Permanent crops in the Brazilian agricultural mesoregions[1]

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Abstract – Food production remains among the biggest challenges for humankind in this century, while Brazil is among the largest food-producing countries that remain with some land for economically or technically profitable farming expansion. Therefore, knowing which areas constitute the Brazilian agricultural frontier is crucial for improving public policies and logistics-infrastructure decisions. Data from the Brazilian Institute of Geography and Statistics from 1995 to 2020 were used in this study. We aimed to map and measure the expansion of agricultural areas for permanent crops in Brazil from 1995 to 2020 according to their mesoregions. We applied a three-stage methodology and identified similar mesoregions based on their share trends in the Brazilian agricultural-harvesting designated area. Some mesoregions must be highlighted in terms of the trend values for their shares of the Brazilian agricultural-harvesting designated area: Paraense Northeast, Minas´ South/Southwest, Triângulo Mineiro/Paranaíba Upstream, Paraense Southwest, Bauru, Woodland Zone, Rio-grandense Northeast, Pernambucano San Francisco, and Minas´ North. Other areas. such as the Espírito-santense North Coast, Bahia´s San Franciscan Valley, Cearense North, Cearense Northwest, Alagoano East, Minas´ West, and Paranaense Southeast, constituted a second-leading group. Policy implications are discussed and directions for further research are suggested, especially a top-down analysis targeting microregions or municipalities in the identified mesoregions.

Keywords: agricultural area, Brazil, Spearman's correlation coefficient.

Safras permanentes nas mesorregiões agrícolas brasileiras

Resumo – A produção de alimentos continua sendo um dos maiores desafios para a humanidade no presente século. Nesse quesito, o Brasil está entre os maiores produtores de alimentos e é um dos poucos países com áreas de expansão agrícola viável técnica e economicamente. Nesses termos, conhecer que áreas constituem a fronteira agrícola brasileira é crucial para aprimorar ou ajustar as respectivas políticas públicas em nível de infraestrutura, oferta de crédito e treinamento dos agricultores e para balizar decisões de investimento privado. Aqui, empregaram-se dados do Instituto Brasileiro de Geografia e Estatística (IBGE), de 1995 a 2020, para mapear as áreas de expansão agrícola para as safras permanentes brasileiras, no período citado, por mesorregião. Aplicou-se uma metodologia de três estágios para identificar mesorregiões similares em termos de tendência na participação da área para colheita (lavouras permanentes). Destacam-se as seguintes mesorregiões: Nordeste Paraense, Sul/Sudoeste de Minas, Triângulo Mineiro/Alto Paranaíba, Sudoeste Paraense, Bauru, Zona da Mata, Nordeste Rio-grandense, São Francisco Pernambucano e Norte de Minas. Outras áreas constituem um segundo grupamento significativo: Litoral Norte Espírito-Santense, Vale São Franciscano da Bahia, Norte Cearense, Noroeste

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Cearense, Leste Alagoano, Oeste de Minas e Sudeste Paranaense. Implicações de política são discutidas, bem como sugestões para continuidades da pesquisa, a exemplo de valorações *top-down*, por microrregião ou município, a partir das mesorregiões identificadas.

Palavras-chave: área agrícola, Brasil, coeficiente de correlação de Spearman.

Introduction

According to Duckett et al. (2022) increasing production to meet the growing demand for food whilst conserving biodiversity and reducing pressure on natural ecosystems is a dual planetary challenge of the highest order. The world population is expected to reach 9.7 billion by 2050 (United Nations, 2019) and feeding this population will require the adoption of new science and technologies and the implementation of science-based conservation plans to sustainably increase agricultural production (USDA, 2022).

Much of the land already employed worldwide has several constraints, such as chemical contamination, physical degradation of soil, endemic diseases, or lack of infrastructure (Bruinsma 2009). Furthermore, according to Iglesias et al. (2011), some of this land is also forested, protected, or supports traditional settlements, while agricultural systems in Africa and Southeast Asia appear to be vulnerable to changes in agricultural water demand against the backdrop of an evolving climate.

Consistent with de Lauwere et al. (2022), a transition towards a circular food system converting the agricultural food chain from a linear production chain to a more circular system with minimal unnecessary losses could be the answer to a range of global challenges, such as climate change, diminished water quality and biodiversity, and food insecurity.

