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Spatial Pattern of Cassava Farms in the Brazilian Amazon: the Western Region of the State of Pará

Padrão Espacial de Ocorrência de Plantação de Mandioca na Amazônia Brasileira: a Região Oeste do Estado do Pará

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Abstract: The main land use and land cover monitoring systems in Brazil are unable to identify small-scale agricultural land, like cassava farms in the Amazon. Establishing the spatial distribution of these cassava farms, historically undetected, is paramount to the development of public policies to strengthen the trade of this product in the region. Our goal is to use features extracted from open-access spatial databases to identify small-scale cassava farmlands in the Western region of Pará, using *Fuzzy* spatial analysis. This study includes spatial data from the cities of Aveiro, Belterra, Santarém, and Mojuí dos Campos. The spatial model to predict the occurrence of cassava farms includes the following features: secondary vegetation and mosaic of occupation rates, the proximity to villages and bodies of water, and the existence of conservation units for sustainable use (UCUS) and settlement projects (PA). All layers were manipulated in a regular 2 x 2 km cell grid and combined by the *Fuzzy* gamma spatial operator. Our model outcomes show 70% accuracy in classifying regions of medium and high potential for the presence of cassava farms. These regions are more prevalent in Santarém (58% – 81%), followed by Mojuí dos Campos (11% – 14%), Aveiro (9% – 14%), and Belterra (9% – 10%). Small-scale cassava farmlands are concentrated along rivers and bodies of water, where most of the UCUS and PA are also located. This robust method can be applied between Census periods, supporting the understanding of cassava farm dynamics and their spatial distribution, which are valuable to the development of agrarian and economic public policies.
Keywords: Geoprocessing. Inference. Fuzzy gamma. Peasantry.

Resumo: Os principais sistemas de monitoramento do uso e cobertura da terra no Brasil não distinguem a agricultura de pequena escala, categoria que inclui áreas de plantação de mandioca na Amazônia. Gerar informações sobre a distribuição espacial desses sistemas historicamente invisibilizados é fundamental para o desenvolvimento de políticas que visem fortalecer essa economia. O objetivo deste trabalho é identificar áreas potenciais de ocorrência de plantação de mandioca em municípios do Oeste do Pará, com o uso de técnica de inferência geográfica *fuzzy*. A área de estudo corresponde aos municípios de Aveiro, Belterra, Santarém e Mojuí dos Campos. Foram utilizadas variáveis associadas a áreas de plantação de mandioca: proporção de área de vegetação secundária e de mosaicos de ocupação, proximidade de vilas e corpos d'água, presença de unidades de conservação de uso sustentável (UCUS) e de projetos de assentamento (PA). As variáveis foram inseridas em uma grade regular de células de 2 x 2 km e combinadas por meio do operador espacial *fuzzy gamma*. Os resultados indicaram um acerto de 70% na classificação de áreas de médio e alto potencial de ocorrência de plantação de mandioca. Essas áreas estão mais presentes no município de Santarém (58 – 81%), seguido por Aveiro (9 – 14%), Mojuí dos Campos (11 – 14%) e Belterra (9 – 10%). As áreas de plantação de mandioca concentram-se em áreas ribeirinhas. Nessas áreas também se localiza a maior parte das UCUS e dos PA. Esse método se mostrou robusto e pode ser replicado em períodos intracensitarios, apoiando a compreensão sobre a dinâmica e a distribuição espacial, importantes para políticas públicas.
Palavras-chave: Geoprocessamento. Inferência. *Fuzzy gamma*. Campesinato.

1 INTRODUCTION

The geographical space is where complex interactions between society and nature take place, and is understood as a constituent dimension of these relationships (BECKER; STENNER, 2008). Pondering about geographical spaces sheds light on regional capabilities and supports proposals based on spatial features, allowing the development of strategies regarding the local population, and reconciling the establishment of economic activities with the conservation of the biome (BECKER; STENNER, 2008). Nonetheless, the knowledge gained on geographical spaces is distributed unevenly across Amazonian territories. Despite current scientific advancements, there are still gaps in the qualitative interpretation of the data collected from the Brazilian Amazon (TILIO NETO, 2010).

The Amazonian peasant, commonly practicing small-scale agriculture, uses the land in several ways and has a deep understanding of the biome, being better adapted to this landscape. Cassava farming is often combined with other types of crop production, such as corn and beans (SOUZA et al., 2019). Farming strategies based on local traditional knowledge, often adapted to economic and environmental demands give peasants greater flexibility in land use. This ability to adapt has historically allowed peasant farmers to survive price instabilities, changes in product demand, and sufficiently supply the market in periods of high demand while conserving forest lands (COSTA, 2020; VOGT et al., 2015). As Costa (2020) explains, peasants in the Amazon use technical solutions that involve the management of natural resources (forest, water, soil), maintaining diversity, and complexity in either agricultural systems based on extractive activities or in agroforestry that reproduces the features of the biome.

Regarding cassava agriculture, archaeological records indicate the existence of complex civilizations and groups with socio-political organization in the Amazon, with not only transient hunters, but also fishermen and cassava farmers (ALVES-PEREIRA et al., 2018; BECKER, 2006; BECKER, STENNER, 2008). The types of cassava plant varieties distributed throughout the Amazon are associated with the cultural practices inherited from these original civilizations through exchange networks (EMPERAIRE; PERONI, 2006). Differences in the spatial distribution of cassava varieties were found in a study carried out along six of the basin's main rivers, which suggests that bitter manioc and sweet manioc have had different dispersions over time (ALVES-PEREIRA et al., 2018).

Nowadays, cassava is still one of the most important food sources for the Amazonian population (GUSMÃO; HOMMA; WATRIN, 2016). Pará is the state with the largest cassava cultivation areas in the country, adding up to 124,234 ha, or 17% of the harvested area in Brazil (IBGE, 2017). Family farming[1] represents 88% of the cassava farmlands in Pará, where 76% is in farms up to 5 ha (IBGE, 2017). This is an inclusive and diversified activity, which is present since the historical formation of peasant structures[2] in the Amazon (COSTA, 2012). The peasant production system has a historical and cultural importance that goes beyond supplying food, which is displayed in the process of producing raw cassava as well as on the production of derived products: cassava flour. Carrying over this local historical knowledge strengthens these traditions and community ties, contributing to the establishment of the cultural identity of this population (PICANÇO, 2017).

Cassava farming in the Amazon region has specific characteristics that set it apart from cassava production in other regions of Brazil. Besides being associated with small-scale agriculture (IBGE, 2017), it adopts the practice of fallow, in which the land is abandoned and allowed to rest for a certain period, while the land naturally recovers, known as "roçado" agriculture (EMPERAIRE; PERONI, 2006; LAUE; ARIMA, 2016). Therefore, secondary vegetation becomes an asset of the production system and can be seen as a restoration mechanism (COSTA, 2016). The frequency of farming and the duration of the fallow period are potential indicators of land use intensification (BOSERUP, 1972; JAKOVAC et al., 2017). Studies show that

[1] For IBGE, the concept of family farming adopted encompasses establishments run directly by the producer or indirectly (through a foreman); or by a person with kinship ties; or by more than one producer (in the case of community farms), and a family work unit larger than the hired work unit, and the total area of the establishment smaller than or equal to the maximum regional area per geographical region (IBGE, 2006).

[2] Peasant agents and structures are part of the agrarian categories that underpin rural production in the Amazon and shape agrarian dynamics in the region based on the respective specificities of reasons and decision-making processes (rationalities), concepts discussed by Costa (2009), which are not categories used by the IBGE.

land use intensification has several implications for the environment, including the loss of resilience of secondary vegetation (GEHRING; MANFRED; VLEK, 2005; JAKOVAC et al., 2015; VILLA et al., 2018), reduced cassava productivity (JAKOVAC et al., 2016), and reduced soil quality (RIBEIRO FILHO; ADAMS; MURRIETA, 2013).

Every ten years, Brazilian Institute of Geography and Statistics' (IBGE) agricultural census provides data on the production systems associated with cassava farming and constitutes an important data repository. The data is collected through questionnaires that are applied to all agricultural land in each city. Annually, an important but smaller and simplified survey, the Municipal Agricultural Production Survey (PAM), collects data through questionnaires to selected municipal institutions of interest. In both surveys, the smallest geographical unit of data available on the Ag Census portal is the municipal boundary[3], which unables the analysis of the spatial distribution of agricultural products within municipalities. As demonstrated by Souza et al. (2019), remote sensing and geoprocessing techniques can generate complementary information, increasing the scientific knowledge of these geographical spaces. This is the case of small-scale agriculture, whose spatial and productive arrangement is rarely reported or often mapped inaccurately in the Amazon's land use and land cover monitoring systems. These small-scale systems are often seen as of little economic importance and are poorly considered in the strategic planning of agrarian policies and trade, reinforcing their invisibility (ADAMS et al., 2009; SOUZA; ESCADA; MONTEIRO, 2017).

