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Foreword

Embrapa Territorial is one of Embrapa's basic-theme research Units, and its focus is on providing territorial intelligence, territorial management and territorial monitoring solutions for Brazilian agriculture. In its projects and actions, the Unit develops and applies methods that equip public and private managers with knowledge about the complexity of the rural world, its challenges and opportunities.

Our multidisciplinary teams make use of a wide range of geotechnologies to produce, integrate, and analyze information of different sources, natures, territories and temporal scales.

We develop and apply methods, techniques and procedures to detect, identify, qualify, cartographically represent, foresee, and monitor several aspects and factors that influence the dynamics of agriculture, animal production, forestry and environment on a local, regional and national scale.

Good territorial forecasts and diagnoses are essential tools for sustainable agricultural development, for balancing production, social economy and environment. Aside from characterizing technical and agricultural aspects, detailed analyses of a given region require understanding how these characteristics interact with each natural, agrarian, agricultural, infrastructure and socioeconomic situation, and enable us to monitor their evolution.

This publication offers an insight into materials, methods used and results obtained by a team of experts along the activities involved in the mapping of aquaculture ponds on a national scale. Identifying these structures may contribute to more adequate public policies for the national aquaculture production chain, by supporting decisions made both in private and public sectors. This work also draws attention to the need new for researches that apply remote-sensing automated techniques and technological resources that convey more agility to maintain, augment and update databases on aquaculture ponds, and are essential for territorial planning with the aim of increasing Brazilian aquaculture's competitiveness and sustainability.

Good reading!

Gustavo Spadotti Amaral Castro

Head of Embrapa Territorial

Sumary

Introduction

Aquaculture activities have been part of mankind's history for centuries. In Aktihep's tomb (2,500 B.C.), ancient Egypt, scenes of men removing tilapias from aquaculture ponds are depicted (Basurco; Lovatelli, 2003). In Brazil, aquaculture is defined by Brazilian federal law no. 11,959, from June 29, 2009, as the total or partial growth of organisms in aquatic environments, typically within a confined or controlled space. Fishing may be defined as the capture of fishery resources in a natural environment. Aquaculture's advantage over fishing is the generation of more homogeneous, traceable, and consistently available products (Embrapa Pesca e Aquicultura, 2022a).

Fishing and aquaculture play an essential role in food production and supply for both human and animal consumption, and also generate employment and income in various parts of the world. Economic forms of production are practiced as standalone activities or in association with other agricultural activities, such as farming and livestock rearing (Allison, 2011). There are also hybrid production systems, such as rice–shrimp or rice–fish (Renaud et al., 2015). In this context, aquaculture has a multiplier economic potential in rural frontiers (Allison, 2011).

The applicability of Remote Sensing products and services to aquaculture may be divided into three areas: i) monitoring water quality, ii) selecting areas for aquaculture activities, and iii) mapping and monitoring aquaculture production structures (Boivin et al., 2004). The latter is essential for the formulation of appropriate regulations and the provision of government incentives, for the territorial planning of aquaculture activities, and to provide statistical and geospatial data for market intelligence studies.

Over the last decades, scientific researches on aquaculture have shed light on the role played by this economic activity as a replacement for fisheries, as well as on its environmental and social impacts and on the outcomes of this change for global food production (Naylor et al., 2000). There is a trend for greater technological developments in management, with the aim of reducing unwanted environmental effects, increasing product quality and improving the industry's potential for employment and income generation (FAO, 2020; 2021).

Aquaculture in the world

The aquaculture industry has strong potential for animal protein production and plays a crucial role in global food security (FAO, 2020). Global fish, crustacean and mollusc fisheries amounted to 177.8 million tons in 2019, only 1% less then in 2018. Capture fisheries accounted for 92.5 million of these tons, a 4.3% decrease in comparison to the previous year. Aquaculture production accounted for 85.3 million tons in 2019, a 3.7% increase in comparison with 2018. In 2019, its estimated total world production value was US$ 406 billion, out of which US$ 260 billion were aquaculture production figures (FAO, 2021).

Also in 2019, the ten largest aquaculture producers (aquatic plants and non-edible goods excluded) were China (48.2 million tons), India (7.8 million tons), Indonesia (6.0 million tons), Vietnam (4.4 million tons), Bangladesh (2.5 million tons), Egypt (1.6 million tons), Norway (1.5 million tons), Chile (1.4 million tons), Myanmar (1.1 million tons) and Thailand (1 million tons). Collectively, their production amounted to 75.4 million tons, 88.4% of the world's total aquaculture production. Brazil occupies the 13^{th} position, with a total production of 599.550 tons (FAO, 2021).

Aquaculture of round fish species in inland waters was the most important sector in global aquatic-animals aquaculture. Its 48.4 million tons accounted for 56.7% of the world's total aquaculture production in 2019. Aquaculture's contribution to the total production of aquatic animals (capture and aquaculture combined) continuously increased from 39.9% in 2010 to 48.0% in 2019 (FAO, 2021).

Over the last two decades, there was a significant increase in aquaculture's importance in comparison to fisheries on a world scale. There was an increasing growth in aquaculture participation, especially inland aquaculture (Figure 1). In 2018, aquaculture accounted for 46% of the total production and 52% of the human consumption of fish (FAO, 2020). In the same year, aquaculture production rates were higher than fisheries rates in at least 39 countries (Bonfá Neto, 2021).