In Brazil, agriculture has expanded from the South towards the Center-West region since the 1980s and has reached the states of Maranhão, Tocantins, Piauí, and Bahia (MATOPIBA) in the northeastern region and southern portions of the North region, largely cultivated for agricultural commodities, as stated by Polizel et al. (2021). Gasques et al. (2015), for example, highlighted increasing land prices as a consequence of agricultural expansion in Pará (PA), Amazonas (AM), and the Tocantins (TO) states. Accordingly, specific agricultural-expansion areas include the Tocantins East, Maranhão South, Piauí Southwest, and Extreme West Bahia. These areas may be responsible for the future expansion of crops in Brazil from 2020 to 2050 (Câmara et al., 2015; Freitas, 2017).

As Brazil is among the most important food producers and exporters worldwide, it is critical to map and monitor the expansion of its agricultural area. First, knowing the locus of the expansion of the Brazilian agricultural area is key for adjusting and supporting the respective public policies related to infrastructure, credit supply, technical assistance, and education for farmers. Second, private sectors that are linked to agricultural inputs can employ such information to model their local operational strategies and investment decisions.

Thus, this study aims to map and measure, by mesoregions, the expansion of agricultural areas for permanent crops in Brazil from 1995 to 2020. Section 2 discusses agricultural-area expansion in Brazil. The third section presents the methodology and database employed; section 4 reports the results and discusses them, and the closing section concludes the paper with final remarks.

A brief review of agricultural-area expansion in Brazil

As highlighted by Awokuse & Xie (2015), the remarkable expansion of the agricultural sector in Brazil has contributed to the growth of the overall economy, becoming a top producer and exporter of beef, broiler chickens, coffee, soybean, oilseeds, sugar, and ethanol extracted from sugarcane. However, the expansion of Brazil's agricultural area is associated with several problems and, according to Anghinoni et al. (2021), the sustainability of agricultural production is critical to meet the growing demand for food, fiber, and energy, and involves economic and environmental components of agriculture.

According to Carauta et al. (2021), farmers have adopted a large variety of integrated land-use systems for crops, livestock, and forestry, with highly diverse, per-hectare carbon balances. Other results (Maia et al., 2021) highlight that the diffusion of agroforestry systems has had positive and relevant impacts on the stocking rate (heads/pasture area). Agroforestry may also have stimulated the shift from cattle raising to other activities with higher gross added value, such as soybean, while the most significant economic impacts of agroforestry occur when the diffusion of its systems is related to soybean cultivation.

In this context, specific techniques can be extremely useful for intercropping. Conforming to Hong et al. (2020), the positive yield and natural-resource effects of intercropping can still be realized if the ongoing farm-scale enlargement policy is combined with one that promotes novel intercropping types, particularly those that can use already available machinery.

Another important aspect is the effect of the expansion of agricultural area on soil coverage. Changes in land use and cover affect the climate through both biogeochemical (BGC) and biophysical (BPH) mechanisms (Duveiller et al., 2020). While BGC effects are assessed on a global scale and are central to climate treaties such as the Paris Agreement, BPH effects are absent despite their increasingly recognized impact, especially at the local scale. According to Cruz et al. (2022), it is crucial to consider that when producers protect PPAs on their properties, they also conserve soil and water resources and contribute to biodiversity maintenance.

At the farm level, different types of farming also have diverse effects on the expansion of agricultural areas, and information and continuous education have become key for all types of farmers under the concept of smart farming. Smart farming refers to the use of information and communication technology in farm management, focusing simultaneously on productivity, profitability, and the conservation of natural resources (Pivoto et al., 2019). However, the adoption of some technologies requires more years of education and knowledge about how they work, while some technologies demand a greater scale.

Berchin et al. (2019) results show that the Brazilian policy framework in terms of strategies to strengthen food security is intrinsically focused on family farming and, indeed, these policies contribute to enhancing food security. Thus, family farming, in conjunction with large-scale farming, is crucial to Brazilian and global food security.

In larger areas such as the Amazon, small farmers occupy a large swath and often lack access to technical assistance, production technology, and markets. Providing quality technical assistance to small farmers could help them better align production practices with local opportunities, increase household income, and improve livelihoods, thus reducing deforestation pressure (Stabile et al., 2020).

Equally, different strategies can be required to stimulate economic development and the environmental protection of land through the application of land consolidation (Pašakarnis et al., 2021). This is even more necessary for Brazil, as the Brazilian Amazon has different levels of agricultural modernization. Lobão & Staduto (2020) found that there was a heterogeneous and dual pattern of agricultural modernization in the Brazilian Amazon between municipalities in the West and North in the Western Amazon region, which showed the worst indicators of agricultural modernization, and those to the South and East (Eastern Amazon), with the best indicators.

