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ESSAYS ON THE GREEN ECONOMY AND PRODUCTIVE COMPLEXITY IN BRAZIL

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Tese apresentada ao Programa de Pós-Graduação em Economia, da Faculdade de Economia, Administração, Contabilidade e Gestão de Políticas Públicas, da Universidade de Brasília como requisito parcial para obtenção do Título de Doutor em Economia.

Orientador: Prof. Dr. Andrei Domingues Cechin
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Brasília, dezembro de 2025.

Aos meus avós,

Elenir Brizola dos Santos e Valmiro Tomé dos Santos,

Hermínia Robinson e Edgar Robinson.

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ENSAIOS SOBRE A ECONOMIA VERDE E A COMPLEXIDADE PRODUTIVA NO BRASIL

Resumo

Esta tese é composta por três ensaios interdependentes e investiga como a transição verde interage com as estruturas produtivas brasileiras. O primeiro ensaio desenvolve um quadro conceitual que combina a teoria da causação cumulativa de Myrdal com a perspectiva da complexidade econômica. Argumenta-se que políticas e investimentos industriais e ambientais, quando implementados em estruturas produtivas desiguais, podem acionar dinâmicas de desenvolvimento regional que se reforçam mutuamente. O segundo ensaio apresenta evidências empíricas para a Amazônia brasileira, construindo o espaço-emprego verde para analisar como as capacidades produtivas locais e o desmatamento afetam a entrada e a permanência de ocupações verdes. Os resultados mostram que a relatedness density exerce efeito positivo sobre a especialização e a persistência dessas ocupações, embora esse efeito seja enfraquecido em áreas de maior desmatamento. O terceiro ensaio amplia a análise para o conjunto das unidades federativas brasileiras, ao construir o espaço-produto verde e calcular indicadores de complexidade econômica verde. Os resultados indicam que os estados das regiões Sul e Sudeste estão mais preparados para adaptar e expandir suas bases produtivas nessa direção, enquanto os demais dispõem de poucas possibilidades de inserção na economia verde. Caso as políticas industriais e ambientais não considerem as especificidades territoriais, o avanço em produtos de maior complexidade e conteúdo ambiental pode aprofundar as desigualdades regionais.

Palavras-chave: Economia verde. Complexidade econômica verde. Desenvolvimento regional. Empregos verdes. Amazônia brasileira.

ESSAYS ON THE GREEN ECONOMY AND PRODUCTIVE COMPLEXITY IN BRAZIL

Abstract

This thesis comprises three interdependent essays investigating how the green transition interacts with Brazil's productive structures. The first essay presents a conceptual framework combining Myrdal's theory of cumulative causation and the perspective of economic complexity. It argues that, when implemented within unequal productive structures, industrial and environmental policies can trigger mutually reinforcing regional development dynamics. The second essay provides empirical evidence from the Brazilian Amazon, examining how local productive capabilities and deforestation influence the emergence and longevity of green occupations. The results demonstrate that relatedness density positively impacts the specialisation and persistence of these occupations, albeit to a lesser extent in regions experiencing higher levels of deforestation. The third essay broadens the analysis to encompass all Brazilian states by constructing a green product space and calculating green economic complexity indicators. The results suggest that states in the southern and south-eastern regions are better prepared to adapt and expand their productive bases in this direction, whereas the remaining states have limited opportunities to participate in the green economy. Without accounting for territorial specificities in industrial and environmental policies, progress in products of higher complexity and environmental content could exacerbate regional inequalities.

Keywords: Green economy. Green economic complexity. Regional development. Green jobs. Brazilian Amazon

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Summary

1. Introduction

At the beginning of the 21st century, the concept of a green economy emerged as a solution to the limitations of economic growth. Green stimulus packages involving large-scale public resources were developed to help economies recover from systemic crises of capitalism. These policies aimed to reconcile inclusive, long-term economic growth with the planet's biophysical limits (Newton and Cantarello, 2014).

Building on this political desire to achieve a sustainable ideal, the literature on the green transition began to argue that the desired transformations unfold within a heterogeneous economic space (Coenen et al., 2012). While this aspect does not always occupy a central place in the debate, there is a risk that political decisions and green investments will affect territories with different productive capacities unevenly (Rodríguez-Pose and Bartalucci, 2024).

Brazil is a typical example of a country whose productive capacity and infrastructure vary widely from region to region. Indicators of economic complexity show that activities involving greater technological sophistication and added value are concentrated in a few states in the South and Southeast regions (Teixeira et al., 2022). From a green economic complexity perspective, regions with a broader and more diverse set of productive capabilities can combine them in multiple ways to adapt to environmental demands (Mealy and Teytelboym, 2022). This necessarily implies that the opportunities and risks of the green transition are not uniformly distributed (Rodríguez-Pose and Bartalucci, 2024), and they may reinforce existing inequalities in Brazil rather than correcting them.

Assuming this is true, how does the green transition reproduce or transform regional inequalities in Brazil?

To answer this question, this thesis consists of three interdependent essays and uses the economic complexity approach, according to which development is a cumulative and trajectory-dependent process (Hausmann et al., 2014; Hidalgo, 2021). This perspective provides empirical tools that can reveal how productive activities and occupations are interconnected, enabling us to identify the bottlenecks and opportunities of the green economy.

The conceptual framework is developed in the first essay through the combination of Myrdal's (1962) diffusion effects and the perspective of economic complexity (Hausmann et al., 2014). The central argument is that environmental and industrial policies can generate self-reinforcing processes of unequal development when interacting with heterogeneous productive structures. This process is referred to as green cumulative causation and arises from the interaction between environmental policies and regional productive capabilities. In practice, it unfolds through two opposing mechanisms. The green spread effect operates through the diffusion of green investments and knowledge within high-complexity regions via related diversification and across regions fostering new productive capabilities. The green backwash effect operates through the reinforcement of regional asymmetries as the same policies concentrate high-value activities and externalize environmental and resource costs to less developed regions. The overall impact of the green transition depends on the balance between these two forces. In Brazil, the green transition appears to be uneven as green backwash effects outweigh green spread effects. A small number of economically complex states located in the South and Southeast seem to benefit from the green transition. Other regions concentrate environmental costs and remain locked into dependent production patterns due to the lack of capabilities required to absorb the positive effects of the green transition. The subsequent essays are designed to empirically assess these regional disparities and to map the productive capabilities underlying the green transition.

The second essay uses the tools of economic complexity to conduct an empirical analysis of the Brazilian Amazon. It examines the biome's green employment opportunities and explores the impact of local productive capabilities and deforestation on the emergence and disappearance of green jobs using occupational data disaggregated at the municipal level. The results demonstrate that relatedness density positively impacts the specialization and persistence of these occupations, albeit to a lesser extent in areas experiencing intense deforestation. Thus, the essay highlights the combined impact of productive and environmental factors on the geography of the green economy in threatened biomes.

The third essay broadens the analysis to encompass all Brazilian states. It uses state-level export product data to construct the green product space and derive green economic complexity indicators to evaluate the capacity of states to diversify their production towards environmentally friendly goods. The results suggest that states in the South and Southeast regions are better placed to adapt and expand their productive bases in this direction, whereas others have limited opportunities to integrate into the green economy. Failure of industrial and environmental policies to account for territorial specificities could deepen regional inequalities by hindering progress towards more complex and environmentally oriented products.

Together, the three essays demonstrate that the green transition is influenced by the capabilities accumulated in each region. By conceptualizing, mapping and measuring these capabilities, this study contributes to the debate on green transition planning and demonstrates the productive potential of the Brazilian economy.

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Essay A. The promise of a green economy in a country marked by regional inequalities and primary dependence

Abstract: This paper presents a conceptual framework integrating Myrdal's theory of cumulative causation and the perspective of economic complexity. This framework aims to explain how the green transition can reinforce structural and regional inequalities. The paper introduces the concepts of green spread and green backwash to describe how industrial and environmental policies interact with different productive structures, creating unequal and self-perpetuating development trajectories. Regions with diversified capabilities are more likely to experience propulsive dynamics and positive spillovers, whereas economies specializing in primary sectors tend to internalize environmental burdens and remain trapped in low-value activities. Drawing on secondary evidence, the case of Brazil illustrates a pattern of green cumulative causation in which the South and Southeast reap the benefits of the transition, while the North, Northeast and Midwest bear its costs disproportionately. The analysis suggests that without place-sensitive green industrial policies aimed at building productive and technological capabilities, the green transition could reproduce historical disparities rather than promoting inclusive and sustainable development.

Keywords: Green Economy; Myrdal, Economic Complexity; Development; Brazil.

1. Introduction

In 2012, Brazil put forward a proposal for an inclusive green economy at the United Nations Conference on Sustainable Development (Rio+20), which was held in Rio de Janeiro. The idea was to address structural development issues alongside environmental concerns through coordinated action by governments, businesses and civil society organizations. Rather than treating the green economy as a new paradigm, the Brazilian delegation defined it as a tool for social development.

However, the recent trajectory of the Brazilian economy points in the opposite direction. The country has specialized in primary production and energy-intensive activities that have a high environmental impact. This production pattern conflicts with changes in the behavior of consumers, companies and governments. These actors have been incorporating sustainability criteria into their purchasing policies (Young, 2013). Compounding this issue, the development of clean and resource-efficient technologies requires specific skills and innovations in product and production design (D'Amato and Korhonen, 2021). Hence, the concentration of skilled labor capable of adapting to structural changes provides highly complex industrial centers competitive advantages over the primary economy (Mealy and Teytelboym, 2022).

If the structural changes associated with the green economy only focus on sectors and regions that are better prepared, achieving the desired inclusive development will be difficult. After all, the economic, social and environmental benefits of the green transition tend to be distributed unequally. This study aims to understand the mechanisms by which the green economy can reproduce historical inequalities in Brazil.

To address this question, we integrate Myrdal's (1962) notion of cumulative causation with the perspective of economic complexity (Hidalgo and Hausmann, 2009). This conceptual synthesis helps explain why the green transition can trigger self-reinforcing processes whose effects tend to be uneven due to the interaction between politics and productive capacity.

The paper proceeds as follows. Section 2 examines green economy discourses and the tensions that characterize them. Section 3 explores how structural inequalities can be reinforced by the green transition through cumulative dynamics and asymmetries in productive complexity. Section 4 examines the productive patterns and disputes in the Brazilian green economy. Section 5 illustrates the framework using evidence from Brazilian regions. Section 6 concludes by outlining the policy and future research implications.

2. Green economy discourse and strategies

2.1 Source and establishment

Pearce et al. (1989) first introduced the idea of a green economy when they suggested integrating the costs of environmental degradation and the economic value of the environment into economic and public policy decisions. However, it was only at the beginning of the 21st century that the concept entered political discourse. The deepening of environmental and social issues, alongside the economic crises of that time, created the opportunity to incorporate environmental issues into political discourse and public budgets (Loiseau et al., 2016). The idea was to combine green stimulus packages involving large-scale public resources with market instruments, to resume and maintain economic growth within the planet's biophysical limits (Newton and Cantarello, 2014).

At the United Nations Conference on Sustainable Development (Rio+20), the green economy was a central theme due to the controversy between economic growth and the environment (Daly, 2013). Conservatives criticized the focus on environmental issues, while progressives argued that the green economy does not represent a macroeconomic paradigm shift, but rather an extension of the existing economic model. Meanwhile, fearing green protectionism and the sovereign right to meet their social and economic needs, countries on the capitalist periphery demanded that the fight against poverty be placed at the center of the debate (Faccer et al., 2014). Hence, the green economy would be understood in a way that integrates physical (ecological), social (inclusive), and economic (long-term) sustainability (D'Amato et al., 2017).

2.2 The incremental, reformist, and transformative discourses

Since the Rio+20 conference, the concept of a green economy has been incorporated into strategic planning and economic and environmental policies around the world. However, due to the breadth of the concept, several overlapping and divergent interpretations have emerged (Loiseau et al., 2016). To deal with this diversity, Faccer et al. (2014) separated the green economy into three discourses based on the premise that the GE can and should be used to achieve the sustainable ideal. These discourses were formulated from possible sources of contradiction, confusion and disputes surrounding the meaning and application of the green economy. The incremental, reformist and transformative discourses are therefore characterized by the degree of transformation required in the current economic paradigm to promote economic and environmental sustainability.

The incremental discourse is characterized by the maintenance of the macroeconomic paradigm and the use of market instruments to mitigate the environmental impacts of economic growth. The idea is to promote efficiency gains and stimulate the development of clean technologies. Incentives for innovation and the development of green products are needed to generate economic opportunities and employment. However, this approach to sustainability is weak because it assumes that capital loss will be offset by manufactured capital and adequate infrastructure. Therefore, green and sustainable economic growth would be achieved through an increase in output and income minus the environmental costs generated during the year (Faccer et al., 2014).

The reformist discourse broadens the scope of incrementalism by proposing a more diverse and ambitious agenda for the green economy. Ecological limits are recognized, as is the need to develop appropriate indicators to account for ecosystem services and natural capital in national accounts. The combination of long-term planning, investments in natural capital, adequate infrastructure and green activities will generate social and environmental benefits. The idea is to adapt and restructure the economy by generating and capturing new value and innovation in markets, industries and national accounts. While economic growth remains essential, this discourse embraces a stronger concept of sustainability, acknowledging that certain types of natural capital are irreplaceable and that decoupling is relative. In other words, environmental efficiency per unit of Gross Domestic Product (GDP) may increase, but there are no guarantees that environmental impact will be eliminated (Faccer et al., 2014).

In contrast, the transformative discourse advocates a radical paradigm shift. The financialization of nature and the use of market instruments to measure environmental value would make traditional resources and communities more vulnerable to commercial exploitation. Furthermore, there is no guarantee that the results produced by the market will be ecologically sustainable. Technological improvements alone are not enough. They can generate rebound effects that negate environmental gains. This discourse is based on a critique of the capitalist system's capacity to create social inequality and environmental degradation. Instead, it proposes an economy that respects absolute ecological limits, human rights and economic sufficiency. To achieve this, it advocates the concept of steady state and/or degrowth for developed countries. It proposes a redefinition of progress, replacing GDP with broader measures of well-being. In short, the transformative discourse seeks to reinvent society's model, guided by socio-environmental justice, ecological limits, and the promotion of alternative lifestyles and production methods (Faccer et al.. 2014).

Fundamentally, these discourses align with Christoff's spectrum of ecological modernization de Christoff (1996, p. 490), "the concept of ecological modernization can encompass both instrumental and institutional change, and that different forms of ecological modernization can be located on a continuum from weak to strong versions, according to their likely efficacy in promoting enduring ecologically sustainable transformations and outcomes". Depending on the effectiveness with which the green economy promotes sustainable and permanent transformations, Faccer et al. (2014) classification ranges from a weak form of ecological modernization to a strong one. The political dispute between environmental movements, governments, and productive sectors centers on which version should prevail. However, it is important to understand the specific context to avoid the erroneous conclusion that the greening of the economy can occur anywhere through similar processes.

2.3 The limits of the dominant discourse

According to Faccer et al. (2014, p. 648), the majority of global green economy strategies can be categorized as reformist. Backed by organizations such as the UNEP, OECD and World Bank, this approach asserts that green investments can boost economic growth, environmental protection and social inclusion simultaneously. However, by prioritizing growth and relying on the market's ability to assign value to natural capital, the structural constraints that countries on the periphery of capitalism face are overlooked.

In the Global South, the assumptions of reformist discourse are challenged by political, technological and institutional conditions. Dependence on extractive industries and technological concentration in central countries makes peripheral economies susceptible to strategies that promote the modernization of natural resource management. These strategies are often guided by narratives that link environmental degradation to poverty, low local productivity and inefficient traditional land use practices. Distributional and environmental issues are viewed as the result of internal failures of the capitalist periphery, justifying external interventions to introduce capital and technology and control the use of land and resources. Thus, the structural factors that sustain dependence also restrict the capacity for local policymaking (Buseth, 2021).

Although it recognizes ecological limits and the importance of natural capital, the dominant discourse assumes that transformations can be achieved by adapting the current economic structure (Faccer et al., 2014). For Cechin and Veiga (2024), such discourses avoid addressing the “Gordian knot” of sustainability, the composition and structure of economic activity, that is, what grows, what needs to decrease, and how the production-consumption system is configured. The centrality attributed to growth reveals an inability to break with the inertia of production and consumption systems. Maintaining or merely adapting the current trajectory tends to reinforce the inertia of unsustainable consumption patterns and the mechanisms of accumulation that reproduce inequalities.

Essentially, the limitations of the dominant discourse extend beyond its environmental effectiveness to encompass its inability to address the structural inequalities that determine the feasibility of a green transition. By promoting growth and the use of specific instruments to capture value from nature, it is reasonable to assume that decision-making power will shift towards transnational financial actors. This shift in power may legitimize historical processes of territorial dispossession, while ignoring the distributional conflicts and power imbalances generated by the current growth model (Yang and He, 2021).

3. Green transition and regional inequalities

Although discourse on the green economy proposes adjustments to the logic of growth to make it compatible with the ideal of sustainability, it often overlooks that the green transition requires skills and structural adaptations that not all regions can provide (Rodríguez-Pose and Bartalucci, 2024). It is therefore necessary to identify the cumulative dynamics and structural barriers that shape territorial development in the context of a green economy.

3.1 Cumulative causation theory and regional traps

According to Myrdal, three social transformations shaped the economic discourse of the post-World War II era: the decolonization movement that led to the formation of numerous independent states, the aspiration of elites in developing countries to foster development, and the Cold War, which rendered the success or failure of competing nations a strategic consideration in the foreign policy of developed countries. It is in this context that Myrdal proposes the existence of mutually reinforcing mechanisms that would lead regions down different paths of economic development (Ferreira and Salles, 2020).

By proposing dynamic interdependence between economic and non-economic variables, Myrdal (1962) rejects the market equilibrium assumption present in traditional economic theory. Economic variables are typically monetary or quantitative factors related to production, such as income, capital and employment. Non-economic variables include social, cultural, political and institutional elements such as power structures, social norms, bureaucracy, infrastructure and social cohesion. Unlike the Walrasian proposition, the interaction between these variables does not converge to a state of equilibrium. In reality, it can accentuate existing imbalances through feedback mechanisms, creating cycles that reinforce and exacerbate regional inequalities (Cruz et al., 2011).

Basically, this dynamic occurs through the backwash and spread effects. The backwash effect describes how the growth of central regions can harm peripheral regions by attracting capital, skilled labor and consumer markets. The spread effect, on the other hand, refers to the potential benefits that spread from more developed regions to less developed ones, such as technological advances, trade and investment (Cruz et al., 2011). However, Myrdal (1962) argues that, in the absence of active public policies, backwash effects tend to predominate over spreads, thereby exacerbating regional inequalities.

Based on these assumptions, the theory of cumulative circular causation offers a historical and procedural perspective on development, proposing that gains and losses accumulate over time in a non-linear and asymmetric manner (Fujita, 2007). Initially favored regions consolidate their advantages, while disadvantaged regions face vicious cycles of stagnation (Myrdal, 1962). The coexistence of national economic growth with intensifying territorial inequalities is explained by this theory, as well as why development traps can be perpetuated by misguided policy guidelines (Furtado, 2009).

3.2 Economic complexity as a metric of (green) capability asymmetry

One way to measure development and the regional capacity to develop specific skills or products is offered by the theory of economic complexity. The idea behind economic complexity theory is that the transformation of materials is dependent on the capabilities present within a region. These capabilities encompass a wide range of non-tradable and intangible inputs, including tacit knowledge, skilled workers, infrastructure, institutions, regulations, and stakeholder decision-making processes. Each product manifests a specific combination of these capabilities. Consequently, regions differ in terms of what they produce and their production capabilities. Regions with a broader and more diverse set of capabilities can combine them in multiple ways to produce and offer a greater variety of more sophisticated products (Hidalgo, 2021; Hidalgo et al., 2018).