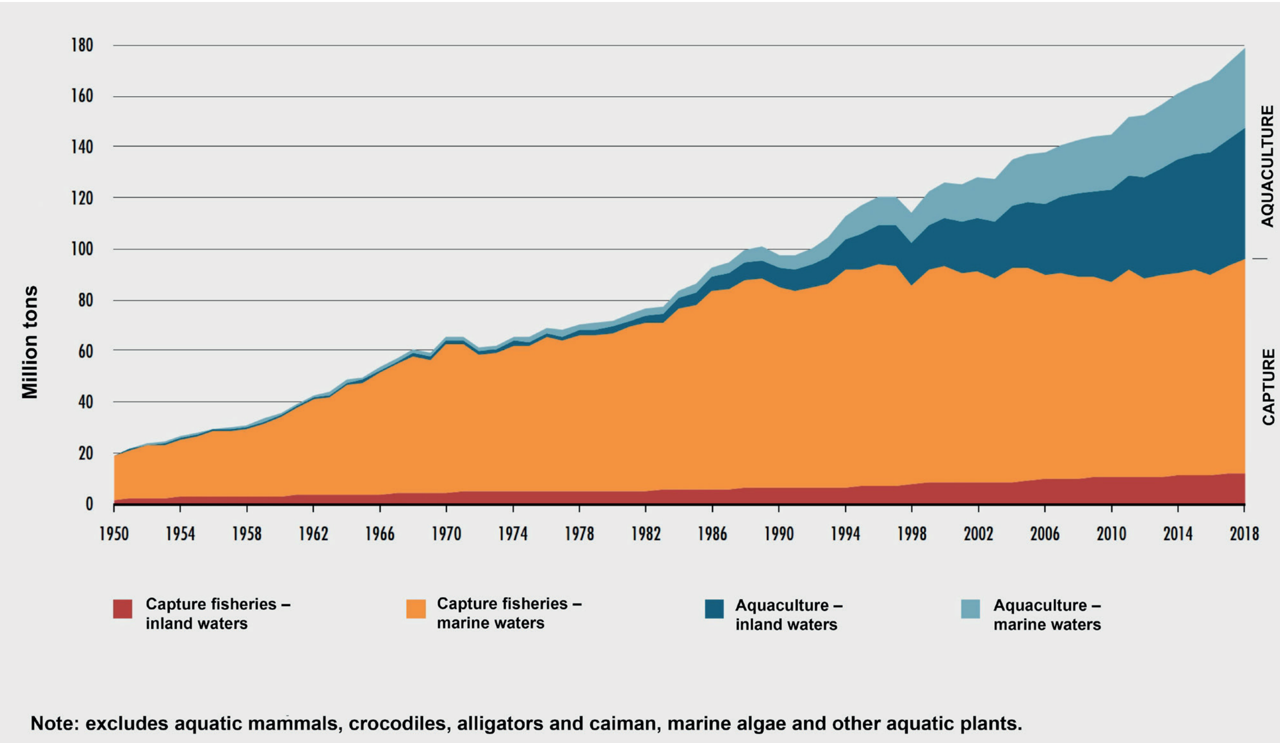

Figure 1. World capture fisheries and aquaculture production.

Source: FAO (2020).

The world consumption of fish as food increased at an average annual rate of 3.1% from 1961 to 2017, almost twice the annual world population growth rate (1.6%) for the same period, and higher than the increase rate for all other animal proteins (meat, dairy, milk, etc.), which increases 2.1%/year on average (FAO, 2021). The demand for fish-based products is likely to increase in the coming decades, due to socio-economy, health or religion reasons (Rocha et al., 2013).

Aquaculture is traditionally concentrated in coastal zones (Ottinger et al., 2018). Due to the advances observed in this industry, the search for new areas favorable for aquaculture enterprises has advanced inland on a global scale (FAO, 2020). Inland aquaculture is mostly freshwater production, and aquaculture ponds are the most common facilities among options such as cages, raceways, aboveground tanks, etc. (FAO, 2020).

Aquaculture in Brazil

Featuring the world's largest freshwater reserve (approximately 5,500,000 ha of water surface represented by reservoirs) and an extensive oceanic coastline of approximately 8,400 km (Brasil, 2012), Brazil has huge potential for the development of aquaculture. Among the strengths for Brazilian growth in the aquaculture sector are favorable geographic and climate conditions for this activity, abundance of water resources, and a strategic location for exporting its production to the entire Americas and Europe, as well as high production rates of grains, a crucial ingredient for feed manufacturing (Embrapa Pesca e Aquicultura, 2022b).

Fish farming practiced in State-owned waterbodies has been increasing in the country. Its declared production has grown 16%, from 61,371 t in 2019 to 71,512 t in 2020 (Brasil, 2021). This production occurs mainly in hydroelectric power plants' reservoirs located in the Tocantins–Araguaia, Paraná and São Francisco river basins, as well as in federal rivers and within the Brazilian territorial sea. It is worth highlighting that there is huge production potential to be explored, since the total production declared for all basins accounts for only 14.6% of the total fish farming capacity in Federal waterbodies (Brasil, 2021).

According to *Boletim Estatístico da Pesca e Aquicultura de 2011*, there was a 51.2% increase in Brazilian production in 2009–2011, and the largest production share comes from inland aquaculture, with a special highlight to inland fish farming, which accounts for 86.6% of the total national production (Brasil, 2011). This growth may be linked to the industry's development, which, on its turn, is due to the expansion of public policies that made it easier to access existing government programs, such as *Plano Mais Pesca e Aquicultura* (More Fisheries and Aquaculture Plan, in English) (Brasil, 2011). According to recent data made available by the Food and Agriculture Organization of the United Nations (FAO), Brazil occupied the 13th position in 2018's world ranking for fish farming in captivity and the 8th position in freshwater fish production (FAO, 2020).

Brazil has not published data on the industry's individual production segments since 2011. However, the Brazilian Institute of Geography and Statistics (IBGE), in its annual report on municipal animal production, *Produção Pecuária Municipal* (PPM), has been offering data about aquaculture since 2013 (Bonfá Neto, 2021). For the year 2020, PPM indicates 551.9 thousand tons, a growth of 4.3% in fish farming in comparison to 2019. The three major producers are the states of Paraná, which accounts for 25.4% of the total national production, São Paulo (10.0%) and Rondônia (8.7%). Among the species produced, tilapia accounts for 62.3% of the total of fish produced (343.6 thousand tons), followed by tambaqui (100.6 thousand tons), the latter produced mostly in the Brazilian Northern region. Farmed shrimp production grew 14.1% in comparison to the previous year, amounting to 63.2 thousand tons, and the Northeastern region is responsible for 99.6% of the Brazilian production (IBGE, 2021).

RD&I in Brazilian aquaculture

Investments in research, development and innovation (RD&I) are essential to elevate technological standards and favor the competitiveness and sustainability of Brazilian aquaculture (Rocha et al., 2013). Knowing the industry's status and trends is essential for the formulation of solid public policies, as well as for evaluating the performance of aquaculture's management system's chain of custody (FAO, 2021). In Brazil, however, the research and innovation field lacks focus on the identification of researches demanded by this industry (Embrapa Pesca e Aquicultura, 2022b).

To address this need, the Brazilian Agricultural Research Corporation (Embrapa) is leading the BRS Aqua project, in a partnership with the Brazilian Development Bank's Technological Fund (Funtec/BNDES) along with the Brazilian Ministry of Agriculture and Livestock's Secretariat for Aquaculture and Fisheries (SAP/Mapa) and the Brazilian National Council for Scientific and Technological Development (CNPq). BRS Aqua is the largest aquaculture research project ever carried out in Brazil (Embrapa Pesca e Aquicultura, 2022a). At a total cost of R$ 57 million and a 4-year span, the project's goal is to provide the infrastructure and scientific research needed to address demands of the Brazilian aquaculture market. One of BRS Aqua's thematic components is a project on 'Structural actions and innovation in the production chains of Brazilian Aquaculture'. Among its activities is the mapping of aquaculture ponds, the object of study of this publication, which presents the results achieved by the project's research actions, lauched in 2019.

