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Dynamics of land use in a rural settlement in the Brazilian Legal Amazon

A dinâmica do uso da terra em um assentamento rural na Amazônia Legal brasileira

Miqueias Lima Duarte[1], Jocy Ana Paixão de Sousa[1], Amazonino Lemos de Castro[1], Roberto Wagner Lourenço[1]

ABSTRACT

Deforestation in the Amazon has reached alarming numbers in recent decades. The main factors causing this issue are not only large and medium-sized farmers, land grabbing, and illegal mining but also agrarian reform settlements, which may be contributing to the increase in deforestation rates. In this context, this study aims to evaluate the dynamics of land use in the rural settlement Santo Antônio do Matupi, located in the south of the State of Amazonas. This time-series study analyzed changes in land use and land cover from 1992 to 2018 using supervised classification techniques. In this scenario, simulations were carried out of the dynamics of land use for the period between 2028 and 2038 using the cellular automaton method of *Markov* (CA-MARKOV). The results show that, in the studied period, the greatest losses were in primary forests and that the most critical period of deforestation rates recorded was from 2004 to 2018 when 63.28% of the area was converted into pastures. Future scenarios based on the period studied indicate losses of up to 5.26% of areas occupied by forests by 2028, and a further 5.60% by 2038, exceeding 80% of the total area deforested in the settlement. This study demonstrates that the current model of land use and occupation practiced in the settlement is unsustainable and that future scenarios are worrying. This situation highlights a need to effectively implement programs that aim a sustainable rural development in the settlement, in addition to monitoring and controlling deforestation, designed for current managers and other sectors of the society concerned with the conservation and preservation of forests.

Keywords: Amazon biome; agrarian reform; deforestation; CA-Markov model.

RESUMO

O desmatamento na Amazônia vem alcançando números alarmantes nas últimas décadas, sendo os principais responsáveis por essas ações não apenas os grandes e médios fazendeiros, a grilagem de terra e o garimpo ilegal, como também os assentamentos de reforma agrária podem estar contribuindo com o aumento nas taxas de desmatamento. Diante desse contexto, este trabalho visa avaliar a dinâmica do uso da terra no assentamento rural Santo Antônio do Matupi, localizado no sul do estado do Amazonas. Foi realizado um estudo temporal sobre a mudança no uso e cobertura da terra de 1992 a 2018, com uso de técnica de classificação supervisionada e, a partir desse cenário, foram realizadas simulações na dinâmica do uso da terra para o período de 2028 a 2038 utilizando o método autômatos celulares de *Markov* (CA-MARKOV). Os resultados mostraram que no período estudado as maiores perdas foram nas florestas primárias, sendo o período mais crítico nas taxas de desmatamento registrado de 2004 a 2018, quando 63,28% da área foi convertida para a implementação de pastagens. Os cenários futuros, com base no período estudado, indicam perda de até 5,26% de áreas ocupadas por florestas até 2028, e mais 5,60% até 2038, superando 80% de área total desmatada no assentamento. O estudo demonstra que o atual modelo de uso e ocupação da terra praticado no assentamento é insustentável, e que os cenários futuros se mostram bastante preocupantes, o que evidencia a necessidade de implementação efetiva de programas voltados ao desenvolvimento rural sustentável no assentamento, além do monitoramento e controle do desmatamento voltado aos atuais gestores e demais setores da sociedade preocupados com a conservação e preservação das florestas.

Palavras-chave: bioma Amazônico; reforma agrária; desflorestamento; modulo CA-Markov.

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Introduction

The creation of the National Plan for Agrarian Reform (PNRA), under decree no. 91.766 of October 10, 1985, has driven the colonization of the Amazon region in Brazil. Its main objective is allocating 43 million hectares for the benefit of more than 1.4 million families (Brasil, 1985). Current data show that more than 87 million hectares have been demarcated in rural settlements, of which 80.23% are located inside the Legal Amazon (Brasil, 2020a).

Currently, the Amazon has been losing a large part of its native vegetation cover due to several factors, such as disordered exploitation of wood and deforestation to benefit the agricultural sector (Congilio and Moraes, 2016; Duarte et al., 2020; Rossoni and Moraes, 2020). The tendency is that the increase in deforestation continues in the coming years mainly in the region located in the "Arc of Deforestation," which comprises the western part of the State of Acre, the southern Amazon and Pará, northern Rondônia, and Mato Grosso, in addition to the area of transition from the State of Pará to Rondônia and Maranhão (Carvalho and Domingues, 2016; Tollefson, 2018).

Studies have indicated that large and medium-sized farmers contribute the most to deforestation activities in the Amazon (Walker et al., 2013; Fearnside, 2017). However, some studies have shown that deforestation in rural settlements may be contributing significantly to deforestation in locations where settlements are concentrated (Farias et al., 2018; Duarte et al., 2020).

Although rural settlements are important means of distributing land, their implementation process, in addition to contributing to deforestation, causes a series of socioenvironmental problems, which may render sustainability unfeasible (Ávila et al., 2019). According to Moutinho et al. (2016), about 10–30% of the deforestation in the Amazon is attributed to small landholders, especially in rural settlements established by the National Institute of Colonization and Agrarian Reform (INCRA).

The increase in deforestation inside the Legal Amazon is strongly associated with the growth of cattle breeding (Walker et al., 2013). Data of the Brazilian Institute of Geography and Statistics (IBGE, 2020) point out that between 1990 and 2017, the Brazilian cattle herd increased from 147 million to 217 million animals (about 140%) and that a large part of this increase occurs mainly in the Amazon region (264% between 1997 and 2017). In a way, it implies the deforestation of new areas for the opening of new pastures (Mello and Artaxo, 2017; Thaler et al., 2019).

The removal of forest areas for agricultural purposes is associated with loss of water and soil quality (Fearnside, 2017), as well as changes in biological, physical, and chemical processes in natural systems (Thomaz et al., 2020). Thus, pressure on forest areas and inadequate land use are determining factors for environmental degradation, ecological imbalance, and loss of biodiversity (FAO, 2017; Thaler et al., 2019; Duarte et al., 2020).

Considering the importance of maintaining natural vegetation to ensure the stability of the environment and the effects of rural settlements on deforestation in the Amazon, it is relevant to assess the current conditions of the dynamics of land occupation in view of such dynamics of suppression of the forest and, consequently, verify the future impacts on the forest. Geographic information systems (GIS) and remote sensing are powerful and low-cost tools to investigate these processes since they allow the evaluation of historical changes using multitemporal data, in addition to building future scenarios that can be used for monitoring and planning purposes (Olmedo et al., 2015; Firozjaei et al., 2019).

Thus, this work presents the results of a case study on the time dynamics of land use and land cover changes between 1992 and 2018 in a rural settlement inside the Brazilian Amazon. Based on this dynamic, this study projects the consequences for future scenarios in 2028 and 2038. The research sought to predict the likely future conservation status of forests in view of the current soil management and use, as well as to demonstrate the feasibility of applying remote sensing and geoprocessing techniques in diagnoses and prognoses of land use and occupation in rural settlements in forest areas of the Amazon Biome.

Characterization of the study area

The study area corresponds to the Santo Antônio do Matupi Rural Settlement Project (RS Matupi), located in the municipality of Manicoré, in the southern region of the State of Amazonas, inside the Legal Amazon (Figure 1). The settlement was created through the resolution no. 148 of June 20, 1992, by the National Institute of Colonization and Agrarian Reform (INCRA) (Brasil, 2020a) and covers an area of 34,889.77 hectares divided into 538 lots with an extension of 60 to 80 hectares.

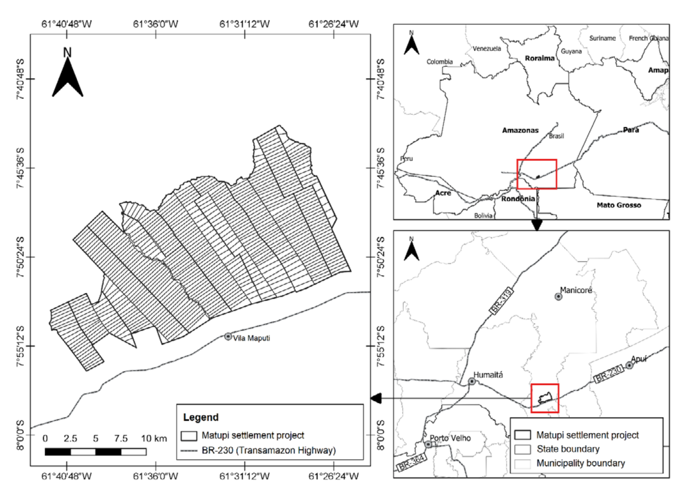

Figure 1 – Location of the Santo Antônio do Matupi rural settlement.

The RS Matupi aimed to incorporate new areas into the regional productive process and order occupations through an implanted infrastructure, thus avoiding invasions in and speculation on land ownership and use, in addition to providing better living conditions for farmers in the region (Leal et al., 2017). As it is a conventional settlement, the RS Matupi followed the occupation and production model of the nearby states (Mato Grosso and Rondônia), which have extensive areas of forested land destined to the possibility of timber extraction and agricultural production (IDESAM, 2016).

Currently, the Technical, Social and Environmental Agrarian Reform Advisory Program (ATES) of the INCRA Regional Superintendence monitors the settlement with support from the Amazonas Sustainable Development Institute (Brasil, 2020a). It is also a part of the Green Settlement Program, which comprises a set of actions aiming to facilitate rural credit, training, and rural organization and assist in the production, sales and marketing system, technical assistance, and environmental conservation aiming a sustainable development of settlements (Brasil, 2020a).

Materials and Methods

Plotting of the map of land use and land cover

The land use and land cover maps for the period between 1992 and 2018 were prepared based on the classification of satellite images obtained by the Thematic Mapper (TM), Landsat 5, Enhanced Thematic Mapper Plus (ETM +) Landsat 7 sensors, and the Operational Land Imager (OLI) Landsat 8, both with a spatial resolution of 30 m, obtained on the Earth Explorer website of the United States Geological Survey (USGS, 2019), at orbit/point 231/65.

The images on different dates were redesigned for the *Universal Transverse Mercator* coordinate system, Datum SIRGAS 2000, Zone 20 South. Then, the atmospheric correction was performed using the Dark Object Subtraction 1 (DOS1) method, as described by Leroux et al. (2018), and its color composition was made using bands 5, 4, and 3 of Landsat 5 and 7, and bands 6, 5, and 4 of Landsat 8.

Next, supervised classification of images was performed using the software QGIS 3.2.1 (OSGEO, 2019) and the function *Semi-Automatic Classification Plugin* v. 6.2.2 (Congedo, 2018), as described by Duarte and Silva (2019).

The supervised classification uses the maximum likelihood method, which calculates the probability that a pixel belongs to a land cover class based on the comparison of spectral signatures obtained from samples of calibration areas referring to the land surface category. In this method, calibration areas were selected to extract the signatures of the different covers of the Earth's surface in the form of polygons on a composition of the Landsat 5, 7, and 8 images. On average, 20 samples were determined for each cover category. The dimensions of the polygons were between 10 and 20 pixels.

Verifying mapping accuracy

To verify the precision and accuracy of the mapping of land use and land cover, fieldwork was carried out between September 17 and 21, 2018, for photographic records and georeferencing of 50 samples obtained randomly, as described by Duarte and Silva (2019). This activity was performed using a Garmin 64s global positioning system (GPS). The land use classes identified were as follows: native forest vegetation—area occupied by dense ombrophylous forest; secondary vegetation—area previously deforested in a natural regeneration process; pasture A—area occupied by pasture in good cultivation conditions; pasture B—areas with abandoned or underused grass, showing signs of erosion and low productivity; and exposed soil—mechanized areas with no vegetation.

The analysis of classification accuracy for the other years (e.g., 1992, 1994, 1996, 1998, 2000, 2002, 2004, 2006, 2008, 2010, 2012, 2014, and 2016) was carried out by obtaining 50 samples randomly distributed on the identified areas with similar characteristics (e.g., tonality, texture, and structure) as those observed in the field for 2018. Figure 2 shows examples of points verified in the field used to validate land use classes.

From the samples obtained in the field, an analysis of classification accuracy was performed based on the construction of a confusion matrix (Fiumi et al., 2014). Then, the kappa coefficient was evaluated. This coefficient is a measure of agreement that provides an idea of the extent by which the observations depart from those expected (Landis and Koch, 1977), thus indicating the level of precision expected in interpretations. The *tau* agreement coefficient was also calculated, which is based on an a priori probability, which allows obtaining the expected agreement value even before verifying the mapping simulation results (Ma and Redmond, 1995).

As defined by Landis and Koch (1977), the kappa index can be classified into six classes considering the relative strength of agreement (Table 1). For the *tau* index, the same categories as the kappa index were considered since they are interpreted in the same way.

Study of the current and future dynamics of land use

The study of the current dynamics and changes between the years studied serves as a basis for predicting future scenarios in terms of land surface cover that may play an important role in the formulation of public policies aiming the planning and drafting of policy goals of environmental protection and conservation (Hasan et al., 2020).

To study possible changes in land use and land cover, a land change modeler (LCM) was used. The LCM considered a transition matrix based on land use change and land cover maps for the years 1998 to 2018 to identify changes in surface coverage during the analyzed period.

The cellular automaton model (CA-MARKOV) was used to study the possible future scenarios. The CA-MARKOV is a stochastic model

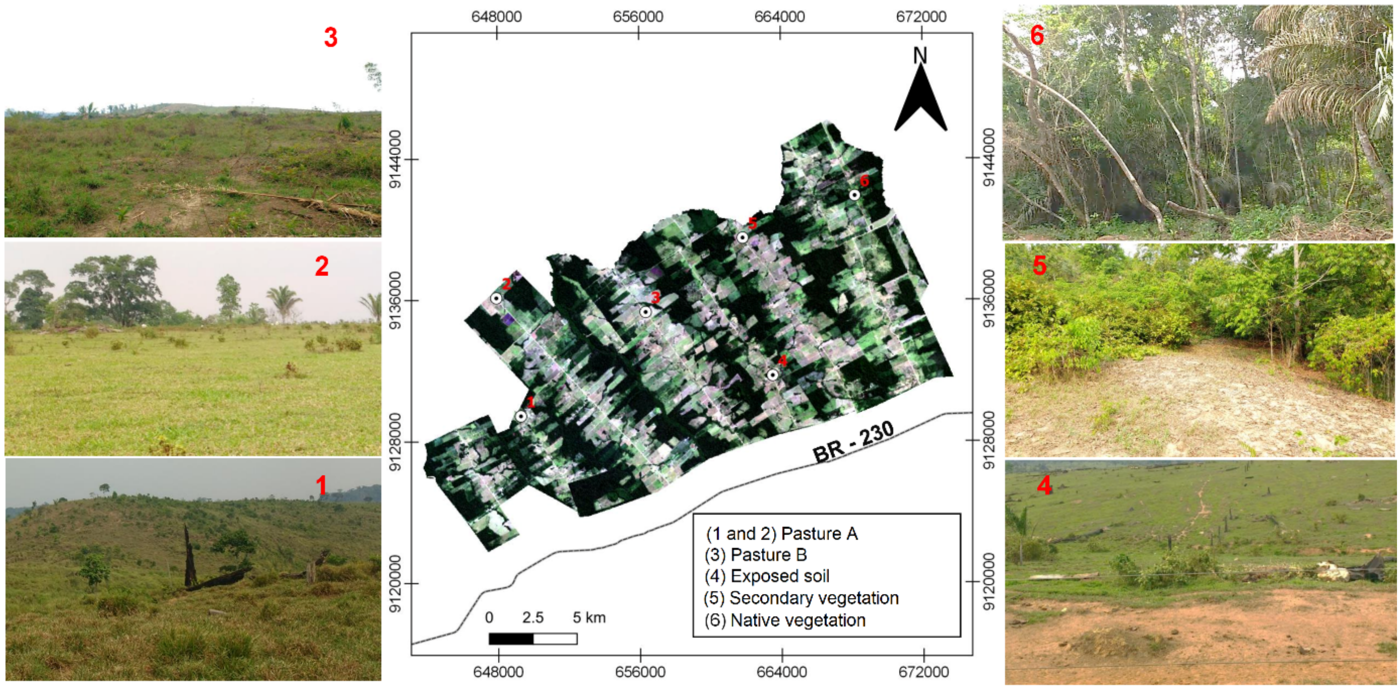

Figure 2 – Example of field verification points for validating land use classification.

Table 1 – Quality of the classification associated with kappa index values.

Kappa value	Level of agreement
< 0.00	None
0.00–0.20	Minimum
0.21–0.40	Weak
0.41–0.60	Moderate
0.61–0.80	Strong
0.81–1.00	Almost perfect

Source: Landis and Koch (1977).

that combines different variations in land use and land cover changes during a studied period (Olmedo et al., 2015; Firozjaei et al., 2019; Hasan et al., 2020). In this case, the time series was the past 20 years (1998 to 2018). This research adds to the system an element of spatial contiguity based on the probable distribution of transitions using the known period to predict future scenarios, in this case the next 20 years (2018 to 2038).

In order to test the suitability of the prediction model for future scenarios, a use forecast was generated for 2018 based on the time series from 1998 to 2008. Its result was evaluated using the kappa coefficient between the real map and the predicted map.

Results and Discussion

Land use and land cover maps

Figure 3 shows the land use and land cover maps of the study area from 1992 to 2018.

As the cartographic series show (Figure 3), there was a significant increase in pasture classes over the forest areas, which shows the impacts of the settlement on forested areas. Table 2 shows the values related to land use and land cover in the studied area and the indicators of accuracy of the performed mapping.

Figure 4A shows the values, in accumulated percentages, of changes in land use and land cover, and Figure 4B shows the deforestation rate in the studied period.

Figure 4A shows that forest losses in 1992 were less than 1% of the total settlement area and that the percentage represented by primary forest was less than 30% in 2018. In addition, deforestation rates (Figure 4B) did not follow the same trends observed for other regions of the Amazon. This statement is based on data from the real-time deforestation detection system (DETER), which indicates a 72% decrease in global deforestation rates between 2004 and 2018 (Brasil, 2018). However, in the studied area, in the same period, there was an increase of 63.28% in deforestation, indicating that efforts to

Figure 3 – Land use and land cover maps from 1992 to 2018.

contain deforestation have not yet been effective in the settlement under study.

Between 2006 and 2018, about 1,300 hectares per year of forest were deforested, totaling 16,952 hectares, which is equivalent to 73.26% of the deforestation in the settlement. The period with the greatest loss was between 2006 and 2008 (25.03%), followed by 2012 to 2014 (17.93%), 2010 to 2012 (15.31%), and 2016 to 2018 (12.06%) (except between 2008 to 2010, which presented the lowest deforestation rate in the historical series, representing about 0.56% of the total deforestation in the settlement). Between 1992 and 2004, about 320 hectares were deforested per year. The highest rates occurred from 1996 to 1998 (8.19%), and the lowest rates were between 1992 and 1994 (0.82%).

The lowest rates of deforestation observed between 1992 and 2004 in the studied area are related to the beginning of the settlement due to the lack of infrastructure and accessibility to properties, as well as high rates of tropical diseases, resulting in a lower level of anthropic activity in the settlement (Souza et al., 2018; Souza et al., 2019).

On the contrary, the highest deforestation rates between 2004 and 2018 may have been caused by the effective occupation of property owners, associated with the inefficiency of the "Command and Control" system in detecting deforestation in small areas. In addition, the

Table 2 – Values obtained by classified images of the study area from 1992 to 2018.

Class	Forest (ha)	Secondary vegetation (ha)	Pasture A (ha)	Pasture B (ha)	Exposed soil (ha)
1992*’	34,361.49	201.34	41.43	1.70	0.17
1994*’	34,171.36	377.84	56.77	0.45	0.72
1996*’	33,586.17	191.03	828.41	1.61	0.63
1998*’	31,690.44	577.30	2,204.79	134.62	0.72
2000**”	31,506.94	2,391.96	496.94	203.04	3.50
2002*’	31,033.23	616.13	2733.6	220.86	4.57
2004**”	30,553.21	543.71	3,128.41	329.23	54.80
2006**”	28,172.67	858.90	4,720.06	632.63	225.11
2008**”	22,380.36	1,553.77	7,612.11	2,949.56	112.28
2010**”	22,251.65	2,310.65	6,146.20	3,602.79	298.38
2012**”	18,709.14	7,813.53	4,073.35	3,766.01	247.35
2014**”	14,559.76	6,163.25	7,761.33	6,005.62	116.41
2016**”	14,011.46	4,110.21	10,103.77	6,127.93	253.00
2018**”	11,219.99	3,226.92	13,941.20	5,451.70	769.56

*Kappa coefficient intervals between 0.81 and 1.00 (almost perfect); **kappa coefficient intervals between 0.61 and 0.80 (strong); ‘tau coefficient intervals between 0.81 and 1.00 (almost perfect); ‘’tau coefficient intervals between 0.61 and 0.80 (strong).

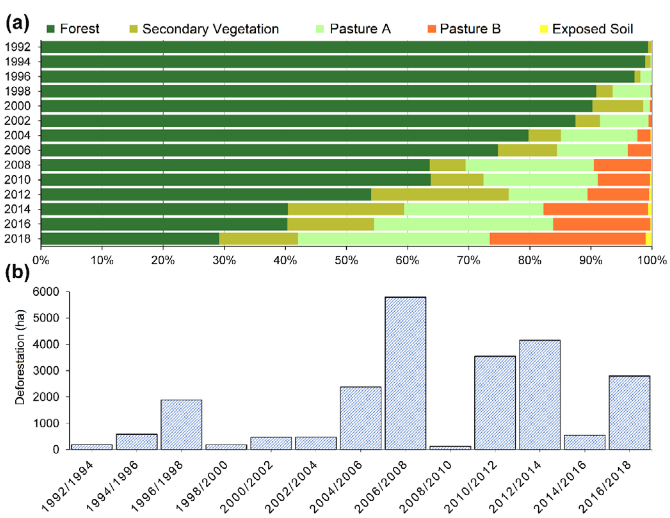

Figure 4 – (A) Accumulated percentage distribution of change in land use and land cover and (B) deforestation rate in the Santo Antônio do Matupi rural settlement between 1992 and 2018.

period of greatest forest loss coincided with an exponential increase in the cattle herd in the region, as IBGE data show (2020), which consequently led to the opening of new areas for pastures. Silva et al. (2011) described the replacement of agricultural areas for pastures in the settlement. According to the authors, this phenomenon began after 2000 and became the main economic activity of the settlement. Souza et al. (2019) described that livestock currently represents about 85.8% of the local economy (55.1% of dairy cattle and 29.7% of beef cattle).

The implementation of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) in 2004 proved to be very efficient in controlling deforestation in large areas, that is, areas over 25 hectares (Brasil, 2020b). In smaller areas, however, as observed in this study (smaller than 10 hectares), this system proves inefficient in fulfilling its main objective, that is, to contain deforestation.

Also, the behavior of the time series up to 2000 shows that the areas occupied by secondary vegetation were larger than the other cover categories (about 6.91% of the total) compared with 2.03% of the others. As of that year, the areas occupied by pasture became predominant, indicating the dominance of livestock activity in the settlement.

In the same way, there are significant percentages (greater than 0.01%) of areas occupied by exposed soil from 2004 onwards, a period during which the greatest losses of the forest began in the settlement and the PPCDAm was implemented. These areas occupied < 1% of the total anthropized areas, except for the period from 2002 to 2004, during which this percentage more than doubled concerning previous years.

Currently, deforested areas are predominantly occupied by pasture in good cultivation conditions (38.42%), followed by degraded pastures (15.75%), vegetation in stages of regeneration (8.75%), and exposed soil (3.95%). These percentages total 66.87% of the settlement area.

Farias et al. (2018) related this increase in deforestation in the Amazon to the increase in the prices of commodities such as meat and soy. Indeed, the data of the IBGE (2020) on the cattle herd in the municipality point to an increase of 200% in the number of animals between 2004 and 2018. Despite being local, these data reflect the increase in the size of the cattle herd in the settlement since it is the main area with anthropic occupation in the municipality, thus justifying the dominance of the agricultural activity, which occupied about 54.29% of the area in 2018. Also, the fact that this type of activity has a low cost and is easy to implement may help to justify its greater occurrence in the settlements (Ávila et al., 2019).

The areas occupied by degraded pasture had significant percentages (> 0.01%) from 1998 onwards. Since then, these areas increased proportionally to the areas occupied by pastures in good conditions, and in 2018, they represented about 15.75% of the total area in the settlement. On the contrary, the presence of areas occupied by secondary vegetation (regenerating vegetation) in large percentages can be associated with low productive pastures and fallow and traditional itinerant agriculture. With the subsequent abandonment of these areas, "capoeiras" (brushwood areas) appear as an initial natural regeneration process (Dick and Schumacher, 2015).

Forecasting future scenarios

The construction of scenarios for 2028 and 2038 based on the historical series from 1998 to 2018, considering the real map forecast for 2018, showed a kappa coefficient of 0.80, indicating a high consistency (Landis and Koch, 1977). Thus, the transition matrix considering the historical series, at least theoretically, can be a good predictor to explain possible changes in future years (Munthali et al., 2020).

Table 3 shows the estimated transition rates from 1992 to 2018 and the probable transition rates from 2018 to 2028 and from 2028 to 2038. Negative values mean losses and positive values mean gains.

From 1992 to 2018, forest losses were 66.87%, while the forecast for losses from 2018 to 2028 is 7.53% of deforested areas. For the period 2028 to 2038, the scenario indicates a 5.60% loss, that is, a forecast of replacement of forest in 80% of the area at the end of the period. This high final percentage is in disagreement with the Law no. 12.651 (Brasil, 2012). For rural properties, including settlements, 80% of native vegetation must be preserved in legal reserves (LR). No matter whether deforestation occurs, it should not compromise the permanent preservation area (PPA); otherwise, the owner of the area is obliged to recompose the vegetation.

The deforestation carried out before 2008 would eventually not be the object of an ecological restoration, considering that the offender would not be fined, for example, for irregularly deforesting the LR vegetation before July 22, 2008. Therefore, the offender would not be obliged to recompose the forest (Brasil, 2012).

In the 1992 and 2018 time series, deforested areas were converted predominantly into pastures in good condition, degraded pastures and areas of secondary vegetation, and small percentages of exposed soil. In the scenario forecast for 2028, the deforested areas follow the same trend, with emphasis on an increase of 5.26% in areas occupied by pastures in good conditions (from 13,341.20 ha in 2018 to 15,508.41 ha in 2028), followed by an increase of 2.72% in pastures in degraded conditions (from 5,451.70 ha in 2018 to 6,529.71 ha in 2028), and an increase of 0.91% in areas in natural regeneration (from 3,226.92 ha in 2018 to 3,544.22 ha in 2028). The exception is a decrease of 1.36% in areas occupied by exposed soil (from 769.56 ha in 2018 to 413.17 ha in 2028).

If no protective measures are taken, in the 2038 scenario, following the same trend as in the previous period, the areas occupied by pasture in good cultivation conditions will increase by 4.52% (from 15,508.41 ha in 2028 to 17,074.02 ha in 2038), and the areas occupied by degraded pasture will increase by 2.02% (from 6,529.71 ha in 2028 to 7,227.71 ha in 2038). The exception is for areas in stages of natural regeneration and exposed soils, which will decrease by 0.77% (from 3,544.22 ha in 2028 to 3,277.14 ha in 2038) and 0.18% (from 413.17 ha in 2028 to 351.47 ha to 2038), respectively.

The prediction of decreases in the natural regeneration area in 2018–2038 is probably due to the fact that this vegetation has reached a dimension that allows its use, culminating in its suppression, or even because the occupied area will be destined to crops or to expanding pastures. Figure 5 shows the predicted maps of land use/land cover change for 2028 and 2038.

The maps of 2028 and 2038 (Figure 5) serve as a basis for the formulation of public policies aiming at the protection and management of land use and land cover in general since they can not only provide scenarios of changes that may occur but also make it possible to predict

Table 3 – Rates of change in land use/land cover for 2028 and 2038.

	Area (%)				Change of use (%)		
Land use class	1992	2018	2028	2038	1992–2018	2018–2028	2028–2038
Forest	99.29	32.41	24.88	19.29	-66.87	-7.53	-5.60
Secondary vegetation	0.58	9.32	10.24	9.46	8.75	0.91	-0.77
Pasture A	0.12	38.54	44.80	49.33	38.42	5.26	4.52
Pasture B	0.00	15.75	18.86	20.88	15.75	2.72	2.02
Exposed soil	0.00	3.95	1.19	1.01	3.95	-1.36	-0.18

future impacts. Therefore, this type of mapping is an important tool for the analysis of environmental degradation resulting mainly from the loss of forests since, with the removal of natural vegetation, there is a compromise of several ecosystem services considered essential for the quality of life of the population.

The results of this study also make it possible to state that the combination of GIS tools and remote sensing techniques is efficient for mapping changes in land use and land cover on a small scale, as they provide essential information about the spatial and temporal dynamics in the settlement and allow predicting possible changes in these patterns.

Regarding the implementation process, there is a close relationship with the increase in deforestation in the settlement, where there is no minimum infrastructure. Even the way by which incentive practices aim to carry out activities that do not contribute to environmental sustainability causes a social distortion of the real beneficiaries of agrarian reforms. Thus, it is of paramount importance to effectively implement programs aiming a sustainable rural development in the settlement, such as the provision of technical assistance to improve agricultural productivity in already deforested areas and the expansion of agricultural credit for environmentally friendly producers, in addition to compensating settlers for the environmental services they provide (Moutinho et al., 2016).

Conclusions

The mapping of land use and land cover between 1992 and 2018 in the settlement made it possible to verify that the period with the highest deforestation rates was between 2008 and 2018, which represents about 73.26% of the accumulated deforestation. In 2018, only about 30% of the primary forest remains in the settlement. The predominant class of land use and land cover is pasture. Livestock is the predominant economic activity in the settlement.

If measures are not taken, the scenarios for 2028 and 2038 indicate the same trend of land use and coverage as of until 2018, which is marked by a landscape formed predominantly by pastures since the current occupation model in the settlement is represented by this category of land use, thereby exerting pressure on native forests.

In view of the predictions, urgent measures are needed not only to provide the minimum infrastructure conditions for settlers to survive but also to directly relate this settlement policy to the maintenance of legal reserves and the protection of permanent preservation areas. In addition, the adoption of stricter control policies and mandatory registration of properties in the CAR are important to prevent any further situations that might result in deforestation.

Finally, this study shows the urgency of implementing more effective measures aiming to monitor settlements and maintain the settled families, especially actions that ensure environmental sustainability focused on reducing the suppression of forests, so that settlements change landscapes in a positive way.

Acknowledgments

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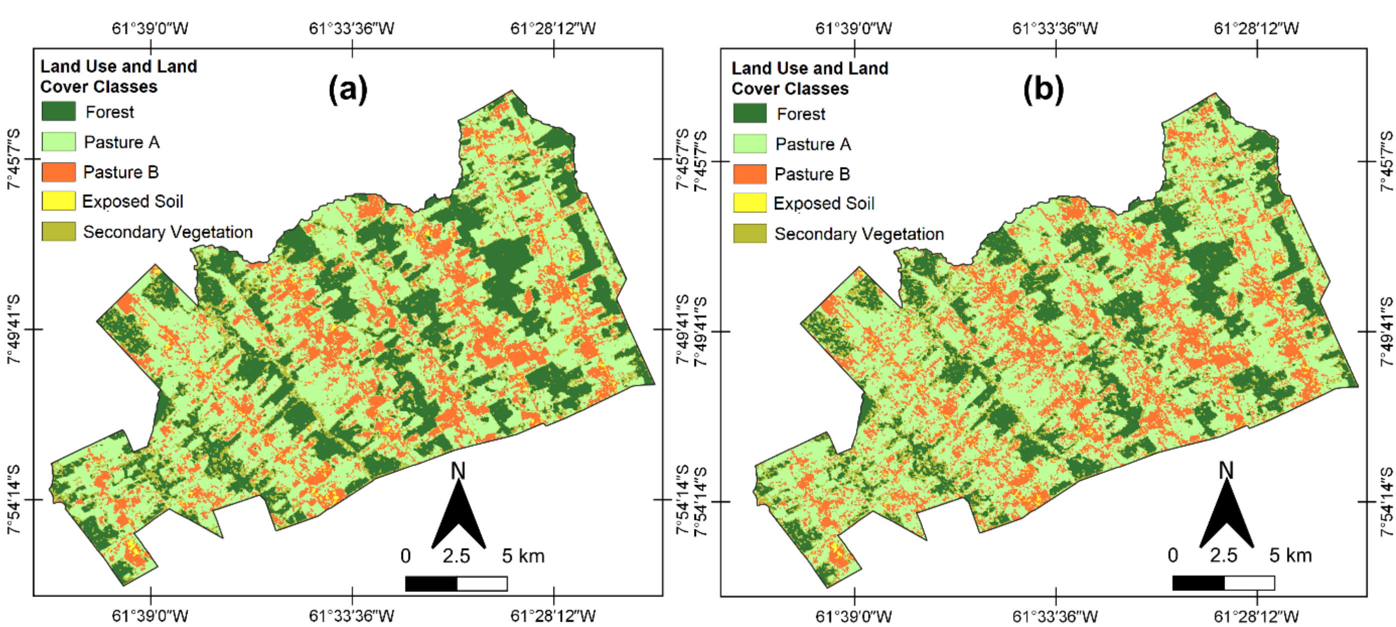

Figure 5 – Future scenarios of change in land use/land cover in the Santo Antônio do Matupi rural settlement: (A) 2028 and (B) 2038.

Contribution of authors:

Duarte, M.L.: Investigation, Methodology, Formal analysis, Writing — original draft; Souza, J.A.P.: Investigation, Methodology, Writing — review and editing; Castro, A.L.: Investigation, Methodology, Writing — review and editing; Lourenço, R.W.: Conceptualization, Supervision, Project administration, Writing — review and editing.

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ABES

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Expansion of Cashew Cultivation and its Environmental and Economic Impacts on Guinea-Bissau

A expansão do cultivo do caju e seus impactos ambientais e econômicos na Guiné-Bissau

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ABSTRACT

Guinea-Bissau has recently become the fifth largest producer in the world of Cashew Nut Shell (CNS) and the product accounts for 90% of the country's total exports. The objective of this study was to analyze the expansion of cashew cultivation and its environmental and economic impacts on the country, from the perspective of sustainable development. In the methodology, correlational statistical analyses were used, based on multiple regression, correlation, and linear regression techniques. To qualify the empirical results based on the historical series of secondary data, an online questionnaire was applied to nine experts to assess the impacts of sector-specific public policies on Cashew Nut Shell Production (CNSP) and Cashew Nut Shell Export (CNSE). Finally, geoprocessing techniques were used to identify the deforestation trends in the country (2002-2018). As main results, it was verified that from 2000 to 2015, the CNSE accounted for an average of 8.9% of the country's GDP. As for environmental impacts, it was found that between 2002 and 2012, the country's deforestation was explained by the CNSP ($p < 0.001$ and $R^2 = 0.91$), whereas between 2013 and 2017, although positively associated, the relationship was not significant. Geoprocessed data on vegetation cover indicate that from 2002 to 2018, accumulated deforestation was intensified mainly in the southern and northern regions of the country. To make full use of cashew, a greater effort is needed from the Government and the productive sectors, which would allow the sustainable development of the sector and a substantial increase in the production of other crops.