The size of small-scale agricultural production lots in the Amazon leads to difficulties in mapping them: in general, these production systems occupy areas of less than 1 ha (DAL'ASTA et al., 2014). The main systems for monitoring land use and land cover in the Amazon (TerraClass, IBGE and MapBiomas), which are responsible for classifying large swathes of the territory, adopt minimum mapping unit sizes that are not suitable for mapping small-scale agriculture: TerraClass uses 6.25 ha and IBGE uses a grid of cells of 1 km² (IBGE, 2020; INPE, EMBRAPA, 2014). Furthermore, small-scale agriculture areas have mixed land cover, with simultaneous plantation of more than one type of crop, causing confusion among different classes, such as pasture and secondary vegetation (DELRUE et al., 2012; PACHECO et al., 2021; RODRIGUES et al., 2020; SOUZA et al., 2019). The mapping and spatialization of small-scale agriculture are limited by the features of the most commonly used orbital sensors and also by the minimum mapping unit used to collect data (PACHECO et al., 2021; SOUZA et al., 2019). As a result, production systems formed by small-scale agriculture remain poorly represented in the literature or invisible.

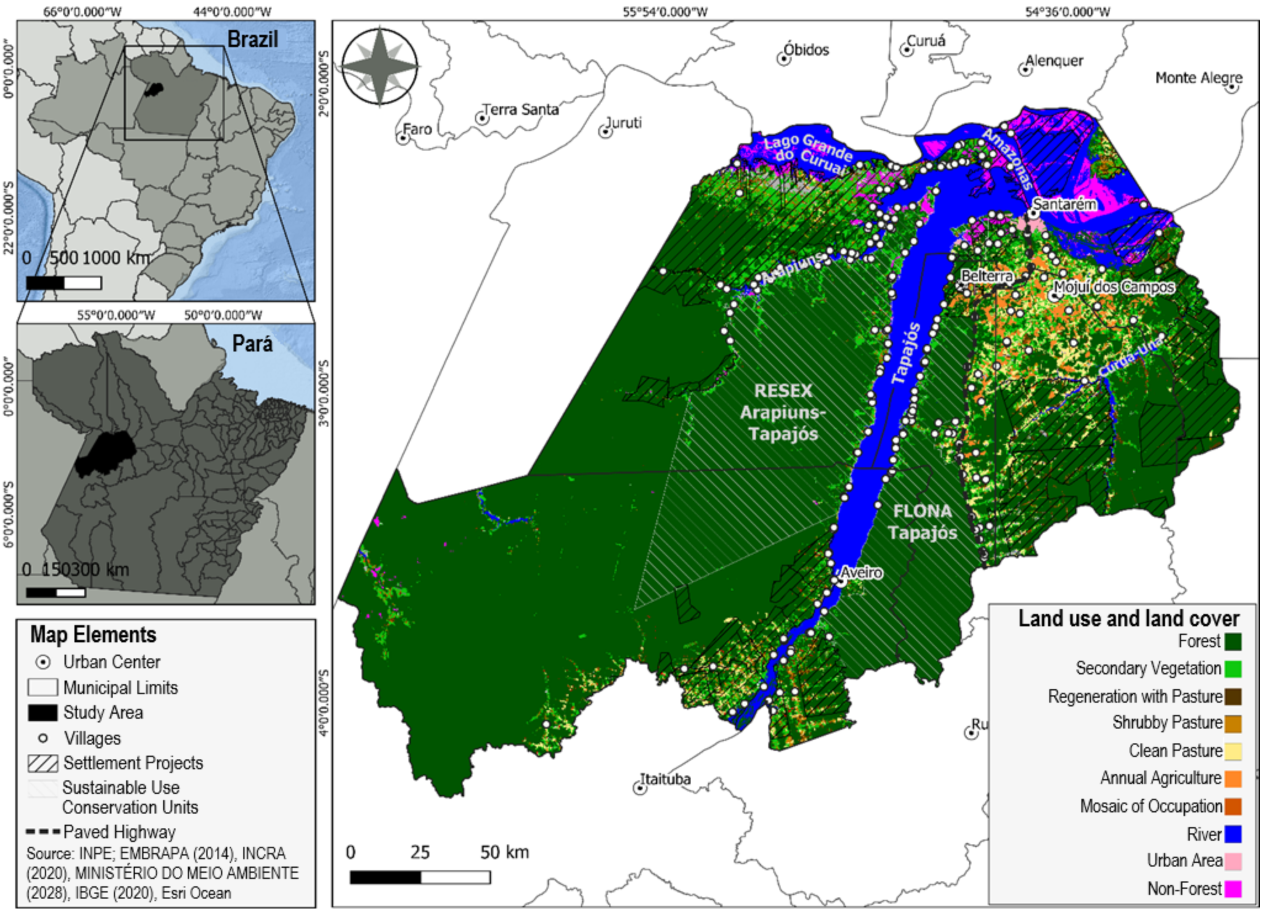
Knowing the areas where cassava is planted through spatialization is necessary so that knowledge about this crop and peasant production can be considered in regional and economic development policies, as well as to support decision-makers in designing political and economic mechanisms to strengthen this production (GUSMÃO; HOMMA; WATRIN, 2016; SOUZA et al., 2019). This study aims to identify areas with potential for small-scale cassava farming in municipalities in the state of Pará, using a *Fuzzy* gamma geographic inference technique applied to the following types of features: environmental, land regime, populational, and land use.

2 STUDY AREA

Small-scale agriculture in Pará is more present in the mesoregions of Northeast Pará and Lower Amazon (CARVALHO et al., 2019). The study area includes municipalities located in the Lower Amazon mesoregion: Belterra, Mojuí dos Campos, and Santarém, as well as the municipality of Aveiro, located in the Southwest of Pará (Figure 1). The municipality of Santarém is the 8th largest producer of cassava in the state of Pará (IBGE, 2017).

[3] It is possible to obtain data at a higher level of disaggregation, but access is difficult due to the need for prior authorization from the IBGE and access only to data on site, at the institution. In addition, for some variables and in some regions, the data cannot be provided for reasons of confidentiality (IBGE, 2017).

Figure 1 – Study area location.



Source: Authors (2024).

The study area stands out for its continuous areas of primary forest in some regions of Aveiro, Santarém, and Belterra (INPE; EMBRAPA, 2014). Secondary vegetation is more present in areas near bodies of water, especially in the stretch between the Amazon River and the Arapiuns River, as these are areas of ancient occupation, with communities established more than 100 years ago (between 20 and 319 years), according to Amaral et al. (2009). In 2014, the Santareno Plateau region[4] had significant areas of annual agriculture, mainly associated with soybean production (SOUZA, 2016). Clean pasture is also prominent in this region and around the BR-163 highway and, to a lesser extent, in the areas near the Tapajós River and in Aveiro.