According to Alves et al. (2021), approximately 50 % of the primary forests in the Brazilian Amazon, mostly tropical forests, were converted to other types of land use between 1985 and 2015. Based on their results, the combination of settlement designs, presence of protected areas (PTAs), and local community participation have helped prevent forest fragmentation and deforestation in the region. Their analysis also suggests that settlement designs alone are insufficient to curb deforestation and forest fragmentation in the Brazilian Amazon.

According to Ferreira & Féres (2020), there is ample room for land use intensification, which would allow agricultural expansion without further deforestation pressures. Nonetheless, many challenges must be overcome to realize this potential. Amazonian states must control illegality, enforce the existing policies and promote innovative ones to halt deforestation, and enable large-scale restoration (Celentano et al., 2022). As reported by Silva et al. (2021), new policies, public-private partnerships, and innovative funding mechanisms must be established to close the large funding gap in the Brazilian federal PTA system, including the Amazonian ones.

Another agricultural frontier area in Brazil is the Brazilian Northeast Region, which includes water restriction areas in tropical drylands; tropical drylands are particularly sensitive to climate change. To achieve groundwater, food, and long-term energy security, agricultural landscapes in tropical drylands require more conservation (including the restoration of degraded areas), more diversification of agricultural practices, and better integration of individual initiatives on a larger spatial scale (Araújo et al., 2021). In this regard, Carlos et al. (2019) analyzed the relationship between farmers' knowledge about climate change and the adoption of adaptive strategies in the Bahia state and found that farmers who were aware of climate change effects were more likely to adapt.

In the Brazilian context, logistics requirements may also affect the expansion profile of agricultural areas. For example, soybean expansion in the Mato Grosso state is strongly associated with the presence of other soybean fields and warehouses within 50–100 km, while soybean expansion is also likely to occur in areas of high conservation value (Celidonio et al., 2019). Therefore, smart logistics investments are crucial for regional development and environmental protection, and for Magalhães et al. (2020), the implementation of the soy moratorium in the Legal Amazon in 2006 had consequences beyond deforestation control in the region.

Silva et al. (2021) raise another issue. Their findings indicate that the total annual funding deficit in the Brazilian PTAs increased in the last decade, including that for PTAs in the Amazon, Atlantic Forest, Savannas, and drylands, requiring new policies, public-private partnerships, and innovative funding mechanisms to close the large funding gap in the Brazilian federal PTA system. In this regard, Cruz et al. (2022) claim that it is important to consider that when producers protect areas in their properties, they also conserve soil and water resources as well as contribute to biodiversity maintenance.

According to Barbosa et al. (2021), from 2019 to 2022, the Brazilian federal government has undermined environmental laws, and the consequent lack of environmental governance in the country will result in severe negative impacts on biodiversity and human well-being.

Last but not least, several studies have evaluated the role of the Brazilian Forest Code (BFC). According to Hissa et al. (2019), there are high expectations that the enforcement of the BFC will drive large-scale forest recovery and carbon mitigation. For the authors, issuing trading certificates for recovering forests may represent a low-cost strategy for compliance with the BFC, a pathway to achieving restoration targets, and an additional source of income for landholders. Conversely, Mueller (2018) argued that the key BFC issue is the level of uncertainty regarding the gap between the *de jure* and *de facto* specifications of property rights.

Methodology and database

This study employs data from the Brazilian Institute of Geography and Statistics (IBGE, 2022), comprising agricultural-harvesting designated areas[3] at the Brazilian mesoregion level for the period 1995–2020, exclusively designated for permanent crops. They include avocado, arboreal cotton, açai, olive, banana, rubber, cocoa, coffee, cashew, khaki, cashew nut, India tea, coconut, palm oil, mate herb, fig, guava, guarana, orange, lemon, apple, papaya, mango, passion fruit, quince, nut, palm heart, pear, peach, black pepper, sisal, tangerine, tung, annatto, and grape.

The methodology comprises three steps. First, a threshold for selecting mesoregions is established. Second, the study calculates the Spearman correlation coefficient for detecting the mesoregions where there is a time trend in the harvesting designated area over the period 1995–2020. Finally, a time trend is estimated for these mesoregions in order to evaluate them based on their pace of agricultural expansion for permanent crops during the period 1995–2020.

Each methodological step is described in detail in the following subsections.

Selecting Brazilian mesoregions

Brazil has 137 mesoregions, according to the IBGE (2022). Only mesoregions with superior expansion in agricultural areas were evaluated. The study established a lower bound for selecting them, defined as the geometric growth rate (GGR) of the Brazilian agricultural area from 1995 to 2020. The geometrical growth rate is defined as follows:

$$GGR_{Br} = \sqrt[26]{\frac{Harvested\ area_{2020}}{Harvested\ area_{1995}}} - 1 \qquad (1)$$

Thus, only mesoregions with GGRs above the Brazilian (national) level during the 26 available years constitute the group measured in subsection 3.2.