Keywords: cashew nuts; deforestation; export; agricultural product; forest conversion; West Africa.

RESUMO

A Guiné-Bissau tornou-se recentemente o quinto maior produtor mundial de Castanha de Caju com Casca (CCC) e o produto corresponde à 90% das exportações totais do país. O objetivo deste estudo foi analisar a expansão do cultivo de caju e seus impactos ambientais e econômicos no país, sob a perspectiva do desenvolvimento sustentável. Na metodologia, utilizaram-se análises estatísticas correlacionais, baseadas em técnicas de regressão múltipla, correlação e regressão linear. Para qualificar os resultados empíricos baseados nas séries históricas dos dados secundários, foi aplicado um questionário online com nove especialistas para avaliação dos impactos das políticas públicas setoriais da Produção de Castanha de Caju com Casca (PCCC) e Exportação de Castanha de Caju com Casca (ECCC). Por fim, utilizaram-se técnicas de geoprocessamento para identificar a evolução do desmatamento no país (2002-2018). Como principais resultados verificou-se que de 2000 a 2015, a ECCC teve contribuição média de 8,9% no PIB. Quanto aos impactos ambientais, constatou-se que entre 2002 e 2012, o desmatamento do país é explicado pela PCCC ($p < 0,001$ e $R^2 = 0,91$), já entre 2013 e 2017, embora positivamente associado, a relação não foi significativa. Os dados geoprocessados da cobertura vegetal indicam que de 2002 a 2018, o desmatamento acumulado foi intensificado principalmente nas regiões sul e norte do país. Para que haja o aproveitamento integral do caju, é necessário um maior esforço por parte do governo e dos setores produtivos, o que permitiria o desenvolvimento sustentável do setor e um aumento substancial de produção de outras culturas.

Palavras-chave: castanha de caju; desmatamento; exportação; produto agrícola; conversão de florestas; África Ocidental.

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Introduction

In recent years, cashew has become the main agricultural product of Guinea-Bissau. The export of cashew nut shells (CNS) varies from 85% to 90% of the country's total exports, with India as the main buyer country (FMI, 2015). In view of the growing international demand for CNS and the government's incentive, the cultivation of cashew (*Anacardium occidentale* Lynn.) became the main economic activity of the rural families that compose most of the population. The production is manually carried out, and the effort to increase productivity only occurs by expanding the agricultural land area used to grow cashews.

Most of the displacement of land use occurred from high-income countries to low-income countries (Weinzettel et al., 2013), with the recent expansion of export-oriented commodity crops causing large-scale deforestation in the humid tropics (Rudel et al., 2009). From 2000 to 2011, 40% of tropical deforestation came from the production of agricultural commodities (Henders et al., 2015). The proportion of underlying deforestation as a share of export-oriented agricultural products has doubled during this period to more than 33% (Henders et al., 2015). Brazil and Indonesia were responsible for 61% of the global tropical deforestation from 2000 to 2005, largely associated with the expansion of soybean production, pastures for cattle, and oil palm plantations (Defries et al., 2010).

South America, Southeast Asia, and Sub-Saharan Africa are experiencing the fastest rates of agricultural land expansion (Ordway et al., 2017). Moreover, Ordway et al. (2017) reports that in Cameroon, recent foreign investment in agriculture and a government boost to increase cocoa and oil palm production provided an opportunity to assess whether large-scale industrial monoculture is expanding into forested areas. In Guinea-Bissau, the cashew crop has been gaining importance for the export of CNS.

Guinea-Bissau has consolidated its status as the fifth largest producer of CNS in the world and the second largest producer and exporter country on the African continent. About a third of the country's agricultural land is occupied by cashew trees (PER, 2019). Guinea-Bissau manages to export almost 100% of its annual production (FAOSTAT, 2020).

Therefore, the challenges addressed in this study consisted of the analysis of the following questions: what are the environmental impacts that occur or may occur due to increased production? What are the factors that influence the dynamics of CNS production and export?

To answer these questions, some objectives were defined. The overall objective of the research is to analyze the expansion of cashew cultivation and its environmental and economic impacts on Guinea-Bissau focusing on sustainable development. Specific objectives are defined as follows: to determine which variables influenced the production dynamics and export in Guinea-Bissau; to assess the impacts of Guinea-Bissau's sector-specific public policies on cashew nut production and export; and to verify spatial patterns of land-use changes associated with the expansion of cashew cultivation over vegetation areas.

Literature review

Guinea-Bissau is located in West Africa and has a population of 1.8 million (World Bank, 2019). It borders the Atlantic Ocean, as observed in Figure 1.

Guinea-Bissau borders Senegal (North), the Republic of Guinea (East and South), and the Atlantic Ocean (West). The country's economy heavily depends on the primary sector. According to data from the Observatory of Economic Complexity (OEC), in 2017 the main products exported from the country were: coconuts, peanuts and cashew nuts, and frozen fish (OEC, 2020). Agriculture, forestry, fishing, and hunting are the dominant economic activities in the country, accounting directly and indirectly for about 46.9% of the gross domestic product (GDP) in 2011 and 39.7% in 2016 (Arvanitis et al., 2017). Cashew nuts are the country's main agricultural product and their exports range from 85% to 90% of the country's total exports, with a strong concentration of exports to India and Vietnam (FMI, 2015).

Cashew is a perennial tree species belonging to the *Anacardiaceae* family and to the *Anacardium* genus (Catarino et al., 2015; FAO, 2020). It is mainly grown in tropical countries, especially in Brazil, Vietnam, India and the Ivory Coast (Dendena and Corsi, 2014; Elakkiya et al., 2017), Nigeria, Indonesia, Philippines and Benin (FAOSTAT, 2020), and Guinea-Bissau (Catarino et al., 2015; Cateia et al., 2018). Brazil, India, and Vietnam are the world's largest processors.

Cashew production in Guinea-Bissau is manually carried out, and the effort to increase productivity only occurs by expanding the agricultural land area used to grow cashews. Production grows not due to the development of new technologies, but by increasing the replacement of native forest or areas used to grow other crops. In the study entitled "Drivers of deforestation and degradation for 28 tropical conservation landscapes," it was noted that rice was the agricultural commodity most often cited as driver for forest change in tropical landscapes, followed by rubber and cassava (Jayathilake et al., 2020). In Tanzania, small-scale cultivation of corn, sesame, cowpea, and sorghum are the main immediate drivers of deforestation (Doggart, 2020).

In Guinea-Bissau, deforestation has been increasing due to agricultural production. Changes in the forest of northern Guinea-Bissau and southern Senegal occurred as a result of the human land use predominantly associated with agricultural activities such as charcoal production, cashew trees and collection of wood for construction and firewood for household needs (Cabral and Costa, 2017).

In the study entitled "Determinants of Guinea-Bissau cashew exports (1986-2011): an analysis under the Bergstrand gravity model," the reported results of the panel data model (OLS-pooled) suggest that the flow of cashew nut exports is positively related to the exchange rate and gross and per capita incomes, which is consistent with the theoretical assumptions of gravitational models and with the seminal studies of economic literature with the application of these models (Cateia et al., 2018).

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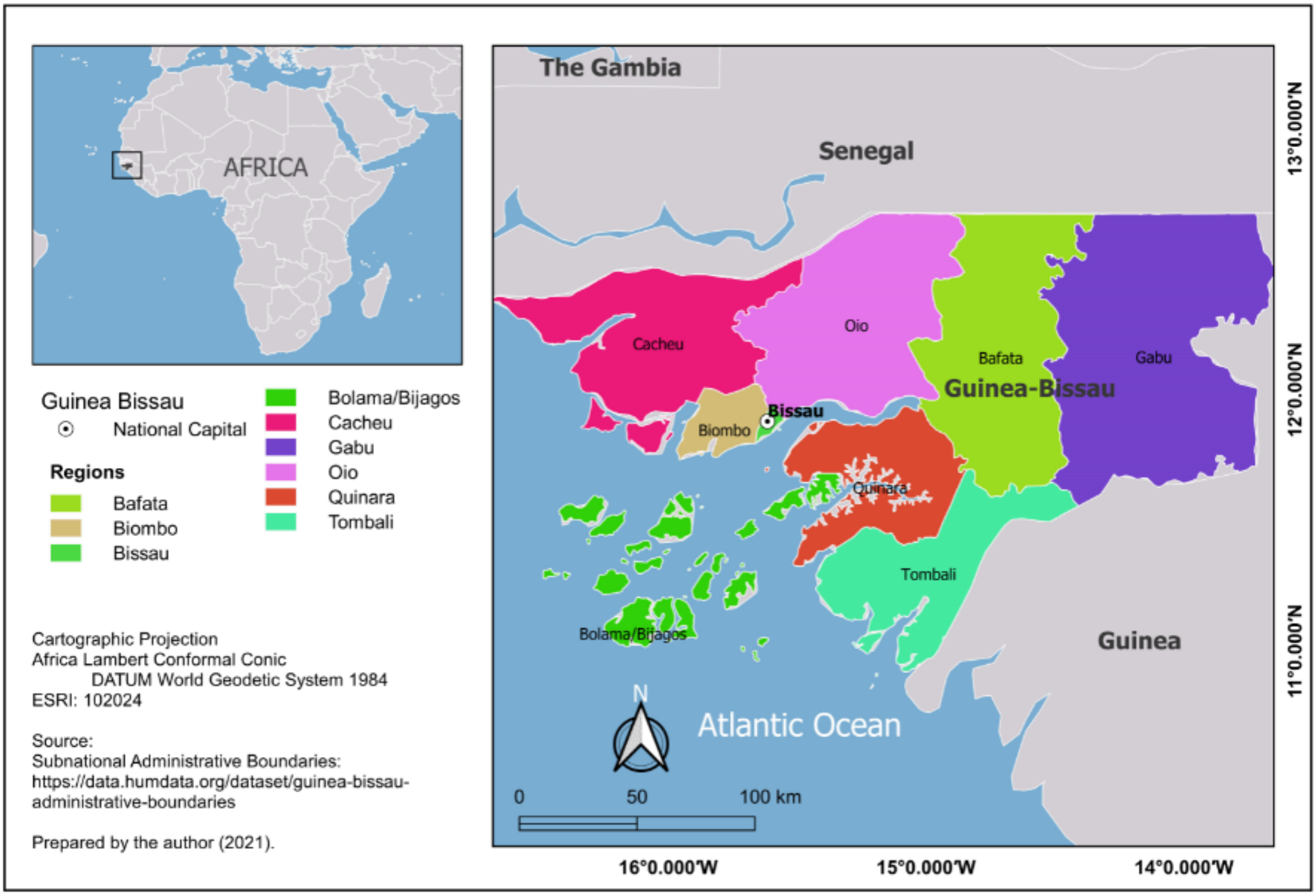

Figure 1 – Administrative regions of Guinea-Bissau.

Materials and Methods

This study was carried out in Guinea-Bissau, a country in West Africa, covering the period from 1990 to 2018, with secondary data and official documents available from the following websites and organizations: BCEAO, FAOSTAT, IMF, WORLD BANK.

The methodological procedures of this research are organized according to the objectives of the study, which are: Overall goal: analysis of the expansion of cashew cultivation and its environmental and economic impacts on Guinea-Bissau with focus on sustainable development. For this purpose, the statistical model of correlation and simple regression was used to assess environmental impacts, and for economic impacts, analysis of statistical data was used to represent the percentage of Cashew Nut Shell Export (CNSE) in the country's GDP. As specific objectives:

- to determine which factors influence the dynamics of Cashew Nut Shell Production (CNSP) and CNSE in Guinea-Bissau. For this purpose, multiple regression analysis was used;
- to assess the impacts of Guinea-Bissau's sector-specific public policies on the CNSP and CNSE, a questionnaire was prepared using Google Forms, sent to nine specialists in the area, and their answers enabled to assess the impacts of public policies on the sectors of CNSP and CNSE;
- to verify spatial patterns of land use changes associated with the expansion of cashew cultivation replacing areas of native vegetation. For this third and last objective, geoprocessing techniques were used to ascertain the possible substitution of forest by cashew cultivation.

Multiple linear regression analysis

The technique of multivariate data analysis consisted of the construction and validation of linear regression models. This model serves to understand the behavior of the independent variables in question.

To this end, the following steps were completed:

1. specification of the objectives for the regression analysis, which includes the selection of the dependent and independent variables;

2. determining the sample size;
3. the assumptions inherent in regression analysis (normality, linearity, homogeneity).

It is also important to verify if there is multicollinearity between the variables.

For Dormann et al. (2013), in the construction of these models, some assumptions must be verified, especially if there is dependence between the independent variables. If these dependencies are strong (when the value is greater than 10) there may be multicollinearity, causing effects on the estimates of the regression coefficients and on the general applicability of the estimated model.

Variables tested for the CNSP model

The sample size of the time series of variables depends on the existence of data available on websites and official documents. In this study, it was established as a goal to construct a historical series with secondary data covering the period from 1990 to 2017 (Table 1). The year 1990 was chosen because this was the year when the country began to have significant global participation as a CNS producer.

Variables for the CNSP model were selected based on a bibliographic and documentary review of topics related to temporal and spatial dynamics in agricultural production and productivity.

CNS Price

In the study entitled "Cashew nut production in Tanzania: constraints and progress through integrated crop management," it was noted that the increase in producer prices and marketing were efficient tools to attract increased production from farmers. In this context, farmers have recovered large areas of previously abandoned cashew farms and are currently improving their cultivation methods by adopting disease control measures and planting improved materials on new farms (Martin et al., 1997).

Table 1 – Main variables that influence CNSP.

Variable	Type	Unit of Measurement	Data Source
CNSP	Dependent (Y)	Tonne (t)	FAOSTAT
National Price	Independent (X_1)	Dollar ($)	BCEAO
Rice Production	Independent (X_2)	Tonne (t)	INE/BCEAO
Climate (Precipitation)	Independent (X_3)	Millimeter (mm)	World Bank
Climate (Temperature)	Independent (X_4)	Degree Celsius (°C)	World Bank
Mancarra Production (Peanut)	Independent (X_5)	Tonne (t)	BCEAO

CNSP: Cashew Nut Shell Production; FAO: Food and Agriculture Organization of the United Nations; INE: National Institute of Statistics; BCEAO: Central Bank of West African States; FAOSTAT: Global Statistical Database of FAO – it provides free access to food and agriculture data.

Climate change and cashew production

The distribution and behavior of precipitation are basic factors for the planning of agricultural activities such as: definition of dates for soil preparation and sowing, sizing of spillways, rain networks, structures to protect against erosion and floods, and preparation of additional irrigation projects. Taking these aspects into account, the volume of rain that falls in a region can be considered as a factor that determines the agricultural activity to be developed in such location (Danfá et al., 2009).

Both temperature and precipitation are important variables for agricultural production in the tropics; overall, the irregularity of rain, high temperatures, and violent winds are the main climate changes indicated by cashew producers in Benin as a factor of low agricultural productivity (Bello et al., 2017).

In order to choose the climate variable that influences cashew productivity, the following data were tested: average monthly temperature and average monthly precipitation, with the sample size from 1990 to 2016. The correlation between CNSP and variable monthly average temperature from January to December was tested; subsequently, the correlation between CNSP and average monthly precipitation from January to December was calculated; and finally, the correlation between CNSP and the climate variables (temperature and precipitation) that have a greater correlation with annual CNS production was estimated. In this case, this estimate enabled to choose the independent variables that have a strong positive correlation with the CNSP, to test in the final model of CNSP.

The main agricultural products: rice and peanuts

Cashew has not always been the Guinea-Bissau's main agricultural and export product. In the colonial period, other products were important to the country's economy such as peanuts and rice (Balde, 2008). Peanut production reached its peak in the period of colonization, when farmers were encouraged to produce for export (Medina, 2008). Once natural resources and production factors, such land and labor, are finite and limited, this study verifies if changes in rice or peanut production could influence the CNSP. In the event that there are years of increases in these products, this influences the SCNP.

Variables tested for the CNSE model

Variables for the CNSE model were selected based on a bibliographic review (scientific articles, theses and dissertations, etc.) related to the topic, collected by Google scholar and magazines available from the CAPES system. The tested variables are presented in Table 2. The sample sizes of the variables vary according to the data available

Table 2 – Main variables that influence CNSE.

Variable	Type	Unit of measurement	Data Source
CNSE	Dependent (Y)	Tonne (t)	INE/BCEAO/ FAO
World Production	Independent (X_1)	Tonne (t)	FAOSTAT
Tax on CNSE	Independent (X_2)	Dollar ($)	MCGUINEA-BISSAU
Exchange rate	Independent (X_3)	Dollar ($)	BCEAO
Instability		Dummy variable (1 or 0)	Literature Review

CNSE: Cashew Nuts Shell Export); MCGUINEA-BISSAU: Ministry of Commerce of Guinea-Bissau; FAO: Food and Agriculture Organization of the United Nations ; INE: National Institute of Statistics; BCEAO: Central Bank of West African States; FAOSTAT: Global Statistical Database of FAO – it provides free access to food and agriculture data.

from the websites and official documents. A historical series of secondary data from 1990 to 2017 was used for this analysis. The year 1990 was chosen as the base year because it was the period when the country began to have significant global participation as an exporter of CNS.

World production

There is a long tradition of quantifying the impact of agricultural trade distortions on the world market, especially in the context of multilateral trade. A small impact on the world market price can lead to substantial changes in production and trade (FAO, 2014). This variable enabled to understand whether, in years when there was an increase in the world production, such increase had an impact on the country's total exports.

Taxes

Tax collection is revenue from resources obtained from the collection of taxes (i.e., taxes, fees, and contributions). According to Anselmo (2013, p. 7), "it is every compulsory cash payment, in currency, or whose value can be expressed therein, that does not constitute a penalty for an illegal act, established by law and charged through fully earmarked administrative activity." Taxation is one of the powerful economic instruments that societies have to implement their public policies and influence the allocation of resources.

Exchange rate

The exchange rate has a great impact on a country's exports; when a country's currency is devalued, the country tends to export more and vice versa. The role of the exchange rate in international trade is essential because its variations can induce changes in the prices of domestic goods in relation to foreign goods (Silva et al., 2016). The final tested variable is instability; Guinea-Bissau is a country that has gone through several decades of political instability.

Political instability

Political instability is one of the major problems for the economic development of any society. Since its independence, Guinea-Bissau has been facing difficulties with political instability, which creates barriers to productivity and economic growth. The literature has shown that violent conflicts, such as civil wars and other forms of instability, have led to the death of people, weaknesses of institutions, and economic losses such as the destruction of physical capital (Samate, 2018).

Expansion of cashew cultivation and its environmental impacts

After Guinea-Bissau independence in 1974, and specifically after the adoption of structural adjustment measures (mid-1980s), CNS exports increased and farmers gradually began to plant cashew trees for CNS marketing and to guarantee their possession of land. They adopted a process of an "agricultural frontier" in which all crop fields are no longer left fallow; instead, cashews are grown together with food crops for three to four years, until the field becomes an orchard, when the cashew tree canopy closes and a new area must be cut and burned, thereby increasing deforestation in a linear manner (Temudo and Santos, 2017).

Thus, a correlation and regression model was used to assess the impact of the CNSP on the accumulated deforestation of the country's native forest (ADNF). With the sample size of the available data, from the years 2002 to 2017, a series was built with the FAOSTAT database (Food and Agriculture Organization of the United Nations) for CNSP data (FAOSTAT, 2020), and with Deforestation Statistics for ADNF (Deforestation Statistics, 2020).

Analysis of economic impacts

Previous studies have shown the importance of CNSP in Guinea-Bissau, with its production destined almost exclusively for export. For this analysis, descriptive statistics and graphs were used. The economic impact was estimated in terms of the percentage of CNSE in the country's GDP, with sample size from 2000 to 2015.

The GDP database was converted into US dollars, having been collected through the World Bank website and for CNSE in XOF (Guinea-Bissau currency). The database of the last variable was obtained from the Central Bank of Guinea-Bissau (BCEAO, 2019). CNSE values were first converted from XOF to euro (EUR) (fixed value of 655 XOF = 1 EUR), because the historical series of the XOF exchange to the US dollar was not found. Subsequently, the amounts in EUR were converted to the US dollar, through an exchange rate series (Banco de Portugal, 2020).

Data collection methods: questionnaire

A questionnaire was prepared using the Google Forms application, designed for specialists working in the deforestation sector, CNSP, CNSE, and in the cashew value chain in Guinea-Bissau. The selection and recruitment of respondents were accomplished through the snowball sampling technique. Snowball is the type of non-probabilistic sampling in which chains of reference are used (Vinuto, 2014).

The e-mails of some interviewees were acquired through studies performed by them and previously published. As inclusion criteria, it was determined that the participants should reside in Guinea-Bissau, have research and studies related to the topic or have investigated the topics of the present study, be over 18 years of age, without distinction regarding sex, religion, and ethnicity. As for the exclusion criteria, it was determined that the participant should not be unemployed for more than one year and have some type of illness that would prevent them from answering the questions. Before sending the questionnaires, these questions were investigated with the individuals invited to participate in the study. This research was approved by the Human Research Ethics Committee (CEP) of Universidade Federal do Amazonas, Brazil.

To assess the impacts of Guinea-Bissau's sector-specific public policies on the CNSP and its exports, nine (9) experts on the topic were interviewed, who work in different sectors: teaching and research institutions, government agencies, and non-governmental organizations. Seven (7) of the interviewees were men and two (2) were women, most (6) of the interviewees lived in Guinea-Bissau and the others, in Portugal. As for age, six (6) of the interviewees were over 50 years of age and have been working in the CNS sector for between 3 and 15 years.

The completion of the questionnaire was preceded by the mandatory reading and acceptance of the Informed Consent Form. A questionnaire form was created with closed-ended questions, such as "What is the main cause of deforestation in Guinea-Bissau?", to which respondents have options for answers, as well as open-ended questions, such as "How do you see the cashew trade and its obstacles?", to which respondents described their opinions. The questionnaire form was structured in three sections: identification, questions about deforestation, and questions about public policy in the cashew sector. The responses enabled to assess the impacts of the country's public policies on the CNS production and export sectors.

Geoprocessing techniques

Geoprocessing is an important tool of environmental sciences applied tothe conservation of natural resources (Novo and Ponzoni, 2001). Based on the principles and methods of geoprocessing, there are some studies that have sought to describe the relations between the causes of deforestation in some regions of Guinea-Bissau. As in the study conducted by Temudo and Abrantes (2014), the authors of the present article also concluded, in the exploratory stage of this research, that when using remote sensing technologies, the spatial and spectral resolution of Landsat satellite images and the tree classifiers do not allow for detecting the spectral difference between coverage by native forests and that by cashew orchards, making it impossible to calculate precise rates of deforestation, forest degradation, and recent changes in land use.

To compensate for this deficiency, data were collected from georeferenced cashew cultivation locations, in collaboration with the National Statistics Institute of Guinea-Bissau (INE), from 44 cashew orchards in the South and East of the country, using the Global Positioning System (GPS), in flat geographical coordinates – UTM 28 N.

These data obtained in 2017 were initially tabulated in electronic spreadsheets, with identification of the name of the owners of the cashew orchards and the geographic coordinates in UTM. The country's spatial data (shapefiles) were provided by the website "The Humanitarian Data Exchange" and the QGIS program allowed the mapping of cashew cultivation areas, based on data collected in the field. The incidence and location of cashew orchards were compared with the spatial deforestation trends in the country.

For the analysis of deforestation, the Global Forest Change database (Hansen_GFC 2001-2018) was used (Global Forest Change, 2013). In the QGIS software, the image was vectored from year to year, then the vectors for each year of deforestation were redesigned (for EPSG projection: 102022 Africa Albers Equal Area Conic) to perform the area calculation in hectares.

Results and Discussion

Multiple regression analysis for CNSP

Taking into consideration the performed research, data analysis, and the bibliographic review, the variables that influenced the CNSP were peanut production, rice production, temperature in July, November and April, and finally the national price of CNS. For this study, variables were tested before defining the final model to be tested. The multicollinearity values were: Peanut (Pe) = 2.71; National Price (Pr) = 1.22; April temperature (TApr) = 1.45; July temperature (TJl) = 2.28; November temperature (TNv) = 1.18; Rice (Ri) = 1.88. It was noted that there is no multicollinearity between the variables because they have correlation values below 10%.

According to the analysis made with the R software, the stepAIC test of the multiple regression model eliminated the national price variable, as it has no impact on the CNSP and has an individual significance value of 0.63, which is a value greater than 0.05 (Table 3). The stepAIC test is used to simplify the model without greatly affecting its performance (Li et al., 2017).

According to analysis with the R software, the overall significance value of the variables is lower than 0.05. The significant variables were Peanut production (Am); Production of rice (Ar); and Temperature for the month of July (TJl). With a 95% confidence interval, it is possible to understand the impact of each variable on the CNSP, with R^2 equal to 93.8%, where 38.2% are explained by the increase in peanut production

Table 3 – Summary of the variables that influence CNSP in Guinea-Bissau (1999 to 2017).

	Estimate	Standard Error	*T*	p (> |*t*|)
Intercept	2.76	2.42	1.14	0.27
Pe	0.004	0.001	2.85	0.01
TApr	0.23	0.04	1.43	0.17
TJl	0.23	0.05	4.01	0.001
Ri	0.002	0.0004	4.94	0.0003

Pe: Peanut production; TApr: April average temperature; TJl: July average temperature; Ri: Annual rice production.

Table 4 – Summary of variables that influenced the Guinea-Bissau CNSE (1999-2017).

	Estimate	Standard Error	*t*	p (> |*t*|)
Intercept	$1.03x10^{1}$	$2.88x10^{-1}$	35.65	$6.44x10^{-16}$
WP	$4.16x10^{-7}$	$5.05x10^{-8}$	8.23	$6.01x10^{-7}$
TX	$5.79x10^{-4}$	$2.04x10^{-4}$	2.84	0.01
ER	$-3.91x10^{-1}$	$2.38x10^{-1}$	-1.64	0.12

WP: World Production; TX: Export taxes; ER: Exchange rate.

(Am), 35.2% by the increase of rice (Ar) production, and 25.3% by the temperature in July (TJl). The adjusted R^2 value equals 0.91. In this case, this means that 91% of the CNSP is explained by the variation in independent variables such as Am, Ar, TJl, TApr. The TApr variable was not significant in the final model.

Corroborating a study conducted by Samate (2018), it was found that there was an increase in the production of the main agricultural products, namely peanut and rice production. Such growth occurs in parallel with the increase in CNS production, and this increase in production is likely in line with the cumulative increase in deforestation in the native forest, generating loss of biodiversity and ecological changes. For CNSE there are independent variables that influence the country's exports. The main purpose of the CNSP is to export.

Multiple regression analysis of CNSE

The variables that influenced the CNSE were as follows: World Production of CNS (WP), Taxes on CNSE (TX), Exchange Rate (ER) and Political Instability (Inst) (Table 4). In this second model, the multicollinearity values are: world production (WP) = 3.09; taxes on CNSE (TX) = 1.76; exchange rates (ER) = 3.49; Instability (Inst.) = 1.06. Based on these values, it was concluded that there no multicollinearity of the variables, as these values are lower than 10 (Dormann et al., 2013).

In this study, the stepAIC test of the multiple regression model excluded the Political Instability variable in the final regression model, as this variable has an individual significance value of 0.67, which is a value greater than 0.05.

The overall significance value of the variables is lower than 0.05, which is lower than 0.5. The significant variables were PM and TX (Table 4). The TC showed an individual significance level lower than 0.05; in this model the exchange rate variation is not significant for CNSE. According to analysis with the R software, with a 95% confidence interval, it is noted that R^2 is equal to 92.74%; it is noteworthy that about 65.5% of the variation in CNSE is explained by the PM, 19.8% is from TX and 14.6% is associated with TC. In this study, the adjusted R^2 value is 0.91; therefore, it can be inferred that 91% of CNSE is explained by the variation of independent variables such as PM, TX, and TC.

Over the years, on average, the government of Guinea-Bissau has been raising taxes on CNSE. The result of the regression analysis suggests that this increase in taxes did not negatively affect exports. It is understood that the government sees an opportunity for greater collection of tax revenue, considering that such increases do not affect the performance of the country's export balance.

The exchange rate is an economic variable used by governments to encourage or discourage exports and imports of goods and services. It is also a variable that impacts on exports, as it affects the price of the final product. In the study by Cateia et al. (2018), the reported results of the panel data model (OLS-pooled) suggest, on the one hand, that the flow of cashew nut exports is positively related to the exchange rate and gross and per capita incomes, which is consistent with the theoretical assumptions of gravitational models and with the seminal studies of economic literature on the application of these models. However, in this study, it was observed that TC is a variable; despite having an R^2 value of 14.6%, it presented an individual significance value of 0.12, which is an indication that its variation would not have affected the CNSE.

CNS is a product that has not yet reached its maximum production peak worldwide, that is, the demand is still greater than the supply. This is verified by the increase in the production of its almond, whose demand is high as a product for final consumption and also as an intermediate good for the production of other byproducts. Its economic value has been encouraging an increase in production, through the intensification of land use.

Environmental impacts

For environmental impacts, according to the statistical test performed in the R software, there is a 3.88×10^{-6} significance between deforestation of native forest (DNF) and CNSP for data recorded between the years 2002 and 2017. The correlation is positive in the period, with R^2 equal to 0.89; in other words, it seems that 89% of the deforestation of the native forest in those years can be attributed to the expansion of CNSP (Figure 2).

Based on the graph, it is possible to observe that in the period between 2002 and 2012 the DNF was consistently followed by the production of CNS. This evidence corroborates the idea that the expansion of CNSP was one of the main causes of deforestation in these years.

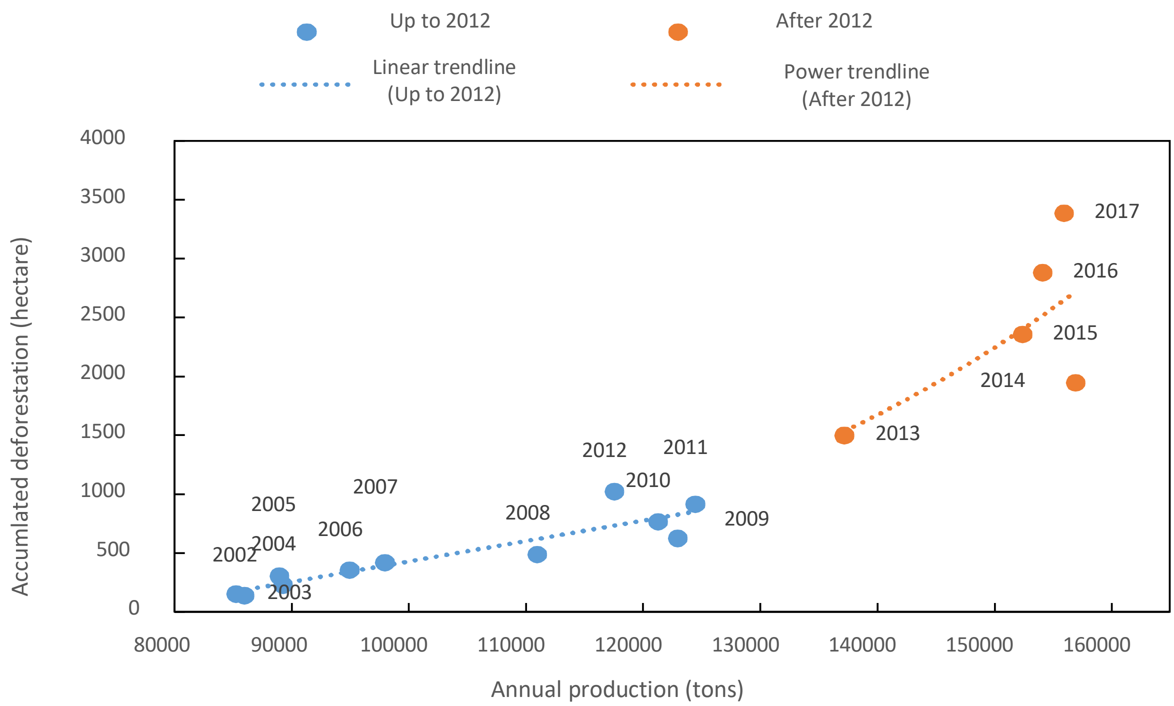

Figure 2 – CNSP and Accumulated Deforestation of Native Forest (ADNF), 2002 to 2017, Guinea-Bissau.
Source: Prepared by the authors based on data from FAOSTAT (2020) and Deforestation Statistics (2020).

In this interval, linear regression was highly significant ($p = 8.62 \times 10^{-5}$; $R^2 = 0.91$).

However, in the period from 2013 to 2017, there is a discrepancy between CNSP and accumulated DNF (i.e., ADNF). Deforestation has become much more accelerated in this period, and it seems that it did not follow the variation in the CNSP. Thus, the value of R^2 is only 0.66 in this range. Although the CNSP can still explain most of the recent deforestation, the result of statistical testing for the 2013 to 2017 interval resulted in a value of $p = 0.21$, that is, not significant.

Thus, there may be other factors that boosted the DNF such as illegal logging and increased rice and peanut production. Although changes in soil cover are a consequence of human land use predominantly associated with agricultural activities, these changes are also associated with the production of charcoal and the extraction of wood, for construction purposes, and firewood for domestic use (Cabral and Costa, 2017).

Motta (2002) demonstrated that deforestation can indirectly increase the probability of floods, and thus cause flood damage. Hence, the value of this loss would consist in an environmental cost associated with deforestation. Forests have a strong connection with the resource base that sustains life on the planet (water, air, soil, fauna, etc.), and have a direct influence on climate, particularly with respect to environmental temperature and humidity (Muteia, 2014). Guinea-Bissau is one of the poorest countries in the world. According to a study performed by the United Nations Development Programme (UNDP, 2019), the Human Development Index (HDI) of Guinea-Bissau in 2018 was 0.46, which places the country in the low development category, in position No. 178 of the 189 countries and territories listed.

Economic impacts

The CNSP is essentially destined for exports, thus contributing to the composition of the national GDP. In the analyzed period (from 2000 to 2015), there was an increase in GDP of about 183.1%, with a minimum value of approximately USD 370.2 million and a maximum of USD 1.1 billion (Figure 3). CNSE also showed a growth of approximately 79.4% in the period, with a minimum value of USD 36.8 million and a maximum of USD 125.6 million (Figure 3).

As the main results, the authors found that from 2000 to 2015, CNSE accounted for an average of 8.9% of the GDP. In 2000, the CNSE share of GDP was 18.9%; in 2003, it was about 7.7%. From 2003 to 2014, the CNSE share of GDP account for an average of approximately 6.6%. In 2015, however, there was a recovery, when CNSE reached an even more significant percentage, achieving the level of 12.0%.