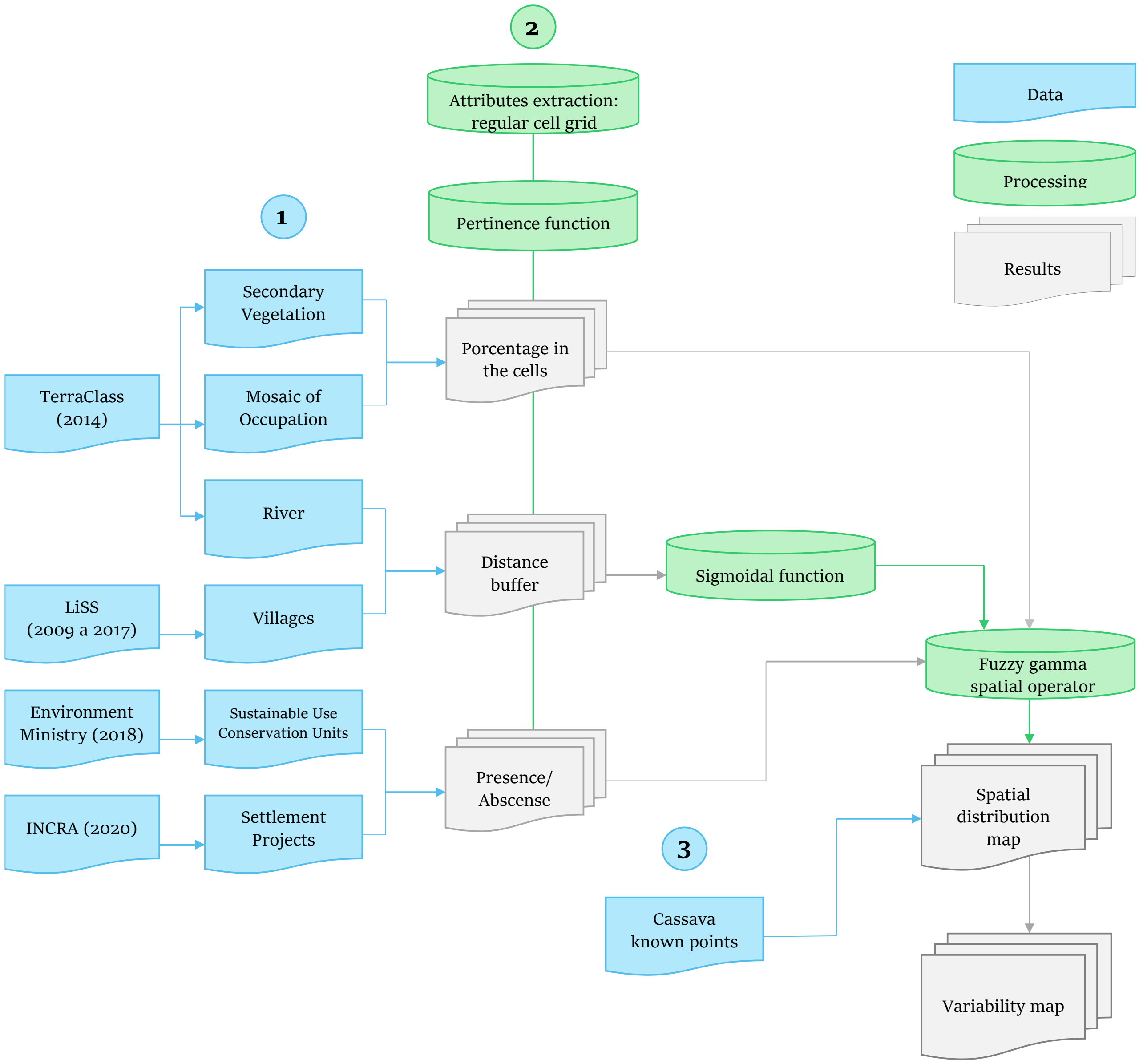
The region of study has two sustainable use conservation units: the Tapajós-Arapiuns Extractive Reserve and the Tapajós National Forest (MINISTÉRIO DO MEIO AMBIENTE, 2018), both of which have the presence of residents, reconciling nature conservation with the sustainable use of natural resources. The National Forest is "an area with forest cover of predominantly native species and its basic objective is the sustainable multiple use of forest resources and scientific research, with an emphasis on methods for the sustainable exploitation of native forests" (BRASIL, 2000). The Extractive Reserve is known for the presence of "traditional extractive populations, whose subsistence is based on extractive activities and, complementarily, on subsistence agriculture and small animal livestock farming, and its basic objectives are to protect the livelihoods and culture of these populations, and to ensure the sustainable use of the unit's natural resources" (BRASIL, 2000). The settlement projects are delimited by both the National Institute for Colonization and Agrarian Reform (INCRA, 2020), and the Pará Land Institute which occupies 21% of the area of study (939,299 ha). There are many villages and communities in this region. Field expeditions between 2008 and 2017 visited and recorded data on 273 localities (AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014, AFFONSO et al., 2016; DAL'ASTA et al., 2017).

[4] The Santareno Plateau is a region made up of firm and high lands on the axis of the Cuiabá-Santarém highway and encompasses part of the municipalities of Santarém, Belterra, and Mojuí dos Campos (SÁ et al., 2006).

3 MATERIALS AND METHODS

The main steps of this study are shown in Figure 2. The flowchart summarizes each of the stages in this study, which involve preparing the data collected (1), the procedures for manipulating it and generating maps with different potential scores for the occurrence of small-scale cassava farms using the fuzzy gamma spatial operator (2), as well as evaluating the model outcomes (3). The following sections present each of these stages in greater detail. The following programs were used to perform these steps: TerraView 5.5.1, TerraView 5.3.3, QGIS 3.10.7, and ArcGIS Pro.

Figure 2 – Methodological flowchart for spatialization of potential areas for small-scale agriculture with cassava plantations based on geographic inference based on the fuzzy gamma spatial operator.



Source: Authors (2024).

3.1. Preparing the database

The database consists of data vectors containing selected indicators associated with small-scale cassava farming in the Amazon. Six indicators of cassava farmlands were defined, taking into account the specificities of the study area, observed in field expeditions (AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014, AFFONSO et al., 2016; DAL'ASTA et al., 2017) and in the literature (DUTRIEUX et al., 2016; EMPERAIRE, PERONI, 2006; JAKOVAC et al., 2016, 2017; LAUE, ARIMA, 2016, PACHECO et al., 2021; SOUZA; ESCADA; MONTEIRO, 2017, 2019; VAN VLIET et al., 2013). The selected features refer to land use and land cover (secondary vegetation and mosaic of occupation rate), the proximity to communities (river and villages), and the presence of special uses (settlement projects and sustainable use conservation units), as shown in Chart 1.

Chart 1 – Factors and indicators used to map areas with different potentials for cassava farming.

Factor/ Indicator	Premise	Source
Environmental/ Secondary vegetation	Rate of deforested areas in the process of natural regeneration due to abandonment, which may indicate family farming practices with fallow periods (ALMEIDA et al., 2016).	TerraClass (INPE; EMBRAPA, 2014)
Land use/ Occupation mosaic	The mosaic of occupation [rate] is composed of areas with diverse land uses and land cover, which cannot be individually identified due to the spatial resolution of the sensors used and the minimum mapping area of 6.25 ha. Among them there is likely small-scale agriculture (ALMEIDA et al., 2016; SOUZA et al., 2019; SOUZA, 2016).	TerraClass (INPE; EMBRAPA, 2014)
Environmental/ Water bodies	Proximity to riverside communities with small rural producers who grow crops for subsistence (AFFONSO et al., 2016; AMARAL et al., 2009; ESCADA et al., 2013)	TerraClass (INPE; EMBRAPA, 2014)
Population/ Villages	Proximity to riverine or land communities with small rural producers who cultivate crops for subsistence, presence of fields (AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014, AFFONSO et al., 2016; DAL'ASTA et al., 2017; JAKOVAC et al., 2017)	Field expeditions (AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014, AFFONSO et al., 2016; DAL'ASTA et al., 2017)
Land regime/ Settlement projects	The presence of areas occupied by families who exploit the land for their own sustenance, using exclusively family labor (INCRA, 2020)	Land collection (INCRA, 2020)
Land regime / Sustainable use conservation units	Category that admits the presence of residents and allows activities that make use of natural resources, without compromising the continuity of renewable resources and ecological processes (ICMBIO, 2021)	Ministry of the Environment (2018)

Source: Authors (2024).

3.2. Fuzzy logic

Models based on fuzzy logic provide greater flexibility in map combinations when compared to boolean models. Burrough and McDonnell (1998) recommend using this technique to deal with ambiguous, vague, or ambivalent phenomena in mathematical or conceptual models. Unlike classical set theory, where a pertinence function is defined as true or false, i.e. 1 or 0, the degree of pertinence of the fuzzy set is expressed in terms of a scale that varies continuously between 0 and 1, whose values are defined using different mathematical functions. Individuals close to the central concept have pertinence function values close to 1, those who are far away receive lower values, close to 0.

The map algebra chosen for this study was fuzzy logic, using the fuzzy gamma spatial operator, represented by Eq. (1). This operator was selected because it can represent intermediate cases between the algebraic sum and the algebraic product, thus producing different results when building maps from the combination of indicators. Fuzzy logic allows the combination of layers with data from different units of measurement, as it operates with values on the same dimensionless scale and, it is possible to use data with continuous values (KOSKO; ISAKA, 1993; ZADEH, 1968).

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$$\mu_{combination} = \left(1 - \prod_{i=1}^{n} (1 - \mu_i)\right)^{\gamma} * \left(\prod_{i=1}^{n} \mu_i\right)^{1-\gamma} \quad (1)$$

Where:

μ_i = fuzzy relevance value for the i-th map
γ = operator fuzzy gamma

The fuzzy gamma operator (γ) is a parameter chosen from [0,1]. When the fuzzy gamma is equal to 1, the combination is equivalent to the algebraic sum, when the fuzzy gamma is equal to 0, the combination is equivalent to the fuzzy algebraic product. Thus, depending on the value of the fuzzy gamma used, intermediate output values can be produced, situated between the tendency to maximize with the fuzzy algebraic sum and minimize with the fuzzy algebraic product.

To prepare the layers to be combined by the fuzzy gamma operator, the data was transformed using pertinence functions and redistribution into a regular grid of cells described in section 3.2.1. Subsequently, different empirically defined values for the fuzzy gamma spatial operator were tested, generating different maps.

3.2.1 DATA TRANSFORMATION WITH PERTINENCE FUNCTION

The pertinence function indicates the correspondence between the phenomenon studied and the data in a given observation unit through a range between 0 and 1, reflecting the relative importance of each map, as well as the relative importance of each class in a single map (BONHAM-CARTER, 1994). This method is based on assigning weights to the input data based on the expertise of the specialist, so the values assigned to the relevance function are empirical (BONHAM-CARTER, 1994).

The indicators and the variables shown in Chart 1 were used with pertinence function values obtained in different ways (Table 1). These variables were generated in a cell grid using cell filling operators with a spatial resolution of 2 x 2 km. The size of the cells was chosen empirically. The cell space was then converted into a regular grid of the same spatial resolution.