Mapping aquaculture ponds by Remote Sensing

Identifying aquaculture ponds used in aquaculture by means of Remote Sensing is a challenging activity, because of the complex spectral and spatial characteristics of these objects (Duan et al., 2020; Xia et al., 2020; Novo et al., 2022). Some works that study the potential of different orbital sensors to map these aquaculture production structures have obtained satisfying results. The range of sensors employed is diverse: Lidar images (Loberternos et al., 2016); images made by optical sensors such as Landsat, Spot, Sentinel–2, QuickBird, Ikonos (Fuchs et al., 1998; Ren et al., 2019; Dwivedi; Sreenivas, 2005; Duan et al., 2020; Xia et al., 2020; Novo et al., 2022); and radar such as Alos Palsar, Radarsat, Sentinel–1 (Travaglia et al., 2004; Alexandridis et al., 2008; Marini et al., 2013; Ottinger et al., 2017). The geoprocessing techniques used to automatically detect aquaculture ponds are also diverse, such as neural networks (Zeng et al., 2021) and object-based image analysis (Zhang et al., 2010; Virdis, 2014). A large part of these works are concentrated in mapping aquaculture structures in coastal zones, but some also focus inland waters on continental zones (Zeng et al., 2021). The most recent works commonly use cloud-based geospatial platforms, such as Google Earth Engine, for geoprocessing the images (Duan et al., 2020; Xia et al., 2020; Yu et al., 2020).

One of the challenges faced when mapping aquaculture ponds in inland waters / continental zones is differentiating them from natural waterbodies or watebodies which are being used for other purposes, such as rice crops or animal hydration. In Brazil, because of the different characteristics in species management, aquaculture ponds' sizes and forms are diverse, which is very challenging for the development of a method for automatic extraction based on orbital images that may be applied to the country's whole territory, especially to inland waters.

Objective and motivation of this work

Although national estimates and international statistics about aquaculture are available in the literature, there is still a large gap when it comes to knowledge about the location of regional production spots, as well as data on the industry's productivity and efficiency, both in international (Ottinger et al., 2018) and national terms. Monitoring aquaculture activities by means of mapping aquaculture ponds is essential for: (i) territorial planning/ordainment, (ii) managing economic activity, and (iii) evaluating natural resources and their environmental impacts. Monitoring human pressures on the environment is the first step to manage natural ecosystems, as well as a method to evaluate the efficacy of the conservation measures applied (Alexandridis et al., 2008).

In the context of these demands, this work aimed to produce new data mapping aquaculture ponds in Brazilian cities that jointly concentrate at least 75% of all the aquaculture production for each of the country's federative units (UF). The mapping is the result of integrating digital processing techniques applied to orbital images with visual interpretation of aquaculture production structures by a team of specialists.

Works like this are relevant, because currently there are no previous records of such systematic initiatives for mapping aquaculture ponds throughout the whole Brazilian territory. The mapping as a product itself and its aforementioned functions may also serve as a initial references and as guides for future experiments that aim to automatically detect characteristic features of aquaculture production, in order to guarantee some uniformity in pond recognition and offer conditions for their continuous monitoring.

Study area

Considering Brazil's continental dimensions and the method proposed for mapping the aquaculture ponds, the stydy area for recognition of aquaculture production structures was defined using a spatial concentration indicator based on the statistical distribution in quartiles, according to the method proposed by Garagorry and Chaib Filho (2008). Based on this reference, we selected the cities in each Brazilian UF whose productions accounted jointly for at least 75% of the UF's total aquaculture production. This group was named G75, and its size, in number of cities, varied according to the spatial concentration of the activity. For example, Rio Grande do Sul's G75 is composed of 154 cities, whereas Espírito Santo's G75 is composed of only 4 cities.

Data on aquaculture production by city were obtained from IBGE's Automatic Recovery System (Sistema de Recuperação Automática do IBGE, Sidra, in Portuguese), table 3940, containing data from *Pesquisa da Pecuária Municipal* (PPM) for 2016. After selecting the G75 for each UF, we identified, in IBGE's 2018 municipal mesh, 513 Brazilian cities to be mapped, amounting to an area of 92.932.575 ha (approximately 930.000 km^2). Figure 2 shows the distribution of the cities mapped, in each UF, that make up this work's study area.

Image and Processes

Image acquisition

The images used for vectorizing the aquaculture ponds were obtained from the MSI multispectral sensor of the Sentinel-2 satellite, which is part of the Copernicus constellation, a project developed by the European Space Agency (ESA) in partnership with the European Union.

The Sentinel–2 satellite was chosen due to its average spatial resolution (10 m), which enables an adequate identification of smaller aquaculture ponds. This sensor features 13 spectral bands, and those in the green (560 nm — band 3) and near infrared (842 nm — band 8) ranges are able of satisfactorily identifying waterbodies on the surface of a terrain by calculating the Normalized Difference Water Index (NDWI) (Du et al., 2016). Also, its temporal resolution is high, its revisit time of a given region on the globe is five days, and, unlike other proprietary solutions, the images are freely available.

To cover all the cities to be mapped, 70 Sentinel–2A and 2B, level 1C, scene size 100 km by 100 km images (Figure 2) were downloaded from Earth Explorer, made available by the United States Geological Survey (USGS). The year 2018 was defined as the temporal reference for the mapping, and the selection of scenes aimed to ensure the least possible cloud cover over the mapping area within that year.