Spearman correlation coefficient

Defining Sh_i as the share of $mesoregion_i$ in the Brazilian agricultural area, the Spearman coefficient was used to evaluate whether the time trend trajectory for Sh_i existed during the period 1995–2020. The test is non-parametric and does not require the original data to be normally distributed (Conover, 1999; Morettin & Toloi, 2006). Here, it means calculating the correlation coefficient between the ranks of the Sh_i levels (S) and time frame. The Spearman coefficient is represented by equations (2) and (3):

$$\rho = 1 - 6d/[N(N^2 - 1)] \qquad (2)$$

where

$$d = \sum_{1}^{T} (R_t - t)^2 \qquad (3)$$

R_t is the variable rank for the corresponding time moment, and $t = 1, 2, 3,..., T$ is the natural rank for the different time moments. The underlying idea is that the greater the difference between R_t and t, the greater the probability of rejecting the null time trend.

Time-trend analysis

If the Spearman coefficient test identifies a non-null time trend, a time trend is estimated. As a first framework, a linear[4] approach is employed; that is, the time (T) is the explanatory variable for Sh_i, according to equation (4), where compound u_i is assumed to respect the classical hypothesis of the residual in linear regression models.

$$Sh_i = \beta_0 + \beta_1 T + u_i \qquad (4)$$

The model decomposes the total sum of squares (TSS) into the explained sum of squares (ESS) and residual sum of squares (RSS) (Barreto & Howland, 2006), which is represented by

[3] Henceforth, "agricultural area" always means agricultural-harvesting designated area; that is, an agricultural area for permanent crops.

[4] Based on a more extensive series, more complex approaches could be applied, for example, including seasonal terms and/or a non-linear framework.

equation (5), where Sh_{im} is the average share of each mesoregion in the Brazilian agricultural area over the period 1995–2020 for permanent crops, Sh_{ie} is the estimated value for each data, and e_e is the corresponding residual.

$$TSS = ESS + RSS = \sum_{t=1}^{T}(Sh_i - Sh_{im})^2 = \\ = \sum_{t=1}^{T}(Sh_{ie} - Sh_{im})^2 + \sum_{t=1}^{T}(e_e)^2 \quad (5)$$

With the variance sources and degrees of freedom in each equation term, it is possible to apply analysis of variance (ANOVA) (Table 1) (Barreto & Howland, 2006), whose *F*-test allows the evaluation of the statistical significance of the coefficients of equation (4).

Results and discussion

The GGR for the Brazilian agricultural area from 1995 to 2020 was -0.3 %. Of the 137 Brazilian mesoregions, only 60 had GGR values above or equal to this value. Table 2 presents them in decreasing GGR order, according to which the next methodological steps will exclusively be conducted.

For the permanent crops analyzed here, the 60 selected mesoregions had 36% of the Brazilian agricultural-harvesting designated area in 1995 and 57% in 2020; that is, they experienced a growth of 21 percentage points (p.ps.) in the Brazilian harvesting designated area over 26 years.

These mesoregions were concentrated in two Brazilian regions: 17 mesoregions in the Southeast region and 15 in the North region[5]. The South, Northeast, and Center-West regions contain 12, 10, and six selected mesoregions, respectively. At the federation unit level, these mesoregions are concentrated in four federation units: eight in Minas Gerais and six in each of Pará, Paraná, and São Paulo.

Spearman correlation coefficient test

Once a mesoregion-targeted group was selected, the next step was the Spearman coefficient analysis. Table 3 presents the test results for the Brazilian agricultural mesoregions for permanent crops for 1995–2020.

The Spearman coefficient test indicates that 45 mesoregions have a time trend for their share in the Brazilian agricultural area for permanent crops from 1995 to 2020. These mesoregions are concentrated in three Brazilian regions: 14 in the Southeast region, 10 in the South, and 10 in the North.

At the federation unit level, Minas Gerais (eight mesoregions), São Paulo (four mesoregions), and Paraná (four mesoregions) must be highlighted. Spatial clusters for Brazilian agriculture occur, as stated by Stege & Bacha (2020), in these states. Of the 60 evaluated mesoregions in this stage, 15 had no significant time trend; thus, they were excluded from the further methodological steps.

Table 1. Analysis of variance (ANOVA).

Source (A)	Degrees of freedom (B)	Mean square = (A)/(B)	F-test
ESS	1	$ESS/1 = MSE$	$F = MSE/MSR$
RSS	$(n - 2)$	$RSS/(n - 2) = MSR$	
TSS	$(n - 1)$	$TSS/(n - 1)$	

Source: elaborate with data from Barreto & Howland (2006).