This CNSE share of GDP is significant, considering that there are several other sources of income that constitute the composition of a country's GDP such as: investments, government spending, household consumption, and exports minus imports, in which CNS plays a major role. Cashew production directly and indirectly employs about 80% of the Guinea-Bissau population. Cashew nuts represent more than 90%

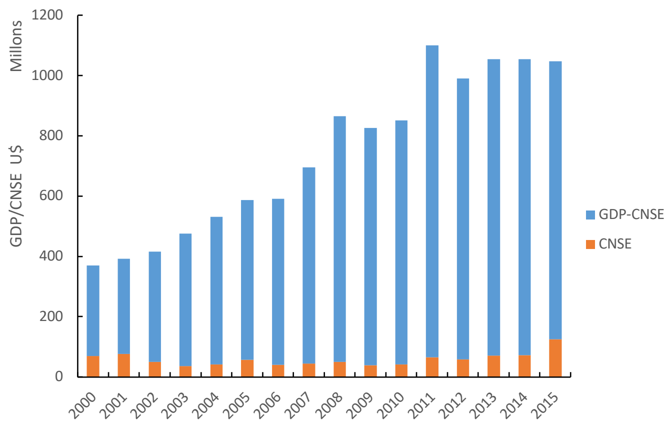

Figure 3 – CNSE as a share of GDP, 2000 to 2015, Guinea-Bissau.
Source: Prepared by the authors based on data from the World Bank (2019) and BCEAO (2019).

of the country's export earnings and still constitute the largest source of cash income (MEPIR, 2012; FMI, 2017).

This economic activity has at least four macroeconomic impacts:

- the commercialization of CNS injects liquidity for producers, intermediaries and exporters;
- it affects the price levels of other goods and services, due to the high propensity of economic actors to consume;
- it is the main source of foreign exchange earnings due to exports;
- it is an important source of tax revenue, due to the taxes collected from the commercialization of CNS, until it is exported (FMI, 2017).

Due to the increasing exodus of young people, older producers consider fruit growing as an old-age insurance, because, in the words of one of them, "even though the children are all gone, we can continue to eat from its income" (free translated by the authors) (Temudo, 2009). They also choose the product because it has relatively lower production costs than other products. The development of the sector benefits most of the population, either directly or indirectly. Thus, some studies show that, due to the economic importance of CNS, this process has been encouraging the deforestation of native forests in the country.

It is worth considering that this intensification of the exploitation of forest resources and changes in land use with loss of native forest cover may not result in improvements in the living conditions of the population. Thus, it is necessary to implement effective public policies for sustainable development in the country.

Impacts of sector-specific public policies on CNSP and CNSE in Guinea-Bissau

The investment structure of rural cashew properties entirely consists of the families' own capital. The absence of financing for investments in rural areas prevents producers from expanding their production capacities through the adoption of the best recommended practices for production to increase productivity (Samate, 2018).

Among the nine respondents, five believe that it is the non-governmental institutions (NGOs) that most contribute to investments for growth and development in the cashew sector. Only one specialist mentioned public institutions as being of major importance. Three respondents do not know how to answer to this matter. Thus, it is perceived that there is no confidence in the action of government public policies that may result in the necessary investments in different areas that would allow the growth and sustainable development of the cashew sector.

According to the responses of the interviewees (respondents), there is a consensus on the need for diversifying agricultural production, with monoculture being perceived as risky for the country's economic sustainability. This was evident in the remarks of one of the interviewees: "Because of the fluctuations in the international price of cashew, the diversification of agricultural production enables to anticipate the country's dependence on cashew production."

Therefore, the specialist perceives the influence of variations in the international market on the country's economy and that the diversification of agricultural production would allow the country to minimize its dependence on cashew production.

Regarding CNSE, there is also a consensus on the need for export diversification, with export monopoly being perceived as risky for the country's economic sustainability, as evidenced in the remarks of one of the interviewees: "The exports of other agricultural products, such as mangoes, peanuts, as well as fishery products, is essential to promote the economic return derived from primary activities."

Export diversification would contribute to reducing negative impacts in the event of a drop in the price of cashew in the international market.

In Guinea-Bissau, only 1% of CNS is transformed into cashew nuts (CN) through processing, whereas in countries such as India and Vietnam, CNS processing is greater than their production. These countries import CNS from countries such as Guinea-Bissau, then process and export it in the form of CN, which has greater added value. Thus, such places earn greater profitability, which contributes to the GDP growth of those countries (ANCA, 2013).

For the vertical integration of the country's economy, investments from public and private sectors are essential to create an efficient and sustainable industrial segment for CNS processing and the full use of cashews as well as other agricultural crops. Thus, such investments would allow the country to have a larger share of the world's cashew market. Steps must be taken to attract foreign investment in the cashew processing sector. The attempts made by domestic investors demonstrated the challenge associated with processing; they did not obtain good results in the sector, considering the high cost of local financing.

The value chain requires an integrated approach to develop the sector, complemented by activities to promote diversification. This integrated approach is critical for addressing food security issues, increasing farmers' resilience to external shocks, encouraging rural communities to participate in the work along the value chain, developing new sustainable opportunities in agriculture, and informing future structural changes in policies. Without public policies, everything indicates that Guinea-Bissau has been suffering from intense forest deforestation due to human activities.

Spatial patterns of changes in land use associated with the expansion of cashew cultivation: replacing areas of native vegetation

Previous studies show the intensification of deforestation for economic purposes in Guinea-Bissau. Changes that have occurred in the soil of Guinea-Bissau are a consequence of the human land use predominantly associated with agricultural activities, urban and infrastructure development, production of charcoal, cashew trees, and collection of wood for construction and firewood for domestic needs (Cabral and Costa, 2017). In this study, it can be observed that until 2001, land occupation occurred on a small scale and more slowly when compared with subsequent years. During this period, the regions of Cacheu, Oio and Bafafá were the most affected, whereas the South of the country, where there is better conservation of biodiversity, and an eastern part (Gabu) were the least affected areas. It is noteworthy that the location assessed in this study in Gabu and Tombali, where the reference cashews are located, did not appear to be intensely deforested at that time (Figure 4).

The occupation of land use has been significantly increasing in all regions of the country, but mainly in the southern region, where the border with the Republic of Guinea is located, and the northern region that corresponds to the border with the Republic of Senegal. The main causes of deforestation may be associated with an increase in population. From 1990 to 2018, there was a population growth of about 92% in the country, with an average annual growth of about 2% based on the year 1990 (World Bank, 2020), which somewhat boosts agricultural production and illegal timber trade, especially in the border regions.

The study performed by Temudo and Cabral (2017) indicated evidence that the fallow agricultural fields are being converted into simple cashew agroforestry interspersed with some trees of other species. Thus, the agroforestry agricultural intensification, instead of allowing the stabilization of the cultivated area, involves the destruction of areas. This is because when an area is converted to simple agroforestry, farmers look for new areas for cultivating agricultural crops, namely rice, peanuts, corn, etc. Only a few farmers intersperse their crop production with cashew plantations, and others prefer not to intersperse other crops with cashew plantations.

In developing countries, the collection of wood for fuel and the conversion of land covered by forests to the collection of wood for commercialization, fuel, and agricultural use led to high rates of deforestation (Field and Field, 2014). Changes that have taken place in Guinea-Bissau's soil are a consequence of land use predominantly associated with agricultural activities, charcoal production, timber exploitation, firewood for domestic use, and exploitation of African palmyra palm (*Borassus aethiopum*) to cover houses (Temudo and Cabral, 2017).

Deforestation and forest degradation are responsible for large part of the global greenhouse gases. Much of the debate on the mechanism for Reducing Emissions from Deforestation and Forest Degradation (REDD+) has focused on the effects of deforestation. Forests are more than carbon stocks and and the REDD+ mechanism must be concerned not only with reducing the effects of climate change, but also with the creation of socioeconomic structures for the sustainable management of forests (Faria et al., 2014). In Guinea-Bissau, as CNS producers begin to invest in new technologies, that is, increasing their CNS production costs, there will be a reduction in fires to clear the land

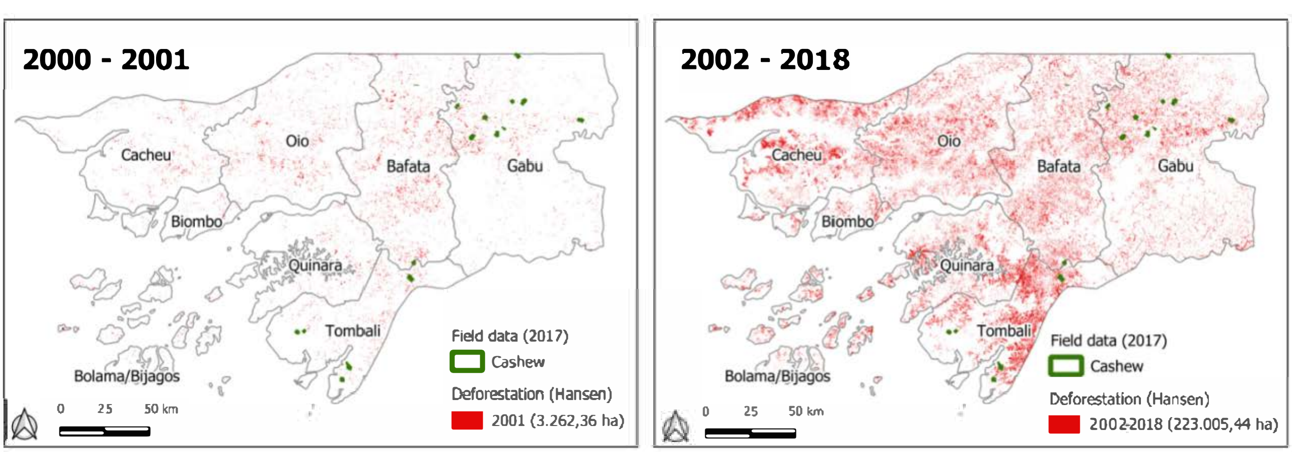

Figure 4 – Intensity of land occupation (2001 to 2018) in Guinea-Bissau.
Source: Prepared by the authors based on data from Global Forest Change (2013).

for cashew orchards, new techniques to combat pests through biopesticides, increased productivity, etc.

Many developing countries may have a bright future if they are able to competently exploit their biodiversity through use of biotechnologies, both to increase biomass production and to increase the spectrum of products derived from it (Sachs, 2008). In Guinea-Bissau, the exploitation of natural resources requires control and costs to reduce environmental pollution.

According to Rivas (2014, p. 98), the cost in this case "is the reduction of pollution to a lower level so that there is little damage." There must be an optimum point of deforestation. Ecosystems provide important services for people's survival, as stated by Rivas (2014, p. 185), "ecosystem services can be defined as the contributions arising from the functioning of ecosystems, ecological characteristics, functions or processes that indirectly contribute to life and human well-being."

Forests have a direct use value, such as ecotourism; indirect use value, as protection of water bodies, soil, fire, and control of floods and microclimate; option value, as for discovering new drugs; and non-use or nonexistence value, as an intrinsic value, existence of nonhuman species, or preservation of cultural, religious and historical values (Motta, 2002). Therefore, forest protection is essential for sustainable development. It is also important to encourage the agencies with jurisdiction to reduce deforestation in the country. An incentive is something that attracts or alienates people and, somehow, leads to a change in their behavior (Field and Field, 2014).

Nonexclusive, sustainable, and sustained development is needed. Sustainable development fulfills the double ethical imperative of solidarity with present and future generations, and requires the explicit definition of criteria for social and environmental sustainability and economic viability (Sachs, 2008). In Guinea-Bissau, it is necessary to address the short-term emergencies linked to crisis management by reflecting on the medium- and long-term strategies. Both must be informed by the same vision of sustainable development that, on the one hand, offers the assessment criteria for the proposed policies and, on the other hand, through a broad social debate, gradually unfolds in a national project.

The transition to sustainable development begins with crisis management, which requires an immediate paradigm shift, moving from growth financed by the inflow of external resources and the accumulation of external debt to a growth based on the mobilization of internal resources, employing people to work in activities with import content (Sachs, 2008). It is important to encourage the internal consumption of goods and services, in such a way economic growth, employment, and income for families can be generated, with the purpose of reducing agricultural exploitation as the main source of income for families with fewer financial resources.

All citizens must have equal access to assistance programs for disabled people, for mothers and children, for older adults, aimed at compensating for natural or physical inequities. Compensatory social policies financed by income redistribution should go further and include unemployment benefits, a task that is practically impossible in countries where only a small minority is employed in the organized sector and where open unemployment is far less significant than underemployment. The population as a whole should have equal opportunities to access public services, such as education, health protection, and housing. Education, for instance, is essential for local and human development, due to its intrinsic value, as it contributes to cultural awakening, awareness, understanding of human rights, increasing adaptability and a sense of autonomy as well as self-confidence and self-esteem.

Conclusions

The environmental impacts associated with the intensification of deforestation in Guinea-Bissau can be attributed to the expansion of the main agricultural products, such as cashew, rice, peanuts and, more recently, to the illegal logging of wood for commercialization destined for the Chinese market.

CNSE accounts for an average of 8.9% of the country's GDP. This economic activity has at least four macroeconomic impacts:

- the commercialization of CNS injects liquidity for producers, intermediaries and exporters;
- it affects the price levels of other goods and services due to the high propensity of economic actors to consume;
- it is the main source of foreign exchange revenue due to exports;
- it is an important source of tax revenue due to taxes collected during the commercialization, until it is exported.

According to the interviewees, most of them believe that the Government does not contribute to public policies for the sustainable development of the cashew sector; non-governmental institutions (NGOs) are the ones that contribute the most with investments for the growth and sustainable development of the cashew sector. It is a consensus among the interviewees that, in recent years, CNSP has been increasing, but this increase is due to the growth of new agricultural areas. They also believe that the decrease in the production of other crops in favor of CNSP is encouraged by the CNS price in the domestic market due to the demand and its price abroad.

With the use of geoprocessing techniques, the authors verified that the country has been significantly increasing the occupation of land use in all regions, mainly in southern areas, close to the borders with the Republic of Guinea and in northern areas, where the borders with the Republic of Senegal ~~of Senegal~~ are located. One of the main causes of deforestation is the population increase, which somewhat boosts agricultural production and the illegal timber trade, especially in the border regions.

Investment incentives are needed for large-scale CNS processing, which is a product with greater added value. This process must have a sustainable structure with less environmental impact. It is necessary to promote the diversification of the economy in all sectors, in accordance with the social and economic potential of the country.

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Contribution of authors:

Seca, A.I.: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft. Pereira, H.S: Conceptualization, Methodology, Review & Editing, Supervision. Pedroza, S.C.: Methodology, Formal Analysis, Investigation, Review & Editing.

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ABES

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Relationship between respiratory diseases and environmental conditions: a time-series analysis in Eastern Amazon

Inter-relações entre doenças respiratórias e condições ambientais: uma análise de séries temporais na Amazônia Oriental

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ABSTRACT

This study examines the relationship between the time-series analysis of climate, deforestation, wildfire, Aerosol Optical Depth (AOD), and hospital admissions for respiratory diseases in the Eastern Amazon. Through a descriptive study with an ecological approach of an 18-year time-series analysis, we made a statistical analysis of two pre-established periods, namely, the rainy season and the dry season. On a decadal scale, analyzing the signals of climate indices [i.e., the Southern Oscillation Index (SOI) and the Atlantic Meridional Mode (AMM)], the city of Marabá presents correlations between hospital admissions, wildfire, and AOD. This is not observed with the same accuracy in Santarém. On a seasonal scale, our analysis demonstrated how both cities in this research presented an increase in the number of hospital admissions during the dry season: Marabá, 3%; Santarém, 5%. The same season also presented a higher number of fire outbreaks, AOD, and higher temperatures. The AOD monthly analysis showed that the atmosphere of Marabá may be under the influence of other types of aerosols, such as those from mining activities. There is a time lag of approximately 2 months in the records of wildfire in the city. Such lag is not found in Santarém. The linear regression analysis shows that there is a correlation above 64% (Marabá) and 50% (Santarém), which is statistically significant because it proves that the number of hospital admissions for respiratory diseases is dependable on the AOD value. From the cities in the study, Marabá presents the highest incidence of wildfire, with an average of 188.5—the average in Santarém is 68.7—, and therefore the highest AOD value, with an average of 0.66 (Santarém, 0.47), both during the dry season. It is evident that the climate component has a relevant contribution to the increase in the number of hospital admissions, especially during the rainy season, where there are few or no records of wildfires.

Keywords: air pollution; deforestation; wildfire; climate; state of Pará.

RESUMO

Este estudo faz uma análise da inter-relação entre as séries temporais do clima, desmatamento, queimadas, profundidade óptica do aerossol (AOD) e internações hospitalares por doenças respiratórias na Amazônia oriental. Através de um estudo descritivo, com delineamento ecológico de séries temporais de 18 anos de dados, foram feitas análises estatísticas para dois períodos preestabelecidos: chuvoso e seco. Em escala decadal, mediante análise dos sinais dos índices climáticos, índice de oscilação sul (IOS) e o modo meridional do Atlântico (MMA), Marabá apresenta concordância entre internações, focos de queimadas e AOD, o que não se observa com a mesma exatidão para Santarém. Em escala sazonal, nossas análises mostram que os dois municípios estudados nesta pesquisa apresentaram um aumento no número de internações na estação seca, Marabá (3%) e Santarém (5%). A mesma estação também apresentou maior número de queimadas, AOD e alto valor de temperatura. A análise mensal do AOD mostrou que a atmosfera de Marabá pode estar sendo influenciada pela presença de outros tipos de aerossóis, como os emitidos pela atividade mineradora, logo há uma defasagem no tempo de aproximadamente 2 meses em relação às ocorrências de queimadas registradas dentro do município. Santarém não apresentou essa defasagem. A análise de regressão linear mostra que há correlação acima de 64% (Marabá) e 50% (Santarém), sendo estatisticamente significante e comprovando que a taxa de internação por doenças respiratórias depende do valor do AOD. Dos municípios investigados, Marabá é a localidade que apresenta o maior número de incêndios florestais com média de 188.5 (Santarém, 68,7) e, portanto, o maior valor de AOD, com média de 0,66 (Santarém, 0,47), ambos para a estação seca. Fica evidente que a componente climática tem relevante contribuição para o aumento das internações, principalmente na estação chuvosa, onde há pouco ou nenhum registro de focos de incêndio.

Palavras-chave: poluição do ar; desmatamento; queimadas; clima; Pará.

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Introduction

Large population clusters are found in urban areas and present multiple physical characteristics in their geoecology, land use and occupation, climate, and social features. When treating a city as an organic space, as somewhere in constant construction and production, it is conceivable to recognize that it promotes an accumulation of social and environmental phenomena that directly influence the population's health and life quality.

Some studies intend to establish a correlation between climate and the increase in air pollution, due to the intensification of wildfire that severely affects the ecological balance and, eventually, human health. Climate variability, such as the Atmosphere–Ocean Dynamics over the Atlantic and the Pacific, influences the modulation of ecological variables (Limberger and Silva, 2016) and, consequently, the combustion of biomass and the continuance of a wildfire.

In recent years, there has been a growing international awareness in controlling forest fires in the Amazon. This is due to climate change and deforestation still at large (Gonçalves et al., 2012). Most diseases are caused by or influenced by environmental factors, including climatic conditions that have increasingly been the subject of epidemiological studies. However, considering the relationship between climate, deforestation, wildfire, and human health, it is evident that studies on this issue are still scarce in Eastern Amazon. The slash-and-burn operation is the greatest issue today. When combined with climate extremes, it can aggravate local human health, especially in cities with a low Human Development Index (HDI) and a weak health-care system (Smith et al., 2014).

Population growth is another issue that may contribute to the increase in air pollution in large urban areas, and it is increasing exponentially. Collectively, people from all over the world utilize an exceedingly large amount of food, water, and raw materials and, thus, produce a lot of pollution, so they tend to be more exposed to the amount of particulate matter produced within the very environment where they live (Miller and Spoolman, 2015).

Studies indicate that the size of the particles that make up the particulate matter, whose diameter may vary from a few nanometers to dozens of micrometers, is directly associated with its potential to cause breathing problems. The smaller the diameter, the greater the effects (Alves et al., 2017).

According to Padilla et al. (2014), socioeconomic factors can also contribute to the effects of particulate matter on human life. Their study demonstrates how populations in precarious living conditions are more vulnerable to breathing problems as they are more exposed to unsanitary environmental conditions. The uneven geographical distribution of living conditions and urban traffic is another key factor to be considered, as differential exposure contributes to the effects of particulate matters, and it can increase the risk of mortality from respiratory diseases (Rodrigues et al., 2019). Other authors such as Forastiere et al. (2007) argue that environmental impacts can significantly contribute to social inequality at a local scale. Therefore, people in precarious living conditions have restricted access to primary health care.

Studies demonstrate how 98% of mortality due to respiratory diseases in children occurs in poor or developing countries (WHO, 2018). In general, children may be more vulnerable when compared with other age groups. Fine Particulate Matter ($PM_{2.5}$) in the atmosphere penetrates more effectively in the lower respiratory tract, bronchi, and pulmonary alveoli of children aged below 10 years and adults aged above 60 years, which can cause genetic changes and the development of tumors (Alves et al., 2015, 2017).

The research on suspended particles from forest fires is still elementary, mainly due to the lack of data on air pollutants. However, remote sensing can offer such data, reading both the Aerosol Optical Depth (AOD) and the Particulate Matter ($PM_{2.5}$), especially in regions with no surface metrology as the Amazon (Andreão and Albuquerque, 2020). Therefore, the AOD is the most appropriate satellite product for estimating the concentrations of $PM_{2.5}$. It is an indicator of aerosols scattering solar radiation in the vertical atmospheric column, which is characterized by wildfire smoke due to the high concentration of organic matter in suspension. In general terms, radiation extinction is measured by reading the scattering and absorption of aerosols in the atmospheric column. Thus, this study intends to foreground the interconnections between the time series of climate, deforestation, wildfire, and hospital admissions for respiratory diseases in the Eastern Amazon.

Methods

The State of Pará, located in the Eastern Amazon (Figure 1), is the study area of this research. From the 144 municipalities distributed throughout the state, we chose the cities of Marabá and Santarém for representing large urban areas, with a considerable population density, industry, and a health-care system for both high and medium complexity procedures. Also, these cities are located along the Arc of Deforestation: Marabá, in the East of the state; and Santarém, in the West, in the region called Lower Amazon.

The environmental and social database available to this study is representative of the period from 2000 to 2017, through a monthly and seasonal scale with the following variables: Aerosol Optical Depth (AOD), The Southern Oscillation Index (SOI), the Atlantic Meridional Mode (AMM), wildfire, deforestation, precipitation, relative humidity, air temperature, and hospital admissions (i.e., a social variable) for respiratory diseases. In the interest of a seasonal analysis, we also arranged the data period to show the rainy season (January–May) and the dry season (June–December).

We employed the estimates of the imaging sensor Moderate Resolution Imaging Spectroradiometer (MODIS), presently aboard the Terra and Aqua satellites (Di Nicolantonio et al., 2009; Van Donkelaar et al., 2010), to obtain the AOD data at 550 nm, with a 3-km resolution as the collection 6.0. This includes the models of the optical spectrum for estimating numerous properties of aerosols, including AOD,

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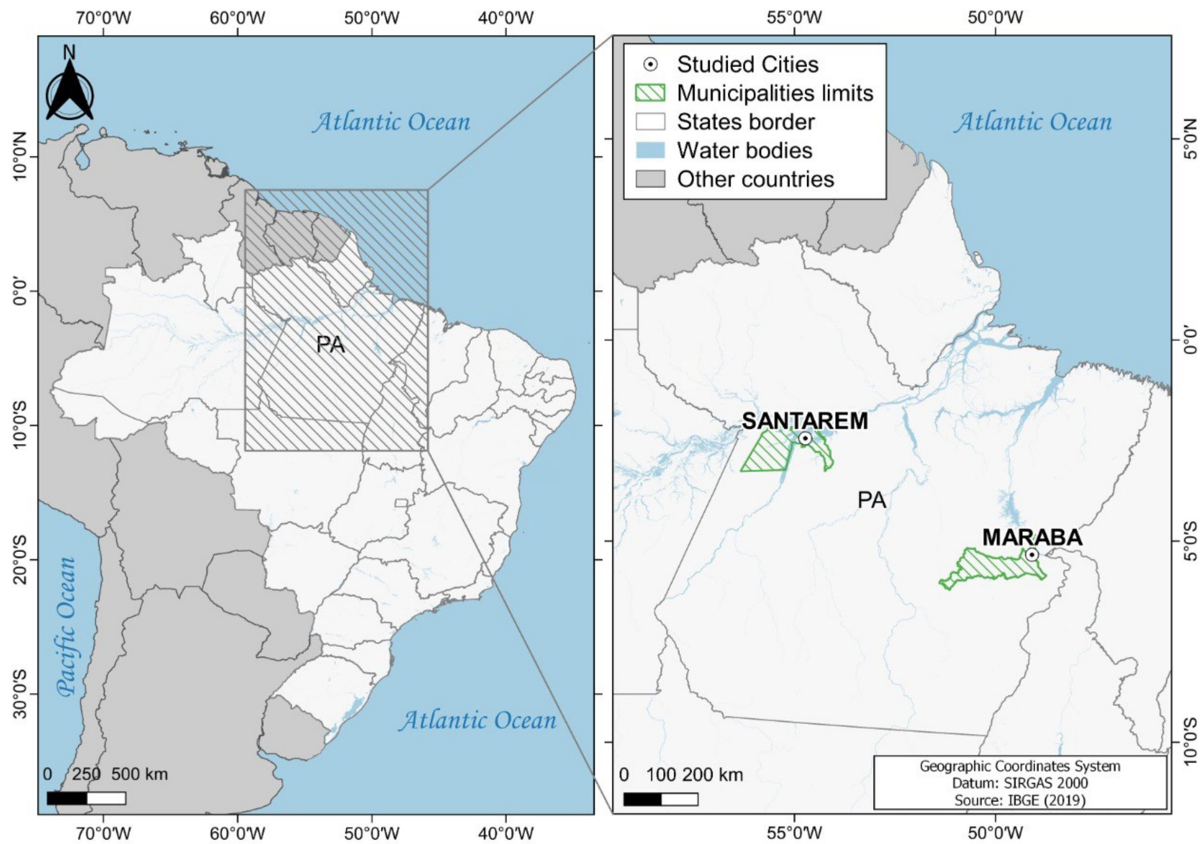

Figure 1 – Map of the study area, with geographic location by country, state, and the cities of Marabá and Santarém, in the State of Pará.

with the product names: MOD04L2-3K and MYD04L2-3K (Lyapustin et al., 2018). The daily AOD data were generated from the average of a morning (10:30 a.m., Satellite Terra) and afternoon (1:30 p.m., Satellite Aqua) reading and then converted into monthly averages for a 40 km^2 area surrounding the cities in the study.

The data from the AMM and SOI climate indices are available on a monthly time-series analysis at NOAA (2018). These data are available to characterize climatic aspects by demonstrating the ocean–atmosphere oscillations from both the tropical Atlantic and Pacific oceans that modulate precipitation and other atmospheric variables. Such indices indicate climatic conditions by considering the phases of the AMM dipoles, which are as follows: Positive (not favorable conditions for rain) and Negative (favorable conditions for rain); as well as the SOI phases, which are as follows: Negative, for El Niño, and positive, for La Niña (Pereira et al., 2017).

The tropical Atlantic surface waters are cooler (warmer) in the southern hemisphere when the AMM is positive (negative), which affects the rainy season in the Amazon, making it scarcer (abundant). In the tropical Pacific, El Niño (La Niña) incidents tend to decrease (increase) the volume of rainfall at the Western and Eastern ends of the Amazon (Sousa et al., 2018; Kayano et al., 2019).

The annual deforestation rates were obtained through the PRODES webpage (i.e., the Measurement of Deforestation by Remote Sensing), powered by INPE (the National Institute for Space Research), which uses LANDSAT satellite imagery (Montibeller et al., 2020). This is a major instrument for planning public policies in the Amazon.

The INPE also makes available information on hotspots. The data are obtained by remote sensing (see INPE, 2018). This research benefited from the data provided by the reference satellite (i.e., geostationary) using the Advanced Very-High-Resolution Radiometer (AVHRR) sensor, with a late afternoon orbital pass, and the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, with an early afternoon orbital pass, 4- to 5-km resolution, provided by NASA.

The Center for Weather Forecasting and Climate Studies (CPTEC/INPE) publishes the data on Precipitation (PRP) from the Integrated Multi-satellitE Retrievals for GPM (IMERG) product. This technique uses the intercalibrated estimates from surface precipitation analyses and the data from precipitation-relevant satellites (Rozante et al., 2010), resulting in binary files with a 20-km resolution, with a daily pass (accumulated figures for 24 h) here transposed to a monthly time series, covering all South America. In addition, the monthly mean relative humidity (RH) and air temperature (T), provided by the Brazilian National Institute of Meteorology (INMET) for the conventional surface stations in Marabá and Santarém, in the Eastern Amazon.

For this research, we developed an ecological time-series analysis considering a list of all types of respiratory diseases, with codes from J00 to J99, under the International Statistical Classification of Diseases and Related Health Problems (ICD-10), entrusted to the World Health Organization (WHO). We established a 1–9 age bracket, with both males and females, as it embodies a group that is reasonably vulnerable to respiratory diseases. Aside from climate indices, all other variables in this study were subjected to anomaly detection based on a 6-month moving average for every variable and every city, so that trends, temporal patterns, oscillations, and extreme periods between variables could be identified as closely as possible, over the time-series study.

Monthly anomalies were detected on every variable in this research. All the time series were divided into two decades to detect dominant qualitative trends in the anomaly variability that may have contributed to the increase in the number of hot spots and, consequently, in the number of hospital admissions.

For a better analysis of the AOD series in association with hospital admissions, we examined both the amplitude and the asymmetry of the available dataset through the maximum, the minimum, and the sample median, correspondingly. We developed boxplots to graphically depict these statistics. This type of analysis enables the reader to visualize the distribution of values per time series, and also possible discrepancies in the dataset (Seward and Doane, 2014).

The linear regression model we applied considered the number of hospital admissions as a dependent variable (y) and the AOD as an independent variable (x). The statistics generated by the regression equation also include the calculation of the coefficient of determination (R^2), the coefficient of correlation (r), and the $p < 0.05$, with a confidence interval of 95%.

For an enhanced understanding of our statistical analysis of the linear regression, the hospital admission rate was calculated from the records of monthly admissions of children up to 9 years old, per 1,000 inhabitants, for both cities.

Results and Discussion

Figure 2 demonstrates that the most anthropized areas in the State of Pará overlap the areas with the lowest annual precipitation rates, as in the extreme East of the state where Marabá is located, in the Amazon Arc of Deforestation, and in the West where Santarém is located. In addition, mosaic deforestation reveals that the surroundings of Marabá show higher natural devastation in comparison with Santarém. Therefore, the effects on local rainfall rates would impact both regions as follows: in Marabá, from annual rainfall rate between 1,800 and 2,000 mm; and Santarém, from annual rainfall rate between 2,000 and 2,400 mm. Studies show that areas with considerable rainfall rates are likely to present higher air quality (Gonçalves et al., 2010), as precipitation cleans the atmosphere, reducing pollution. The opposite is true in areas with limited rainfall rates. Debortoli et al. (2017) concluded that, on a local scale, there is a strong correlation between forest cover and local precipitation, which suggests that large areas of preserved forest enable the viability of higher rainfall rates, in opposite direction to the effects observed on a local scale (Davidson et al., 2012).

Studies suggest that the local contribution of evapotranspiration toward precipitation in the Amazon is in the order of 20-35% (Rocha et al., 2015). Consequently, the expansion of deforestation directly impacts the rainfall rate of a given region, and it is directly related to the increase of wildfire due to land-use change (Seixas and Pinheiro, 2014; Coutinho et al., 2018), mainly in the Arc of Deforestation.

The AMM and SOI climatic indices are imperative for the modulation of rainfall in the Amazon. Figure 3 shows that even with some negative peaks, the signal on the AMM series is predominantly positive over time, which is unfortunate for precipitation because it decreases humidity transport and rises air temperature in the Eastern Amazon (Limberger and Silva, 2016). The SOI series also shows a higher number of positive peaks over time, indicating a higher incidence of La Niña events, which favors precipitation, mainly from 2003 to 2005, 2015, and 2016, when the index was negative.

The first three variables in Figures 4A-4C demonstrate how Marabá has had the stages of approximately 10 years (2000–2009) in which rainfall rates were mostly positive in the first decade (+70.0 ± 60.6 mm), consistent with the first decade of SOI that was correspondingly mainly positive and therefore presented more frequent occurrences of La Niña events, which favored rainfall in the region (Araújo et al., 2013). Nevertheless, air temperature and relative humidity behave contrarily, with temperatures above average and humidity below average during the first decade (+0.6°C ± 0.5°C and -2.9% ± 2.1%). This behavior is also true in the second decade.

It is important to reiterate that the air humidity series in Marabá was contrary to the precipitation series due to the high degree of vegetation degradation in the city, causing the hydrological cycle to change. There is a minimal infiltration and thus increased evaporation, even with positive rainfall anomalies, altering the hydrological cycle in the region (Duarte et al., 2009).

This suggests that Marabá, a city with a highly degraded natural environment, large deforested areas, different soil coverings, and diverse land use activities, presents an imbalance in the behavior of environmental variables, in addition to being influenced by the global climatic fluctuations in comparison with other cities with different natural landscapes. It is in agreement with Pires and Costa (2013), who demonstrated how environmental degradation in the Arc of Deforestation may trigger serious bioclimatic imbalances.

Although the SOI had a positive phase in the second decade, the one with more La Niña incidents, the precipitation in Marabá

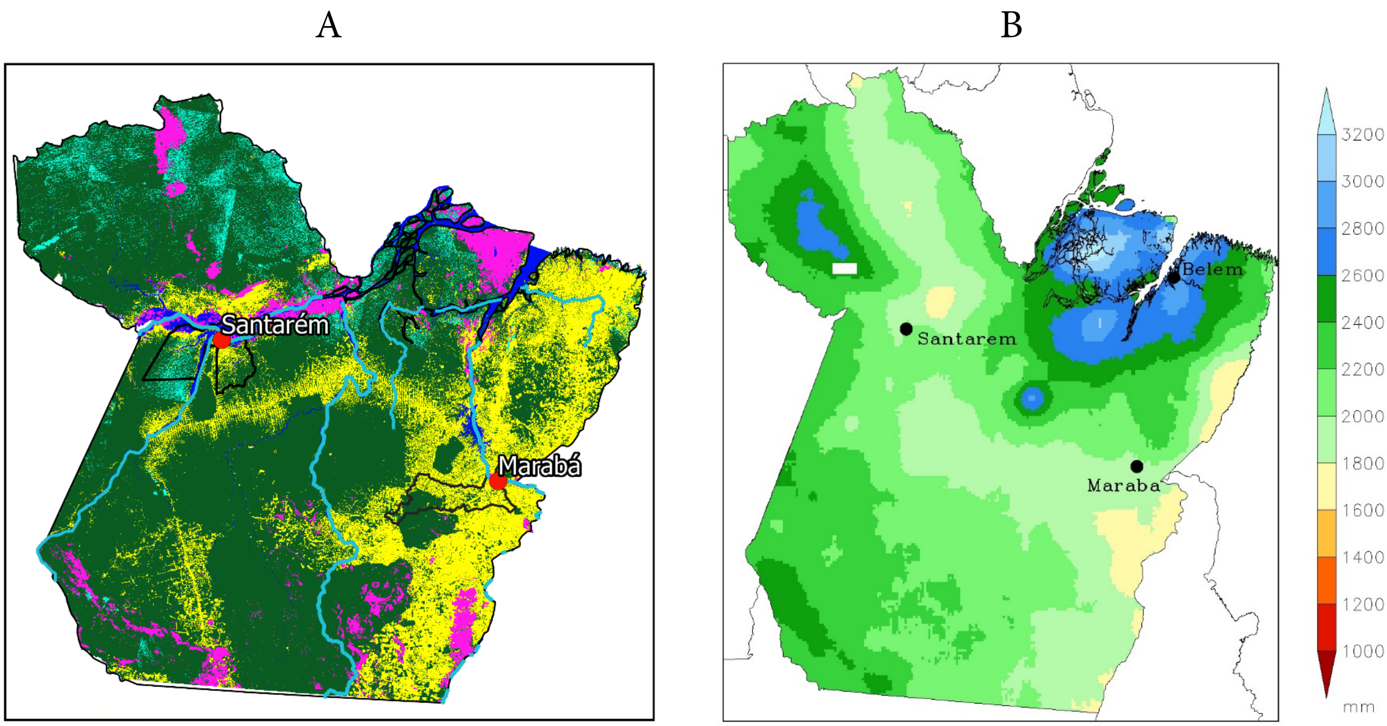

Figure 2 – Environmental characteristics of the State of Pará, with its hydrography and the location of Marabá and Santarém. (A) Total of deforested areas (in yellow) and anthropized forest areas (in green) from 2000 to 2017 and (B) average climatological for annual precipitation. IMERG, 1981–2017.