A recent application of this approach involves adapting complexity indicators to measure green economic complexity (Mealy and Teytelboym, 2022). This metric captures the extent to which existing capabilities facilitate the diversification of environmental products. In other words, it involves assessing the potential and level of green sophistication of regional and national production trajectories (Pérez-Hernández et al., 2021).

In both the economic complexity (Hidalgo and Hausmann, 2009) and the green economic complexity (Mealy and Teytelboym, 2022) approaches, productive diversification does not occur randomly. It is influenced by the existing structure. The likelihood that a region will develop a particular (green) product depends on how closely related it is to the products that make up its production portfolio. The structural dependence proposed by the theory of economic complexity helps explain why the green transition unfolds unevenly across territories. Regions endowed with a broader and more diversified set of capabilities can adapt their productive base to emerging green sectors, while others remain trapped in less dynamic economic structures (Mealy and Teytelboym, 2022).

3.2.1 Integrating Myrdal’s theory and (green) economic complexity

In the theories of cumulative causation and economic complexity, development is a nonlinear, interdependent and path-dependent process. Both reject the equilibrium assumption of traditional economic theory. Indeed, emphasis is placed on how feedback mechanisms and historical trajectories produce patterns of development that reinforce each other through regional capabilities (Fujita, 2007; Hidalgo and Hausmann, 2009). However, they differ in their approach. Myrdal offers a qualitative and institutional formulation (Fujita, 2007). Economic complexity provides tools based on complex networks to represent and quantify these patterns (Hausmann et al., 2014).

From the perspective of complexity theory, economic systems are adaptive networks composed of agents and capabilities whose interactions generate emergent properties (Morçöl and Wachhaus, 2009). Each node in the network represents the materialization of productive capabilities. Each link between nodes indicates complementarities and interdependencies between these capabilities. Development occurs when new links are formed through the combination and recombination of capabilities. The loss of nodes or connections reduces the potential for diversification and innovation, resulting in lock-in and stagnation (Andres et al., 2023; Hausmann and Klinger, 2007)

In Myrdal's (1962) approach, these processes emerge through economic and social forces that reinforce each other via spread and backwash effects. By analogy, spread effects correspond to the diffusion of capabilities within the network. In other words, the processes through which innovation, learning and institutional improvements expand the set of possible links and combinations between nodes. The backwash effects reflect the depletion of capabilities or the loss of links between nodes in the network. When flows of capital, labor, and knowledge move from one region to another, the structure of the regional network becomes sparser. The capacity to generate new productive combinations through related diversification is reduced. In practice, the economic complexity quantifies the structural development process described by Myrdal. Cumulative cycles can be interpreted as adaptive topologies of link creation and loss within complex productive networks. Economic complexity indicators derived from the network synthesizes this process.

Although Gala et al. (2018) interpret economic complexity as an empirical update of classical structuralist theses, reading Myrdal alongside the tools of economic complexity provides an analytical framework for explaining why the green transition can trigger a process of “green cumulative causation”, the effects of which tend to be uneven due to the interaction between politics and productive capacity.

3.3 How the green transition can widen territorial inequalities

Conceptually, the green cumulative causation refers to the process by which industrial and environmental policies, when implemented within heterogeneous productive structures, trigger self-reinforcing development dynamics that reproduce or amplify pre-existing structural bottlenecks. These dynamics do not arise directly from the policies themselves, but from their interaction with the underlying networks of productive and technological capabilities that characterize regional economies (Coenen et al., 2012; Rodríguez-Pose and Bartalucci, 2024).

Like Myrdal’s (1962) framework, the driving forces behind this proposition can be broken down into “green spread” and “green backwash” effects. . For example, the need to reduce pollutant emissions in centers of high economic complexity to align them with the demands of the energy transition could lead to the creation of renewable energy investment hubs in regions that have a natural comparative advantage in this area. These hubs tend to stimulate demand for specialized professionals in construction and maintenance, as well as for adequate logistics and infrastructure for energy generation and distribution to be developed. Likewise, bioeconomy initiatives may arise from collaboration between universities, firms, and rural producers on low-carbon technologies and the utilization of biomass resources. This would contribute to the development of new local production capacities. Following Myrdal's (1962) reasoning, the green spread effect can be understood as the positive spillovers that one region generates for another.

The green backwash effect describes how industrial and environmental policies can widen structural disparities and increase the environmental vulnerability of less developed regions (Myrdal, 1962). This process reinforces patterns of dependence and specialization in low value-added activities, which are often associated with supplying raw materials, natural resources, and agricultural products to more complex production chains. Also, these regions bear a disproportionate share of the environmental costs associated with the expansion of green activities, such as pressure on local ecosystems and competition for land and water resources.

In the end, the impact of the green transition on regional development stems from the interplay between driving and countervailing forces. When green backwash effects prevail over green spread effects, industrial and environmental policies tend to reinforce the concentration of productive activities and environmental burdens. When green spread effects dominate, the transition can promote regional convergence by diffusing technologies, investments, and institutional capacities across less developed areas (Coenen et al., 2012; Fujita, 2007; Rodríguez-Pose and Bartalucci, 2024).

Some propositions can be derived from these conceptual arguments:

- **P1.** Regions with high economic complexity tend to generate propulsive effects during the green transition, expanding opportunities for related diversification.
- **P2.** In regions characterized by low economic complexity and primary-sector specialization, the green transition tends to produce regressive effects when the productive structure lacks the adaptive capacities required to meet new technological and environmental demands.
- **P3.** The extent to which green transition policies shape regional inequality depends on the strength and interaction of propulsive (green spread) and regressive (green backwash) effects.

These propositions can be illustrated by a hypothetical example in which two regions are subject to the same green financing policy. Region A, characterized by high economic complexity and productive diversity, has universities with active innovation networks, modern infrastructure, and a skilled workforce. Owing to its combination of capabilities, Region A is able to attract companies and develop green products related to its existing productive base. New investments expand the local market, increase tax revenues, and stimulate the development of new capabilities, creating a cumulative cycle of growth. Region B is historically characterized by limited productive diversification and possesses natural comparative advantage. New green ventures originating in Region A could stimulate the development of energy parks in Region B, generating short-term increases in income and demand for skilled labor. In the long term, however, this momentum tends to lose strength, as the jobs created are temporary and the highest value-added activities remain concentrated in Region A. If incentives to develop local capacities are insufficient, and the environmental costs of projects are high, the benefits of the policy tend to accrue primarily to Region A. In this scenario, the green economy in Region A is driven by local capabilities, which enhancing (green) economic complexity, while Region B remains trapped in a dependent and environmentally vulnerable production pattern (Cruz et al., 2011; Hidalgo and Hausmann, 2009; Rodríguez-Pose and Bartalucci, 2024)

The example shows that the green economy demands skills and structural adaptations that not all regions are prepared to offer (Rodríguez-Pose and Bartalucci, 2024). The absorption of financing varies within the same territory and depends on local capacities (Coenen et al., 2012). Regions with higher economic complexity can attract new investments and skilled labor, reinforcing cumulative cycles of growth (green spread effects). Regions with lower economic complexity generate resources and inputs for more dynamic centers, without achieving significant gains in productivity or technology. This deepens their dependence and stagnation (green backwash effects) (Coenen et al., 2012; Cruz et al, 2011).

Although the public sector can aggravate these imbalances through misguided policies, circular causation processes must be identified and redirected through targeted interventions (Myrdal, 1962). As Loiseau et al. (2016) point out, the green economy encompasses multiple approaches and tools, each with different levels of structural transformation and institutional requirements. Consequently, public policies aimed at a green transition can be designed according to the productive and institutional capacities of each territory.

Regions with highly complex productive bases can adopt strategies of incremental innovation based on related diversification (Hidalgo et al., 2018). However, for less economically complex regions, diversifying into related (green) activities carries the risk of becoming trapped in low-value-added sectors with limited economic dynamism (Pinheiro, 2024). To avoid this, public policies must be coordinated and geared towards developing new productive, technological and institutional capacities (Andreoni and Chang, 2019). The implementation of a green economy is dependent on the existence of adequate institutions and strategies to sustain different degrees of structural transformation (Loiseau et al., 2016). After all, if backwash effects outweigh spread effects, existing regional imbalances are likely to be amplified through cumulative circular causation (Myrdal, 1962).

4. Brazil: trajectory, productive structure, and disputes in the green economy

4.1 From National Developmentalism to economic liberalization

The decline in revenues from the primary-export model in the 1930s drove Brazil to adopt a strategy of development through import substitution (Furtado, 2007). The objective was to industrialize the nation and emancipate it from economic reliance on developed countries. The state promoted this model by providing the basic infrastructure and financing conditions necessary for industrialization to take place. In many cases, the Brazilian state took on the risk of ventures requiring substantial resources and became an industrial producer itself. (Giambiagi, 2016).

The literature called this model National Developmentalism. During this period, the Brazilian state acted as the planner, financier and producer of essential resources. It provided the necessary infrastructure in strategic areas such as communications, transport, and energy. It also adopted general industrial policies and tariff protection for the entire industrial sector (Bresser-Pereira, 2016). Even with these measures, National Developmentalism was marked by imbalances in the trade balance in sectors importing capital goods, technological backwardness and low competitiveness in the international market (Baer and Kerstenetzky, 1964).

The main reasons for the decline of this model were the failure of the import substitution strategy and the external debt crisis (Giambiagi, 2016). Excessive protectionism failed to promote the expected integration into the international market and limited economic growth. The external debt crisis and high inflation rates that affected the economy for decades also generated uncertainty about production and exacerbated the financial situation of the public sector, limiting its financing capacity (Lyne, 2015).

The abandonment of national developmentalism occurred alongside the rise of neoliberal policies between 1980 and 1990 (Bielschowsky, 2012). This period was characterized by increased financial speculation, economic stagnation, high inflation, fiscal crises in the public sector and the financialization of national wealth (Lavinas, 2016). The impact on society was reflected in high unemployment and social exclusion rates, which were among the highest in the world (Giambiagi, 2016).

4.2 The current production pattern and vulnerability of the green economy

In recent decades, Brazil has experienced a shift in the composition of its GDP and exports. While the economy has become more service-oriented and specialized in raw materials, the lack of industrial linkages has resulted in early deindustrialization and low productive complexity (Gabriel et al., 2025). This process has been accompanied by a trend of rising material intensity of the economy (economic metabolism) without efficiency gains (Andrade et al., 2018; Andrade and Sobel, 2024) and has consolidated a polarized production pattern (Pochmann and Silva, 2020). A significant proportion of high-value-added, knowledge-intensive production is undertaken in the South and Southeast regions. Other regions have specialized in primary production and supplying labor and inputs to the most developed centers (Sanguinet et al., 2023).

This configuration creates regional imbalances that lead to economic inequality and environmental degradation. Primary production does not require complex or specialized labor. Consequently, economic gains tend to be concentrated among a small group of producers, while the costs disproportionately affect the most vulnerable members of society. A typical example of this is the expansion of the agricultural frontier in the Amazon. The benefits are concentrated at the top of the agribusiness chain, while the costs manifest as social imbalances. For example, health problems are caused by air pollution resulting from the burning of forests to clear land. In addition, the displacement of traditional communities and the degradation of ecosystem services have a more severe impact on poor populations who depend on natural resources for subsistence. Export-oriented industrial and mining centers also present problems of this nature. Without adequate investment in infrastructure and sanitation, the expansion of production has resulted in human agglomeration in urban peripheries, where the poorest face adverse economic and health conditions (Young, 2013).

Research shows that cities such as São Paulo exemplify this duality by combining sectors of high economic complexity with high levels of urban inequality (Hartmann et al., 2017). However, most regions in the states of North, Northeast and Midwest remain tied to activities with low productive sophistication (Teixeira et al., 2022). These regions face limited opportunities for diversification, which reinforces the centre–periphery pattern of the national economy (Sanguinet et al., 2023).

Although these problems are well known and solutions are being debated , it is thought that the structural change of the green economy may exacerbate them (Rodríguez-Pose and Bartalucci, 2024). In del Rio-Chanona et al. (2025), a dynamic labor market simulation model was employed to develop scenarios for the agricultural and green manufacturing sectors in Brazil. The authors' objective was to analyze how the effect of productivity changes in different sectors and regions, with different environmental impacts, can affect and be limited by the Brazilian labor market. The results suggest that productivity increases in agriculture tend to exacerbate regional and occupational inequalities. These losses are concentrated in low-paying occupations and rural and Amazonian regions, where workers have less occupational and geographical mobility. Conversely, productivity gains in green manufacturing have less unequal impacts and greater potential for inclusion.

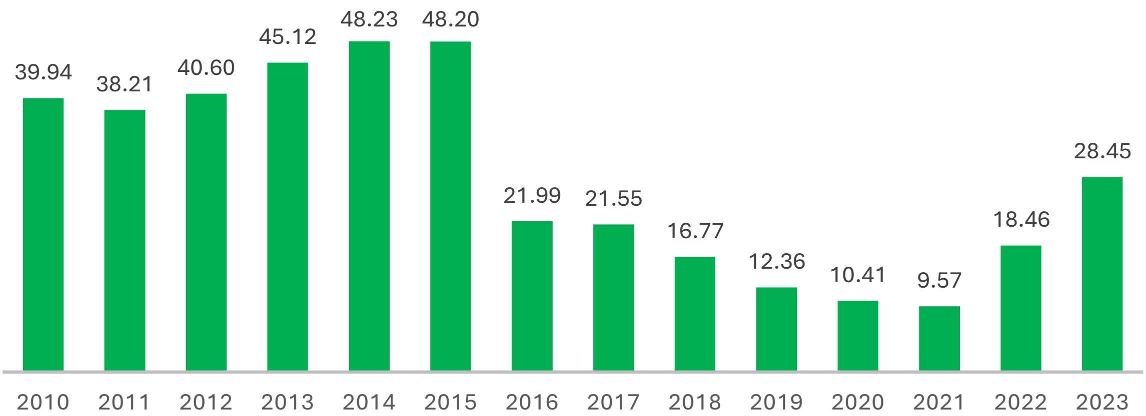
The study also reveals a geographical mismatch. Regions with higher unemployment rates do not necessarily have more job openings, particularly for highly skilled occupations. In other words, job vacancies remain unfilled due to a lack of skilled workers or workers willing to relocate. Simultaneously, there are unemployed individuals unable to fill these positions due to skill or mobility barriers (Rio-Chanona et al., 2025). This misalignment can slow down the green transition in some Brazilian regions due to structural bottlenecks.

4.3 Financing mechanisms and incentives for a green economy in Brazil

One way to correct structural bottlenecks and guide sustainable development is through public financing mechanisms, which are a key part of the process (D'Amato et al, 2017). In Brazil, for example, the National Bank for Economic and Social Development (BNDES) has incorporated environmental criteria into its credit analyses since the 1970s. More recently, to allocate resources to the green economy, the institution adopted the Sustainable Taxonomy, aligning its indicators with the Green Taxonomy of the Brazilian Federation of Banks. Based on this classification, BNDES disbursements are distributed across nine categories: Renewable energy and energy efficiency; hydroelectric plants above 30 MW; public passenger transport; freight transport; water and sewage management; solid waste management; forestry; agricultural improvements; climate change adaptation and disaster risk management.

Between 2010 and 2015, disbursements for the green economy grew steadily, with a consistent increase in funding for environmentally sustainable projects and initiatives. On average, R$ 43.38[1] billion was distributed among the nine categories. However, from 2016 onwards, the figures fell year after year until 2021. During this period, the average was R$ 15.44 billion, R$ 27.94 billion less than in the previous period. This difference is the result of the change in economic policy that followed the impeachment of President Dilma Rousseff, during which time the institution was unable to sustain the volume of resources allocated to the green economy (Bartelega and Mendonça, 2024). The results for 2022 and 2023 show a resumption of disbursements.

Fig. 1 – The annual disbursements made by the BNDES for the green economy*

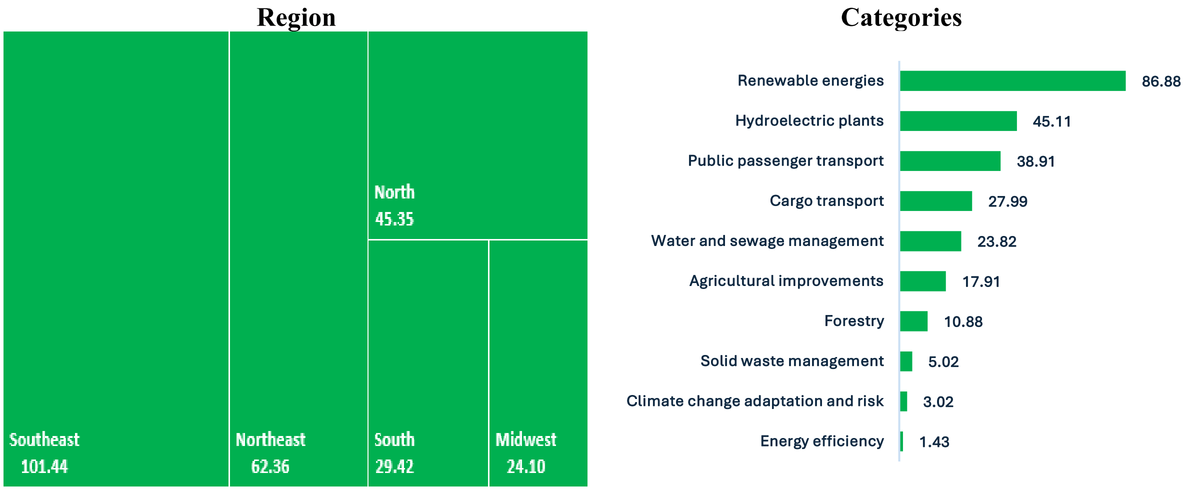


*Billions of reais adjusted by the IPCA to 2023 prices.
Source: BNDES

[1] Prices as of December 2023.

Although disbursements are sensitive to political orientation, the categories that received the largest number of resources allocated to the green economy between 2010 and 2023 were activities focused on energy generation and infrastructure, such as renewable energy, hydroelectric power, transport, and water and sewage management. The regions that received the largest volume of resources were the southeast and northeast. The former is Brazil's industrial center and the target of green infrastructure development policies (Sanguinet et al., 2023). The latter has the largest number of wind farms due to its geographical advantages (Sobrinho Junior et al., 2022).

Fig. 2 – Disbursements by region and category between 2010 and 2023*



*Billions of reais adjusted by the IPCA to 2023 prices.
Source: BNDES

However, the regional allocation of wind power investments has not always translated into local welfare. The study by Galvão et al. (2020) examines the installation of 114 wind farms in the Mato Grande territory of Rio Grande do Norte. Despite technological progress and the increase in clean energy generation, they found that economic and social benefits have not been distributed locally. The income generated has had little impact on local economic activity. The jobs created have been temporary and low-skilled, and rural communities surrounding the wind farms continue to experience high levels of poverty and social vulnerability. The authors also highlight environmental impacts and the reduction of agricultural areas without effective compensation.

Similar patterns are observed in hydroelectric projects. For example, Catolico et al. (2021) present evidence that the construction of the Estreito hydroelectric plant in the states of Maranhão and Tocantins generated temporary economic growth and employment but failed to produce lasting improvements in local living conditions. Most of the benefits were concentrated in the municipality that already had better infrastructure. Likewise, Mayer et al. (2022) demonstrate that the Jirau and Santo Antônio dams on the Madeira River in Rondônia caused widespread displacement and loss of income, with affected populations receiving insufficient compensation.

Although these studies show that large energy projects in Brazil are not inclusive, the BNDES's financing and disbursement mechanisms for the green economy indirectly foster the development of occupations and skills associated with the green transition.