[5] It must be mentioned that some permanent crops (cupuassu and açai berry, for example) in the Amazon areas are not encompassed by the data from IBGE (2022) since it mixes seeded and cultivated areas. Furthermore, for crops like cocoa the data from IBGE are not consensus. These observations require greater care concerning the results related to the North region´s mesoregions.

Table 2. Brazilian selected mesoregions according to the geometric growth rate (GGR), 1995–2020.

Mesoregion (Federation Code)	GGR (%)
Marajó	10.0
Amapá´s North	8.3
Paranaense Southeast	8.2
Pernambucano San Francisco	7.0
Sergipano Hinterland	6.9
Amapá´s South	6.7
Roraima´s South	6.6
Paraense Northeast	5.8
Mato Grosso do Sul East	5.5
Baiano Extreme West	5.4
Bahia´s San Franciscan Valley	5.3
Madeira-Guaporé	4.7
Minas´ North	4.6
Amazonense Southwest	3.9
Paranaense Center-South	3.8
Belém´s Metropolitan Area	3.8
Minas Northwest	3.6
Alagoano Hinterland	3.6
Goiano Center	3.5
Serrana	3.5
Fluminense Northwest	3.3
Alagoano East	3.3
Itajaí´s Valley	3.1
Paranaense West	2.9
Paraense Southwest	2.8
Alagoano Harschland	2.6
Juruá´s Valley	2.5
Rio-grandense Southwest	2.2
Mato Grosso do Sul Center-North	2.2
Amazonas Downstream	1.9
Bauru	1.9
Rio-grandense Northeast	1.8
Triângulo Mineiro/Paranaíba Upstream	1.5
Goiano East	1.4
Marília	1.4
Curitiba´s Metropolitan Area	1.4
Catarinense North	1.4
Roraima´s North	1.2
Amazonense South	1.2
Itapetininga	1.1
Minas´ South/Southwest	1.1
Assis	1.1
Campo das Vertentes	0.9
Mato Grosso do Sul Southwest	0.8
Minas´ West	0.8
Paranaense Center-Eastern	0.6
Pernambucana Woodland	0.6
Woodland Zone	0.5
Cearense Northwest	0.4
Araçatuba	0.3
Amazonense Center	0.2
Espírito-santense North Coast	0.2
Paulista South Coast	0.1
Paraense Southeast	-0.1
Rio-grandense Center Western	-0.1
Cearense North	-0.1
Goiano South	-0.1
Espírito-santense Center	-0.1
Doce River Valley	-0.2
Paranaense North Pioneer	-0.2
Brazil	**-0.3**

Source: elaborate with data from IBGE (2022).

Table 3. Spearman coefficient tests for Brazilian agricultural mesoregions, permanent crops, 1995–2020.

Mesoregion (Federation Code)	Spearman Coefficient Test
Marajó	0.096
Amapá´s North	0.831***
Paranaense Southeast	0.407*
Pernambucano San Francisco	0.969***
Sergipano Hinterland	0.764***
Amapá´s South	0.316
Roraima´s South	0.905***
Paraense Northeast	0.929***
Mato Grosso do Sul East	0.163
Baiano Extreme West	0.270
Bahia´s San Franciscan Valley	0.858***
Madeira-Guaporé	0.470**
Minas´ North	0.990***
Amazonense Southwest	-0.61***
Paranaense Center-South	0.106
Belém´s Metropolitan Area	0.126
Minas Northwest	0.983***
Alagoano Hinterland	0.517***
Goiano Center	0.968***
Serrana	0.976***
Fluminense Northwest	0.971***
Alagoano East	0.494**
Itajaí´s Valley	0.979***
Paranaense West	-0.51***
Paraense Southwest	0.942***
Alagoano Harschland	0.762***
Juruá´s Valley	0.716***
Rio-grandense Southwest	0.898***
Mato Grosso do Sul Center-North	-0.23
Amazonas Downstream	0.835***
Bauru	0.901***
Rio-grandense Northeast	0.979***
Triângulo Mineiro/ Paranaíba Upstream	0.850***
Goiano East	0.781***
Marília	0.567***
Curitiba´s Metropolitan Area	0.182
Catarinense North	0.922***
Roraima´s North	0.730***
Amazonense South	-0.26
Itapetininga	0.693***
Minas´ South/Southwest	0.756***
Assis	0.541***
Campo das Vertentes	0.408*
Mato Grosso do Sul Southwest	-0.44*
Minas´ West	0.885***
Paranaense Center-Eastern	0.450*
Pernambucana Woodland	-0.38
Woodland Zone	0.896***
Cearense Northwest	0.851***
Araçatuba	-0.04
Amazonense Center	-0.53***
Espírito-santense North Coast	0.867***
Paulista South Coast	0.078
Paraense Southeast	0.232
Rio-grandense Center Western	0.844***
Cearense North	0.517***
Goiano South	0.232
Espírito-santense Center	-0.36
Doce River Valley	-0.77***
Paranaense North Pioneer	-0.50**

Note: *** 1% significance level, ** 2% significance level, and * 5% significance level
Source: elaborate with data from IBGE (2022).