Table 1 – Representation of the indicators on the regular cell grid with 2 x 2 km.

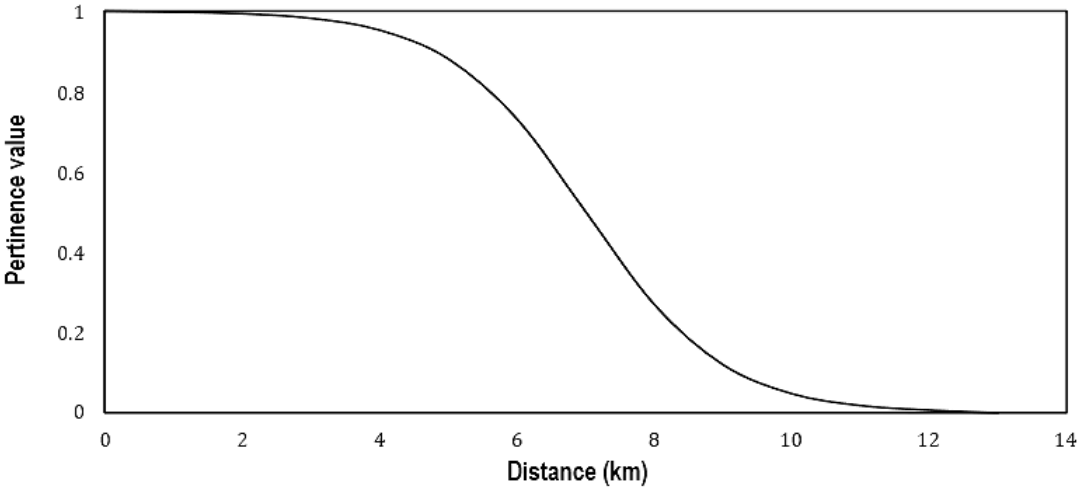
Indicator	**Variable**	**Grid values**
Secondary vegetation	% of class in cell	[0,02 - 1]
Mosaic of occupation	% of class in cell	[0,02 - 1]
Rivers	Distance to bodies of water	[0,02 - 1]
Villages	Distance to villages	[0,02 - 1]
Settlement projects	Absence/presence	0,02 ou 1
Sustainable use conservation units	Absence/presence	0,02 ou 1

Source: Authors (2024).

The layer range was modified to [0.02 - 1]. This adjustment was necessary because the second part of the equation is a multiplication of all the layers and, for all the cells in which at least one layer has a value of 0, the result will be 0, regardless of the relevance of the other layers, which is not a feasible situation.

For the land use and land cover data, it was calculated the percentage occupied by the mosaic of occupation and secondary vegetation classes in the cells. For the mosaic of occupation, the maximum value obtained was 0.73, so the data was rescaled to the pertinence interval. For the rivers and villages layers, a vector with a buffer of up to 12 km was generated to define the relevance values, given that this is the maximum distance traveled between homes and farming areas (AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014, AFFONSO et al., 2016; DAL'ASTA et al., 2017). For this, the sigmoidal function was used, so the cells closest to the water bodies/villages receive a value of 1. This value decreases as the distance increases and, after 12 km, the cells receive a value of 0.02 (Figure 3). For the data from settlement projects and sustainable use conservation units, attributes were also extracted, considering the presence and absence of each layer in the cell, i.e. the cells that overlapped with settlement projects/sustainable use conservation units received a value of 1 and the others received a value of 0.02.

Figure 3 - Sigmoidal function used to assign pertinence values to the river and village buffer.



Source: Authors (2024).

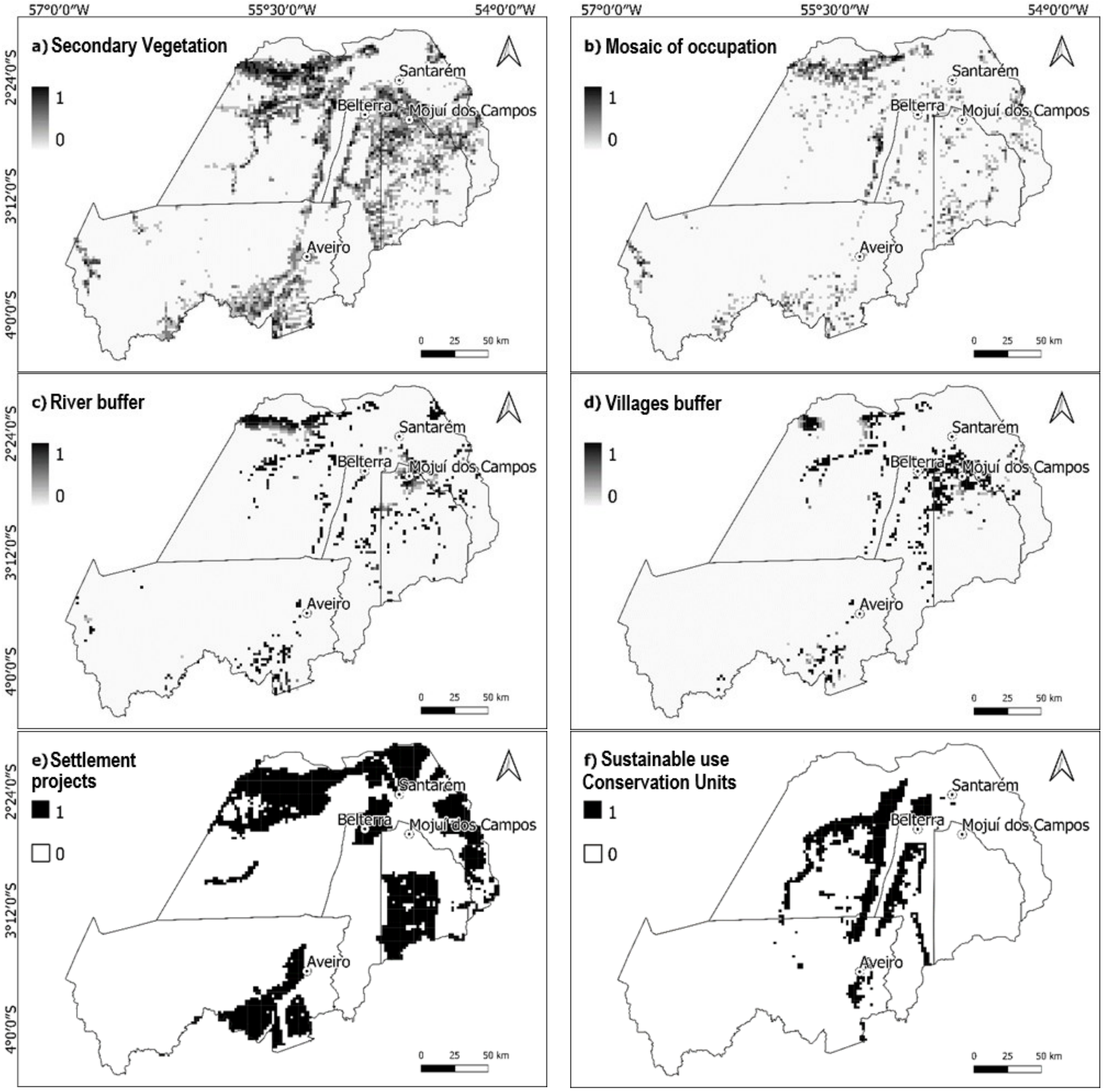
After transforming the data and preparing the indicators, a mask was created with the land use and land cover classes that, by definition, do not include cassava farmlands, namely: urban areas, forest, reforestation areas, clean pasture, pasture with exposed soil, mining, rivers, and non-forest areas (INPE; EMBRAPA, 2014). The mask was used to exclude these areas from the layers of settlement projects, sustainable use conservation units, river buffers, and village buffers. As a result, six grids of cells were obtained (Figure 4), which were combined using the fuzzy gamma spatial operator to generate the map with the spatial distribution of the different potential scores for cassava farming.

3.2.2 COMBINING THE MAPS WITH THE FUZZY GAMMA SPATIAL OPERATOR

The values of the fuzzy gamma operator were tested over the range from 0 to 1 to create different maps. After, the maps were split into the following classes of potential for cassava farming: low [0, 0.25], medium [0.25, 0.5] and high [0.5, 1].

Visually analyzing the spatial distribution of the cells classified with the different potential scores for cassava farming, fuzzy gamma values between 0.91 and 0.92 were consistent with the literature and with the patterns observed in previous field expeditions (COELHO et al., 2021; SOUZA, 2016; SOUZA; ESCADA; MONTEIRO, 2017; AMARAL et al., 2009; ESCADA et al., 2013; DAL'ASTA et al., 2014; AFFONSO et al., 2016).

Figure 4 - Regular grids of cells with the indicators used to manipulate the fuzzy gamma operator.



Source: Authors (2024).

