causes for farmland abandonment (Díaz et al. 2011; Alexander V. Prishchepov et al. 2013; Corbelle-Rico and Crecente-Maseda 2014; Xie, P. Wang, and Yao 2014; Laue and Arima 2016; Vinogradovs et al. 2018), in addition to legal constraints associated with proximity to natural fragments and protected areas (Alexander V. Prishchepov et al. 2013; Pazúr et al. 2014; M. Schneider et al. 2015; R. F. d. Silva, Batistella, and Emilio F. Moran 2016), for regions in Brazil, Chile, Spain, Latvia, Russia, and China.

Despite being known for its massive crop production and extensive cultivated lands, Brazil has experienced cropland abandonment across different regions (Laue and Arima 2016; R. F. d. Silva, Batistella, and Emilio F. Moran 2016). Previous studies have linked cropland abandonment in Sao Paulo State to reduced deforestation in Atlantic Forest areas and the subsequent regrowth of natural vegetation (R. F. d. Silva, Batistella, and Emilio F. Moran 2016; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017). Similarly, there has been evidence of cropland abandonment in Rio de Janeiro, located in the Atlantic Forest in southeastern Brazil - the region faced a decrease of nearly 440,000 hectares from 1970 to 2017 (IBGE 2018a). Cropland abandonment in Rio de Janeiro mainly occurred in the Norte Fluminense region, significantly impacting traditional sugarcane producers (Azevedo 2002; Fauré and Hasenclever 2005; Alentejano 2006).

The abandonment of cropland in the Norte Fluminense region was previously attributed to underlying factors that consisted of various policy interventions in the late 1980s and the oil industry's boom, particularly after discovering pre-salt reserves (P. Castro et al. 2020). However, the role of moderating biophysical and geographical factors in cropland abandonment in the Norte Fluminense region has not been sufficiently explored. There is an ongoing debate regarding the influence of water scarcity in the region, as local farmer associations, supported by studies from (Marques et al. 2001) and (André et al. 2008), suggest that prolonged droughts associated with climate disturbances may have intensified in recent decades and contributed to cropland abandonment. Further research is needed to investigate the relationship between climatic factors and regional cropland abandonment.

Regression modeling approaches have frequently been used to study the effect of different moderating factors on cropland abandonment. A couple of different regression modeling approaches have been used in the past. Logistic regression (Hosmer and Lemeshow 2000) is the most straightforward approach for binary outcome variables (Müller and Munroe 2008; Díaz et al. 2011; Alexander V. Prishchepov et al. 2013; Corbelle-Rico and Crecente-Maseda 2014; Pazúr et al. 2014; Xie, P. Wang, and Yao 2014; Laue and Arima 2016; Vidal-Macua, Ninyerola, et al. 2018; Rai et al. 2019; Rajpar et al. 2019). Machine learning approaches have been used in this domain as well. (R. F. d. Silva, Batistella, and Emilio F. Moran 2016), for example, utilized a multi-layer perception neural network to analyze the drivers of forest transition and small-scale cropland abandonment in the Atlantic Forest. Spatial dependence, such as spatial autocorrelation in the data, requires proper handling of this nuisance by tools such as the spatial autoregressive probit model (Laue and Arima 2016) or spatial eigenvector mapping (SEVM) (Griffith and Chun 2014).

Our objective is to quantify the influence of multiple biophysical and distance/cost-related moderating factors on sugarcane abandonment in the Norte Fluminense region of the federal state of Rio de Janeiro. We included in our analysis climatic variables accessibility and institutional factors such as legal constraints to farming.

5.2 Materials and Methods

5.2.1 Study Site

Sugarcane has been cultivated in the Norte Fluminense region, Rio de Janeiro State (cf. Figure 5.1) for many centuries, specifically in the fluvial floodplain of the Paraíba do Sul River (Lamego 1945; Azevedo 2002; Smiderle 2010). The sugarcane plantations were mainly concentrated in flat areas, including the fluvial-lacustrine/marine floodplains of the Paraiba do Sul delta and the coastal tablelands (Dantas 2000).

Despite the recent reduction in cultivated areas, sugarcane plantations remained the most extensive crop in the Norte Fluminense region in 2021 (IBGE 2021). By 2016, farming in the Norte Fluminense region was rain-fed, labor-intensive, and mainly comprised of smallholdings (61%) (INCRA 2016) with relatively low levels of mechanization. Although national regulations have been implemented to gradually eliminate the pre-harvest burning of sugarcane fields (Law No. 11,241/2002), by 2018, slash-and-burn remained a common practice for sugarcane in the region (Gaese et al. 2019).

The Norte Fluminense region is characterized by relatively low levels of rainfall (1,000 mm/year) and higher average temperatures (ranging from 26° C in winter to 33.5 ° C in summer) compared to other parts of the state (Davis and Naghettini 2000; W. L. Silva and Dereczynski 2014) (see Figure A1). Water availability for farming has been discussed at least since the 1980s (Azevedo 2002). Recent studies suggest climatic disturbances have caused more frequent and prolonged drought periods, calling out for discussing whether the Norte Fluminense region could be classified as semi-arid (Marques et al. 2001; André et al. 2008; Mendonça et al. 2009). Human-made interventions in the river channels might have contributed to worsening these drought conditions (Leite 2017; Soffiati 2018).

Sugarcane outputs are primarily sold to local sugarmills, which expanded their capacity in the 1970s (Azevedo 2002). However, the productivity of sugarcane crops did not keep pace with the increased capacity, leading to a shortage of sugarcane for the mills. This shortage and the absence of critical infrastructure, such as an adequate irrigation system, are believed to have contributed to the decline of the sugar and ethanol industry and the subsequent abandonment of sugarcane plantations in the region (P. Castro et al. 2020).

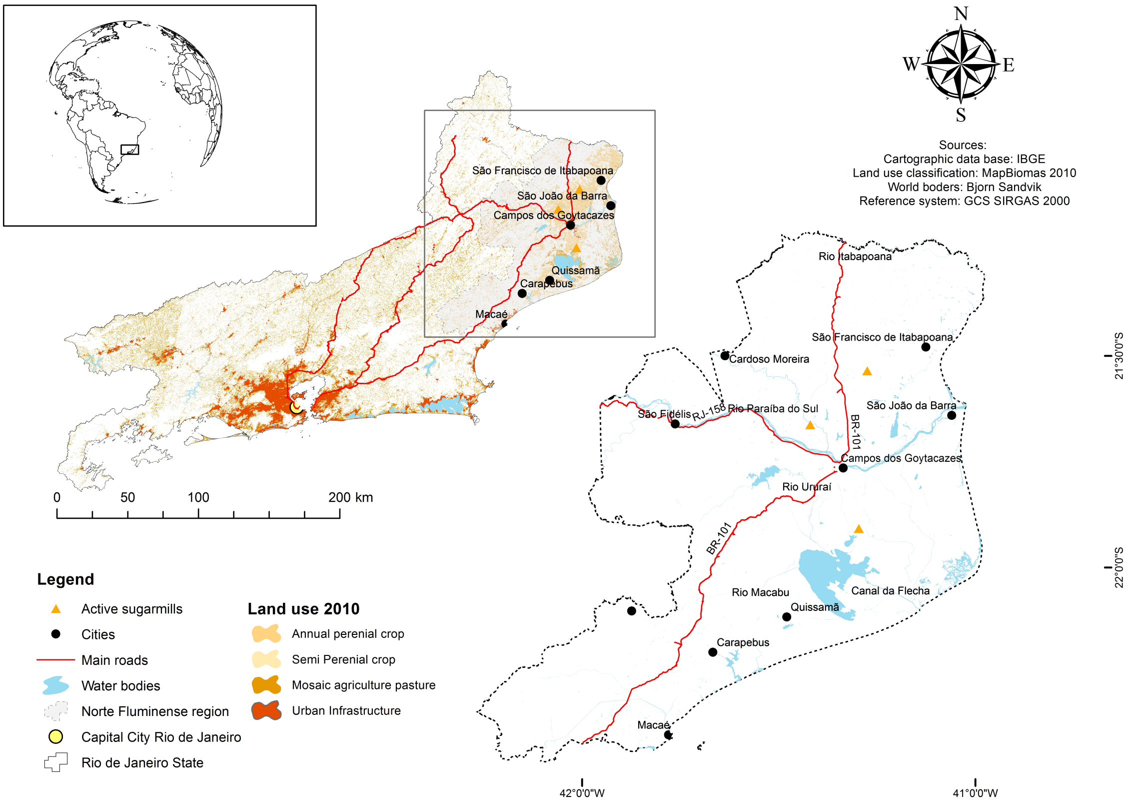

Figure 5.1: Location and overview of the case study region: The Norte Fluminense Region is located in Northeastern Rio de Janeiro. The region is characterized by the highest concentration of sugarcane crops and the abandonment of sugarcane fields.

5.2.2 Data

We created 0.86 km^2 hexagon units covering our study site (Figure 5.2). The hexagons were used to aggregate our multiple source datasets, i.e., the outcome variable sugarcane abandonment and the multiple source predictors. The choice of the size of the hexagon units aimed to balance spatial resolution and computational ease. Several biophysical and distance/cost-related datasets were gathered and selected for our study (cf. Table 5.1). Aggregation criteria varied from one variable to another, and their explanation follows.

(P. I. B. d. Castro et al. 2022) used Landsat imagery to produce annual sugarcane maps from 1986 to 2020. Based on these maps, sugarcane areas were classified into three trajectories: sugarcane, sugarcane fallow, and sugarcane abandonment, covering the period from 1990 to 2016 (P. I. B. d. Castro et al. 2022). We transformed the sugarcane classification from (P. I. B. d. Castro et al. 2022) into a binary variable: sugarcane and fallow sugarcane areas were reclassified as non-sugarcane abandonment, while sugarcane abandonment was used as the other category.

For the response variable, we summed up the number of abandonment pixels in each hexagon. We calculated the area covered by sugarcane in 1990 mapped by (P. I. B. d. Castro et al. 2022) in each hexagon and used it as an offset variable. The average slope and elevation per hexagon cell were calculated using a hydrologically corrected digital elevation model. We aggregated the monthly precipitation data from the global Multi-Source Weighted-Ensemble Precipitation (MSWEP V2) (Beck et al. 2019) dataset - with a spatial resolution of 0.1° - to compose average annual

Table 5.1: Predictors used in the models and hypothesized direction of the effect on sugarcane abandonment. [a] Obtained based on ICMBio legally protected areas [b] Calculated based on IBGE Project RJ25k database; [c] Calculated based on MSWEP V2.2

Variables	Time period	Expected relationship	Source
Share of legally protected areas (%)	2013	+	ICMBio[a]
Distance to roads (m)	2013	-	IBGE[b]
Distance to rivers (m)	2013	-	IBGE[b]
Elevation (m)	2013	+	IBGE[b]
Slope (degrees)	2013	+	IBGE[b]
Distance to urban sites (m)	2020	+	Mapbiomas Col.6
Coastal tablelands (binary)	2000	-	CPRM
Fluvial-lacustrine and marine floodplains (binary)	2000	-	CPRM
Precipitation variability dry season (%)	1979 - 2019	+	MSWEP 2.2[c]
Precipitation variability raining season (%)	1979 - 2019	+	MSWEP 2.2[c]
Average annual precipitation (mm) dry season	1979 - 2019	-	MSWEP 2.2 [c]
Average annual precipitation (mm) raining season	1979 - 2019	-	MSWEP 2.2[c]
Roads network distance to the closest Sugarmill (m)	2019	+	authors' primary data

precipitation and the coefficient of variation (Equation 5.1) datasets for the raining and dry season to include in the model as a climatic predictor. We considered the dry season the months from April until September (I), and the rainy season the months from October reference year (i) until March year (i+1).

$$c_v = (\frac{sd}{\mu}) * 100 \tag{5.1}$$

Where:

c_v : coefficient of variation;

sd: the precipitation's standard deviation across all years;

μ : the average precipitation across all years;

We calculated four distance variables using the minimum distance criterion to i) Mapbiomas 2020 urban sites, ii) IBGE RJ25 geographic features' roads, iii) IBGE RJ25 geographic features' rivers, and iv) Distance -through the IBGE's road network - for the location of active sugarmills collected using a GPS Garmin device during our field visit to the region in 2019. Based on the ICMBio's geographic feature of legally protected areas, we calculated the legally protected areas per hexagon as a proxy for agricultural activity constraint.

The choice of distance-based predictors was based on Von Thünen's and Ricardo's land rent theories, whereby the distance of a land parcel to markets (von Thunian ideas) and its 'quality' of land, in terms of physical and geographical characteristics (Ricardian beliefs), determine the land-use decision of each landowner (Gellrich and Zimmermann 2007). In the Norte Fluminense Region of Rio de Janeiro State, the cultivated areas of sugarcane rely on the sugarmills as primary consumers. We expect sugarcane plantations closer to sugarmills to be less likely to be abandoned because they have better market access.

Distance to roads is another proxy for accessibility. Therefore, we expected a positive relationship: the lower the distance, the lower the sugarcane abandonment.

The proximity to river channels is a proxy for farming costs with irrigation. We, therefore, expected that the lower the distance to the rivers, the lower the irrigation costs and, therefore, the lower the likelihood of sugarcane abandonment. We hypothesized that sugarcane abandonment occurred mainly in isolated and poorly connected areas. Therefore, we assumed a positive relationship between sugarcane abandonment and distance to urban sites, meaning the farther the urban sites, the higher the likelihood of sugarcane abandonment.