Time trend

The time trend was calculated for 45 Brazilian mesoregions, based on the results of the previous subsections. The measurement represents the time trend for each mesoregion's share in the Brazilian agricultural area for permanent crops during the period 1995–2020. Table 4 presents the corresponding results in descending order and their statistical significance levels.

Forty-four mesoregions present time trends at the 1 %, 2 %, or 5 % significance level for their shares in the Brazilian agricultural-harvesting designated area for the period 1995–2020. Most have positive time trends, although Amazonense Southwest, Paranaense West, Mato Grosso do Sul Southwest, Amazonense Center, Doce River Valley, and Paranaense North Pioneer show negative time trends.

The nine leading mesoregions in terms of this aspect are Paraense Northeast, Minas´ South/Southwest, Triângulo Mineiro/Paranaíba Upstream, Paraense Southwest, Bauru, Woodland Zone, Rio-grandense Northeast, Pernambucano San Francisco, and Minas´ North. Their share´s time-trend in the Brazilian agricultural-harvesting

Table 4. Time trends of mesoregions' shares of Brazilian agricultural-harvesting designated area.

Mesoregion (Federation Code)	Time Trend
Paraense Northeast (PA)	0.0018865***
Minas´ South/Southwest (MG)	0.0006875***
Triângulo Mineiro Paranaíba Upstream (MG)	0.0005903***
Paraense Southwest (PA)	0.0004891***
Bauru (SP)	0.0004443***
Woodland Zone (MG)	0.0003166***
Rio-grandense Northeast (RS)	0.0002864***
Pernambucano San Francisco (PE)	0.0002174***
Minas´ North (MG)	0.0002037***
Espírito-santense North Coast (ES)	0.0001969***
Bahia´s San Franciscano Valley (BA)	0.0001862***
Cearense North (CE)	0.0001796***
Cearense Northwest (CE)	0.0001748***
Alagoano East (AL)	0.0001634***
Minas´ West (MG)	0.0001297***
Paranaense Southeast (PR)	0.0001019***
Minas Northwest (MG)	0.0000982***
Assis (SP)	0.0000944***
Goiano Center (GO)	0.0000912***
Amazonas Downstream (PA)	0.0000865***
Catarinense North (SC)	0.0000844***
Serrana (SC)	0.00008***
Madeira-Guaporé (RO)	0.0000799***
Roraima´s South (RR)	0.0000573***
Itapetininga (SP)	0.0000568***
Fluminense Northwest (RJ)	0.0000501***
Marília (SP)	0.0000413*
Itajaí´s Valley (SC)	0.0000407***
Goiano East (GO)	0.0000274***
Campo das Vertentes (MG)	0.0000212*
Rio-grandense Southwest (RS)	0.0000113***
Roraima´s North (RR)	0.00000807***
Juruá´s Valley (AC)	0.00000756***
Alagoano Harschland (AL)	0.00000574***
Sergipano Hinterland (SE)	0.00000547***
Amapá´s North (AP)	0.00000482***
Alagoano Hinterland (AL)	0.00000451**
Rio-grandense Center Western (RS)	0.0000026***
Paranaense Center-Eastern (PR)	0.00000205
Mato Grosso do Sul Southwest (MS)	-0.00000636***
Paranaense West (PR)	-0.0000235*
Paranaense North Pioneer (PR)	-0.0000542**
Amazonense Southwest (AM)	-0.0000716***
Amazonense Center (AM)	-0.000077***
Doce River Valley (MG)	-0.000153***

Note: *** 1% significance level, ** 2% significance level, and * 5% significance level.
Source: elaborate with data from IBGE (2022).

designated area fall in the interval [0,0018865; 0,0002037], which can produce substantial accumulated effects over time. Remarkably, no Center-West mesoregion belongs to this leading group concerning Brazilian permanent crops.

A second relevant grouping contains mesoregions for which the share´s time-trend in the Brazilian agricultural-harvesting area fall in the interval [0,0002;0,0001]. It comprises Espírito-santense North Coast, Bahia´s San Franciscan Valley, Cearense North, Cearense Northwest, Alagoano East, Minas´ West, and Paranaense Southeast.