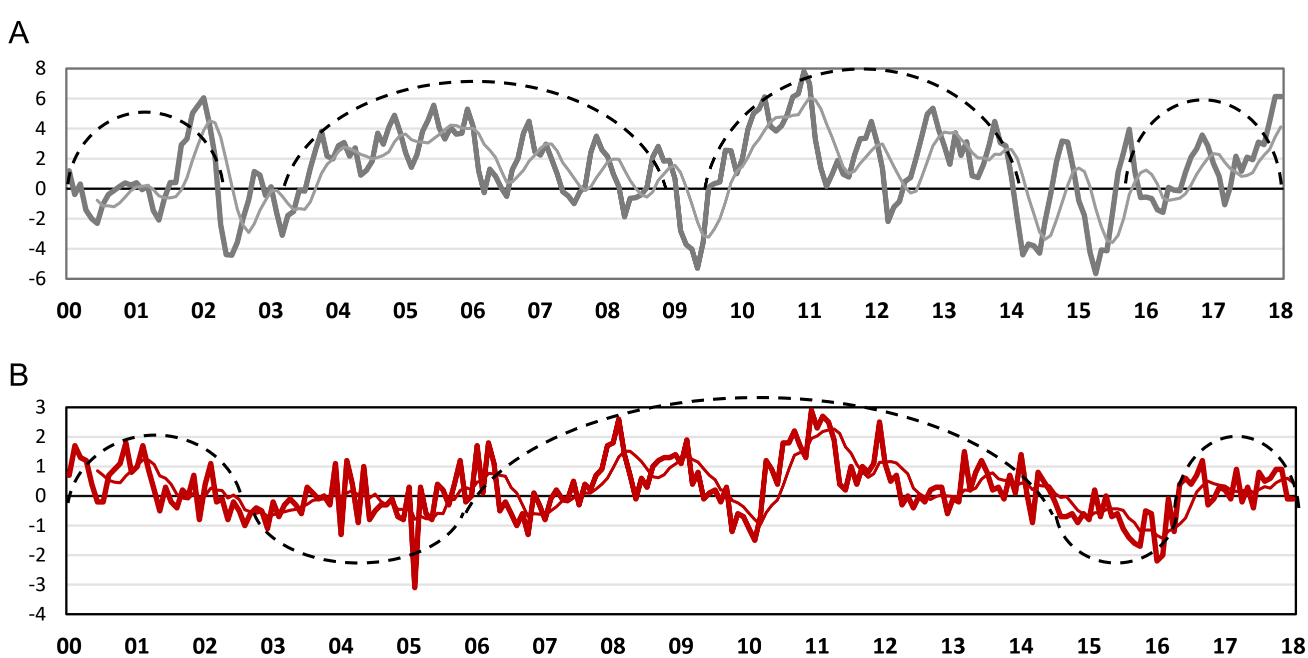

Figure 3 – Distribution of monthly anomaly values for the 2000–2017 climate indices. (A) AMM (the Atlantic) and (B) SOI (the Pacific). The smoothed line displays the 6-month moving average values, and the dashed line presents the dominant signals for both the positive and the negative phases.

showed a negative phase in the second decade, this time due to the AMM signal that showed mostly positive values throughout the series, particularly in the second decade, which impairs precipitation in the Amazon (De Jesus et al., 2017). Different from the first decade, rainfall was above average, and humidity was below average (-0.6°C ± 0.5°C and -2.5% ± 2.1%).

It is patent that Santarém (Figure 4D-4F), observed in the aforementioned graphs, has rather similar phases in comparison with the SOI series,

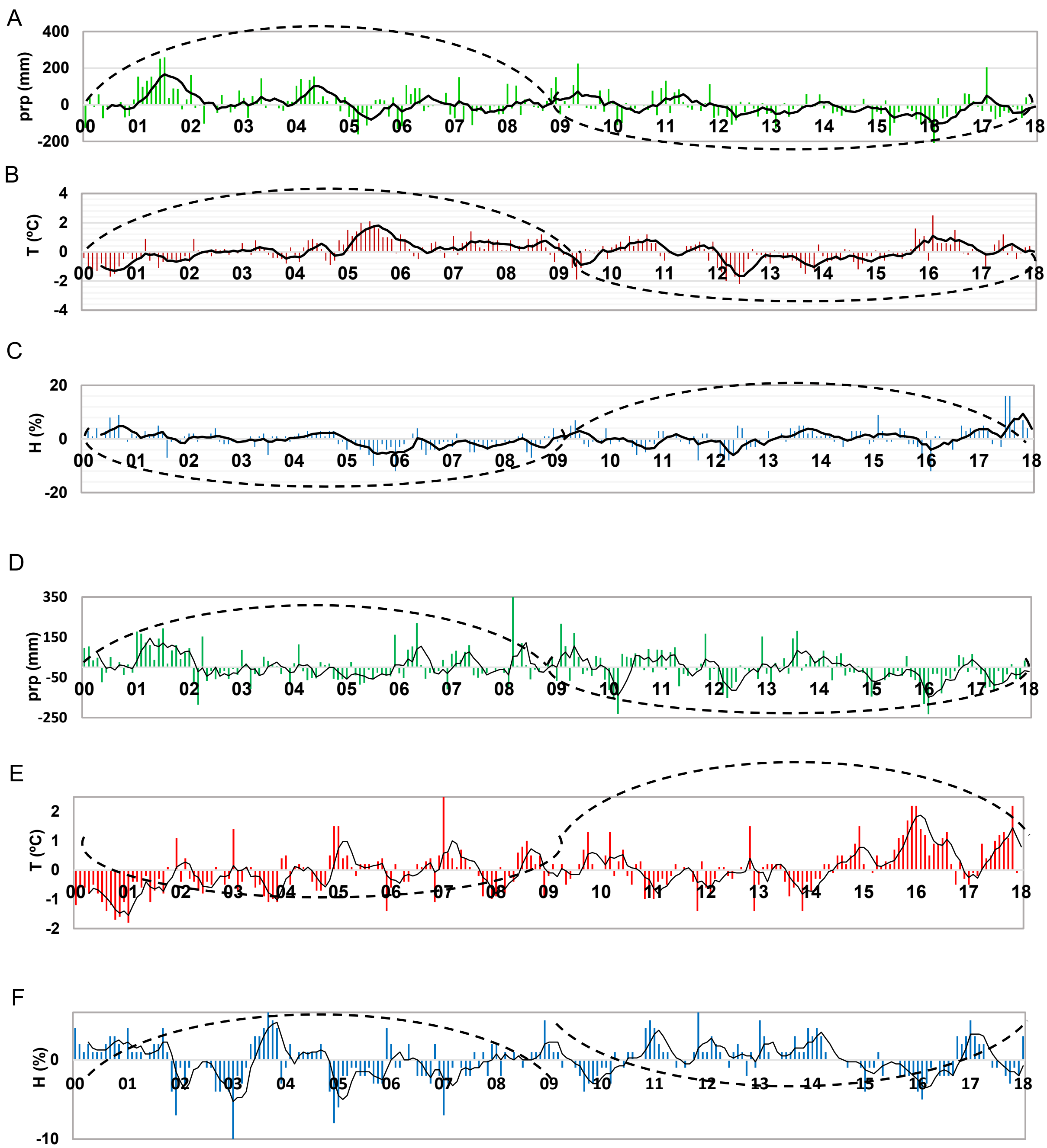

Figure 4 – (A, B, C) Distribution of monthly anomalies values for PRP, T, and RH in Marabá; (D, E, F) PRP, T, and RH in Santarém, both from the 2000–2017 time series. The dashed line presents the dominant signals for both the positive and the negative phases.

with the same variables analyzed for Marabá. As the SOI indicates that the first decade has a higher incidence of La Niña events, that is, it prominently a positive phase (Figure 3B), Santarém also shows a positive phase for rainfall and a negative phase for temperature, with values below average.

In general, the relative air humidity in Santarém remained below average in the first decade, although a balance (+2.0% ± 1.5% and -2.4% ± 2.1%) between positive and negative values is observed (Figure 4F). Considering the meteorological variables, it is understood from this analysis that Santarém reacts well to the modulations of large-scale climate mechanisms. Despite the increase in deforestation (2016-2019) in the past 4 years, the annual deforested area rate is on a downward trend (INPE, 2020) since the beginning of the time series in 2000. It is the result of a change in public policies, the creation of conservation units, extensive improvements in the Forest Code, and the involvement of civil society and NGOs. These efforts managed to contain the expansion of deforestation for over two decades (Bistene and Guimarães, 2019), allowing Santarém to preserve a considerable part of its natural features. Despite an increasing trend in deforestation in the past 8 years, Bandeira Castelo et al. (2020) considered that The Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm), which is currently in its fourth phase, has shown satisfactory results in terms of reducing deforestation in the State of Pará, including Santarém.

Unlike the trends in climate variables observed in Figure 4, Figure 5 shows that for other environmental variables the city of Marabá displays the same anomalies for the two long periods of the series, with concordant phases. Deforestation and hotspots indicate agreement with the two periods, with mostly positive values in the first decade and negative values in the second, supporting the hypothesis that the increase of wildfire is mostly a consequence of unbridled deforestation, which considerably increases the chances for wildfire, as demonstrated by Fearnside (2005). According to Rivero et al. (2009), several factors lead to intense forest clearing and, subsequently, to wildfire. For the authors, agriculture and livestock activities are the two driving factors because they require low capital and less soil preparation. This is a context of scarce economic alternatives, low educational standards, and a lack of technology. These factors, in association with the rooted cultural values carried by rural workmen, enable the process of deforestation and wildfire to extend throughout the Amazon rainforest.

Even with an apparent decrease in the incidence of wildfires in the Amazon over the decade we studied, the number of hotspots in Marabá is still dramatic and always worsens during the second semester, at the peak of the dry season (Figure 5). According to Fearnside (2006), when there is a fire in the forest, it takes trees, increases fuel loads, and dries the forest understory, elevating the risk of future wildfire and the complete degradation of the forest. Analyzing Figure 5C, it is possible to state that the AOD time series also illustrates how Marabá has a phase with the above-average values in most months of the first decade, and a negative phase in the second decade.

Regarding hospital admissions, we illustrated in Figure 5D that Marabá experienced a positive phase in the first decade (2000-2009), followed by a negative phase in the second decade (2010-2018), which is in agreement with the deforestation time-series analysis, hot spots analysis, and AOD.

Unlike the wildfire time series, the AOD series presents peaks of positive anomalies in the second decade, even without peaks of forest fires, which can be explained by the number of aerosols coming from remote regions to Marabá *via* wind flow, as demonstrated by Kaufman et al. (1998): particles in suspension seek trajectories, *via* wind flow, of several kilometers in the atmosphere, and can reach remote regions.

This is evidence that the number of hospital admissions in Marabá followed the increase in air pollution caused by wildfire aerosols, a consequence of large-scale deforestation, not only in Marabá but also in the entire Arc of Deforestation. Barcellos et al. (2019) introduced the research that determined the impact of wildfires and particulate matter in the health of children living in the Arc of Deforestation, where the city of Marabá is located. This research analyzed samples in the course of 1 year and concluded that the number of hospital admissions doubled in areas with excessive incidence of hotspots.

In the decadal analysis, most years of the entire deforestation time series show values below average for the period (59 km^2), especially in the second decade, in agreement with the AOD time series and the number of hospital admissions in the same period.

The analysis of the same variables culminated in different results in Santarém: the number of hospital admissions for respiratory diseases shows a predominantly positive phase in the first decade (+12.7 ± 12.3) and a predominantly negative phase in the second (-10.3 ± 8.9), regardless the positive anomalies at some points, mainly in 2013.

The same trend was observed in the historical series of deforestation and AOD. However, the wildfire time series does not present the same behavior: a few fire outbreaks in the first decade, and most months within the average.

The decadal analysis confirmed that the city of Marabá is more affected by local wildfires and forest fire from neighboring cities, as observed by comparing the analysis of decadal phases and by considering the historical series of wildfire and hospital admissions, which made apparent that deforestation and wildfire modulate both the optical depth time series and the number of hospital admissions. The analyses of decadal phases are not the same in Santarém, mainly concerning the number of fire outbreaks, i.e., a low rate for the region.

Therefore, the number of hospital admissions may be influenced by the variation of temperature and humidity in the city (Table 1), which may increase the hospital admission records for respiratory diseases due to fungal pollution of indoor environments, accelerating the emergence of diseases such as asthma, as explained by Rosa et al. (2008).

Andrade Filho et al. (2013), years later, when performing a seasonal analysis of a series of hospital admissions, found that high

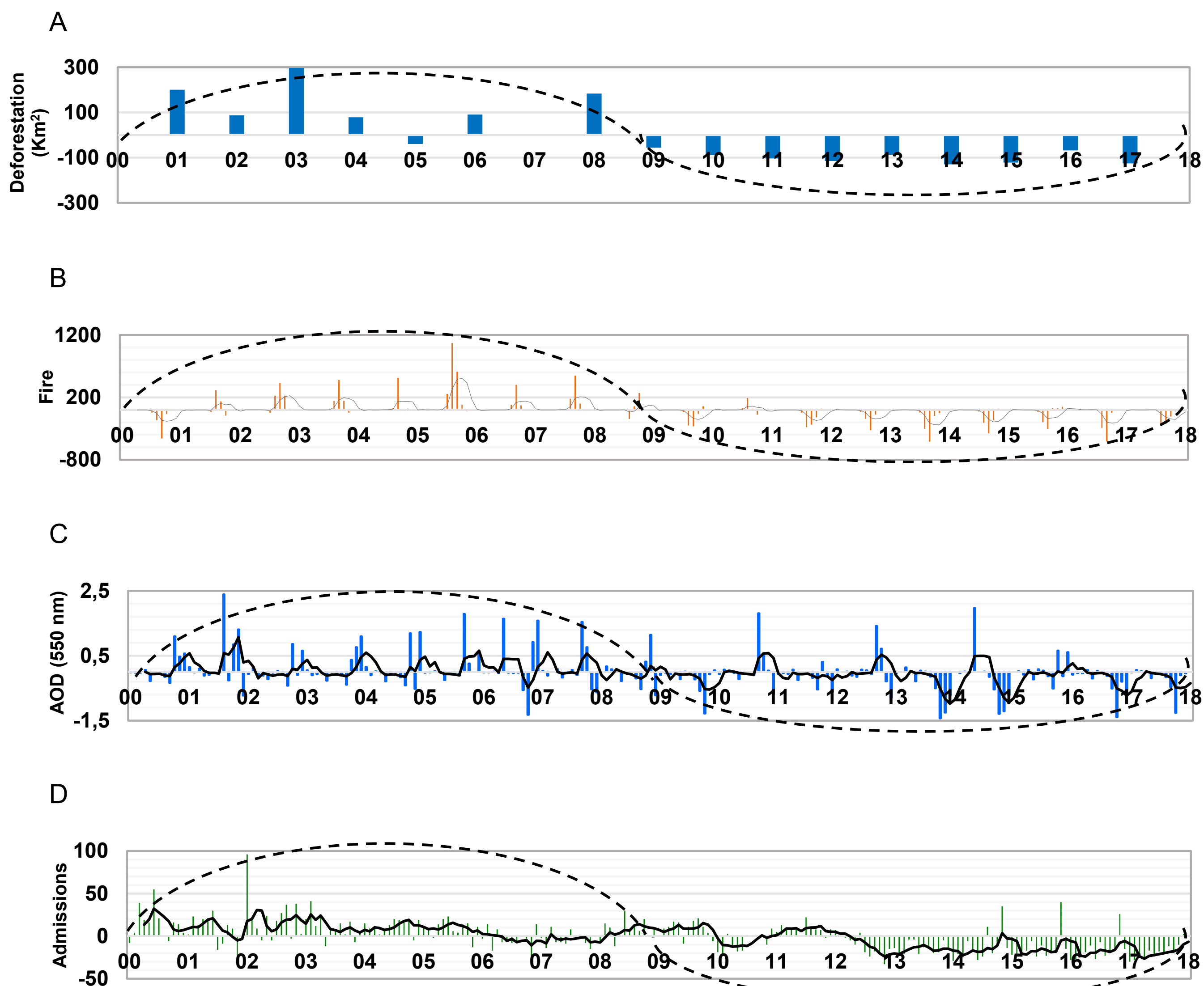

Figure 5 – Distribution of monthly anomalies values for the socio-environmental variables of Marabá from 2000 to 2017: (A) deforestation, (B) fire, (C) AOD, (D) admissions. The dashed line presents the dominant signals for both the positive and the negative phases. The continuous line presents the 6-month moving average.

humidity can influence the number of admissions for respiratory diseases. These results were later confirmed by Smith et al. (2014) when they demonstrated how the peak of hospital admissions of children occurs during the peak of the rainy season due to excessive humidity.

We also calculated the anomalies for the same socio-environmental variables in Santarém, namely, deforestation, wildfire, AOD, and hospital admissions (Figure 6). Unlike Marabá, phases were not so coincident over the time-series period, thus showing a higher data variability.

Table 1 shows that hospital records for respiratory diseases in Marabá. The average number of children hospitalized during the rainy season is 32 (±15.4) and during the dry season is 33 (±11.4), i.e., a 3% increase in hospitalizations from one season to the other. In Santarém, the average is 45.8 (±12.1) during the rainy season and 49.2 (±16.5) during the dry seasons, i.e., an increase of 5%.

The AOD value draws a growing trend following the increase of wildfire and temperature, with a significant rise during the dry season. In Marabá, there is a higher variation from one season to an-

Table 1 – Seasonal descriptive statistical analysis of the study variables for the two cities surveyed, with emphasis on the most relevant values in bold.

Marabá	Average (SD)	Min	P25	P50	P75	Max
Rainy season						
Hospital admissions < 9 years old	32 (15.4)	8.0	18.0	33.0	45.0	61.0
Temperature (°C)	32.4 (0.6)	31.2	32.1	32.6	32.7	33.8
Humidity (%)	80 (2.4)	73.0	79.0	81.0	81	84.0
AOD (550 nm)	0.28 (0.03)	0.24	0.27	0.28	0.29	0.33
Wildfire	0.7 (0.8)	0.0				2.8
Dry season						
Hospital admissions < 9 years old	**33 (11.4)**	15.0	18.0	32.0	**44**	**50.0**
Temperature (°C)	**34.4 (0.7)**	33.3	34.0	34.5	**34.9**	**35.5**
Humidity (%)	**68 (4.2)**	65.0	65.0	67.0	**69.8**	**82.0**
AOD (550 nm)	**0.66 (0.69)**	0.21	0.27	0.35	**0.79**	**2.9**
Wildfire	**188.5 (166.0)**	45.9	155	346	**484**	**475.1**
Santarém						
Rainy season						
Hospital admissions < 9 years old	45.8 (12.1)	19.4	26.0	43.0	57.0	61.4
Temperature (°C)	30.2 (0.4)	29.6	29.9	30.1	30.4	31.2
Humidity (%)	90 (1.0)	89.0	90.0	91.0	91.0	92.0
AOD (550 nm)	0.29 (0.03)	0.25	0.28	0.29	0.31	0.35
Wildfire	6.0 (8.0)	0.0				27.6
Dry season						
Hospital admissions < 9 years old	**49.2 (16.5)**	16.9	29.0	39.0	**53.0**	**78.0**
Temperature (°C)	**32.7 (0.7)**	31.2	32.3	32.5	**32.5**	**34.1**
Humidity (%)	**83 (2.1)**	80.0	81.0	83.0	**84.0**	**88.0**
AOD (550 nm)	**0.47 (0.48)**	0.31	0.32	0.35	**0.39**	**2.39**
Wildfire	**68.7 (25.3)**	8.9	73	87	**114**	**111.0**

SD: standard deviation; P: percentile; MAX: maximum value; MIN: minimum value (2000-2017); AOD: Aerosol Optical Depth.

other (0.38), whereas Santarém experiences a lower variation (0.18). The AOD value is an indication that the local atmosphere is polluted, as it estimates the concentration of aerosols in the atmospheric column by the scattering of solar radiation (Paixão, 2011). Other studies also indicate an increase in both the AOD and wildfires in locations with high atmospheric pollution (Rocha and Yamasoe, 2013).

Regarding temperature and humidity, Marabá presented higher temperatures, mainly during the dry season, with an average of 34.4°C (±0.7), and also presented a less humid atmosphere, with an average of 68% (±4.2) during the dry season, with a 12% amplitude from one season to another. Santarém was more humid, with an average of 83% (±2.1) during the dry season, however, with a much smaller amplitude, only 7%, from one season to another.

The AOD monthly variability shows coherence between Marabá and Santarém with maximum values during dry season fires (Figure 7). Both cities have a higher AOD value in the second semester, every year. Marabá presents the higher magnitude throughout the time series, especially in 2005 and 2015, years in which extreme climate incidents took place, such as the severe and prolonged droughts in the Amazon (Zeng et al., 2008; Jiménez-Muñoz et al., 2016), whereas the AOD value reached 2.0, which is a trace of areas with a higher incidence of fire outbreaks.

Figure 8A shows the relationship between the AOD averages and the number of hospital admissions for respiratory diseases in Marabá during the dry seasons (June-December). In the time-series analysis, there is a noticeable decrease in hospital admissions (i.e., the continuous line) as the AOD value (i.e., dashed line) decreases. From 2010, it is possible to verify that the AOD value falls sharply, reaching the average value of 0.60 nm during the dry season in 2017. These results are consistent with the anomaly values in the time-series analysis in Figure 5, where Marabá (from 2009 to 2010) recorded the values below the average for deforestation and wildfire.

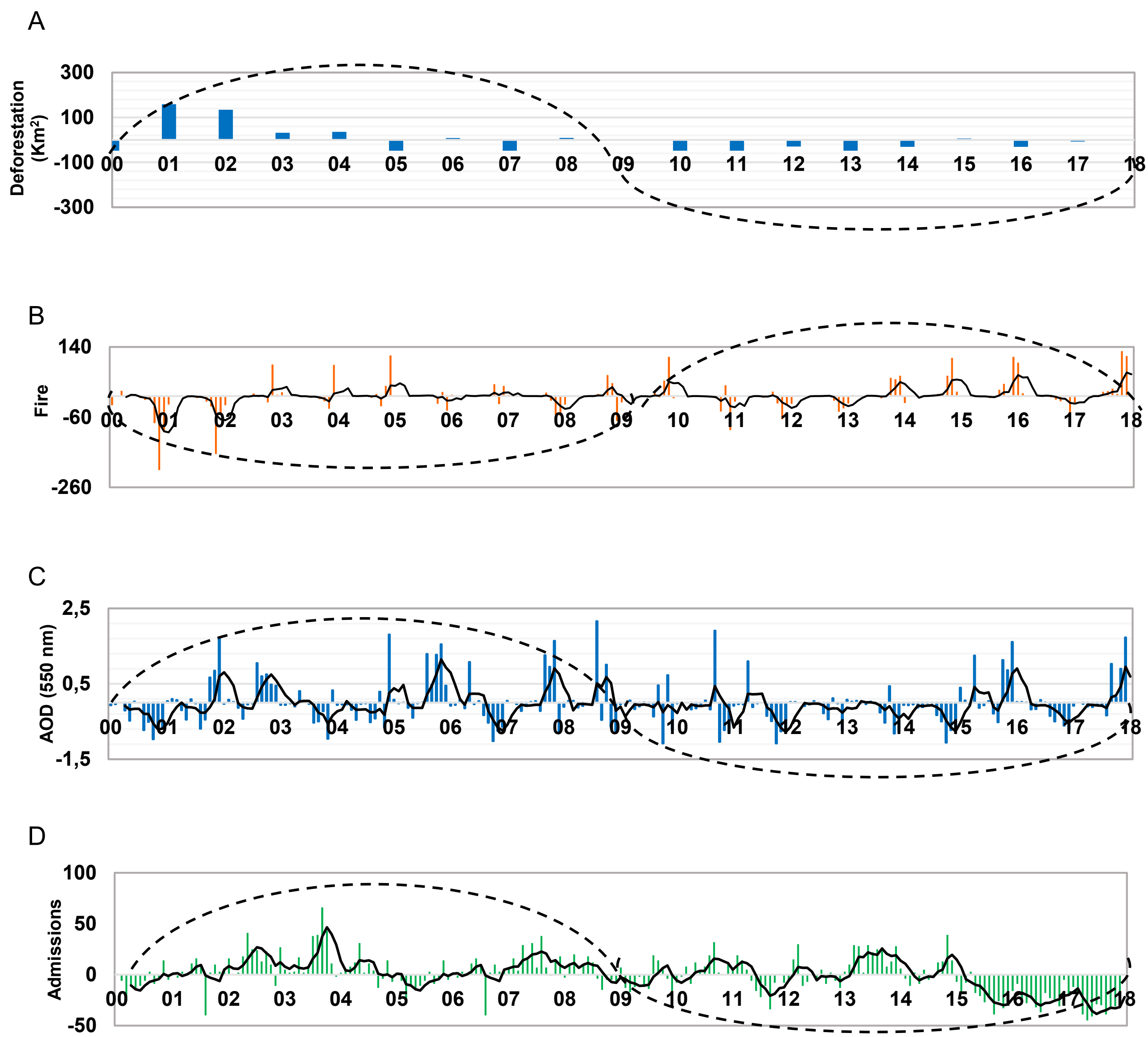

Figure 6 – Distribution of monthly anomalies values for the socio-environmental variables of Santarém from 2000 to 2017: (A) deforestation, (B) fire, (C) AOD, (D) admissions. The dashed line presents the dominant signals for both the positive and the negative phases. The continuous line presents the 6-month moving average.

The linear regression model (Figure 8B) shows a good performance, with a correlation of 64% and confidence interval of 95%, proving that the number of respiratory disease cases in children under 9 years old is dependable on the value of AOD in the atmosphere of Marabá. These results are compatible with those shown by Smith et al. (2014) where they demonstrate the substantial increase in the number of hospitalized children in cities highly exposed to forest fires, located in the Arc of Deforestation, where Marabá is located. According to this study, in 2005, when the Amazon suffered from a severe and prolonged drought, the AOD was responsible for the high incidence of respiratory diseases in Marabá and Santarém. It proves how harmful it is to exposure vulnerable groups to air that has been polluted by wildfire.

Similar to the analysis in Figure 8, Figure 9 shows the average behavior of two variables, namely, AOD and number of hospital admissions in Santarém during the dry seasons of the time-series analysis. Unlike Marabá, the city of Santarém did not present a sharp drop in the number of hospitalizations for respiratory diseases, remaining from 0.80 to 1.40, with similar behavior for the AOD value.

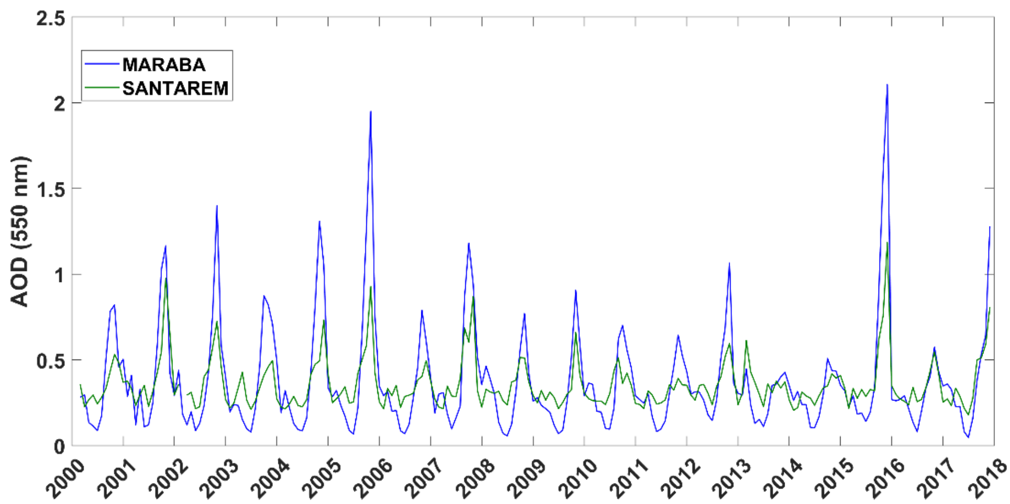

Figure 7 – Variability of monthly values for Aerosol Optical Depth (AOD), based on the MODIS data for Marabá (in blue) and Santarém (in green), from 2000 to 2017.

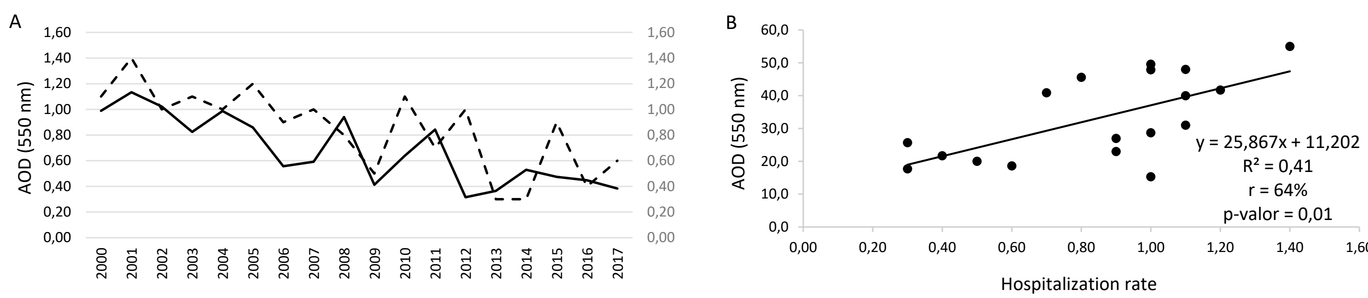

Figure 8 – Correlation between AOD and the number of hospital admissions of children under 9 years of age in Marabá per 1000 inhabitants. (A) Average variability of AOD (dashed line) and the number of hospital admissions (continuous line) during the dry season in every year of the time-series analysis and (B) linear regression model between AOD and hospitalization rate, with $p < 0.05$ for the average during the dry season in every year of the time-series analysis.

However, the linear regression model (Figure 9B) shows a degree of dependence between these two variables, with a 50% statistical correlation and a 95% confidence interval.

The time-series analysis made in Santarém shows how wildfire pollution (embodied in the AOD) can modulate the number of hospital admissions for respiratory diseases. However, despite having a lower annual wildfire rate in comparison with Marabá, the city of Santarém does not show a downward trend for the AOD variability during dry season fires. This can be explained by the increase of pastures in large properties, the deficient structure of land agencies, and the land documentation along highway BR-163 (from the city of Cuiabá to Santarém). This context facilitates the migration of large and medium landowners to the region in search for better work (Coy and Klingler, 2014; Souza et al., 2017), enabling other sources of pollution. The research of Bandeira Castelo et al. (2020) supports these arguments by showing that in over a decade the deforestation has increased in the Lower Amazon region, Western Pará, where Santarém is located. It was considered a very low level and now it is a moderate level of deforestation. This is according to the research carried out within the city itself, with help from INPE and Brazilian Institute of Geography and Statistics (IBGE).

The monthly analysis in Figure 10 shows Marabá as the city that burns the most forest biomass, reaching an average of 10,000 fire outbreaks in September. In general, for the two cities in the time-series analysis, the highest number of fire outbreaks and the maximum AOD value occur in the second semester, i.e., from September to November.

The boxplot statistical analysis shows that Marabá has a higher amplitude of AOD in comparison with Santarém, as evident in the difference between maximum and minimum values (0.5-2.0) for each month, by the interquartile range (box size), and the median value (1.0) in November.

This demonstrates how Marabá presents a higher data variability, while Santarém, in addition to showing less amplitude, also does not reach maximum values comparable to Marabá, for both wildfire and AOD.

In Figure 10, it is possible to observe that the joint analysis of the monthly average of the number of fire outbreaks in association with the AOD shows a time lag between the maximum peaks of wildfire and the AOD. In the case of Marabá, the time lag reaches 2 months, with the highest number of fire outbreaks in September, followed by the highest AOD value in November. Santarém does not present a lag concerning these two variables, with peaks in November of both wildfire and AOD.

The time lag can be explained by the presence of other types of aerosols emitted through the mining process that remain in the atmosphere even after the peak of forest fire in the region of Marabá. This massive presence of ore aerosols in the atmosphere, as presented in Barroso et al. (2021), corroborates the presence of particulate matter in the form of sulfides, sulfates, silicates, and carbonates, all above the

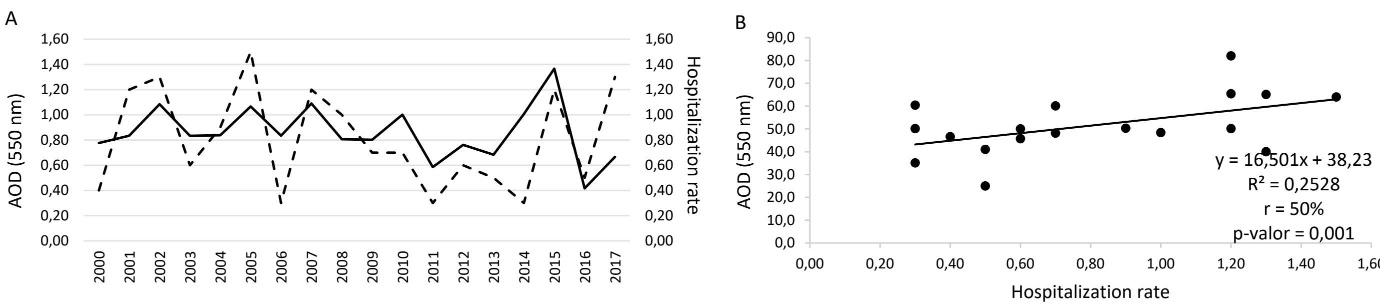

Figure 9 – Correlation between AOD and the number of hospital admissions of children under 9 years of age in Santarém per 1,000 inhabitants. (A) Average variability of AOD (dashed line) and the number of hospital admissions (continuous line) during the dry season in every year of the time-series analysis and (B) linear regression model between AOD and hospitalization rate, with $p < 0.05$ for the average during the dry season in every year of the time-series analysis.