We hypothesized that areas with higher rates of legally protected areas are keener

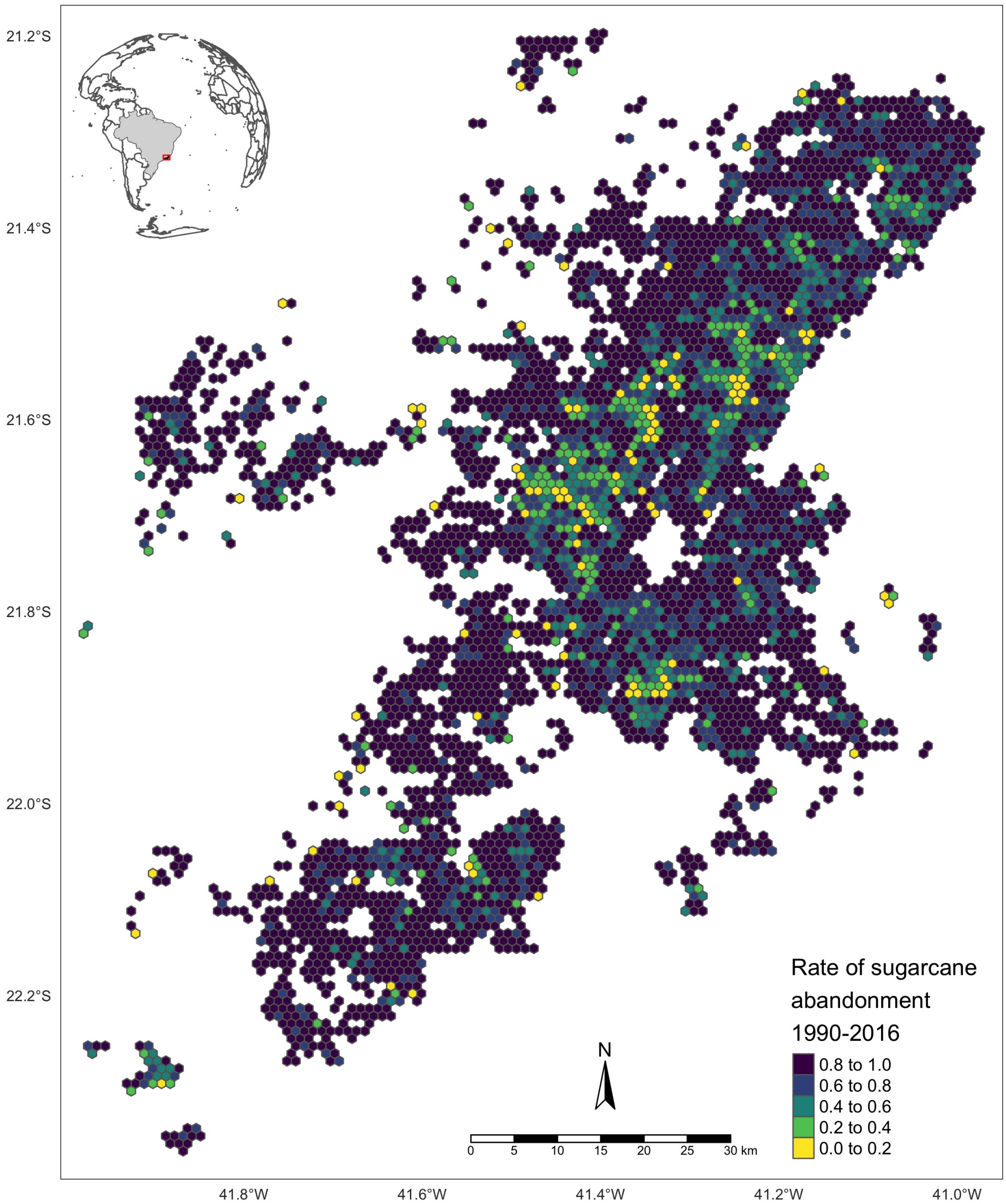

Figure 5.2: Sugarcane variable aggregated to 0.86 km^2 hexagons. We only considered hexagons, whereby in 1990, sugarcane areas were observed. The values in the legend are the sugarcane abandonment rates in each hexagon.

to sugarcane abandonment because of a legally imposed agricultural expansion constraint. We also expected a positive association between sugarcane abandonment and elevation and slope. Steeper slopes would constrain mechanization and, therefore, high-productivity crop production.

In the Norte Fluminense region, the sugarcane production remains over coastal tablelands or fluvial and fluvial marine plains. We expected, therefore, a lower abandonment across those geomorphological features. Lack of precipitation is a crucial issue in the region. We hypothesized, therefore, that the lower the average precipitation and the higher its annual variability, the higher the sugarcane abandonment. Lower precipitation associated with higher seasonal variability would negatively affect sugarcane plant development and constrain sugarcane productivity, contributing to sugarcane abandonment.

5.2.3 Method

Our conceptual model aims to explain the sugarcane abandonment in the Norte Fluminense Region of Rio de Janeiro state as a function of distance/cost-related (accessibility, legally protected areas) and biophysical variables (rainfall, elevation, geomorphological features). We used the count of the 30m x 30m pixels of sugarcane abandonment per hexagon cell as the response variable. We used generalized linear models (GLM) (McCullagh and Nelder 1989) and an offset variable (area of potential occurrence) to model the rate. We started with Poisson models but switched to negative binomial GLMs to account for over-dispersion in the residuals. Spatial autocorrelation in the residuals was detected by means of global Moran's I (P. A. P. Moran 1950). We used a SEVM approach (Griffith and Chun 2014) to account for the spatial dependence in the model residuals (Equation 5.2).

$$\ln(Y) = X\beta_x + E_k\beta_k + \epsilon \tag{5.2}$$

Where:

$\ln(Y)$: response variable using a Log link function;

X: an n-by-(p+1) matrix containing covariates;

β_X: corresponding (p+1)-by-1 vector of regression parameters;

E_k: an n-by-k matrix containing k eigenvectors;

β_k is the corresponding vector of regression parameters;

$\epsilon \sim nb(r, p)$: an n-by-1 error vector whose elements are independent and negative binomial distributed random variables.

To avoid problems with collinearity (Dormann et al. 2013), we identified all pairs of predictors with a Pearson's correlation coefficient above 0.6 and selected the covariate that seemed more meaningful with respect to the relationship with the response variable. From the initial set of variables, we kept only those correlated lower than 0.6 (Fig.A2) except for the sugarcane areas (sqm) in 1990, which was highly correlated to sugarcane abandonment (R2 = 0.81). The sugarcane areas (sqm) in 1990 were kept because the variable was used as an offset variable in the regression. As expected, slope and elevation variables showed a high Pearson's correlation (R2= 0.87). From elevation and slope, we kept the slope in the model.

We used a combination of a contiguity neighborhood definition and an Euclidean distance-based neighborhood definition (using a threshold of 1km) as our neighborhood definition. We estimated the influence of the neighborhood through an inverse-distance weighting approach ($w_{ij} = 1/d_{ij}$) and row-standardized the spatial weight matrix W. W was composed into the (orthogonal) spatial eigenvectors for the spatial eigenvector mapping approach.

We used a minimum Moran Coefficient (MC) value of 0.1 as a criterion to select candidate proxy eigenvector variables and account for spatial autocorrelation (Griffiths, Kuemmerle, et al. 2014). These eigenvectors proxy variables were derived from a symmetric matrix C, utilized to establish the Moran Coefficient range. Matrix C's use preserves orthogonality, and the associated projection matrix M ensures eigenvectors with zero means, guaranteeing uncorrelatedness. The SEVM approach allows for the extraction of spatially structured random elements from trends and random noise, thereby enriching statistical inference and enabling meaningful visualization within statistical modeling (Griffiths, Kuemmerle, et al. 2014).

We standardized all our numeric variables except the response, offset, and binary variables. The standardization method was performed by centering and scaling each variable. Centering was done by subtracting the variable means (omitting NAs) of each value from the corresponding variable. Scaling was done by dividing the (centered) variable of x by the variable's standard deviations. This approach allows a direct comparison of the size of the regression coefficients with respect to their impact on the response. We conducted our analyses using R (R Core Team 2021) with the packages spdep (Bivand and Wong 2018) and MASS (Venables and Ripley 2002).

5.3 Results

Our model explained around 55% of the deviance in the sugarcane abandonment. Our results also showed that precipitation variability during the dry season positively correlated with sugarcane abandonment ($\beta_1 = 1.420$) and precipitation variability during the wet season with the opposite behavior ($\beta_2 = -0.143$). The results also showed that average precipitation during both dry and wet seasons presented negative relationships with sugarcane abandonment ($\beta_3 = -0.560$, and $\beta_4 = -0.178$, respectively), meaning the lower the average precipitation, the higher the likelihood of sugarcane abandonment. The scaled results also showed that precipitation variability during the dry season had the most substantial influence on the response variable. Slope also showed a positive relationship with abandonment ($\beta_5 = 0.085$), suggesting sugarcane abandonment preferentially in steep areas. The coefficient suggested, however, that this influence was somewhat modest. Model results also showed sugarcane abandonment occurred mainly outside the coastal tablelands ($\beta_6 = -0.582$). Coastal tablelands had the second most substantial influence on sugarcane abandonment. That was an expected behavior since the coastal tablelands are the most suitable place for cropping in our region (Figure 5.3).

Our results also showed a negative relationship between Fluvial-lacustrine and

Marine Floodplains and sugarcane abandonment ($\beta_7 = -0.319$). Legally protected areas were positively associated with our response variable ($\beta_8 = 0.038$), indicating that the legal constraints impacted our region's sugarcane abandonment. It is worth mentioning that this coefficient was marginally statistically significant ($p - value = 0.108$). Minimum Euclidean distance (m) to roads and minimum Euclidean distance (m) to rivers had no significant effect on the response ($p - value = 0.232$, $p - value = 0.338$, respectively). Other distance/cost-related variables, such as minimum Euclidean distance (m) to urban centers and closest network distance to active sugarmills, presented positive relationships with our response variable sugarcane abandonment ($\beta_{11} = 0.118$ and $\beta_{12} = 0.214$, respectively).

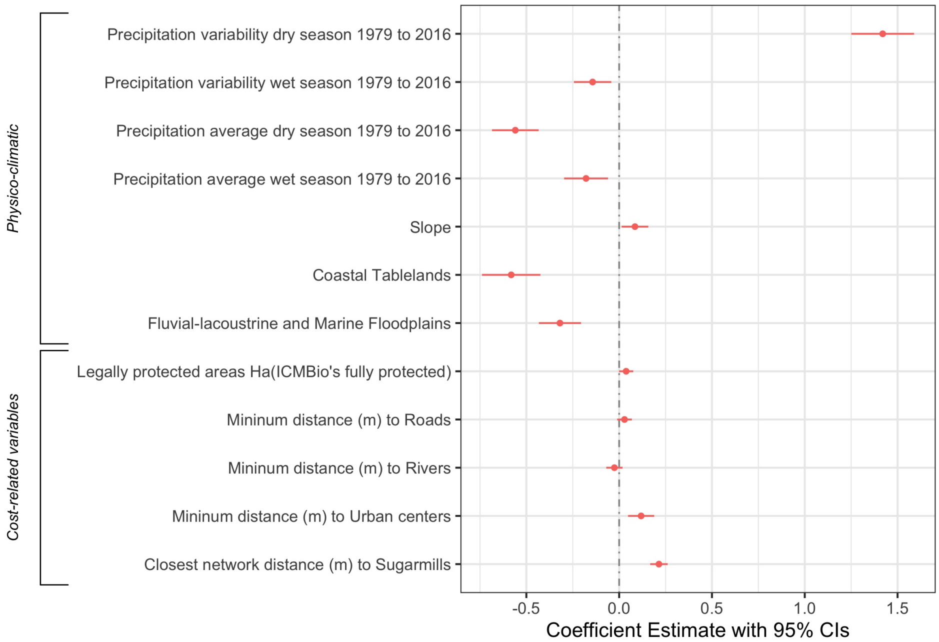

Figure 5.3: Coefficient estimates for standardized predictors (red dots) and 95 % confidence intervals (CI, horizontal red lines) for the spatial regression model. Coefficients for the spatial eigenvectors are not shown.

5.4 Discussion

Our coefficients showed that sugarcane areas with higher precipitation variability in the dry season were more susceptible to sugarcane abandonment (c.f. Table 5.1). This confirmed the expected positive association between precipitation variability in the dry season and sugarcane abandonment: abandonment would be, on average higher, with higher variability in the dry season. High precipitation variability is possibly associated with extreme weather events linked to uneven rainfall distribution, whereby prolonged droughts follow torrential storm events. Extreme events were observed in the study region in 2014 and 2015 when the Paraíba do Sul River Basin underwent the most severe drought in the region's recorded history spanning 85 years. Although our study did not focus on the trend analysis of time-series climate data to explicitly prove causality between this extreme drought event and the abandonment of sugarcane crops, the relationship between climate variables, especially the precipitation variability and the sugarcane abandoned areas, suggests extreme weather events might be contributing to abandoning sugarcane areas in the case study region.

Other climatic variables also helped to explain the sugarcane abandonment: the lower the average precipitation in both wet and dry seasons, the higher the likelihood of abandonment. The direction of both coefficients agreed with our expectations (c.f. Table 5.1). Water scarcity is a known issue in the region, where lack of precipitation plays a vital role. Our findings align with previous studies by (Marques et al. 2001) and (André et al. 2008) that showed a significant decline in annual precipitation values from 1961 to 2000, with a decrease of up to 30% in Campos dos Goytacazes, the major city in the Norte Fluminense region. These previous studies also indicated that between 1999 and 2004, the Campos do Goytacazes station experienced precipitation levels approximately 25% lower than the long-term average.

Furthermore, a study by (Marques et al. 2001) revealed that several areas in the Norte and Noroeste regions of the State of Rio de Janeiro have been consistently facing annual soil water deficits throughout the year. A Legislative proposal - Bill 1440/19 - was written based on these findings (Garotinho 2019) and submitted to the State Legislative Chamber. Bill 1440/19 aims to create an Economic Development Fund for the semi-arid Norte and Noroeste Fluminense Geographical Mesoregion, aiming to provide financial support to rural producers in these areas. It's worth noting that, as of now, Bill 1440/19 has not been reviewed or approved by the State Legislative Chamber.

The passing of Bill 1440/19 is of interest to sugarcane farmers represented by the Agroindustrial Cooperative (COAGRO) and the Fluminense Association of Sugarcane Farmers (ASFLUCAN). For decades, these local producers have called on the local authorities to implement a comprehensive irrigation plan for the sugarcane farms in the region (Azevedo 2002). In the 1980s, the Sugar and Alcohol Institute (IAA/PLANALSUCAR) brought about the "Irrigation and Drainage Project in the sugarcane culture in the Norte Fluminense (Projeto de Irrigação e Drenagem na cultura da cana-de-açúcar no Norte Fluminense - PROJIR)" to carry out the technical and financial evaluation for the implementation of the irrigation project for the region. However, the farmers claimed that little progress had been made since then.

Passing Bill 1440/19 should not necessarily be seen as an attempt to satisfy this specific demand for the irrigation project. It, instead, can be seen as an attempt to correct distortions in the rural credit mechanism to address regional particularities. A primary concern was the access of local farmers in the region to economic resources, as previous policy reforms negatively impacted these. As a previous study showed (P. Castro et al. 2020), changes in the national rural credit system brought about by macroeconomic policy shifts underlay the sugarcane industry's breakdown. The debate around Bill 1440/19 is part of the efforts to prevent an even more substantial loss of sugarcane areas and to safeguard the remaining local sugarcane industry from a total collapse.

The drought in the region has not only been attributed to a lack of precipitation but also to the successive drainage works in the Paraiba do Sul floodplain (Leite 2017; Soffiati 2018). Such interventions were undertaken over the years to provide additional agricultural land for the sugar industry. However, these interventions led to excessive water runoff, diminishing the region's ability to retain moisture and causing the disappearance of vital ecological niches. As a result, the region is currently experiencing desertification (Leite 2017; Soffiati 2018). Instead of benefiting the sugarcane industry as intended, these continual drainage efforts likely exacerbated the adverse impacts on the region's agricultural activity. Although our study did not explicitly investigate the relationship between drainage works and drought, such interventions may have indirectly contributed to sugarcane abandonment.

Sugarcane plantations over the coastal tablelands were less prone to abandonment. Our findings indicate the persistence of sugarcane plantations over flat areas and agree with our hypothesized relationship, whereby areas over coastal tablelands are more suitable for farming and, therefore, less prone to abandonment. Moreover, the coefficient of the variable "slope" verified our hypothesis that sugarcane abandonment was more likely to occur on steep slopes and that sugarcane crops became concentrated in flat areas of the coastal tablelands. Numerous studies (Pazúr et al. 2014; Laue and Arima 2016; Kolecka et al. 2017; Yu et al. 2017; Vidal-Macua, Ninyerola, et al. 2018) consistently recognize the importance of topographic constraints to mechanized agriculture as a proximate cause for farmland abandonment. Thus, our findings align with the existing body of research on this topic and highlight topography's role in cropland abandonment.