Both groupings mostly gather Southeast´s and Northeast´s mesoregions. The Southeast mesoregions (in MG, SP and PR states) had already been highlighted by Stege & Bacha (2020) as areas where clusters for Brazilian agriculture happen. Simultaneously, several studies (Carlos et al., 2019; Araújo et al., 2021) identified challenges and options for further agricultural production in Northeast´s areas, especially those related to climate change.

Moreover, a majority of the evaluated areas, summing 15 mesoregions, have share´s time-trend in the Brazilian agricultural-harvesting area in the interval [0,0001; 0,00001], that is, Minas Northwest, Assis, Goiano Center, Amazonas Downstream, Catarinense North, Serrana, Madeira-Guaporé, Roraima´s South, Itapetininga, Fluminense Northwest, Marília, Itajaí´s Valley, Goiano East, Campo das Vertentes, and Rio-grandense Southwest. In this group, the presence of six Southeast´s mesoregions must be highlighted.

In summary, Figure 1 highlights the main results discussed thus far. It shows the main expanding mesoregions according to the measured crops and a second leading group in the Brazilian agricultural mesoregions.

Policy implications

The results presented above highlight the Southeast´s (especially the Minas Gerais state), Northeast´s (mostly in the Ceará state and San Francisco River Valley), and North´s (the Pará state) mesoregions in terms of dynamic agricultural-area expansion for permanent crops. Remarkably, Center-West mesoregions are not identified as leading areas, probably because their areas have experienced an intense growth in temporary

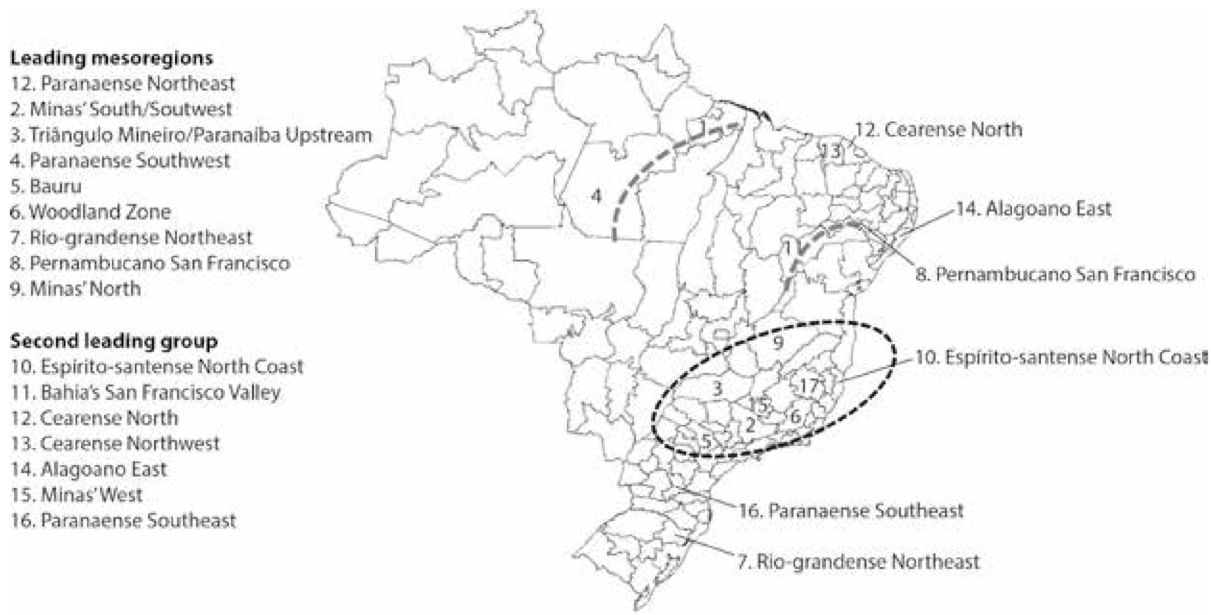

Figure 1. Highlighted areas in Brazilian agricultural-area expansion for permanent crops, 1995–2020.

Source: elaborate with data from IBGE (2022).

crops (mainly soybean, corn, and cotton) during the last forty years (Freitas, 2017, 2022).

Based on these results, some ideas can be discussed at the level of policy implications. First, the Northeast mesoregions featured here can benefit from an expansion and consolidation of railways, such as the North-South and West-East Integration railways. These railways represent connections to the Maranhão harbors and the option for multi-product transportation to the Brazilian South-Southeast industrial areas. Simultaneously, the West-East Integration railway has direct effects over the Bahia and Tocantins railway corridors, and it is also hoped to be integrated into the North-South railway.