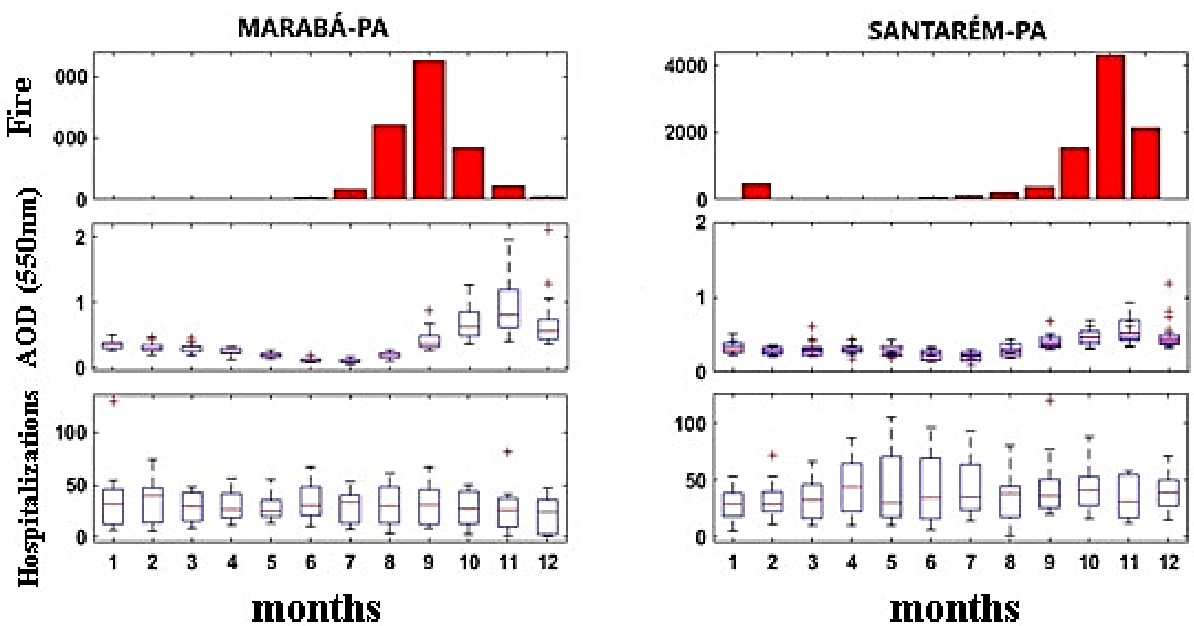

Figure 10 – Statistical information presented by histograms and boxplot of the monthly average of wildfire, AOD, and hospital admissions in Marabá and Santarém from 2000 to 2017.

established guidelines for the regions of intense mining. The authors concluded that there is a strong correlation between the aerosol suspended in the atmosphere and the ore found in the contaminated soil. It is noteworthy that large companies operating in Marabá measure the surface particulate matter, but the results were not provided to assist in this study. Another factor that can contribute to this gap between wildfire peaks and AOD is the transport of aerosols from remote regions with a high incidence of forest fire. In this case, Marabá can suffer the influence of neighboring cities, as confirmed by Nascimento and Medeiros (2012). The study was carried out in the State of Mato Grosso, where large amounts of aerosols can reach kilometers following the wind flow, significantly affecting remote regions, including the number of hospital admissions. However, it is necessary to take into account the maximum number of hospitalizations in Santarém during May, at the end of the rainy season, where there are fewer records of fire outbreaks. The number of hospitalizations can be caused by other factors, such as the climatic conditions that also lead to hospital admission (Andrade Filho et al., 2013; Silva et al., 2013).

Conclusions

The research aimed to demonstrate the importance of environmental protection, considering how locations with very different natural characteristics respond to climatic oscillations and anthropic actions toward the environment.

The decadal analysis of time series indicates the advance of deforestation as the primary cause of forest fire and, consequently, the cause of atmospheric pollution that aggravates the emergence of respiratory diseases.

The climatic oscillations presented by the indices of SOI (the Pacific) and AMM (the Atlantic) modulate the environmental variables that, in turn, modulate social variables, including human health. However, local natural features are essential in this modulation process, as evident in different decadal phase signals between Marabá and Santarém, cities from the regions of different natural features.

It appears that wildfire contributes significantly to increase the number of hospital admissions, as the regression analysis showed a statistically meaningful association between hospitalization rates and the AOD in both cities, but with a stronger correlation in Marabá, above 60%. In other words, during the dry season, the greater the number of fire outbreaks, the greater the number of hospital admission of 9-year-old children for respiratory diseases.

From the two cities in the study, we concluded that Marabá presents the highest number of forest fires, a more polluted and drier atmosphere, and also the highest AOD value, the main indicator of aerosol in the local atmosphere. This consideration is evident through the monthly statistical analysis, although it presents a time lag between the peaks of wildfire and AOD, exposing the presence of other types of aerosols, such as from ore mining, an activity developed by large mining companies operating in the Southeastern region of Pará.

The seasonal analysis with descriptive statistics allows us to state that both Santarém and Marabá show an increase in the number of hospital admissions for respiratory diseases, 3% and 5%, respectively, during the dry season in contrast to the rainy season. In the second semester, this growth occurs in conjunction with the increase in the number of fires and the value of AOD.

This study expresses the importance of government actions to mitigate public health problems and improve the quality of life of its population, facing climate change and the destruction of the forest by illegal deforestation, especially in the Arc of Deforestation in the Legal Amazon, amid a scenario of increased forest fires in the last 2 years and with an increasing trend for the upcoming years.

If synergistic and planned actions are taken to minimize environmental problems, the expenses of health treatment will decrease, especially in the most vulnerable regions. A more in-depth analysis of the $PM_{2.5}$ in the atmosphere of these cities will be presented in an upcoming study.

Contribution of authors:

Moura, M.: Conceptualization, Data curation, Formal analysis, Research, Programs, Visualization, Writing — original draft, Writing — review and editing. Vitorino, I.: Conceptualization, Formal analysis, Research, Methodology, Programs, Supervision, Visualization, Writing — review and editing. Cirino, G.: Conceptualization, Programs, Supervision, Visualization, Writing — review and editing. Andrade, V.: Research, Formal analysis, Writing — review and editing.

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Carbon emissions in hydromorphic soils from an estuarine floodplain forest in the Amazon River

Emissão de carbono de solos hidromórficos em floresta de várzea estuarina do rio Amazonas

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ABSTRACT

Carbon dioxide (CO_2) is produced only in biological activities. Understanding how soil tillage practices affect the dynamics of CO_2 production is important, as these processes are influenced by the temperature and humidity conditions of the place. This paper aimed at quantifying CO_2 flux in hydromorphic floodplain soils under different açai palm tree grove management strategies, correlating it with litter deposition, soil environment, and season of the year. Conducted in the city of Mazagão-AP, four areas of açai palm tree groves were selected with different types of management. During the evaluation period (October, November, and December 2012, and February, March, and April 2013), CO_2 flux, soil moisture, and temperature were measured, and litter samples were collected. In addition, rainfall data for the region were also obtained. The CO_2 fluxes obtained ranged from 0.37 to 28.55 μmol CO_2 m^{-2} s^{-1}, with a total average of 6.20 μmol CO_2 m^{-2} s^{-1}. In broad analysis, soil variables did not show significant correlations with CO_2 emissions. A positive relationship between flux and litter and soil temperature, as well as a negative relationship with its moisture, were observed only in a few months and specific systems.

Keywords: soil respiration; wetlands; Amazon estuary; *Euterpe oleracea* management.

RESUMO

A produção de dióxido de carbono (CO_2) do solo de várzea está relacionada às atividades biológicas, interagindo com sua dinâmica de inundação e manejo. Compreender a forma pela qual práticas de manejo de açaizais afetam as dinâmicas da produção de CO_2 é importante, pois elas podem aumentar a emissão em relação à floresta. O objetivo do trabalho foi quantificar o fluxo de CO_2 do solo hidromórfico de várzea sob diferentes manejos de açaizais, analisando suas relações com a deposição de serapilheira, ambiente do solo e o período do ano. Realizado no município de Mazagão-AP, foram selecionadas quatros áreas de açaizais com diferentes tipos de manejos. Durante o período avaliado (out/2012, nov/2012, dez/2012, fev/2013, mar/2013 e abr/2013), abrangendo períodos sem inundação (verão amazônico) e com inundação (inverno), foram medidos o fluxo de CO_2, umidade e temperatura do solo, e deposição de serapilheira. Além disso, também foram obtidos dados de precipitação da região. O fluxo de CO_2 variou de 0,37 a 28,55 μmol CO_2 m^{-2} s^{-1}, com média de 6,20 μmol CO_2 m^{-2} s^{-1}. No geral, as variáveis do solo não apresentaram correlações significativas com a emissão de CO_2. Apenas em alguns meses e em sistemas específicos, observou-se relação positiva do fluxo com a serapilheira e temperatura do solo e relação negativa com sua umidade.

Palavras-chave: respiração do solo; áreas úmidas; estuário amazônico; manejo de *Euterpe oleracea*.

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Introduction

Global observations recorded by the World Meteorological Organization (WMM) until 2018 show that carbon dioxide concentration (CO_2) in the atmosphere is now 147% higher than in the pre-industrial era. This occurs, mainly, due to emissions from the burning of fossil fuels, deforestation, and other changes in soil management. Radiative forcing of long-lasting greenhouse gases (GHGs) has increased 43%, with 81% of that percentage related to CO_2 (WMO, 2019). It is common sense that greenhouse gases, notably CO_2 and methane (CH_4), are more and more associated with the rising of the Earth's surface temperature and other climate imbalances.

In Brazil, near 74% of GHG emissions occur due to soil management, being 36% in the Amazon (Seeg, 2018), which can release carbon stocks from trees and the land. Forests and forest lands are the primary land sinks for atmospheric carbon (C), that is the reason why vegetation cover may change C stocks, both from arboreal biomass and lands (Gomes, 2014). In the case of floodplains, it is modulated by floods, because in anaerobic environments such as saturated soils exposed to anoxia conditions, CH_4 is also formed, and it is another important GHG occurring during the process of organic matter decomposition (Bartlett et al., 1990).

In the Amazon region, floodable areas are covered with floodplain forests, meadows, *igapós*, and mangroves (Prance, 1980). Floodplains are seasonally inundated by the waters of whitewater rivers with a high load of sedimentary material of Andean and pre-Andean origin (Wittmann et al., 2010). In the Amazon estuarian region, these forests are subjected to a daily cycle of floods and ebbs, due to the effect of oceanic tides (Almeida et al., 2004). In addition to daily variation, tidal cycles also vary depending on the moon and the seasonality of precipitation.

In the first half of the year, when there is greater precipitation (Amazonian winter), the level of the Amazon River rises, increasing the flooding capacity of the forest by its waters dammed by ocean tides. In the second semester (Amazonian summer), precipitation is lower, with the least rainy months being September, October, and November (Souza and Cunha, 2010). During this period, most of the estuarine floodplain area is not flooded, and flooding may occur for a shorter period, only in low floodplains and in large spring tides (Nunes Filho, 2016).

Due to flooding, floodplain environments are considered wet areas that have several peculiar characteristics, such as their floristic diversity. Many species are endemic to this environment and play an important role in balancing the ecosystem and maintaining biodiversity (Lima et al., 2014).

In estuarine floodplain forests, families usually extract natural resources as a livelihood opportunity because several forest species of high economic value are found in these areas. Among these, the açai palm tree (*Euterpe oleraceae* Mart.) stands out. This palm tree provides the heart of palm and açai berries (Almeida and Jardim, 2012; Farias, 2012). In the last three decades, açai palm trees have been standing out for their positive impact on the economy, with the extractive exploitation of palm hearts and, since the 1980s, with the increase in the consumption of açai drink (Azevedo, 2010), named locally as "açai wine". Due to the countless alternative uses of açai, strategies were proposed to maintain the production and sustainability of açai palm tree groves, among them: the establishment of a local production organization and implementation of public policies to aid in the conservation of traditional management practices, among other suggestions (Almeida and Jardim, 2012).

As a result, this drink, which has been consumed as part of the meals of Amazonian populations for centuries, has gained national and international notoriety in recent decades. Thus, riverside populations have been increasingly dedicating themselves to the management of açai palm tree groves, increasing the areas and production, to meet the demand of local, regional, national, and international markets (Oliveira et al., 2017; Tagore, 2017). The production of açai berries in 2018 turned around approximately 600 million Brazilian *reais*, nearly half of the value of all Brazilian extractive production (IBGE, 2019).

The empirical management of açai trees native to the Amazon estuary includes selective thinning of trees and other palm trees, in addition to enriching the area with açai trees to increase the penetration of sunlight and fruit production. The intensity of these interferences depends on the profile of the producers, which can be classified into different categories, from light management, carried out more frequently during the harvest period, to more intensive management, when there is excessive thinning of the forest (Araújo and Navegantes-Alves, 2015).

However, even in the case of light management, these interferences can affect aspects of ecosystem functioning. The thinning and pruning of trees, for example, by introducing organic material into the soil in addition to the natural fall, can influence their biological activity, especially biogeochemical cycling and decomposition of organic matter by edaphic organisms. Thus, depending on the type of management, there may be a greater or lesser CO_2 flux inside the soil, due to root respiration and the activity of organisms that make up the soil (Primavesi, 2002), including, hydromorphic soils.

As the flux of CO_2 from the soil is the result of the interaction of various chemical, physical and biological processes that favor the production and transportation of this gas within the soil, both biotic and abiotic factors can be related to CO_2 flux (Silva et al., 2016), among them, temperature and humidity (Panosso et al., 2008). Regarding humidity, there is an optimal level, which favors the escape of gases. When this limit is exceeded, the water forms a protective layer in the soil, inhibiting the emission of CO_2 into the atmosphere, when the area floods (Sotta et al., 2004).

The exchanges of CO_2 between vegetation and the atmosphere create a balanced system that consists of the difference between the gains and losses of C from biological processes, which are fundamental in the absorption and release of greenhouse gases, such as CO_2 (Heimann and Reichstein, 2008). C balance may be more important than simply quantifying registers, as it is usually done in most works. The recognized lack of studies on carbon dynamics is even more accentuated in floodplain environments in the Amazon estuarine floodplain, especially in areas where açai palm tree groves are managed. Thus, this work aimed to quantify CO_2 flux from lowland soils under managed and unmanaged açai palm tree groves, establishing its relationship with litter deposition, soil environment, and season of the year, due to periods with different flooding capacities of the area by the tide.

Materials and Methods

This study was conducted in açai palm tree groves in an estuarine floodplain forest, in the city of Mazagão, south of the State of Amapá, Brazil, with an area of approximately 1,318,900 ha (00º06'58.62" S and 51º17'20" O). According to Koppen's classification, the climate of the region is classified as Ami, equatorial super-humid (Brasil, 1974; Kottek et al., 2006), with an average annual temperature of 28.3°C and annual rainfall of 2,927 mm per year^{-1}. Rainfall is concentrated from January to June, and the typical dry season is from September to November (Inmet, 2019).

The vegetation is classified as Alluvial Dense Rainforest (IBGE, 2012), with a large number of arboreal individuals belonging to few species and families, with low diversity and high floristic similarity (Carim et al., 2008). The relief is relatively flat, with recessed areas and a shallow water table (IEPA, 2002). The soil is classified as melanic typic eutrophic gleysol Ta with texture, predominantly silty, and with high fertility (Pinto, 2014).

Floodplain forests are energetically open ecosystems, associated with the tidal regime of the whitewater river, in addition to presenting topographical differences as it is distanced from the main riverbank (Freitas, 2019). The interior of the forest is flooded daily, ranging from a high tide (high tide — maximum level reached by river waters) to a low tide (low tide — minimum level reached by river waters), because the waters of the Amazon River and its tributaries are dammed by the waters of the Atlantic Ocean (Nunes Filho, 2016). The phases of the moon (new and full moon) and the rainfall also increase the volume of the Amazon River, causing the water level in its channels to raise, overflowing the main river and flooding the entire forest (Pinto, 2014; Nunes Filho, 2016).

To quantify carbon dioxide flux from the soil, four areas of açai palm tree groves were selected:

- SYSTEM 1: native açai palm tree grove, without any type of management;
- SYSTEM 2: açai palm tree grove with traditional management, as performed by agricultural extractivists;
- SYSTEM 3: açai palm tree monoculture at Embrapa Amapá;
- SYSTEM 4: native açai palm tree grove, located close to the monoculture.

Systems 1 and 2 were located in the district of Mazagão Velho, and systems 3 and 4 were located near the city of Mazagão Novo. In each location, one managed and one reference açai palm tree grove located in an unmanaged forest were assessed.

The four açai palm tree grove systems were selected based on the following criteria:

- the açai palm tree grove had to be flooded during high tide;
- the number of clumps of açai trees had to be greater than the average of the forest;
- it had to be close to the managed areas for better comparison.

For each açai palm tree grove, an area of 50 m × 50 m was segregated and subdivided into four quadrants of 25 m × 25 m. In each quadrant, four sampling points were allocated, equidistant 12.5 m from each other, making up 16 collection points per area (Figure 1).

CO_2 flux measurements were performed monthly, from October to December 2012, and from February to April 2013, except for January, when no evaluation was performed for being the transition period between the two evaluating periods:

- the period with lower precipitation and flooding of the areas (late Amazonian summer);
- the three months of greatest rainfall (peak of the Amazonian winter).

An EGM-4 infrared gas analyzer (PP Systems, Environment Gas) coupled to a closed-circuit chamber was used. A small part of the cutting ring of the air retention chamber was inserted 1 cm into the ground, without removing the litter to cause minimal impact on the soil and rhizosphere, so that there would be no gas exchange between the sampled volume inside the chamber and the surrounding atmosphere. The chamber was left for 5 minutes at each point, according to the methodology used by Sotta et al. (2006). Measurements were taken between 9 a.m. and 3 p.m.

At each point, in addition to CO_2 flux, the following measurements were also taken: soil temperature, recorded in degrees Celsius at 5 cm depth, obtained with the aid of the STP-1 (Soil Temperature Probe)

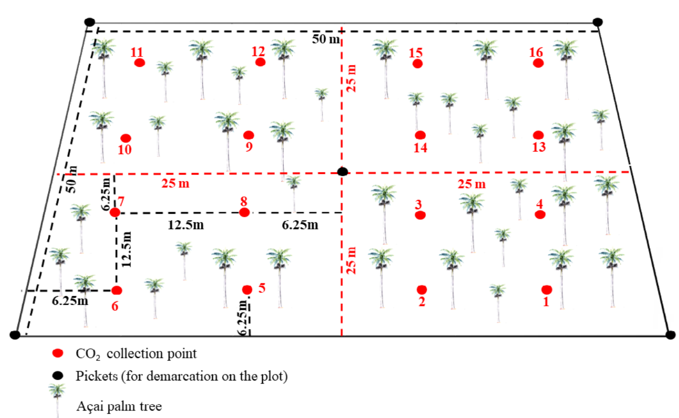

Figure 1 – Schematic drawing of the sampling design of the açai area, divided into four quadrants and their respective collection points.

sensor coupled to EGM-4; and soil moisture, obtained through a portable HH2 sensor — Moisture Meter, using Delta-T soil moisture sensors.

Rainfall data were obtained from the conventional meteorological station of Macapá (AP), located approximately 41 km from the city of Mazagão (AP).

To verify if there was any variation in the soil due to the types of açai palm tree grove management, soil and litter samples were collected. The litter was collected monthly, at the same evaluation points, after measuring the CO_2 flux. To collect the litter, a cylindrical iron collector with a cutting edge and an area of 0.13 m² was used. Subsequently, the samples were sent to Embrapa Amapá's laboratory, where they were placed in a forced circulation oven, at 65°C, until they showed constant weight. Monitoring was carried out with two daily weighing sessions, removing the samples from the oven and weighing each sample at once. After stabilization and three weighing sessions with no weight reduction, data from the last evaluation were entered in a spreadsheet as dry biomass until constant weight.

Soil samples were collected in October 2012 and April 2013, the first and last months of evaluation, which represent the Amazonian summer and winter, respectively. To assess physical soil properties, 16 soil samples (undisturbed) were collected per plot, using a 98 cm³ metallic ring attached to an auger. To assess the chemical properties and texture of the soil, five simple soil subsamples (deformed) were collected per quadrant, with the aid of a Dutch auger at a depth of 0.10 cm. The samples were homogenized, forming one composed sample per quadrant, totaling 4 composed samples per plot. All analyses were carried out in the Soil Laboratory of Embrapa AP, according to Embrapa's methodology (2011).

In the different management systems, typical hydromorphic soil characteristics are predominant in the Amazon estuary, with silty loam texture, a high number of exchangeable bases, and medium to high levels of organic matter. They are eutrophic soils, with base saturation above 50%, and high fertility (Table 1).

Data were analyzed using descriptive statistics, homoscedasticity tests, and normality of residuals. The relationships between the CO_2 flux and the litter deposited in each type of açai palm tree grove, as well as soil moisture and temperature, were analyzed using Spearman's correlation. To assess whether CO_2 flux is altered by the management of native açai palm trees and whether the response depends on the variation over the months, a multiple analysis of variance (Shapiro-Wilk test) was performed with repeated measurements over time. A posteriori statistical analysis, to isolate the effects between the levels of the factors, was performed by comparing the confidence intervals generated with 95% certainty. All statistical analyses were performed using Statistica 7.0 trial version software (Statsoft, 2011).

Results and Discussion

The emission of CO_2 in the hydromorphic soils of floodplain forests, in the studied açai palm tree groves, ranged from 0.37 to 28.55 µmol CO_2 m^{-2} s^{-1}, with an average of 6.20 µmol CO_2 m^{-2} s^{-1}. The temperature of these soils also varied, with a minimum of 25.2°C, a maximum of 30.5 °C, and an average of 27.2°C. The average soil moisture was 39.8% and the average amount of the litter pool was 49.52 g m² (Table 2).

Table 1 – Average of soil properties, at 10 cm depth, in the four açai palm tree grove management systems (S), in a lowland estuarine forest in the city of Mazagão (AP).

Soil Properties	S1	S2	S3	S4
pH	5.8	5.8	5.6	5.8
MO (g kg^{-1})	51.6	42.4	44	35.7
P (mg dm^{-3})	19.1	14.7	6.1	18.4
K ($cmol_c$ dm^{-3})	0.2	0.2	0.2	0.4
Ca+Mg ($cmol_c$ dm^{-3})	13.4	13.6	12.2	11.2
Ca ($cmol_c$ dm^{-3})	10.6	10.3	9.15	8.15
Al ($cmol_c$ dm^{-3})	0.1	0.1	0.3	0.1
H+Al ($cmol_c$ dm^{-3})	4.6	4.7	6.8	5.5
SB ($cmol_c$ dm^{-3})	13.6	13.8	12.4	11.6
CTC ($cmol_c$ dm^{-3})	18.3	18.5	19.1	17.2
V (%)	74.9	74.7	64.9	68
M (%)	1	1	2.3	1.5
Clay (g kg^{-1})	210.4	232.1	208.5	192.5
Total Sand (g kg^{-1})	69.5	62.6	116.2	79.4
Silt (g kg^{-1})	720.1	705.2	675.2	738.1
DA (g cm^{-3})	0.8	0.8	0.8	0.8
DP (g cm^{-3})	2.3	2.4	2.5	2.5
Porosity (%)	60.7	64.7	66	68.5
Moisture (%)	61.6	62.3	55.2	66

pH: hydrogen potential; MO: organic matter; P: phosphorus; K: potassium; Ca+Mg: calcium and magnesium; Ca: calcium; Al: aluminum; H+Al: exchangeable acidity; SB: base sum; CTC: cation exchange capacity; V: base saturation; M: aluminum saturation; DA: apparent density; DP: particle density. S1 and S4 Systems (açai palm tree groves in the forest, no management), S2 (traditional management), S3 (monoculture).

In general, the average CO_2 flux found in this study was higher than the average found in studies on tropical forests in the Amazon, in dryland environments (Pinto-Júnior et al., 2009; Silva Júnior et al., 2013), being the same as the average found by Teles (2018) in the Central Amazon only. For the floodplain environment, studies on CO_2 emission are incipient, but other authors have concluded that hydromorphic soils have greater microbial activity than drained soils (Acosta et al., 2019). This was also verified in a laboratory experiment when soils that were irrigated up to field capacity (100%) and those that were flooded and kept under flooding, with a water depth of 2 cm above the ground, were observed to be the ones with the highest accumulation of CO_2 emission in 64 days (Denardin et al.,

Table 2 – General descriptive statistics (n = 384) of carbon flux and soil variables in an estuarine floodplain forest with açai palm tree groves in the city of Mazagão (AP), after monthly measurements from October 2012 to April 2013.

Parameters	CO_2 Flux (µmol m^{-2} s^{-1})	Temperature (°C)	Moisture (%)	Litter (g m^{-2})
Minimum	0.37	25.2	8.8	5.23
Maximum	28.55	30.5	85.3	304.80
Average	6.20	27.2	39.8	49.52
Median	5.30	27.2	42.0	35.01
Variance	13. 22	1.36	260.6	1,813.36
Asymmetry	2.24	0.23	-0.03	2.37

2020). Therefore, a possible explanation is the increased respiration of microorganisms associated with high moisture levels and flooding of the soil in the floodplain environment.

Additionally, the higher fertility and lower acidity of the soils in the studied açai palm tree groves (Table 1), compared to dryland soils in the Amazon, usually with lower pH values (Worbes, 1997), may also help explain the higher CO_2 flux averages in the floodplain. It has been proven that high active acidity conditions and low pH contribute to reduced microorganism activity (Silva et al., 2014; Alves and Martins, 2015).

Another factor that must also be considered to explain a high flux of CO_2 in the floodplain is its phytosociology, with a greater abundance of palm trees (Almeida et al., 2004; Jardim et al., 2007; Carim et al., 2008; Souza and Jardim, 2015) compared to dryland forests. Palm trees, like grasses, have a fasciculate root system, with greater production of fine roots that are metabolically more active, which can lead to higher CO_2 emissions (Hanson et al., 2000; Konda et al., 2010).

In general, when analyzing all data from the systems collectively, there were no significant correlations between the CO_2 flux and the environmental variables analyzed. In the case of soil temperature, the low variability between areas over time may explain the absence of correlations. In the case of soil moisture and the amount of litter, factors for which a greater association would be expected, the lack of a general correlation indicates that this may depend on the period in which the areas are flooded and on the specific interactions of the factors with each system. Thus, it is likely that the variables that determine CO_2 emissions from the soil in these açai palm tree groves are associated with the different characteristics of the local vegetation and the internal spatial variability of each system. It has already been demonstrated that CO_2 emissions in native forests are complex phenomena, and it is not possible to identify a single attribute of the soil or the environment that would explain, in isolation, its variation in space (D'Andrea et al., 2010).

The multiple analysis of variance of the responses (CO_2, litter, humidity, and temperature), evaluated between the levels of management systems of the açai palm tree groves with repeated measurement over time, showed a significant response (Wilks = 0.002; F = 13.9; $p < 0.001$). This indicates significant differences between the management systems, of the means of at least one of the evaluated responses. When analyzing only the main response of interest in this paper, which is the emission of CO_2, it appears that the interaction between types of management and the temporal variation over the months of data collection was also significant (F = 4.430, $p < 0.001$). However, the comparison between management systems, considering the average of total CO_2 flux over all the monitoring months, was not significant (F = 1.241, p = 0.303). So, this variable will be analyzed later, considering the interactions with each management system.

On the other hand, the variation in CO_2 flux over the months of data collection, the average of all areas for each evaluation, was significant (F = 3.054, p = 0.010). This can be seen in Figure 2, mainly between November (5.12 µmol CO_2 m^{-2} s^{-1}) and December (7.18 µmol CO_2 m^{-2} s^{-1}). It appears that, even with a high variation between the averages, there are excluding confidence intervals that do not capture other averages, which ensures significant differences in CO_2 emissions between months.

The lower CO_2 emission in November may be related to the lower precipitation in this month and the previous one, with precipitation below 20 mm, resulting in lower soil moisture in November and lower river levels. However, in October, soil moisture was higher, even with less rainfall than in November (Table 3), which may be a result of accumulated rainfall in September and/or flooding of the areas by a tide before measurement. During this period, the areas are only flooded in the high tides.

Even though it is a typical Amazonian summer month, also with little rainfall, October had a greater emission of CO_2 from the soil than November. This was probably due to rainfall that occurred at the beginning of the second fortnight, a period close to the fortnight period of measurement. Although rainfall was low [9.6 mm] (Inmet, 2012), it was enough to generate greater soil moisture compared to November, when rainfall was concentrated in the last two days of the month, after the evaluations were carried out.

December had the maximum value of CO_2 flux, both in terms of average values (7.18 µmol CO_2 m^{-2} s^{-1}) and absolute values, which can be explained by constant rainfall in the beginning, with an increase of 329 mm per month, providing an immediate stimulus to soil decomposing microorganisms as a response to increased water availability. After a dry period, the first rainfall and the accumulation of a greater amount of organic matter in the soil favor an increase in CO_2 flux (Nunes, 2003), in addition to filling the soil pores with water, expelling CO_2 (Zanchi et al., 2003). This variation in CO_2 flux according to seasonality is mainly due to rainfall patterns and water potential between the soil and the atmosphere (Salimon, 2003). The highest CO_2 fluxes in the rainy season, regardless of the system, corroborate other studies carried out in the Amazon (Dias, 2006; Silva Júnior, 2008; Zanchi et al., 2012; Oliveira, 2014; Lessa, 2016).

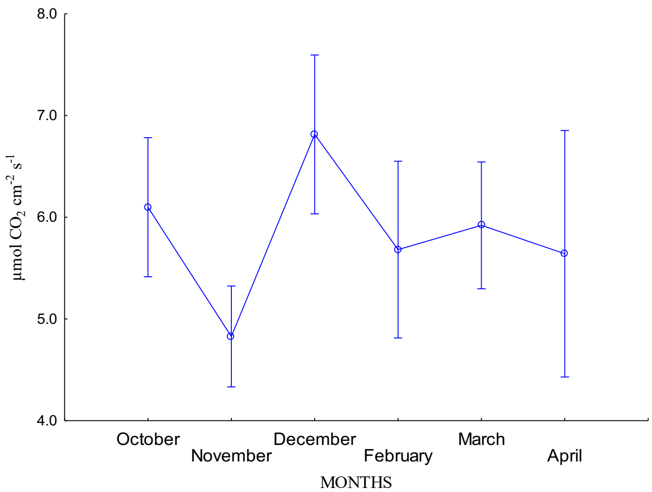

Figure 2 – The average flux of CO_2 from the soil (with a 95% confidence interval — CI), considering all the different management systems of açai palm tree groves, depending on the months of evaluation (Oct/2012, Nov/2012, Dec/2012, Feb/2013, Mar/2013, and Apr/2013), in an estuarine floodplain forest in the city of Mazagão (AP).

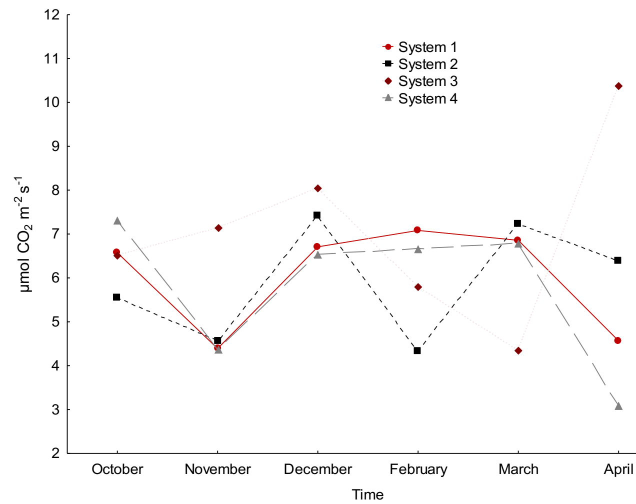

Figure 3 – Average monthly flux of CO_2 from the soil, from October 2012 to April 2013, as a result of the type of açai palm tree grove management in an estuarine floodplain forest in Mazagão (AP). Systems 1 and 4 (açai palm tree groves in the forest, no management), 2 (traditional management), 3 (monoculture).

Table 3 – Total monthly precipitation values and average soil moisture and temperature values over the months of study conduction on CO_2 emission in an estuarine floodplain forest in the city of Mazagão (AP).

Months	Precipitation (mm)	Soil moisture (%)	Soil temperature (°C)
October	9.6	26.7	26.7
November	16.4	17.9	28.1
December	111.2	38.6	28.5
January	328.8	---	---
February	427.4	46.9	25.8
March	387.7	53.3	27.8
April	516.5	55.3	27.0

Source: Inmet (2012) and elaborated by the authors.

The significant interaction between types of management and temporal variation shows that differences in average CO_2 emissions between the systems depend on the period analyzed and vice versa. Thus, it is important to analyze the behavior of each of the systems throughout the entire collection period, as shown in Figure 3. It is verified that the two reference açai palm tree groves, System 1 and System 4, located in an unmanaged forest, had a unique pattern of variation over time despite being located in different spots. There were lower emissions in November and April, and December to March had values of approximately 7 µmol CO_2 m^{-2} s^{-1}. This is consistent with the seasonal variation expected for natural systems in estuarine floodplains due to extreme periods of lower (November) and higher (April) flooding capacity of the forests by river waters dammed by ocean tides (Nunes Filho, 2016).

Although soil moisture and periodic flooding favor microbial activity and, consequently, CO_2 emission (Denardin et al., 2020), in longer periods of flooding, such as in April and May, this relationship can become negative due to a long anoxia time without soil aeration. Sotta et al. (2004) state that the formation of a water layer on the ground for a long period prevents the emission of CO_2 into the atmosphere when the area is flooded.

On the other hand, the managed systems showed different and divergent behaviors over time, justifying the significance of the interaction between the factors. Considering the interactions and differences between the management systems in each month and the differences between the months within each management system, CO_2 emissions in the area traditionally managed by riverside communities were observed, in general, to replicate the trends of unmanaged forests. A divergence was only found in February, when there was a greater reduction in this system.

The monoculture of açai trees was the system that showed the greatest divergence and variation. In November, when all the other systems presented similar and low values, the highest CO_2 emissions were observed in the monoculture, and in March it was the opposite (Figures 4A and 4B).

In April, when there was a reduction in the other systems, the açai palm tree monoculture area showed a marked increase, reaching the maximum mean value observed during the entire monitoring period, above 10 µmol CO_2 m^{-2} s^{-1} (Figure 3). This high average is the result of five measurements (out of the 16 measurements performed in this system in April) above that value, with some measurements close to 20 µmol CO_2 m^{-2} s^{-1}.