Our model suggested a tendency for areas closer to primary and secondary roads to be more prone to the abandonment of sugarcane. However, this effect was not significant (p-value: 0.232). This aligns with another study in Southeast Brazil, where (R. F. d. Silva, Batistella, and Emilio F. Moran 2016) tested the variable proximity to roads and found no significant relationship with cropland abandonment. When examining Rio de Janeiro's case, there are significant limitations in using Euclidean distance to roads as a predictor related to market access. This becomes particularly apparent when considering the principles of classical agricultural land rent theory, which suggests that landowners' land-use decisions are determined by the proximity of their land parcels to markets. In the Norte Fluminense region, local sugarmills are primary consumers of sugarcane. Therefore, the accessibility of sugarmills in terms of network distance appears to have a more decisive impact on sugarcane abandonment than the Euclidean distance to roads. Our assessment of the network distance to sugarmills revealed a strong positive relationship, supporting our hypothesis that areas farther away from markets were more prone to abandonment.

Other geographical predictors presented intriguing patterns. Despite its non-significance, the negative relationship between minimum Euclidean distance to rivers and sugarcane abandonment is somewhat intriguing in light of our previously established hypothesis of a positive relationship. Nevertheless, an alternate hypothesis based on the geomorphological processes in the region might help explain the inverse relationship between the variable Euclidean distance to the rivers and sugarcane abandonment. Coastal tablelands are flat surfaces dissected by rivers in parallel drainage patterns. Commonly, fluvial incisions characteristic of the coastal tablelands are found in contact with high slopes. The inverse relationship between Euclidean distance to the rivers and sugarcane abandonment might be attributed to the fact that river channels are near some steepest slopes, where crop mechanization is hampered.

Our results also showed the likelihood of sugarcane abandonment increased with the distance to built-up areas. This behavior was expected since abandoned sugarcane areas undergo a transition into grasslands and are distinct from the transformation into urban locations.

The use of Brazilian Geography and Statistics Institute (IBGE) farming production data (census-tract level) was impractical due to many missing data. For instance, out of the fifty farming production variables we examined from IBGE's database, none covered more than 45% of the 2227 census tracts in our region. For this reason, additional socioeconomic factors influencing the abandonment of sugarcane could not be accessed.

Despite not using additional farm-level data, we consider that the explanatory variables accessed in this study represent the cornerstone of the pre-disposing local factors of sugarcane abandonment. Variables selection resulted from discussions with a wide range of local stakeholders. Moreover, several socio-economic farm-related factors were accessed through proxy, cost-related variables. We, therefore, believe that our study provides a comprehensive and nuanced assessment of the factors contributing to sugarcane abandonment in Rio de Janeiro, shedding light on critical aspects of this complex issue.

5.5 Conclusions

Policymakers' decisions have underlay sugarcane abandonment in our region (P. Castro et al. 2020), and several predisposing environmental and geographical factors have shaped its occurrence in different locations. Among these predisposing factors, water scarcity has been identified to play the most critical role in the sugarcane farming development in the Norte Fluminense region. Over the past 40 years, sugarcane crops significantly reduced their extension, remaining restricted to the most suitable areas over coastal tablelands. Previously, traditional sugarcane areas in the region were abandoned, affecting the livelihood of thousands of families. Climate disturbances have led to prolonged drought periods in the region. The prolonged droughts have contributed most to the negative impacts of rural public policy reforms that occurred in the past. Our results show that the persistence of drought events might continually impact the remaining sugarcane areas, likely causing an even more substantial abandonment of sugarcane plantations.

Such prognosis raises again the awareness of the need for policies aiming at strengthening the efficiency of sugarcane farms either by effectively implementing irrigation programs (moving beyond the designing phase and reaching effective implementation), facilitating credit access for small and medium holders, the continuing development of seeds and technology for improving the yields, and the optimization of the harvesting in smallholders. Such measures might play a crucial role in ensuring the continuation of this traditional livelihood and feeding the remaining industry with the necessary inputs to ensure the continuation of the production chain and contribute to the diversification and the general functioning of the regional economy.

Furthermore, it is worthwhile to identify and measure the beneficial outcomes of natural regeneration in abandoned areas. Future research efforts that focus on assessing the effects of soil carbon accumulation in these areas could provide valuable insights to decision-makers. This information can aid in distinguishing between areas suitable for agricultural production reintegration and those more suited for natural regeneration.

Appendix

Table A1 summarizes the ID and variables description used in describing the supplementary figures.

Table A1: Reference table variables after removing cases of multicolinearity

ID	Acronym	variable description
1	SugAban	Sugarcane abandonment
2	StableSug1990	Sugarcane stable areas (sqm) in 1990
3	PreVarDry	Precipitation variability dry season 1979 to 2016
4	PreVarWet	Precipitation variability wet season 1979 to 2016
5	PreAvDry	Precipitation average dry season 1979 to 2016
6	PreAvWet	Precipitation average wet season 1979 to 2016
7	Slp	Slope
8	CoastTabl	Coastal Tablelands
9	FloodP	Fluvial-lacoustrine and Marine Floodplains
10	ConservHa	Legally protected areas ha (ICMBio's fully protected)
11	RoadsDistMin	Mininum Euclidean distance (m) to Roads
12	RiversDistMin	Mininum Euclidean distance (m) to Rivers
13	UrbDistMin	Minimum Euclidean distance (m) to Urban sites
14	SugMilNetDist	Closest network distance (m) to Sugarmills

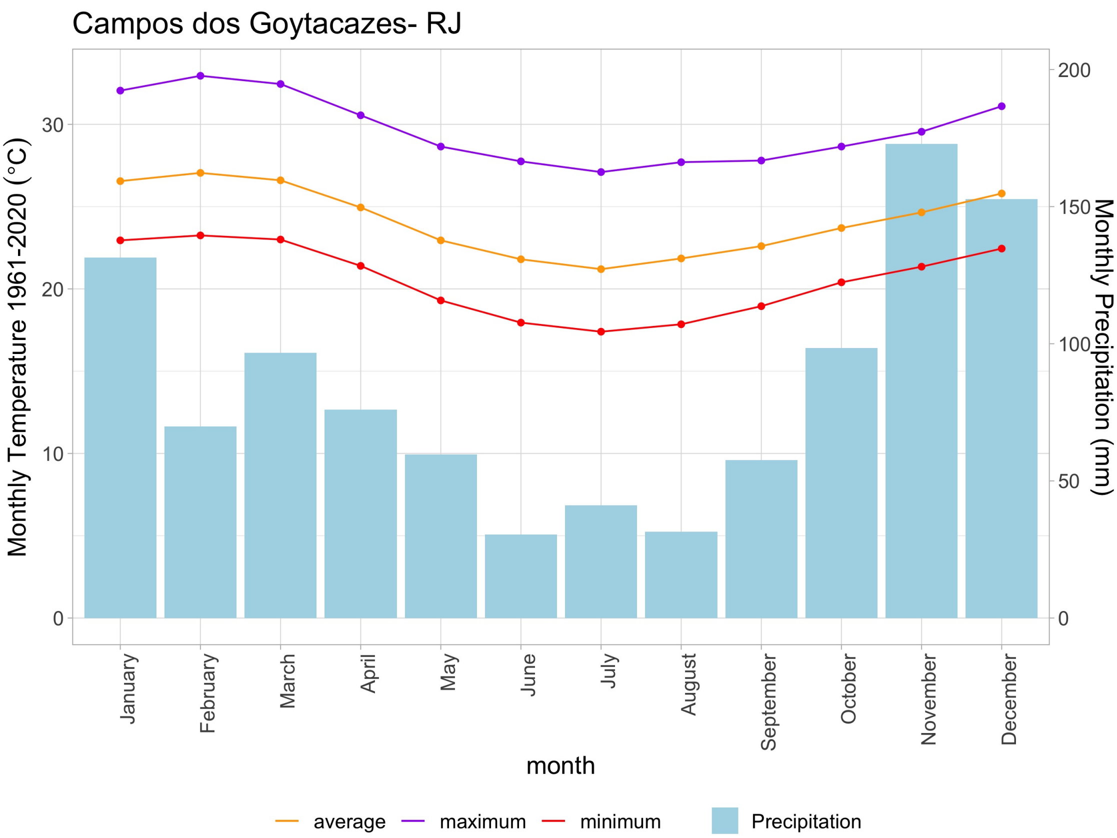

Figure A1: Climatological data from 1961 to 2020 show that annual precipitation in Campos dos Goytacazes - Norte Fluminense Region lies around 1000 mm, and minimum temperatures are $26°C$ during winter and maximum temperatures circa $33.5°C$ in the summer. Source: INMET, 2021.

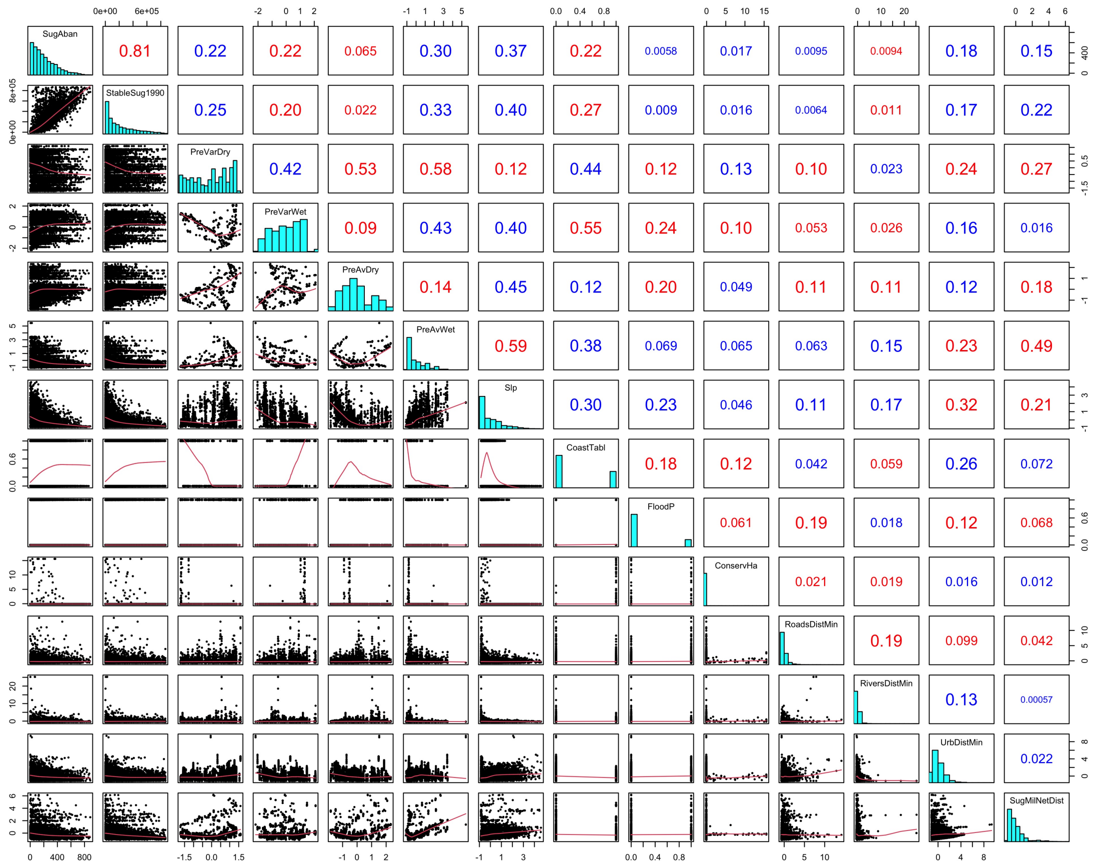

Figure A2: Our variables' correlations after removing variables with Pearson's correlation (R^2) equal to or higher than 0.6 (red flags mean positive correlation, blue flags mean negative). The only exception is the pair SugaAban and Stable Sug ($R^2 = 0.81$). Because the latter was used as an offset variable to estimate the rates of sugarcane abandonment in the model.

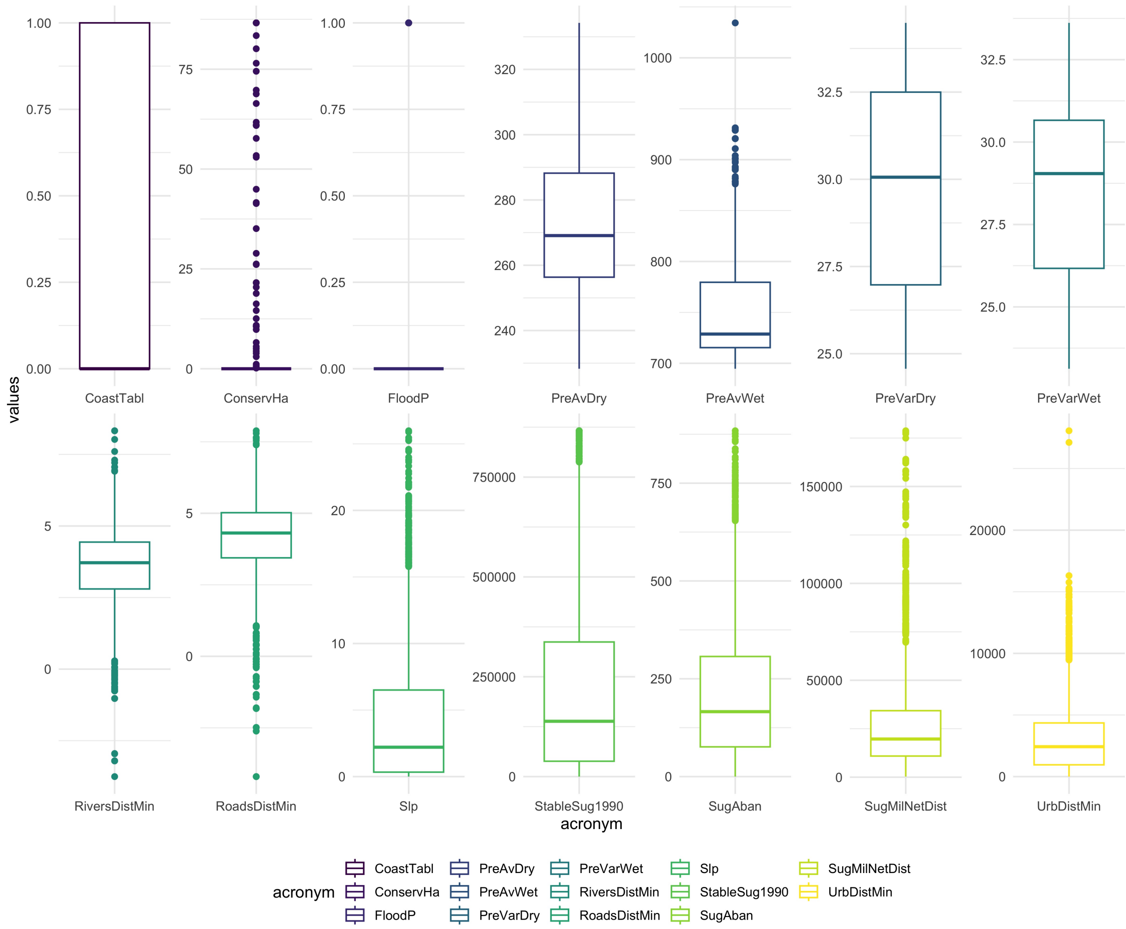

Figure A3: Most of our continuous variables were asymmetrical and over-disperse, with many outliers. Coastal tablelands and Fuvial-lacustrine, and Marine Floodplains were binary variables.