3.3. Map of classification variability

The map of classification variability was obtained by selecting a collection of maps that were endorsed by the literature and had similar patterns observed in field expeditions. Maps with fuzzy gamma values of 0.910, 0.911, 0.912, 0.913, 0.914, 0.915, 0.916, 0.917, 0.918, 0.919 and 0.920 were combined. For each cell, the number of times the classes' medium or high potential for cassava farming was computed. This number was used to define zones of stability and instability in the classification of cassava farmlands. Stability zones are defined by having more often medium or high classification of potential for cassava farming in the cells' grid, indicating an area where the classification is more consistent. In instability zones, the frequency of occurrence of these classes varies, indicating regions with less consistent results.

Given the limitations due to the lack of points collected in the field, the results were validated using known points of cassava farming. In total, 80 known cassava farming points were collected via visual interpretation of satellite images available on Google Earth Pro and Planet Explorer.

4 RESULTS AND DISCUSSIONS

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The identification and spatialization of areas with different potential for cassava farming are discussed concerning the occurrence of cassava farming indicators in each context, and the presence of regional features. Since spatialization is the main result and contribution of this work, the discussion is based on the cassava farmland areas identified by the method and the scientific and social contribution of the method. Note that the results were generated from a combination of land use and land cover data from 2014 and therefore reflect the conformation of the landscape in that year.

The spatial distribution of the classes of potential occurrence of cassava farming sheds light on new interpretations of the organization of the territory by its social agents, in this case those responsible for small-scale agriculture. The results are, above all, an initial effort to identify new territorialities in the Amazon and their relationship with production systems (SÁ; COSTA; TAVARES, 2006), emphasizing the manner and spatial arrangement with which these classes are distributed in the landscape.

4.1. Contribution of the indicators for the classes of potential occurrence of cassava farming

The grid cells classified as having low potential for cassava farming, which were outside the exclusion mask, have contributions from up to three indicators: only one indicator for land use and land cover and two indicators for the proximity to communities. Cells with medium potential for cassava farming have at least one indicator from each group: land use and land cover, proximity to communities, and presence of land regime. The cells with a high potential for cassava farming have the maximum contribution, equivalent to five indicators, since the presence of land regime indicators (sustainable use conservation units and settlement projects) cannot occur simultaneously in the space. See Table 2.

Table 2 - Minimum number of indicators for each class of potential of occurrence of cassava farming.

Class	Land use and land cover	Communities proximity	Land regime
Low	0	0	0
Medium	1	1	1
High	2	2	1

Source: Authors (2024).

4.2. Potential Occurrence of Cassava Farming

The resulting spatialization of different potential classifications for cassava farming (Figure 5) corroborates Souza (2016), who observed family farming where peasant production is located, which is indicative of areas with medium and high potential for cassava farming. Using a typology of landscape patterns, the author identified peasant production systems associated with agriculture activities only or extractive activities alongside agriculture activities. Souza (2016) names Family Farming 1 the areas of peasant production that are allocated for agricultural activities, which cultivate white crops (rice, beans, corn, cassava), livestock, fruit, and cocoa, occupying areas between 0.0023 and 100 ha. The landscape patterns are predominantly marked by patches of continuous secondary vegetation, while the Extractivism and Family Farming 2 category also includes areas of peasant production, but in these areas, extractive activities are practiced alongside agriculture. The size of agricultural areas usually does not exceed 0.05 ha and the patches of secondary vegetation and primary forest are large and continuous, the latter being predominant. Most cassava production in the study area takes place in farms smaller than 5 ha (98%) and in family farms (92%), according to the 2017 Agricultural Census (IBGE, 2017). Although the methodological approaches and scale of analysis of IBGE (2017) and Souza (2016) are different, both indicate the same type of actors associated with cassava production.

The results for the spatial distribution of areas with potential for cassava farming with different values for the fuzzy gamma spatial operator support both more accurate interpretations in terms of area, but which do not incorporate fallow areas (lower fuzzy gamma values), and less accurate results in terms of area, but with cells that incorporate fallow areas (higher fuzzy gamma values). This method can be replicated between census periods, supporting the understanding of cassava farming dynamics and its spatial distribution over shorter intervals.

Analyzing the results by municipality (Table 3), Santarém has the largest part of its territory with areas of medium and high potential for cassava farming, occupying between 13% and 23% of its area. In Belterra, the areas with medium and high potential for cassava farming range from 8% to 17%, and in Mojuí dos Campos from 8% to 20%. In Aveiro, these classes cover between 3% and 7% of the territory. In absolute terms, the areas with medium and high potential for cassava farming corroborate the performance of the municipalities in terms of cassava harvested area, as indicated in the Agricultural Census (IBGE, 2017): Santarém had the highest values, Aveiro and Mojuí dos Campos had similar intermediate values to each other and Belterra had the lowest values (Table 4).

Table 3 – Class intervals of potential occurrence of cassava farming, by municipality, in thousand hectares, considering the fuzzy gamma from 0.910 to 0.920.

Potential	Aveiro		Belterra		Mojuí dos Campos		Santarém	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Low	1,593.5	1,660.2	365.9	404.1	399.0	458.9	1,386.1	1,565.2
Medium	42.5	103.6	29.76	66.7	39.9	99.8	179.2	341.4
High	4.8	10.4	5.9	7.2	0	0	45.5	62.5

Source: Authors (2024).

Table 4 - Harvested area of cassava, by municipality, in hectares.

	Aveiro	**Belterra**	**Mojuí dos Campos**	**Santarém**	**Total**
Harvested area	918.00	246.00	904.00	3,507.00	5,575.00

Fonte: Censo Agropecuário. IBGE (2017).

Over the study area, Santarém had the highest record of medium potential for cassava farming, where between 58% and 65% of the grid cells fall into these classes. This is noteworthy because this is a municipality that has undergone major transformations due to the entry of soybean farming. Many peasant production areas have transitioned farmland to soybean production (COELHO et al., 2021), but the total conversion of these areas to large-scale agriculture has not occurred (SOUZA, 2016). In Belterra and Mojuí dos Campos, the areas with medium potential for cassava farming were scattered throughout the territory, mainly in the Santareno Plateau region. Together, the two municipalities have between 21% and 25% of medium and high potential cassava farming cells. In Aveiro, there are 14% to 16% of the areas with medium potential for cassava farming, most of which are scattered around the Tapajós River, mostly within the Tapajós FLONA and the Tapajós-Arapiuns RESEX.

Aveiro was the main municipality in terms of areas with low potential for cassava farming (41% - 43%) and is also the municipality with the largest continuous areas of primary forest. Santarém was attributed 37% to 38% of the grid cells with low potential for cassava farming, mainly due to the presence of primary forest and large-scale annual agriculture. Belterra and Mojuí dos Campos registered, respectively, 10% and 11% of this class, with a significant presence of large-scale annual agriculture and pasture.

