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Integrated Spatial Analysis of Land Degradation in Submedium São Francisco Basin, Brazil

Análise Espacial Integrada da Degradação da Terra no Submédio São Francisco, Brasil

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Abstract: The São Francisco river Submiddle basin holds one of the highest concentrations of land degradation in the Brazilian Semi-arid region. The study analyzed land degradation in this basin using indices based on the DPSIR framework (Driver-Pressure-State-Impact-Response). Seventeen indicators were selected through a literature review and correlation analysis. These indicators were generated in 5 x 5 km cell grids using QGIS GIS software based on secondary and primary sources data. Outliers were removed, and the indicators were normalized. Indices for each DPSIR component were created by calculating the median of the indicators, and maps of the indicators and indices were developed. The areas most vulnerable to degradation (highest values in the DPSI indices) are primarily located in the northwest, central, and southeast regions of the basin. Regarding the response component (highest values in the R index), the western, northwest, and southeast areas of the basin stand out. The indicators that most influenced the DPSI indices were Municipal Human Development Index, establishments with occupant producer, deforestation, erodibility, aridity index, and degraded pastures. In the case of the Response index, technical guidance and credit programs played a significant role. Public policies and private initiatives for restoring environmental quality are crucial to reversing the degradation process and contributing to the sustainable management of the Caatinga.

Keywords: Indicators; DPSIR framework; Land Degradation.

Resumo: A bacia do submédio São Francisco detém uma das maiores concentrações de degradação da terra no Semiárido. O estudo analisou a degradação da terra nesta bacia por meio de índices segundo o modelo FPEIR (Força-Pressão-Estado-Impacto-Resposta). Para seleção dos 17 indicadores foi feita revisão bibliográfica e análise de correlação, os indicadores foram gerados em células de grade de 5 x 5 km no SIG QGIS através de dados de fontes secundárias e primárias. Foi feito um tratamento para exclusão de *outliers*, seguido de normalização dos indicadores. Foram gerados índices para cada componente FPEIR por meio da mediana dos indicadores e elaborados mapas dos indicadores e índices. As áreas mais vulneráveis à degradação (maiores valores nos índices FPEI) localizam-se principalmente nas regiões noroeste, centro e sudeste da bacia. Em relação à resposta (maiores valores no índice R), destacam-se as áreas a oeste, noroeste e sudeste da bacia. Os indicadores que mais influenciaram os índices FPEI foram Índice de Desenvolvimento Humano Municipal, estabelecimentos com produtor ocupante, desmatamento, erodibilidade, índice de aridez e pastagens degradadas. E no caso do índice de Resposta, a orientação técnica e programas de crédito. As políticas públicas e iniciativas particulares de restauração da qualidade ambiental são fundamentais para reverter o processo de degradação, contribuindo para o manejo sustentável da Caatinga.

Palavras-chave: Indicadores; FPEIR; Degradação da terra.

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1. Introduction

Land degradation is a complex phenomenon that affects about 3.2 billion people in all parts of the world (IPBES, 2018) and to be understood in its totality, it needs an integrated analysis that considers social, economic and environmental issues. Land degradation is defined by UNCCD (2017) as the reduction or loss of the biological or economic function of the land, whether in areas of cultivation, pasture and natural coverage environments.

The São Francisco river Submiddle basin is totally inserted in the Caatinga biome, which is exclusively Brazilian (LEAL *et al*., 2005). There is great interest in studying this site, for being a proper place for agriculture (VANDERLEI; QUADROS; SÁ, 2020). Also, it is target of soil exploration for pasture (MEDEIROS *et al*., 2018), but above all because it holds large areas in the desertification process - degradation in arid, semiarid and dry sub-humid areas - being one of the main in the semiarid and Caatinga (CGEE, 2016; UNCCD, 1994). Bezerra et al. (2020), observed from vegetation rate analysis that a good portion of the northeastern semiarid region which corresponds to 4%, has heavily degraded areas. In respect to the quality of the pasture, Santos *et al*. (2022) shows that 26.7% of Brazilian's pasture in contrast with 20.4% of Caatinga's pasture (MAPBIOMAS, 2018).

The Caatinga's land degradation is a product of continuous and positive feedbacks from anthropogenic and biophysical factors (PEREZ-MARIN *et al*., 2022). Being the inadequate handling of land and intensive expansion of agriculture the main anthropic factors that booster it in the semiarid (VIEIRA *et al.*, 2015). The first process is mainly related to practices in areas of natural coverage, transitional mosaic, overgrazing or wood extraction (many times with aid of fire) that, if done continuously (SILVA *et al.*, 2020), will degrade the soil and will decrease the vegetation's recovery capacity. The second process is linked with the substitution of natural vegetation for rainfed or irrigated cultivation. That may lead to erosive processes and salinization of adjacent cultivation areas (VENDRUSCOLO *et al.*, 2019). Such processes lead to the soil exhaustion with loss in productivity. The continuity of them will imply in a bigger degradation process, that along with the regional low annual rainfall concentration will reduce the vegetation's resilience (CARREIRO; ARCOVERDE; BARROS, 2022).

To evaluate, comprehend and chain the socio-economic and environmental factors the conceptual DPSIR framework (Force - Pressure - State - Impact - Response) can be used with indicators. This model consists of presenting the driving forces in which society acts (D). The direct pressure that humanity exerts on the nature (P). Variation on natural resources' quality and quantity (S). Socio-economic impacts (I). And, the responses of the government, citizens and other groups to the studied phenomenon (EEA, 1999).

The use of maps alongside with the DPSIR framework allows the verification of geographic patterns of the areas more vulnerable to degradation and those with bigger potential of recovering from this process. Thus, is possible to verify topological relations linked with the socio-economic and environmental dimensions. This enables a better comprehension of the DPSIR's components. This article analyzes the factors that promote and might avoid the soil degradation process in the Submiddle São Francisco's hydrographic sub-basin by building rates following the DPSIR model.

2. Methodology

2.1. Characterization of the area

This work considered as study area the São Francisco river Submiddle basin. This region is located in the Caatinga biome within the limits of Pernambuco and Bahia states mainly, covering 84 municipalities (Figure 1). It is of great importance for supplying water to the population and it is an important national waterway for exportation of agricultural products (MINISTÉRIO DA INFRAESTRUTURA, 2021).

In the São Francisco Submiddle basinand in barely all the Caatinga biome the semiarid climate prevails,with less than 800 mm per year of average rainfall (ALVARES *et al*., 2014). The vegetation is adapted to large dry seasons. The phytophysiognomies reflect the dry soil conditions (COUTINHO, 2016).