4.3.1 Green Jobs

The Occupational Information Network (O*Net) defines the green economy as comprising economic activities that are related to reducing the use of fossil fuels, decreasing pollution and greenhouse gas emissions, improving energy efficiency, recycling materials and developing renewable energy sources. Dordmond et al. (2021) used this proposition to analyze the creation of green jobs in Brazil. In other words, they examined occupations that contribute directly or indirectly to the development of these activities, as well as the influence of economic complexity on this process across Brazilian states.

The results show that states with greater economic complexity and located in the southern and south-eastern regions have the highest green job rates. Despite these regional differences, the authors identified signs of convergence. Those states, with the lowest rates in the initial period of the sample, showed relatively greater progress than the more developed ones. Nevertheless, the greening of the economy remains dependent on the productive base and the level of regional development.

This empirical pattern aligns with findings from other studies, which suggest that entities with high economic complexity, both at the subnational (Pérez-Hernández et al., 2021) and national level (Mealy and Teytelboym, 2022) tend to be better prepared for the green transition. Therefore, economic complexity is a key factor in developing these skills.

4.5 Bioeconomy

In recent years, the idea of a bioeconomy has grown in popularity as an alternative to structural limitations and a potential solution to sustainability challenges. However, the term is often characterized by conceptual confusion and ambiguity in its definitions and interpretations. (Giampietro, 2019). Vivien et al. (2019) identify three main narratives that coexist within the broader discourse, each associated with a distinct vision of economic development, technological trajectories, and the relationship between the economy and nature. The first is rooted in Georgescu-Roegen's entropic view of the economic process, which emphasizes ecological limits and sustainability. The second centers on the industrial promises of the biotechnology revolution, portraying innovation as the key driver of growth. The third focuses on the bio-based carbon economy, which promotes the use of biomass as a pathway toward green economic expansion.

According to Giampietro (2019), the two main narratives reflect a deeper theoretical tension between contrasting paradigms. One narrative is a techno-economic interpretation that envisages bioeconomy as a strategy for achieving sustained growth through innovation and replacing fossil fuels. The other is a thermodynamic (entropic) perspective which highlights the biophysical limits to growth and advocates redefining the relationship between the economy and nature. The broad range of interpretations increases the risk that the term bioeconomy will be used to legitimize environmentally unsustainable or extractive initiatives, often framed under the rhetoric of "green" or "sustainable" innovation. Without a clear definition, powerful economic and political actors can strategically appropriate the term, channeling resources and investments towards conventional production models that preserve existing structures of power and accumulation (Ollinaho and Kröger, 2023).

According to Lima (2022), incentives for the bioeconomy in Brazil have focused on well-established agribusiness sectors, particularly the sugarcane and soybean industries. In his analysis of Brazil's national programs for ethanol and biodiesel, the author shows that, although official discourse associates the bioeconomy with social inclusion and sustainability, in practice it has reinforced oligopolistic structures and historical inequalities. The case of ethanol illustrates how the expansion of the sugarcane sector has consolidated oligopolistic structures and intensified land concentration, displacing small producers and traditional communities. The National Program for the Production and Use of Biodiesel, which was created to include family farmers through the Social Fuel Seal, was progressively taken over by large economic groups, who came to dominate soy and animal fat-based production.

For Ollinaho e Kröger (2023), this capture can be explained by the governance structure of the bioeconomy itself. It's characterized by the absence of mechanisms for effective social participation, accountability for socio-environmental impacts and redress of historical injustices. Consequently, the current model in Brazil is rooted in the logic of conservative ecological modernization, with agribusiness occupying a central position. For development policy purposes, the authors argue that it is necessary to distinguish between the plantation economy and the socio-biodiversity economy. The plantation economy is characterized by the large-scale expansion of monocultures oriented towards global markets, while the socio-biodiversity economy is grounded in diversified agroecological systems, local autonomy, and cultural valorization. This distinction can help to address Brazil's regional heterogeneity and the interconnected development trajectories that operate through multi-species logics, which only make sense in environments where diversity exists.

Despite these criticisms, the literature suggests that Brazil has significant potential to develop a forest-based bioeconomy (Maximo et al., 2022). However, to avoid being limited to the role of a mere biomass supplier in international trade (Nifatova et al., 2024), institutional coordination and investment in research and development are needed to reduce dependence on traditional monocultures, stimulate more diversified production and add value to production.

5. Interpreting Brazil through green spread and backwash effects

From the perspective of Myrdal (1962) and the literature on the green transition (Coenen et al., 2012; Rodríguez-Pose and Bartalucci, 2024), the interaction between industrial and environmental policies and unequal productive structures can trigger feedback mechanisms that reinforce divergent regional development trajectories. The green spread effect refers to the mechanisms through which industrial and environmental policies stimulate diversification and the development of productive capacities in different regions. The green backwash effect describes how these same policies can exacerbate structural disparities and environmental vulnerabilities.

Evidence on green economic complexity (Mealy and Teytelboym, 2022) suggests that states in the South and Southeast are better prepared to develop green products and activities due to their greater complexity. These regions also concentrate on the largest share of green jobs (Dordmond et al., 2021) and host resilient infrastructure projects financed by the BNDES (Bartelega and Mendonça, 2024). Due to the diversification required to meet the demands of the green economy, it is reasonable to assume that these regions are experiencing a self-reinforcing development process. The greater the economic complexity, the greater the capacity to absorb new technologies, attract investment and diversify activities. This process also produces interregional spillover effects. A typical example is the increased demand for clean energy, which encourages the development of power generation projects in regions with natural advantages. Financing flows from BNDES for alternative energy and wind and hydroelectric projects in the North and Northeast illustrate this proposition. However, although all regions benefit from consuming alternative energy sources, the impact on local ecosystems and communities is considerable and rarely translates into lasting economic or social gains (Catolico et al., 2021; Galvão et al., 2020; Mayer et al., 2022). In practice, low productive complexity limits the ability to add value and establish local linkages. When this does not occur, less developed regions end up internalizing production costs while environmental and economic gains are concentrated in highly complex centers in the South and Southeast (green backwash effect).

Similarly, bioeconomy initiatives are often appropriated by large-scale agricultural enterprises (Lima, 2022), or risk being reduced to mere suppliers of biomass for transformation and value-adding processes (Nifatova et al., 2024). Consequently, despite its transformative and inclusive potential, the bioeconomy becomes a vector of regressive specialization, reinforcing the cumulative cycle of dependence and concentration.

In summary, the balance between green spread and green backwash effects determines the extent to which the green transition is inclusive or exclusive. When propulsive effects prevail, industrial and environmental policies can generate positive spillovers, encourage productive diversification and reduce regional inequalities. However, when backwash effects predominate, the transition tends to reproduce historical patterns of dependence and concentration (Fujita, 2007; Myrdal, 1962). This appears to be the situation in Brazil, where structural constraints on development limit the regional spread of benefits associated with the green economy.

6. Final thoughts

Although the green economy is often presented as a means of reconciling inclusive economic growth with environmental sustainability, this study suggests that it may, depending on the circumstances, perpetuate or exacerbate bottlenecks in economic development.

Drawing on contributions from the literature on the green transition, economic complexity and the Myrdal's approach, it is argued that a process of green cumulative causation can be triggered by the interaction between industrial and environmental policies and heterogeneous productive structures.

The mechanisms through which this process unfolds are the green spread effect, which is related to the diffusion of capabilities, investments and innovation between regions. And the green backwash effect, which describes how industrial and environmental policies can widen structural disparities and increase the environmental vulnerability of less developed regions.

The balance between these two effects determines whether the green transition acts as a vector for convergence or for the deepening of regional inequalities. Following this, the impact of the green transition on regional development stems from the cumulative interaction between these two forces.

Based on secondary evidence, it is argued that Brazil's green transition has occurred asymmetrically. Regions with high economic complexity show signs of propulsive effects, as their diversified productive capacities reinforce the internal dynamics of cumulative growth. Through demand for clean energy and green infrastructure, these regions generate spillovers that stimulate complementary activities in regions with natural advantages. In such settings, the productive complexity itself strengthens the interaction between industrial and environmental policies and existing structures, intensifying the green spread effect (green spread effect). Conversely, regions that are less developed and have low economic complexity, and which have not developed the capabilities required by the green economy, are more susceptible to green backwash effects. In Brazil, it seems that the benefits of the green transition are concentrated in a few highly complex states in the South and Southeast, while the costs disproportionately affect states specializing in primary production and energy production in the North, Northeast and Midwest.

To avoid repeating this pattern, public policies must be inclusive and geared towards disseminating clean technologies, promoting productive diversification and developing regional capabilities. Combining credit for small and medium-sized enterprises, green innovation funds, research and development grants, and technical training programs with fiscal, financial, and regulatory mechanisms can help to align green economy objectives with the structural bottlenecks of Brazilian regional development.

Unfortunately, this study did not produce the empirical evidence required to test these hypotheses. However, future research may overcome this limitation. Economic complexity tools can help to map production possibilities and identify structural bottlenecks to green development. Through empirical inference, it may be possible to determine whether Brazilian states with high (or low) economic complexity are the most (or least) prepared to produce green products. Lock-in indicators derived from the productive network can be useful for testing the regressive effects of regional specialization and their impact on environmental damage. Finally, mapping green productive capacities in environmentally threatened regions and biomes provides an empirical basis for public policies aimed at mitigating the adverse effects of the green transition.

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Essay B. Looking at a threatened biome through a magnifying glass: an analysis of green occupation space and relatedness density in the Brazilian Amazon.

Abstract: The accelerating pace of environmental degradation in the Brazilian Amazon underscores the urgent need to align economic development with ecological conservation. This study maps the green occupation space of the Amazon biome and analyzes the role of relatedness density in the entry and exit of green jobs across municipalities. Using detailed occupational data from the Ministry of Labor and Employment, we construct a network of occupations and measure the proximity between green jobs and the local productive structure. The results show that green jobs are distributed across the occupational space, with more specialized roles concentrated in peripheral areas with low connectivity. We find that relatedness density significantly influences the emergence and persistence of green jobs, although this effect is weakened in regions with more intense deforestation. Additionally, deforestation is negatively associated with the exit of green jobs, which may indicate that certain occupations tend to persist even in degraded contexts. Municipalities whose production is based on forestry, fishing, and aquaculture also show a higher likelihood of specializing in green jobs. These findings suggest that the local capacities to support green economy activities already exist but require targeted regional policies that promote skill adaptation and knowledge transfer, particularly in areas most vulnerable to environmental degradation.

Keywords: Green Jobs. Green Space Jobs. Relatedness Density. Amazon. Brazil.

1. Introduction

The accelerating pace of environmental degradation in the Brazilian Amazon biome underscores a pressing need for green activities to balance economic development with ecological preservation (Silveira et al., 2025). This paper explores the "green occupation space" and examines the role of related activities in the emergence and decline of green jobs in the region, contributing to the green economy and economic complexity literature.

The concept of a green occupation space integrates ecological sustainability into the analysis of labor markets by identifying and assessing employment opportunities with lower environmental impacts, or even those that improve the environmental quality of a region (Dierdorff et al., 2009; Shutters et al., 2016). In recent years, the literature has shown that adaptive capacity is determined by the proximity of industries (Neffke et al., 2011), skills

(Muneepeerakul et al., 2013) and technologies (Kogler et al., 2013) related present at different spatial scales (Hidalgo, 2021). The principle of relatedness (Hidalgo et al., 2018) suggests that these capacities offer opportunities for adaptation to promote economic development.

In the context of the Brazilian Amazon, this framework offers insights into how green jobs can be harnessed to mitigate the negative impacts of economic activities on these sensitive ecosystems.

In this study, we used the employment information provided by the Brazilian Ministry of Labor and Employment to construct the green occupation space of the Brazilian Amazon. This dataset is disaggregated at the municipal level and allows us to make a minimally accurate cut of the biome to analyze the proximity relationships between occupations and the dynamics of green job entry and exit. We investigate how the productive specialization of municipalities influences the entry and exit of green jobs, and whether increased deforestation undermines the capacity of Amazonian municipalities to attract or retain these occupations. By mapping, quantifying and identifying possible barriers or drivers of green opportunities, we provide a nuanced understanding of how these occupations can contribute to both economic and ecological resilience. This perspective not only enhances our knowledge of green job dynamics in emerging economies but also informs policy strategies aimed at fostering sustainable development in critical biomes. Therefore, our analysis offers new insights into how green jobs intersect with the economic structure of biomes and are affected by economic activities.

The theoretical background used in this study is presented in the next section. The third section presents empirical strategy. The fourth section analyzes the results, and the fifth section concludes the paper.

2. Theoretical background

2.1 The relatedness density and the space of product, technology and occupation

Relatedness density measures the degree of connection between the activities present in a region. Two activities are considered related if they share similar technical production requirements (Hidalgo et al., 2018). However, because these capabilities are not directly observable, relatedness is inferred through the proximity between activities, estimated by the probability that they co-occur in locations with revealed comparative advantage. This approach reveals, for instance, that agricultural activities such as farming and agricultural engineering are more closely related than farming and aerospace engineering. This connection highlights that the supply of products reflects the capacities available in a region, and similarity between products corresponds to the capacities required and developed to produce them. Consequently, if a region specializes in producing a particular product (e.g., corn), it is more likely to expand production into similar products (e.g., soybeans) than into unrelated industries, such as aircraft manufacturing (Fraccascia et al., 2018; Hidalgo et al., 2018).

Hidalgo et al. (2007) proposed the "product space" to analyze these relationships through networks of connections. Growth opportunities are associated with the proximity between new products and those with Revealed Comparative Advantage (RCA). In most cases, less developed countries tend to have products with RCA located in the peripheral regions of the product space — areas where connections between products are limited. In contrast, products from developed countries are situated in the central regions, characterized by the predominance of sophisticated products and a higher density of connections. According to Hausman et al. (2014), a country's export basket reflexes the set of capabilities available in the country, shaping its economic development opportunities. Countries capable of exporting sophisticated products exhibit greater potential for economic growth because they can reorganize and recombine production to offer a wider array of sophisticated products. This capacity enables advanced countries to diversify their production baskets more quickly than others.

Hidalgo et al. (2007) analyzed countries' production structures using export data. Following this approach, various studies have explored the development paths of countries (Hausmann et al., 2014; Hidalgo, 2021), comparative analyses of these paths (Britto et al., 2019; Jankowska et al., 2012), and investigations into green products (Fraccascia et al., 2018; Hamwey et al., 2013). Additional research has focused on green products in the context of the green economy (Mealy and Teytelboym, 2022; Pérez-Hernández et al., 2021) and the brown economy (Andres et al., 2023).

This methodology was latter transposed to other applications. The “technology space” was constructed using patent data to analyze the nature of technological progress (Kogler et al., 2013). The “industry space” (Essletzbichler, 2015; Neffke et al., 2011) and the “occupation space” (Jara-Figueroa et al., 2018; Muneepeerakul et al., 2013) were developed using workforce data to analyze the proximity between industries and occupations, thus characterizing workers' skills in production structures. Here, human capital emerges as a critical driver of occupational diversity and industry development. Shutters et al. (2016) demonstrate that the “green occupation space” can be used to analyze the proximity relationship between green jobs and the skill structure of workers to develop the green economy.

Although these studies provide an overall picture of production structures in terms of exports, activities, skills and innovation, it was the study by Frenken et al. (2007) that empirically demonstrated how related industries offer more opportunities for learning and, consequently, foster local knowledge spillovers. Their analysis of the Dutch economy showed that regions with higher levels of related variety experienced the greatest employment growth. Building on this perspective, Neffke et al. (2011) demonstrated the potential to analyze economic diversity as a function of the proximity between production structures and economic sectors. They introduced a method to examine how relatedness influences industrial dynamics by applying econometric models with dummy variables to track industry entry, exit, and survival over a five-year period across 70 Swedish regions between 1969 and 1994. Using Ordinary Least Squares (OLS), probit, and logit models, their findings confirmed that the likelihood of firm entry, survival, and exit depends on the degree of relatedness to existing industries. Since then, this approach has been widely adopted in regional studies to explore the relationship between relatedness density and the diversification of economic activities.

For the United States, Essletzbichler (2015) derived the proximity between activities from the monetary flows in the input-output matrix. The findings indicate that proximity between sectors increases the probability of entry and decreases the probability of exit in 360 metropolitan areas. Using municipal patent data, Rigby (2015) and Boschma et al. (2015) found that the relatedness with existing technologies enhances the probability of diversification. Boschma et al. (2014) biotech cities, showing that new scientific themes in biotechnology emerge in regions with correlated scientific fields.

For Brazil, Françoso et al. (2024) examined this relationship at the mesoregional level between 2006 and 2019. Their results align with existing literature but highlight that in less complex regions, higher levels of economic complexity reduce the probability of entry. Similarly. Queiroz et al. (2024) classified Brazilian microregions into categories of low, medium-low, medium-high, and high economic complexity. Their models, analyzing entry and exit dynamics, confirmed the relatedness density hypothesis across all complexity levels between 2009 and 2019.

All studies for Brazil utilized sectoral data from the Annual Social Information Report (RAIS) of the Brazilian Ministry of Labor and Employment. Galetti et al. (2021) adapted this database to align it with information from O*Net. Their study aimed to assess whether workers' related skills influence the entry and exit of industries in Brazilian microregions. While their results corroborate the literature, they vary across regions: entry is more likely in larger regions and depends on average income, while related skills play a preventative role in industry exits in smaller regions. In Galetti et al. (2024), the effects of three types of relatedness were analyzed: local synergy, complementarity, and similarity relatedness densities. These were derived from the residuals obtained by regressing one type of relatedness against the others. The findings suggest that local synergy and complementarity relatedness are more significant in preventing the decline of specializations than in promoting the emergence of new specialized activities in Brazilian microregions.

While these studies validate the principle of relatedness density across different spatial scales of economic activity, they do not directly address production structures in environmentally sensitive biomes. Building on these approaches, this study stands out by constructing the green occupation space for the Brazilian Amazon biome and analyzing the dynamics of entry and exit of green activities in municipalities within this region. This joint analysis enables the identification of mechanisms that can support or limit the development of green jobs in Brazil's one of the most threatened biomes.

2.2 Defining green jobs

In this study, we assume that green jobs are crucial not only to reduce environmental damage, but also to create opportunities for economic development in terms of production, distribution and consumption (D'Amato and Korhonen, 2021). For this reason, they need to be mapped to identify promising activities and mechanisms that facilitate the flow of productive knowledge carried out in the Brazilian Amazon. The main problem in achieving this is the classification of green jobs.

Generalizations are often made about industrial activities or occupations that, in some way, contribute to environmental and conservation goals. Consoli et al. (2016) highlight that four main approaches are commonly used to classify green jobs. The first approach, based on green industrial processes, faces challenges due to the specificity of the information involved, such as occupations related to waste management and recycling, which are often confined to internal company practices, making broader classification difficult. The second approach links jobs to environmental goods and services but may result in false negatives by overlooking green activities not directly tied to specific products, such as internal energy conservation initiatives. The third approach focuses on industries with a high level of engagement in environmental goals, but it suffers from insufficient detail in industrial classifications, which can lead to false positives by failing to distinguish adequately between green and non-green products.

According to Consoli et al. (2016), these three types of classification are inaccurate because they create an isomorphism between productive activities, industrial organization, and the nature of occupations. The solution lies in the proposal from the of the Green Economy Program of the Occupation Information Network (O*Net), where "the "greening" of occupations refers to the extent to which green economy activities and technologies increase the demand for existing occupations, shape the work and worker requirements needed for occupational performance, or generate unique work and worker requirements (Dierdorff et al., 2009, p. 4)".