6

Discussion

The findings of this thesis suggest that farmland abandonment in Rio de Janeiro is primarily linked to the decline in sugarcane cultivation. The analysis identifies several factors contributing to this trend, which can be categorized as: 1) proximate causes related to local infrastructure and geographical contexts, such as proximity to market outlets, water sources, roads, and urban/industrial development; 2) biophysical predisposing factors, including topographic conditions and climatic patterns; and 3) underlying causes, such as agricultural policy reforms. These results not only contribute to the academic understanding of farmland abandonment but also have broader implications for agricultural policy, land management, and rural development in Brazil and similar contexts.

Proximate Causes

Urban and industrial development factors are often regarded as proximate causes of farmland abandonment. This thesis provided evidence supporting the role of these factors in the southeastern region, including the impact of the industrial boom associated with the oil industry in Rio de Janeiro (Chapter 3, RQ IV). These results align with previous studies (R. F. d. Silva, Batistella, and Emilio F. Moran 2016; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017) that have identified similar trends in the upper part of the Paraíba do Sul Basin. The convergence of findings across different studies underscores the importance of considering urban and industrial growth as significant drivers of land-use change. This has direct implications for regional planning and policy-making, particularly in balancing industrial development with the need to preserve agricultural lands and maintain rural livelihoods.

Geographical context variables, such as proximity to infrastructure and access to retailers and input suppliers, were also identified as proximate causes of farmland abandonment. In Rio de Janeiro, these factors were particularly relevant in explaining sugarcane abandonment, with poor accessibility to sugar mills being a significant driver (Chapter 5, RQ IV). These results are consistent with existing literature (Gellrich and Zimmermann 2007; Müller and Munroe 2008; Pazúr et al. 2014; Corbelle-Rico and Crecente-Maseda 2014; Vidal-Macua, Ninyerola, et al.

2018), which has documented the importance of infrastructure in maintaining viable agricultural practices. This highlights the critical need for targeted infrastructure investments in rural areas to prevent further abandonment. For instance, improving access to markets and processing facilities could mitigate the impact of such factors, potentially revitalizing abandoned or underutilized farmlands.

Biophysical Predisposing Factors

The thesis highlighted the role of biophysical conditions, such as steep slopes and uneven rainfall distribution, as important predisposing factors of sugarcane abandonment (Chapter 5, RQ IV). These findings are in line with other studies that have identified similar relationships between topographic constraints and farmland abandonment (Gellrich and Zimmermann 2007; Corbelle-Rico and Crecente-Maseda 2014; Vidal-Macua, Zabala, et al. 2018). The consistency of these findings across different geographic contexts suggests that biophysical factors are universally important in influencing agricultural viability. This has implications for land-use planning, particularly in regions with challenging terrains, where agricultural practices might need to be adapted, or alternative land uses considered. For example, in areas where steep slopes make conventional agriculture difficult, promoting agroforestry or conservation efforts could be a viable alternative, contributing to both economic sustainability and environmental protection.

Underlying Causes

Policy interventions were identified as underlying causes of the sugarcane industry's decline and subsequent farmland abandonment in Rio de Janeiro. The analysis showed that shifts in agricultural policy during the 1990s, including the end of subsidies and the closure of the IAA, significantly impacted the region (Chapter 3, RQ III). These findings are consistent with studies in the Paraíba Valley of Southeast Brazil, where small-scale agriculture was most affected by these policy changes (R. F. d. Silva, Batistella, and Emilio F. Moran 2016; R. F. B. d. Silva, Batistella, and Emilio Federico Moran 2017). The broader implication here is agricultural policy's critical role in sustaining or undermining rural economies. The case of Rio de Janeiro illustrates how abrupt policy shifts, particularly those that remove support for key industries, can lead to widespread abandonment and economic decline. This underscores the need for more nuanced and carefully managed policy transitions, especially when moving from a highly subsidized agricultural economy to a market-driven one. Future policy interventions should consider the long-term impacts on rural communities and aim to support transitions that minimize disruption and promote sustainable agricultural practices.

Methodological Drawbacks and Limitations

One of the key contributions of this thesis is the application of Interrupted Time Series Analysis (ITSA) to test the impact of policy interventions on sugarcane abandonment (Chapter 3, RQ III). However, separating the effects of confounding factors, such as the Collor reforms and the oil boom, presented significant challenges.

While the study demonstrated that a combined approach using the Synthetic Control Group Method and multi-group ITSA could differentiate these effects, the results should be viewed with caution due to the inherent complexities in isolating the impact of multiple overlapping drivers (Abadie, Diamond, Hainmueller, et al. 2010b; Abadie, Diamond, and J. Hainmueller 2010; Linden 2018b). Despite these challenges, the methodological approach used in this thesis provides a robust framework for future studies examining the impact of policy changes on land use. The application of ITSA in this context is particularly innovative, as it allows for a more precise quantification of policy impacts, which is essential for designing effective interventions in the future.

Another methodological challenge involved assessing the accuracy of existing datasets for mapping farmland abandonment, particularly focusing on sugarcane crops (Chapter 4, RQ II). While remote sensing methods proved effective in mapping annual sugarcane crops, the limitations of available data, especially regarding socioeconomic variables, constrained the analysis. Consequently, the study focused on biophysical and geographical determinants, but this exclusion of socioeconomic factors represents a limitation that should be addressed in future research. The use of remote sensing has shown great potential in accurately mapping land use changes, but integrating more comprehensive socioeconomic data could provide a more holistic understanding of the drivers of farmland abandonment.

Implications and Applications

The findings of this thesis have several practical implications for policymakers, land managers, and rural development planners. First, identifying key proximate, predisposing, and underlying causes of farmland abandonment provides a clear framework for developing targeted interventions. For example, investments in rural infrastructure, such as improving road access and market connectivity, could directly address some of the proximate causes identified in this study. Additionally, recognizing the role of policy in driving land use changes suggests that future policy reforms should be carefully designed to support agricultural sustainability, particularly in regions vulnerable to economic and environmental pressures.

Furthermore, the methods developed and applied in this thesis, particularly the use of remote sensing and ITSA, offer valuable tools for monitoring and analyzing land use changes over time. These techniques could be applied in other regions facing similar challenges, providing a means to track the effectiveness of interventions and adapt strategies as needed. For instance, remote sensing could be used to monitor the success of reforestation or agroforestry projects in areas of abandoned farmland, providing real-time data that can inform adaptive management strategies.

Comparison with Other Studies

The findings of this thesis are consistent with a growing body of literature on the drivers of farmland abandonment. Similar studies in Europe, for instance, have identified the importance of infrastructure, policy changes, and biophysical constraints in driving land use changes (Gellrich and Zimmermann 2007; Müller and Munroe 2008; Corbelle-Rico and Crecente-Maseda 2014; Vidal-Macua, Zabala, et al. 2018).

However, this thesis adds to the literature by providing a detailed case study from Brazil, a context that is less represented in the global discourse on farmland abandonment. The focus on sugarcane cultivation, in particular, offers unique insights into the dynamics of crop-specific abandonment, which can inform both national and international agricultural policies.

Overall, this thesis provides significant insights into the factors driving farmland abandonment in Rio de Janeiro, particularly concerning sugarcane cultivation. However, the findings should be interpreted cautiously, considering the methodological limitations and the context-specific nature of the study. Further research is needed to validate these results and explore additional factors that may contribute to the broader understanding of farmland abandonment in the region.

7

Conclusions

This thesis set out to achieve two main goals: i) to characterize farmland abandonment in Rio de Janeiro State and assess its spatial and temporal extent, and ii) to identify the proximate, predisposing, and underlying causes of this abandonment.

One of the key contributions of this study is the effective use of remote sensing techniques to map the abandonment of single crops, particularly sugarcane (Chapter 4, RQ II). This approach has provided a clear and detailed view of land use changes over time, overcoming the limitations of traditional agricultural datasets that often fail to capture the spatial extent of these changes. The successful application of these methods directly supports the first overarching goal of this thesis and offers a valuable tool for accurately assessing farmland abandonment in other regions as well.

This thesis also demonstrated the utility of applying Interrupted Time Series Analysis (ITSA) within a longitudinal and comparative framework to assess the impact of land policy interventions (Chapter 3, RQ III). This methodological approach has allowed for a more nuanced understanding of how specific policy changes—such as the withdrawal of subsidies and the closure of the Institute of Sugar and Alcohol (IAA)—have contributed to the decline of the sugarcane industry and subsequent farmland abandonment in Rio de Janeiro. By providing quantitative evidence of these impacts, this study contributes to the second overarching goal and sets a precedent for applying ITSA in the field of Land Use Science.

Furthermore, the thesis explored the predisposing and proximate causes of farmland abandonment, particularly in the Norte Fluminense region (Chapter 5, RQ IV). The findings highlighted the critical role that geographical and biophysical variables, such as infrastructure accessibility, precipitation, and topography, play in driving sugarcane abandonment. This deepens our understanding of the specific conditions that lead to farmland abandonment in Rio de Janeiro.

To advance the work presented in this thesis, several directions for future research are recommended. First, while this study primarily focused on biophysical and geographical factors, future research should incorporate a more comprehensive analysis of socioeconomic determinants, such as labor availability, market access, land ownership patterns, and the economic viability of small-scale farming. These factors, though not directly examined in this study, likely play a role in farmland abandonment. A detailed exploration of these variables, potentially in collaboration with the Brazilian Institute of Geography and Statistics (IBGE), could offer further insights, as suggested in Chapter 4. Harmonizing and integrating data across enumeration areas will be crucial in this effort.

Comparative studies in other regions of Brazil and beyond could also provide valuable insights into how different geographical, climatic, and policy contexts influence farmland abandonment. Such research would contribute to a broader understanding of regional variations in land use changes and could inform more tailored policy responses, further advancing the goals outlined in this thesis.

The potential impacts of climate change on farmland abandonment, as briefly mentioned in Chapter 5, remain underexplored. Future studies should investigate how changing weather patterns, temperature fluctuations, and extreme weather events might affect the viability of sugarcane and other crops in Rio de Janeiro and similar regions. Evaluating the impacts of sugarcane abandonment and the transition to pasture on soil carbon sequestration presents another critical area for research. By considering strategies tailored to specific rural development goals, future research could play a key role in climate change mitigation efforts, supporting policymakers in developing effective land management strategies. This would extend the research goals and ensure a comprehensive understanding of the environmental factors contributing to farmland abandonment.

Finally, building on the findings related to policy impacts, as discussed in Chapter 3, further research could focus on developing specific policy recommendations to promote sustainable land use in regions prone to farmland abandonment. This could involve studying successful interventions in other contexts, such as reintroducing sustainable agricultural practices, supporting small-scale farmers, or promoting alternative livelihoods in areas affected by land abandonment. This research direction aligns with the broader objectives of this thesis, aiming to provide actionable insights for policymakers.

The work presented in this thesis, particularly through the contributions made in mapping single-crop abandonment and applying ITSA for policy assessment, lays a strong foundation for understanding the drivers of farmland abandonment in Rio de Janeiro. These approaches enhance our understanding of land use dynamics and provide powerful tools for future research. By addressing the gaps identified in this study and linking them back to the initial research questions and goals, future research can contribute to more effective strategies for managing and reducing farmland abandonment in the region and beyond.

A. List of publications during the development of the Dissertation

During the development of this research, different chapters were peer-reviewed and published on different platforms.

Peer-reviewed articles

Castro, P.; Pedroso, R. Lautenbach, S.; Vicens, R. Farmland Abandonment in Rio de Janeiro: underlying and contributory causes of an announced development. Land Use Policy. Vol. 95. June 2020. https://doi.org/10.1016/j.landusepol.2020.104633

Castro, P. I. B., Yin, H., Teixera Junior, P. D., Lacerda, E., Pedroso, R., Lautenbach, S., Vicens, R. S. (2022). Sugarcane abandonment mapping in Rio de Janeiro state Brazil. Remote Sensing of Environment, 280, 113194. https://doi.org/10.1016/j.rse.2022.113194

Castro, P., Lautenbach, S., Pedroso, R., Vicens, R. (2023). Predisposing Factors of Sugarcane Abandonment in Rio de Janeiro: Exploring Policy Implications. Under Review in Land Use Policy.

Peer-reviewed book Chapter

Castro, P., Pedroso, R., Lautenbach, S., Villanueva, O.M.B., Vicens, R., 2019. Spatial Patterns of Farmland Abandonment in Rio de Janeiro State, in: Nehren, U., Schlueter, S., Raedig, C., Sattler, D., Hissa, H. (Eds.), Strategies and Tools for a Sustainable Rural Rio de Janeiro. pp. 69–85. `https://doi.org/10.1007/978-3-319-89644-1_6`

B. Presentations of this Dissertation's results at scientific conferences

Oral Presentations

Castro, P., Pedroso, R., Lautenbach, S., Vicens, R., Spatial Patterns of Farmland Abandonment in Rio de Janeiro State (2018). Fifth Global Conference on Economic Geography.

Poster Presentations

Castro, P., Pedroso, R., Lautenbach, S., Vicens, R., (2021) Preliminary assessment of spatial determinants of farmland abandonment in Rio de Janeiro State. American Association of Geographers: Annual Meeting (Virtual).

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References

Abadie, Alberto, Alexis Diamond, and Jens Hainmueller (2010). *SYNTH: Stata module to implement Synthetic Control Methods for Comparative Case Studies.*

— (2010a). "Synthetic control methods for comparative case studies: Estimating the effect of California's Tobacco control program". In: *Journal of the American Statistical Association.* ISSN: 01621459. DOI: 10.1198/jasa.2009.ap08746.

— (2010b). "Synthetic control methods for comparative case studies: Estimating the effect of California's Tobacco control program". In: *Journal of the American Statistical Association* 105.490, pp. 493–505. ISSN: 01621459. DOI: 10.1198/jasa.2009.ap08746.

Adami, Marcos et al. (2012). "Remote sensing time series to evaluate direct land use change of recent expanded sugarcane crop in Brazil". In: *Sustainability* 4 (4), pp. 574–585. ISSN: 20711050. DOI: 10.3390/su4040574.

Aguiar, Daniel Alves et al. (2011). "Remote Sensing Images in Support of Environmental Protocol: Monitoring the Sugarcane Harvest in São Paulo State, Brazil". In: *Remote Sensing* 3.12, pp. 2682–2703. DOI: 10.3390/rs3122682.