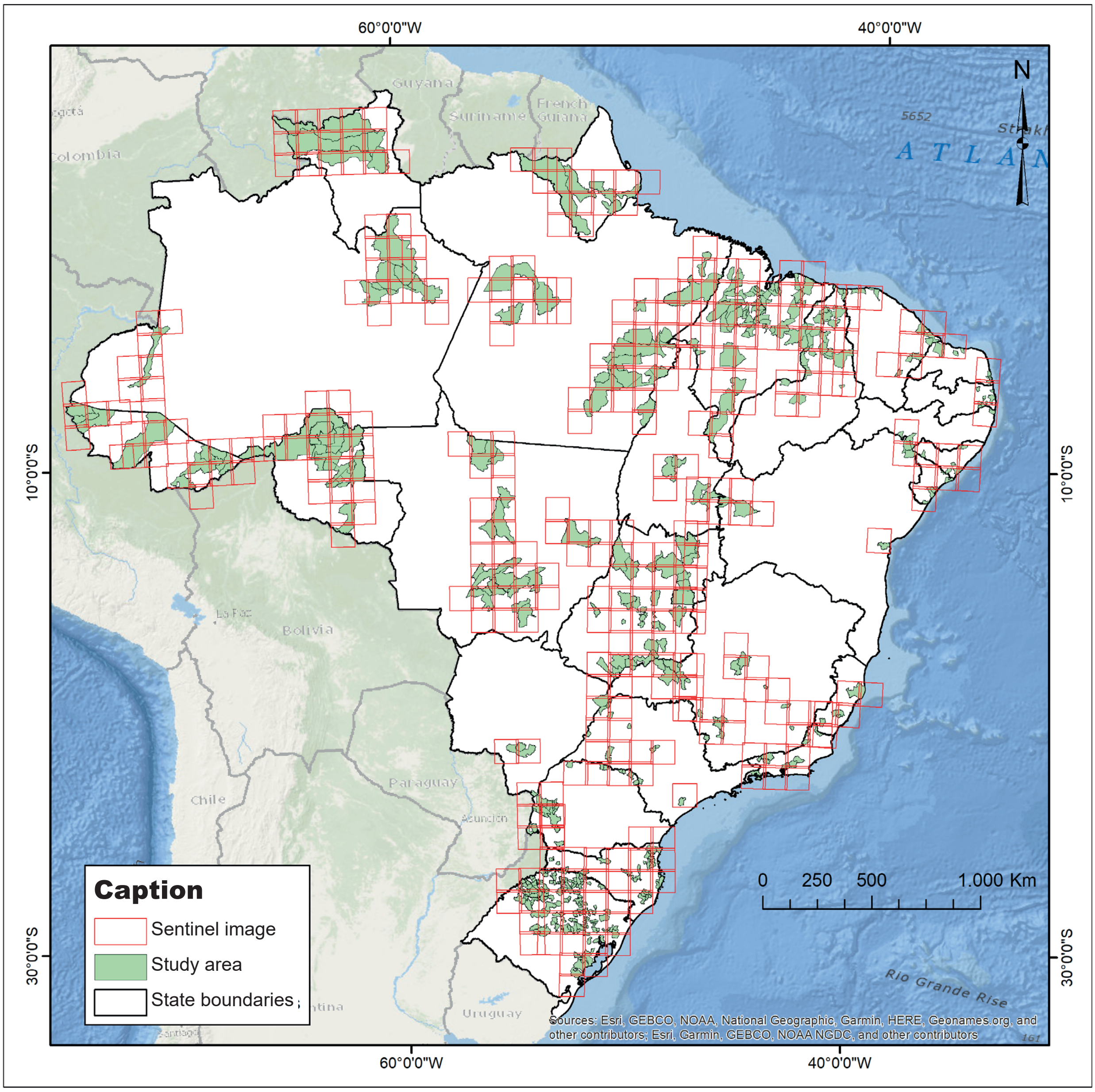

Figure 2. Map of the distribution of mapped cities (G75) that compose the study area, and location of Sentinel–2A and 2B images obtained from the Earth Explorer platform.

Image processing

For each UF, true-color RGB (bands 04/03/02) and false-color RGB (bands 08/04/03) mosaics were composed using the SNAP 7.0 software, freely distributed by ESA for geoprocessing Sentinel images. Then, using the ArcGIS 10.7.2 software (ESRI, 2018), we calculated the NDWI index using bands 3 and 8, to highlight waterbodies on the surface of the terrain.

The NDWI index aims to maximize the reflectance of water in the green band and to minimize the reflectance in the near infrared (NIR) band, and was calculated using Equation 1:

$$NDWI = \frac{(B3 - B8)}{(B3 + B8)} \quad (1)$$

B3 is the Top-Of-Atmosphere (TOA) reflectance of the green band and B8 is the TOA reflectance of the near infrared band in Sentinel–2A and 2B images.

We used the NDWI index obtained to reclassify the values for each pixel, and selected only the pixels showing values higher than zero, which indicates the presence of water in the target. From this set, we performed an automatic vectorization to generate the polygons (Raster to Polygon tool in the ArcGIS 10.7.2 software).

With the aim of systematizing the visual scan of the images to select the waterbodies related to aquaculture activity, as well as to make manual adjustments to the contours of the polygons vectorized using the NDWI index, the study area was divided into 3 km x 3 km grids using the Create Fishnet tool in the ArcGIS 10.7.2 software.

To perform the systematic terrain scan, we employed the ArcGIS 10.7.2 software, which internally provides high spatial resolution images taken by several satellites (WorldView, Ikonos, etc.). These images were used to aid the interpretation team when selecting waterbodies used only for aquaculture based on the recognition of typical features. The features observed in the high resolution images were:

- Presence of sheds, generally used for storing feeds and equipment used in aquaculture activities;
- Access roads, commonly unpaved;
- Presence of aerators within the waterbodies, which produce a turbulence that may be recognized in high-resolution images;
- Geometry of the waterbodies, which typically have rectangular features. In some cases, however, triangular, oval or even unshapely features may be observed. They generally appear in the form of 'sets', a sequence of more than one rectangular waterbody, all close to one another and divided by a containment ditch.

Once the waterbody singled out by the spectral index was confirmed to be an aquaculture production unit according to the mapping criteria, polygons were manually drawn around the group of individual ponds. The group of individual ponds highlighted by each polygon was named 'set of aquaculture ponds'. The mapping process by means of visual interpretation techniques used in this work is detailed in Figure 3.

Data validation

Validating the results is an important step in the digital mapping of targets. Due to the impossibility of making field trips to check one sample for each UF, the team chose to perform an office-based validation by crossing-referencing the results obtained against other spatial databases. The intention of this validation was to include in the attributes of the mapped polygons of aquaculture ponds information on whether they were validated or not against secondary information external to the mapping phase.

For this purpose, polygons representative of the rural properties registered in the Brazilian Rural Enviromental Registry (*Cadastro Ambiental Rural*, CAR, in Portuguese) were used as auxiliary elements in the validation process. CAR is a public, electronic Brazilian registry which is mandatory for all rural properties and aims to integrate environmental information about rural properties and ownerships (Brasil, 2022).

Also, secondary data about aquaculture activity were used as reference, and named 'validation points' (PV). PV are point data – points featuring geographic coordinates on the terrain – which indicate the presence of aquaculture activity recorded in that location.