Based on this definition, O*Net classifies existing occupations into three groups to account for environmental changes. The first group, Green Increased Demand, includes occupations whose environmental demand is increased by the context of the green economy, such as welders, electricians, and chemists, whose activities are not changed by the context of the green economy. The second group includes professionals whose technical requirements change significantly. This is the case for engineers and construction managers who must take environmental quality into account in their daily work. Due to the changes in the established routine, this group is referred to as Green Enhanced Skills. Finally, the third group includes occupations that emerge in response to the specific needs of the green economy. Environmental economists and climate change analysts are typical examples of occupations where the impact of the green economy creates demand for jobs with unique requirements. This group is referred to as Green New & Emerging (Dierdorff et al., 2009).

Shutters et al. (2016) used this definition to construct the green job space, and Dordmond et al. (2021) matched the 204 green jobs classified by O*Net with the 185 work occupations available from the Brazilian Ministry of Labor and Employment. We used this compatibility table to do conduct this study. As a result, the relationships obtained in the occupational space and the green occupational space capture the proximity between the skills of workers in the Amazon biome. The empirical strategy used in this study is described in the next section.

3. Empirical Strategy

The construction of the occupation space of the Amazon biome requires a measure of the distance between occupations i and j. This can be constructed using information from the location quotient – an indicator that captures the degree of specialization of activities in a given region:

$$LQ_{b,i} = \frac{L_{b,i}/\sum_i L_{b,i}}{\sum_b L_{b,i}/\sum_b \sum_i L_{b,i}} \tag{1}$$

the term $L_{b,i}$ defines the number of workers employed in activity i in municipalities located in biome b. The occupation i is specialized if $LQ_{b,i} \geq 1$. This measure is analogous to the Revealed Comparative Advantage (RCA) developed by Balassa (1965), the difference lies in the application. RCA uses information about exports, LQ uses information about occupation. In both cases, the indicator captures the specialization of a region's productive structure. By restricting the analysis to the Amazon biome, we follow the methodological approach employed by Shutters et al. (2016) and Muneepeerakul et al. (2013), who construct occupation spaces using subsets of U.S. metropolitan areas; Thus, the LQ serves as a proxy for the comparative advantage developed by local communities as a result of settlement conditions such as ecological characteristics, infrastructure, resource endowments, historical trajectories, and cost differentials (Costinot, 2009).

Through the calculation of the conditional probability it is possible to verify whether the presence of a specialized activity in a certain context is not just a coincidence (Hausmann et al., 2014). The conditional probability applied to the results obtained in Eq. 1 allows us to identify whether the presence of a specialized activity in the municipalities of the Amazon biome is determined by the presence of another occupation, also specialized. Formally, the interdependence between two occupations i and j is expressed in Eq. 2:

$$\phi_{ij} = \min\left(\mathbb{P}\left(LQ_i > 1 \middle| LQ_j > 1\right), \mathbb{P}\left(LQ_j > 1 \middle| LQ_i > 1\right)\right) \tag{2}$$

Here, we take the minimum to ensure that $\phi_{ij} = \phi_{ij}$ and compute the conditional probability $\mathbb{P}\left(LQ_i > 1 \middle| LQ_j > 1\right)$ of the Amazonian municipality being specialized in occupation i, given its specialization in occupation j. In this way, it is possible to obtain the structure of the occupation space in the form of connection networks, where each occupation is represented by a node and the distance between the nodes is determined by the interdependence of the occupations.

To graphically visualize the connection networks, we followed the procedures defined in Hidalgo et al. (2007). First, the maximum spanning tree (MST) was computed with the information obtained from Eq. 1. Then, using the Kruskal algorithm, the information was organized in descending order and included in the MST if it led to an isolated occupation. This method uses the minimum number of connections and the maximum number of possible sums. The Force-Direct layout algorithm was used to visualize the computed connections.

Finally, we calculate the density relatedness between the activities of sector j and the specialized activities in the municipalities of the Amazon biome b:

$$\delta_{b,j} = \sum_{i} \rho_i \phi_{ij} \Big/ \sum_{i} \phi_{ij} \tag{3}$$

the term ρ_i is a binary matrix that takes the value 1 if the activity is specialized in the municipality of biome b and 0 otherwise. In essence, Eq. 3 measures the proximity of a given activity to the existing production structure in the municipalities of the Amazon.

3.1 Empirical model

To test the association between increase in deforestation, specialized municipal production, relatedness density and changes in the green job portfolio of municipalities in the Amazon biome, we followed the procedures defined by Neffke et al. (2011). Accordingly, two dummy variables were created to represent the entry and exit of green jobs in each municipality's portfolio over a 5-year interval. The entry is defined as 1 if municipality i is not specialized in the green job in t $(LQ < 1)$, but becomes specialized in $t + 5$ $(LQ \geq 1)$. Similarly, the exit of green jobs is defined as 1 if municipality i is specialized in the green job in t $(LQ_{b,i} \geq 1)$, but ceases to be specialized in $t + 5$ $(LQ_{b,i} < 1)$. In all other cases, the dummies assume the value 0. Eq. 4 presents the basic model used to test the effect of the variables of interest on green job entry and exit.

$$Y_{i,m,b} = \alpha_1 RD_{b,j} + \alpha_2 D_{m,b} + \alpha_3 SP_{m,b} + \sum_{j} \beta_k X_{ik} + \sum_{j} \lambda_n Z_{in} + u_i \tag{4}$$

The dependent variable $Y_{i,m,b}$ represents the entry or exit of the green job i do in municipality m within Amazon biome b. The term $RD_{b,j}$ captures the relatedness density of green jobs. The variable $D_{m,b}$ symbolizes the increment of deforestation, while $SP_{m,b}$ is a dummy variable that takes the value 1 for the specialized sector in the municipality, and 0 otherwise. X_{ki}, with $k = 1,..,5$, contains the control variables available for all municipalities. The Z_{in}, with $n = 1, 2, 3$, represents the fixed effects for municipality, occupation and time. All independent variables are in $t-5$. The α_1, $\alpha_2, \alpha_3, \beta_k$ and λ_n denote the slope parameters associated with each explanatory variable, and the model's error term is represented by u_i.

3.2 Database

Tab. 1 summarizes the data used in the empirical model (Eq. 4).

Tab. 1 – Data used in the empirical model

Variable	Description	Source
Entry	Dummy variable that takes the value 1 if the municipality i is not specialized in green job j at t, but becomes specialized at t+5.	[A]**rais.gov.br**
Exit	Dummy variable which takes the value 1 if the municipality i is specialized in green job j at t, but ceases to be so at t+5.	
Relatedness Density (Density)	A measure of the number of green related activities. It is used to quantify the distance between the Green Jobs and the productive structure of a biome.	
Diversity	Diversity of exports measured by Shannon index	
Average Wage (Wage)	Average wage in the municipality	
Employment	Total number of workers in an occupation	
Gross domestic product of municipalities per capita (GDP per capita)	Gross domestic product measured in R$, at 2010 prices.	[B]IPEAdata **ipeadata.gov.br**
Population density (Demography)	The total number of inhabitants in the municipality is divided by the total area of the municipality.	[C]IBGE **sidra.ibge.gov.br**
Agriculture, including agricultural and post-harvest support (Agriculture)	Dummy variable that takes the value of 1 if the main gross value added in the municipality is in agriculture and 0 otherwise.	
Livestock farming, including (Livestock)	Dummy variable that takes the value of 1 if the main gross value added in the municipality is in Livestock and 0 otherwise.	
Forestry, fishing and aquaculture production (FFA)	Dummy variable that takes the value of 1 if the main gross value added in the municipality is in FFA and 0 otherwise.	
Manufacturing industries (Transformation)	Dummy variable that takes the value of 1 if the main gross value added in the municipality is in Transformation and 0 otherwise.	
Extractive industry (Extractive)	Dummy variable that takes the value of 1 if the main gross value added in the municipality is in Extractive and 0 otherwise.	

[A]Annual Social Information Report.
[B]Institute for Applied Economic Research (IPEA)
[C]Brazilian Institute of Geography and Statistics (IBGE).
Prepared by the authors.

To calculate Eq. 1 to Eq. 4 we used the Annual Social Information Report (RAIS), which provides occupational information disaggregated by worker, occupation, and industry for approximately 5,570 municipalities per year on the online platform of the Ministry of Labor and Employment (MTE). This level of disaggregation allows for a more accurate mapping of the Amazon biome than would be possible with micro-regional or meso-regional information.

Nevertheless, although the Brazilian Institute of Geography and Statistics (IBGE) registers 558 municipalities in the Amazon, it was possible to collect information from 554 municipalities for the year 2021 to construct the occupation space and the green occupation space. This difference exists because some small municipalities do not report occupational data. Also, no distinction was made between municipalities with enclaves or transitional biomes.
Finally, the 627 CBO occupations were matched to the list of 204 green jobs in O*Net, as conducted by Dordmond et al. (2021), where a total of 185 green jobs were matched. The list of occupations grouped into Green Enhanced Skills, Green Increased Demand, and Green New & Emerging is presented in Tab. 1 A, in the Appendix

4. Analysis of the results

4.1 Green occupation space

Fig. 1 and Fig. 1A shows the proximity of worker skills using the Force Atlas 2 layout. This algorithm emphasizes community structures by grouping densely connected nodes in the center and pushing less connected groups towards the periphery of the network. Each node represents an occupation, and the distance between nodes reflects the degree of interdependence between them. Node size corresponds to the number of connections, with larger nodes representing occupations with higher connectivity. In this way, 16 communities were identified in the Amazonian occupation space (Fig. 1A), and green jobs were highlighted according to the three categories defined in O*NET (Fig. 1).

The Green Increased Demand category includes occupations that indirectly support the green economy through increased demand for their functions. In the green occupation space, core occupations include agricultural supervisors, forestry engineers, and public administrators. At the periphery, key associated nodes include industrial production engineers, safety engineers, and oil and gas extraction and refinery operators. These occupations relate to two main skill clusters: the first centred on mineral extraction (e.g. supervisors, geologists, geophysicists, mechanics, electromechanics); the second linked to technological and process innovation (e.g. bioengineers, thermochemists, rigid coating roofers). Although the expansion of the green economy in the Amazon may increase employment in these roles, it is not expected to significantly change their task composition or skill requirements.

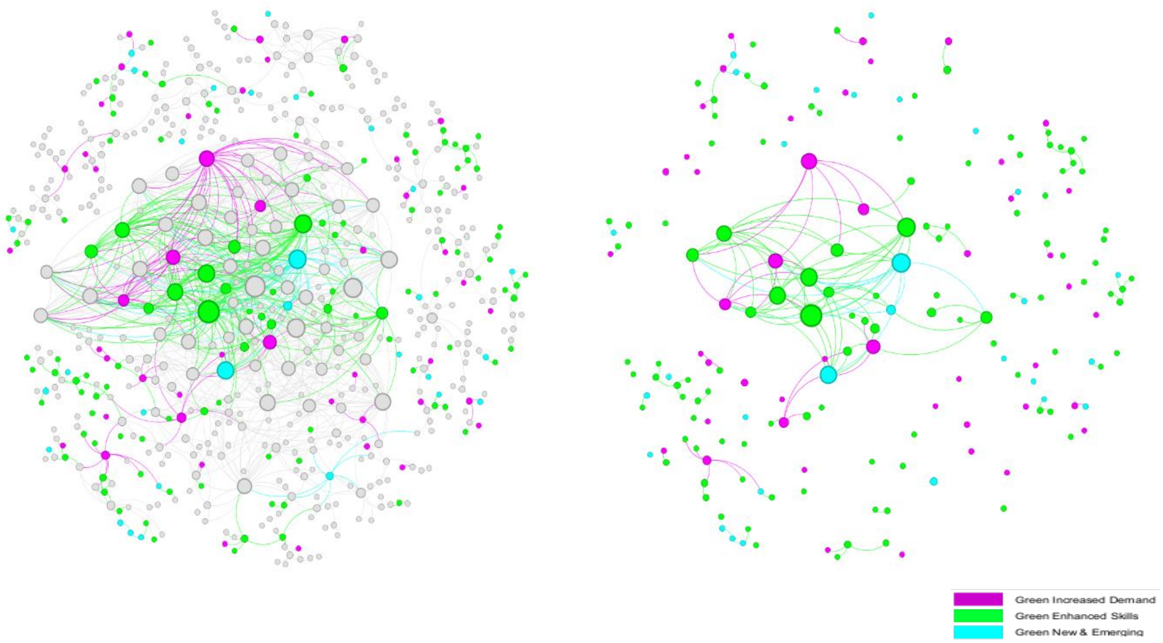
Green Enhanced Skills includes occupations where technical skill requirements are likely to change as the green economy develops. Agricultural technicians, production managers in the extractive and industrial sectors, marketing and financial professionals are at the core of the network. At the periphery, key nodes include technicians in topography, surveying and hydrography, who are connected to electrical workers, chemical technicians, and civil construction supervisors; mechatronic engineers, associated with research and development managers, metal-mechanical assembly supervisors, and development support technicians; and workers in the foundry of pure metals and metal alloys, linked to metallurgical furnace operators, production supervisors in steel industries, and filtering and separation operators. Given the anticipated technological transformations in these segments, targeted policy incentives could foster spillover effects, strengthening skill connectivity across the occupational space.

Finally, Green New & Emerging occupations represent the basic skills that are increasingly demanded by the green economy. Financial administrators, risk managers and vehicle maintenance electricians are key hubs in the core of the network. In the periphery of the network, the links of this group are specific. However, as the green economy expands, the demand for such specialized skills is expected to increase.

Fig. 1 – Amazon green occupation space

a. Green occupation space

b. Connections between green jobs



Prepared by the authors

In sum, the Amazon green occupation spaces have a structure with dense proximities between urban and agricultural occupations at the core, and more specific, less dense connections at the periphery. However, the methodology used to construct these spaces does not allow for a detailed sectoral analysis of the biome. Although sectoral occupational spaces could be constructed using industry data (Jara-Figueroa et al., 2018; Queiroz et al., 2023), the isomorphism of green jobs identified by Consoli et al. (2016) would limit any detailed analysis. In the next section, we present a regression model with disaggregated municipal-level data to analyze the entry and exit dynamics of green jobs in the Amazon biome.

4.2. Entry and exit analysis

Following the procedures established by Neffke et al. (2011), we examine the dynamics of the entry and exit of green jobs in municipalities within the Amazon biome. The results of the OLS, Probit and Logit models are presented in Tab. 4A and Tab. 5A in the Appendix. While the coefficients remain consistent across models, we analyze the results using the Logit models.

Tab. 2 presents the relationship between relatedness density and the entry and exit of green jobs based on logistic regression models. In Amazonian municipalities, relatedness density positively influences the probability of green job entry. Additionally, it reduces the probability of green job exits. These findings suggest that relatedness density enhances the capacity to attract and retain green jobs within the Amazon biome. The results align with the patterns observed across all relatedness measures developed in the literature (Boschma et al., 2015; Galetti et al., 2024; Jara-Figueroa et al., 2018; Neffke et al., 2011; Queiroz et al., 2024), indicating that the proximity between activities strengthens local capacities for developing and sustaining occupations within the green economy.

However, the interaction with increased deforestation shows that the ability of municipalities to acquire green specialization, as well as the protection exerted by relatedness density against the loss of specialization, diminishes in municipalities where deforestation is more intense. This effect may occur because, in some regions of the Amazon, workers' skills are tied to economic development models that are less aligned with a sustainable ideal in terms of production, development, and remuneration (Bento et al., 2019). Nonetheless, despite the weakening of this effect, the principle of relatedness remains valid (Hidalgo et al., 2018), as the productive structures of the Amazon create opportunities to diversify production by fostering skills that not only generate economic benefits but also support the development and maintenance of more sustainable capabilities in response to the productive pressures in these regions, a fundamental requirement of the green economy (D'Amato and Korhonen, 2021).

At the same time, increased deforestation is negatively associated with the probability of a municipality losing green specialization. This might occur because some green jobs, once created, become resilient to deforestation. Public administrators, economists, environmental technicians, agricultural engineers, and similar professionals are often required to meet legal obligations, such as compensating for environmental impacts, overseeing environmental monitoring, regularization, or even the restoration of degraded areas.

Tab. 2 – Logistic regression of green job entry and exit in Amazon municipalities

Independent variable	Entry	Exit
Density $_{t-5}$	8.101*** (0.641)	-8.367*** (0.607)
Log Deforestation $_{t-5}$	0.024 (0.016)	-0. 097* (0.039)
Log Deforestation*Density $_{t-5}$	-0.169** (0.060)	0.243** (0.084)
Agriculture $_{t-5}$	0.042 (0.052)	-0.104 (0.162)
Livestock $_{t-5}$	0.202 (0.124)	-0.049 (0.049)
FFA $_{t-5}$	0.387*** (0.058)	0.480 (0.603)
Extractive $_{t-5}$	-0.117 (0.133)	-0.061 (0.128)
Transformation $_{t-5}$	-0.434 (0.241)	-0.464 (0.362)
Controls	✓	✓
Period F. E.	✓	✓
City F. E.	✓	✓
Occupation F. E.	✓	✓
Observations	181524	22164
Pseudo R^2	0.178	0.130

Robust standard errors clustered by region and occupation.
Initial periods (t-5) are 2011 and 2016. Final periods (t) 2016 and 2021.
Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Finally, in municipalities where production is predominantly derived from forestry, fishing, and aquaculture (FFA), there are positive effects on the entry of green jobs. This type of production aligns with the logic of the bioeconomy, which, by definition, depends on the conservation of ecosystems and biomass for productive purposes (D'Amato et al., 2017). As a result, specialized human capital, such as public agents and forest engineers, is needed to carry out specific tasks, including monitoring predatory fishing and implementing forest management practices.

5. Conclusion

This study contributes to the emerging literature at the intersection of environmental sustainability and economic complexity by mapping the green occupation space of the Brazilian Amazon and evaluating the mechanisms that support or hinder the diversification of these jobs.

The occupation space shows that green jobs are distributed across the network of connections. In the periphery, the most specialized green jobs stand out due to their limited connectivity. In the core, typically urban skills, such as public agents, salespeople, and financial risk managers, show the highest number of connections, together with agricultural activities. Although the connections in the network emphasize occupations associated with low value-added production, their proximity to other occupations is essential, as they form the backbone of economic relations in Amazonian municipalities. In the context of a green economy, these occupations can generate the necessary spill-over effects to promote green skills within local production structures.

Empirical evidence suggests that the entry and exit of green jobs in the Amazon are moderated by relatedness density. Although its effect is weakened in regions where deforestation is more intense, it remains the primary mechanism for the development of green jobs in the Amazon biome. In addition, deforestation is negatively associated with the exit of green jobs, which may indicate that certain occupations tend to persist even in degraded contexts, and municipalities where production is largely based on forestry, fishing and aquaculture are more likely to specialize in green jobs. These results highlight the need for specific development strategies that not only focus on biomass production but also strengthen the relatedness density in communities that are most vulnerable to environmental degradation. Although the mechanisms required to develop activities aligned with the principles of the green economy are present in municipalities of the Amazon biome, it is essential to implement regional policies that facilitate knowledge transfer and foster the adaptation of productive capacities, enabling the transformation of existing skills and the development of new ones in accordance with green economy principles.

These findings highlight the importance of regional development policies that not only enhance the technical qualifications and adaptability of the workforce but also align productive specialization with conservation goals. Strengthening relatedness density in the most environmentally vulnerable municipalities can support more resilient and inclusive economic development.

Future research could explore the interaction between relatedness density and environmental degradation. If polluting firms are regionally concentrated, it is reasonable to assume that pollution itself could strengthen relatedness density. Industry-specific analyses could offer deeper insights into how local economies generate economic output through more sustainable practices, while also shedding light on the dynamics of the brown economy. Unfortunately, this type of investigation lies beyond the scope of this article, which focuses on workers' skills.