Aide, Mitchell and Ricardo Grau (2004). "Globalization, Migration, and Latin American Ecosystems". In: *Science* 300.September, pp. 1725–1727. ISSN: 00368075. DOI: 10.1126/science.1103788. URL: http://www.sciencemag.org/content/306/5701/1482.short.

Alcantara, Camilo et al. (2012). "Mapping abandoned agriculture with multi-temporal MODIS satellite data". In: *Remote Sensing of Environment* 124, pp. 334–347. ISSN: 00344257. DOI: 10.1016/j.rse.2012.05.019. URL: http://dx.doi.org/10.1016/j.rse.2012.05.019.

Alentejano, Paulo (2006). *Um breve balanço da política agrária no estado do Rio de Janeiro nas últimas décadas.*

Algeet-Abarquero, Nur et al. (2015). "Implications of land use change on runoff generation at the plot scale in the humid tropics of Costa Rica". In: *Catena* 135, pp. 263–270. ISSN: 03418162. DOI: 10.1016/j.catena.2015.08.004. URL: http://dx.doi.org/10.1016/j.catena.2015.08.004.

André, Romisio Geraldo Bouhid et al. (2008). *Identificação de Regiões Pluviometricamente Honogêneas no Estado do Rio de Janeiro, utilizando-se valores mensais*, pp. 501–509.

Azevedo, Hamilton Jorge De (2002). *Uma Análise da Cadeia Produtiva de Cana-de- Açúcar na Região Norte Fluminense.* Tech. rep.

Baatz, Martin and Arno Schäpe (2000). "Multiresolution Segmentation : an optimization approach for high quality multi-scale image segmentation". In.

Bahiense, D. (2014). "Análise do desenvolvimento da fruticultura e seus efeitos sobre a produção agrícola no Estado do Rio de Janeiro". PhD thesis. Universidade Estadual do Norte Fluminese.

Bahiense, N., D. Souza, and P. Ponciano (2015). "Incentivos à produção de frutas e as mudanças na agricultura da Região Norte do estado do Rio de Janeiro". In: *Rev. Bras. Frutic., Jaboticabal - SP,* 37.2, pp. 387–395.

Barbosa, Antonio Ivo Gomes et al. (2020). "O uso de Sensoriamento Remoto para estimar área plantada de cana-de-açúcar em Campos dos Goytacazes – RJ, Brasil". In: *Revista Cerrados* 18.02, pp. 69–99. ISSN: 1678-8346. DOI: 10.46551/rc24482692202010.

Bastos, André da Cunha and Márcia Azanha Ferraz Dias de Moraes (2014). "Perfil dos fornecedores de cana-de-açúcar na região Centro-Sul do Brasil". In: *Informações Econômicas* 44.2, pp. 5–16.

Baum, Christopher F and Mark E Schaffer (2015). "ACTEST: Stata module to perform Cumby-Huizinga general test for autocorrelation in time series". In: *Statistical Software Components*.

Baumann, Matthias et al. (2011). "Patterns and drivers of post-socialist farmland abandonment in Western Ukraine". In: *Land Use Policy* 28.3, pp. 552–562. ISSN: 02648377. DOI: 10.1016/j.landusepol.2010.11.003. URL: http://dx.doi.org/10.1016/j.landusepol.2010.11.003.

Baxter, Ryan E. and Kirby E. Calvert (Sept. 2017). "Estimating Available Abandoned Cropland in the United States: Possibilities for Energy Crop Production". In: *Annals of the American Association of Geographers* 107 (5), pp. 1162–1178. ISSN: 24694460. DOI: 10.1080/24694452.2017.1298985.

Beck, Hylke E. et al. (Mar. 2019). "MSWEP V2 Global 3-Hourly 0.1° Precipitation: Methodology and Quantitative Assessment". In: *Bulletin of the American Meteorological Society* 100 (3), pp. 473–500. ISSN: 0003-0007. DOI: 10.1175/BAMS-D-17-0138.1.

Bell, Stephen M., Samuel J. Raymond, et al. (Dec. 2023). "Quantifying the recarbonization of post-agricultural landscapes". In: *Nature communications* 14 (1), p. 2139. ISSN: 20411723. DOI: 10.1038/s41467-023-37907-w.

Bell, Stephen M., César Terrer, et al. (Mar. 2021). "Soil organic carbon accumulation rates on Mediterranean abandoned agricultural lands". In: *Science of The Total Environment* 759, p. 143535. ISSN: 00489697. DOI: 10.1016/j.scitotenv.2020.143535.

Bernal, James Lopez, Steven Cummins, and Antonio Gasparrini (2017). "Interrupted time series regression for the evaluation of public health interventions: A tutorial". In: *International Journal of Epidemiology* 46.1, pp. 348–355. ISSN: 14643685. DOI: 10.1093/ije/dyw098.

Bivand, Roger S. and David W. S. Wong (2018). "Comparing implementations of global and local indicators of spatial association". In: *TEST* 27.3, pp. 716–748. ISSN: 1133-0686. DOI: 10.1007/s11749-018-0599-x.

Brannstrom, Christian et al. (2008). "Land change in the Brazilian Savanna (Cerrado), 1986-2002: Comparative analysis and implications for land-use policy". In: *Land Use Policy* 25.4, pp. 579–595. ISSN: 02648377. DOI: 10.1016/j.landusepol.2007.11.008.

Breiman, Leo (2001). "Statistical Modeling: The Two Cultures". In: *Statistical Science* 16.3, pp. 199–231. ISSN: 08834237. DOI: 10.2307/2676681. arXiv: 0010.

Burton, Glenn W. and Houston B. Couch (2021). *Grass crop*. DOI: 10.1036/1097-8542.298500. URL: https://www.accessscience.com/content/grass-crop/298500.

Carvalho Filho, Amaury de et al. (2000). *Mapa de aptidão agrícola das terras do estado do rio de janeiro*. Tech. rep. b c. Brasília, p. 3.

Castillo, Carolina Perpiña et al. (2021). "Modelling agricultural land abandonment in a fine spatial resolution multi-level land-use model: An application for the EU". In: *Environmental Modelling & Software* 136.2, p. 104946. ISSN: 13648152. DOI: 10.1016/j.envsoft.2020.104946. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364815220310033.

Castro, P. (12th of March, 2021). *Padroes de produção e variedades de cana-de-açúcar no Norte Fluminense: Interview*.

Castro, P. et al. (June 2020). "Farmland abandonment in Rio de Janeiro: Underlying and contributory causes of an announced development". In: *Land Use Policy* 95, p. 104633.

ISSN: 02648377. DOI: 10.1016/j.landusepol.2020.104633. URL: https://linkinghub.elsevier.com/retrieve/pii/S0264837719310361.

Castro, Pedro et al. (2019). "Spatial Patterns of Farmland Abandonment in Rio de Janeiro State". In: *Strategies and Tools for a Sustainable Rural Rio de Janeiro*. Ed. by Udo Nehren et al. Chap. 6, pp. 69–85. ISBN: 978-3-319-89643-4. DOI: 10.1007/978-3-319-89644-1. URL: http://link.springer.com/10.1007/978-3-319-89644-1.

Castro, Pedro Ivo Bastos de et al. (Oct. 2022). "Sugarcane abandonment mapping in Rio de Janeiro state Brazil". In: *Remote Sensing of Environment* 280, p. 113194. ISSN: 00344257. DOI: 10.1016/j.rse.2022.113194. URL: https://linkinghub.elsevier.com/retrieve/pii/S0034425722003042.

CEPERJ (2017). *Produto interno bruto do Estado do Rio de Janeiro. Participação das atividades econômicas no valor adicionado bruto a preço básico no Estado do Rio de Janeiro de 2002 a 2017.* CEPERJ/Centro de Estatísticas, Estudos e Pesquisas - CEEP. URL: http://www.ceperj.rj.gov.br/%20ceep/pib/pib.html..

Chaddad, Fabio Ribas et al. (2006). "The Evolution of Agricultural Policies and Agribusiness Development in Brazil". In: *Choices: The Magazine of Food, Farm, and Resource Issues* 21.2, pp. 85–90. URL: https://econpapers.repec.org/article/agsaaeach/94415.htm.

Chaudhary, Suresh et al. (Mar. 2020). "A Synopsis of Farmland Abandonment and Its Driving Factors in Nepal". In: *Land* 9 (3), p. 84. ISSN: 2073-445X. DOI: 10.3390/land9030084.

Coelho, Carlos (2001). "70 anos de política agrícola no Brasil (1931-2001)". In: *Revista de política agrícola* 10.3, pp. 3–58. ISSN: 2317-224X.

Corbelle-Rico, Eduardo and Rafael Crecente-Maseda (2014). "Evaluating IRENA indicator "Risk of Farmland Abandonment" on a low spatial scale level: The case of Galicia (Spain)". In: *Land Use Policy* 38, pp. 9–15. ISSN: 02648377. DOI: 10.1016/j.landusepol.2013.10.013.

Cramer, Viki A., Richard J. Hobbs, and Rachel J. Standish (2008). "What's new about old fields? Land abandonment and ecosystem assembly". In: *Trends in Ecology and Evolution* 23.2, pp. 104–112. ISSN: 01695347. DOI: 10.1016/j.tree.2007.10.005.

Crosbie, John (1993). "Interrupted Time-Series Analysis with Brief Single-Subject Data". In: *Journal of Consulting and Clinical Psychology*. ISSN: 0022006X. DOI: 10.1037/0022-006X.61.6.966.

Dantas, Marcelo Eduardo (2000). *Geomorfologia do Estado do Rio de Janeiro*. Tech. rep. Brasília.

Daskalova, Gergana N. and Johannes Kamp (May 2023). "Abandoning land transforms biodiversity". In: *Science* 380 (6645), pp. 581–583. ISSN: 0036-8075. DOI: 10.1126/science.adf1099. URL: https://www.science.org/doi/10.1126/science.adf1099.

Davis, E. G. and M. C. Naghettini (2000). *Estudo de chuvas intensas no Estado Do Rio De Janeiro*. Tech. rep. Brasília.

Deng, Lei et al. (Jan. 2016). "Global patterns of the effects of land-use changes on soil carbon stocks". In: *Global Ecology and Conservation* 5, pp. 127–138. ISSN: 23519894. DOI: 10.1016/j.gecco.2015.12.004.

UN-DESA (2019). *World Population Prospects 2019: Data Booket. ST/ESA/SER. A/424*. United Nations, Department of Economic and Social Affairs, Population Division. URL: https://population.un.org/wpp/publications/Files/WPP2019_DataBooklet.pdf.

Díaz, G. Ignacio et al. (2011). "Drivers of land abandonment in Southern Chile and implications for landscape planning". In: *Landscape and Urban Planning* 99.3-4, pp. 207–217. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2010.11.005.

Dormann, Carsten F. et al. (2013). “Collinearity: A review of methods to deal with it and a simulation study evaluating their performance”. In: *Ecography* 36.1, pp. 027–046. ISSN: 09067590. DOI: 10.1111/j.1600-0587.2012.07348.x. arXiv: NIHMS150003.

Eric P. Crist (1985). “A TM Tasseled Cap Equivalent Transformation for Reflectance Factor Data”. In: *Remote Sensing of Environment* 17, pp. 301–306. ISSN: 00344257.

Estel, Stephan et al. (2015). “Mapping farmland abandonment and recultivation across Europe using MODIS NDVI time series”. In: *Remote Sensing of Environment* 163, pp. 312–325. ISSN: 00344257. DOI: 10.1016/j.rse.2015.03.028.

FAO (2006). *The Role of Agriculture and Rural Development in Revitalizing Abandoned / Depopulated Areas*. Tech. rep. June, p. 28.

Fauré, Yves-A and Lia Hasenclever (2005). *O desenvolvimento Local no Estado do Rio de Janeiro: Estudos avançados nas realidades municipais*. E-papes Se. Rio de Janeiro, p. 460. ISBN: 8576500329.

Fayet, Catherine M.J. et al. (Jan. 2022). “What is the future of abandoned agricultural lands? A systematic review of alternative trajectories in Europe”. In: *Land Use Policy* 112, p. 105833. ISSN: 02648377. DOI: 10.1016/j.landusepol.2021.105833.

Foley, Jonathan A., Ruth Defries, et al. (2005). “Global consequences of land use”. In: *Science (New York, N.Y.)* 309.5734, pp. 570–574. DOI: 10.1126/science.1111772.

Foley, Jonathan A., Navin Ramankutty, et al. (2011). “Solutions for a cultivated planet”. In: *Nature* 478.7369, pp. 337–342. ISSN: 0028-0836. DOI: 10.1038/nature10452. arXiv: 9605103 [cs]. URL: http://www.nature.com/doifinder/10.1038/nature10452.

Gaese, Carl-Friedrich et al. (2019). “Adequate Harvesting Technology for Small- and Medium-Scale Sugarcane Farmers in Rio de Janeiro: The “Cologne Solution””. In: *Strategies and Tools for a Sustainable Rural Rio de Janeiro*. Ed. by Udo Nehren et al. Cham: Springer International Publishing, pp. 121–135. ISBN: 978-3-319-89644-1. DOI: 10.1007/978-3-319-89644-1_9. URL: https://doi.org/10.1007/978-3-319-89644-1%7B%5C_%7D9.

Gao, Bo-cai (Dec. 1996). “NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space”. In: *Remote Sensing of Environment* 58 (3), pp. 257–266. ISSN: 00344257. DOI: 10.1016/S0034-4257(96)00067-3. URL: https://linkinghub.elsevier.com/retrieve/pii/S0034425796000673.

García-Barrios, Luis et al. (2009). “Neotropical Forest Conservation, Agricultural Intensification, and Rural Out-migration: The Mexican Experience”. In: *BioScience* 59.10, pp. 863–873. ISSN: 1525-3244. DOI: 10.1525/bio.2009.59.10.8. URL: https://academic.oup.com/bioscience/article-lookup/doi/10.1525/bio.2009.59.10.8.

Garotinho, Wladimir (2019). *PROJETO DE LEI N.º 1.440, DE 2019*.

Gasques, Z., J. Filho, and J. Navarro (2010). *A Agricultura Brasileira : desempenho, desafios e perspectivas*. Brasília, p. 298. ISBN: 9788578110505.

Geist, Helmut et al. (2006). “Chapter 3: Causes and Trajectories of Land-Use/Cover Change Helmut”. In: *Land-use and Land-Cover Change: Local process and global impacts*. Wiggins 2000, pp. 41–70.

Geist, Helmut J. and Eric F. Lambin (2002). “Proximate Causes and Underlying Driving Forces of Tropical Deforestation”. In: *BioScience* 52.2, p. 143. ISSN: 0006-3568. DOI: 10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2.

Gellrich, Mario, Priska Baur, et al. (2008). “Combining classification tree analyses with interviews to study why sub-alpine grasslands sometimes revert to forest: A case study from the Swiss Alps”. In: *Agricultural Systems* 96.1-3, pp. 124–138. ISSN: 0308521X. DOI: 10.1016/j.agsy.2007.07.002.