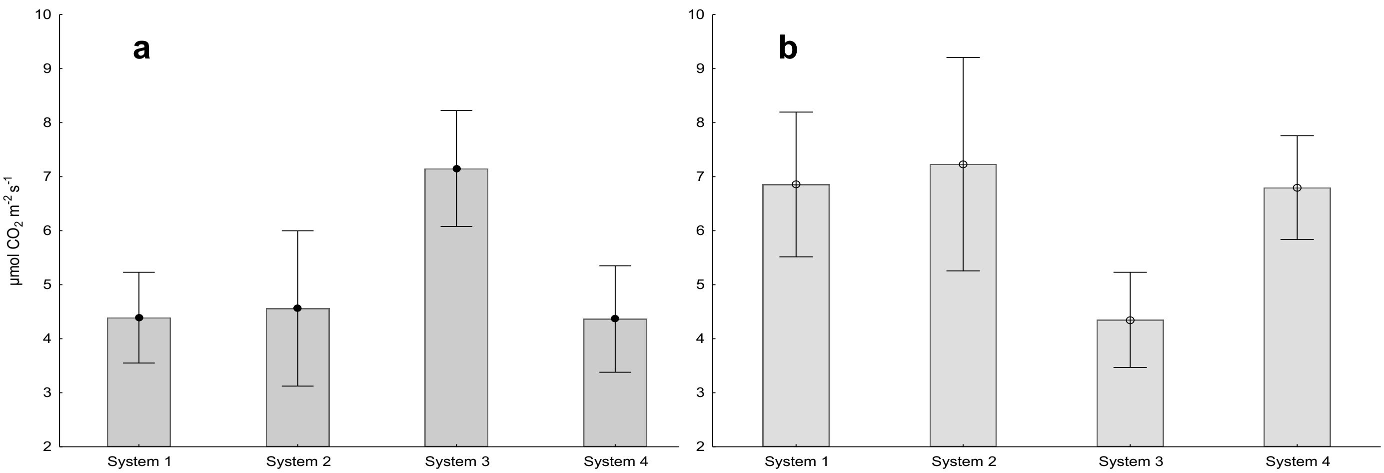

Figure 4 – Average soil CO_2 flux (confidence interval - 95% CI) as a function of the açai palm tree grove management system, in the months of (A) November and (B) March, in an estuarine floodplain forest in the city of Mazagão (AP). Systems 1 and 4 (açai palm tree groves in the forest, no management), 2 (traditional management), 3 (monoculture).

The greatest significant difference ($p = 0.005$) observed between the systems occurred in April, with greater emissions in System 3 when compared to System 4. This maximum CO_2 value, found in the açai palm tree grove of System 3, must be related to the tidal flood (Table 4), which started at the time of flux measurement, causing the CO_2 present in the soil to be released into the atmosphere (diffusion process) by the entry of water into the soil.

Sotta et al. (2004) state that water in the soil is an important controller of CO_2 flux. Zanchi et al. (2003) claim that after a rainfall event, water fills the pores, forcing the emission of CO_2. Vincent et al. (2006) elucidate that if the soil has a moisture content above 40%, there is CO_2 emission due to excess water and lack of oxygen in the soil. But this increase in CO_2 emission occurs as soon as the pores are filled with water. Over time, it is expected that the flux will decrease considerably since most of the microorganisms that are most efficient in decomposing the organic matter found in the soil are aerobic. With the flooding of the area and the formation of an environment with anoxia, without oxygen availability, the aerobic microbial activity decreases, as already verified by Pinto-Júnior et al. (2009), who found a reduction in the average CO_2 flux in the rainy season due to the effect of pore saturation with water and reduced aerobic activity.

The absence of forest and understory in this monoculture system, which is always kept clean with frequent weeding and cleaning, facilitates the inflow and outflow of water from the area when tidal flooding occurs, also facilitating the loss of moisture through evaporation. This probably also contributes to less accumulation of litter and sediment, which are carried away by the tides that invade the area, in addition to determining the existence of a lower abundance of fine roots. The homogeneity and low contribution of litter in the soil, due to the presence in the area of açai trees only, also reduce the contribution of biogeochemical nutrient recycling. In general, monocultures and poorly diversified systems can reduce environmental quality (Silva et al., 2016).

All of these factors affect root respiration and the role of microorganisms in the process of soil decomposition and mineralization, and, consequently, may be associated with a variation in the emission of CO_2 into the atmosphere, as well as the saturation of water in the soil during periods of flooding. Therefore, simplifying systems in monocultures of açai palm trees can contribute to their greater susceptibility to environmental variations and, consequently, variability in CO_2 measurements over time.

Forest systems have a denser and more heterogeneous litter on the soil surface due to the high presence of arboreal species, in addition to açai trees and other palms, such as *murumuru* (*Astrocaryum murumuru*), in its floristic composition. This also favors the greater contribution of roots, activity, and diversity of microorganisms found in the soil. Systems that have species diversity in space and time enhance the physical structure and chemical composition of the soil, improving energy and the amount of matter retained in the form of organic compounds and edaphic biota, enabling the soil to exercise its functions in nature (Vezzani and Mielniczuk, 2009).

Analyzing the relationships between the variables for each month, there is a negative relationship between CO_2 emission and soil moisture in October ($r = - 0.83$; $p < 0.05$) and November ($r = - 0.59$; $p < 0.05$), these months have lower soil moisture and low precipitation when areas are only flooded sporadically. Lowland silty soil is rich in 2:1 clay minerals, such as smectite and illite, favoring contraction movements during the wetting and drying cycles (Pinto, 2014). All these dynamics can cause cracks and the physical release of CO_2 through the diffusion process (Guedes, 2007).

Analyzing each system separately, it was possible to verify that in the unmanaged forest, there was a positive correlation between tem-

Table 4 – Time of measurements for Systems 3 (monoculture) and 4 (açai palm tree grove in an unmanaged forest) concerning the tidal dynamics in April, on 04.05.2012, based on the tide table at Port of Santana, Amapá.

Tidal range (m)	Tide times	CO_2 efflux measurement points	System 3		Sistema 4	
			Measurement time	Efflux CO_2 (μmol CO_2 m^{-2} s^{-1})	Measurement time	Efflux CO_2 (μmol CO_2 m^{-2} s^{-1})
0.4	07:04	1	10:36	5.10	08:21	3.09
2.9	12:04	2	10:42	2.95	08:26	3.10
0.5	19:36	3	10:48	2.52	08:32	5.71
		4	10:53	3.68	08:38	5.19
		5	11:00	3.90	08:44	2.51
		6	11:06	20.99	08:50	4.37
		7	11:12	7.02	08:55	4.29
		8	11:17	4.98	09:02	1.49
		9	11:22	4.43	09:09	1.69
		10	11:26	4.50	09:15	1.85
		11	11:33	2.56	09:22	2.09
		12	11:39	28.55	09:27	2.14
		13	11:44	26.60	09:35	3.80
		14	11:51	18.30	09:40	3.13
		15	11:57	10.46	09:47	3.51
		16	12:07	19.77	09:53	1.50

perature and CO_2 flux in December, both for System 1 ($r = 0.71$; $p < 0.05$) and for System 4 ($r = 0.91$; $p < 0.05$). This may be an indication that increased rainfall in December (Table 3) activated the microbial community and the decomposition of organic matter in these systems, contributing to higher CO_2 emissions, since microbial activity in the soil releases heat and can contribute to an increase in its temperature (Xavier et al., 2006; Karhu et al., 2014).

Conclusions

In general, the hydromorphic soils of estuarine floodplains with the presence of açai palm trees indicate high levels of CO_2 emissions. Those under monoculture show a high variation in the emission rate when compared to systems where other forest species are found.

There is a variation in CO_2 flux over the evaluation period, with increased emissions at the beginning of the rainy season and a rise in the water table during floods. There is no correlation between CO_2 emission and litter, but in specific situations, there are positive relationships with soil temperature and negative relationships with soil moisture, in the period of less rainfall during the Amazonian summer.

Further studies aiming at analyzing variations in GHG fluxes in estuarine floodplains are recommended, which should focus on physical processes (gas diffusion), as these may be more relevant than chemical or biological soil processes.

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Contribution of authors:

Lira-Guedes, A.C.: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing; Leal, G.A.: Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Fischer, G.R.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Aguiar, L.J.G.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Melém Júnior, N.J.: Conceptualization, Investigation, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing; Baia, A.L.P.: Investigation, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Guedes, M.C.: Conceptualization, Funding, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing.

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Contributions to improve sustainability conditions in gemstone-benefiting companies

Contribuições para melhoria das condições de sustentabilidade em empresas beneficiadoras de gemas

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ABSTRACT

The gemstones and jewels production chain have been an important source of income and job creation in several regions of Brazil. However, sometimes, its activities haven't been developed in an environmentally correct and sustainable context. In this sense, this work seeks to investigate indicators, to propose a framework of indicators to evaluate and monitor the sustainability conditions of companies that process gemstones. Therefore, a proposal was prepared considering the specificities of the sector, containing 10 indicators and 24 variables distributed in the environmental, economic, social, and technological dimensions. The proposal was verified empirically with a company, a case study, located in Teutônia/RS, which presents the main characteristics of the companies belonging to the sector. The use of the framework of indicators provided information on the company's sustainability conditions, identifying positive aspects and also those that need to be improved to assist in the search for a more sustainable management of activities. On the other hand, the results achieved present information that can serve as a reference for comparison with other companies in the sector, as well as assist in the decision-making process in search of more sustainable conditions.

Keywords: indicators; sustainability; gemstone benefiting companies.

RESUMO

A cadeia produtiva de gemas e joias tem sido uma importante fonte de divisas e de geração de empregos em diversas regiões do Brasil. No entanto, por vezes, suas atividades não têm sido desenvolvidas em um contexto ambientalmente correto e sustentável. Nesse sentido, este trabalho busca investigar indicadores, com a finalidade de propor um quadro de indicadores para avaliar e monitorar as condições de sustentabilidade das empresas beneficiadoras de gemas. Para tanto, foi elaborada uma proposta considerando as especificidades do setor, contendo 10 indicadores e 24 variáveis distribuídos nas dimensões ambiental, econômica, social e tecnológica. A proposta foi verificada empiricamente junto a uma empresa: um estudo de caso, localizada em Teutônia/RS, que apresenta as principais características das empresas pertencentes ao setor. A utilização do quadro de indicadores forneceu informações sobre as condições de sustentabilidade da empresa, identificando aspectos positivos e também os que necessitam ser melhorados para auxiliar na busca de uma gestão mais sustentável das atividades. Por outro lado, os resultados alcançados apresentam informações que podem servir de referência para fins de comparação com outras empresas do setor, assim como auxiliar no processo de tomada de decisão em busca de condições mais sustentáveis.

Palavras-chave: indicadores; sustentabilidade; empresas beneficiadoras de gemas.

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Introduction

In many countries, especially developing ones, mining is a sector with a significant share of the economy (Ranängen and Lindman, 2017), as a source of income, employment, and inputs to other industries (Azapagic, 2004; UN, 2016). Among the different minerals that can be extracted from nature, there is the mining of precious stones, including diamonds, emeralds, and garnets (Hentschel et al., 2003) and given these characteristics, the factors that interfere in mining activities depend on where they are carried out (Ranängen and Lindman, 2017).

Despite its economic importance, there are only few studies that discuss the economic, social, and environmental aspects of gem production (Oliveira and Ali, 2011) and it becomes relevant due to the non-renewable nature of most mineral resources and its ability to generate a series of environmental and social impacts that affect regions negatively (Falck and Spangenberg, 2014; Lodhia and Martin, 2014). This way, the maintenance of the activity is necessary, but must be carried out in a more sustainable context so that it is less harmful to the environment in which it is inserted.

In this context, Brazil stands out for the variety of gems found in its territory, since it has one of the largest gemological provinces in the world. Estimates indicate that the country is responsible for one third of the world's production of gems, except for the production of diamonds, rubies, and sapphires (Barreto and Bittar, 2010).

In the state of Rio Grande do Sul, where this work was developed, the main product in terms of exported value refers to precious (except diamond) or semi-precious stones (COMEX STAT, 2021). According to Barreto and Bittar (2010), the state is the largest producer of uncut colored gemstones in Brazil and one of the main producers of agate and amethyst. Activities of extraction, manufacture of artifacts, and processing of gems (polishing, hammering, dyeing, cutting, among others) are generally carried out by small companies, which need to make improvements in the production processes and investments in technologies, seeking improvements in the flow of materials, in the reduction of losses, and in the management of the environmental liabilities resulting from the activity, in order to achieve more sustainable conditions. According to Brasil (2021), companies in the segment had an average of 10 formal workers in 2019, demonstrating that most activities were carried out in small companies (a reality that has not changed much in the last decade, since it maintained the average number of workers of 2009).

These companies face problems and conditions similar to other small-scale mining activities, such as the use of rudimentary methods, manual and low-level technology (Massaro and Treije, 2018), poor qualification of the workforce and informality (Zvarivadza and Nhleko, 2018), inefficiency for adding value, low level of productivity, limited use of mechanization, lack of investments, extraction of minerals in unauthorized deposits, among others (Hentschel et al., 2003; Oliveira and Ali, 2011).

To soften this situation, companies belonging to the gem processing sector need to adopt different actions that help to face these difficulties, like the use of sustainability indicators, which serve to monitor the development of their activities and, thus, contribute to the achievement of more sustainable conditions.

In literature, it is possible to observe several initiatives to propose general indicators for industries (Azapagic and Perdan, 2000), manufactures (Lee and Lee, 2014), and micro and small companies (MSC) (Chen et al., 2014). However, due to the specificities of different sectors and organizations, the use of standardized methodologies is not always efficient. According to Chen et al. (2014), there are still few tools easily applicable for MSC to assess sustainability. Therefore, the development of initiatives of proposals of indicators for these companies in specific sectors (Chen et al., 2012; Joung et al., 2013) has been observed. In addition, Ranängen and Lindman (2017) argue that, although mining sustainability is on the global agenda, the criteria to be prioritized depend on the regions where it is developed.

Based on the above, the scope of this study is defined as the investigation of indicators, with the purpose of proposing a framework to assess and monitor the sustainability conditions of gemstone processing companies, taking into account their characteristics.

Sustainability indicators

In the literature, there are different functions and definitions for sustainability indicators, such as:

- providing information to decision makers on the global level of sustainability of a system and contributing to the elaboration of strategies in pursuit of this objective (UN, 2007);
- providing information to facilitate the understanding and communication of complex systems (Falck and Spangenberg, 2014);
- making a problem visible (Dahl, 2012);
- assisting in the selection of the best alternative and contributing to the identification of the causes of unsustainability (Callens and Tyteca, 1999);
- allowing the elaboration of more sustainable development strategies (Azapagic and Perdan, 2000), among others.

To Joung et al. (2013), a set of indicators, through the combination of environmental, economic and social indicators, guarantee a holistic view of sustainability, as they assess reality from a larger scale than that of individual indicators. They can also be used to compare the situation at a given moment and the desired situation (where it is intended to go), showing the extent to which sustainability objectives are being met (Ragas et al., 1995).

Unlike other indicators, sustainability indicators are differentiated by the obligation to measure the capacity of a system to adapt to changes over a period of time and continue to operate, that is, sustainability indicators must contribute so that a system maintains its state or function over time, and it is therefore essential to consider antecedents that also explain the system's resilience (Milman and Short, 2008).

Resilience is generally understood as the adaptive capacity of a system (Folke, 2006), being initially considered only from an environmental-ecological perspective (Xu et al., 2015). However, considering that impacts are caused by productive activities and human interactions, it is also essential to assess resilience in the social dimensions, considering their ability to access critical resources (Langridge et al., 2006), including water, land, finance, and human skills, and economics, associated with the ability to withstand market shocks and allocate resources efficiently (Perrings, 2006).

Initiatives for building sustainability indicators applied to companies were led by the Global Reporting Initiative (GRI), which seeks to motivate organizations to adopt more sustainable practices through the use of sustainability reports and, thus, contribute to sustainable development (GRI, 2013). Other proposals for evaluating the performance of companies in reaching these goals are proposed by the Organization for Economic Co-Operation and Development (OECD, 2003) and by the World Business Council for Sustainable Development (Verfaillie and Bidwell, 2000). Chen et al. (2014) also highlight that there are a variety of methods and tools available in the literature that contribute to the development of indicators at different levels and dimensions.

However, although these proposed sustainability reports are developed for organizations in general, regardless of their size, sector or location, they do not provide a universal framework of indicators that can be used indiscriminately by everyone (Segnestam, 2002), nor they indicate sufficient conditions for sustainable development, as there are no reference values (Callens and Tyteca, 1999), especially for MSC due to the type and amount of information requested.

For this reason, it is possible to observe the development of several initiatives to propose indicators to assess sustainability conditions of companies of this size, such as: Ragas et al. (1995) present a proposal for the construction of sustainability indicators applied to production systems, seeking to measure all forms of environmental pressure during the life cycle of a product; Callens and Tyteca (1999) developed a methodology of indicators that allow the assessment of the participation of companies in sustainable development; Azapagic and Perdan (2000) propose a general framework for sustainable development indicators for the industry; Veleva and Ellenbecker (2001) present a structure and methodology for the use of sustainable production indicators as a tool to promote greater awareness, measurement, and preparation of sustainability reports; Krajnc and Glavic (2003) presented a set of sustainable production indicators to assess a company's level of sustainability and help define more sustainable options for the future; Azapagic (2004) proposed a comprehensive set of indicators that are specifically relevant and adapted for the mining and minerals industry; Joung et al. (2013) reviewed a set of indicators available to the public and provided a categorization of quantifiable and clearly related indicators to manufacturing; Chen et al. (2014) presented a holistic sustainability assessment tool for the manufacture of MSC, among others.

Even so, small companies, especially manufacturing companies, have been challenged to choose which are the best indicators to evaluate their processes and products, and to interpret these indicators in their decision-making (Chen et al., 2012; Joung et al., 2013). And this has been the reality faced by companies in the gem processing sector, as there is a lack of management of the usefulness of the many proposals for indicators and the specificities of the sector. Therefore, this work aims to investigate indicators, with the purpose of proposing a framework to evaluate and monitor the sustainability conditions of gem benefiting companies, given their importance for many countries, as is the case of Brazil.

Next, the methodological procedures used to prepare proposals for sustainability indicators applied to the industries that benefit from gems are stated.

Methodological procedures

This section presents the considerations that guided the development of the proposed sustainability indicators aimed at companies in the gem processing sector and their empirical verification in a case study company. Considering this objective, the study is classified as exploratory, quantitative, and qualitative.

The methodology for defining the proposed indicators was guided based on the steps described by Joung et al. (2013). Thus, sustainability objectives were defined, indicators were selected, reference values and measurement procedures were defined and, afterward, the data analysis and report elaboration showing the results for the company's case study were carried out, which can serve as a comparison for other companies in the segment.

Specificities and key issues for the development of activities of the gem processing sector in a sustainable context were also considered. These issues were identified through the analysis of previous studies on the sector (Hentschel et al., 2003; IBGM, 2005; Oliveira and Ali, 2011) and the monitoring and analysis of the production process directly in the manufacturing environment.

During three years, the researchers made weekly visits and follow-ups to the company's case study in order to understand the functioning of its activities, the changes in the economic scenario, and the solution of the problems they faced. In this company, an inventory of the inputs and outputs of the process was also carried out, based on the analysis of the life cycle of the materials (Callister and Rethwisch, 2013), in order to identify critical points in terms of resource consumption and waste generation, effluents, and emissions. However, it is noteworthy that the assessment was restricted to the impacts generated during the production process and the possibility of recycling materials in the process itself, that is, the phases of mining and extraction of gems, oil, and other materials in the phases were not considered prior to their arrival at gem processing companies, as well as in the later stages of waste disposal and recycling.

This step also contributed to the definition of values that need to be minimized (such as consumption of resources and environmental responsibility), as well as those that must be maximized (recovery and recycling of materials), in order to achieve efficiency in the activity (Callens and Tyteca, 1999). This occurs because, initially, for the development of sustainability metrics, the main aspects that need to be managed and included in the proposal need to be identified (Tanzil and Beloff, 2006). In addition, an interview was conducted with the company's case study managers, based on a structured questionnaire, which aimed to identify the conditions necessary to achieve the sector's sustainability conditions.

The selection of indicators was carried out taking into consideration the observations made from the process inventory and issues highlighted by the managers, as well as the literature review and analysis of initiatives related to the construction of sustainability indicators and guidelines discussed in the second section of this article, for industries and manufactures, especially in MSC, or companies associated with the mining sector.

Literature review was carried out based on works available especially in the SciELO, ScienceDirect (Elsevier), and Google Scholar databases. For this purpose, keywords were used as an initial search reference (such as: Sustainability indicators, Manufacturing, Industry, Mining Sector, Sustainability indicators, Manufacturing, Industry, Mining Sector), and from them, other relevant works referred to were consulted, following the snowball methodology, with the objective of expanding the scope of research. Given the systemic nature of the theme, in this study, Boolean operators were not used, as there were few works published directly in the area under study and, as new related terms appeared, the searches were expanded. This review was not exhaustive, since not all the works found in the search were analyzed, although it sought to identify the main proposals for indicators applied to companies, in order to support the achievement of the objective of this work.

In this context, for the assessment of the sustainability conditions of gem processing companies, a proposal for indicators was developed considering four dimensions of sustainability: environmental, economic, social, and technological. This selection took into account the concept of the Sustainability Tripod (Triple Bottom Line) (environmental, economic, and social dimensions), proposed by Elkington (1998), widely recommended in the literature, as well as the need to incorporate technologies to meet sustainability goals, as suggested by Joung et al. (2013). The purpose of this dimension is to assess the ability of companies to introduce technological advances. According to Hentschel et al. (2003), among the main difficulties of artisanal or small-scale mining activities are the limited use of mechanization and the lack of investment capital. In addition, according to Oliveira and Ali (2011), the low level of technology used in the sector is an obstacle to increasing productivity and income.

In addition, it was decided to consider two sustainability attributes in each dimension: productivity and resilience. The first attribute is directly associated with the concept of sustainable production, since, to obtain this quality, it is necessary to improve the productivity of processes (Porter and Van Der Linde; 1995) through a more efficient use of resources and minimizing the generation of waste, considering that some resources used by the sector are finite (gems and oil). Meanwhile, resilience is associated with the ability of systems to absorb disturbances, to reorganize themselves during the process of changes and recovery, and to maintain their function, structure, and identity over time (Costanza and Daly, 1992; Folke, 2006; Xu et al., 2015). Other attributes were not inserted in order not to make the tool more complex and, at the same time, it was understood that if companies were efficient in achieving these two attributes, they would also indirectly achieve other sustainability attributes, such as stability, diversity, security, among others.

Thus, based on the analyzed sustainability indicator proposals, in the reality of companies that benefit gems, and on the dimensions and attributes of sustainability to be considered, sustainability indicators and variables that would compose each indicator were selected and defined with the help of the managers of the company's case study (Table 1).

The proposed indicators were empirically verified with a case study company, through the analysis of documents, including production management documents, monitoring of technical reports, and waste management plans. The project was chosen for convenience and is in the interior of the state of Rio Grande do Sul (Brazil); it can be classified as small, given the number of employees and annual turnover. In addition, the company operates using a typical gem processing process, as occurs in other companies in the sector and in face of difficulties similar to those previously reported.

And, considering that each indicator was measured in different units of measurement, in order to be able to group the results and calculate a sustainability index, it was necessary to normalize the results, transforming them into the same unit, as highlighted by Nardo et al. (2005). Therefore, it was chosen to assign weights from 1 to 3 for each variable, in order to show the worst situation (grade 1), an intermediate situation (grade 2), and the best situation to achieve more sustainable conditions (grade 3). To define the parameters related to each weight, studies of the mining sector were consulted (Azapagic, 2004; ANA, 2006; Norgate and Haque, 2012; Strezov et al., 2013; Lodhia and Martin, 2014; Thammaraksa et al., 2017; Chen et al., 2018). Other parameters were defined with the help of the company's case study managers, who have a deeper understanding of the sector's reality (practitioners) and the context in which the gem processing activities are carried out. The parameters were defined to indicate a bad, intermediate or ideal result for the processing of gems considering the principles of sustainability. Table 1 shows the weights and parameters by sustainability variables and indicators.

After measuring and normalizing the variables, the indicators were aggregated by arithmetic mean. For example, Equation 1 shows how the 'resource consumption' indicator was calculated.

Table 1 – Weights, parameters, variables, indicators, attributes, dimensions of sustainability.

Weights, parameters, variables, indicators, attributes, dimensions of sustainability

Dimension	Attribute	Indicator	Variable	Parameters	Weight
Environmental (25%)	Productivity (50%)	Consumption of resources (33.3%)	Water consumption	Up to 50 m^3 / ton From 50 to 100 m^3 / ton More than 100 m^3 / ton	3 2 1
			Energy consumption	More than 60% renewable 30 to 60% renewable Less than 30% renewable	3 2 1
			Fuel consumption	Up to 60 l / ton From 60 to 120 l / ton More than 120 l / ton	3 2 1
		Material recovery/ recycling (33.3%)	Oil recycling	More than 60% 30 to 60% Less than 30%	3 2 1
			Gem recovery	More than 60% 30 to 60% Less than 30%	3 2 1
		Environmental liability (33.3%)	Total waste generation (sludge)	Less than 30% 30 to 60% More than 60%	3 2 1
			Production of defective parts	Less than 1% Between 1% and 5% More than 5%	3 2 1
			Generation of waste without treatment	Less than 30% 30 to 60% More than 60%	3 2 1
	Resilience (50%)	Environmental management (100%)	Adoption of environmental management system	Yes - No	3 2 1
			Adoption of CSR / Sustainability practices	Yes - No	3 2 1
			Irregularity notifications	No - Yes	3 2 1
Economic (25%)	Productivity (50%)	Management and diversification of the activity (50%)	Savings from material recovery or recycling of material	More than 5% Between 1% and 5% Less than 1%	3 2 1
			Waste disposal costs	Less than 1% Between 1 and 5% More than 5%	3 2 1
			Making investments	Yes - No	3 2 1
			Commercialization channels	5 or more channels Between 3 to 4 channels Up to 2 channels	3 2 1
	Resilience (50%)	Adaptability to changes (50%)	Development of new products	Yes - No	3 2 1
			New product revenue	More than 5% Between 1 and 5% Less than 1%	3 2 1
Continue …					
Social (25%)	Productivity (50%)	Working conditions (50%)	Qualification and training of employees	Yes - No	3 2 1
			Incidence of accidents at work	Yes - No	3 2 1
	Resilience (50%)	Worker satisfaction (50%)	Turnover	Up to 10% Between 10 and 25% More than 25%	3 2 1
			Benefits offered by the company	Yes - No	3 2 1
Technological (25%)	Productivity (50%)	Technological Investments (100%)	Introduction of technological innovations	Yes - No	3 2 1
			Adoption of Cleaner Production practices	Yes - No	3 2 1
	Resilience (50%)	Innovation capacity (100%)	Participation in R & D	Yes - No	3 2 1

$$I1 = \frac{V1.1 + V1.2 + V1.3}{3} \quad (1)$$

The higher these results for the indicators (closer to 3), the better the company's performance in pursuit of the objective; and the lower the values (closer to 1), the greater the distance to be traveled by the company to achieve sustainability conditions.

Indicators were aggregated by attributes, and attributes by dimension, considering the same previous criteria. Equations 2, 3, 4, and 5 show how indicators were aggregated by dimension.

$$D_{Environmental} = \frac{A_1 + A_2}{2} = \frac{\left(\frac{I_1 + I_2 + I_3}{3}\right) + \left(\frac{I_4}{1}\right)}{2} \quad (2)$$

$$D_{Economic} = \frac{A_1 + A_2}{2} = \frac{\left(\frac{I_5}{1}\right) + \left(\frac{I_6}{1}\right)}{2} \quad (3)$$

$$D_{Social} = \frac{A_1 + A_2}{2} = \frac{\left(\frac{I_7}{1}\right) + \left(\frac{I_8}{1}\right)}{2} \quad (4)$$

$$D_{Technological} = \frac{A_1 + A_2}{2} = \frac{\left(\frac{I_9}{1}\right) + \left(\frac{I_{10}}{1}\right)}{2} \quad (5)$$

Finally, it was possible to calculate the level of sustainability that indicates the current condition of the company that collaborates in this study in relation to the search for sustainability. This index was obtained from the aggregation of the evaluations by dimension, with each dimension receiving the same weight in the calculation of the index (Equation 6).

$$S_{index} = \frac{D_{environmental} + D_{economic} + D_{social} + D_{technological}}{4} \quad (6)$$

The results found in the company's case study in relation to the proposed sustainability indicators are described in the following sections.

Results and Discussion

This section first describes, briefly, the characteristics of the gem processing process. Next, the table of sustainability indicators suggested for the companies in the sector is presented, and afterward the results of the assessment of the sustainability conditions of the case study company are demonstrated. Finally, some general discussions are presented.

Gem benefiting process

The typical gem processing process consists of several stages (cutting, turning, sanding, polishing, finishing, among others), some of which are marked by manual processes, while others are characterized by semi-automatic or automatic processes, varying according to the type of gem and the final product to be obtained, with the average time required for the development of this process being approximately 30 to 45 days.

In these stages, different types of resources are used, especially natural gems and marine diesel oil, and different types of solid and liquid residues are generated, as shown in the inventory of inputs and outputs of the process (Figure 1).

Given this scenario, companies in the sector need to find alternatives to minimize the use of inputs and the generation of waste, with the aim of making the activity more efficient and sustainable. Therefore, the use of a framework of sustainability indicators can be useful.

Proposed sustainability indicators

The indicator table for gem benefiting companies was developed according to the sustainability objectives (Joung et al., 2013) and the characteristics of the activity and is based on four dimensions (environmental, economic, social, and technological) and two sustainability attributes (productivity and resilience), consisting of 10 indicators (quantitative and qualitative) and 24 variables (Figure 2).

The environmental dimension seeks to portray the impact that the productive activity can cause on the environment, as well as to identify whether production has been developed in an environmentally correct context. It consists of four indicators and 11 variables. The indicators associated with the productivity attribute (consumption of natural resources, the recovery and recycling of materials, and the environmental liability resulting from the beneficiation process) are traditional indicators, considered in evaluations of the life cycle of a product, as they seek to measure the main resources used and the environmental impacts resulting from the production process (Lee and Lee, 2014). For parameter purposes, the best (most sustainable) situation will be one in which the consumption of materials and the environmental liability are as low as possible per quantity of gems processed; at the same time that the reuse of materials is maximized. The resilience of companies in this dimension is expressed by the indicator called environmental management, which can be guaranteed with the adoption of environmental management systems and sustainable practices. In addition, companies must comply with rules and legislation to mitigate their environmental impact and thus avoid notifications of irregularities. Although this last issue seems simple to meet, in practice it is not due to the informality of the sector, the inadequate working conditions, or the acquisition of gems from unauthorized deposits (Azapagic and Perdan, 2000; Hentschel et al., 2003; Azapagic, 2004).

The economic dimension is formed by two indicators and six variables. The first indicator, associated with the productivity attribute, aims to analyze the management and diversification of the activity, through the analysis of the economy resulting from the reduction and reuse of materials, the costs associated with the disposal of waste, the investment, and the dependence on relation to the commercialization channels. In this case, companies would achieve more sustainable conditions if the values associated with the first and third variables

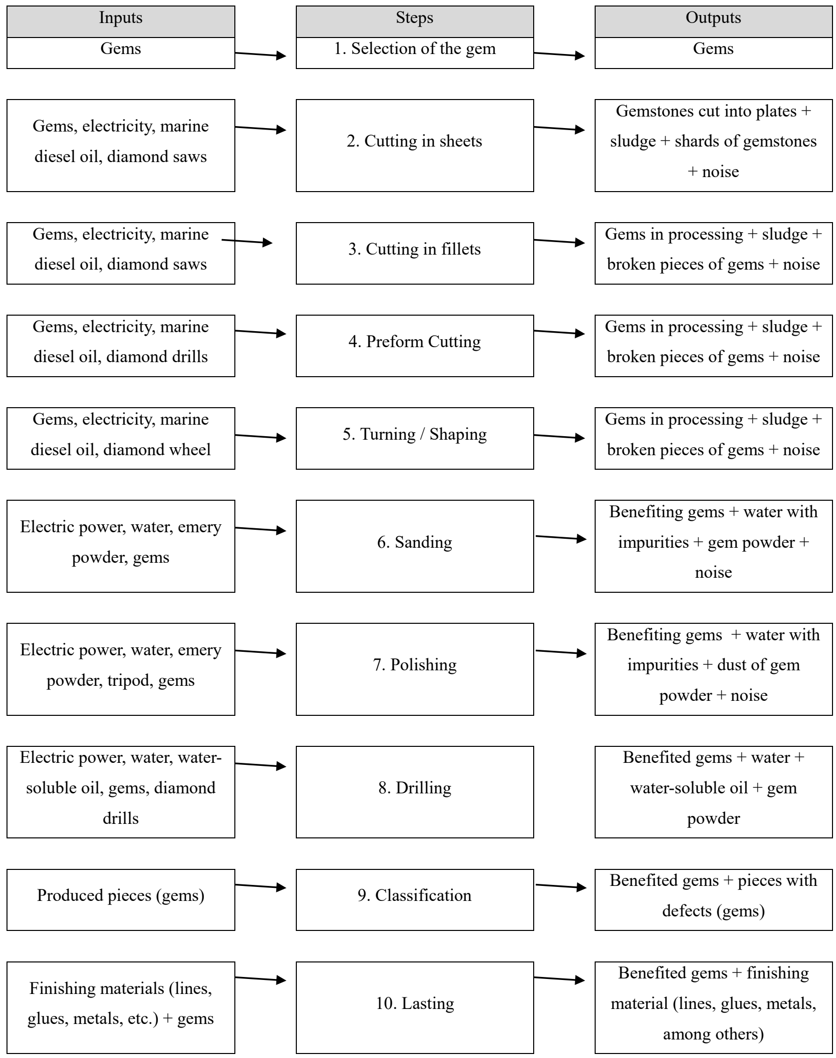

Figure 1 – Inventory of inputs and outputs of the gemstone benefiting process.

are maximized and the values for the second and fourth variables have been minimized. The second indicator of this dimension, linked to the resilience attribute, the company's ability to adapt to changes in the market, assesses the capacity to develop new products and the revenue associated with them in relation to the total invoiced by the company. As the gem processing market produces products considered superfluous, not essential for the survival of human beings, it is very susceptible to market changes; therefore, companies must always be in search of development of new attractions for consumers, *i.e.*, the best performance will be obtained when these values are maximized. In addition, no indicator is included to measure the actual billing, present in other proposals, as it was considered vital that the company needs to make a profit in order to continue its activities.

Social dimension consists of two indicators and six variables. The productivity attribute is expressed by the working conditions indicator, formed by two variables that demonstrate the accomplishment of qualifications and training of employees and the number of incidents of work accidents, as it is expected that no company represents work risks (Joung et al., 2013). The indicator associated with the resilience attribute seeks to measure the satisfaction of workers through the analysis of the turnover index and the benefits offered by companies as a means of encouraging employees to remain in the activity, in addition to those required by the legislation in the country. Indicators that could measure the company's impact on the local community were not included in the proposal, as suggested by Azapagic and Perdan (2000) and Joung et al. (2013), given the difficulties faced by small companies, they will hardly be able to develop specific actions directed to the population in their surroundings, and their positive impact on society will be through the generation of jobs, income, and the respect for the environment and legislation.

The technological dimension is composed of two indicators and three variables. The productivity attribute is expressed by the technological investment indicator, which aims to inform whether companies are introducing technological innovations and Cleaner Production practices. The innovation capacity indicator, associated with the resilience attribute, seeks to identify whether companies participate in research and development projects or in sectoral projects, whose objective is to develop actions that benefit the sector. The performance of the indicators of this dimension are fundamental to guarantee the increase of the efficiency of the productive processes, therefore, the better the performance of these indicators, the more sustainable the systems tend to be (Oliveira and Ali, 2011; Joung et al., 2013).