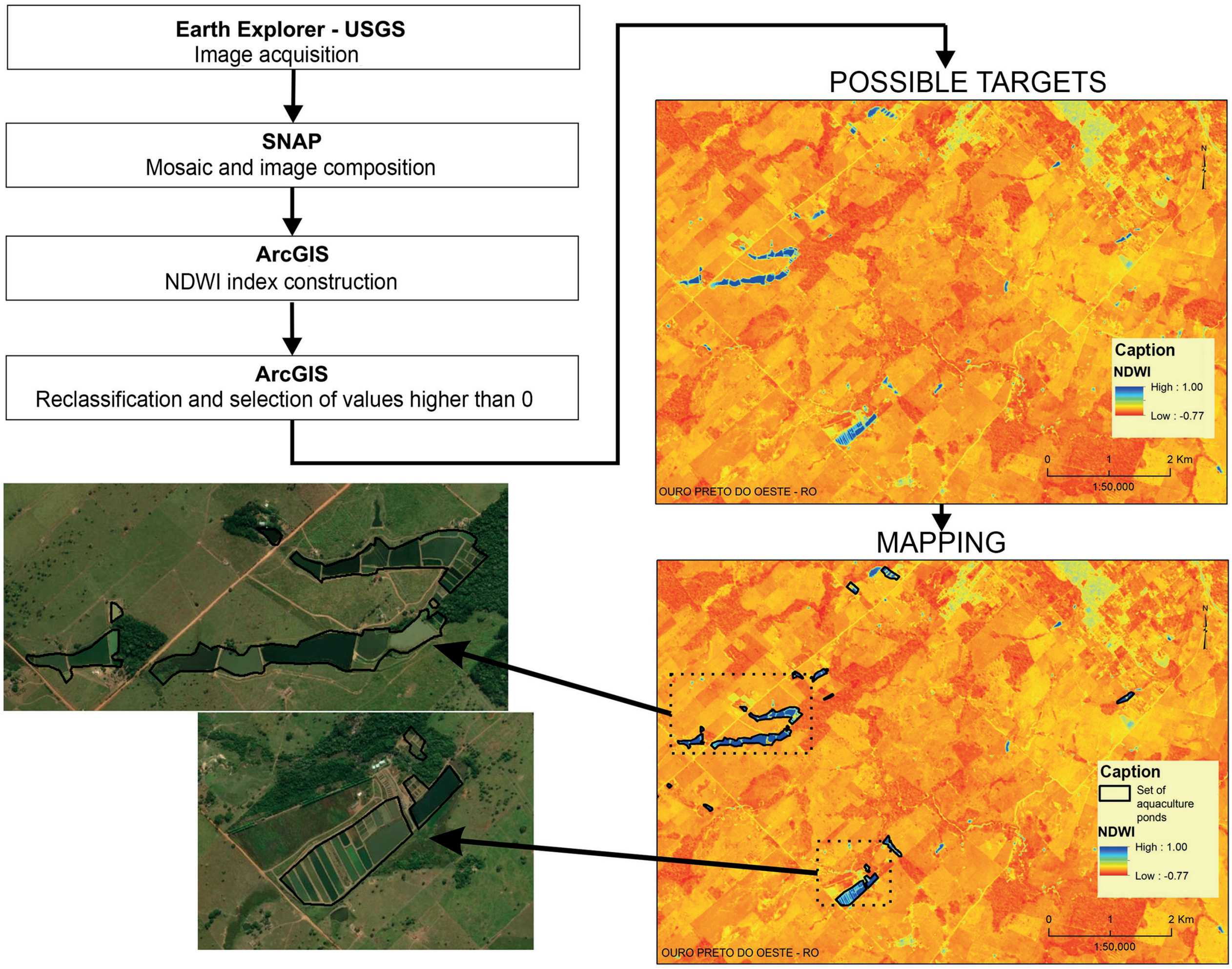

Figure 3. Method used for mapping aquaculture ponds by means of visual interpretation.

These data come from several government institutions or aquaculture producer associations, such as the Brazilian National Portal for Environmental Licensing (*Portal Nacional de Licenciamento Ambiental*, in Portuguese), state secretariats for environment, technical assistance institutions, among others.

Table 1 shows the list of institutions that provided data about aquaculture activities of each UF for the validation of our mapping, as well as the amount of PVs obtained and effectively used. It is worth highlighting that for some UFs, PVs were obtained from more than one institution, and their data were used in the validation process. Thus, the ponds validated in each UF are the combination of all validations obtained using data from each institution. For some states, no data were available to support the office-based validation process, therefore no ponds were validated.

PV data were obtained from the institutions by means of official requests and institutional contact. The data obtained were checked, and the geographic coordinates for each point of aquaculture activity were spatialized in a geographic information system (GIS) environment.

In this quality certification process we excluded from the sample: points that identified locations within urban centers, points with duplicated geographic coordinates, and points located in cities that are not part of the study area (G75).

Table 1. Institutions that provided data for the validation of aquaculture ponds, total number of PVs obtained from each institution, and total number and percentage of PVs used in the validation process.

Abbreviation	State	Validating institution	No. of PVs obtained	No. of PVs used	%
AC	Acre	PNLA environmental licensing	4,363	413	9.5
AL	Alagoas	Secretaria de Estado da Agricultura, Pecuária, Pesca e Aquicultura – Agricultura AL	24	24	100
		Instituto de Meio Ambiente de Alagoas (IMA)	11	11	100
		PNLA environmental licensing	25	15	60.0
AP	Amapá	PNLA environmental licensing	2	0	0.0
AM	Amazonas	Instituto de Proteção Ambiental do Amazonas (Ipaam)	1,400	1,047	74.8
		PNLA environmental licensing	1,805	762	42.2
BA	Bahia	No data	-	-	-
CE	Ceará	Empresa de Assistência Técnica e Extensão Rural (Emater CE)	202	172	85.1
DF	Distrito Federal	PNLA environmental licensing	12	9	75.0
ES	Espírito Santo	No data	-	-	-
GO	Goiás	PNLA environmental licensing	117	22	18.8
MA	Maranhão	Secretária de Agricultura, Pecuária e Pesca (Sagrima)	172	162	94.2
		PNLA environmental licensing	224	92	41.1
MT	Mato Grosso	No data	-	-	-
MS	Mato Grosso do Sul	No data	-	-	-
MG	Minas Gerais	Empresa de Pesquisa Agropecuária de Minas Gerais (Epamig)	51	50	98.0
		Outorga ANA MG	27	26	96.3
		Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável (Semad)	26	25	96.2
		Empresa de Assistência Técnica e Extensão Rural (Emater MG)	24	0	0.0
PA	Pará	PNLA environmental licensing	361	0	0.0
PB	Paraíba	Superintendência de Administração do Meio Ambiente (Sudema)	75	19	25.3
PR	Paraná	Instituto Água e Terra	5,474	5,390	98.5
		PNLA environmental licensing	322	217	67.4
PE	Pernambuco	Agência Estadual de Meio Ambiente CPRH	110	67	60.9
PI	Piauí	No data	-	-	-
RJ	Rio de Janeiro	PNLA environmental licensing	56	11	19.6
RN	Rio Grande do Norte	Instituto de Desenvolvimento Sustentável e Meio Ambiente (Idema)	188	171	91.0
RS	Rio Grande do Sul	No data	-	-	-
RO	Rondônia	Semagric (Porto Velho)	33	33	100
		Secretaria de Estado de Desenvolvimento Ambiental (Sedam)	4,272	3,082	72.1
		PNLA environmental licensing	421	253	60.1
RR	Roraima	PNLA environmental licensing	8	3	37.5

to be continued...

Table 1. Continuation.

Abbreviation	State	Validating institution	No. of PVs obtained	No. of PVs used	%
SC	Santa Catarina	Instituto do Meio Ambiente (IMA)	615	182	29.6
SP	São Paulo	No data	-	-	-
SE	Sergipe	PNLA environmental licensing	64	36	56.3
TO	Tocantins	Instituto de Desenvolvimento Rural do Tocantins (Ruraltins)	1,099	133	12.1
		Instituto Natureza do Tocantins (Naturatins)	1,891	150	7.9
		PNLA environmental licensing	733	38	5.2
		TOTAL	**24,207**	**12,615**	**52.1**

The validation was performed for each UF and according to the method highlighted in Figure 4. First, we intersected the CAR polygons (Figure 4a) and the PVs provided by each institution (Figure 4b). Two products were obtained:

i) The polygons of rural properties registered in CAR which had at least one PV within them, here named Validation CAR (Figure 4c);

ii) The set of PVs whose geographic location does not coincide with the boundaries of the rural properties registered in CAR (Figure 4d).