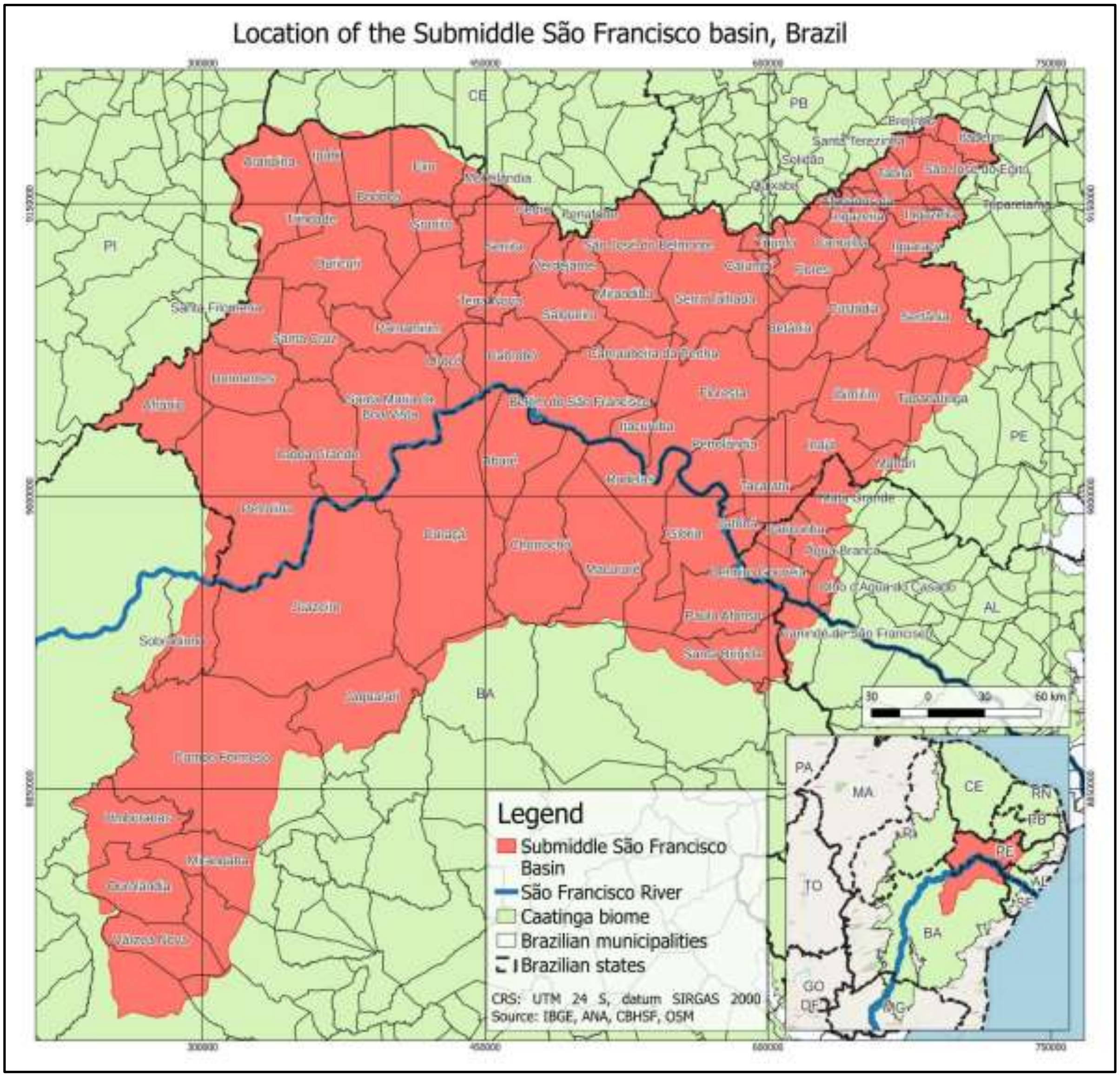

Figure 1 – Location map of the studied area.
Source: By author (2022).

There were a 6% rise in the semiarid Brazilian population from 2000 to 2017. The HDI (Human Development Index) of cities from this region is lower than the Brazilian average (0,727) (IBGE, 2010; ATLAS BRASIL, 2010) and around 24 million people live there (ALVALÁ *et al*., 2019). It is important to highlight the productive development of Petrolina (PE) and Juazeiro (BA) where the agriculture received public investments. Nowadays, they are very important for investment in agribusiness (URBAN SYSTEM, 2020).

2.2. Methodological procedures

2.2.1. Selection of indicators

Firstly, a bibliographical review about the studied area was made. Previous works involving soil degradation and use of indicators. A search for articles in the Google Scholar was made with the aim of selecting possible themes that would correlate the indicators to the degradation. From the reading of the national and international article's abstracts. Were selected those that would give degradation indicators that could be distributed among the DPSIR components. Those articles were fully read. The FAO reports (1994 and 2003) were also taken into account for their relevance in degradation studies.

The selected indicators were classified into their respective component of the DPSIR framework (EEA, 1999). It is a system that organizes the indicators to identify and describe the processes and interactions in socio-environmental systems (CARR et al., 2007). The DPSIR framework allows a systematic understanding of the degradation process. It identifies the indirect and direct causes of degradation (Drivers and Pressures). How they affect the state of the environment (State). The outcomes of land degradation (Impact) and solutions to undo this process (Response). The indicators built to the identified themes also followed some methodological steps from Maggino (2017). The 2010s was the major temporal reference and the minimum scale was the municipal level or more detailed data than that level if possible.

Table 1 presents the list with the eighteen previously selected indicators, organized with the DPSIR framework components in mind. The table also presents the source used to obtain the data. As well as the references that each indicator were grounded and if the indicator direction. In other words, if it possesses a direct or inverse relation with the DPSIR component indicated.

Table 1 – Previously selected indicators in the research.

Indicator's name	DPSIR component	Data sources	Year	Chosen reference for the indicator	Direction
Agricultural establishments with occupant producer	Drivers	IBGE (agricultural census) https://sidra.ibge.gov.br/tabela/6878	2017	Lima *et al* (2016); FAO (2003); Agyemang, McDonald e Carve (2007)	Direct
Average Municipal Human Development Index	Drivers	Atlas Brasil http://www.atlasbrasil.org.br/acervo/biblioteca	2010	Lima *et al* (2016)	Inverse
Rural population percentage	Drivers	IBGE (agricultural census) https://censos.ibge.gov.br/resultados-censo-agro-2017/cnefe.html e https://portaldemapas.ibge.gov.br/portal.php#homepage	2017	FAO (2003); Agyemang, McDonald e Carve (2007); Vieira *et al*, 2015	Direct
Firewood produced (m³)	Pressure	IBGE (agricultural census) https://sidra.ibge.gov.br/Tabela/289	2017	Gessesew (2017)	Direct
Livestock yield	Pressure	AdaptaBrasil https://adaptabrasil.mcti.gov.br/sobre/lista-de-indicadores	2017	Lima *et al* (2016); Porta e Poch (2011)	Inverse
Quantity of fire spots (accumulated)	Pressure	BDQueimadas https://queimadas.dgi.inpe.br/queimadas/bdqueimad	2000-2017	Lima *et al* (2016); Porta e Poch (2011)	Direct

		as			
Percentage of deforestation (accumulated)	Pressure	PRODES/INPE http://terrabrasilis.dpi.inpe.br/downloads/	Until 2016	Lima *et al* (2016) e Porta e Poch (2011)	Direct
Agriculture and livestock expansion (%)	Pressure	MapBiomas https://mapbiomas.org/colecoes-mapbiomas-1?cama_set_language=pt-BR	2000 and 2017	Lima *et al* (2016)	Direct
Percentage of establishments using pesticides (**excluded from the analysis after correlation**)	Pressure	IBGE (agricultural census) https://sidra.ibge.gov.br/Tabela/6851	2017	FAO (1994) and FAO (2003)	Direct
Erodibility (high and very high) and eroded phase (%)	State	Embrapa http://geoinfo.cnps.embrapa.br/documents/2924	2019	Lima *et al* (2016); Porta e Poch (2011)	Direct
Average aridity index	State	Trabucco e Zomer (2019)	Published in 2019, data from 1970-2000	Vieira *et al* (2015); Lima *et al* (2016)	Inverse
Average slope	State	TOPODATA/INPE http://www.webmapit.com.br/inpe/topodata/	2010	Vieira *et al.* (2015); Cowie *et al.* (2018)	Direct
Agricultural yields of basic products	Impact	IBGE (Pesquisa Agrícola Municipal) https://sidra.ibge.gov.br/pesquisa/pam/tabelas	2010 to 2019	Lima *et al* (2016)	Inverse
Degraded pastures (%)	Impact	MapBiomas https://mapbiomas.org/colecoes-mapbiomas-1?cama_set_language=pt-BR	2017	Included by ourselves	Direct
Credit program conceived to agricultural establishments	Response	IBGE (agricultural census) https://sidra.ibge.gov.br/Tabela/6895	2017	Lima *et al* (2016)	Inverse

Water supply alternatives	Response	AdaptaBrasil https://adaptabrasil.mcti.gov.br/sobre/lista-de-indicadores	2010	Lima *et al* (2016)	Inverse
Technical guidance conceived to agricultural establishments	Response	IBGE (agricultural census) https://sidra.ibge.gov.br/tabela/6881	2017	Included by ourselves	Inverse
Percentage of Conservation Units	Response	Ministério do Meio Ambiente http://mapas.mma.gov.br/i3geo/datadownload.htm	2021	Lima *et al* (2016)	Inverse

Source: By author (2022).

2.2.2. Data extraction and processing

The data used to generate the indicators were extracted in various ways depending on their nature (vector, matrix or tabular). To obtain the average of the values in grids, and considering 25 km² as the minimum mapping unit, 5 x 5 km grids were generated in a Geographic Information System (GIS) environment using the QGIS software. All data in tabular format had municipal representation. So, they possessed a geocode that allowed the union with the municipalities' *shapefile* from IBGE of 2021. The free access software FillCell was used to obtain the average of the data at municipal level for the grids. It was developed to create and fill regular cellular spaces (grids) in a geoprocessing environment that is compatible with LUCCME, a program developed by INPE (2017) for generating dynamic spatial models.

The indicators that possessed municipal tabular representation were: Percentage of establishments with occupant producer, Firewood produced (m³), Average Municipal Human Development Index (MIDH), Agricultural yields of basic products, Livestock yield, Percentage of establishments using pesticides, Credit program concieved to agricultural establishments, Water supply alternatives and Technical guidance concieved to agricultural establishments. The sources used to generate the indicators are shown in Table 1.