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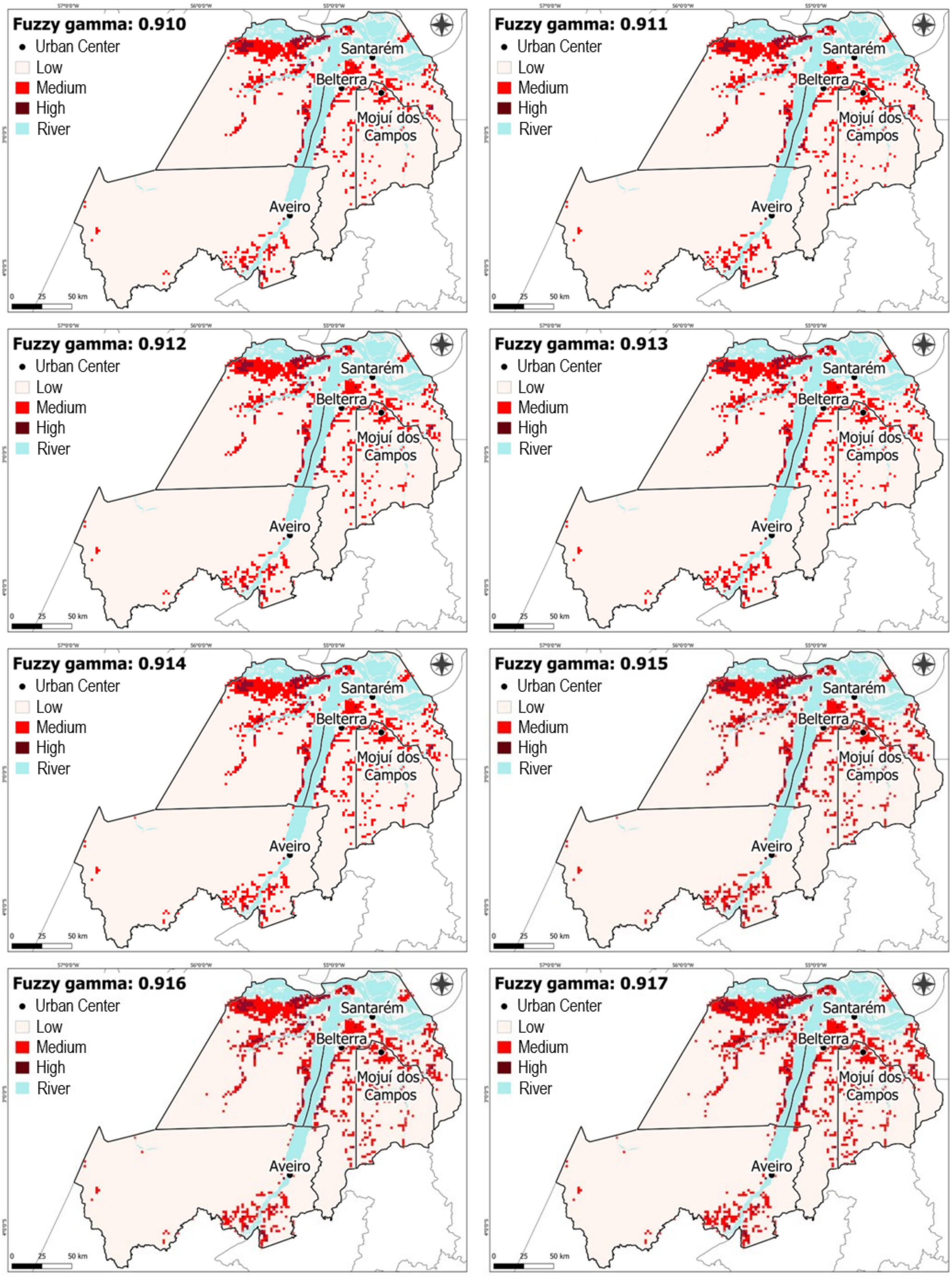
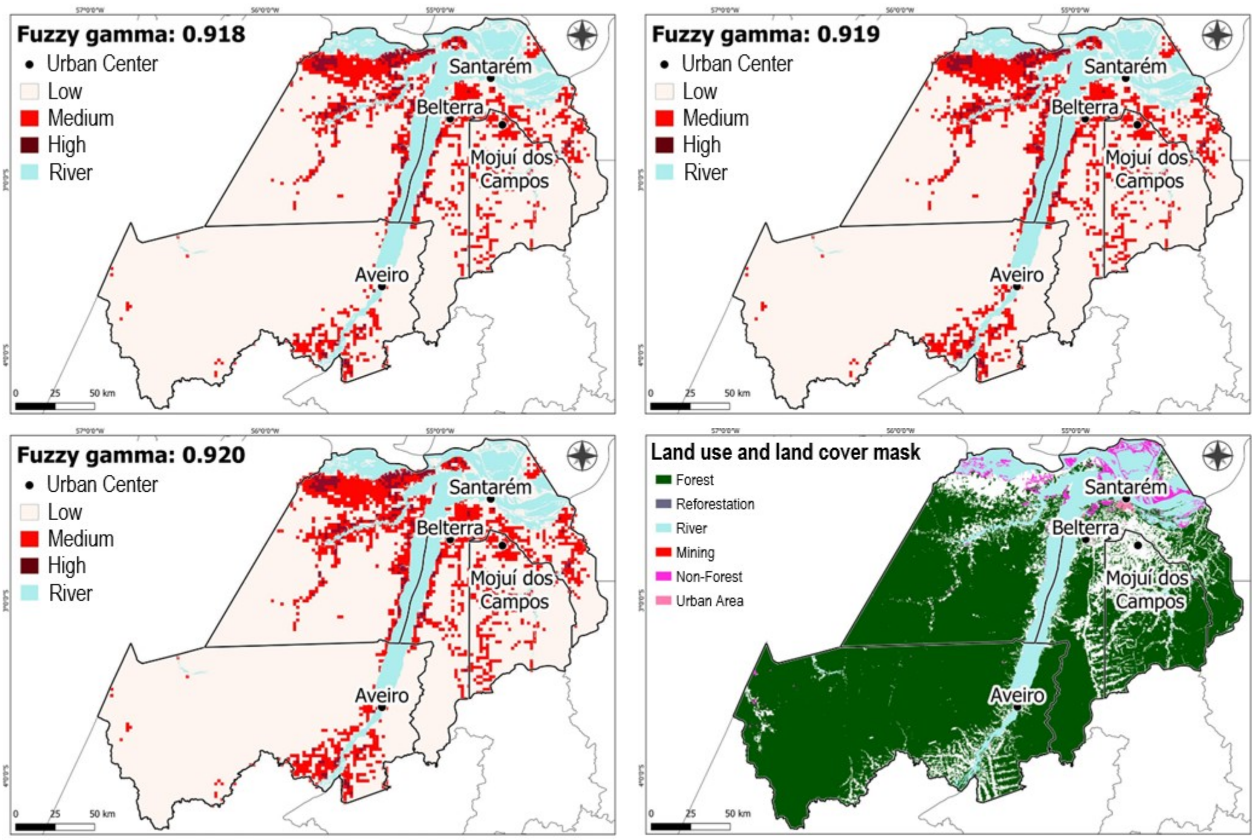
Figure 5 - Spatial distribution maps with the classes of potential for cassava farming with different values for the fuzzy gamma spatial operator.



Source: Authors (2024).

Figure 5 - Spatial distribution maps with the classes of potential for cassava farming with different values for the fuzzy gamma spatial operator.



Source: Authors (2024).

4.3. Areas with low potential for cassava farming

The areas with low potential for cassava farming range from 2.5M to 3.7M ha and are predominantly in Aveiro (41% - 43%), followed by Santarém (37% - 38%), Mojuí dos Campos (11%), and Belterra (10%). The presence of land regime is very important in these areas: 41% to 70% of these cells are located in settlement projects or sustainable use conservation units. The high proportion of areas with low potential scores is due to the presence of primary forest, which represented the main land cover in the 2014 TerraClass (INPE; EMBRAPA, 2014).

The cells classified as having low potential for cassava farming are in land use and land cover classes that do not support this activity. The mask excluded approximately 3,800.00 ha where land use and cover, by definition, do not support cassava farming, such as primary forest (84%) and hydrography (14%). The application of the exclusion mask strongly contributed to defining these areas. However, there are cells with low potential for cassava farming that are outside of the exclusion mask, as shown in Figure 6. This is more frequent in the Santareno Plateau region, where there is large-scale annual agriculture, as well as pastureland. The cells that were not incorporated into the mask have, on average, around 10% large-scale annual agriculture and 33% pasture (clean or dirty), according to INPE; EMBRAPA (2014). In this region there are no areas with favorable land regimes for cassava farming (settlement projects and conservation units). Despite the presence of riverine populations and communities, as well as areas with secondary vegetation, the indicators associated with these elements are not significant enough for the cells to be classified as having medium or high potential for cassava farming.

On the other hand, some cells had part of their land use and land cover excluded by the mask, but still were classified as having medium or high potential for cassava farming due to the presence of other features, which explains the exclusion mask having a larger area than the areas with low potential for cassava farming. These excluded areas were more common on riverbanks and in grid cells that had both primary forest and

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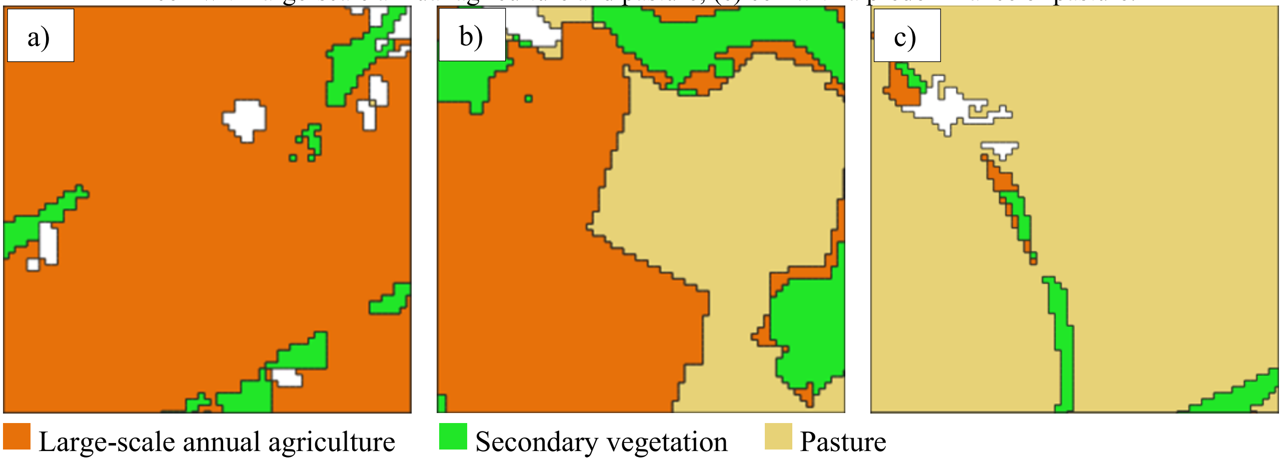
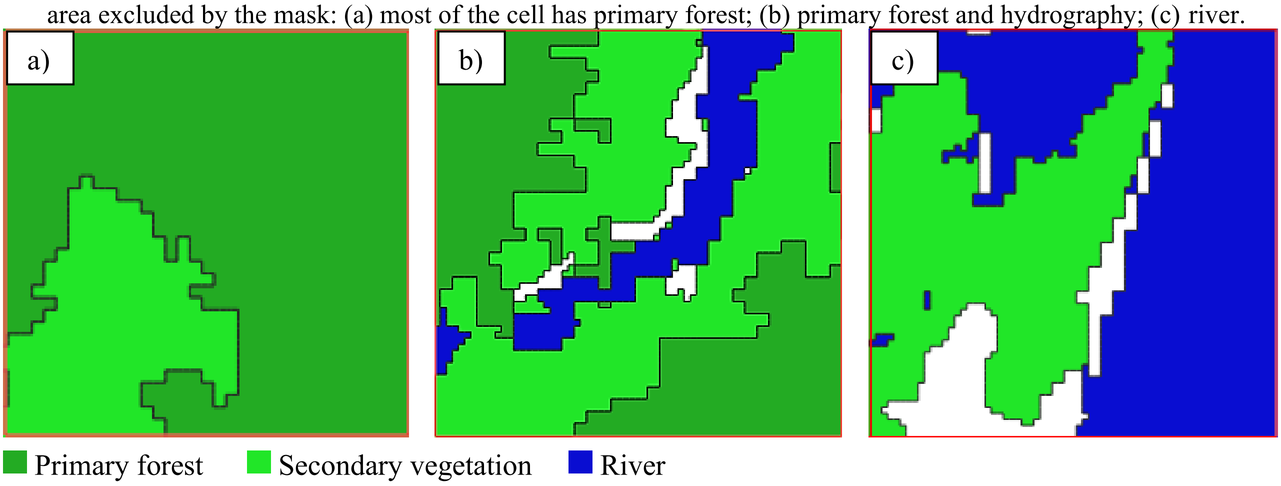
secondary vegetation, as shown in Figure 7. Despite the excluded areas of primary forest and/or rivers, the cells have the presence of patches of secondary vegetation and are in settlement projects and within the buffer of rivers and villages, explaining its classification.