Based on these products, a new intersection was made, this time using the Validation CAR polygons (Figure 4c) along with the sets of ponds originally mapped (Figure 4f). Three new results were obtained:

i) Set of aquaculture ponds validated using Validation CAR (Figure 4–1), which correspond to the sets of ponds located within Validation CAR polygons, i.e., within the limits of a rural property which also had one or more validation points associated with it;

ii) Set of PVs within Validation CAR containing sets of ponds identified within the rural property's polygon (Figure 4e);

iii) Set of PVs within Validation CAR but featuring no sets of ponds identified within the rural property's polygon (Figure 4g).

The validation process continued, and PVs that were not located within the boundaries of rural properties registered in CAR (Figure 4d) were combined with another set of PVs which were located within the perimeter of the properties but had not displayed sets of ponds mapped within the polygon (Figure 4g). The product of this combination was named 'PV outside added CAR'. It accounts for the selection of PVs which were not used in the approach using rural properties registered in CAR, and may undergo another validation technique, one based on the creation of a buffer (range radius) for these PVs. This technique is based on the premise that sets of aquaculture ponds which are located within a given range radius would be associated with these PVs, and therefore validated. Our decision for this type of validation is justifiable by the fact that the PVs are not necessarily near the aquaculture ponds and their coordinates may be registered in places around the property.

The range radius was determined by means of a statistical analysis of the distances from the centroids of the polygons of sets of ponds mapped within the rural properties registered in CAR (Figure 4j) up to their respective PVs (Figure 4e). This set of distances was obtained using the Near tool of the ArcGIS 10.7.2 software. The value defined for the range radius would correspond to the

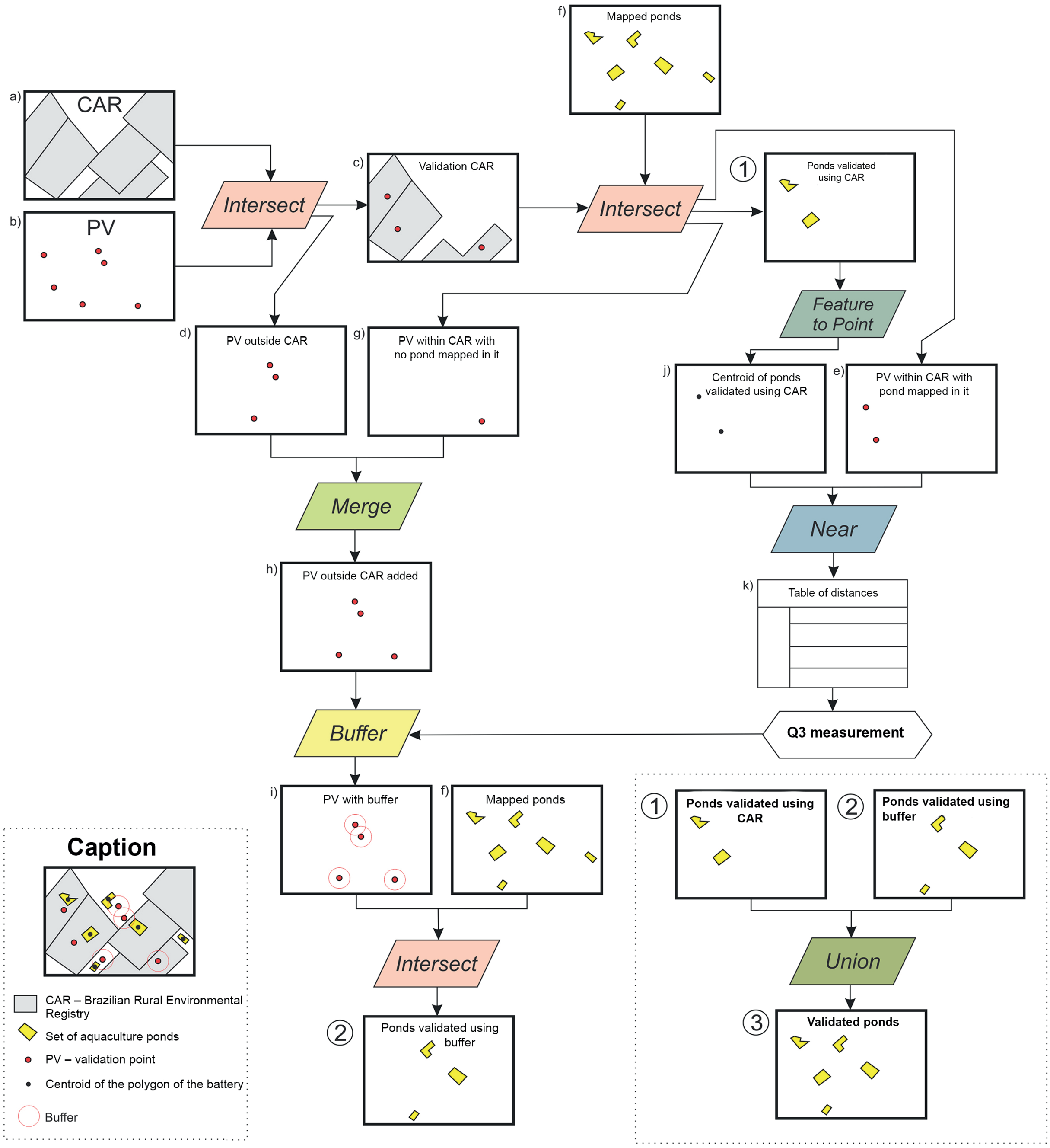

Figure 4. Flowchart of the method used for validating the mapped sets of aquaculture ponds.

third quartile, Q3 = median + 25% of the distances measured (Figure 4k). After this range radius was defined for each UF, the buffer was applied to 'PV outside added CAR' (Figure 4i), and then to the intersection of this range radius toward the mapped sets of ponds. If the set of ponds mapped was located within the PV's range radius, the mapping of this feature was considered validated.

To conclude the validation process, we combined the sets of ponds validated using Validation CAR (Figure 4–1) with the sets of ponds validated using the buffer (Figure 4–2), by means of the Union tool, to finally obtain the validated sets of aquaculture ponds (Figure 4–3).

The result of the mapping was made available in the form of a 1:100,000-scale vector shapefile. Each line of the data's table of attributes identifies a set of ponds with its respective location in a city, state and region. It also includes information on calculated area and identifies whether the set of ponds is located within a rural property (CAR). Finally, it contains a specific validation attribute that identifies, for each set of ponds, whether it was or was not validated by any validation institution within the UF where it is located. Some examples of sets of ponds mapped in some UFs are shown in Figure 5.