Second, infrastructure questions remain central to agricultural-area expansion in the northern mesoregions. According to Ferrante et al. (2021), new roads are being paved, such as Highway BR-319, which connects Porto Velho to Manaus in relatively intact central Amazônia, and can act as a spearhead penetrating one of the Amazon's most preserved forest blocks.

To minimize the risks associated with irregular occupation on the right-of-way resulting from anthropic processes related to land use and coverage, it is necessary to monitor the areas close to the highways (Barros et al., 2022). Especially in the North´s mesoregions, a crucial aspect, according to Arvor et al. (2021), is an accurate land use mapping in the Amazon to support the implementation of environmental policies.

Moreover, integrating northern Brazilian mesoregions into the national economy without excessive environmental damage requires a set of diverse and articulated public policies, including those targeting improvements in the local economic dynamics (Rodrigues et al., 2022). Such an integration can boost the local supply of agricultural inputs and generate close markets for the local agricultural products.

Third, deforestation occurs primarily where property rights are not clearly established, mostly on land directly or indirectly under state responsibility (Reydon et al., 2020). This means that efforts to reduce deforestation will only be possible through more efficient land governance, especially in the Amazon region, which *mutatis mutandis* applies to all Brazilian geographical subpaces.

As a general message, land tenure in many parts of Brazil remains uncertain and controversial; a particular challenge facing attempts to improve land-tenure security and governance in Brazil is the lack of a single, integrated assessment of all types of land (Sparovek et al., 2019). Institutional and integrated public policies designed to address this question would also be welcome.

Closing remarks

Knowing the *locus* of the Brazilian agricultural-area expansion is crucial for adjusting and supporting the respective public policies related to infrastructure, credit supply, technical assistance, and education for farmers. Additionally, private sectors linked to agricultural inputs can also employ such information to model their local operational strategies and support its investments decisions. Therefore, this study aimed to measure and map agricultural-area expansion for permanent crops in Brazil from 1995 to 2020 at the mesoregion level.

Paraense Northeast, Minas´ South/Southwest, Triângulo Mineiro/Paranaíba Upstream, Paraense Southwest, Bauru, Woodland Zone, Rio-grandense Northeast, Pernambucano San Francisco, and Minas´ North are the leading mesoregions in terms of the share´s time-trend in the Brazilian agricultural-harvesting designated area from 1995 to 2020.

Simultaneously, a second relevant grouping comprises Espírito-santense North Coast, Bahia´s San Franciscan Valley, Cearense North, Cearense Northwest, Alagoano East, Minas´ West, and Paranaense Southeast. This second grouping is basically constituted by Southeast´s and Northeast´s mesoregions.

Generally, the results highlight the mesoregions in the Southeast (especially the Minas Gerais state), Northeast (mostly in the Ceará state and San Francisco River Valley), and North (Pará state) in terms of dynamic agricultural-area expansion for permanent crops. Center-West mesoregions are not identified as relevant areas, probably because their areas have experienced an intense growth in temporary crops (mainly soybean, corn, and cotton) during the last forty years in Brazil.

Still, a mandatory remark must be done regarding some permanent crops in the Amazon areas. Data from IBGE (2022) do not encompass the areas dedicated for cupuassu and açai berry, for example, since it mixes seeded and cultivated areas. Additionally, for cocoa production the data from IBGE are not consensus. Then, a greater care concerning the results related to the North region´s mesoregions is required.

Some ideas can be discussed at the level of policy implications. First, the Northeast mesoregions featured here can benefit from an expansion and consolidation of the railways, such as the North-South and West-East Integration railways. Second, infrastructure questions remain central to agricultural-area expansion in northern mesoregions; especially in these mesoregions, an accurate and continuous land-use mapping in the Amazon is crucial to support the implementation of environmental policies.

Another crucial aspect is to understand that integrating northern Brazilian mesoregions into the national economy without excessive environmental damage requires a set of diverse and articulated public policies, including those aimed at improving the local economic dynamics. Such an integration can stimulate the local supply of agricultural inputs and generate close markets for the local agricultural products. Last, efforts to reduce deforestation will only be possible through more efficient land governance, especially in the Amazon region, which *mutatis mutandis* applies to all Brazilian geographical spaces.

Further analysis can focus on two potential extensions. First, overlapping biome and infrastructure databases with the main areas here identified. Second, a top-down evaluation targeting microregions or municipalities in the highlighted mesoregions, which can provide more detailed information about the focal points on the Brazilian agricultural frontier.

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