Gellrich, Mario and Niklaus E. Zimmermann (2007). “Investigating the regional-scale pattern of agricultural land abandonment in the Swiss mountains: A spatial statistical modelling approach”. In: *Landscape and Urban Planning* 79.1, pp. 65–76. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2006.03.004.

Gorelick, Noel et al. (2017). “Google Earth Engine: Planetary-scale geospatial analysis for everyone”. In: *Remote Sensing of Environment* 202.3, pp. 18–27. ISSN: 00344257. DOI: 10.1016/j.rse.2017.06.031.

Grădinaru, Simona R., Felix Kienast, and Achilleas Psomas (2019). “Using multi-seasonal Landsat imagery for rapid identification of abandoned land in areas affected by urban sprawl”. In: *Ecological Indicators* 96.September 2016, pp. 79–86. ISSN: 1470160X. DOI: 10.1016/j.ecolind.2017.06.022. URL: http://dx.doi.org/10.1016/j.ecolind.2017.06.022.

Griffith, Daniel and Yongwan Chun (Jan. 2014). *Spatial autocorrelation and spatial filtering.* DOI: 10.1007/978-3-642-23430-9_72.

Griffiths, Patrick, Tobias Kuemmerle, et al. (2014). “Forest disturbances, forest recovery, and changes in forest types across the carpathian ecoregion from 1985 to 2010 based on landsat image composites”. In: *Remote Sensing of Environment* 151, pp. 72–88. ISSN: 00344257. DOI: 10.1016/j.rse.2013.04.022.

Griffiths, Patrick, Daniel Müller, et al. (2013). “Agricultural land change in the Carpathian ecoregion after the breakdown of socialism and expansion of the European Union”. In: *Environmental Research Letters* 8.4, p. 045024. ISSN: 1748-9326. DOI: 10.1088/1748-9326/8/4/045024. URL: http://stacks.iop.org/1748-9326/8/i=4/a=045024?key=crossref.590e48e00f33a50f2f4442a2fc8113e3.

Grinand, Clovis et al. (2013). “Estimating deforestation in tropical humid and dry forests in Madagascar from 2000 to 2010 using multi-date Landsat satellite images and the random forests classifier”. In: *Remote Sensing of Environment* 139, pp. 68–80. ISSN: 00344257. DOI: 10.1016/j.rse.2013.07.008. URL: http://dx.doi.org/10.1016/j.rse.2013.07.008.

Hansen, M.C. C et al. (2013). “High-Resolution Global Maps of”. In: *Science* 342.November, pp. 850–854. ISSN: 0036-8075. DOI: 10.1126/science.1244693. arXiv: 1011.1669v3. URL: http://www.ncbi.nlm.nih.gov/pubmed/24233722.

Hansen, Matthew C. and Thomas R. Loveland (2012). “A review of large area monitoring of land cover change using Landsat data”. In: *Remote Sensing of Environment* 122.1, pp. 66–74. ISSN: 00344257. DOI: 10.1016/j.rse.2011.08.024.

Helfand, Steven M. and Gervásio Castro De Rezende (2004). “The impact of sector-specific and economy-wide policy reforms on the agricultural sector in Brazil: 1980-98”. In: *Contemporary Economic Policy* 22.2, pp. 194–212. ISSN: 10743529. DOI: 10.1093/cep/byh014.

Helfand,S.; Rezende, G.C. (2003). *Região e espaço no desenvolvimento agrícola brasileiro.* Rio de Janeiro: IPEA - Instituto de Pesquisa Econômica Aplicada. ISBN: 8586170518.

Hoornweg, Daniel, Perinaz Bhada-Tata, and Chris Kennedy (2013). “Waste production must peak this century”. In: *Nature* 502.7473, pp. 615–617. ISSN: 14764687. DOI: 10.1038/502615a.

Hosmer, D. W. and S. Lemeshow (2000). *Appllied Logistic Regression.* 2nd. John Wiley & Sons, Inc. ISBN: 0-471-35632-8.

Hostert, Patrick et al. (2011). “Rapid land use change after socio-economic disturbances: the collapse of the Soviet Union versus Chernobyl”. In: *Environmental Research Letters* 6.4, p. 045201. ISSN: 1748-9326. DOI: 10.1088/1748-9326/6/4/045201. URL: https://iopscience.iop.org/article/10.1088/1748-9326/6/4/045201.

IBGE (1990). *Divisão Regional do Brasil em Mesorregiões e Microrregiões Geográficas v.1.* Ed. by Departamento de Geografia DEGEO.

— (2002). *Pesquisas Agropecuárias.* Tech. rep. Rio de Janeiro: IBGE, Departamento de Agropecuária.

— (2010). *Censo Agropecuário 2006.* Tech. rep. Rio de Janeiro: IBGE, pp. 1–777. arXiv: arXiv:1011.1669v3.

— (2011). *Censo Demográfico 2010*. Tech. rep. DOI: ISSN0101-4234. arXiv: arXiv:1011.1669v3.

— (2017). *A geografia contemporânea da cafeicultura brasileira.*

— (2018a). *Estatísticas do Cadastro Central de Empresas de 2016*. Tech. rep. Rio de Janeiro: IBGE, p. 101.

— (2018b). *https://sidra.ibge.gov.br/pesquisa/pam/tabelas.* (Visited on 11/21/2018).

— (2018c). *https://sidra.ibge.gov.br/pesquisa/ppm/quadros/brasil/2017.* URL: https://sidra.ibge.gov.br/pesquisa/ppm/quadros/brasil/2017 (visited on 11/21/2018).

— (2019). *https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017.*

— (2021). *https://sidra.ibge.gov.br/pesquisa/pam/tabelas.*

INCRA (2016). *Sistema Nacional de Cadastro Rural - SNCR*. Tech. rep. INCRA.

INPE (2017). *PRODES – Monitoramento da Floresta Amazônica Brasileira por Satélite.* URL: http://%20www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes..

Irons, James R., John L. Dwyer, and Julia A. Barsi (2012). "The next Landsat satellite: The Landsat Data Continuity Mission". In: *Remote Sensing of Environment* 122, pp. 11–21. ISSN: 00344257. DOI: 10.1016/j.rse.2011.08.026.

Izquierdo, Andrea E. and H. Ricardo Grau (Feb. 2009). "Agriculture adjustment, land-use transition and protected areas in Northwestern Argentina". In: *Journal of Environmental Management* 90.2, pp. 858–865. ISSN: 03014797. DOI: 10.1016/j.jenvman.2008.02.013. URL: http://www.ncbi.nlm.nih.gov/pubmed/18439743%20http://linkinghub.elsevier.com/retrieve/pii/S0301479708000601.

Jägermeyr, Jonas et al. (Nov. 2021). "Climate impacts on global agriculture emerge earlier in new generation of climate and crop models". In: *Nature Food* 2 (11), pp. 873–885. ISSN: 2662-1355. DOI: 10.1038/s43016-021-00400-y. URL: https://www.nature.com/articles/s43016-021-00400-y.

Janitza, Silke and Roman Hornung (Aug. 2018). "On the overestimation of random forest's out-of-bag error". In: *PLOS ONE* 13 (8), e0201904. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0201904.

Jarvis, Lovell S. (2005). "The rise and decline of rent-seeking activity in the Brazilian coffee sector: Lessons from the imposition and removal of coffee export quotas". In: *World Development* 33.11, pp. 1881–1903. ISSN: 0305750X. DOI: 10.1016/j.worlddev.2005.06.003.

Jiang, Hao et al. (Apr. 2019). "Early season mapping of sugarcane by applying machine learning algorithms to sentinel-1A/2 time series data: A case study in Zhanjiang City, China". In: *Remote Sensing* 11 (7). ISSN: 20724292. DOI: 10.3390/RS11070861.

Katayama, Naoki et al. (2015). "Are both agricultural intensification and farmland abandonment threats to biodiversity? A test with bird communities in paddy-dominated landscapes". In: *Agriculture, Ecosystems and Environment* 214, pp. 21–30. ISSN: 01678809. DOI: 10.1016/j.agee.2015.08.014. URL: http://dx.doi.org/10.1016/j.agee.2015.08.014.

Kearney, John (2010). "Food consumption trends and drivers". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* 365.1554, pp. 2793–2807. ISSN: 14712970. DOI: 10.1098/rstb.2010.0149. arXiv: 1011.1669.

Keenleyside, C. and G.M. Tucker (2010). "Farmland abandonment in the EU: an assessment of trends and prospects. Report prepared for WWF. London: Institute for European Environmental Policy (IEEP)." In: November.

Kennedy, Robert E., Warren B. Cohen, and Todd A. Schroeder (2007). "Trajectory-based change detection for automated characterization of forest disturbance dynamics". In: *Remote Sensing of Environment* 110.3, pp. 370–386. ISSN: 00344257. DOI: 10.1016/j.rse.2007.03.010.

Kennedy, Robert E., Zhiqiang Yang, and Warren B. Cohen (2010). “Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr - Temporal segmentation algorithms”. In: *Remote Sensing of Environment* 114.12, pp. 2897–2910. ISSN: 00344257. DOI: `10.1016/j.rse.2010.07.008`. URL: `http://dx.doi.org/10.1016/j.rse.2010.07.008`.

Kennedy, Robert E., Zhiqiang Yang, Noel Gorelick, et al. (2018). “Implementation of the LandTrendr algorithm on Google Earth Engine”. In: *Remote Sensing* 10.5. ISSN: 20724292. DOI: `10.3390/rs10050691`.

Kolecka, Natalia et al. (2017). “Understanding farmland abandonment in the Polish Carpathians”. In: *Applied Geography* 88, pp. 62–72. ISSN: 01436228. DOI: `10.1016/j.apgeog.2017.09.002`.

Kuemmerle, Tobias et al. (2008). “Cross-border Comparison of Post-socialist Farmland Abandonment in the Carpathians”. In: *Ecosystems* 11.4, p. 614. ISSN: 1435-0629. DOI: `10.1007/s10021-008-9146-z`. URL: `https://doi.org/10.1007/s10021-008-9146-z`.

Kussul, Nataliia et al. (2017). “Deep Learning Classification of Land Cover and Crop Types Using Remote Sensing Data”. In: *IEEE Geoscience and Remote Sensing Letters*. ISSN: 1545598X. DOI: `10.1109/LGRS.2017.2681128`.

Lambin, Eric F. and Patrick Meyfroidt (2010). “Land use transitions: Socio-ecological feedback versus socio-economic change”. In: *Land Use Policy* 27.2, pp. 108–118. ISSN: 02648377. DOI: `10.1016/j.landusepol.2009.09.003`.

Lambin, Eric F., B. L. Turner, et al. (2001). “The causes of land-use and land-cover change: Moving beyond the myths”. In: *Global Environmental Change* 11.4, pp. 261–269. ISSN: 0959-3780. DOI: `10.1016/S0959-3780(01)00007-3`. arXiv: `arXiv:1011.1669v3`.

Lamego, A.R. (1945). *O homem e o brejo*. IBGE, p. 208. URL: `http://scholar.google.com/scholar?hl=en%7B%5C&%7DbtnG=Search%7B%5C&%7Dq=intitle:O+HOMEM+E+O+BREJO%7B%5C#%7DO`.

Lasanta, T. et al. (1995). “Hydrological problems resulting from farmland abandonment in semi-arid environments: The central Ebro depression”. In: *Physics and Chemistry of the Earth* 20.3-4, pp. 309–314. ISSN: 00791946. DOI: `10.1016/0079-1946(95)00042-9`.

Laue, Justin E. and Eugenio Y. Arima (2016). “Spatially explicit models of land abandonment in the Amazon”. In: *Journal of Land Use Science* 11.1, pp. 48–75. ISSN: 17474248. DOI: `10.1080/1747423X.2014.993341`.

Leite, Adriana Figueira (2017). “Gestão dos recursos hídricos e desastres relacionados à água na baixada Campista. In: ENCONTRO NACIONAL DOS PROGRAMAS DE PÓS-GRADUAÇÃO EM GEOGRAFIA (ENANPEGE)”. In: Anais eletrônicos, p. 12.

Lewis, Stephen (1984). “Development Problems of Mineral-Rich countries”. In: *Economic Structure and Performance: Essays in Honor of Hollis B. Chenery*. Ed. by Moshe Syrquin, Lance Taylor, and Larry E. Westphal. Academic Press Inc. Chap. 8. ISBN: ISBN 0-12-680060-X.

Li, Shengfa and Xiubin Li (Sept. 2017). “Global understanding of farmland abandonment: A review and prospects”. In: *Journal of Geographical Sciences* 27.9, pp. 1123–1150. ISSN: 1009-637X. DOI: `10.1007/s11442-017-1426-0`. URL: `http://link.springer.com/10.1007/s11442-017-1426-0`.

Li, Yuling et al. (2021). “Spatial pattern and mechanisms of farmland abandonment in Agricultural and Pastoral Areas of Qingzang Plateau”. In: *Geography and Sustainability* 2.3, pp. 139–150. ISSN: 26666839. DOI: `10.1016/j.geosus.2021.06.003`. URL: `https://linkinghub.elsevier.com/retrieve/pii/S2666683921000250`.

Linden, Ariel (2015). “Conducting interrupted time-series analysis for single- and multiple-group comparisons”. In: *Stata Journal*. ISSN: 1536867X. DOI: `TheStataJournal`. arXiv: `TheStataJournal`.

— (2017). “A comprehensive set of postestimation measures to enrich interrupted time-series analysis”. In: *Stata Journal* 17.1, pp. 73–88. ISSN: 1536867X. DOI: 10.1177/1536867x1701700105.

— (2018a). “A matching framework to improve causal inference in interrupted time-series analysis”. In: *Journal of Evaluation in Clinical Practice* 24.2, pp. 408–415. ISSN: 13652753. DOI: 10.1111/jep.12874.

— (2018b). “Combining synthetic controls and interrupted time series analysis to improve causal inference in program evaluation”. In: *Journal of Evaluation in Clinical Practice* 24.2, pp. 447–453. ISSN: 13652753. DOI: 10.1111/jep.12882.

Liu, Yaolin et al. (2016). “Socioeconomic drivers of forest loss and fragmentation : A comparison between different land use ...” In: *Land Use Policy* 54.July, pp. 58–68. ISSN: 0264-8377. DOI: 10.1016/j.landusepol.2016.01.016. URL: http://dx.doi.org/10.1016/j.landusepol.2016.01.016.

Lobao, Linda and Katherine Meyer (2001). “THE GREAT AGRICULTURAL TRANSITION : and Social Consequences Crisis , Change , of Twentieth Century US Farming Linda Lobao1 and Katherine”. In: *Annual Review of Sociology* 27, pp. 103–124.

Lott, John R. and David B. Mustard (2008). “Crime, deterrence, and right-to-carry concealed handguns”. In: *Economics Law and Individual Rights*. ISBN: 0203930886. DOI: 10.4324/9780203930885. arXiv: arXiv:1011.1669v3.

Maddox, James G (1960). “American Economic Association Private and Social Costs of the Movement of People Out of Agriculture”. In: *The American Economic Review* 50.2.

Maranhão R. (2015). “Análise da dinâmica da produção de soja, cana de açúcar, milho e bovina no território brasileiro.” PhD thesis. Universidade de Brasília, pp. 1–112.