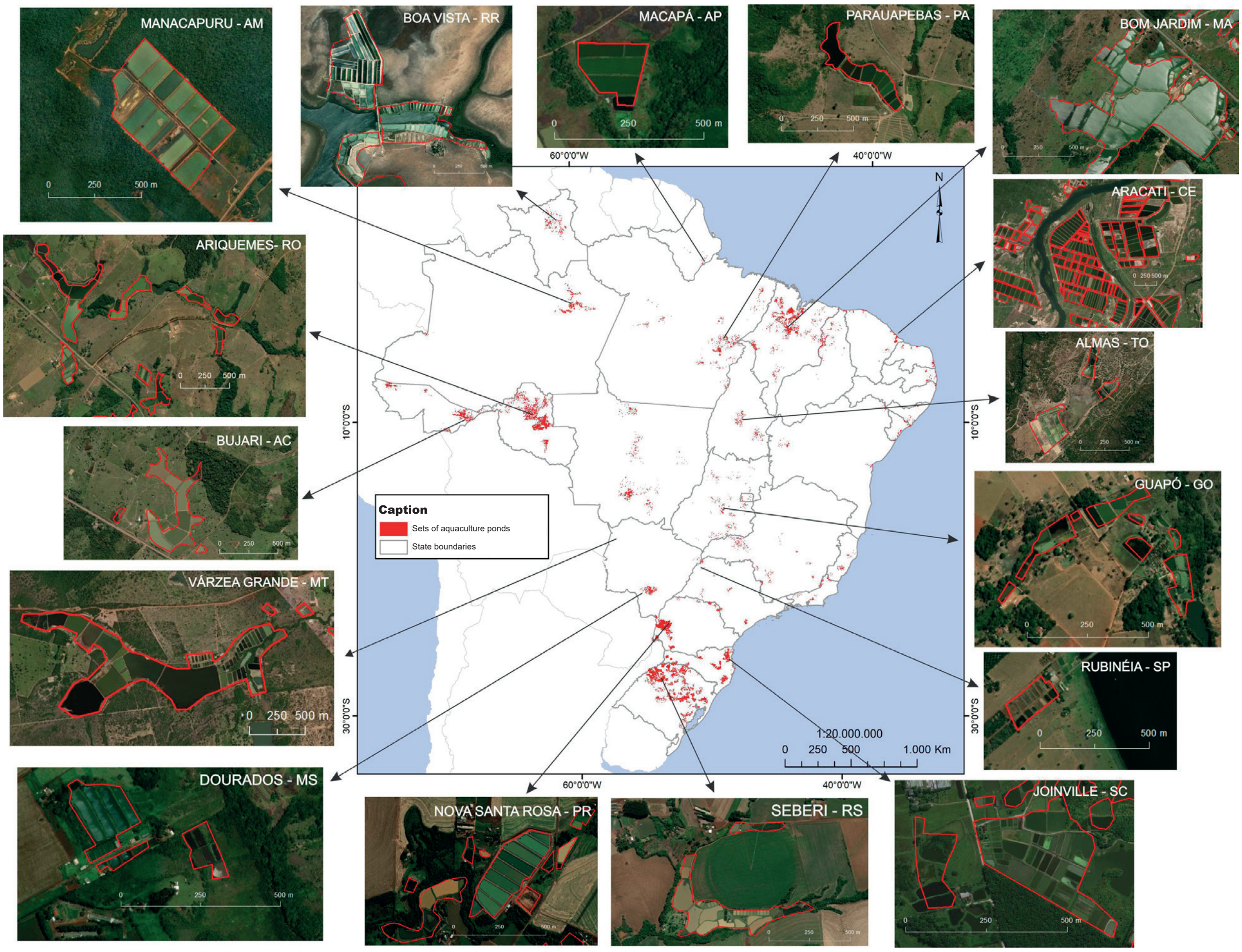

Figure 5. Sets of aquaculture ponds mapped in the cities that compose the G75 group of aquaculture production in each Brazilian state, with emphasis on selected locations.

Results

The total number of cities that compose G75 for each UF, as well as the area and total number of polygons mapped and validated, with their respective percentages, are shown in Table 2.

The polygons mapped depict sets of aquaculture ponds used for aquaculture.The first column informs the number of cities that compose G75, followed by the number of polygons mapped and validated and their respective percentages. The same information is provided for the total area of the polygons. The values for the number of validated sets of ponds reflect all the institutions used in the validation process for each UF. The dash indicates the UFs for which no secondary data about aquaculture were obtained for the validation process.

Table 2. Result of the mapping of sets of aquaculture ponds for each UF.

Abbreviation (UF)	State	Cities (G75)	Mapped sets of aquaculture ponds (No. of polygons)	Validated sets of aquaculture ponds (No. of polygons)	%	Mapped sets of aquaculture ponds Area (ha)	Validated sets of aquaculture ponds Area (ha)	%	PPM 2018 (t)	Productivity (t per hectare)
RO	Rondônia	18	5,686	2,427	42.7	12,530.9	7,225.9	57.7	50,180.7	4.0
CE	Ceará	8	1,108	46	4.2	8,449.3	700.4	8.3	24,196.7	2.9
MA	Maranhão	51	6,041	477	7.9	8,195.8	731.1	8.9	27,699.3	3.4
RS	Rio Grande do Sul	154	9,010	-	-	8,012.6	-	-	14,312.3	1.8
MT	Mato Grosso	17	1,505	194	12.9	5,532.9	1,244.9	22.5	33,974.7	6.1
PR	Paraná	28	4,937	1,996	40.4	5,228.1	2,927.1	56.0	121,475.1	23.2
AC	Acre	10	4,418	1,628	36.8	4,086.9	1,851.6	45.3	3,825.8	0.9
RN	Rio Grande do Norte	8	990	389	39.3	3,618.8	1,250.2	34.5	22,164.6	6.1
SE	Sergipe	8	500	12	2.4	3,431.6	350.1	10.2	4,372.3	1.3
RR	Roraima	5	1,235	11	0.9	3,429.6	39.3	1.1	10,818.0	3.2
PI	Piauí	24	731	-	-	2,807.0	-	-	13,126.6	4.7
SC	Santa Catarina	40	3,211	144	4.5	2,671.7	245.7	9.2	44,299.6	16.6
AM	Amazonas	7	1,520	1,280	84.2	1,809.5	1,491.7	82.4	8,162.5	4.5
MS	Mato Grosso do Sul	4	652	-	-	1,722.1	-	-	13,993.3	8.1
PA	Pará	17	2,616	0	0.0	1,190.7	0.0	0.0	13,601.2	11.4
BA	Bahia	4	328	-	-	1,179.4	-	-	15,351.0	13.0
TO	Tocantins	5	679	367	54.1	1,145.7	776.2	67.8	11,360.5	9.9
GO	Goiás	33	1,120	37	3.3	841.6	47.4	5.6	15,540.1	18.5
PE	Pernambuco	4	55	38	69.1	834.1	773.1	92.7	22,838.1	27.4
PB	Paraíba	10	415	89	21.4	658.1	225.2	34.2	5,032.6	7.6
SP	São Paulo	14	340	-	-	369.5	-	-	51,661.0	139.8
MG	Minas Gerais	18	389	109	28.0	278.5	70.4	25.3	35,414.1	127.2
RJ	Rio de Janeiro	11	429	14	3.3	254.4	14.3	5.6	1,257.8	4.9
ES	Espírito Santo	4	260	-	-	177.5	-	-	4,073.1	23.0
AL	Alagoas	6	100	48	48.0	140.3	88.9	63.4	9,776.6	69.7
AP	Amapá	4	103	0	0.0	88.4	0.0	0.0	823.4	9.3
DF	Distrito Federal	1	93	17	18.3	58.8	15.5	26.3	1,218.9	20.7
	TOTAL	**513**	**48,471**	**9,323**	**19.2%**	**78,743.8**	**20,069.2**	**25.5%**	**580,549.7**	**7.4**

The counting for both Amapá and Pará states was zero, because we could not validate any of the mapped ponds using the data provided by the instutions. The state of Rondônia features the largest area of mapped sets of ponds, followed by Ceará and Maranhão. Rio Grande do Sul features the highest number of mapped polygons, followed by Maranhão and Rondônia.