Figure 6 - Examples of cells outside the exclusion mask, which have been classified as having low potential score due to the low prevalence of cassava farming indicators: (a) cell with a predominance of large-scale annual agriculture; (b) cell with large-scale annual agriculture and pasture; (c) cell with a predominance of pasture.



Source: Authors (2024).

Figure 7 - Examples of cells classified as having medium or high potential for cassava farming, which had part of their area excluded by the mask: (a) most of the cell has primary forest; (b) primary forest and hydrography; (c) river.



Source: Authors (2024).

4.4. Areas with medium and high potential for cassava farming

The medium and high potential areas for cassava farming summarize the results obtained from the spatial distribution of cassava farmlands. Therefore, the discussion of these classes will be better informed if performed concurrently.

The areas with medium potential for cassava farms appear mainly in Santarém (58% - 65%), followed by Aveiro (14% - 16%), Mojuí dos Campos (11% - 14%), and Belterra (10% - 11%). Aveiro and Mojuí dos Campos showed similar results, but for different reasons. The areas with medium potential are concentrated on the banks of the Arapiuns, Tapajós, and Lago Grande do Curuai rivers and near downtown Santarém. In general, the areas with medium potential for cassava farming have in common a significant association with secondary vegetation, proximity to rivers, and the presence of a settlement project or sustainable use conservation unit. In other words, these areas are influenced by at least one indicator from each category: land use and land cover rates, the proximity to communities, and the presence of land regimes.

Only 1% to 2% of the study area was considered to have a high potential for cassava farming. Most of these regions are in Santarém (78% - 81%), followed by Aveiro (9% - 13%), and Belterra (9% - 10%), while Mojuí dos Campos did not have any areas with this classification. All of the high potential classification areas are at a maximum distance of 5.8 km from the main rivers and are found mainly in the riverside areas between the Arapiuns River and Grande do Curuai lake. Regarding the villages, the maximum distance to the cells with high potential for cassava farmlands is 12.7 km. Between 88% and 89% of these areas are within RESEX Tapajós-Arapiuns or FLONA Tapajós or are part of a settlement project. All of the cells have at least part of their area overlapping with settlement project areas or sustainable use conservation units. In terms of land use and land cover, these areas had an average of 47% ± 19% secondary vegetation rate and 9% ± 9% mosaic of occupation rate (INPE; EMBRAPA, 2014). Considering the thresholds used, these areas have five out of six features, which is the maximum possible number of features in a cell, given that the presence of a settlement project and a sustainable use conservation unit cannot occur simultaneously[5].

4.4.1 ANALYSIS OF THE SPATIAL DISTRIBUTION OF CASSAVA FARMING POTENTIAL SCORE

The areas on the banks of the Arapiuns, Tapajós, and Grande do Curuai rivers form the most important region with medium and high potential for cassava farming. This is a region of ancient occupation, with communities established more than 100 years ago (AMARAL et al., 2009) and using the roçado system, which includes cassava farming and has a low likelihood of land use intensification (ESCADA et al., 2013; SOUZA; ESCADA; MONTEIRO, 2017). More specifically on the edges of FLONA Tapajós and RESEX Tapajós-Arapiuns, particularly at the mouth of the Tapajós river, where there is high level of landscape diversity, implying heterogeneity of land use and land cover. Among these is the peasant production practiced by the riverinee communities (SOUZA; ESCADA; MONTEIRO, 2017). Although both regions are important for small-scale agriculture and cassava farming, some particularities differentiate them.

Agriculture within FLONA Tapajós is more diversified than in RESEX Tapajós-Arapiuns and their communities are closer to Santarém (30.7 ± 15.4 km), some of which even have access to roads (CAMILOTTI et al., 2020). The access to roads allows for more frequent travel and access to other markets, increasing opportunities for financing and commercialization of agricultural products. This changes the way communities use their resources, whether through encouraging diversification of crop production or specialization, increasing the volume of agricultural products produced, or extractive activity in the community (BRONDIZIO, 2009; CAMILOTTI et al., 2020).

In the Tapajós-Arapiuns RESEX, cassava cultivation is predominant and accounts for 70% of farmers' income, with products from extractive activities also playing an important role (CAMILOTTI et al., 2020; ESCADA et al., 2013; SOUZA, 2016). A significant part of the agricultural production of the communities located in the Tapajós-Arapiuns RESEX is devoted to non-commercial use and most of the commercial trade is within or between local communities (CAMILOTTI et al., 2020). Less often, monthly trips are made to Santarém to trade manioc flour and medicinal plants (CAMILOTTI et al., 2020). Due to the greater distance from these communities to Santarém, the forest's extractive activities are more important for their economy than in other groups (agro-extractive communities of FLONA Tapajós and land communities around the Transamazônica highway), indicating a strong correlation between the diversity of the products extracted from the forest and the distance to Santarém (CAMILOTTI et al., 2020; DAL'ASTA et al., 2014). Ratifying that small-scale agriculture is impacted by the location of producers, the easy access to roads, and local markets, which is historically one of the biggest limitations of the regional economy in the Amazon (AGUIAR, 2012; BRONDIZIO, 2009). Local initiatives encourage forest-dependent communities practicing small-scale agriculture to work together to have better access to markets, increasing their products' added value (BRONDIZIO et al., 2021). In a survey carried out in 174 municipalities in the Legal Amazon, half of the local initiatives mapped were in private lands/ communities and the other half in areas with a land regime favorable to small-scale agriculture: 18% in communities located in conservation units, 15% on indigenous or Quilombola land and 17% in settlement project areas (BRONDIZIO et al., 2021). When mapping the Tapajós-

[5] Settlement project areas and sustainable use conservation units, as a rule, do not overlap. However, in Santarém, there is an exception: the Alter do Chão Environmental Protection Area overlaps with two INCRA settlement projects (INCRA, 2020; MINISTÉRIO DO MEIO AMBIENTE, 2018). This situation exposes an institutional difficulty in delimiting these areas and highlights the need to monitor the dynamics of the interests of the actors involved in these territories (FREIXO, 2019).

Arapiuns RESEX region, the typology found by Souza (2016) was precisely the production system in which the peasant is based on extractive activity and small-scale agriculture, called by the author as Extractivism and Family Farming 2. This region is characterized by the long presence of indigenous and mixed communities, some of which are over 150 years old (ESCADA et al., 2013). In riverside areas with caboclo and indigenous communities, swidden agriculture remains the main land use (VAN VLIET et al., 2013).

Despite the persistence of swidden agriculture in riverside regions of the Amazon, these systems have changed in response to recent socio-economic transformations (JAKOVAC, 2015). The territorial organization of the villages of the Santareno Plateau, near urban downtown Santarém, has been modified to encourage grain production, especially soybean, which is responsible for land use intensification (LAURANCE; GOOSEM; LAURANCE, 2009; SOUZA, 2016; SOUZA; ESCADA; MONTEIRO, 2017). The expansion of industrial and mechanized agriculture in the Santarém region between 1999 and 2015 took place over areas of secondary vegetation (20%), pasture (20%) and forest (18%), but mostly over areas of peasant agriculture (42%), according to Coelho et al. (2021).