A specific geoprocessing treatment was done with the percentage indicator of populated countryside. Since it is composed by visited area points in the 2017 Agricultural Census and by polygons with urbanized census sectors in the countryside (5, 6 and 7 situations of countryside sensus sectors). These layers were converted to a matrix format with a resolution of 1km. Later, the percentage of these pixels (with occupation) in the 5 x 5 km grid was extracted.

Livestock yield refers to the quantity of cattle, goats and sheep on pasture areas sown in good conditions. Therefore, areas that maintained the higher number of animals preserving the quality of the pasture had greater value and were considered positive areas. The calculation of this indicator was carried out by averaging the productivity of herds (R) and milk (L). Herd productivity was calculated by the division between the quantity of grazing animals and the pasture area planted in the municipality (in hectare). Then, the quotient is multiplied by the percentage of pastures considered to be in good condition. Milk productivity was calculated by the quotient between the total milk production (thousand liters) by cows, sheep and goats and their quantity. The neperian log of the average amount between the normalized values of the two considered productivities (R and L) was calculated to approach the extreme values to the average.

In the case of the Percentage of accumulated deforestation and the Percentage of Conservation Units (UCs) indicators, a division was made between the area of each theme in the grid and the total grid area. Then, the quotient was multiplied by 100 to obtain the percentage. About the Quantity of heat sources (accumulated from 2000 to 2017) indicator, was used the Counting points in QGIS polygons tool, to obtain the number of sources in each grid.

The Agriculture and livestock expansion indicator was generated from rasters of use and coverage of the land in the studied region from 2000 to 2017. The classes involving agricultural areas were extracted and then the zonal statistics tool was used in order to extract the sum of agricultural pixels for each year. The area of each year was obtained by multiplying the pixel area (in meters) by the quantity of the pixels and then divided by 10,000 to obtain the value in hectares. The expression below was used to obtain the agricultural expansion.

$$ExpAgr=((Área\ 2017-Área\ 2000)/Área\ 2000)*100$$

The Percentage of Erodibility high and very high and eroded phase indicator came from the soil erodibility to water erosion of Brazil map (EMBRAPA, 2020). Despite the small scale (1:250,000) in relation to the other data, it is not a critical factor. Since the mapping unit of 25km² used reaches cartographic scales up to 1:25,000,000. Considering the permissible error of 0.2 mm in a cartographic mapping (IBGE, 1998). The chosen classes from the data were eroded phase, high and very high erodibility. The region was intersected in the QGIS with the grid to calculate the area with erodibility in each grid and then the percentage was calculated. In the case of the average aridity rate and average slope indicators, zonal statistics were used to calculate the respective averages in each grid.

The Agricultural yields of basic products quantifies the efficiency of municipal production of basic foods. Were taken into account rice, beans, cassava, corn and wheat. The calculation is first made by the division of the harvested quantity of each of the agricultural crops mentioned in tons and the respective planted areas. The quotient average of each agricultural crop was calculated between the years 2010 to 2019. Considering their maximum and minimum values a standardization was applied for each agricultural crop. The final value was taken from the average of the standardized values of each crop. This way, the bigger the indicator's value the higher the agricultural productivity of basic food per municipality.

And finally, in the case of Percentage of Degraded Pastures indicator was used the zonal statistics tool to obtain the count of pixels with degraded pastures and total amount of pixels in the grid. Then, to obtain the percentage, the two results were divided by one another and the quotient multiplied by 100.

2.2.3. Correlation and exclusion of indicators

With all the indicators ready, the Spearman correlation between the indicators was calculated. Pairs with strong correlation greater than or equal to 0.7 or less than or equal to -0.7 were observed (FIGUEIREDO FILHO; SILVA JÚNIOR, 2009). An elimination analysis was performed based on a discussion among the team and a literature review. For such methods, the hmisc, Corrplot, XLSX and Rcorr packages of the R program were used. Figure 2 shows the correlogram prepared with the correlation between the selected indicators. The values with a " X " mean that the correlation has not achieved a significant level of 5% between the pairs. So, they are not amenable to the analysis.

The indicators that obtained the highest correlation of the same DPSIR component were: Average slope x Average aridity rate (0,49), Firewood produced (m³) x Percentage of establishments using pesticides (0,90), Percentage of accumulated deforestation x Fire spots (0,57). The team decided to exclude only the Percentage of establishments using pesticides because the firewood extraction is way more expressive in the Caatinga region.

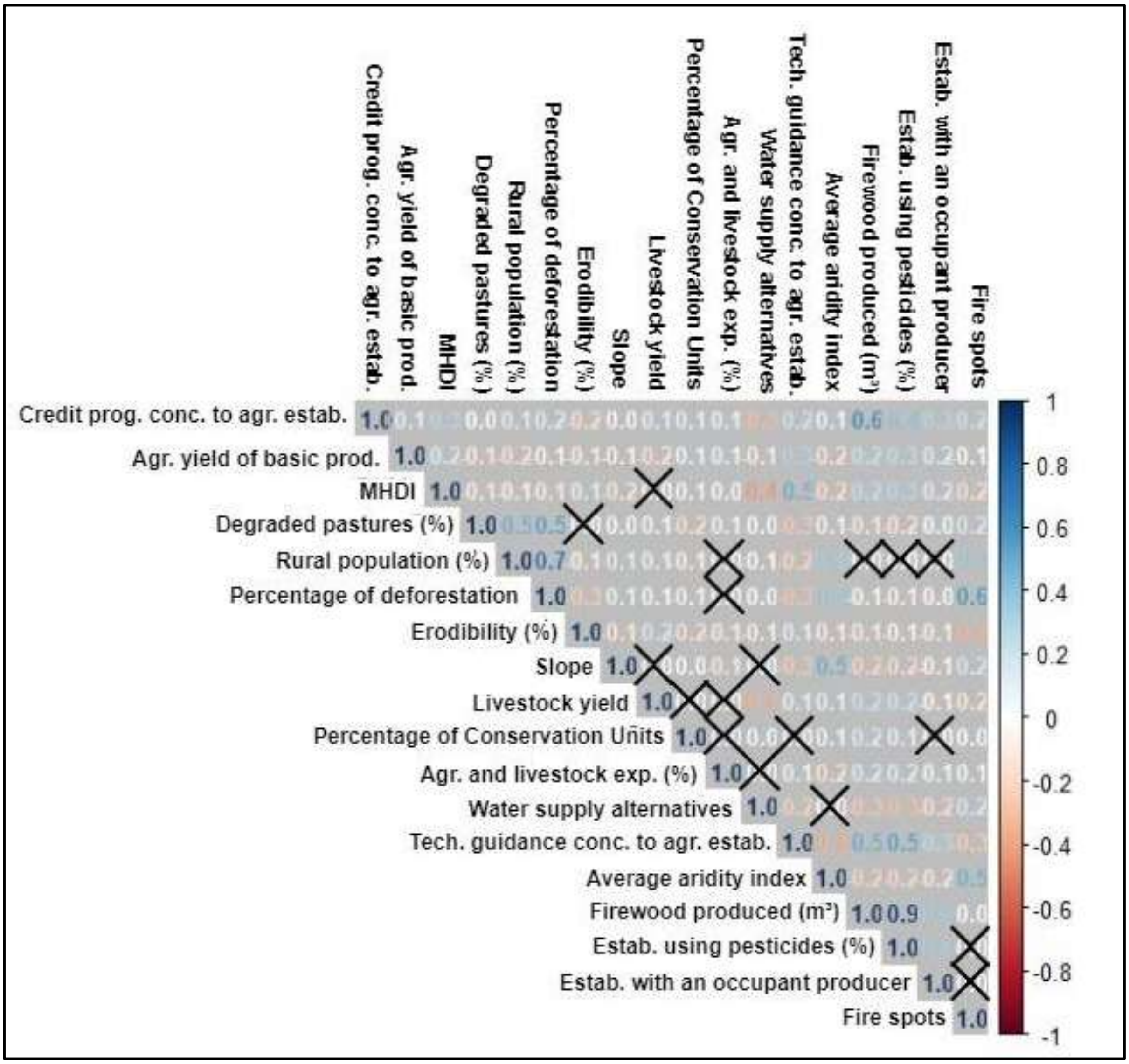

Figure 2 – Correlogram of the indicators.
Source: By author (2022).

2.2.4. Data standardization

The seventeen selected indicators were normalized between 0 to 1 and the *outliers* treated accordingly the *winsorization* technique, as proposed by Nardo *et al.* (2008).