Marques, V. S. et al. (2001). *Possíveis Modificações na Classificação Climática das Regiões Norte e Noroeste do Estado do Rio de Janeiro.* Relatório SIMERJ, pp. 0-15.

Martinelli, Luiz A., Rachael Garrett, et al. (2011). “Sugar and ethanol production as a rural development strategy in Brazil: Evidence from the state of São Paulo”. In: *Agricultural Systems* 104.5, pp. 419–428. ISSN: 0308521X. DOI: 10.1016/j.agsy.2011.01.006. arXiv: 9809069v1 [arXiv:gr-qc]. URL: http://dx.doi.org/10.1016/j.agsy.2011.01.006.

Martinelli, Luiz A., Rosamond Naylor, et al. (2010). “Agriculture in Brazil: Impacts, costs, and opportunities for a sustainable future”. In: *Current Opinion in Environmental Sustainability* 2.5-6, pp. 431–438. ISSN: 18773435. DOI: 10.1016/j.cosust.2010.09.008.

Masek, J. G. et al. (2006). “A Landsat Surface Reflectance Dataset for North America, 1990–2000”. In: *IEEE Geoscience and Remote Sensing Letters* 3.1, pp. 68–72. ISSN: 1545-598X. DOI: 10.1109/LGRS.2005.857030.

Maus, Victor et al. (2019). “dtwSat : Time-Weighted Dynamic Time Warping for Satellite Image Time Series Analysis in R”. In: *Journal of Statistical Software* 88.5. DOI: 10.18637/jss.v088.i05.

Mcafee, Kathleen (2005). “Geographies of risk and difference in crop genetic engineering”. In: *The Geographical Review* 94.1, pp. 80–106.

McCullagh, P. and J. A. Nelder (1989). *Generalized Linear Models*. Boston, MA: Springer US. ISBN: 978-0-412-31760-6. DOI: 10.1007/978-1-4899-3242-6.

McGill, Brian (2015). “Land use matters”. In: *Nature* 520, pp. 38–39. ISSN: 0028-0836. DOI: 10.1038/520038a.

McKnight, Scott D., Joseph W. McKean, and Bradley E. Huitema (2000). “A double bootstrap method to analyze linear models with autoregressive error terms”. In: *Psychological Methods*. ISSN: 1082989X. DOI: 10.1037/1082-989X.5.1.87.

Mehta, Aashish and Jean Paul Chavas (2008). “Responding to the coffee crisis: What can we learn from price dynamics?” In: *Journal of Development Economics* 85.1-2, pp. 282–311. ISSN: 03043878. DOI: 10.1016/j.jdeveco.2006.07.006.

Mendonca, José C. et al. (2011). "Mapeamento das áreas de cana-de-açúcar na região Norte Fluminense - RJ por uso de Sensoriamento Remoto". In: *Eng. Agríc., Jaboticabal* 31.3, pp. 561–571.

Mendonça, J. C. et al. (2009). "Indices de aridez e umidade nas regiões Norte e Noroeste do Estado do Rio de Janeiro." In: *III Simpósio Internacional de Climatologia*, Canela, RS.

Meyfroidt, Patrick et al. (2016). "Drivers, Constraints and Trade-Offs Associated with Recultivating Abandoned Cropland in Russia, Ukraine and Kazakhstan". In: *Spatial Economics* 2.46, pp. 55–103. ISSN: 18159834. DOI: 10.14530/se.2016.2.055-103.

Moran, P. A. P. (1950). "Notes on Continuous Stochastic Phenomena". In: *Biometrika* 37.1/2, pp. 17–23.

Moreira, Francisco, Francisco C. Rego, and Paulo G. Ferreira (2001). "Temporal (1958–1995) pattern of change in a cultural landscape of northwestern Portugal: implications for fire occurrence". In: *Landscape Ecology* 16, pp. 557–567.

Muller, Andreas (Apr. 2004). "Florida's Motorcycle Helmet Law Repeal and Fatality Rates". In: *American Journal of Public Health* 94.4, pp. 556–558. ISSN: 00900036. DOI: 10.2105/AJPH.94.4.556.

Müller, Daniel, Pedro J. Leitão, and Thomas Sikor (2013). "Comparing the determinants of cropland abandonment in Albania and Romania using boosted regression trees". In: *Agricultural Systems* 117, pp. 66–77. ISSN: 0308521X. DOI: 10.1016/j.agsy.2012.12.010.

Müller, Daniel and Darla K. Munroe (Sept. 2008). "Changing Rural Landscapes in Albania: Cropland Abandonment and Forest Clearing in the Postsocialist Transition". In: *Annals of the Association of American Geographers* 98.4, pp. 855–876. ISSN: 0004-5608. DOI: 10.1080/00045600802262323. URL: http://www.tandfonline.com/doi/abs/10.1080/00045600802262323.

Munroe, Darla K. et al. (2013). "Alternative trajectories of land abandonment: Causes, consequences and research challenges". In: *Current Opinion in Environmental Sustainability* 5.5, pp. 471–476. ISSN: 18773435. DOI: 10.1016/j.cosust.2013.06.010.

Natalia Kolecka (2021). "Greening trends and their relationship with agricultural land abandonment across Poland". In: *Remote Sensing of Environment* 257, p. 112340. ISSN: 00344257. DOI: 10.1016/j.rse.2021.112340. URL: https://www.sciencedirect.com/science/article/pii/S0034425721000584.

Newbold, Tim et al. (2015). "Global effects of land use on local terrestrial biodiversity". In: *Nature* 520.7545, pp. 45–50. ISSN: 14764687. DOI: 10.1038/nature14324. arXiv: 0803973233.

Novara, Agata et al. (2017). "Agricultural land abandonment in Mediterranean environment provides ecosystem services via soil carbon sequestration". In: *Science of the Total Environment* 576, pp. 420–429. ISSN: 18791026. DOI: 10.1016/j.scitotenv.2016.10.123. URL: http://dx.doi.org/10.1016/j.scitotenv.2016.10.123.

OEC (2019). *Exporters of Raw sugarcane 2019*. URL: https://oec.world/en/profile/hs92/raw-sugar-cane#exporters-importers.

OECD, Food, and Agriculture Organization of the United Nations (2021). *OECD-FAO Agricultural Outlook 2021-2030*, p. 337. DOI: https://doi.org/https://doi.org/10.1787/19428846-en. URL: https://www.oecd-ilibrary.org/content/publication/19428846-en.

Olofsson, Pontus, Giles M. Foody, Martin Herold, et al. (2014). "Good practices for estimating area and assessing accuracy of land change". In: *Remote Sensing of Environment* 148. ISSN: 00344257. DOI: 10.1016/j.rse.2014.02.015.

Olofsson, Pontus, Giles M. Foody, Stephen V. Stehman, et al. (2013). "Making better use of accuracy data in land change studies: Estimating accuracy and area and quantifying uncertainty using stratified estimation". In: *Remote Sensing of Environment* 129, pp. 122–131. DOI: 10.1016/j.rse.2012.10.031. URL: http://dx.doi.org/10.1016/j.rse.2012.10.031.

Pan, Yude et al. (Nov. 2013). "The Structure, Distribution, and Biomass of the World's Forests". In: *Annual Review of Ecology, Evolution, and Systematics* 44 (1), pp. 593–622. ISSN: 1543-592X. DOI: 10.1146/annurev-ecolsys-110512-135914.

Pax-Lenney, Mary et al. (2001). "Forest mapping with a generalized classifier and Landsat TM data". In: *Remote Sensing of Environment* 77.3, pp. 241–250. ISSN: 00344257. DOI: 10.1016/S0034-4257(01)00208-5.

Pazúr, Robert et al. (Oct. 2014). "Spatial determinants of abandonment of large-scale arable lands and managed grasslands in Slovakia during the periods of post-socialist transition and European Union accession". In: *Applied Geography* 54, pp. 118–128. ISSN: 01436228. DOI: 10.1016/j.apgeog.2014.07.014. URL: http://linkinghub.elsevier.com/retrieve/pii/S0143622814001702.

Piquet, Rosélia, Érica Tavares, and João Monteiro Pessôa (2017). "Emprego no setor petrolífero: dinâmica econômica e trabalho no Norte Fluminense". In: *Cadernos Metrópole* 19.38, pp. 201–224. DOI: 10.1590/2236-9996.2017-3808.

Plieninger, Tobias et al. (Nov. 2016). "The driving forces of landscape change in Europe : A systematic review of the evidence". In: *Land Use Policy* 57, pp. 204–214. ISSN: 02648377. DOI: 10.1016/j.landusepol.2016.04.040. URL: http://dx.doi.org/10.1016/j.landusepol.2016.04.040%20http://linkinghub.elsevier.com/retrieve/pii/S0264837715301769.

Poortinga, Ate et al. (Oct. 2021). "Mapping sugarcane in Thailand using transfer learning, a lightweight convolutional neural network, NICFI high resolution satellite imagery and Google Earth Engine". In: *ISPRS Open Journal of Photogrammetry and Remote Sensing* 1, p. 100003. ISSN: 26673932. DOI: 10.1016/j.ophoto.2021.100003.

Prishchepov, Alexander V et al. (2012). "Effects of institutional changes on land use: agricultural land abandonment during the transition from state-command to market-driven economies in post-Soviet Eastern Europe". In: *Environmental Research Letters* 7.2, p. 024021. ISSN: 1748-9326. DOI: 10.1088/1748-9326/7/2/024021.

Prishchepov, Alexander V. et al. (Jan. 2013). "Determinants of agricultural land abandonment in post-Soviet European Russia". In: *Land Use Policy* 30.1, pp. 873–884. ISSN: 02648377. DOI: 10.1016/j.landusepol.2012.06.011. URL: https://linkinghub.elsevier.com/retrieve/pii/S0264837712001160.

Pupim de Oliveira, J A (2002). "The policymaking process for creating competitive assets for the use of biomass energy: the Brazilian alcohol programme". In: *Renewable and Sustainable Energy Reviews* 6, pp. 129–140.

R Core Team (2021). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing. Vienna, Austria. URL: https://www.R-project.org/.

Rai, Raju et al. (2019). "Status of Farmland Abandonment and Its Determinants in the Transboundary Gandaki River Basin". In: *Sustainability* 11.19, p. 5267. DOI: 10.3390/su11195267.

Raj Khanal, Narendra and Teiji Watanabe (2006). "Abandonment of Agricultural Land and Its Consequences". In: *Mountain Research and Development* 26.1, pp. 32–40. ISSN: 0276-4741. DOI: 10.1659/0276-4741(2006)026[0032:aoalai]2.0.co;2.

Rajpar, Habibullah et al. (2019). "Agricultural Land Abandonment and Farmers' Perceptions of Land Use Change in the Indus Plains of Pakistan: A Case Study of Sindh Province". In: *Sustainability* 11.17, p. 4663. DOI: 10.3390/su11174663.

Ramankutty, Navin, Jonathan A. Foley, and Nicholas J. Olejniczak (2008). *Land-Use Change and Global Food Production.* DOI: 10.1007/978-1-4020-6778-5_3.

Renwick, Alan et al. (Jan. 2013). “Policy reform and agricultural land abandonment in the EU”. In: *Land Use Policy* 30.1, pp. 446–457. ISSN: 02648377. DOI: 10.1016/j.landusepol.2012.04.005. URL: https://linkinghub.elsevier.com/retrieve/pii/S026483771200066X.

Rico, Julieta A.Puerto, Sonia S.P. Mercedes, and Ildo L. Sauer (2010). “Genesis and consolidation of the Brazilian bioethanol: A review of policies and incentive mechanisms”. In: *Renewable and Sustainable Energy Reviews* 14.7, pp. 1874–1887. ISSN: 13640321. DOI: 10.1016/j.rser.2010.03.041. URL: http://dx.doi.org/10.1016/j.rser.2010.03.041.

Roy, D. P. et al. (2016). “Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity”. In: *Remote Sensing of Environment* Volume 185.Iss 1, pp. 57–70. ISSN: 00344257. DOI: 10.1016/j.rse.2015.12.024.

Rudel, Thomas K., Laura Schneider, and Maria Uriarte (2010). “Forest transitions: An introduction”. In: *Land Use Policy* 27.2, pp. 95–97. ISSN: 02648377. DOI: 10.1016/j.landusepol.2009.09.021.

Rudorff, Bernardo Friedrich Theodor, Daniel Alves de Aguiar, et al. (2010). “Studies on the rapid expansion of sugarcane for ethanol production in São Paulo state (Brazil) using Landsat data”. In: *Remote Sensing* 2.4, pp. 1057–1076. ISSN: 20724292. DOI: 10.3390/rs2041057.

Rudorff, Bernardo Friedrich Theodor, Miura Sugawara Berka Luciana, et al. (2005). “Imagens de Satelite no Mapeamento e estimativa da area de cana-de-acucar em Sao Paulo: ano-safra 2003/2004”. In: *Agricultura em São Paulo* 1, pp. 21–39.

Ruskule, Anda et al. (2013). “The perception of abandoned farmland by local people and experts: Landscape value and perspectives on future land use”. In: *Landscape and Urban Planning* 115, pp. 49–61. ISSN: 01692046. DOI: 10.1016/j.landurbplan.2013.03.012. URL: http://dx.doi.org/10.1016/j.landurbplan.2013.03.012.

Russell, Bill, Sushil Mohan, and Anindya Banerjee (2012). “Coffee market liberalisation and the implications for producers in Brazil, Guatemala and India”. In: *World Bank Economic Review* 26.3, pp. 514–538. ISSN: 02586770. DOI: 10.1093/wber/lhr055.

Sanne Diek, Fabio Fornallaz, and Michael E. Schaepman and Rogier de Jong (2017). “Barest Pixel Composite for Agricultural Areas Using Landsat Time Series”. In: *Remote Sensing* 9.12, p. 1245. DOI: 10.3390/rs9121245.

Santos Luciano, Ana Cláudia dos, Michelle Cristina Araújo Picoli, Jansle Vieira Rocha, Daniel Garbellini Duft, et al. (Aug. 2019). “A generalized space-time OBIA classification scheme to map sugarcane areas at regional scale, using Landsat images time-series and the random forest algorithm”. In: *International Journal of Applied Earth Observation and Geoinformation* 80, pp. 127–136. ISSN: 15698432. DOI: 10.1016/j.jag.2019.04.013.

Santos Luciano, Ana Cláudia dos, Michelle Cristina Araújo Picoli, Jansle Vieira Rocha, Henrique Coutinho Junqueira Franco, et al. (Sept. 2018). “Generalized space-time classifiers for monitoring sugarcane areas in Brazil”. In: *Remote Sensing of Environment* 215, pp. 438–451. ISSN: 00344257. DOI: 10.1016/j.rse.2018.06.017.

Schmidt, Michael et al. (2016). “A framework for large-area mapping of past and present cropping activity using seasonal landsat images and time series metrics”. In: *Remote Sensing* 8.4, p. 312. ISSN: 20724292. DOI: 10.3390/rs8040312. URL: http://www.mdpi.com/2072-4292/8/4/312.