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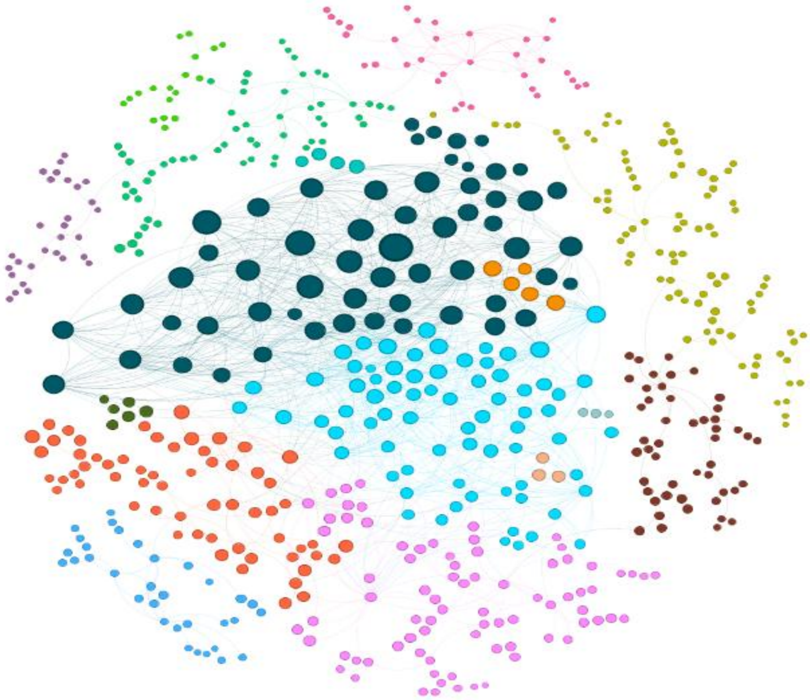
Annex

Fig. 1A – Amazon occupation space



Tab. 1A – List of 185 green jobs extracted from the CBO

Green New & Emerging	Green Increased Demand		Green Enhanced Skills		
1421	1112	8114	1210	3142	7233
2030	1114	8115	1221	3143	7241
2031	1115	8131	1222	3144	7244
2146	1130	8214	1223	3181	7311
2527	1142		1226	3182	7772
3012	1144		1227	3185	7822
3115	2011		1232	3186	7825
3121	2033		1233	3211	8101
3122	2034		1311	3421	8102
3131	2035		1312	3423	8111
3161	2132		1313	3424	8201
3183	2140		1411	3425	8202
3187	2145		1412	3426	8212
3541	2149		1413	3522	8221
4102	2211		1414	3951	8233
7232	2221		1415	6120	8281
7242	2222		1416	6121	8611
7245	2533		1417	6122	8612
7251	2624		1422	6123	8621
7252	3141		1423	6124	9141
7253	3180		1426	6125	9142
7254	3201		1427	6126	9501
7256	3212		2021	6127	9503
7301	3213		2032	6130	9511
8112	3253		2123	6131	9541
8113	5151		2124	6132	9912
8622	5152		2133	6133	9914
9531	5192		2134	6134	
	6110		2141	6301	
	6201		2142	7101	
	6320		2143	7102	
	7243		2144	7155	
	7255		2343	7156	
	7312		2513	7162	
	7411		2531	7201	
	7701		2532	7202	
	7711		2543	7214	
	7771		3111	7221	
	7811		3112	7222	
	7821		3114	7223	
	7824		3123	7224	
	7826		3133	7231	

Prepared by the authors

Tab. 2A – Amazon 30 highest average densities

CBO	Density
5151 - Workers involved in promoting and supporting health	0.246
2516 - Social assistants and domestic economists	0.242
2515 - Psicologists and Psicanalists	0.238
5174 - Doormen, watchmen and similar	0.238
2312 - Elementary school teachers (grades 1 to 4)	0.238
1112 - General managers of public administration	0.237
7823 - Drivers of small and medium-sized vehicles	0.236
5142 - Workers in waste collection services, cleaning and maintenance of public areas	0.234
3522 - Health and environment agents	0.234
6231 - Forest extractivists of species that produce fibers, waxes and oils	0.234
2544 - State and municipal tax inspectors	0.233
1231 - Financial and administrative directors	0.233
2232 - Dental surgeons	0.233
4121 - Data input and transmission equipment operators	0.232
2394 - Programmers, evaluators and teaching advisors	0.230
6210 - Agricultural workers in general	0.230
1313 - Directors and managers of educational service institutions	0.225
1411 - Production and operations managers in agricultural, fishing, aquaculture and forestry companies	0.224
2237 - Nutritionists	0.224
3211 - Agricultural technicians	0.224
6410 - Agriculture mechanization workers	0.223
6230 - Multiskilled animal handlers	0.222
6201 - Agricultural supervisors	0.222
2234 - Pharmacists	0.222
3222 - Nursing technicians and assistants	0.222
3224 - Dental technicians	0.221
7741 - Assemblers of furniture and wood products	0.221
6220 - Agricultural support workers	0.220
1417 - Service operations managers in a financial intermediation institution	0.220
1312 - Managers and operations specialists in companies, departments and health service units	0.219

Prepared by the authors.

Tab. 3A – Amazon's 10 highest average densities per green job group

Green Enhanced Skills		Green New & Emerging		Green Increased Demand	
Ocupation	**Density**	**Ocupation**	**Density**	**Ocupation**	**Density**
3522 - Health and environmental agents	0.234	1421 - Administrative, financial, risk and similar managers	0.208	5151 - Workers involved in promoting and supporting health	0.246
1313 - Directors and managers of educational service institutions	0.225	4102 - Supervisors of financial, exchange and control services	0.185	1112 - General managers of public administration	0.237
1411 - Production and operations managers in agricultural, fishing, aquaculture and forestry companies	0.224	8622 - Water collection, treatment and distribution plant operators	0.171	6201 - Agricultural and livestock supervisors	0.222
3211 - Agricultural technicians	0.224	9531 - Eletricistas eletronicos de manutencao veicular (aerea, terrestre e naval)	0.168	2221 – Agricultural, foresty and livestock engineers	0.204
1417 - Service operations managers in a financial intermediation institution	0.220	3115 - Technicians in environmental control, utilities and effluent treatment	0.155	5152 - Health lab assistants	0.198
1312 - Managers and operations specialists in companies, departments and health service units	0.219	3131 - Electrical and electrotechnical technicians	0.130	1114 - Public service managers	0.181
5143 - Building maintenance workers	0.214	3121 - Construction technicians (buildings)	0.126	7824 - Urban, metropolitan and bus drivers	0.177
1311 - Directors and operations managers in a personal, social and cultural services company	0.205	2527 - Planning, scheduling and logistics control professionals	0.119	7711 - Carpenters and similar	0.173
7825 - Freight vehicle drivers in general	0.198	3541 - Specialists in product promotion and sales	0.118	2140 - Environmental engineers and similar	0.164
1232 - Human resources and labor relations directors	0.197	7242 - Metal and composite structure assembly workers	0.116	6110 - Farmers and livestock in general	0.164

Prepared by the authors.

Tab. 4A – Regressions of green job entry in Amazon municipalities

Independent variable	OLS I	OLS II	OLS III	Probit IV	Logit V
Density $_{t-5}$	0.759** (0.112)		0.813*** (0.089)	3.920*** (0.365)	8.101*** (1.696)
Deforestation $_{t-5}$	0.000 (0.001)		-0.002* (0.001)	0.007 (0.008)	0.029 (0.023)
Deforestation*Density $_{t-5}$			0.012 (0.004)	-0.060* (0.030)	-0.169* (0.085)
Agriculture $_{t-5}$	-0.002 (0.006)		0.005 (0.005)	0.004 (0.029)	0.042 (0.077)
Livestock $_{t-5}$	0.014 (0.005)		0.011 (0.006)	0.092 (0.069)	0.222 (0.203)
FFA $_{t-5}$	0.012*** (0.001)		0.025** (0.005)	0.220*** (0.033)	0.387*** (0.086)
Extractive $_{t-5}$	-0.028** (0.008)		-0.001 (0.009)	0.042 (0.068)	0.117 (0.129)
Transformation $_{t-5}$	-0.022 (0.019)		-0.026 (0.018)	-0.223 (0.120)	-0.434 (0.233)
Diversity $_{t-5}$		-0.011* (0.004)	-0.029** (0.006)	-0.274*** (0.067)	-0.591*** (0.149)
Log Wage $_{t-5}$		-0.000 (0.000)	0.001 (0.001)	-0.019 (0.011)	-0.040 (0.029)
Log Employ		-0.006** (0.002	-0.011*** (0.002)	-0.125*** (0.027)	-0.248*** (0.067)
Log GDP per capita $_{t-5}$		-0.012** (0.003)	-0.026** (0.004)	-0.175** (0.034)	-0.368** (0.068)
Log Demography $_{t-5}$		-0.012 (0.018)	-0.031 (0.019)	-0.326 (0.217)	-0.793 (0.417)
Period F. E.	✓	✓	✓	✓	✓
City f. e.	✓	✓	✓	✓	✓
Occupation f. e.	✓	✓	✓	✓	✓
Observations	182073	222594	182073	181524	181524
R^2	0.156	0.154	0.157		
Pseudo R^2				0.182	0.178
Log Likelihood				-32363.450	-32520.101

Robust standard errors clustered at Region.
Initial periods (t-5) are 2011 and 2016. Final periods (t) are 2016 and 2021.
Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Tab. 5A – Regressions of green job exit in Amazon municipalities

Independent variable	OLS I	OLS II	OLS III	Probit IV	Logit V
Density $_{t-5}$	-1.328*** (0.081)		-1.617*** (0.124)	-5.057*** (0.358)	-8.367 (0.607)
Deforestation $_{t-5}$	-0.007 (0.005)		-0.019* (0.008)	-0.058** (0.022)	-0.097* (0.039)
Deforestation*Density $_{t-5}$			0.047* (0.016)	0.144** (0.045)	0.243** (0.084)
Agriculture $_{t-5}$	-0.021 (0.034)		-0.021 (0.028)	-0.075 (0.091)	-0.104 (0.158)
Livestock $_{t-5}$	-0.007 (0.010)		-0.006 (0.009)	-0.027 (0.031)	-0.049 (0.074)
FFA $_{t-5}$	0.078 (0.136)		0.096 (0.113)	0.281 (0.355)	0.480 (0.582)
Extractive $_{t-5}$	0.012 (0.039)		-0.017 (0.025)	-0.044 (0.078)	-0.061 (0.145)
Transformation $_{t-5}$	-0.103 (0.055)		-0.090 (0.069)	-0.281 (0.216)	-0.464 (0.384)
Diversity $_{t-5}$		0.080*** (0.012)	0.159*** (0.014)	0.501*** (0.056)	0.846*** (0.096)
Log Wage $_{t-5}$		-0.007* (0.003)	-0.005 (0.005)	-0.017 (0.018)	-0.028 (0.029)
Log Employ$_{t-5}$		0.014 (0.027)	0.024 (0.024)	0.067 (0.082)	0.113 (0.136)
Log GDP per capita $_{t-5}$		-0.021 (0.025)	0.004 (0.024)	0.017 (0.074)	0.025 (0.126)
Log Demography $_{t-5}$		-0.045 (0.089)	0.065 (0.111)	0.280 (0.357)	0.476 (0.607)
Period F. E.	✓	✓	✓	✓	✓
City F. E.	✓	✓	✓	✓	✓
Occupation F. E.	✓	✓	✓	✓	✓
Observations	22722	26416	22722	22164	22164
R^2	0.219	0.213	0.222		
Pseudo R^2				0.130	0.130
Log Likelihood				-12296.759	-12295.894

Robust standard errors clustered by Region.
Initial periods (t-5) are 2011 and 2016. Final periods (t) are 2016 and 2021.
Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Essay C. Challenges of the Green Economy in Brazil: Does related productive diversification favor more developed states?*

Abstract: In the presence of environmental constraints, it is essential to develop products and technologies that reduce the environmental pressures caused by current patterns of production and consumption. This paper's objectives are to map sustainable paths of economic development, by quantifying green productive possibilities in Brazilian federative units, and to analyse their probability of success of in diversifying their production with environmental goods. To achieve these, we used the Economic Complexity approach combined with the OECD list of environmental products and a panel data. The results indicate the existence of significant regional differences in Brazil. The federative units of the South and Southeast are better prepared to offer environmental goods and develop the Green Economic Complexity. For this reason, strategic planning and stimulus policies for a green economy in Brazil must take this gap into account so as not to deepen the existing regional inequalities in the country.

Keywords: Green Economy. Green Products. Economic Complexity. Product-space. Brazil.

1. Introduction

The idea of a green economy dates back to the late 1980s, when Pearce et al. (1989) suggested making the system greener to deal with the problems caused by pollution (Merino-Saum et al., 2020). However, it was only in the 21st century, especially after the events of the 2008 crisis, that institutions around the world began to discuss the transition to a cleaner system more vigorously (D'Amato et al., 2017; D'Amato and Korhonen, 2021). Despite the lack of consensus, the idea of a "green transition" addresses environmental constraints in the development process, with the aim of making it more sustainable (Zhai et al., 2022).

In the presence of this condition, it is essential to develop products and technologies that reduce the environmental pressures caused by current production and consumption patterns (Dangelico, 2016). Although the typical example is renewable energies for their role in mitigating climate change (Sarkodie et al., 2020), rain monitoring devices, forest management tools and noise reduction devices are part of a wider range of products that together can gain market share due to their environmental role in the transition to a green economy.

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The green transition is an opportunity to develop a new range of products with environmental benefits (Kannan et al., 2022). However, the Economic Complexity literature shows that specific attributes are obtained in a cumulative process of developing and acquiring new capabilities (Sbardella et al., 2018). As eco-friendly products are part of this group due to their path-dependent nature, territorial differences in terms of specialization influence the potential for diversification of environmental goods (Mealy and Teytelboym, 2022).

Brazil fits perfectly into this picture, because sub-national entities with different degrees of productivity and specialization share the same territory (Morais et al., 2021). While the states with the highest per capita income, located in the Southeast, have a diversified basket of products, the states located in the Mideast, North and Northeast have a lower per capita income and offer less sophisticated products (Teixeira et al., 2022). For this reason, analysing the potential and uncovering the opportunities for diversification can help draw conclusions about the specific policies to be adopted to promote green development paths in Brazil.

With this study, we intend to enter into this discussion by establishing the following objectives: (i) verify which Brazilian states have the most productive capacities for a green economy; (ii) construct the green product-space for Brazil and analyse it at the state level; (iii) define how states can take advantage of their existing productive capacities to move towards a green economy; and (iv) verify the probability of success of the Brazilian states in placing an environmental good on the market. To achieve this, we used the Economic Complexity approach and the OECD's combined list of environmental products. In all, 248 products were grouped into 11 environmental categories. They are available according to the 6-digit international standardization system (hs-6) and have served as a basis for more recent work about the green economy and Economic Complexity (Mealy and Teytelboym, 2022; Pérez-Hernández et al., 2021).

However, it turns out that green products are a subset of the economy's basket of goods. Although the procedures defined by Hausmann and Hidalgo (2014) are designed to capture the complexity of the entire basket of products, Mealy & Teytelboym (2022) developed the Green Complexity Index (GCI) and the Green Complexity Potential (GCP) to measure the complexity of the subset of green products. We used these indicators model to achieve objectives one and three.

The second objective can be achieved using the product-space. With this technique, similar products are listed on a diversification map in the form of networks of connections (Hamwey et al., 2013). The main idea is to map green products that require capacities which are similar to those required by green products that are already exported (Hidalgo and Hausmann, 2009, p. 10575).

In adopting these procedures, we are not promoting methodological innovation. In fact, we followed the suggestion of Mealy & Teytelboym (2022) to investigate the relationship between Economic Complexity and the green economy in specific regions, as Pérez-Hernandez et al. (2021) did to Mexico. The novelty lies in its application to the 26 Brazilian states and the Federal District. Further, this paper differs from previous studies in that it uses an entry model to capture the regional probability of success to diversify production with environmental goods.

The main concepts and indicators have been reviewed in the second section of this document, which also presents other empirical studies on 'Green Economic Complexity', and the gap in the literature, with no application to Brazil. The third section presents the methodological approach. The fourth section presents the results and the fifth concludes the paper.

2. Literature review

In economic equilibrium, factors of production are perfectly allocated. When facing restrictions, individuals and companies rationally use all available information and allocate these factors to new activities that provide maximum net benefit. Although this movement is consistent with the ideal of a new equilibrium, it produces hypothetical scenarios that are generally restrictive and unrealistic. To get around these drawbacks, Complexity Economics relaxes the propositions adopted by traditional economic theory. It assumes that heterogeneous agents, equipped with a limited and asymmetrical set of information, react, and exploit mutually created possibilities. The economic process is evolutionary. After all, from the strategies, beliefs and actions that exist in society, new phenomena and patterns emerge, and the economy moves from a comparative static state to something organic, in constant change and formation (Arthur, 2021).

While the aforementioned complexity is discussed as an alternative paradigm for equilibrium neoclassical economics (Kirman, 2016), the Economic Complexity theory of development is more specific and understands material transformation as a function of the available knowledge in society (Balland et al., 2022). Its fundamental proposition is that the technical knowledge to transform natural resources, labour, machinery, and equipment into products is available in the markets. The greater the diversity of productive skills retained in society, the greater the capacity and probability of combining them into new and more diverse products. As a result, the wealth or poverty of a nation depends on the quantity and diversity of productive skills contained in individuals and manifested in networks of market connections (Hausmann et al., 2014; Hidalgo and Hausmann, 2009).

This proposition is particularly useful for discussing the transition to a green economy. Despite making no major assumptions about the nature of the factors of production, Economic Complexity estimates them in the presence of activity-specific inputs. In this way, regardless of the specific forms of institutions or factors of production, it is possible to examine in greater detail the abstract factors inherent in production. As a result, patterns of growth and product specialization that can influence a region's success in making the green transition can be revealed (Hidalgo, 2021; Pérez-Hernández et al., 2021).

The two indicators that are used to examine production capacities and specialization patterns from the perspective of Economic Complexity were introduced by Hidalgo e Hausmann (2009). The first is the Product Complexity Index (PCI), which establishes an order of similarity between the products in the basket of exported goods. The second is the Economic Complexity Index (ECI), which ranks countries based on the similarity of their exports. Normally, less advanced economies have a low ECI because their export baskets are made up of less sophisticated products – low PCI. In contrast, advanced economies export relatively more sophisticated products – high PCI (Mealy and Teytelboym, 2022). When compared over time, the ECI can explain variations in countries' economic output more effectively than variables such as institutional quality, competitiveness and education (Hausmann et al., 2014; Hidalgo and Hausmann, 2009; Mealy and Teytelboym, 2022). As a result, the literature has used complexity indicators to explore other facets of the economic structure. For example, human development and income inequality (Caous and Huarng, 2020), the brown economy (Andres et al., 2023), ecological footprint (Wang et al., 2023), greenhouse gases (Romero and Gramkow, 2021) and the green economy (Mealy and Teytelboym, 2022; Pérez-Hernández et al., 2021).

Particularly, a few green economy studies have also used the product-space technique (Hamwey et al., 2013; Mealy and Teytelboym, 2022; Pérez-Hernández et al., 2021). Applying it implies looking beyond spatial and cultural forms of proximity (Hidalgo, 2021). It is, fundamentally, the proximity of technological and cognitive requirements that allow new knowledge to be absorbed because of accumulated knowledge in the past (relatedness) (Hamwey et al., 2013; Hidalgo, 2021). Since the green transition requires production structures and products designed to reduce environmental impact (Wang et al., 2023), it is reasonable to assume that two products of this nature are considered close because they require similar infrastructure, technologies, and technical capabilities to produce them (Pérez-Hernández et al., 2021). Precisely, the usefulness of the space-product method to study the green economy is the possibility of identifying the proximity between products with specific characteristics, whether established or emerging (Hamwey et al., 2013).