The DPSI component indicators with inverse direction to degradation (which contribute to reduce it) were inverted to allow the comparison with the other indicators. They are the Average MHDI, Herd Productivity, Average aridity rate and Average agricultural commodity yield. All indicators that integrate the Response component were not inverted. This is because they have the potential to reverse the degradation and they were grouped in a separated rate aside the other DPSI components.

Afterwards, the indicators of each DPSIR component were grouped to generate the rates. A median between the indicators was made to generate the rates. The rates values were standardized and the resulting tables were imported into QGIS.

Spreadsheet with rates of each DPSIR component were merged with the grids, five thematic maps of each component generated and one more map with the average DPSI values calculated by the final values of the individual rates.

3. Results and discussion

Results coming from the seventeen indicators in the form of 5 spatialized rates show distinct patterns in each component. In the D, P, S and I components the areas with greater vulnerability to degradation are those closer to the value of 1. And in the R component the areas with greater potential to reverse degradation correlate to the values closer to 1.

The driving force indicators presented in Figure 3 were: Agricultural establishments with occupant producer, Average MHDI and Rural population percentage. This set of indicators represents the population growth in the countryside and the living conditions of the population. Vieira *et al* (2015) considered that the population interfere in the northeast region through land usage that might lead to greater degradation. About MHDI, Lima *et al* (2016) say that the inhabitants of the region below poverty line may not know how to properly manage the soil or do not understand the importance of this inherent resource to the nature. Summed with the absence of programs of rural technical assistance and environmental education. The lack of access to the land represented by establishments with occupant producer might also contribute as a indirect cause for this process of degradations (FAO, 2003).

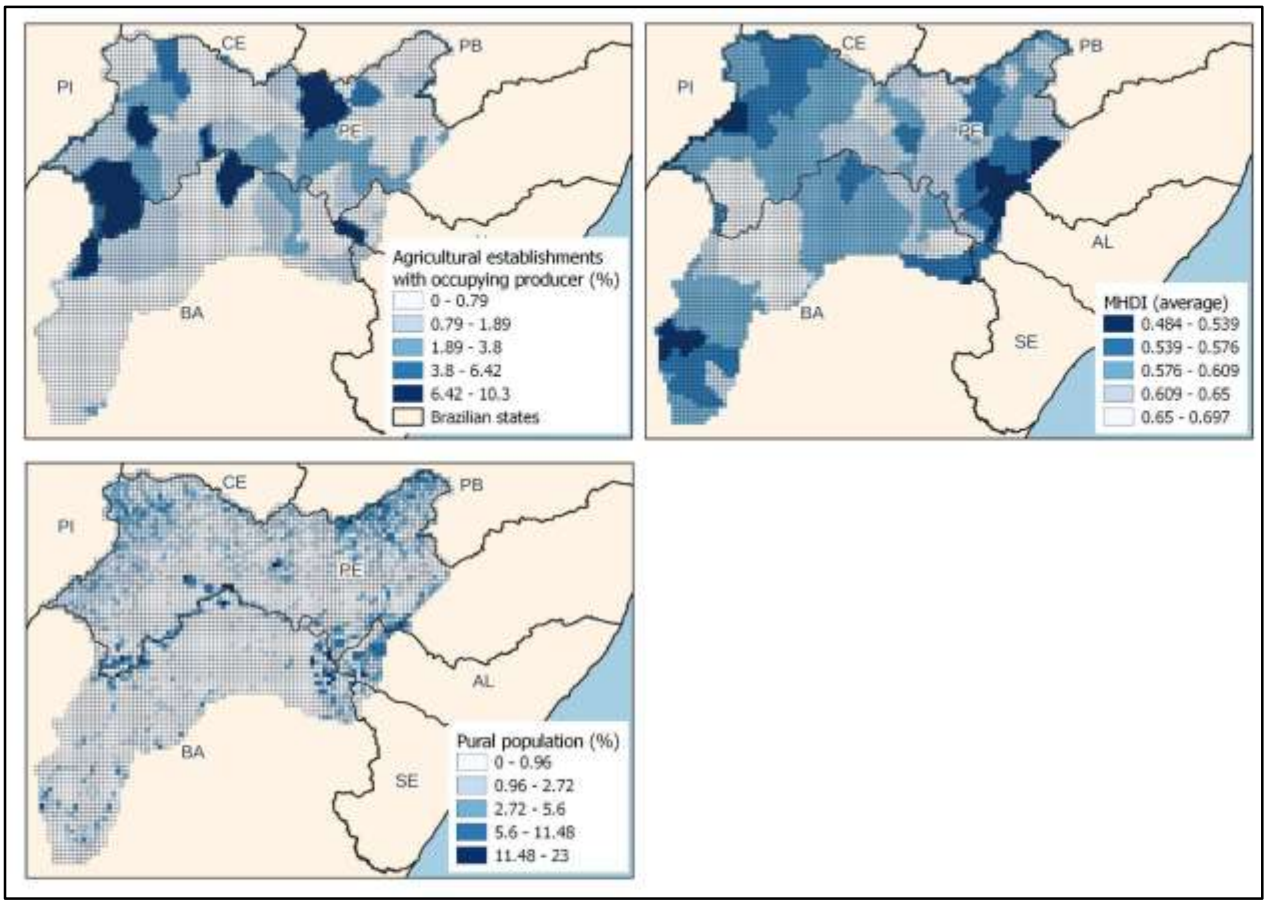

Figure 3 – Spatial distribution of Driving Force Rate indicators.
Source: By author (2022).

The map of this rate (Figure 4) shows areas with greater degradation potential in many regions of the basin. With lower values in the southern portion of the basin, in Bahia. In the East and southern end of the basin the indicator that contributes more to the highest value of the rate was the MHDI. These areas have a lower MHDI rate than the others. While the areas with occupant producer had more influence on the center and northwest of the basin (class of 0.8 to 1). The populated rural areas of São Francisco River are mainly distributed along the border between Bahia and Pernambuco and in the northeast of the basin. They had less influence on the rate results.

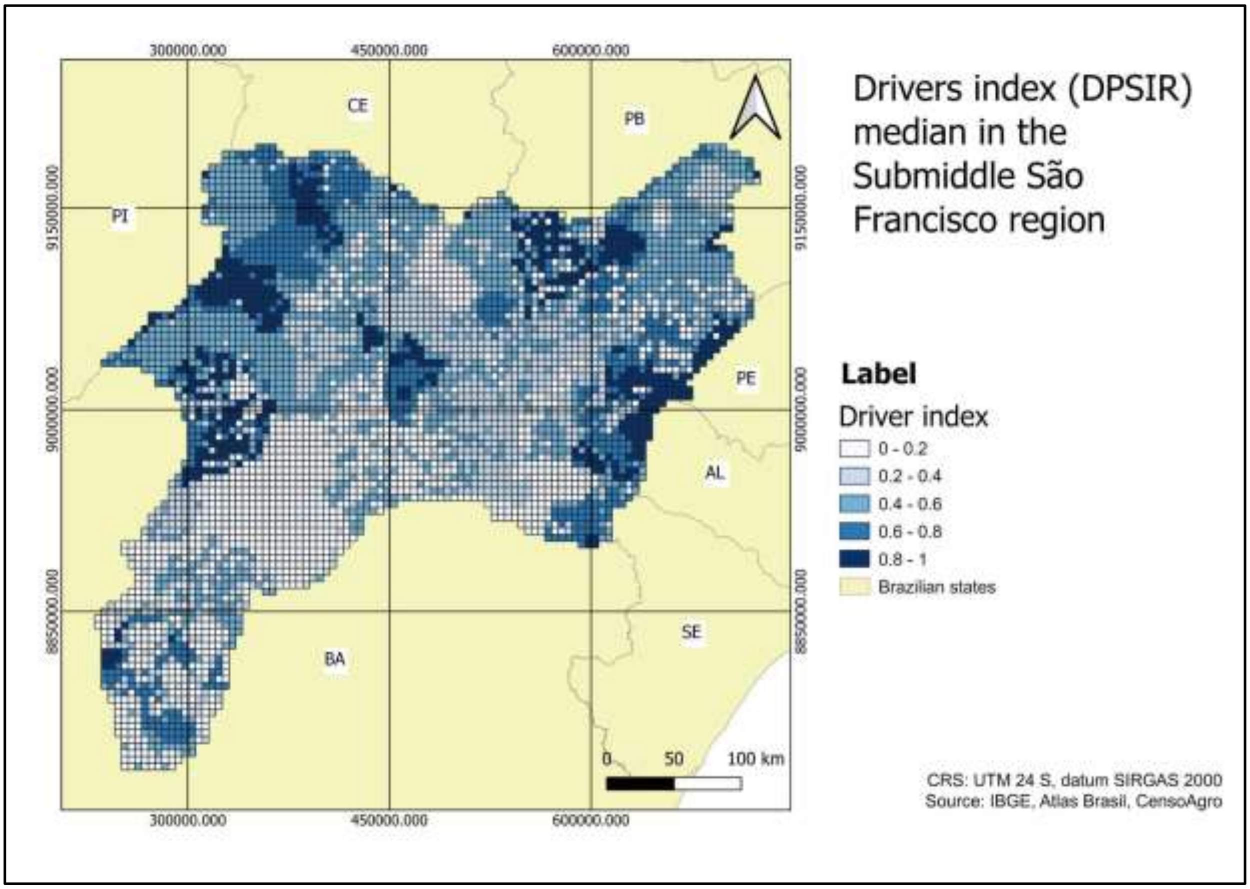

Figure 4 – Driving Force Rate.
Source: By author (2022).