Schneider, Max et al. (2015). “Spatial Variation of Drivers of Agricultural Abandonment with Spatially Boosted Models”. In: *Procedia Environmental Sciences* 27, pp. 53–57. ISSN: 18780296. DOI: 10.1016/j.proenv.2015.07.114. URL: http://dx.doi.org/10.1016/j.proenv.2015.07.114.

Seto, Karen and Navin Ramankutty (2016). "Hidden linkages between urbanization and food systems." In: *Science* 352.6288, pp. 943–945. ISSN: 00368075. URL: http://10.0.4.102/science.aaf7439%7B%5C%%7D5Cnhttp://search.ebscohost.com/login.aspx?direct=true%7B%5C&%7DAuthType=ip,url,cookie,uid%7B%5C&%7Ddb=eue%7B%5C&%7DAN=115542145%7B%5C&%7Dsite=ehost-live%7B%5C&%7Dscope=site.

Silva, Ramon F.B. da, Mateus Batistella, and Emilio F. Moran (2016). "Drivers of land change: Human-environment interactions and the Atlantic forest transition in the Paraíba Valley, Brazil". In: *Land Use Policy* 58, pp. 133–144. ISSN: 02648377. DOI: 10.1016/j.landusepol.2016.07.021. URL: http://dx.doi.org/10.1016/j.landusepol.2016.07.021.

Silva, Ramon Felipe Bicudo da, Mateus Batistella, and Emilio Federico Moran (2017). "Socioeconomic changes and environmental policies as dimensions of regional land transitions in the Atlantic Forest, Brazil". In: *Environmental Science and Policy* 74.April, pp. 14–22. ISSN: 18736416. DOI: 10.1016/j.envsci.2017.04.019. URL: http://dx.doi.org/10.1016/j.envsci.2017.04.019.

Silva, Wanderson Luiz and Claudine Pereira Dereczynski (2014). "Caracterização Climatológica e Tendências observadas em extremos climáticos no Estado do Rio de Janeiro". In: *Anuario do Instituto de Geociencias* 37.2, pp. 123–138. ISSN: 19823908. DOI: 10.11137/2014_2_123_138.

Silver, W. L., R. Ostertag, and A. E. Lugo (Dec. 2000). "The Potential for Carbon Sequestration Through Reforestation of Abandoned Tropical Agricultural and Pasture Lands". In: *Restoration Ecology* 8 (4), pp. 394–407. ISSN: 1061-2971. DOI: 10.1046/j.1526-100x.2000.80054.x.

Sklenicka, Petr (2016). "Classification of farmland ownership fragmentation as a cause of land degradation: A review on typology, consequences, and remedies". In: *Land Use Policy* 57, pp. 694–701. ISSN: 02648377. DOI: 10.1016/j.landusepol.2016.06.032.

Smiderle, Dilcéa de Araújo Vieira (2010). "Etanol sem futuro: a inusitada trajetória da cana em Campos dos Goytacazes (RJ)". In: *Agenda Social* 2.2, pp. 76–95. DOI: ISSN1981-9862.

Soffiati, Arthur (2018). *A planície do norte do Rio de Janeiro antes e durante a ocidentalização do mundo: três estudos de eco-história*. 1st ed. Autografia.

Southworth, Jane and Catherine Tucker (2001). "The Influence of Accessibility, Local Institutions, and Socioeconomic Factors on Forest Cover Change in the Mountains of Western Honduras". In: *Mountain Research and Development* 21.3, pp. 276–283. ISSN: 0276-4741. DOI: 10.1659/0276-4741(2001)021[0276:TIOALI]2.0.CO;2.

Souza, Carlos M. et al. (2020). "Reconstructing Three Decades of Land Use and Land Cover Changes in Brazilian Biomes with Landsat Archive and Earth Engine". In: *Remote Sensing* 12.17. ISSN: 2072-4292. URL: https://www.mdpi.com/2072-4292/12/17/2735.

Statistics, Pasw (2013). "Interrupted time series (ITS) analyses". In: *The Effective Practice and Organisation of Care (EPOC)*. ISSN: 0021-8898. DOI: 10.1107/S002188988608915X.

Stehman, Stephen V. (2014). "Estimating area and map accuracy for stratified random sampling when the strata are different from the map classes". In: *International Journal of Remote Sensing* 35.13, pp. 4923–4939. ISSN: 0143-1161. DOI: 10.1080/01431161.2014.930207.

Strijker, Dirk (Apr. 2005). "Marginal lands in Europe—causes of decline". In: *Basic and Applied Ecology* 6 (2), pp. 99–106. ISSN: 14391791. DOI: 10.1016/j.baae.2005.01.001.

Su, Guandong, Hidenori Okahashi, and Lin Chen (2018). "Spatial pattern of farmland abandonment in Japan: Identification and determinants". In: *Sustainability (Switzerland)* 10.10, pp. 4–6. ISSN: 20711050. DOI: 10.3390/su10103676.

Terres, Jean Michel et al. (2015). "Farmland abandonment in Europe: Identification of drivers and indicators, and development of a composite indicator of risk". In: *Land Use*

Policy 49, pp. 20–34. ISSN: 02648377. DOI: 10.1016/j.landusepol.2015.06.009. URL: http://dx.doi.org/10.1016/j.landusepol.2015.06.009.

Tilman, David, Christian Balzer, et al. (Dec. 2011). "Global food demand and the sustainable intensification of agriculture". In: *Proceedings of the National Academy of Sciences* 108 (50), pp. 20260–20264. ISSN: 0027-8424. DOI: 10.1073/pnas.1116437108.

Tilman, David and Michael Clark (2014). "Global diets link environmental sustainability and human health". In: *Nature* 515.7528, pp. 518–522. ISSN: 14764687. DOI: 10.1038/nature13959. URL: http://dx.doi.org/10.1038/nature13959.

Trebat, Thomas J and Nicholas M Trebat (2012). "The Regional Impact of Federal Government Programs in Brazil: The Case of Rio de Janeiro". In: *The Regional Impact of National Policies*. Ed. by Werner Baer. Edward Elgar Publishing. Chap. 13. URL: https://econpapers.repec.org/RePEc:elg:eechap:14562%7B%5C_%7D13.

Ustaoglu, Eda and Marcus J. Collier (2018). "Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications". In: *Environmental Reviews* 26.4, pp. 396–416. ISSN: 1181-8700. DOI: 10.1139/er-2018-0001.

Venables, W. N. and B. D. Ripley (2002). *Modern Applied Statistics with S*. Fourth. ISBN 0-387-95457-0. New York: Springer. URL: https://www.stats.ox.ac.uk/pub/MASS4/.

Verbesselt, Jan et al. (2010). "Phenological change detection while accounting for abrupt and gradual trends in satellite image time series". In: *Remote Sensing of Environment* 114.12, pp. 2970–2980. ISSN: 00344257. DOI: 10.1016/j.rse.2010.08.003.

Verburg, Peter H. and Koen P. Overmars (2009). "Combining top-down and bottom-up dynamics in land use modeling: Exploring the future of abandoned farmlands in Europe with the Dyna-CLUE model". In: *Landscape Ecology* 24.9, pp. 1167–1181. ISSN: 09212973. DOI: 10.1007/s10980-009-9355-7. arXiv: 9901227v1 [cond-mat].

Verburg, Peter H., Jeannette van de Steeg, et al. (2009). "From land cover change to land function dynamics: A major challenge to improve land characterization". In: *Journal of Environmental Management* 90.3, pp. 1327–1335. ISSN: 03014797. DOI: 10.1016/j.jenvman.2008.08.005. URL: http://dx.doi.org/10.1016/j.jenvman.2008.08.005.

Vermote, Eric et al. (2016). "Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product". In: *Remote Sensing of Environment* 185, pp. 46–56. ISSN: 00344257. DOI: 10.1016/j.rse.2016.04.008. URL: http://dx.doi.org/10.1016/j.rse.2016.04.008.

Vesterdal, Lars, Eva Ritter, and Per Gundersen (Sept. 2002). "Change in soil organic carbon following afforestation of former arable land". In: *Forest Ecology and Management* 169 (1-2), pp. 137–147. ISSN: 03781127. DOI: 10.1016/S0378-1127(02)00304-3.

Vidal-Macua, Juan José, Miquel Ninyerola, et al. (2018). "Environmental and socioeconomic factors of abandonment of rainfed and irrigated crops in northeast Spain". In: *Applied Geography* 90, pp. 155–174. ISSN: 01436228. DOI: 10.1016/j.apgeog.2017.12.005.

Vidal-Macua, Juan José, Alaitz Zabala, et al. (2018). "Environmental and socioeconomic factors of abandonment of rainfed and irrigated crops in northeast Spain". In: *Applied Geography* 90.December 2017, pp. 155–174. ISSN: 0143-6228. DOI: 10.1016/j.apgeog.2017.12.005.

Vieira, Edson Trajano and Moacir José dos Santos (2012). "Industrialização e desenvolvimento regional: política do codivap no vale do paraíba na década de 1970". In: *DRd – Desenvolvimento Regional em debate* 2.

Vinogradovs, Ivo et al. (2018). "Assessment of site-specific drivers of farmland abandonment in mosaic-type landscapes: A case study in Vidzeme, Latvia". In: *Agriculture, Ecosystems and Environment* 253.October 2017, pp. 113–121. ISSN: 01678809. DOI: 10.1016/j.agee.2017.10.016.

Vörösmarty, C. J. et al. (Sept. 2010). "Global threats to human water security and river biodiversity". In: *Nature* 467 (7315), pp. 555–561. ISSN: 0028-0836. DOI: 10.1038/nature09440.

Wang, Ming et al. (Nov. 2019). "Mapping sugarcane in complex landscapes by integrating multi-temporal Sentinel-2 images and machine learning algorithms". In: *Land Use Policy* 88. ISSN: 02648377. DOI: 10.1016/j.landusepol.2019.104190.

Woodcock, Curtis E. et al. (2001). "Monitoring large areas for forest change using Landsat: Generalization across space, time and Landsat sensors". In: *Remote Sensing of Environment* 78.1-2, pp. 194–203. ISSN: 00344257. DOI: 10.1016/S0034-4257(01)00259-0.

Xie, Hualin, Peng Wang, and Guanrong Yao (2014). "Exploring the dynamic mechanisms of farmland abandonment based on a spatially explicit economic model for environmental sustainability: A case study in Jiangxi Province, China". In: *Sustainability (Switzerland)* 6.3, pp. 1260–1282. ISSN: 20711050. DOI: 10.3390/su6031260.

Xu, Jinfan et al. (Sept. 2020). "DeepCropMapping: A multi-temporal deep learning approach with improved spatial generalizability for dynamic corn and soybean mapping". In: *Remote Sensing of Environment* 247. ISSN: 00344257. DOI: 10.1016/j.rse.2020.111946.

Yin, He, Amintas Brandão, et al. (2020). "Monitoring cropland abandonment with Landsat time series". In: *Remote Sensing of Environment* 246, p. 111873. ISSN: 00344257. DOI: 10.1016/j.rse.2020.111873.

Yin, He, Alexander V. Prishchepov, et al. (2018). "Mapping agricultural land abandonment from spatial and temporal segmentation of Landsat time series". In: *Remote Sensing of Environment* 210. ISSN: 00344257. DOI: 10.1016/j.rse.2018.02.050.

Young, Juliette et al. (2005). "Towards sustainable land use: identifying and managing the conflicts between human activities and biodiversity conservation in Europe". In: *Biodiversity and Conservation* 14.7, pp. 1641–1661. ISSN: 0960-3115. DOI: 10.1007/s10531-004-0536-z.

Yu, Zhonglei et al. (2017). "Exploring the Factors Driving Seasonal Farmland Abandonment: A Case Study at the Regional Level in Hunan Province, Central China". In: *Sustainability* 9.2, p. 187. ISSN: 2071-1050. DOI: 10.3390/su9020187. URL: http://www.mdpi.com/2071-1050/9/2/187.

Zakkak, Sylvia et al. (2015). "Assessing the effect of agricultural land abandonment on bird communities in southern-eastern Europe". In: *Journal of Environmental Management* 164, pp. 171–179. ISSN: 10958630. DOI: 10.1016/j.jenvman.2015.09.005. URL: http://dx.doi.org/10.1016/j.jenvman.2015.09.005.

Zanden, Emma H. van der et al. (Mar. 2017). "Trade-offs of European agricultural abandonment". In: *Land Use Policy* 62, pp. 290–301. ISSN: 02648377. DOI: 10.1016/j.landusepol.2017.01.003. URL: http://linkinghub.elsevier.com/retrieve/pii/S0264837716314417.

Zaragozí, B. et al. (2012). "Modelling farmland abandonment: A study combining GIS and data mining techniques". In: *Agriculture, Ecosystems and Environment* 155, pp. 124–132. ISSN: 01678809. DOI: 10.1016/j.agee.2012.03.019.

Zavalloni, Matteo et al. (2021). "Farmland abandonment, public goods and the CAP in a marginal area of Italy". In: *Land Use Policy* 107, p. 104365. ISSN: 02648377. DOI: 10.1016/j.landusepol.2019.104365. URL: https://linkinghub.elsevier.com/retrieve/pii/S0264837719305782.

Zhang, Ying, Xiubin Li, and Wei Song (2014). "Determinants of cropland abandonment at the parcel, household and village levels in mountain areas of China: A multi-level analysis". In: *Land Use Policy* 41, pp. 186–192. ISSN: 02648377. DOI: 10.1016/j.landusepol.2014.05.011.

Zheng, Qiming et al. (Sept. 2023). “The neglected role of abandoned cropland in supporting both food security and climate change mitigation”. In: *Nature Communications* 14 (1), p. 6083. ISSN: 2041-1723. DOI: 10.1038/s41467-023-41837-y.

Zhong, Liheng, Peng Gong, and Gregory S. Biging (2014). “Efficient corn and soybean mapping with temporal extendability: A multi-year experiment using Landsat imagery”. In: *Remote Sensing of Environment* 140, pp. 1–13. ISSN: 00344257. DOI: 10.1016/j.rse.2013.08.023.

Zhong, Liheng, Lina Hu, et al. (Nov. 2019). “Deep learning based winter wheat mapping using statistical data as ground references in Kansas and northern Texas, US”. In: *Remote Sensing of Environment* 233. ISSN: 00344257. DOI: 10.1016/j.rse.2019.111411.

Zhou, Ting, Eric Koomen, and Xinli Ke (Mar. 2020). “Determinants of Farmland Abandonment on the Urban–Rural Fringe”. In: *Environmental Management* 65 (3), pp. 369–384. ISSN: 0364-152X. DOI: 10.1007/s00267-020-01258-9.

Zhu, Zhe and Curtis E. Woodcock (2014). “Continuous change detection and classification of land cover using all available Landsat data”. In: *Remote Sensing of Environment* 144, pp. 152–171. ISSN: 00344257. DOI: 10.1016/j.rse.2014.01.011. URL: http://dx.doi.org/10.1016/j.rse.2014.01.011.

Zhu, Zhe, Michael A. Wulder, et al. (2019). “Benefits of the free and open Landsat data policy”. In: *Remote Sensing of Environment* 224.6, pp. 382–385. ISSN: 00344257. DOI: 10.1016/j.rse.2019.02.016.