An alternative to the methods defined in Hausmann et al. (2014) is the Fitness of Countries. Developed by Tacchella et al. (2012), this approach to complexity is defined in a non-linear manner. Exported products are weighted by estimated complexity. Despite being used as an alternative measure to Hausmann et al.(2014), except for Sbardella et al. (2018), the literature on the green economy and complexity, examined in greater detail in the next section, uses the procedures defined in Hausmann et al. (2014).

2.2 Green Economic Complexity and the literature gap regarding Brazil

In a study with patent data, Tacchella et al. (2012), found that countries can be classified into three groups: backward, lagging and catching up. The authors draw attention to East Asian countries, which began their journey on the periphery and are now emerging as protagonists. According to Mealy and Teytelboym (2022), although patent data are important sources of information on technological development and innovation capacity, it is difficult to associate them with the geographic and physical production of a country.

Fraccascia et al. (2018) get around this problem by working with countries' export baskets. The idea was to identify green products with high export potential. Conceptually, the Revealed Comparative Advantage indicator (RCA), developed by Balassa (1965), allows identifying products that have a comparative advantage in relation to the production and exports of a given country. When applied to the green economy, the green products closest to the products that have a revealed comparative advantage greater than unity ($RCA > 1$) would be those with the greatest growth potential. Using the product-space technique, 41 green products and 141 countries were analysed between 2005-2013. The results indicate that there is a geographic proximity between countries with greater diversification of green products, whose growth potential is linked to the ability to produce them efficiently.

With the aim of investigating the impact of industrial policy on promoting the green sector in the European context, Huberty and Zachmann (2011) investigated the position of 6 green products in the product space. Based on their results obtained, suggest that green industrial policy should not create new industrial capabilities, but rather capitalize on pre-existing ones.

Although Fraccascia et al. (2018) and Huberty e Zachmann (2011) relate product-space to green goods, the idea of a Green Product-Space refers to Hamwey et al. (2013). Using Brazil as an illustrative example, 11 green products were mapped with the aim of demonstrating how the product-space can be useful to verify diversification opportunities.

In general, the studies presented so far have worked with a limited set of green products. This changes after the contribution of Mealy and Teytelboym (2022) to the literature. By considering 293 green and 57 renewable products as a subset of the basket of goods exported by countries, they developed the Green Complexity Index (IGC) and the Green Complexity Potential (GCP). While the GCI classifies countries in terms of their current capabilities to produce green goods, the GCP aggregates information on adjacent production possibilities into a single number. They concluded that the countries that will carry out the green transition first are those that have already gathered green capabilities.

Based on the idea that Revealed Comparative Advantages can be disaggregated to analyse the exports of subnational entities, Pérez-Hernandez et al. (2021) applied the GCI, GCP and product-space to analyse Mexico's current and potential capacity to promote the green economy. The analysis focuses on 32 regions between 2004-2018 and the basket contains 106 exported green goods. The results indicate that the evolution of GCI and GCP between states is heterogeneous. It is noteworthy that the state of Jalisco, despite not appearing among the 10 states with the highest GCI, is among the 5 with the greatest potential for developing green products.

Çınar et al. (2023) examined the relationship between green production and the environmental quality of subnational units in the United States of America (US). In a panel with data from 2002-2018, they linked the GCI and the Economic Fitness Index (EFI) with pollution data. The results captured by the EFI suggest that environmental quality improves with more sophisticated products. However, the results of the GCI were not significant. For the authors, it is necessary to limit the environmental impact of green products. For this reason, they suggest that the classification of these products should include the production and use phases.

To test the link between Green Economic Complexity, environmental quality and institutional quality, Wang and Yang (2022) use information from 78 countries between 1994 and 2014 in the finite mixture model. Environmental quality is measured by CO_2 emissions and Green Economic Complexity by the GCI. The results show that increasing green complexity improves environmental quality in countries with well-functioning institutions. In countries where institutions do not function well, increasing green complexity worsens environmental quality.

Dordmond et al. (2021) analyzed the influence of economic complexity on green jobs in Brazilian states, using data from 2003-2013. Their empirical strategy was developed by Muneepeerakul et al. (2013) to capture the interdependencies of urban jobs in the job-space, and later applied by Shutters et al. (2016) to capture the interdependencies of green jobs in the green-job-space of North American cities. Dordmond et al. (2021) showed in their panel study that the economic complexity of states has a positive impact on the green jobs indicator. However, the authors did not present the green job spaces. Since they did not use Mealy and Teytelboym's (2022) approach, they did not examine the potential of green jobs and the distance to the most advanced technological capabilities of the states.

Although studies on economic complexity have made progress in terms of methodological development to analyze the "greenness" of the economy (Fraccascia et al., 2018; Mealy and Teytelboym, 2022), no studies have been identified that analyze the likelihood of green products entering the market.

The first analysis of this kind was conducted by Neffke et al. (2011), who employed ordinary least squares (OLS), probit, and logit econometric models to examine the entry, exit, and persistence of activities over a five-year period. Their findings indicate that proximity to the existing production structure positively influences both the entry and persistence of activities while also preventing the loss of specialization in various sectors across 70 Swedish regions. Since then, several studies have investigated these relationships across different spatial scales (Boschma et al., 2015, 2014; Kogler et al., 2013; Neffke et al., 2011; Rigby, 2015).

In the empirical literature applied to Brazil, the methodologies established by Neffke et al. (2011) have been employed to test the relationship between the entry and exit of activities at different regional levels. For instance, studies by Queiroz et al. (2023), Galetti et al. (2021), and Galetti et al. (2024) have focused on microregions, whereas Françoso et al. (2024) examined mesoregions. In all cases, the results corroborate the proposition that related activities positively influence the specialization of new activities and help prevent specialization loss.

Other studies on economic complexity have also focused on analyzing production structures and regional disparities. For example, Pereira et al. (2023) combined Economic Complexity with an input-output matrix to identify the linkage effects of the Brazilian production structure. Teixeira et al. (2022) and Queiroz et al. (2023) analyzed how regional differences in economic complexity, in terms of exports and employment, impact economic growth in Brazilian states. Morais et al. (2021) explored the relationship between economic complexity and income inequality, while Magalhães et al. (2023) examined the formation of economic complexity in Belo Horizonte, Minas Gerais.

In short, these studies illustrate the profound regional disparities in economic complexity across Brazil. However, they do not address the role of green and complex production in shaping these differences. Despite the growing body of international literature on Green Economic Complexity, its application to Brazil remains limited. Without a thorough understanding of regional disparities, it is impossible to construct scenarios and define appropriate policies to facilitate the green transition in the country.

Teixeira et al. (2022), Queiroz et al. (2023), and Queiroz et al. (2024) have previously explored regional differences in Economic Complexity and specialization. However, the empirical foundation of this study is based on the works of Pérez-Hernandez et al. (2021) and Mealy and Teytelboym (2022), which focus on Green Complexity. This study contributes is twofold: first, by applying the Green Economic Complexity approach to Brazil, and second, by employing the procedures outlined by Neffke et al. (2011) to analyze entry dynamics and assess the probability of success in capturing regional differences in green diversification. This integrated approach allows us to draw conclusions about how Green Economic Complexity develops across Brazilian states.

The next section presents the methodological procedures adopted in this study.

3. Methodology

3.1 Economic complexity and product complexity

The Green Complexity Index (GCI) is a subset of the Economic Complexity Index (ECI). Both indices originate from the Revealed Comparative Advantage (RCA) index developed by Balassa (1965), and used to examine national exports. The index can be extended to explore sub-national entities and verify the presence or absence of comparative advantage in the production of a given good. This relationship is expressed by Eq. 1, whose objective is to define whether state/region (r) has comparative advantages in the product (p):

$$RCA_{r,p} = \frac{x_{r,p} / \sum_p x_{r,p}}{\sum_r x_{r,p} / \sum_r \sum_p x_{r,p}} \quad (1)$$

the term $x_{r,p}$ represents the exports of product p by state r. $\sum_p x_{r,p}$ is the total of exports of state r. Total exports of product p throughout Brazil are represented by $\sum_r x_{r,p}$. Similarly, $\sum_r \sum_p x_{r,p}$ symbolizes total exports throughout the country. If the result of Eq. 1 for product p is greater than unity ($RCA_{r,p} > 1$), then the State has a comparative advantage in product p.

Hausman and Klinger (2007) define $M_{r,p}$ as a binary matrix that combines the results obtained in Eq. 1. The matrix element $M_{r,p}$ takes on the value 1 if the state r has a comparative advantage in product p. Otherwise, $M_{r,p}$ takes on the value 0 if the state r does not have a comparative advantage in product p:

$$M_{r,p} = \begin{cases} M_{r,p} = 0, & RCA_{r,p} < 1 \\ M_{r,p} = 1, & RCA_{r,p} \geq 1 \end{cases} \tag{2}$$

The sum of the columns of $M_{r,p}$ matrix allow identify the level of ubiquity(u_p) and diversity (d_r) of the products:

$$u_p = \sum_r M_{r,p} \tag{3}$$

$$d_r = \sum_r M_{r,p} \tag{4}$$

The ICE is defined by the association between the eigenvector and the second largest eigenvalue of the matrix:

$$\widetilde{M} = D^{-1}R \tag{5}$$

while D represents the diagonal matrix obtained from Eq. (4), R is a matrix that captures the similarity between the exports of state r and another r^*:

$$R_{r,r^*} = \sum_p \frac{M_{r,p} M_{r,p}}{u_p} \tag{6}$$

Based on these procedures, Mealy and Teytelboym (2022) developed a formula to identify regions where a diverse set of green products are exported competitively:

$$GCI_r = \sum_g \rho_g \widetilde{PCI_g} \tag{7}$$

where ρ_g is a binary variable that takes the value of 1 if the Brazilian state has $RCA > 1$ in the green product g and 0 otherwise, the term $\widetilde{PCI_g}$ is the complexity index of the product v, normalized to obtain values between 0 and 1. As with ICE, the Eq. 7 is standardized by subtracting the mean and dividing the result by the standard deviation.

The fundamental difference between the ECI and the GCI is the range of considered products. While the ECI starts from the average PCI of all competitively exported products, the GCI only works with the PCI of green products in which the region is competitive (Mealy and Teytelboym, 2022, p. 6). This detail is what makes Eq. 7 general and allows it to be extended to other subsets of products, as Anders et al. (2023) did to the subset of the brown goods.

In addition, the measures of proximity (ϕ_{ij}) and density $\left(\omega_j^r\right)$ defined in Hidalgo et al. (2007) are used to calculate the underlying production between two products (Eq. 8) and the distance between the product and the existing production structure in the region (Eq. 9).

$$\phi_{ij} = \min\left(\mathbb{P}\left(RCA_i > 1 \middle| RCA_j > 1\right), \mathbb{P}\left(RCA_j > 1 \middle| RCA_i > 1\right)\right) \tag{8}$$

$$\omega_j^r = \sum\nolimits_i \rho_i \phi_{ij} \Big/ \sum\nolimits_i \phi_{ij} \tag{9}$$

In the Eq. 8, the minimum is taken to ensure that $\phi_{ij} = \phi_{ij}$ and the condition probability $P\left(VCR_j > 1\right)$ of a region being competitive in product i given its competitiveness in product j is calculated. Thus, Eq. 9 determines the average proximity between a given product j and other products competitively exported by region r.

Finally, the Green Complexity Potential (GCP), developed by Mealy and Teytelboym (2022), is calculated. This indicator enables us to examine the diversification potential of green products that are not competitive in the region.

$$GCP_r = \frac{1}{\sum_g \left(1 - \rho_g\right)} \sum_g \left(1 - \rho_g\right) \omega_g^r \widetilde{PCI_g} \tag{10}$$

where $1 - \rho_g$ representes the vector of green products that does not have $RCA > 1$ in the region r. The term ω_g^r symbolizes the proximity between the product g and the region r. $\widehat{PCI_g}$ refers to the PCI of the normalized product g.

3.2 The green product space

Product-space analysis is a graphical tool for visualizing the probability of products being co-exported in a network of connections. The proximity of products in the network reflects the skills developed by the entity to produce them (Hausmann et al., 2014). Therefore, applying it to the subset of green products means tracing the relationships and production capacities that sustain them in the economy.

The processes defined in Pérez-Hernández et al. (2021) were used to visualize the space-green products in Brazil and in the subnational entities. Through the usual procedures of Economic Complexity, the proximity matrix of green products was obtained (Eq. 8). Next, the maximum spanning tree (MST) was calculated and the Kruskal algorithm was used to visualize it in space. This method uses the maximum possible sums and the minimum number of connections to link all the nodes in the network. The algorithm organizes the values obtained in Eq. 8 in descending order and includes them in the MST if they connect to an isolated product (Hausmann et al., 2014; Pérez-Hernández et al., 2021). Finally, the Force-Direct layout algorithm is used to visualize the connections between green products in the Brazilian economy.

3.3 Econometric approach

The analysis of regional difficulties in developing the green economy is based on a panel data econometric model. This technique is particularly useful because it allows us to control for unobserved effects and model divergent behaviour in the sample, while facilitating the treatment of heterogeneity and providing robust estimates (Greene, 2020). The model used is defined in Eq. 11:

$$\begin{aligned} Entry_{ist+5} = \alpha + \beta_1 Density_{ist} + \beta_2 ECI_{st} + \beta_3 GCI_{st} + \beta_4 Density_{ist} * GCI_{st} \\ + \beta_4 GDP\ per\ capita_{st} + \beta_5 Population_{st} + \tau_i + \lambda_t + \varepsilon_{it} \end{aligned} \quad (11)$$

where Entry indicates the acquisition of revealed comparative advantage in product the green product i in state s at time t. The variables of interest are Relatedness Density, Economic Complexity (ECI) and Green Economic Complexity (GCI) at time $t - 5$. GDP per capita and

Population are control variables at $t-5$. The expression α is the constant of the model, τ_i is the fixed effect of region, λ_t captures the fixed effect of time. The terms β represent the parameters obtained from the estimates. Finally, ε_{it} it is the error term of the model.

3.4 Dataset

The other variables used in the empirical test (Eq .11) are summarised in Tab. 1.

Tab. 1 – List of variables used in Eq. 11

Variable	Description	Source
Entry	Binary variable. Assume 1 if the region becomes specialized in green product and 0 otherwise.	**comexstat.mdic.gov.br**
Relatedness Density (Density)	A measure of the number of related activities in a region. It is used to quantify the distance between the product and the productive structure of a region.	
Economic Complexity Index (ECI)	Economic Complexity Index of exports.	
Green Economic Complexity (GCI)	Index obtained from state export data for green products.	Eq. 7 **comexstat.mdic.gov.br**
Population	Region total population.	[A]IBGE **sidra.ibge.gov.br**
Gross Domestic Product (GDP per capita)	Gross domestic product per capita of the states measured in R$. 2010 prices.	[B]IPEAdata **www.ipeadata.gov.br**

[A]Brazilian Institute of Geography and Statistics (IBGE).
[B]Institute for Applied Economic Research (IPEA).
Prepared by the authors.

The procedures defined in Eq. 1 through Eq. 10 were performed using the OECD Combined List of Environmental Goods (CLEG), in which a set of 248 goods – classified in the six-digit harmonization system (hs-6) – is distributed into 11 groups according to their environmental sector: renewable energy plant (REP); cleaner or more resource efficient technologies and products (CRE); management of solid and hazardous waste and recycling systems (SWM); wastewater management and potable water treatment (WAT); air pollution control (APC); environmentally preferable products based on end use or disposal characteristics (EPP); heat and energy management (HEM); environmental monitoring, analysis and assessment equipment (MON); natural resources protection (NRP); noise and vibration abatement (NVA); and clean up or remediation of soil and water (SWR) (Sauvage, 2014).

Based on this list, the information was collected from the Comex Stat platform of the Ministry of Development, Industry, Trade and Services (MDIC). The platform provides product descriptions and export data for Brazilian states broken down by the 6-digit harmonization system. The period of analysis begins in January 1997 and ends in December 2022, during which Brazil exported all 248 goods on the OECD list, and an average of 241 green products entered international trade each year.

4. Results and Discussion

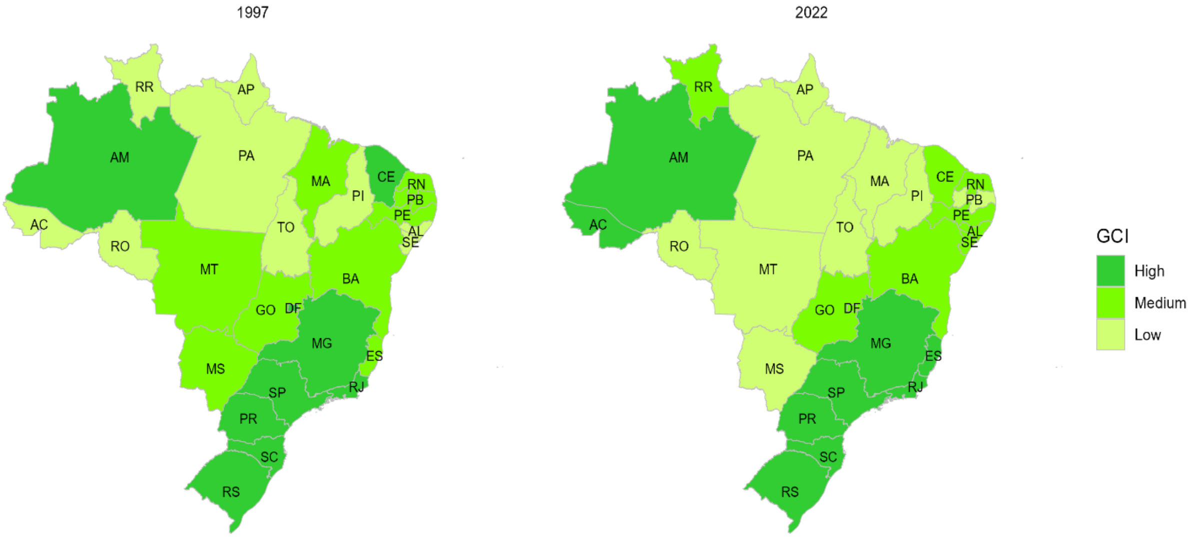
4.1 Green economic complexity

While the Green Complexity Index (GCI) reflects the region's current capabilities in the production of environmental goods, the Green Complexity Potential (GCP) synthesizes adjacent production possibilities into a single number (Mealy and Teytelboym, 2022). Fig. 1 and Fig. 2 show these indicators for the first year, 1997, and for the last year of the sample, 2022. The Brazilian states were classified into high, medium and low Green Economic Complexity and Potential Green Complexity by dividing GCI (Fig. 1) and GCP (Fig. 2) into tertiles.

Anyway, the theory of economic complexity suggests that economic growth is determined by the diversity and sophistication of productive knowledge in a region. This means that an economy's ability to transform factors of production into products depends on the combination of skills, technologies and knowledge distributed across individuals and firms. Advanced economies can integrate these elements to produce more complex goods, resulting in a diversified production base. In contrast, less advanced economies, with concentrated and less diversified production structures, find it difficult to produce more complex products, which limits their economic growth potential (Hidalgo and Hausmann, 2009). The Brazilian economy is a typical example of a less diversified production structure, with production in most states concentrated on agricultural and mineral commodities (Pereira et al., 2023). According to Mealy & Teytelboym (2022), this characteristic is a key factor in explaining the regional differences found in the Green Economic Complexity and Potential Green Economic Complexity indicators (Fig. 1 and Fig. 2).