In Figure 5 is possible to check the Average amount of firewood produced (m³), Animal husbandry productivity, Quantity of heat sources (accumulated), Percentage of deforestation (accumulated) and Percentage of agricultural expansion indicators. Together they compose the Pressure Index. The deforestation causes irreversible damage to the Caatinga according to Demartelaere *et al* (2022). For, it can lead to desertification in association with wildfires that begin anthropically and damage the soil (LATUF; RIOS; PEREIRA, 2022) and the Brazilian exploitation of firewood, that is not enough to sustain the plaster industry (GRANJA *et al*, 2017). Lima *et al* (2016) also talks about the overgrazing which compacts the soil making it loses its biological activity.

Petrolina and Juazeiro together represents one of the national centers of irrigated agriculture. It is the most developed in the São Francisco basin (ANA, 2019). Although the agriculture importance to economy studies show that inappropriate handling might degrade the soil through water erosion and salinization (FAO, 2003; KOSMAS *et al*, 2014). According to the São Francisco River Basin Water Resources Plan (CBHSF, 2016), irrigated agriculture is one of the main causes of soil salinization. The São Francisco Submiddle basin is included in the high-risk class of salinization.

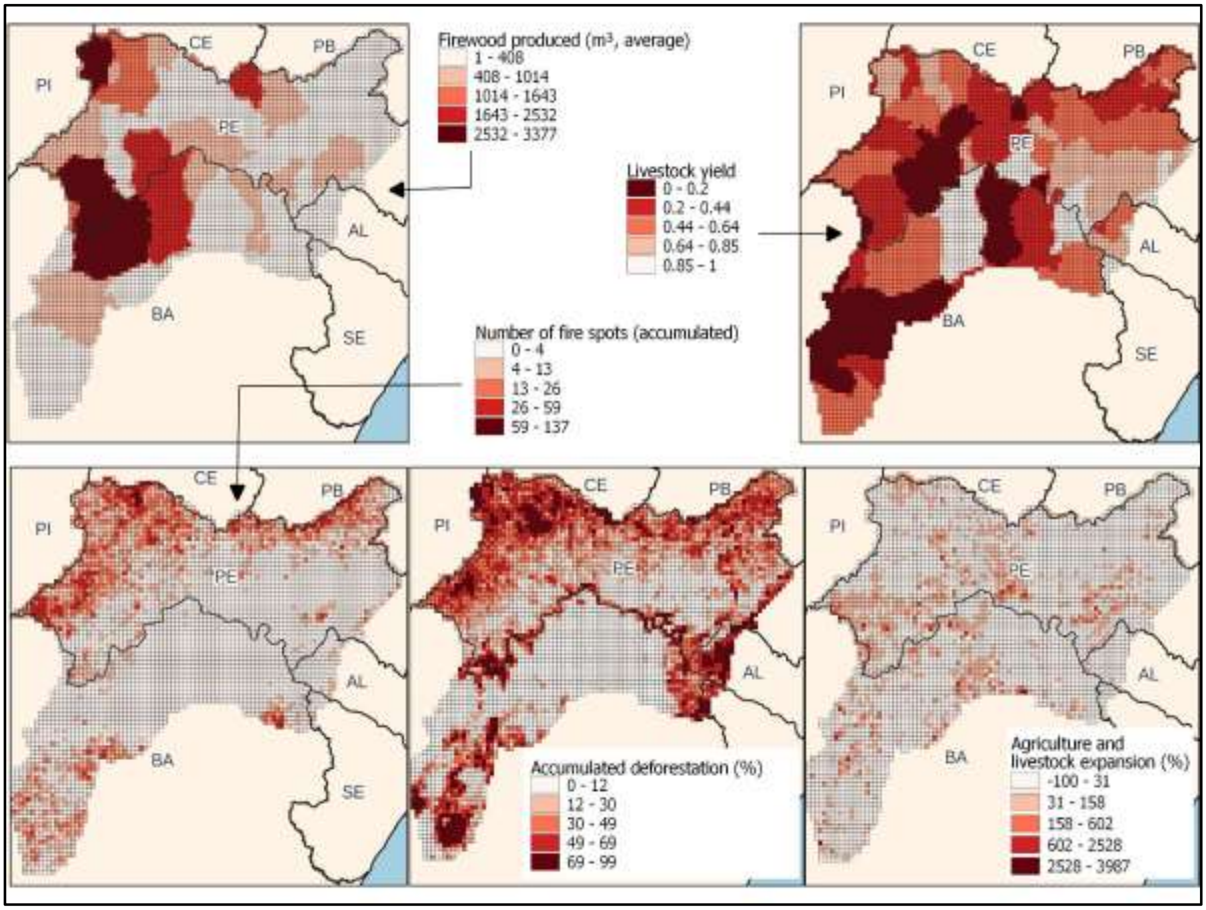

Figure 5 – Spatial distribution of Pressure Index indicators.
Source: By author (2022).

In the Pressure Index (Figure 6), the most critical areas are in the West and north of the basin, with higher values in the municipalities of Petrolina, Santa Maria da Boa Vista and Araripina (> 0.6). These places are of great economic importance for the region. Petrolina (PE) has huge investment in irrigated agriculture (MANETA *et al*, 2009). Santa Maria da Boa Vista (PE) is located in an influential region, Petrolina-Juazeiro. And Araripina takes part in the Plaster Pole that extracts Gypsum. It is an important component to the plaster production (GRANJA *et al*, 2017).

In general, the rate follows the spatial patterns of the deforestation indicator. That, accordingly with figure 4, it is higher along the entire northern area of the basin, throughout the São Francisco River and East of the basin and in the southern end of the basin. In agreement with the grids with values from 0.4 to 1. According to FAO (2003) the deforestation is one of the main causes of land degradation. The animal husbandry productivity influenced the entire western portion of the basin. From the southern end until the northwest and north of the basin. The concentration of heat sources occurs principally in the northwest of the basin. While the agricultural expansion occurs in a scattered way over the territory.