Regarding the values obtained after validating the mapped sets of ponds, Amazonas features the highest index of validated polygons, followed by Pernambuco and Tocantins. The remaining states show validation values below 50%. The total mapping detected 48,471 sets of ponds, 9,323 of which were validated, at an average validation rate of 19.2% by state. A similar result is found when the analysis criterium is total mapped area, which amounted to over 78 thousand hectares, 25.5% of which was validated. It is worth highlighting, as indicated in Table 1, that one of the factors that condition the validation process is the low availability of PVs in some states, which hinders the georeferenced analysis of secondary data against the mapping of ponds and reinforces the need for institutional partnerships and field campaigns for the validation of the national mapping.

Furthermore, Table 2 displays aquaculture production numbers recorded in IBGE's municipal livestock survey (*Pesquisa Pecuária Municipal*, PPM, in Portuguese) for 2018, the year of the images used in this work. The values are presented in tons and are the sum of aquaculture production according to Sidra's table 3940, except for fish larvae, mollusc seeds, shrimp larvae and 'other products', which are presented in other measurement unit (thousand). The remaining categories used for calculating the total aquaculture production are available in Sidra in kilograms and refer to the following species: carp, *curimatã*, *curimbatá*, *dourado*, *jatuarana*, *piabanha* and *piracanjuba*, *lambari*, *matrinxã*, *pacu*, *patinga*, *piau*, *piapara*, *piauçu*, *piava*, *pintado*, *cachara*, *cachapira* and *pintachara*, *surubim*, *pirapitinga*, *pirarucu*, *tambacu*, *tambatinga*, *tambaqui*, tilapia, *traíra*, *trairão*, trout, *tucunaré*, shrimp, oysters, scallops and mussels.

Based on the PPM data for 2018, we estimated the productivity by dividing the total aquaculture production (IBGE) by the total area of mapped sets of aquaculture ponds. Thus, we calculated the average amount, in tons per hectare of water surface in the cities evaluated in each UF. The highest values were observed in São Paulo (139.8 t/ha) and Minas Gerais (127.2 t/ha), while the lowest values were observed in Acre (0.9 t/ha) and Sergipe (1.3 t/ha). We must point out that these numbers also reflect other singularities. The state of São Paulo, despite being one of the country's largest producers, features one of the smallest areas occupied by aquaculture ponds, since a large part of its production comes from fish cultivation in net cages in State-owned waters.

The cross-referencing of PPM data with mapped sets of aquaculture ponds may also be depicted as in Figure 6, in which data about produced amount (left vertical axis) and mapped area (right vertical axis) are plotted. The productivity data recorded in Table 2 for each UF are also plotted. For the states Rondônia, Maranhão, Ceará, Rio Grande do Sul, Piauí, Roraima, Sergipe and Acre, the number of sets of ponds mapped was significantly higher than that of most of the states showing similar aquaculture production numbers, and may even indicate mapped targets that are not used for aquaculture.

It is important to mention that the data shown in Figure 6 are general data, and that differences in production values and in mapped area are expected. First, the methods used for surveying data are completely different. Furthermore, Brazilian aquaculture uses different production systems, such as net cages in reservoirs and natural streams, and those were not included in this mapping. Also, the form of the ponds and the thickness of the water surfaces vary according to the management technique employed for each species.

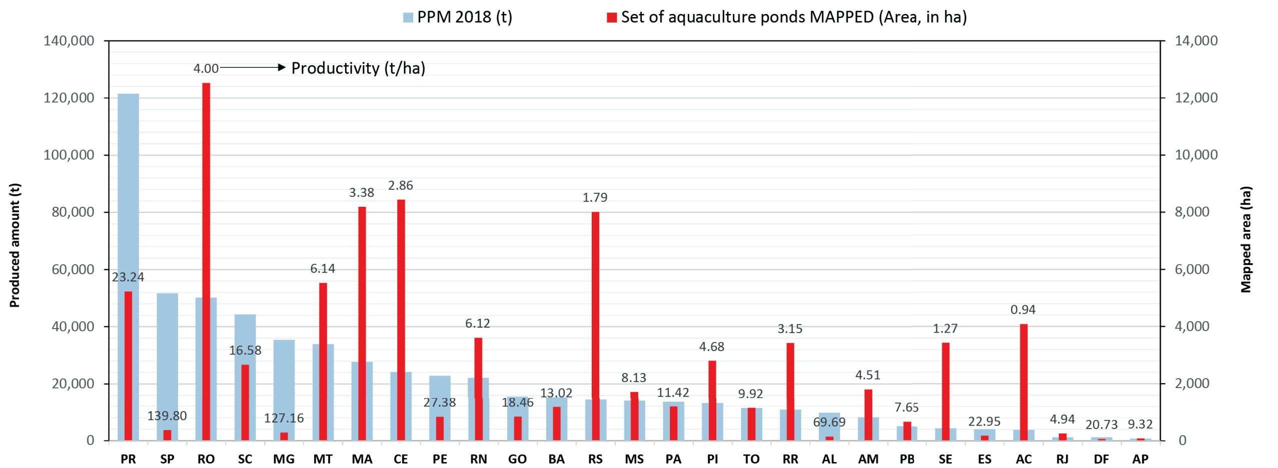

Figure 6. Data on aquaculture production made available by IBGE's PPM-2018 plotted with the total area of mapped sets of aquaculture ponds for each UF.

Conclusion

This is a first attempt at a systematic mapping of aquaculture ponds, one of the main production structures in the aquaculture production chain, on a national scale. As a result, approximately 79 thousand hectares of sets of aquaculture ponds were mapped, and approximately a quarter of this area was validated using secondary data about aquaculture activities.

The cross-referencing of the mapping with production data revealed different correlations, since the forms of obtaining information are different and several management techniques are employed for a significant range of species reared all over the Brazilian territory. Errors of commission in the mapping may be complementarily pointed out, i.e., the inclusion of structures which are not actually used for aquaculture.

This mapping has potential for providing the public sector with information to be used in the development of public policies to encourage farmers to make their activities official and professional, to create more assertive policies with potential for promoting results with greater added value, and to improve the quality of reared aquaculture products. It may also be of relevance to future works on automatic detection of aquaculture ponds, and serve as reference for model parameters. An automated process may enable a systematic, temporal monitoring of aquaculture activities in Brazil, and contribute to the territory ordainment of this economic activity and to organizing the different rings in the national aquaculture production chain. The validation method developed in this project also serves as reference for future works and partnerships with federal and state institutions to manage the use of water in aquaculture.

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