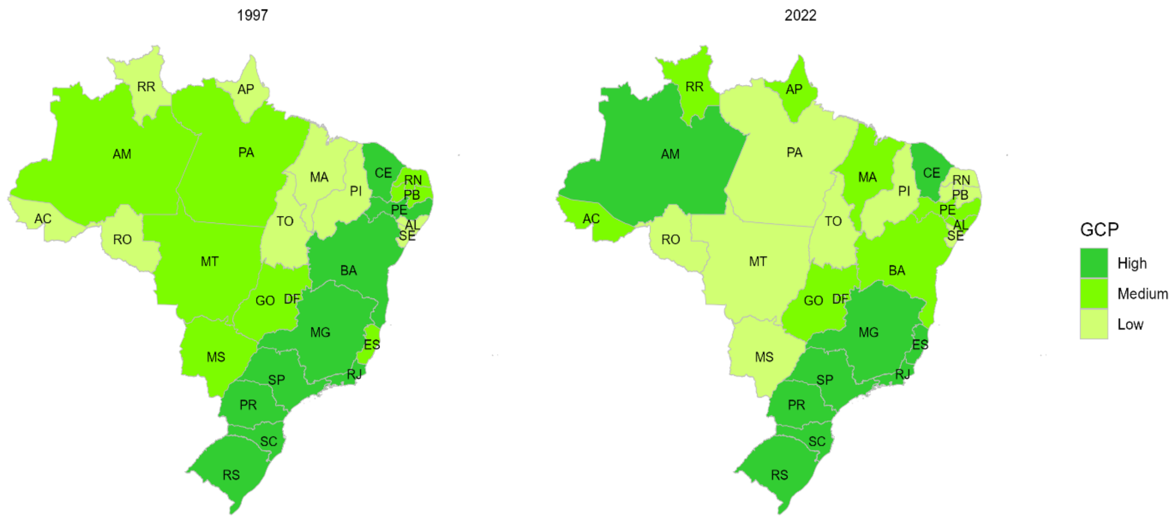
From a geographical point of view, the largest GCI and GCP are present in two of the regions with the greatest productive diversity in Brazil (Teixeira et al., 2022). The South is represented by the states of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS), and the Southeast by Espírito Santo (ES), São Paulo (SP), Minas Gerais (MG) e o Rio de Janeiro (RJ). Although Amazonas and Acre are classified as states with high relative Green Complexity in 2022, they belong to a larger group of states whose dependence on low value-added natural resources limits the potential for productive diversification in the Midwest – Mato Grosso (MT), Mato Grosso do Sul (MS), Distrito Federal (DF), Goiás (GO) –, North –Amazonas (AM), Amapá (AP), Pará (PA), Roraima (RR), Rondônia (RR) and Tocantins (TO) – and Northeast – Alagoas (AL), Maranhão (MA), Paraíba (PB), Piauí (PI), and Sergipe (SE).

Fig. 1 – [A]Green Complexity Index of Brazilian States



[A]In some years, the states of Acre, Alagoas, Amapá, Maranhão, Piauí, Rondônia, Roraima, Sergipe and Tocantins did not provide export information on green products.
Prepared by the authors.

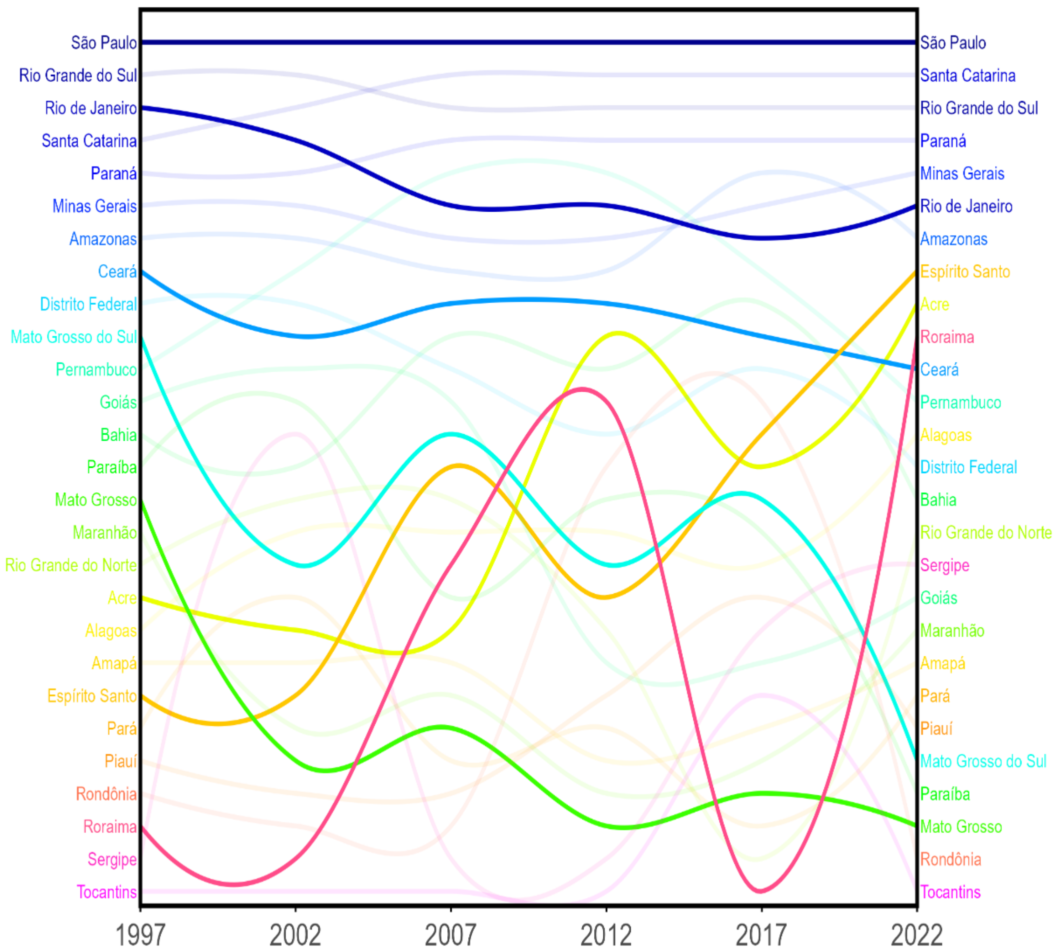
Fig. 2 – [A]Green Complexity Potential of Brazilian States



[A]In some years, the states of Acre, Alagoas, Amapá, Maranhão, Piauí, Rondônia, Roraima, Sergipe and Tocantins did not provide export information on green products.
Prepared by the authors.

The greater diversity of production helps to explain the regional differences found with these indicators, and why most of the states located in the Midwest, North and Northeast have the worst indicators comparatively. While the South and Southeast have managed to develop a solid base for green complexity, states such as Acre, Amapá, Maranhão, Roraima and Tocantins didn't even export green products consistently until 2015. This means that the skills needed to develop green products are underdeveloped in most Brazilian states, and consequently there are abrupt changes and oscillations in the ranking of the states that are present in the medium and low GCI and GCP (Fig. 3).

Fig. 3 – Green Complexity Index Ranking 1997-2022.



Prepared by the authors

This proposition is supported by the fact that the South and the Southeast states alternate at the top of the Green Complexity Ranking (Fig. 3). From this perspective, the significant and abrupt changes in other regions during the period do not represent a mere gain or loss in Green Economic Complexity, but rather a levelling down of green production in the Midwest, Southeast and Northeast, perhaps because the competitive advantages developed in these places are less aligned with the idea of a green economy (D'Amato et al., 2017). The recent rise of Acre and Roraima and the loss of position of Mato Grosso do Sul, Goiás and Paraíba are examples that reinforce this position. As a result, it is reasonable to assume that the development of the technological and productive capacities needed to produce environmental goods will be more difficult in the states out of South and Southeast. To deepen this analysis, in the next section we apply the product-space technique.

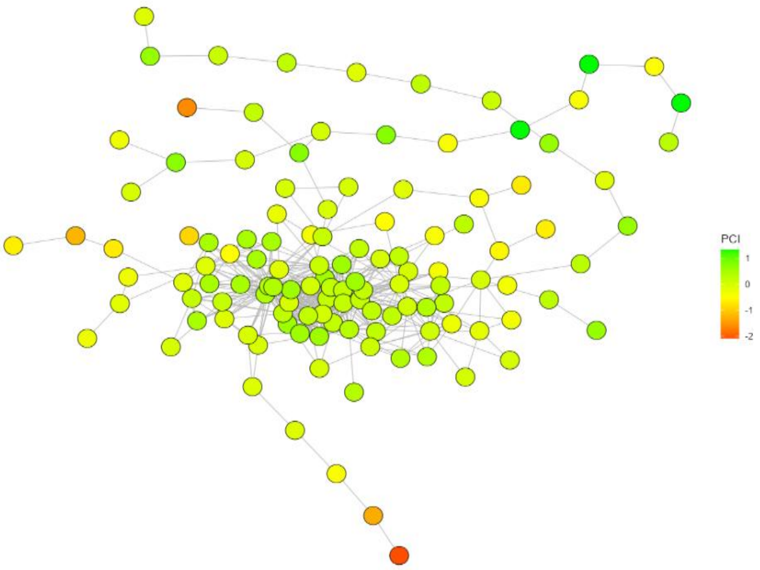
4.2 Product-space of green goods

Product-space is a tool for visualizing the connection between a set of products based on the probability of exporting them simultaneously. The green products that enter international trade are mapped in space according to the criterion of proximity between the goods that the entity has strong points for exporting (Eq. 8). The proximity between goods whose revealed comparative advantage is equal or greater than unity ($RCA \geq 1$) defines know-how capabilities (Hausmann et al., 2014) and the production and export potential of green products (Hamwey et al., 2013). This is why the greening of the economy requires complex products (Pérez-Hernández et al., 2021).

To identify the existing connections, Fig. 4 shows the green product space for Brazil in 2022. At first glance, most of the green products have a PCI of around 0. The network structure is dense, forming long, branching arms. Most products are of low to moderate complexity, and proximity relationships suggest that those in the network's core have similar technological requirements. Low PCI values are found at the periphery of the network. The long arms consist of linear chains or loosely connected subgroups. Products distant from the core are less related to the set of green products. Therefore, it is reasonable to assume that products with a relatively high PCI, such as rail-based goods transportation options, steam turbines, and steam turbine components, depend more on related production within the state than on green production itself.

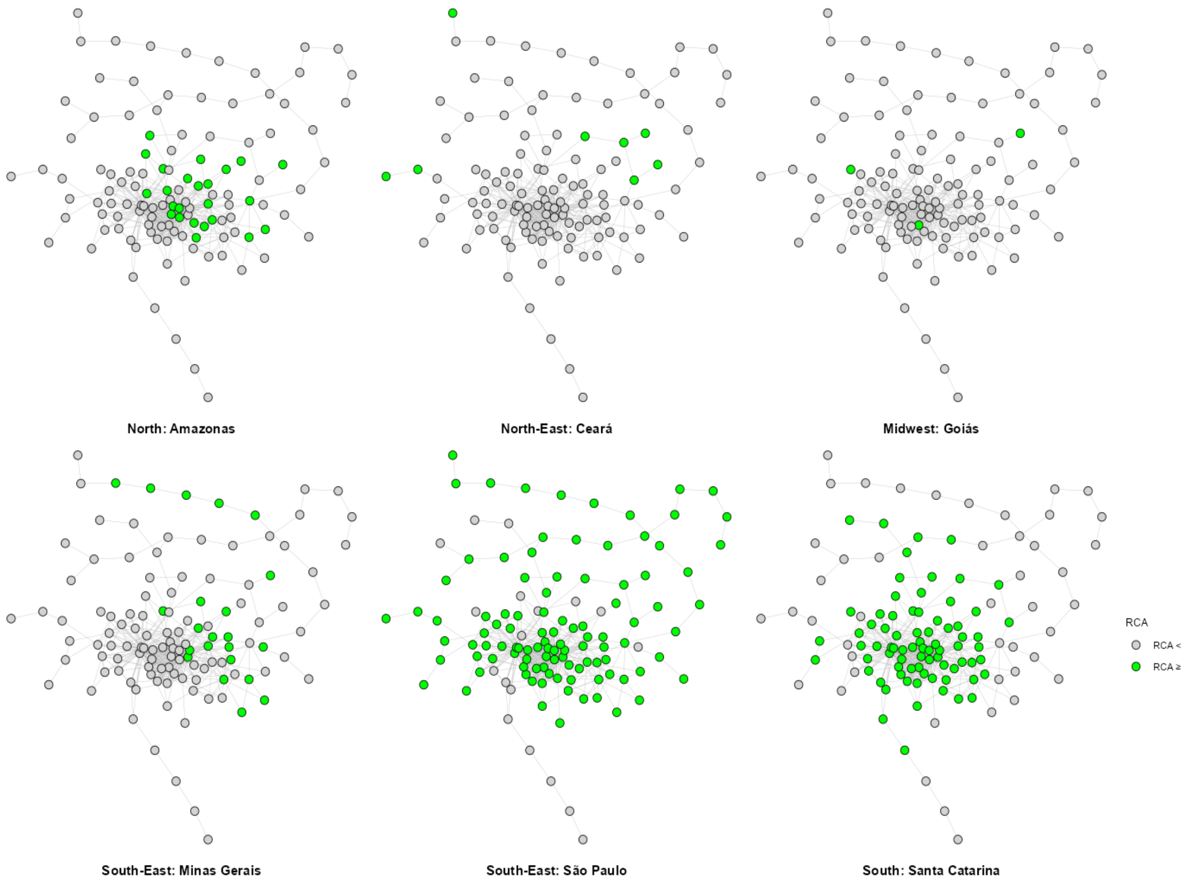
A more detailed analysis of the product-space allows us to identify the competitiveness of green goods in the Brazilian states. Fig. 5 shows the main state in each region in terms of product connectivity. We added a Southeastern state (Minas Gerais) to contrast the productive diversity of São Paulo with another state in the same region. Green products with an $RCA \geq 1$ have been colored in green.

Fig. 4 – Green product-space of the Brazilian economy in 2022.



Prepared by the authors.

Fig. 5 – Green Product-space of the selected states

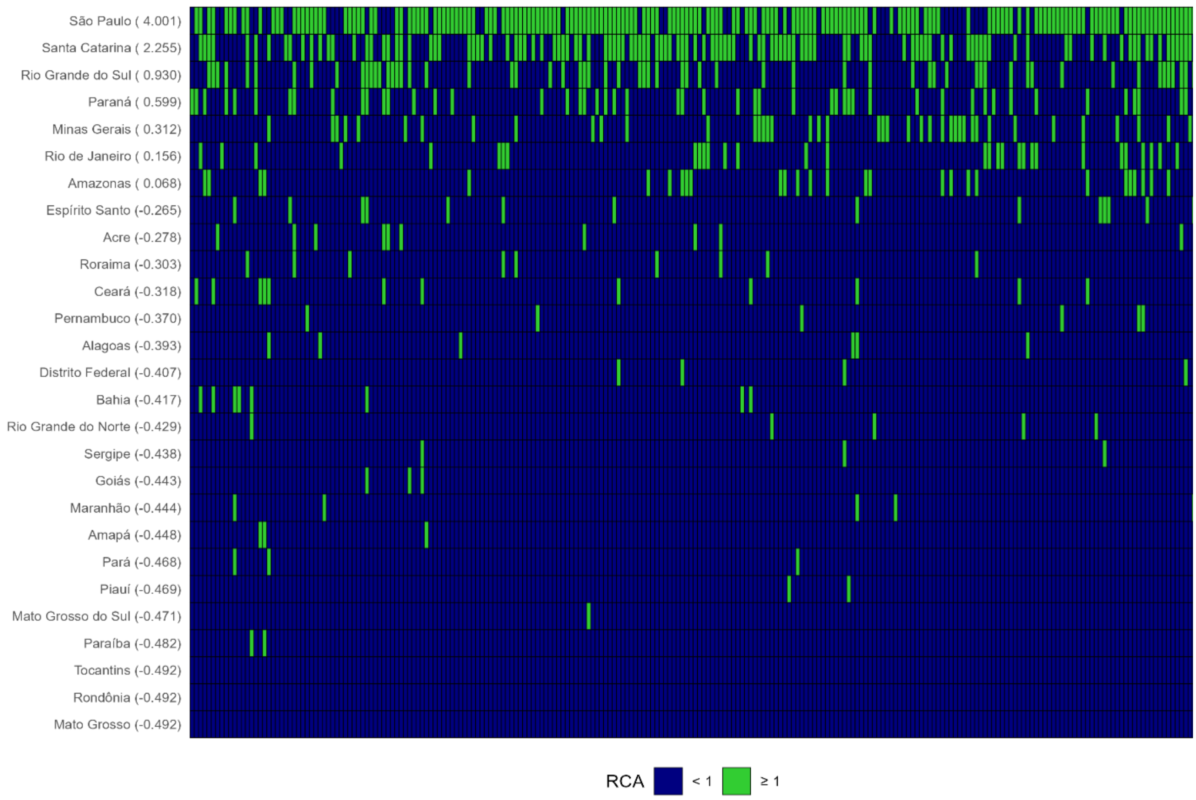


Prepared by the authors.

São Paulo is the most diversified state. In 2022, it was competitive in 178 green products, which had an average PCI of 0.41. In contrast, the other Southeastern state, Minas Gerais, showed $RCA \geq 1$ in 42 green products with an average PCI of -0.25. In Southern Brazil, Santa Catarina stands out with 119 green products and an average PCI of 0.18. In the North, Amazonas had $RCA \geq 1$ in 28 products with an average PCI of -0.15. In the Northeast, the state of Ceará was competitive in 12 products with an average PCI of -0.73. In Goiás, in the Midwest, three products with an average PCI of -0.53 had $RCA \geq 1$. In practice, the negative averages in Amazonas, Ceará, and Goiás indicate that the PCI distribution tends toward lower values. This suggests that specialization in these states is concentrated in green products of low complexity.

To visualize the diversification possibilities of all Brazilian states, Fig. 6 shows the heat map of the 236 green products exported in 2022. Based on the binary matrix ρ_g in Eq. 4, it takes on the colour green and the value of 1 when the Brazilian state has an $RCA \geq 1$ in the green product g. Otherwise, for products with an $RCA < 1$, the value is 0 and the quadrant is blue. According to Pérez-Hernández et al. (2021), the heat map is an indication of the possibilities a given state has for increasing the diversity of green products produced.

Fig. 6 – Heat map of green products by Brazilian state.



Green Complexity Index in parenthesis
Prepared by the authors.

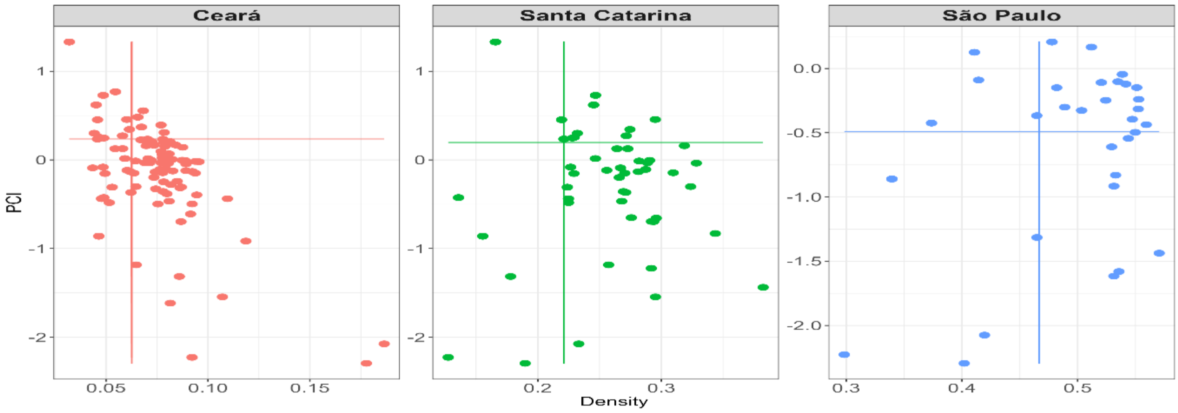
[Fig. 6](#) shows that 24 Brazilian states had at least one product with $RCA \geq 1$. While subnational entities with a high GCI, such as São Paulo, have scope to diversify their production structure with green products, most states are competitive in only a few green products. For example, Paraíba is specialized in sisal or fiber cords (-2.06) and knotted mesh nets made of textile materials (-1.44). Mato Grosso do Sul specializes in non-domestic, non-electric dryers (-0.03). Meanwhile, despite recording exports of green products in 2022, Tocantins, Mato Grosso, and Rondônia, did not show $RCA \geq 1$ for any of them.