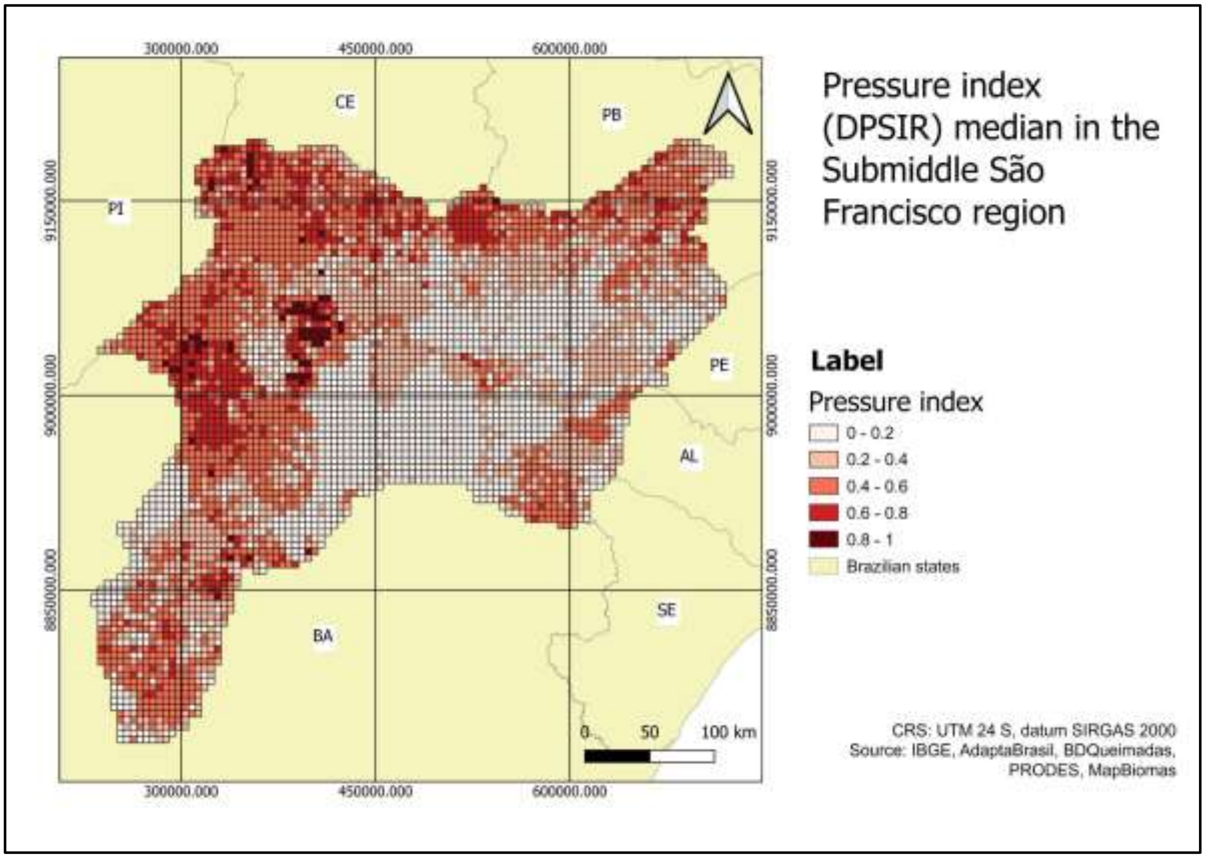

Figure 6 – Pressure Index.
Source: By author (2022).

The State indicators (Figure 7) are represented by Percentage of areas with high and very high erodibility and eroded phase, Average aridity rate and Average slope. The higher slope of the terrain makes the soil more susceptible to erosive processes. And the average slope indicator is higher on isolated areas that border the northeast, east and southwest of the basin. Soil erodibility is represented by intrinsic soil factors, such as granulometry, depth and organic carbon content (EMBRAPA, 2020). Another issue to be taken into account is the climate for influencing degradation (LOPES; LEAL, 2015). It is expressed in the research by the aridity rate, which relates precipitation and evapotranspiration. This natural susceptibility presented by the three indicators associated with impactful human activities contributes to intensify degradation.

In relation to the State index (figure 8), it is possible to verify large regions more susceptible in the center and southwest of the basin. Areas of high and very high erodibility predominate in the São Francisco river Submiddle basin. With the exception of the region northwest of the basin, which has a lower index on the State index map. It influences the result represented in Figure 10. The aridity rate also contributed to the spatial pattern of the State index. With higher aridity values throughout the central and southern regions of the basin. It is possible to verify in the work of Bezerra *et al*. (2020) that the areas at the center and south of the basin possess a very high susceptibility to degradation. The same pattern of higher vulnerability to degradation can be visualized in the State index (Figure 8).

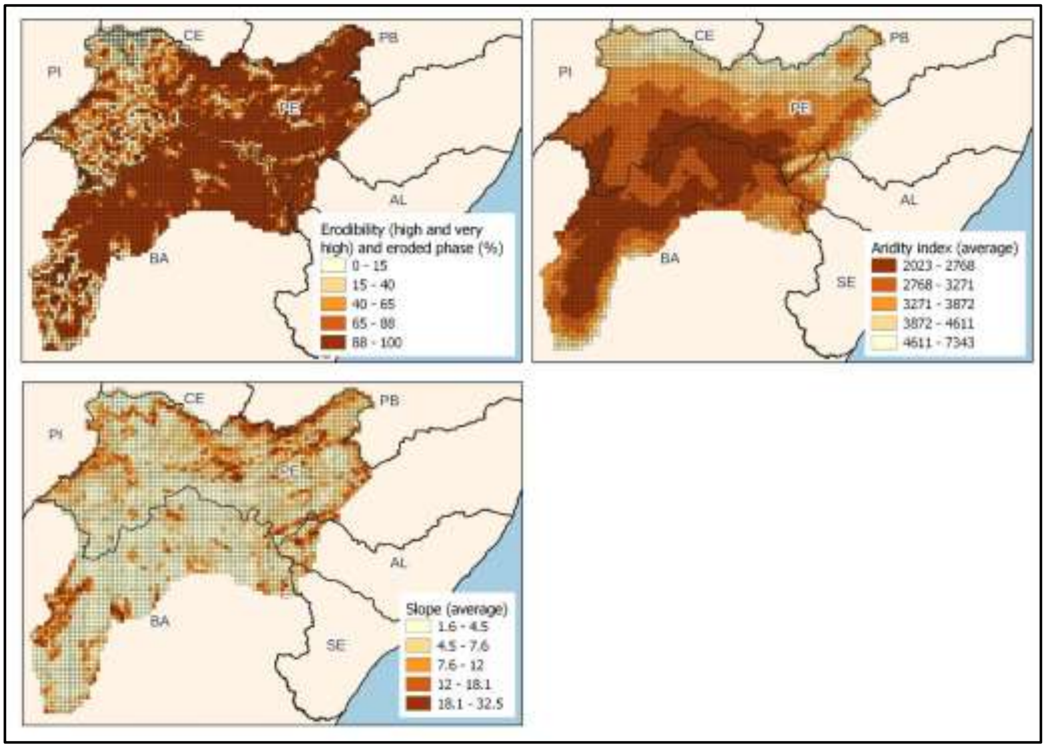

Figure 7 – Spatial distribution of State Index indicators.
Source: By author (2022).

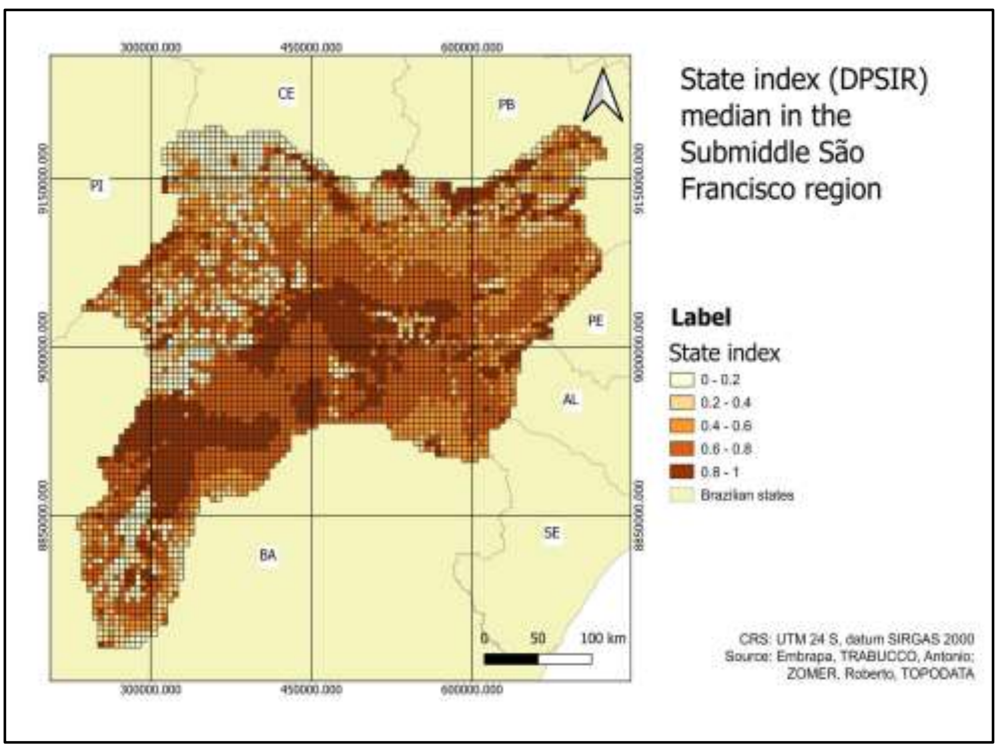

Figure 8 – State Index.
Source: By author (2022).

The impact index represents socio-economic changes triggered by the changes in the state of the environment (EEA, 1999). Land degradations leads to a loss of biological and economic productivity of the land (UNCCD, 2017). Consequently, it is important to verify the loss of commodity productivity for feeding those who live in the basin. Such as rice, beans, corn, cassava and wheat. As well as the quality of pastures for it affects animal husbandry, just as presented in the indicators' map (Figure 9).