In addition, although the indicators have been classified by sustainability dimension, their improvement tends to provide positive results over the other dimensions as well, as highlighted by Tanzil and Beloff (2006), causing an overflow effect. In other words, the better performance of environmental indicators guarantees a reduction in the costs of production and treatment of waste in order to contribute to economic performance as well. Thus, the introduction of investment in technologies can contribute, for example, to a more efficient use of resources, bringing positive impacts on the environmental, economic, and social dimensions.

Assessment of the sustainability conditions case study company

In 2014, the case study company benefited an average of four tons of gems per month; the production consisted of jewelry and decorative items, which were destined for both the domestic and foreign markets.

In environmental terms, associated with the productivity attribute, it was found that the company used a significant amount of non-renewable materials (in particular gems and marine diesel oil) and reused a reduced volume of materials (approximately 45% of the oil and 8% of the total volume of gem waste). As a result, due to the low percentage of finished product, the benefiting process generated a significant volume of sludge, which, due to its characteristics, is classified by the Brazilian legislation as hazardous and cannot be disposed anywhere in the environment, which represents a high environmental liability.

In the period analyzed, the company generated approximately 20.4 tons of sludge, representing 42.5% of the total volume of processed gems. Although this sludge was treated through the washing process, which partially recovered the oil, and which was reused in the production process, approximately 80% of the total volume was stored in barrels, while waiting for a more efficient treatment, so as not to be sent to an industrial landfill.

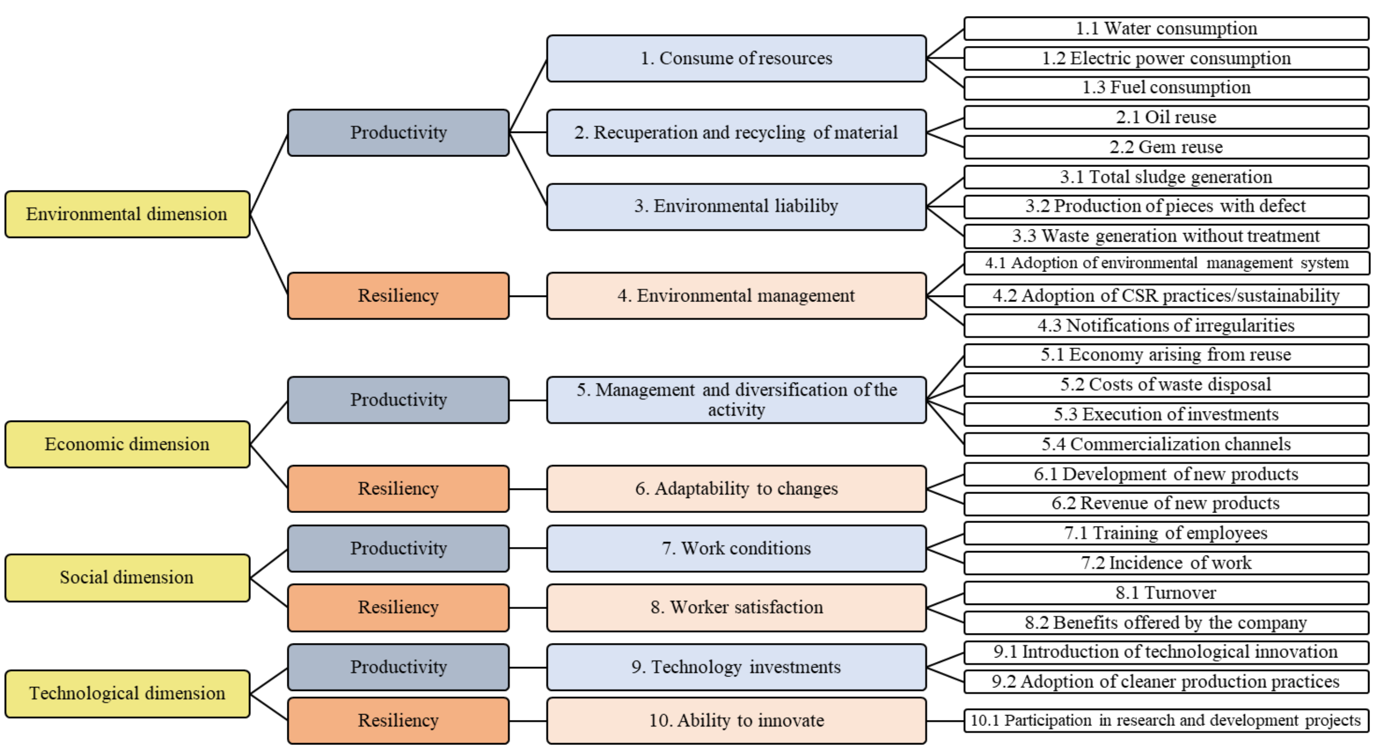

Figure 2. Proposed indicators for assessing sustainability conditions in companies in the gem processing sector, classified by attributes and dimensions.

In addition, the environmental management indicator, related to the resilience attribute, demonstrated that the company, despite adopting practices that contribute to sustainability, such as the use of techniques aimed at Cleaner Production (reuse of waste) and development of a new product from the residue formed by gem powder, and not having committed irregularities, it did not adopt any environmental management system, due to the reduced availability of resources and manpower, as highlighted in other studies (Hentschel et al., 2003; Azapagic, 2004; IBGM, 2005).

The economic dimension is formed by two indicators that seek to measure the company's ability to manage and diversify its activity (productivity attribute), and to adapt to changes that may occur in the market (resilience attribute). Regarding the performance of these indicators, it was observed that although the company has made investments in the productive sector, contributing to the improvement of efficiency, there was no cost with waste disposal, as it accumulated the waste in vats in the company's yard while developing techniques for its treatment, having used several channels for the commercialization of its products (wholesale, retail, website, at fairs, among others). However, it saved only 2% by reusing materials, as well as it had a small increase in revenue due to the development of new products with reuse of materials, showing that it still needs to adopt measures to improve its performance in search of sustainability, especially associated to waste reuse and increased billing with the commercialization of new products. On the other hand, it is observed that if the company improves the environmental indicators it will also be contributing to the results of the economic dimension, demonstrating the interrelationship between them.

The social dimension was assessed by the indicators: working conditions (productivity attribute) and employee satisfaction (resilience attribute). As the analyzed company is characterized as small, its involvement with the community occurs through the generation of jobs and income, while not polluting the environment, respecting the legislation applied to the sector. The indicators associated with this dimension performed well, as the company provided training and qualifications to its employees and there was no incidence of work accidents, although the company needs to adopt measures to reduce employee turnover and offer benefits to its employees, contributing for their better quality of life.

On the other hand, the company's performance in view of the technological dimension was adequate to achieve the conditions of sustainability, as suggested by the literature (Oliveira and Ali, 2011; Joung et al., 2013), the company has sought to introduce technological innovations in the productive process, through automatic faceting machine, and cleaner production practices, aimed at reusing materials and making 5S, in addition to participating in research and development projects, developed by a university located in the region and representative agencies of the sector in the state, which aim to make better use of resources and reduce the generation of waste resulting from productive activity (Figure 3).

These indicators were also aggregated by attribute so that it was possible to obtain an index by dimension (Figure 4) and a general index of sustainability.

The environmental sustainability index for the collaborating company was 2.25. The indicator that most contributed to this result was the consumption of materials (2.67), since, when compared to other industries, the company uses a reduced volume of water per volume benefited and, in terms of energy, it only consumes electricity from renewable sources. The performance of the environmental passive indicator (2.33) was also satisfactory, as well as the environmental management indicator of the activity (2.33), since the company did not allocate any waste to industrial landfills during data collection and has adopted practices favorable to sustainability and received no notification of irregularity. On the other hand, the indicator that contributed less to this indicator was the reuse and recycling of materials (1.50).

The economic sustainability index obtained a result equal to 2.38. In this dimension, the activity management and diversification indicator (2.38) performed well, since the company had no expenses with the disposal of waste, made investments in the productive sector and used several marketing channels to place its products. The adaptability to changes indicator, however, needs to be improved (2.00), as, despite the company developing new products to meet customer demand and seeking to reuse materials, the revenue from this development is still insignificant.

The sustainability index for the social dimension was 2.25. While the working conditions indicator got the best score, since the company trains employees and no accidents at work were recorded, the employee satisfaction indicator underperformed, provided the turnover rate is not only low, but it does not offer any benefits to its employees.

The technological dimension of sustainability index was 3.00, that is, it presented the best score of all indicators. This result is due to the investments in innovation that the company has made, as well as

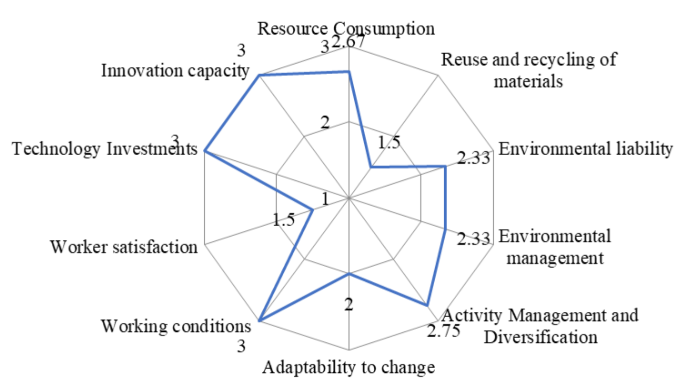

Figure 3 – Diagram of sustainability by indicator.

the adoption of Cleaner Production practices aiming at increasing productive efficiency and its involvement with research and development projects and sectorial entities.

And, finally, the company's sustainability index of 2.47 was also measured, demonstrating that the company has managed to achieve a satisfactory performance in the search for sustainability conditions. However, it is recommended that the company seeks to develop actions to improve, mainly, the performance of the variables associated with the environmental and social dimensions. In addition, considering the relationships between the dimensions of sustainability, it is evident that, by improving the performance of one dimension, one will also be contributing to the performance of other dimensions.

This was an initial exercise for the assessment of sustainability conditions in gemstone benefiting companies; the indicators have been validated from a case study and generalizations cannot be made from the results found.

Discussions

Along the development of this work, three aspects become evident. First, identifying evidence about the production process. Although the activities developed by the mining sector are important for the economy, the literature presents few studies associated with the gem processing sector. The inventory of inputs and outputs of the gem processing process, presents detailed information on the main critical points. It highlights the aspects that need to be minimized during the process of gem processing and those that must be maximized to achieve efficiency in the perspective of sustainability, as highlighted by Callens and Tyteca (1999). In particular, it was identified that benefiting companies need to minimize the use of inputs (especially gems and diesel oil) and the generation of waste and maximize the reuse of gems and improve their productivity to become more efficient and sustainable.

The second contribution of the study is related to the proposition of the framework of sustainability indicators, composed of indicators linked to the environmental, economic, social, and technological dimensions, and based on the attributes of productivity and resilience for the development of activities in this sector. The proposal is advantageous for companies because it followed the recommendation of works widely recognized in the literature, it considered the reality in which they are inserted and counted on the participation of practitioners involved in the activity (company managers of the case study), thus contributing with small companies that have limited resources in terms of time and personnel (Dahl, 2012; Falck and Spangenberg, 2014) and have more difficulties in using more generic indicators for all types of industry, as for example proposed by GRI (2013).

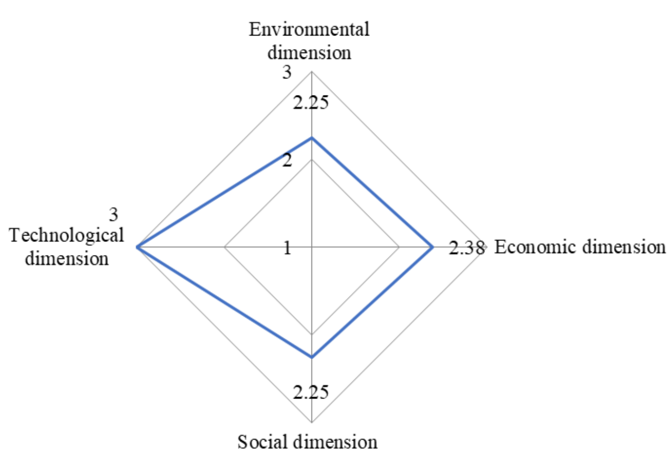

Figure 4 – Assessment of sustainability conditions by dimension.

However, despite the advantages associated with the adoption of the proposal, it is worth noting that it may have limitations, since this is a simplified framework of indicators that will not be able to measure everything that happens in the company, according to a characteristic identified by Bossel (1999), neither guarantees its sustainability (Dahl, 2012). This is an initial proposal that can be adjusted according to the emergence of new needs and demands in the sector. For this reason, the list of indicators cannot be considered exhaustive and rigid (fixed).

Also, another obstacle that companies in the sector may face in adopting the proposal is associated with the collection of information and monitoring of the indicators due to difficulties with the workforce, which is generally unskilled, with a low level of education and is often reduced (the same person has several functions within the company) (Hentschel et al., 2003), it can also present high turnover, directly related to the regional economic performance (employees easily change jobs when other sectors pay better). The third contribution of the study is associated with its applicability. The empirical verification of the proposal in the case study company presents an overview (by indicator, dimension, and general sustainability index) objectively evidencing the main difficulties faced. Thus, the practical implication of this study is that company managers can use the results as an instrument for evaluating and monitoring their activities in search of a more sustainable context. The results can also be used to disclosure reports to stakeholders, so as to communicate the actions developed by the company.

Furthermore, the proposal can also be used by companies that are part of the sector, for the purpose of comparison among them; as well as it can be useful for carrying out a general evaluation of the sector. Consequently, this information could be used as a subsidy of governmental or non-governmental organizations for the development of policies aimed at the sector that presents numerous difficulties (Hentschel et al., 2003).

Conclusions

This study provided information about the production process of gemstone benefiting; an important economic activity for many countries, especially in Brazil, and proposed a framework of sustainability indicators to assess and monitor the sustainability conditions of small companies. The main advantage of the proposal is that it was developed taking into consideration the reality and the specificities of the sector and it had the involvement of stakeholders for the selection of variables, in addition to being applied in a case study company. Thus, the indicators express the main limitations that this segment faces and expose opportunities for improvements to be implemented along the process to achieve better sustainability conditions.

It is suggested as a future work to conduct a survey to confirm the parameters. Obtaining these results will contribute to the review of the reference parameters for the measured variables and, if necessary, to make changes to the initial proposal. The proposed indicators applied to other companies in the sector will allow a comparison among them and a general assessment of the sector. Monitoring these indicators will also contribute to verifying whether the companies are managing to develop their activities under more sustainable conditions and whether the proposed tool favors or not the improvement of the productive process.

Contribution of authors:

Sindelar, F.C.W.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing — original draft. Barden, J.E.: Conceptualization, Methodology, Formal analysis, Supervision. Stulp, S.: Conceptualization, Methodology, Formal analysis, Supervision.

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ABES

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Actions and policy tools for local governments to achieve integrated sustainable waste management

Ações e ferramentas políticas para governos locais alcançarem a gestão integrada sustentável de resíduos sólidos

Valdir Eduardo Olivo[1], Pedro Domingos Marques Prietto[1], Eduardo Pavan Korf[2]

ABSTRACT

Integrated management of municipal solid waste seeks sustainability under the premises of environmental protection, health promotion, and economic development. In this context, this article proposes actions and policy tools for local governments to improve quality and governance in waste management. A set of 23 actions is proposed based on existing conceptual models and available legislation. The results are presented in three levels as follows: planning of the administrative and operational structure, waste management, and performance evaluation. The results showed that the proposed actions need to be implemented through policy tools, such as municipal legislation, social communication, normative instructions, and technical studies. The applicability of the proposed methodology, which might be replicated in any municipality to increase the efficiency of the waste management system, was positively evaluated in a medium-sized Brazilian city, which presented an overall attendance level of 52%.

Keywords: public management; sustainability; governance; municipal solid waste.

RESUMO

A gestão integrada de resíduos sólidos urbanos busca a sustentabilidade sob as premissas da proteção ambiental, promoção da saúde e desenvolvimento econômico. Nesse contexto, o presente artigo propõe ações e ferramentas políticas para os governos locais melhorarem a qualidade e a governança na gestão de resíduos. Um conjunto de 23 ações é proposto com base em modelos conceituais existentes e legislação disponível. Os resultados são apresentados em três níveis: planejamento da estrutura administrativa e operacional, gestão de resíduos e avaliação de desempenho. Os resultados mostraram que as ações propostas precisam ser implementadas por meio de ferramentas de política, como legislação municipal, comunicação social, instruções normativas e estudos técnicos. A aplicabilidade da metodologia proposta pode ser replicada em qualquer município para aumentar a eficiência do sistema de gestão de resíduos e foi avaliada positivamente em uma cidade brasileira de médio porte, que apresentou um índice geral de atendimento de 52%.

Palavras-chave: gestão pública; sustentabilidade; governança; resíduos sólidos urbanos.

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Introduction

Waste management is one of the essential public services and is considered a "basic human right." If not properly provided, it represents a threat to public health and the environment (UNEP, 2015). Most municipalities in underdeveloped and developing countries face significant challenges in waste management, mainly regarding the implementation of sustainable practices, due to the economic and technological limitations and the lack of trained staff, which causes fragility in the system's operation, particularly in smaller cities (Marino et al., 2018; Deus et al., 2020).

Integrated management is being widely adopted by municipalities to properly handle local waste (Asefi and Lim, 2017). This system allows the municipalities to adapt to the existing norms, guaranteeing physical structure, economic sustainability, and social responsibility. It includes the physical elements of the system, the interested parties, encompassing the technical, environmental, financial, sociocultural, institutional, and political dimensions (Van De Klundert and Anschutz, 2001).

The Integrated Sustainable Waste Management (ISWM) conceptual model has four main objectives as follows: the promotion of health and well-being of the entire population, the protection of the environment and the guarantee of sustainability, the promotion of efficiency and productivity in the economy, and the generation of jobs and income (Schübeler, 1996). This model is widely discussed at a conceptual level (Schübeler, 1996; Van De Klundert, 1999; Mwangi and Thuo, 2014). However, there is a lack of studies that address practical actions to be taken by government officials to meet ISWM requirements (Marino et al., 2018).

The integrated urban solid waste management system is divided into three steps as follows: planning, management, and evaluation (Figure 1), with each stage having axes of actions for the integrated management (Schübeler, 1996; Van De Klundert and Anschutz, 2001; Mwangi and Thuo, 2014).

The purpose of this article is therefore to present a set of actions and tools for the local government to achieve integrated solid waste management. Thus, municipalities can implement an integrated management system through these actions. They are based on the principles of sustainability, current legislation, and the local capacity of the municipalities. The actions can be applied to all municipalities that need technical guidance to implement this management system, enabling managers to increase local sustainability by reducing environmental impacts, minimizing operating expenses, and engaging society.

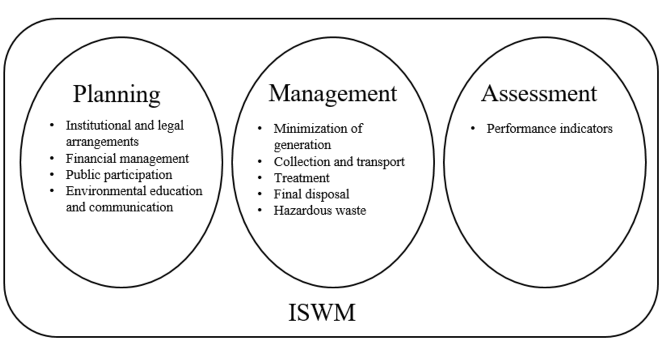

Figure 1 – The ISWM system.

This study was conducted on the medium-sized municipalities with a population between 100,000 and 250,000 inhabitants, and Brazil has 172 cities with this population (Brazil, 2019). Due to the great relevance in the economic market and for becoming a regional pole for services and infrastructure, these municipalities have high growth potential, thus requiring the planning of actions aimed at sanitation.

Methodology

The research was conducted initially through a systematic review and performed in two steps as follows: the first one comprised three database searches using the key words relevant to the research and the analyses of selected articles and documents from the database search (Figure 2).

Initially, a search for national legislation regarding the management of solid waste was carried out. The research took place on the legislation portal of the Brazilian federal government and identified 24 legislations on the subject, in the period between 2001 and 2021. Eight federal laws were selected, which served as a legal basis for this work. After, a systematic literature review was realized to this article. ScienceDirect and Scopus databases were consulted using three search criteria as follows: all types of articles, time interval from 2011 to 2021, and the following key-word associations: "municipal solid waste" and "policy tools," "guidelines" and "municipal solid waste" and "policy tools," and "municipal solid waste" and "integrated management."

A total of 448 articles were identified and selected by the abstract reading, and 29 were selected for the in-depth discussion for this study.

The guidelines were defined based on the analysis of the 29 articles. From these, actions and policy tools to ISWM were selected.

The municipality of Chapeco (SC), Brazil, was selected to assess the conditions of applicability of the study. The municipality presented an excellent performance in waste management in 2018 (Brazil, 2019).

Actions and policy tools to implement ISWM

The actions and tools were established for each of the axes and were based on the principles of sustainable management (Van De Klundert and Anschutz, 2001) and on the legislation available at the national level (Brazil, 2007, 2010).

Each ISWM area of activity generated a set of practical actions that the local government must adopt to achieve sustainable management. The vast majority of actions are based on structuring legal support through standardization and inspection, social mobilization, technical studies, increasing physical structure, and projects to minimize environmental impacts.

Several authors approached the ISWM as a methodological alternative to improve the municipal management system. These practices were observed in studies conducted by Dutra et al. (2018), Fuss et al. (2018), and Marino et al. (2018).

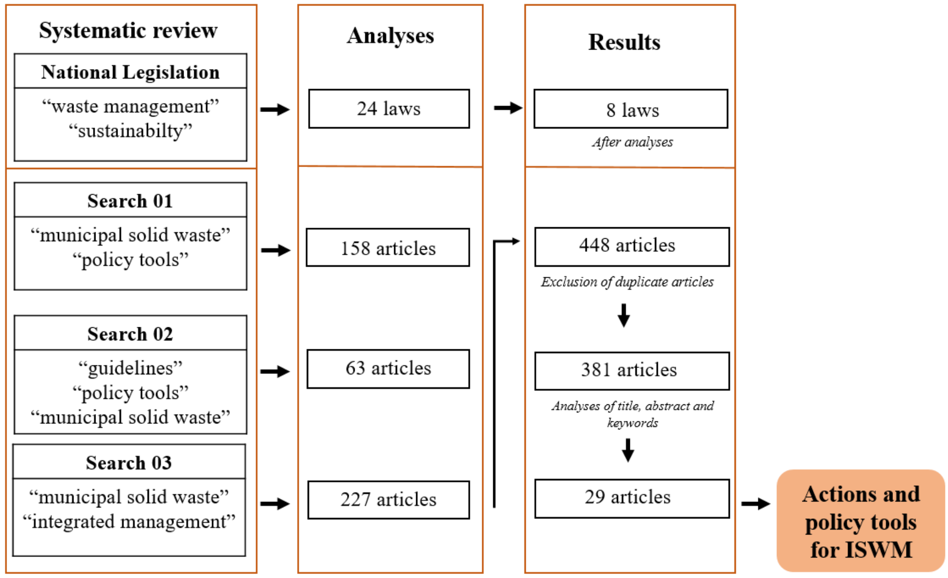

Figure 2 – Methodology.

Step 1: Planning

The first step in starting a municipal management system is to develop adequate planning based on the current situation of local governance. Planning must involve institutional, legal, financial, and social aspects. Table 1 shows the government actions proposed for this step. The letter "P" was assigned to establish a relationship between the action and the step it refers to. It is also presented the necessary tool for the action implementation.

In waste management planning, communication must involve all levels of government and stakeholders (Kaza et al., 2018). The basis of a management system occurs through the development of sound public policies that guarantee the availability and continuity of services. Government actions in the institutional and legal aspects emphasize the importance of drafting the Brazilian Policy on Solid Waste (BPSW). In Brazil, this policy is provided in federal laws. ISWM will contemplate all the actions present in this article. The plan will serve as a base document for government officials and should be implemented through municipal law (i.e., actions P.1 and P.2).

According to Marino et al. (2018), the biggest problems of planning public management in the area of solid waste are related to the technical and operational incapacity of local governments. Low- and middle-income countries find it difficult to achieve adequate management due to poor sector planning (Kaza et al., 2018). Therefore, the creation of a municipal public cleaning department with a qualified technical staff guarantees responsible execution of planned actions, monitoring and implementation of plans, contract management, technical studies, standardization, inspection, and social mobilization (i.e., actions P.3–P.5).

The local government team should prepare normative manuals and instructions that involve, for example, guidance for minimizing waste generation, segregation at source, encouraging home reduction and reuse of waste, the requirements for waste management plans, the licensing of potentially polluting activities, and the standardization of waste disposal facilities (i.e., action P.6). As provided in the Brazilian Policy on Basic Sanitation (BPBS), the local government should promote sectoral agreements to reach reverse logistics among the parties involved, guaranteeing participation at all levels (i.e., action P.7; Brazil, 2010).

The inclusion of waste pickers in integrated management (i.e., action P.8) is foreseen in the BPSW (Brazil, 2010). The municipality should encourage the establishment of cooperatives so that waste pickers can work in an organized and wholesome environment, yet provide subsidies and technical partnership to support the structuring of sorting spaces (Fidelis et al., 2020; Siman et al., 2020).

According to Schübeler (1996), ISWM provides priority assistance to the needy population and vulnerable areas at risk. A detailed study of these areas must be prepared and instituted in municipal legislation to guarantee the care of this population (i.e., action P.9).

The structure of a management system must contain legal support to guarantee the execution and continuity of actions. The single legislation can facilitate the understanding of users (e.g., municipal code for urban cleaning; action P.10). The code will provide guidance on the segregation of waste, the responsibilities of each user, the service charge, the inspection process, penalties, and tax incentives (Kaza et al., 2018). According to Fernando (2019), for the effectiveness of local regulations, the punishment process must be provided for cases of noncompliance with local guidelines.

To standardize and supervise the provision of basic sanitation services (Brazil, 2010), the BPSW determines the adhesion of municipalities to regulatory agencies (i.e., action P.11).

The financial area of management proposes to standardize and make the financial issues of the local government feasible. The government should implement a program of continuous assessment of the management system, allowing the assessment of available technologies and the necessary instruments to match financial availability and to achieve greater efficiency (Asian Development Bank, 2017). The preparation of a detailed economic feasibility study will assess the financial deficiencies and deficits in the operational area (i.e., collection, transportation, treatment, and disposal; action P.12).

Public services must be sustainable (Bartolacci et al., 2018); therefore, charging of the waste collection tariff (i.e., action P.13) is a determining factor for the functioning of the solid waste management system (Brazil, 2010). The charging can be carried out through a fixed tariff or as a function of the amount of waste generated (Welivita et al., 2015). However, the fixed tariff does not encourage the population to minimize the generation of waste (Chung and Yeung, 2019). It is recommended that the best alternative be evaluated and chosen according to the technologies available to the municipality.

According to Xu et al. (2018), there are two ways to engage the population in the waste segregation at source as follows: through intensive environmental education and through financial incentives. The local government can institute financial support legislation for users who

Table 1 – Actions and policy tools for ISWM planning.

Government actions	Policy tools
Planning – institutional and legal arrangements	
P.1) Implement the municipal policy of basic sanitation	Municipal law
P.2) Implement the municipal plan for integrated solid waste management	Municipal law
P.3) Create the municipal department responsible for waste management	Municipal law
P.4) Encourage employee participation in waste management training	Social communication
P.5) Network with municipalities with similar characteristics	Social communication
P.6) Establish operational procedures for the management plan, considering all types of waste	Normative instruction
P.7) Promote sectoral agreements between the parties involved and guarantee reverse logistics	Social communication
P.8) Include recyclable material collectors in the integrated management	Municipal law
P.9) Define priority areas and actions for social inclusion	Municipal law
P.10) Implement the municipal code of urban cleaning	Municipal law
P.11) Join a regulatory agency to monitor contracts and tariffs	Municipal law
Planning – financial management	
P.12) Prepare technical–economic feasibility study in all operational sectors	Technical study
P.13) Institute the collection of services	Municipal law
P.14) Stimulate the creation of management consortia and public–private partnerships	Social communication
P.15) Establish norms for participation in transparent bidding processes, guaranteeing publication in user access channels	Normative instruction
P.16) Create incentive programs for companies in the waste area	Municipal law
P.17) Seek external financing for new investments	Technical study
P.18) Institute a tax incentive and certification program for companies that adopt environmental responsibility regarding their waste	Municipal law
Planning – public participation and environmental education	
P.19) Create an environmental education program ensuring the minimization of waste generation	Technical study
P.20) Increase social communication through social media, newspapers, and television	Social communication
P.21) Develop training courses for users for proper waste management	Technical study
P.22) Promote local events and discussion forums focused on waste management	Social communication
P.23) Establish partnerships with universities for research, technological development, and innovation	Social communication

adopt good waste management practices and contribute to local management. Companies engaged in the proper management of waste must be recognized and encouraged. An environmental certification and tax incentive programs are recommended for companies that contribute to the proper management of waste (i.e., action P.18).

Public participation is an important aspect to be considered and must be guaranteed through an active environmental education program. In addition to adequate social communication to transmit information, guidance, and recommendations to users of the system (i.e., actions P.19 and P.20), environmental education should primarily target organized groups and schools, to which information will be disseminated. The user must be provided with training courses for the proper handling of waste (i.e., action P.21). Environmental education for solid waste must be included in the public education curriculum for all levels (Fernando, 2019).

The municipality must encourage and hold debates, discussion forums, and local events that allow the exchange of experiences, information, and knowledge for waste management (i.e., action P.22). Local universities can develop research projects to solve local problems with waste management (i.e., action P.23).

Step 2: Management

The management step addresses the operational aspects of the process. In this step, all operational tasks previously defined and institutionalized are carried out (Table 2).

Minimizing generation is the first axis of the waste management hierarchy (UNEP, 2005). This topic must be worked on with appropriate public policies and an intense process of environmental education. Decentralized composting is an example of minimizing waste for conventional collection. In addition to the economic benefits, the user will obtain a compound to be used at their residence. The government might encourage the provision of domestic composters (i.e., action M.1).

Municipalities that adopt voluntary delivery points have higher recycling rates than others (Brazil, 2019). The green points are structures for concentrating the reception of previously segregated waste, ensuring greater efficiency in the recycling of materials and less waste (action M.2).

For workers in the waste area (e.g., collectors and drivers), continuous training should be carried out according to the demand of each sector (Fernando, 2019; action M.3). Also, individual safety equipment (i.e., action M.4) and adequate physical structure (i.e., action M.5) suitable for the development of activities must be available.

Differentiated collection for dry and wet waste (i.e., action M.6) is decisive for the engagement of the population, guaranteeing the quality of the recyclable material and the health and safety of workers.

The recovery of waste (i.e., action M.7) is the highlight of the process, since almost all waste is liable to treatment and reuse, thereby reducing the impacts on the environment. The waste that was treated as an environmental liability can be transformed into an asset for the local government if appropriate technologies are used. The proposal for a waste recovery park must contain the feasibility study for the sorting unit, the centralized composting of organic waste, the composting of green waste, the energy use of composting or incineration systems, the use of civil construction aggregates, the recycling of unserviceable items (e.g., furniture, mattresses, and other waste), and the recycling of electronics.

As for the final disposal of waste, measures to reduce impacts must be taken (i.e., action M.8), for example, the control of the exclusive destination of tailings for landfills, adequate treatment of leachate, and periodic inspection of the units. Controlled landfills and dumps must be closed and recovered in accordance with the NSWP (Brazil, 2010).

According to NSWP, large generators are responsible for the proper destination of waste (i.e., hazardous or nonhazardous; Brazil, 2007). Therefore, it is up to the local government to guarantee the inspection regarding the disposal of waste. For small generators, voluntary deliv-

Table 2 – Actions and policy tools for ISWM management.

Government actions	Policy tools
Management – minimization of waste generation	
M.1) Make domestic or community composters available to the population	Bidding process
Management – collection and transport	
M.2) Implement voluntary delivery points and green points for proper waste disposal	Bidding process
M.3) Promote training for waste workers	Social communication
M.4) Provide safety equipment for workers	Bidding process
M.5) Provide adequate work structure and equipment for workers	Bidding process
M.6) Establish differentiated collection for recyclables, organic, and tailings	Technical study
Management – waste treatment	
M.7) Study and enable the installation of a solid waste recovery park containing waste sorting and transformation units	Technical study
Management – final provision	
M.8) Carry out mitigating measures for the environmental impacts	Bidding process
Management – hazardous waste	
M.9) Implement hazardous waste disposal points for small generators and ensure supervision of large generators	Bidding process

ery points (i.e., action M.9) must be made available for waste classified as hazardous, which is not suited to reverse logistics.

Step 3: Assessment

The planning and management steps should be evaluated and revised periodically. Performance indicators are an important tool for analyzing the performance of the local government waste management system (Table 3).

The local government must constantly evaluate its management system through the use of performance indicators (i.e., action A.1; Zurbrügg et al., 2014). It is recommended to use indicators validated by the literature to assess the efficiency of the management system through information previously stored in a database. The sustainability indicators presented by Silva et al. (2019) are specific to small- and medium-sized municipalities and cover all areas of action of integrated management. These indicators must be evaluated at least once a year and can be compared with other municipalities with similar characteristics. Revisions and improvements must be made in case of the inefficiency of the system.

Applying ISWM in a medium-sized Brazilian municipality

The governmental action proposal was tested in a medium-sized municipality located in the southern region of Brazil. The municipality of Chapeco has 220,000 inhabitants and is located in the state of Santa Catarina (IBGE, 2020). The city stands out among small- and medium-sized municipalities due to adequate solid waste management (Brazil, 2019). Therefore, the application of this model can make the municipality a reference for others with similar characteristics in the dissemination of environmentally appropriate practices.

The applicability of the model of sustainable integrated management of solid urban waste for the municipality was evaluated (Table 4). The data collection related to local management was obtained through a questionnaire sent to the responsible sector of the local government. To identify the status of the current situation of the local management, a color traffic code was used for each action. The green color represents full service (i.e., actions taken or in progress), the yellow color represents partial service (i.e., actions started and not finished or actions suspended), and the red color represents no service (i.e., actions not implemented).

Among the 33 actions proposed, the municipality of Chapeco serves 17 actions (52%) with full service, 8 actions (24%) with partial service, and 8 actions (24%) without service. The biggest challenges are related to the planning aspects due to the lack of standardization, the lack of technical studies to evaluate the operating conditions of the system, and the lack of incentive to develop new businesses and to strengthen existing companies. It is recommended that the municipality restructures its management system, starting with the update of the BPSW so that all the items in Table 4 will be covered. The planning stage is fundamental for the involvement of the parties and to guarantee the engagement of the local government.

The municipality must implement the actions provided in the BPSW using the tools presented. The municipality needs to establish the responsibilities of reverse logistics through municipal legislation to inspect these activities. The municipality may adopt measures for the inclusion of recyclable material collectors in the selective collection, in an organized and remunerated manner. The municipality will be able to prepare a feasibility study for all operational sectors involved in waste management; thus, it will be possible to assess the demand for interventions in the management model.