In this region of the Santareno Plateau, in Belterra, Mojuí dos Campos and part of Santarém, the areas with medium potential for cassava farming appear further away from urban centers and scattered across the landscape, where annual agriculture and pasture are important land uses (INPE; EMBRAPA, 2014). Along the highways, areas of swidden agriculture have been replaced by large-scale agriculture and pasture (VAN VLIET et al., 2013), registering an increase in the land use intensification (LAURANCE; GOOSEM; LAURANCE, 2009; SOUZA, 2016; SOUZA; ESCADA; MONTEIRO, 2017). Highway construction boosted the movement of people and goods among different areas, shaping the settlement occupation processes in the region (SÁ; COSTA; TAVARES, 2006).

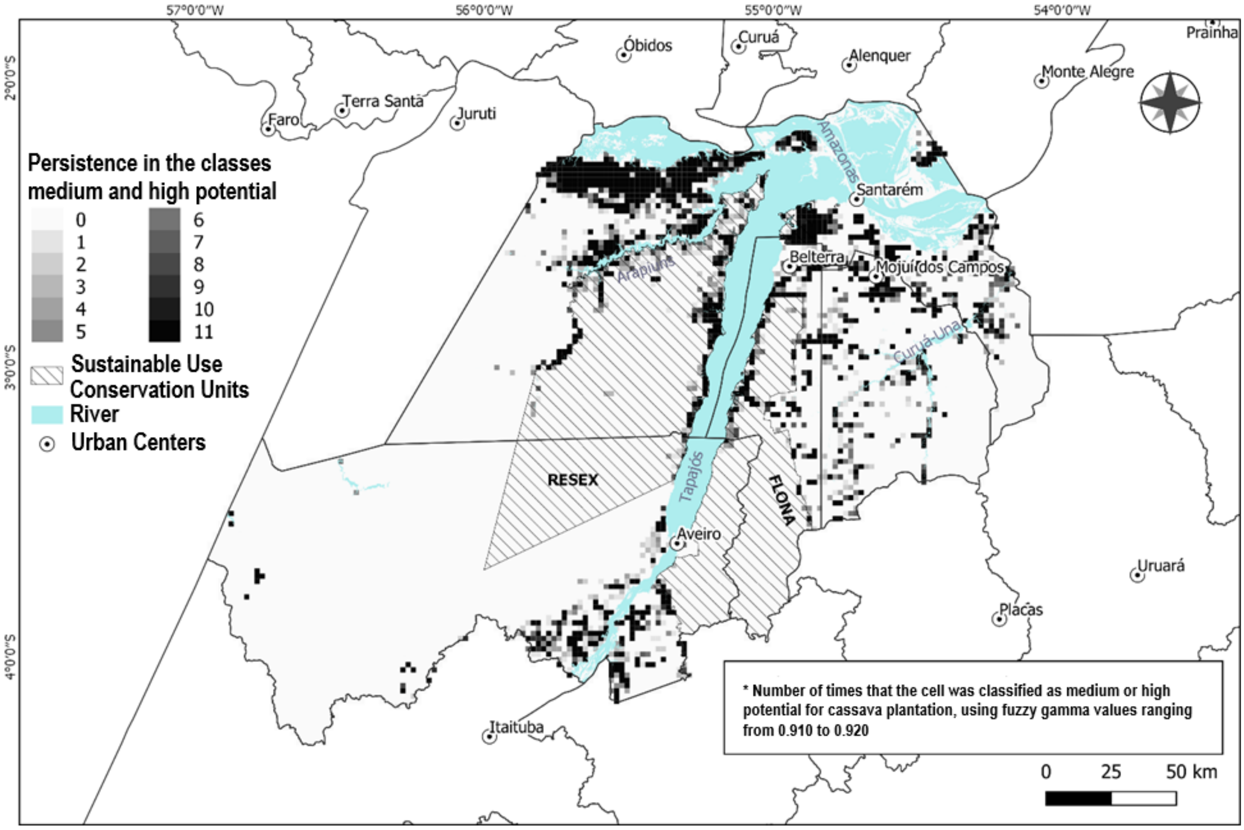
In the municipality of Aveiro, the areas with medium and high potential for cassava farming predominate around the Tapajós River, where the communities are located. In this region, in addition to secondary vegetation, areas of clean pasture and dirty pasture are also important. Therefore, the cells with medium and high potential for cassava farming appear due to the presence of secondary vegetation, the villages, and the proximity to the river, but they are scattered among pasture areas.

4.5. Stability zones

The spatial distribution map in Figure 8 shows the cells classified as low, medium, or high potential for cassava farming. Most of the cassava farm points collected by visual interpretation appear within the medium and high cassava farming potential cells (51% - 71%), for the fuzzy gamma values of 0.910 to 0.920. The smallest proportion of visually classified points representing cassava farms appears in the cells with low potential for cassava farming (29% - 49%). On the persistence map and stability zones (Figure 8), 51% of the points are in areas that have been classified as having medium or high potential for cassava farming for all the fuzzy gamma values in the 0.910 to 0.920 range. Around 18% of the points are in areas classified as medium or high potential between 1 and 9 times for the fuzzy gamma range mentioned above. Finally, 30% of the points are in areas that have been classified as low potential for cassava farming for all fuzzy gammas.

In summary, 70% of the visually classified cassava farm points appear within cells that have been classified at least once as medium or high potential for cassava farming by the classification variability map. The variability map supports the discussion by indicating the areas where the medium and high classes persist and therefore represent the greatest potential for cassava farming. This accuracy is similar to studies mapping small-scale agriculture in the Amazon using object-oriented classification, which achieved results with accuracy between 60% and 80% (PACHECO et al., 2021; SOUZA, 2016). Therefore, the technique used in this research is a viable alternative to other more cumbersome and complex models resulting in comparable accuracy, and reasonably estimating the spatial distribution of areas with potential for cassava farming by taking advantage of geographic inference approaches.

Figure 8 - Map of persistence in the medium and high potential classes for cassava farming.



Source: Authors (2024).

5 CONCLUSION

The spatial distribution of areas with different potential for cassava farming is concentrated in riverine areas, mainly on the banks of the Grande do Curuai lake, as well as the Arapiuns, Tapajós, and Curuá Una rivers, where sustainable use conservation units and settlement projects are present, and the main land cover was secondary vegetation. In the land areas, where large-scale annual agriculture and cattle ranching are predominant, the potential areas for cassava farming are more dispersed across the landscape. Santarém is highlighted as the main municipality in terms of areas with medium and high potential for cassava farming. The studied areas in Belterra and Mojuí dos Campos were classified as having medium potential for cassava farming. Aveiro is the municipality where areas with low potential for cassava farming predominate. Cassava farm points classified by visual interpretation, when compared with the persistence map and stability zones to assess model accuracy, showed 70% agreement, where these points are in cells that have been classified at least once as having medium or high potential for cassava farming by the classification variability map approach. This is similar to other studies mapping small-scale agriculture in the Amazon.

The fuzzy logic, supported using pertinence functions and the fuzzy gamma spatial operator, proved to be suitable for analyzing spatial distributions, providing results that were validated by the known cassava farming points, as well as by the existing literature for the region, which agrees with the spatial distribution of areas with potential for cassava farming. Selecting the most relevant features to input in the model was just as important as determining the mask with land uses and land cover which, by definition, does not support cassava farming. In addition, the choice of the fuzzy gamma approach allowed the inclusion of different types of indicators in the model, enabling results from models using continuous variables as indicators for cassava farming areas. Further, the stability zones' map highlighted the most relevant areas, more likely to have higher cassava farming potential.

The spatial distribution of the potential for cassava farming areas using this geographic inference technique is a novel methodology that can reveal priority areas and guide public entities when creating policies for this important yet disregarded cropping system in Amazonian communities. Further, when studying agriculture systems in the Amazon, there is a need to adapt classic methodologies to new approaches that can capture the specific features of this complex biome. The fuzzy gamma approach proved to be robust and provided adequate results when compared to other more cumbersome classification methods. The results obtained contribute to the study of agricultural production systems and can be used to support the drafting of policies aiming at regional development, as well as the spatialization of official cassava production data using area data distribution models.

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Authors Contribution

Conceptualization: F.D.P. and M.I.S.E. Data curation: F.D.P. Formal analysis: F.D.P. and M.I.S.E. Acquisition of funding: M.I.S.E. Research: F.D.P., A.R.S. and M.I.S.E. Methodology: F.D.P. and M.I.S.E. Project management: F.D.P. and M.I.S.E. Supervision: M.I.S.E. Validation: A.R.S. and M.I.S.E. Visualization: F.D.P. Writing - initial draft: F.D.P. Writing - revision and editing: F.D.P., A.R.S. and M.I.S.E.

Conflicts of Interest

The authors state that there is no conflict of interest.

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