The impact Index (Figure 10) presents the highest values in the southern and northwest regions of the basin. In these areas the pastures were mapped as severely degraded by Santos *et al*. (2022) study. The Degraded Pastures (%) indicator presents a similar pattern to the map in Figure 10. It is the most correspondent to the impact index. In the case of agricultural productivity, the areas with the lowest productivity occur in the Northwest, Center and northeast of the basin.

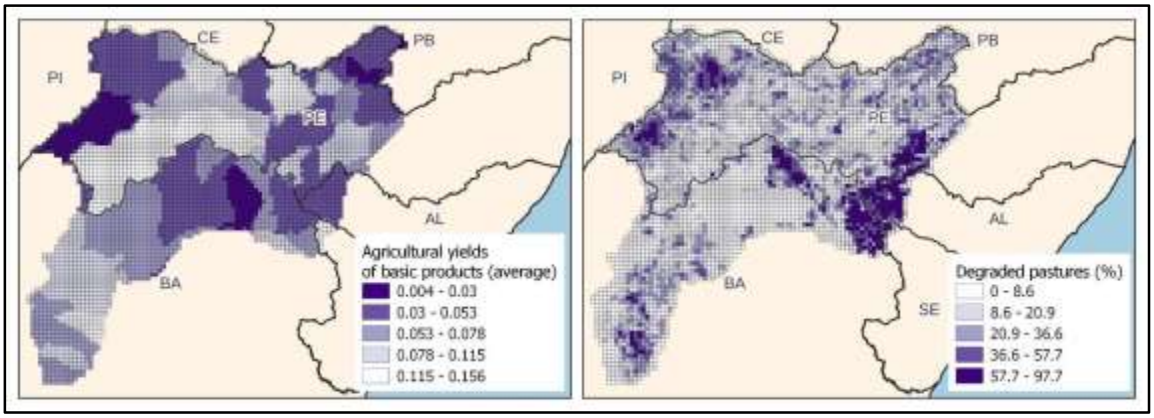

Figure 9 – Spatial distribution of State Index indicators.
Source: By author (2022).

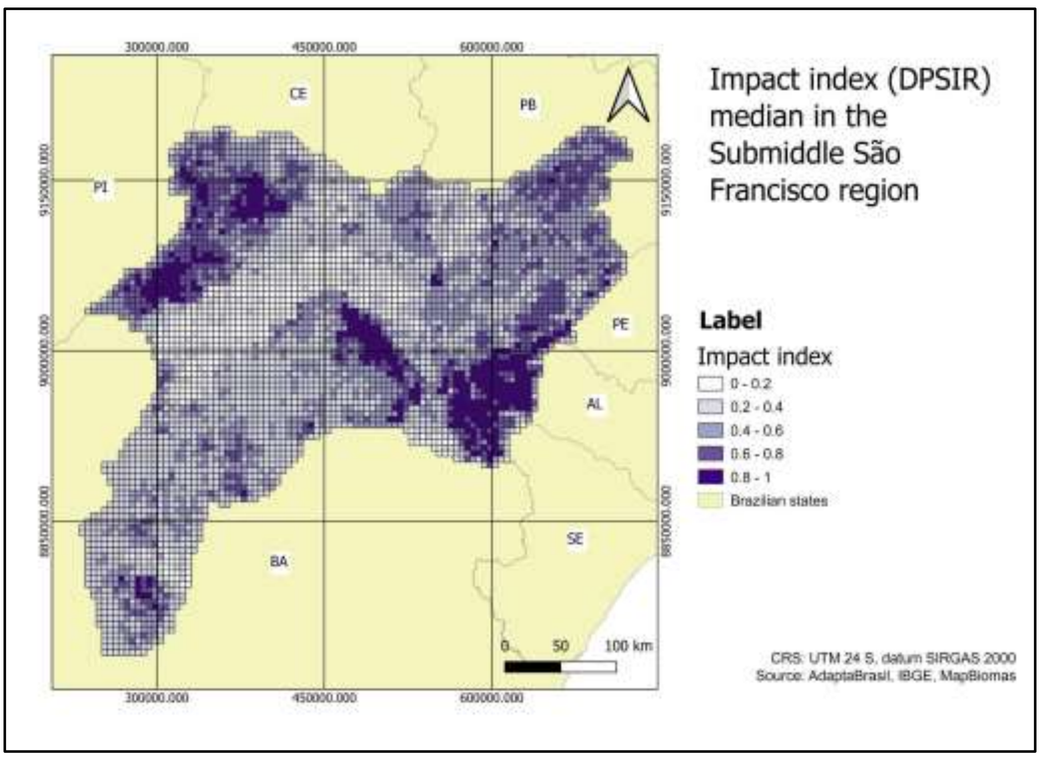

Figure 10 – State Index.
Source: By author (2022).

The map in Figure 12 shows the average of the DPSI rates and brings to light where the four components that contribute to degradation have higher values (0.6 to 0.83) and lower values (less than 0.6). The areas more vulnerable to degradation and with higher values are located especially in the northwest and southeast regions of the basin. However, there are also smaller spots in the center, southern end and northwest edge of the basin.

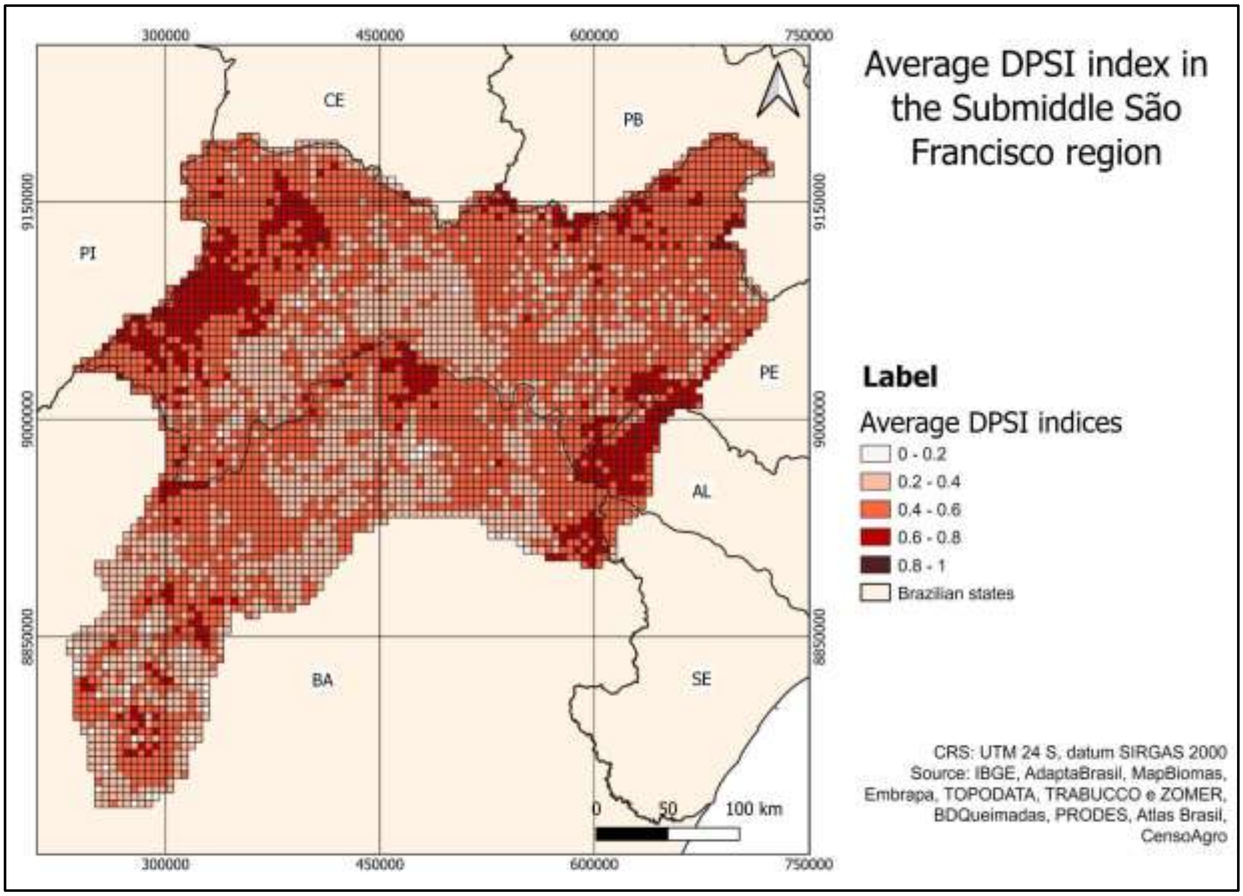

Figure 12 – Average of DPSI rates.
Source: By author (2022).