These observations show that all states have "space" to sophisticate and diversify their production structure towards green products. Still, the question that must be asked is: are the products located in the dark part of the heat map close to the state's most advanced technological capabilities? If the answer is yes, then these regions would be closer to a green economy. The next section seeks to answer this question.

4.3 The adjacent possibilities of green products

[Fig. 7](#) shows the adjacent possibilities of three Brazilian selected states. The dots on the graph represent the green products in which the state is currently uncompetitive ($RCA < 1$) and the y-axis corresponds to the respective PCI. On the x-axis, density is the measure that attempts to capture the productive capacities and know-how of these products. The averages of these two variables are shown by the lines in the middle of the graph. When the product's density is close to zero, the entity is further away from the group of green products (Mealy and Teytelboym, 2022; Pérez-Hernández et al., 2021).

Fig. 7 – Adjacent possibilities of green products from selected Brazilian states



Prepared by the authors.

This is the case for most states in the North (AC, AM, AP, PA, RO, RR and TO), Northeast (BA, MA, PB, PE, PI, RN and SE) and Centre-West (Distrito Federal (DF), Goiás (GO), Mato Grosso (MT) and MS) regions, where the average density of environmental goods is close to zero (see Fig. 1A in annex. Although low-complexity products such as twine of sisal or of other textile fibres of the genus Agave for binding or bailing and bogies, bissel, for traction, for railway or similar vehicles stand out in Ceará, these regions are unlikely to allocate factors of production to the green economy, as the most advanced local technological capacities are not related to green products (Fig. 7). Overall, the southern and south-eastern states are more likely to diversify production towards green products, as their products are close to the most advanced technological capacities in these states.

For example, in Santa Catarina, the products with the highest PCI and aligned with the state's advanced technological capabilities include surveying instruments (levels), hydraulic or pneumatic automatic regulating or controlling instruments, and mounted optical elements such as prisms and mirrors. Among the existing opportunities in the state of São Paulo, there is a group of products that combine relatively high economic complexity with notable proximity to the state’s current capabilities, as reflected by density indicators above 0.50. These include floating structures such as rafts and buoys, trailers and semi-trailers for goods transport excluding tanker types, electrical machines and apparatus with individual functions not classified elsewhere, and alternating current generators with power output between 375 and 750 kVA.

The literature shows that countries (Mealy and Teytelboym, 2022; Sbardella et al., 2018) and regions (Pérez-Hernández et al., 2021) with greater Green Economic Complexity are the most prepared to carry out the green transition. This observation illustrates the position of the Brazilian states. The South and Southeast are better prepared to offer green products competitively on the international market. The adjacent production possibilities reveal relatively greater proximity between green products that are not exported competitively and more advanced technological capacities, mainly in São Paulo, Santa Catarina, Paraná, and Rio Grande do Sul. In most cases, there is no such relationship in the states of the North, Northeast and Midwest. At most, Alagoas have only one green product that is close to the least advanced technological capabilities (Fig. 1a). Therefore, it is likely that states in the North, Northeast and Midwest regions have more difficulty in reducing the gap between their technological structure and green products than states in the South and Southeast. In the next section, In the next section, we measure the probability of success for green product supplies from Brazilian states

4.4 Entry and Probability of success

To analyse the probability of success of Brazilian states in diversifying production with the green economy, an entry model was estimated (Eq.11). The time interval assumed for the entry of an environmental good is 5 years, as defined in the literature (Boschma et al., 2015; Neffke et al., 2011; Queiroz, 2009). In this way, a balanced data panel was obtained with the initial period (t-5) set to 1997 and the final period (t) set to 2022.

Tab. 2 shows the results of the estimations. All models include fixed effects for time and regions. Regional fixed effects were chosen because Density and GCI vary very little within Brazilian states. This allows some variation in these coefficients to be captured between states within the same region. To address this type of issue, Mealy and Teytelboyn (2022) estimated independent cross-sectional models for different periods, and Andres et al. (2023) used only time fixed effects to control for the impact of macroeconomic shocks on brown goods indicators. In Models I to III, the variables of interest $Density_{t-5}$, ECI_{t-5}, and GCI_{t-5} were regressed individually and controlled for GDP per capita and population. Models IV and V represent the final version specified in Eq.11. Taken together, these models demonstrate consistent signs for the variables of interest. The analysis will proceed with the Probit model (V), as this produced the best results.

Tab. 2 – Entry of new environmental goods

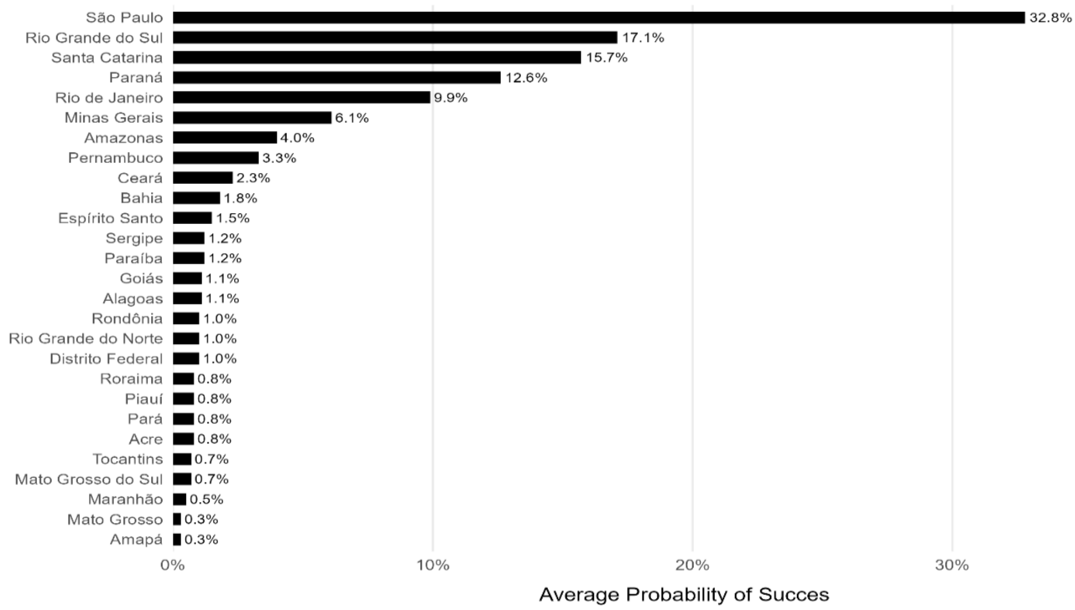
Variables	OLS I	OLS II	OLS III	OLS IV	Probit V
$Density_{t-5}$	0.745*** (0.048)			0.343** (0.108)	2.251* (0.936)
ECI_{t-5}		0.021* (0.008)		0.003 (0.002)	0.266*** (0.044)
GCI_{t-5}			0.062*** (0.004)	0. 066*** (0.014)	0.231*** (0.054)
$Density*GCI_{t-5}$				-0.087 (0.043)	-0.790** (0.264)
Log $Population_{t-5}$	0.003 (0.003)	0.014* (0.006)	0.005 (0.003)	0.000 (0.002)	0.126** (0.045)
Log GDP per capita $_{t-5}$	0.010* (0.004)	0.001 (0.009)	0.004 (0.004)	-0.003 (0.005)	-0.042 (0.134)
Year f. e.	✓	✓	✓	✓	✓
Region f. e.	✓	✓	✓	✓	✓
Observations	22839	22839	22839	22839	22839
R^2	0.085	0.070	0.088	0.089	
Pseudo R^2					0.191

Robust standard errors clustered at the subnational entity and product levels.
Initial periods (t-5) are 1996, 2002, 2007, 2012 and 2017. Final periods (t) are 2002, 2007, 2012, 2017 and 2022.
Significance levels: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The positive relationship between relatedness density ($Density_{t-5}$) and green product entry is consistent with the principle of relatedness (Hidalgo et al., 2018) and empirical evidence (Boschma et al., 2015; Neffke et al., 2011; Queiroz et al., 2024). The Economic Complexity Index (ECI_{t-5}) and Green Economic Complexity (GCI_{t-5}) also showed a positive effect on green product entry. An increase in these variables raises the probability that a state will specialize in a green product in the subsequent period. However, the interaction between Density and GCI suggests that in regions with higher green complexity, Density has a smaller effect on green specialization. This may indicate that the economy already possesses the capabilities required to produce a limited set of green products (Sauvage, 2014). Consequently, the importance of local relatedness in enabling new green product entries decreases.

Based on the probit model's prediction coefficients, Fig. 8 shows the average probability of success in green diversification for each subnational entity. On the one hand, São Paulo stands out with a probability of success of around 32.8%. It is followed by Rio Grande do Sul (17.1%), Santa Catarina (15.7%), Paraná (12.6%), Rio de Janeiro (9.9%) and Minas Gerais (6.1%). Not coincidentally, these are the leading states in terms of GCI (Fig. 1), GCP (Fig. 2) and Economic Complexity (Queiroz et al., 2023; Teixeira et al., 2022). On the other hand, the subnational entities with low green complexity, Amapá (0.3%), Mato Grosso (0.03%) and Maranhão (05%), have average probabilities close to zero, not significantly different from the states in the middle of the table, such as Goiás (1.1%) and Bahia (1.8%).

Fig. 8 – Average probability of success for environmental product market entry



Prepared by the authors.

As pointed out by Mealy and Teytelboym (2022), specialization in agricultural commodities and resource-intensive products can lead to underdeveloped capacities to develop green complexity. Since Brazil has the characteristics of an primary production economy specializing in the export of commodities (Hausmann et al., 2014), this proposition helps to position the Brazilian subnational entity not only in terms of green complexity (Fig. 1) and potential green complexity (Fig. 2), but also in terms of the likelihood of diversifying production with green products (Fig. 8). The most diversified and complex regions, located in the South and Southeast (Queiroz et al., 2023; Teixeira et al., 2022), have the best indicators and possibilities for diversifying production with environmental goods.

Pinheiro (2024) cautions that a strong focus on related diversification may constrain development by locking regions into established trajectories. In contrast, within the green economy, targeting unrelated sectors could expand the portfolio of environmental products beyond what is currently observed (Belmartino, 2025). Both theory (Pinheiro, 2024) and empirical findings (Belmartino, 2025) support the relevance of such diversification. Strategic planning and targeted industrial policies have enabled several countries to build capabilities in sectors where they previously lacked comparative advantages.

5. Conclusions

Mapping the path and quantifying the possibilities for greening the Brazilian economy were the main objectives of this work. To achieve them, we used the Economic Complexity approach, which allowed us to identify the regional differences present in Brazil.

In the short term, the federative units of the South and Southeast are better prepared than the others to offer environmental goods and develop the Green Economic Complexity. The problem is that if the green economy takes hold in the international competitive scenario, the supply of products with greater environmental appeal could deepen the regional differences that exist in Brazil. For this reason, strategic planning and stimulus policies for a green economy in Brazil must take this gap into account so as not to deepen the existing regional inequalities in the country. The results can help public officials formulate specific regulatory policies to promote the development of environmental products in the most economically backward states.

An important policy implication is to develop highly complex products in the states of the North, Northeast and Midwest regions, with the long-term aim of making them greener. Specialization in highly complex products will most likely increase the amount of collective knowledge and the capacity to generate novel green products from existing knowledge. With more specialized individuals and firms, cities, states, and macro-regions will diversify to the point where they can develop the potential of the green economy. Through this dynamic effect, the more economically backward states should be able to offer green products with higher technical requirements, thus increasing their economic complexity and reducing not only the internal distances between green products and more advanced technological capabilities, but also the external distances related to more developed states.

In the big picture, the promotion of green specialization policies in products with high complexity can enhance the efficacy of public investments. At present, it is possible that such institutional measures target sectors and products with low green complexity. If this is indeed the case, the less complex states may be caught in a trap that perpetuates the wide divergence observed in the indicators presented in this paper. Unfortunately, the lack of investigation of this hypothesis is a limitation of this study. For this reason, we also recommend additional studies to better understand the impact of the public sector in green products. Finally, since there is no guarantee that green complexity is ecologically sustainable in Brazil, further studies should also investigate the relationship between green economic complexity and green economic potential with natural resource extraction and other environmental quality indicators.

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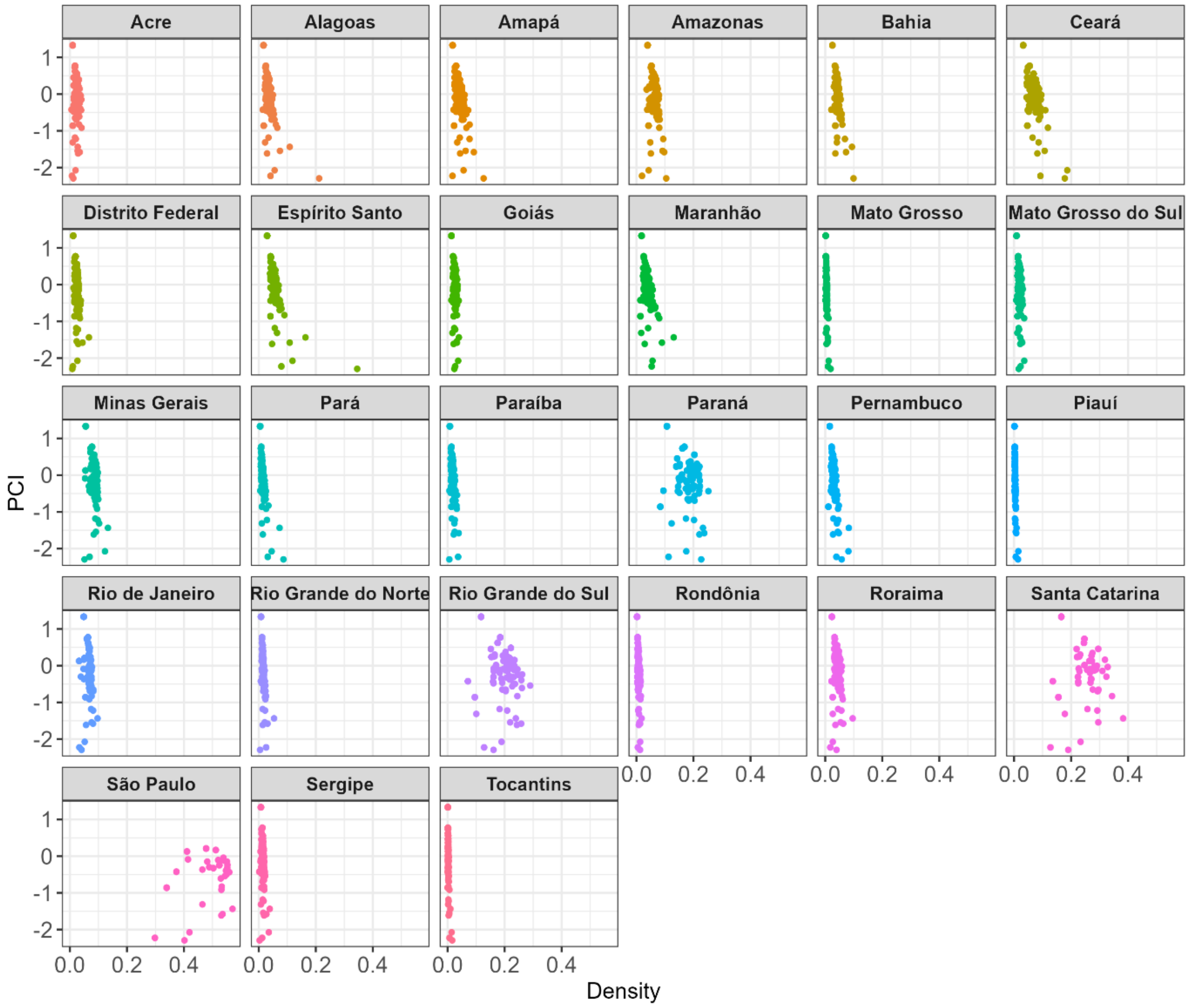
Annex

Fig 1A – Adjacent possibilities of green products from Brazilian states



Prepared by the authors.

2. Conclusion

One of the political contributions of the literature on green economics is the idea that environmental policies and green investments can reshape regional production structures in multiple ways. This thesis supports the hypothesis that Brazil's transition to a green economy tends to reproduce existing structural bottlenecks in economic development. This argument is examined through one theoretical essay and two empirical essays, which apply economic complexity tools to analyze how productive capacities influence the opportunities and risks of the green transition.

The first essay presents an analytical framework explaining how a process of cumulative green causation can arise from the interaction between industrial and environmental policies and heterogeneous productive structures. In general, regions with high economic complexity have the capacity to adapt production to the demands of the green economy, generating positive effects that can spread to other regions (green spread effect). However, regions with low economic complexity often lack the capacity to absorb these benefits. As a result, they remain locked into low-value activities and/or disproportionately bear the environmental and productive costs of the green transition (green backwash effect). In Brazil, the green backwash effect appears to outweigh the green spread effect. This occurs because the environmental burden associated with sustaining the productive structures of high-complexity centers is largely borne by lower-complexity regions specialized in primary production and input supply.

Mapping regional productive capacities for industrial and environmental policy design can generate the information needed to design public policies that mitigate the adverse effects of the green transition. The two empirical essays address this issue from different geographical perspectives.

The second essay explores the green job-space of municipalities in the Brazilian Amazon and tests the principle of relatedness. The results suggest that the entry and permanence of green jobs in the biome are dependent on existing local skills. Although the principle of relatedness remains, its effect is weakened in municipalities with high levels of deforestation. Even so, green jobs tend to persist, including in degraded areas, and municipalities whose economies rely on forestry, fishing, and aquaculture show a greater likelihood of specializing in green jobs.

The third essay expands the analysis to Brazil's federal units, constructing green product-space and evaluating regional productive capacities. The results reveal marked differences between regions. States in the South and Southeast exhibit the strongest readiness to diversify into green products, reflecting their broader productive base and more advanced capabilities. By contrast, states in other regions remain constrained by their limited productive diversity and have not yet developed the capabilities required to integrate into greener sectors.

The findings of this thesis suggest that, in the absence of specific policies, the green transition tends to exacerbate regional inequalities in Brazil. While high-complexity regions are able to follow related diversification paths, low-complexity regions require coordinated policies to develop the capacities needed to green the economy. Industrial and environmental policies must be designed to reduce structural gaps and prevent the green economy from reinforcing existing imbalances.

This research has some limitations. Although the theoretical framework is consistent with the observed empirical patterns, further progress would require a more explicit translation of the results into policy guidelines and the incorporation of additional secondary evidence. The analysis relies on export data and formal occupations, which do not fully capture the broader relationship between green economic complexity, income distribution, and economic growth. The empirical findings are also conditional on the conceptualization of the green economy adopted in this thesis. Alternative taxonomies of green products and occupations may emphasize different dimensions of environmental performance and productive transformation, potentially leading to different empirical outcomes. The thesis does not incorporate direct measures of environmental degradation, which would be necessary to assess whether higher green complexity effectively reduces ecological pressure. Finally, distributive effects and lock-in mechanisms associated with productive specialization are not directly measured. Taken together, these limitations point to promising avenues for future research.