At last, in the Figure 13 are represented the Response indicators. They are: Average number of establishments that received loan program, Alternatives to water supply, Number of establishments that received technical orientation and percentage of UCs.

The indicators with the highest similarity to the Response rate were: Percentage of the number of establishments that receive technical orientation and Average number of establishments that received loan program. With the municipalities of Petrolina and Juazeiro having the highest values at west of the map. Araripina (PE) at the northwest of the basin stands out in the case of loan. The percentage of UCs of Integral Protection contributed in the influence of the pattern observed in the northwest and southwest of the basin. The alternatives to water supply indicator contributed to the higher value in the southeast of the map.

Lima *et al.* (2016) work also takes into account similar themes to those mentioned here in. Such as income transfer programs, families assisted with social technologies for access to water and protection of UCs.

The Response Rate (Figure 14) focuses the highest values, with the highest potential to reverse degradation, at the west and northwest of the basin. This rate points out which actions might reverse degradation. Especially with public policies for environmental conservation, technical assistance and water availability. In the map is possible to verify municipalities such as Petrolina (PE), Juazeiro (BA) and Araripina (PE), with greater potential to go against degradation.

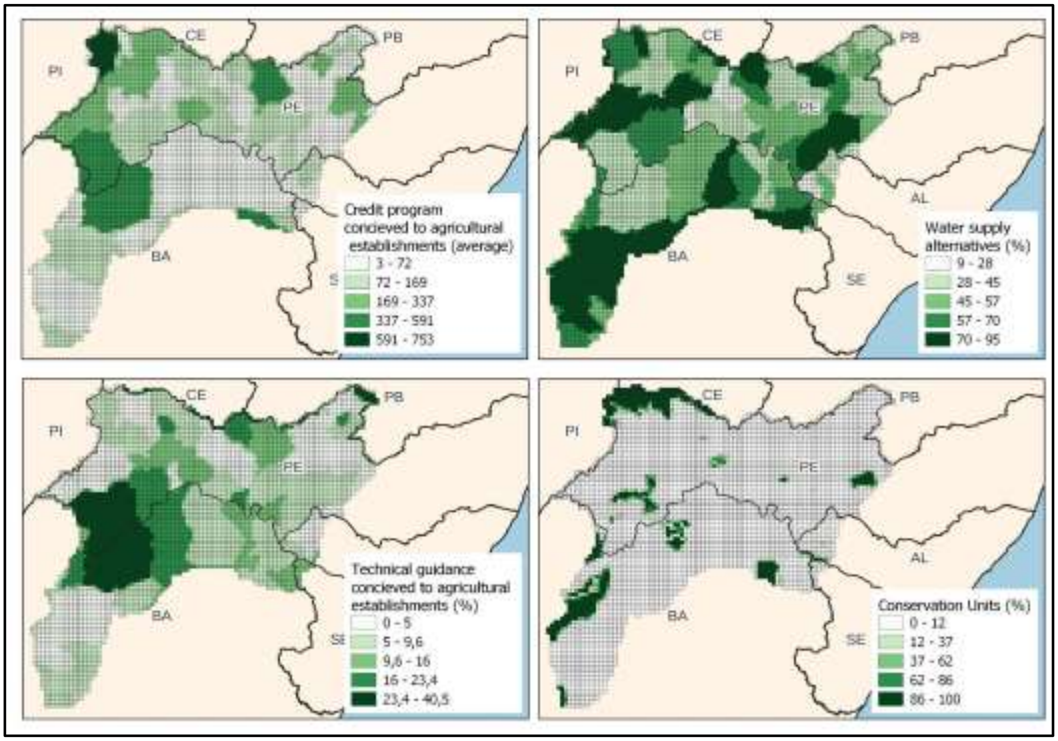

Figure 13 – Spatial distribution of Response Rate indicators.
Source: By author (2022).

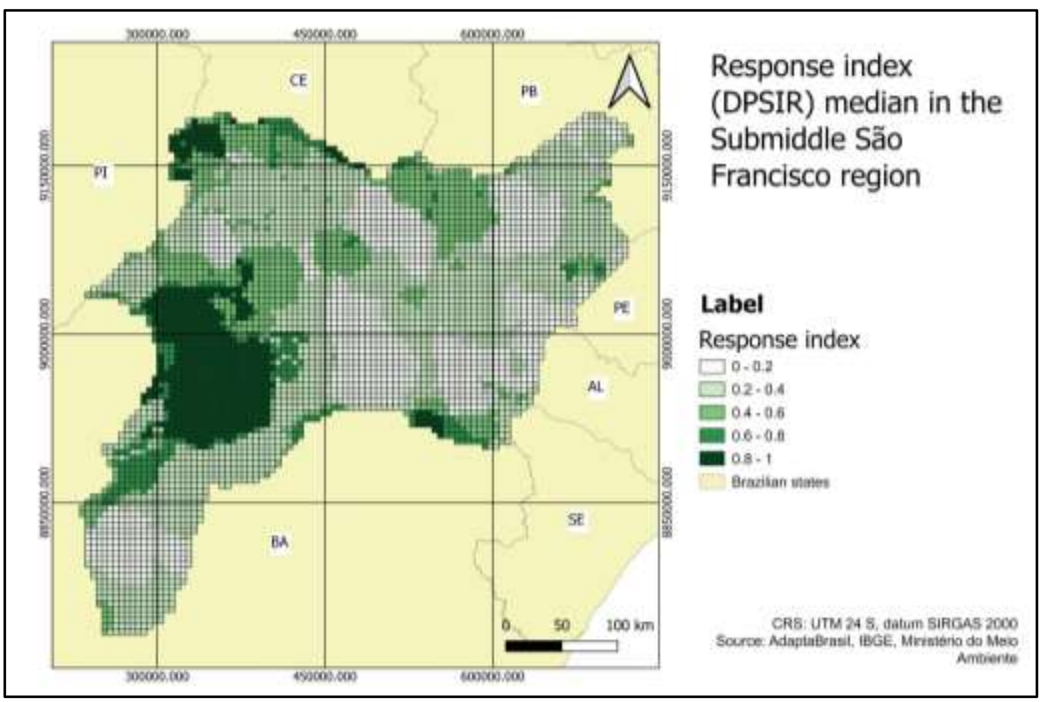

Figure 14 – Response Rate.
Source: By author (2022).

It is important to emphasize that there are practices being applied in the Brazilian semiarid to reduce land degradation that could not be quantified in the present study, such as agroecology and reforestation. The experiences presented by Curado, Santos and Oliveira (2014) show the importance of agriculture based on agroecology in the promotion of the sustainable use of Natural Resources. The Pérez-Marin *et al.* (2017) emphasize that reforestation and the diversification of agroecosystems are the starting point to soil conservation practices and to increase the capacity to coexist with the semiarid. They contribute to fight the land degradation.

4. Conclusion

The DPSIR framework is an important tool for understanding land degradation in a systemic way, understanding it as a process composed of socio-environmental relationships that interact with each other. The usage of indexes allowed the measurement of the degradation in a way that made the understanding of this complex phenomenon easier. It was observed that each DPSIR component has the ability to reveal particular characteristics of the degradation process, since the spatial patterns differ for each index.

From the indicators it was possible to observe that the living conditions of the population and the occupation characteristics in countryside areas, together with activities that change the environmental conditions, such as wildfire and deforestation, affect the physical environment. These drivers and pressures, joint to climatic conditions, generate a susceptibility to degradation. The consequence of these changes in the environment also impacts the society and the economy. Then, results in agricultural yield decreases.

The indicators that contributed to the main spatial patterns of indexes were: MHDI to Driver, Deforestation to Pressure, Aridity Index to State, Degraded pastures in the Impact, and Agricultural establishments that receive technical orientation and loan programs in the Response index.

The most vulnerable areas to degradation are located mainly in the northwest and southeast regions of the basin. But there are also smaller spots in the center, southern end and northwest edge of the basin. Regarding the Response, the areas to the west, northwest and southeast of the basin stand out.

Some public policies that were taken into account in the study may contribute to the reduction of the degradation in the basin. Some of them are the level of technical orientation and loan gave to rural producers and the presence of conservation units. It is important to emphasize that initiatives to restore the vegetation can also contribute to reverse this process. Although they were not measured in the present study due to the lack of data available about the basin.

This study hopes to contribute to highlight the most vulnerable areas. Expecting that public and private authorities give the necessary importance to them and that initiatives to restore them are carried out. It also hopes that future studies can analyze response indicators not mentioned in this article, such as reforestation and agroecosystems.

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