In this sense, the municipality will be able to encourage the creation of a consortium to manage waste management in an inter-municipal manner. Economic development can be expanded through specific programs for companies that value waste in their process.

As for the treatment of waste, the municipality should implement a differentiated collection system for the fraction to be used in composting. The municipality will also be able to set up a waste recovery center, ensuring maximum efficiency in sorting and making use of recyclable material.

Finally, from this analysis, it was possible to assess the municipality's level of sustainability in relation to integrated waste management. The municipality is recommended to adopt an action plan defining priority actions and the resource planning to apply them.

Conclusions

Integrated waste management must be based on the principles of sustainability and depends on the commitment of the local government to carry out the actions proposed in this article. For this, an analysis must be carried out to identify which measures can be adopted by each municipality according to their demands and socioeconomic characteristics. Planning is the first step at which the municipality must structure itself. Through sound public policies, the local government will obtain support to define the responsibili-

Table 3 – Actions and policy tools for ISWM assessment.

Government actions	Policy tools
Assessment – performance indicators	
A.1) Establish quality indicators to assess the efficiency of the municipal management system	Normative instruction

Table 4 – Assessment conditions of application of ISWM in the municipality of Chapeco.

Government actions	Situation
Planning	
P.1) Implement the municipal policy of basic sanitation	
P.2) Implement the municipal plan for integrated solid waste management	
P.3) Create municipal department responsible for waste management	
P.4) Encourage employee participation in waste management courses and training	
P.5) Network with municipalities with similar characteristics	
P.6) Establish operational procedures for the management plan (considering all types of waste)	
P.7) Promote sectoral agreements between the parties involved and guarantee reverse logistics	
P.8) Include recyclable material collectors in the integrated management	
P.9) Define priority areas and actions for social inclusion	
P.10) Implement the municipal code of urban cleaning	
P.11) Join a regulatory agency to monitor contracts and tariffs	
P.12) Prepare technical–economic feasibility study in all operational sectors	
P.13) Implement the collection of services	
P.14) Stimulate the creation of management consortia and public–private partnerships	
P.15) Establish norms for participation in transparent bidding processes, guaranteeing publication in user access channels	
P.16) Create incentive programs for companies in the waste area	
P.17) Seek external financing for new investments	
P.18) Implement a tax incentive and certification program for companies that adopt environmental responsibility with their waste	
P.19) Create an environmental education program ensuring the minimization of waste generation	
P.20) Increase social communication through social media, newspapers, and television	
P.21) Develop training courses for users for proper waste management	
P.22) Promote local events and discussion forums focused on waste management	
P.23) Establish partnerships with universities for research development	
Management	
M.1) Make domestic or community composters available to the population	
M.2) Implement voluntary delivery points and green points for proper waste disposal	
M.3) Promote training for waste workers	
M.4) Provide safety equipment for workers	
M.5) Provide adequate work structure and equipment for workers	
M.6) Establish differentiated collection for recyclables, organic, and tailings	
M.7) Study and enable the installation of a solid waste recovery park containing waste sorting and transformation units	
M.8) Carry out mitigating measures for the environmental impacts caused in the process	
M.9) Implement hazardous waste disposal points for small generators and ensure supervision of large generators	
Assessment	
A.1) Establish quality indicators to assess the efficiency of the municipal management system	

ties of each party involved. The proposed actions consider environmental, social, and economic aspects, through environmental education programs that promote the minimization of waste generation and the reduction of impacts on the environment, the valorization, and social inclusion of recyclable material collectors and economic development through the standardization of service provision.

Following the management step, the municipalities will carry out actions related to the operational part of the management system, complying with the technical, environmental, and legal requirements regarding the collection, transportation, treatment, and final disposal of solid waste, guaranteeing the service to all users, economic sustainability, and appropriate technologies for each activity.

For the management stage, the municipality must establish differentiated waste collection and implement waste collection points not served by conventional collection, physical structure of machines and equipment suitable for the operation of activities and training of the team.

It is recommended to evaluate the implemented integrated management system through the use of selected reference indicators for small- and medium-sized municipalities. Municipalities can consult government reports to identify the data related to waste management, thereby establishing a benchmarking.

Finally, the study evaluated the conditions of applicability of the proposed methodology in the Brazilian city of Chapeco. The municipality can implement the actions proposed presenting an initial attendance of 52% of the proposed actions. It is recommended that the municipality should carry out a planning so that the other actions are adequate.

Contribution of authors:

Olivo, V.E.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, and Writing – original draft; Prietto P.D.M.: Conceptualization, Validation, Formal analysis, Investigation, Resources, Project administration, and Review & Editing; Korf E.P.: Conceptualization, Validation, Formal analysis, Investigation, Visualization, Supervision, and Review.

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Characterization and distribution of pesticide use from 2015 to 2019, by health regions in the state of Rondônia (RO), Amazon, Brazil

Caracterização e distribuição do uso de agrotóxicos no período de 2015 a 2019, por regiões de saúde em Rondônia (RO), Amazônia, Brasil

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ABSTRACT

Colonization projects and the consolidation of commodities production made ranching and agriculture one of the main economic activities in Rondônia (RO). Simultaneously to this process, there was an increase in the consumption of pesticides, resulting in risks to human health and the environment. Based on datasets of different origins, this article analyzed the spatial distribution of pesticide commercialization in the different health regions of the state of Rondônia (RO), between 2015 and 2019. We used data from the Rondônia State Pesticide Trade Inspection System (*Sistema de Fiscalização do Comércio de Agrotóxicos do Estado de Rondônia* – SIAFRO), managed by the Agrosilvopastoral Health Defense Agency of the State of Rondônia (*Agência de Defesa Sanitária Agrosilvopastoril do Estado de Rondônia* – IDARON); the Phytosanitary Pesticides System (*Sistema de Agrotóxicos Fitossanitários* – AGROFIT), the National Health Surveillance Agency (*Agência Nacional de Vigilância Sanitária* – ANVISA), the Brazilian Institue of the Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA) and of the IBGE Automatic Recovery System of the Brazilian Institute of Geography and Statistics (*Sistema IBGE de Recuperação Automática do Instituto Brasileiro de Geografia e Estatística* – SIDRA/IBGE). The consolidation of these data contributed to the analysis and presentation of the spatial distribution of the average amount of pesticides sold by health regions in RO and the main active ingredients sold, their use classification and quantity applied to each culture. We conclude that the production of commodities such as soy, corn, coffee, and pasture are the main drivers of pesticide commercialization in the study region. The main

RESUMO

A criação de projetos de colonização e a consolidação da produção de *commodities* tornou a agropecuária uma das principais atividades econômicas de Rondônia (RO). Simultaneamente a esse processo, deu-se o aumento do consumo de agrotóxicos, resultando em potenciais riscos à saúde humana e ao meio ambiente. Este artigo apresenta, com base no processamento de diversos bancos de dados, a distribuição espacial da comercialização de agrotóxicos em RO por regiões de saúde entre os anos de 2015 e 2019. Para tanto, foram utilizados dados do Sistema de Fiscalização do Comércio de Agrotóxicos de RO (SIAFRO), gerenciado pela Agência de Defesa Sanitária Agrosilvopastoril de RO (IDARON), consultas ao Sistema de Agrotóxicos Fitossanitários (AGROFIT), Agência Nacional de Vigilância Sanitária (ANVISA), Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA) e Sistema IBGE de Recuperação Automática do Instituto Brasileiro de Geografia e Estatística (SIDRA/IBGE). A consolidação desses dados contribuiu para a análise e a apresentação da distribuição espacial da quantidade média de agrotóxicos comercializada por regiões de saúde de RO e dos principais ingredientes ativos comercializados, classificação de uso e quantidade destinados por cultura. Concluiu-se que a produção de *commodities* como soja, milho, café e pastagem é o principal destino dos agrotóxicos comercializados nas regiões de saúde de RO e que os principais ingredientes ativos comercializados apontam um potencial risco à saúde pública e ao

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marketed active ingredients suggest potential risks to public health and the environment. In addition, the present safety criteria regarding pesticides, especially in Brazil, are outdated and lead to public health and environmental vulnerability.

Keywords: environment; environmental health; agriculture; Amazon.

meio ambiente. Além disso, os padrões de segurança atuais para agrotóxicos, sobretudo no Brasil, estão desatualizados e evidenciam a vulnerabilidade ambiental e de saúde pública.

Palavras-chave: meio ambiente; saúde ambiental; agricultura; Amazônia.

Introduction

In the 1970s, the federal government started to include the state of Rondônia (RO) in the movement to expand the agricultural frontier. This process generated transformations in the territorial division of labor and in the social relationship of traditional Amazonian communities and peasants through the creation of colonization projects focused on consolidating the production of commodities, which differed according to implementation strategies and occupational dynamics (Nunes, 1996; Oliveira et al., 2014; Oliveira, 2000; Beckmann and Santana, 2019).

In order to boost agribusiness, the Development Program for the Northwest Region of Brazil (*Programa de Desenvolvimento da Região Noroeste do Brasil* – POLONOROESTE (1981)), financed by the World Bank, and the Agricultural and Forestry Plan of Rondônia (*Plano Agropecuário e Florestal de Rondônia* – PLANAFLORO (1986)) were implemented in the 1980s. These programs served as stimuli to large businesses through tax exemption, non-refundable financing, and land distribution (Pelaez et al., 2012). Shortly before, in 1975, the federal government launched the National Agricultural Defense Program (*Programa Nacional de Defensivos Agrícolas* – PNDA), part of the policy to modernize agriculture at the time, which subsidized credit and encouraged the establishment of the pesticide industry in the country (Agência Câmara, 2006).

As a result of these stimuli, agriculture has become one of the main economic activities in RO, being in full expansion, with a great mobilization of agribusiness aimed at the production of agricultural commodities (Beckmann and Santana, 2019; Lobão and Staduto, 2020).

This type of agricultural production is generally linked to transnational corporations and sectors of the national elite that have a specificity: the appropriation and exploitation of nature, carried out predominantly illegally, legitimizing deforestation, regularizing land appropriation, consolidating and formalizing a market dynamic and modifying economic, social and cultural structures (Beckmann and Santana, 2019; Bühler and Oliveira, 2019).

Parallel to the scenario of growth in agricultural production, there is an increase in the consumption of pesticides. As a result, the intensification of the outcomes of socio-environmental impacts is observed, which affect biological and ecosystem diversity, environmental matrices such as soil, surface water, air, rain, and food. In addition, this increase in pesticide consumption affects the health of rural workers and surrounding residents with irreversible damage, such as cancer, malformations, kidney and liver damage, endocrine and neurological disorders, among others (Carneiro et al., 2015; Pignati et al., 2017; Bassani et al., 2018; Lorenzatto et al., 2020).

In an attempt to make invisible the implications of environmental, human, food, and occupational exposures, which are often ignored and neglected, public institutions, researchers, health professionals, and society face difficulties in obtaining reliable information on the consumption of pesticides in Brazilian municipalities (Pignati et al., 2017; Gaboardi et al., 2019).

In some states, a database system has been implemented with the objective of monitoring and inspecting the pesticide trade, managed by state agricultural defense agencies. Following this trend, since 2011 the Agrosilvopastoral Health Defense Agency of the State of Rondônia (*Agência de Defesa Sanitária Agrosilvopastoril do Estado de Rondônia* – IDARON) has had the Pesticide Trade Inspection System of the State of Rondônia (*Sistema de Fiscalização do Comércio de Agrotóxicos do Estado de Rondônia* – SIAFRO), through which companies declare the sales of these inputs (through monitoring agronomic receipts issued and controlling the packaging of the products sold).

This article proposes to present, based on the SIAFRO database, the spatial distribution of pesticide sales in the state of RO, by health regions (Rondônia, 2014), between the years 2015 and 2019. The information obtained can support the evaluation of exposure to pesticides and potential risks to human health and the environment, serving as an important source of information for future studies.

Material and Methods

The methodological construction of this article began with the collection of raw data at IDARON, the official body responsible for SIAFRO.

The data obtained via SIAFRO — after formal request — include the quantity sold and the commercial name of the pesticides, the purpose of use and the place of origin and destination by municipality in the period from 2015 to 2019. From the year 2016, the quantities of pesticides imported from other states were also obtained. Although SIAFRO has been available since 2011, its data became more consistent only from 2015; nonetheless, this is currently the most consolidated database in terms of quantifying pesticide use in the state of RO.

Next, the data were classified by health regions, considering units of interest for this study. The health regions are territorial sections of the Unified Health System (*Sistema Único de Saúde* – SUS) that bring together neighboring municipalities to gain sufficient scale and technological density to ensure comprehensive health care in at least 90% of people's needs. They are delimited based on cultural, economic, and social identities and on communication networks and shared transport infrastructure, in order to integrate the organization, planning and execution of health actions and services (Brasil, 2011; Santos, 2017). The health regions of RO are divided into seven territories and comprise the 52 municipalities of the state, namely: Madeira-Mamoré, Vale do Jamari, Central, Zona da Mata, Café, Cone Sul, and Vale do Guaporé (Rondônia, 2014).

The characterization of the quantity traded data was carried out considering the destination location. However, some of these locations were named by IDARON as "ignored districts" when filling out the registration in SIAFRO, on occasions when the destination location was not yet registered in the system. In these situations, for the purposes of this study, the place of origin was considered.

Based on the purpose of use data, available in the database, the percentage distributions of pesticides per crop were calculated. At SIAFRO, sales are entered in accordance with the agronomic prescription prescribed by a qualified professional with the commercial name of the pesticides. These data were used for classification of use and its active components were obtained based on the online consultation tool of the Phytosanitary Pesticides System (*Sistema de Agrotóxicos Fitossanitários* – AGROFIT). This system consists of a database of all pesticides and related products registered with the Ministry of Agriculture, Livestock, and Supply (*Ministério da Agricultura, Pecuária e Abastecimento* – MAPA), with information from the National Health Surveillance Agency (*Agência Nacional de Vigilância Sanitária* – ANVISA) of the Ministry of Health and information from the Brazilian Institute of Environment and Renewable Natural Resources (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* – IBAMA) of the Ministry of Environment.

The indicators of agricultural production and economic situation — Demographic Census, Agricultural Census and Municipal Agricultural Production (*Produção Agrícola Municipal* – PAM) — were obtained from the IBGE Automatic Recovery System of the Brazilian Institute of Geography and Statistics (*Sistema IBGE de Recuperação Automática do Instituto Brasileiro de Geografia e Estatística* – SIDRA/IBGE). Data from IBAMA and MAPA were obtained in the Brazilian Open Data Portal, a tool made available by the federal government since 2019.

The formation and processing of the various databases into a single consolidated database for the analyses were carried out using Microsoft® Office Excel® software and R software, version 3.6.2. To interpret the results, descriptive analysis of the data by position and amplitude parameters was applied. The preparation and analysis of the maps was also carried out using R software, version 3.6.2.

Results

In RO, the area of agricultural establishments accounts for 40% (9,219,883 ha) of the total area of the state. Of these, 2.4% (223,522 ha) represent permanent crops, 5.9% (544,793 ha) temporary crops, 88.5% (8,159,651 ha) are destined to livestock and other animals, and 3.2% (291,917 ha) are intended for other activities in the agricultural sector, such as horticulture, floriculture, forestry, fishing, and aquaculture. In 2017, there were 91,438 agricultural establishments, and 81% (74,329) of them carried out family farming, occupying 3,480,247 hectares. Non-family establishments consisted of 19% (17,109) and occupied 5,739,636 hectares of the total area (IBGE, 2017a).

Figure 1 shows the areas of agricultural establishments by municipality and the average planted area by municipality in the period from 2015 to 2019. The Madeira-Mamoré region comprises five municipalities, including the state capital — Porto Velho — and has a total of 1,367,638 hectares for agriculture, 1,082,228 hectares for livestock and for raising other animals, and 59,560 hectares for plantations (IBGE, 2020b).

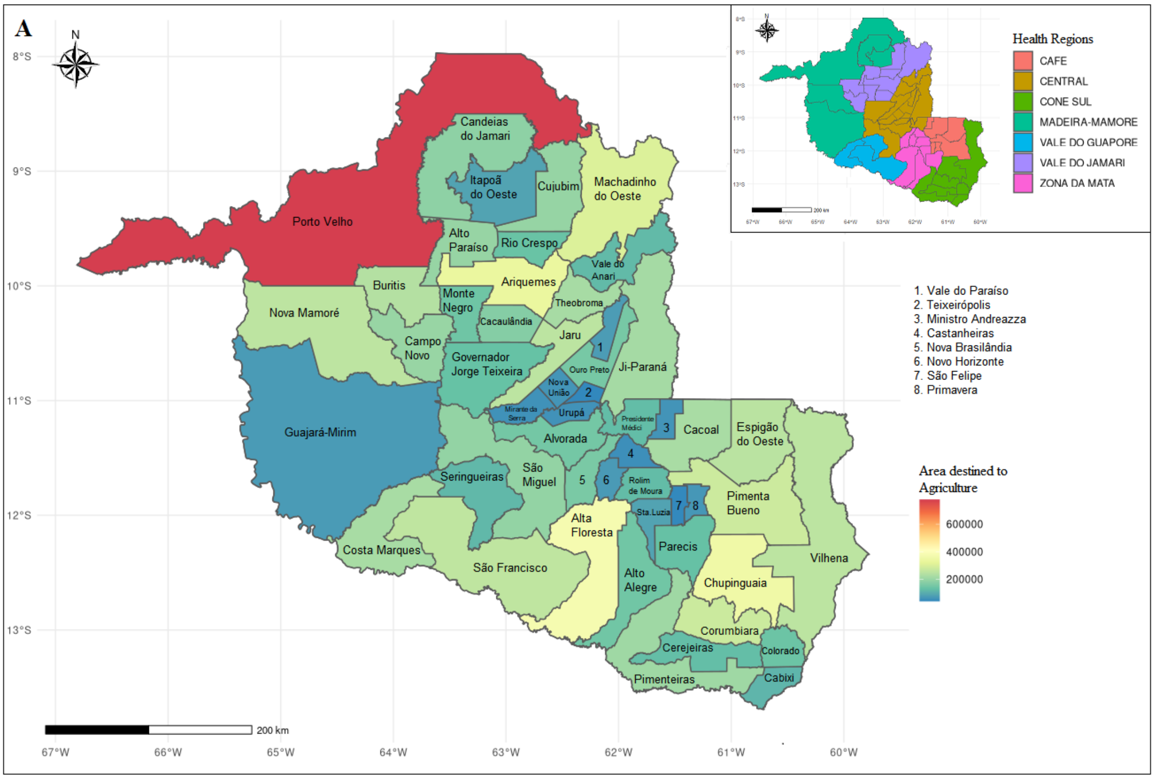
The Central region is made up of fourteen municipalities, with 1,842,585 hectares destined to agriculture and a planted area of 57,569 hectares. The region of Vale do Guaporé, with only three municipalities (Costa Marques, São Francisco do Guaporé and Seringueiras) has 592,773 hectares destined to agriculture, 12,905 hectares of planted area, and 98% (579,868 ha) of area destined to cattle raising.

The Vale do Jamari region stands out for covering the largest area destined for cattle raising in the state, with a total of 1,826,229 hectares, while the Cone Suk region, with 349,360 hectares, has the largest planted area in the state.

The Zona da Mata region, with eight municipalities, represents 1,135,216 hectares of agricultural establishments and has a planted area of 68,169 hectares. The Café region is made up of six municipalities, totaling 909,437 hectares for agriculture and 33,895 hectares of planted area.

According to the 2017 Agricultural Census, the state of RO is among the 15 largest consumers of pesticides in Brazil and in first place in the North region (IBGE, 2017a). In the same year, the Gross Domestic Product (GDP) of the state of RO, in current values, totaled R$ 43 billion (R$ 24,092.81 per capita), representing 11.83% of the GDP of the North Region and 0.7% of the Brazilian GDP, mainly influenced by agriculture (Sepog, 2017).

The contribution of a given activity to the GDP is sized through the Gross Value Added (GVA), which is the final result of the productive activity in a given period. The state's total GVA grew 19.6% in volume between the years 2016 and 2017. The agricultural GVA had a 13.5% share (BRL 5.8 billion) in the state's GDP and represented 15% of the state's total GVA (IBGE, 2017b).



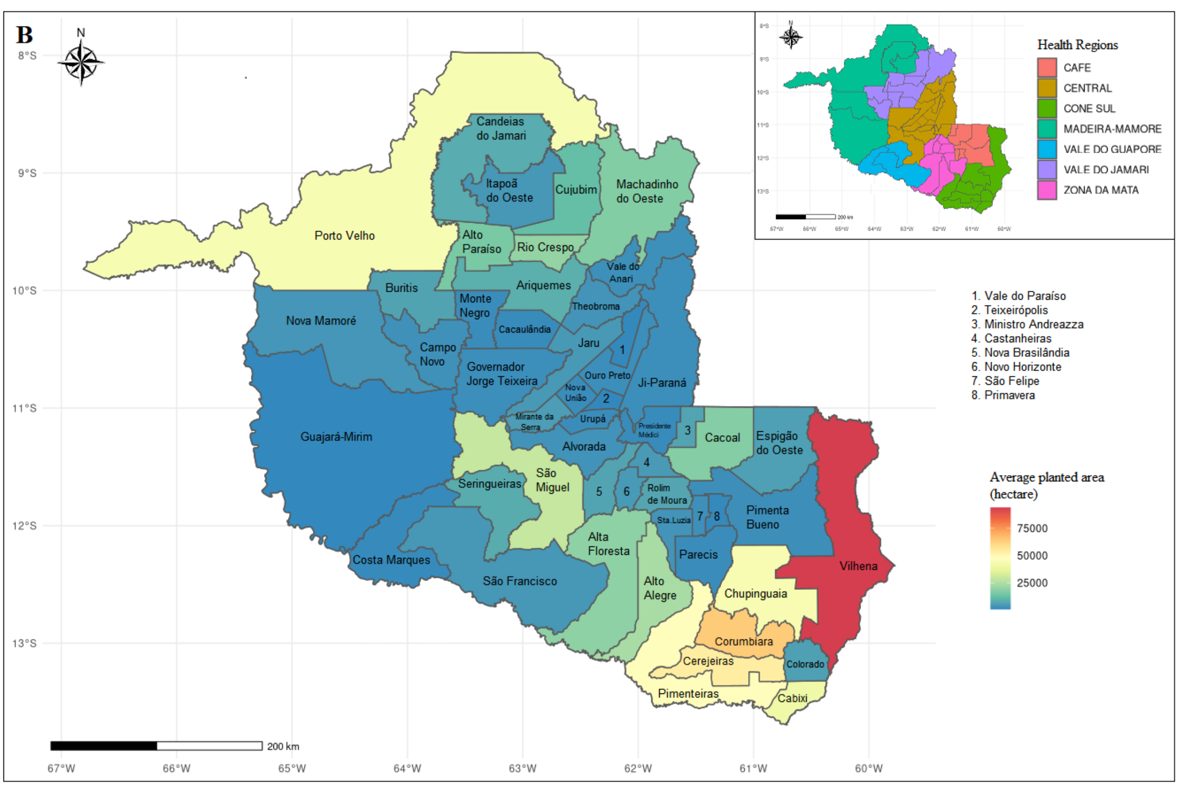


Figure 1 – Distribution of areas of agricultural establishments and average planted area (in hectares) in the municipalities of Rondônia. (A) Distribution of area destined to agriculture (in hectares) in the municipalities of Rondônia. (B) Distribution of the average planted area (in hectares) in the municipalities of Rondônia.
Source: data from IBGE (2020b).

According to the Secretary of State for Planning, Budget, and Management (*Secretaria de Estado do Planejamento, Orçamento e Gestão* – SEPOG), agriculture accounted for 3.3% of the state's total GVA and the main products that contributed to the growth of the activity in volume (which was 31.6% in the year) were: soy, corn, coffee, rice, and beans. Livestock, which corresponded to 9.9% of the state's GVA, had an increase in volume of 11.1%, with emphasis on milk production and the increase in the number of cattle. Forest production, fishing, and aquaculture represented 1.7% of the state's GVA (Sepog, 2017).

Regarding the participation of municipalities in the agricultural GVA, Porto Velho stood out in relation to the others, contributing with 10% (R$ 589,995) of the state's total amount. Some municipalities concentrated more than 50% of their GDP in agriculture, namely: Corumbiara 69%; Castanheiras 68%; Pimenteiras do Oeste 62%; Rio Crespo 56%; Cacaulândia 53%; Alto Alegre do Parecis and Governor Jorge Teixeira 52% (IBGE, 2017b).

Between 2015 and 2017, the total amount of pesticides sold in RO registered an annual increase. In 2015, 7,231 tons of pesticides were sold, 8,961 tons in 2016 and 11,152 in 2017. A gradual reduction began in 2018, with the sale of 9,563 tons, while in 2019 there were 9,090 tons, according to data from IDARON/SIAFRO (2020).

Figure 2 shows the amount of pesticides sold in tons (average 2015–2019) in the municipalities of RO. The Cone Sul region, located in eastern Rondônia, on the border with the state of Mato Grosso, acquired a total of 17,833 tons of pesticides in the period, with an average of 3,567 tons per year, accounting for 38.8% (17,833 t) of the total acquisition of the state and standing out in relation to other regions.

The region of Vale do Guaporé, the smallest in the state, purchased a total of 1,717 tons of pesticides, with an average of 343 tons per year, the smallest amount sold among the health regions.

Figure 3 shows the amount, in kilograms per inhabitant, of pesticides sold (average 2015–2019) in the municipalities of RO. Data provided by IDARON/SIAFRO (2020) showed that between 2015 and 2019, in terms of per capita consumption, the state had an average of 5.2 liters/inhabitant, while the national average is 8.1 liters/inhab. according to IBGE (2020a).

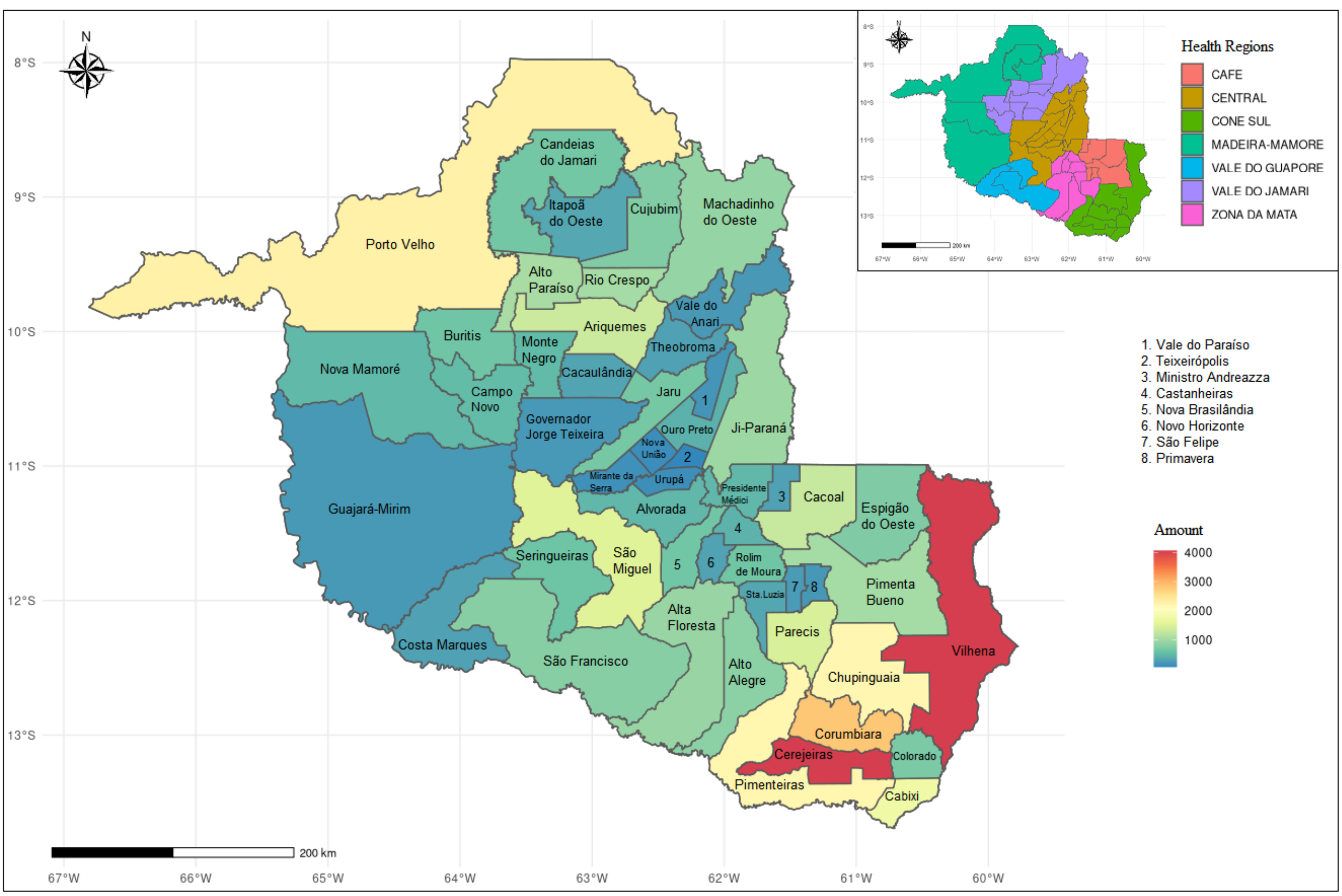


Figure 2 – Amount of pesticides sold in tons (average 2015–2019) in the municipalities of Rondônia.
Source: data from IDARON/SIAFRO (2020).

The Cone Sul region, with an average of 22.6 kg/inhabitant, stood out in relation to the national average and to other health regions. The municipality of Pimenteiras do Oeste, which integrates the region, had 191.34 kg/inhabitant, the highest amount of pesticide consumption per inhabitant, surpassing the averages of the other municipalities of RO, the health regions, and the state and the national averages.

The Madeira Mamoré region, with an average quantity of 1.3 kg/inhabitant, had the lowest average among the health regions and was below the state and national averages. The municipality of Itapuã do Oeste stood out among the municipalities in the region, with an average quantity of 6.70 kg/inhabitant, surpassing the average for the state. However, it is important to emphasize that the region has the highest population concentration compared to other regions, a factor that contributes to the reduction in the average amount of pesticides per inhabitant.

Figure 4 shows the amount of pesticides sold (average 2015–2019) in relation to the cultivated area of temporary and permanent crops. In Brazil, in the same period, the average amount of pesticides sold in relation to the cultivated area of temporary and permanent crops was 21.5 kg per hectare, with a maximum in 2019 of 23.6 kg per hectare (IBAMA, 2020; IBGE, 2020b).

The state of RO presented an average of 13.8 kg per hectare. As for the health regions, Vale do Guaporé had the highest average amount per hectare in the period (26.7 kg/ha), the highest in 2016 (30.5 kg/ha). The Cone do Sul region, with 10.2 kg/ha, the highest also in 2016 (11.9 kg/ha), had the lowest average amount of kilograms per hectare. In more than 75% (39) of the municipalities the average quantity per hectare was higher than the state average and 46% (24) of them had a higher average than that in Brazil.

In the period from 2015 to 2019, the amount of pesticides sold was distributed as follows: 17,635 t (38.3%) for pasture application, 16,655 t (36.2%) for soybean cultivation, 5,707 t (12.4 %) for corn cultivation, 2,390 t (5.1%) for coffee, and 3,612 t (8%) for other crops such as beans, rice, fruits, vegetables, and others.

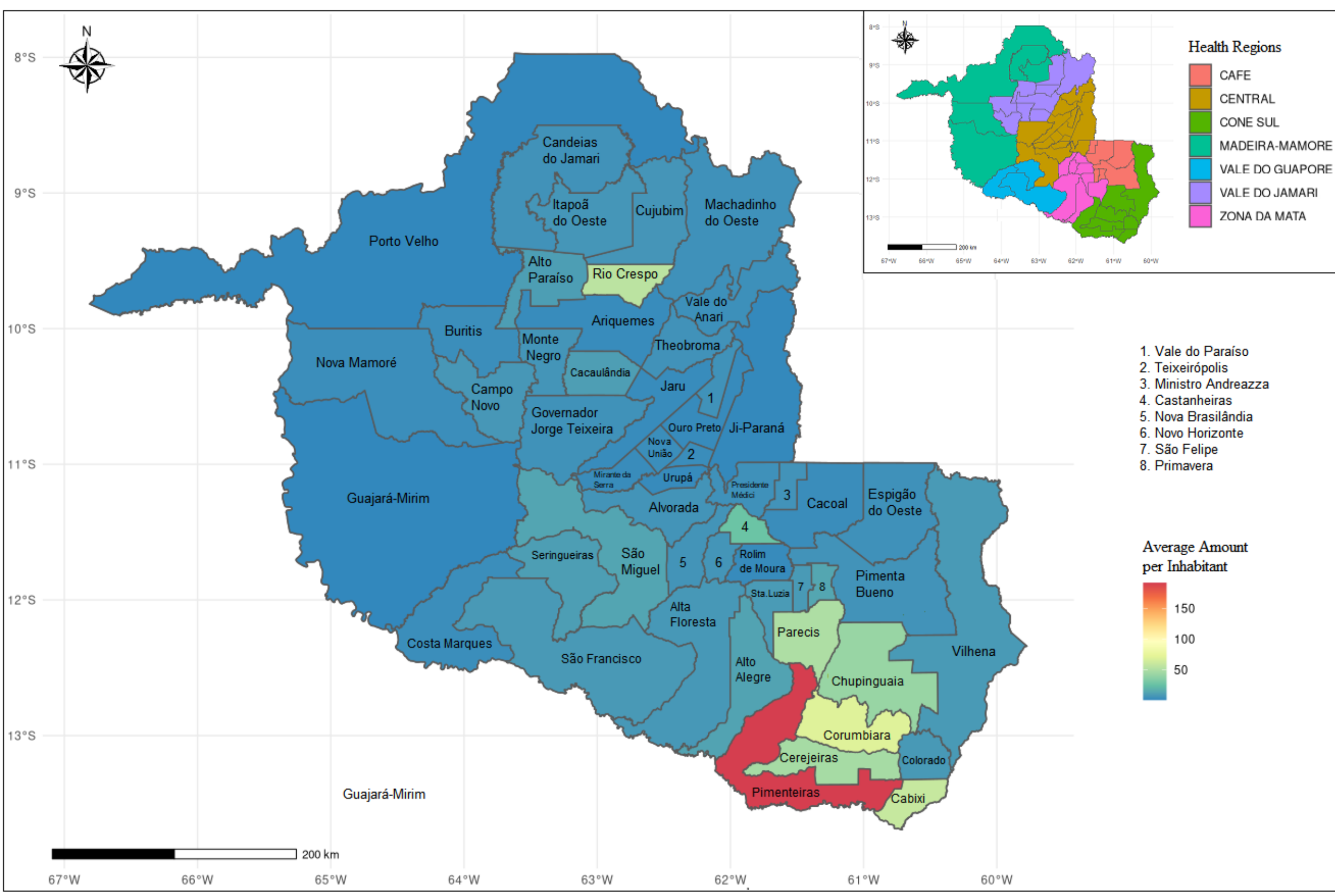


Figure 3 – Quantity in kilograms per inhabitant of pesticides sold (average 2015–2019) in the municipalities of Rondônia.
Source: data from IDARON/SIAFRO (2020).

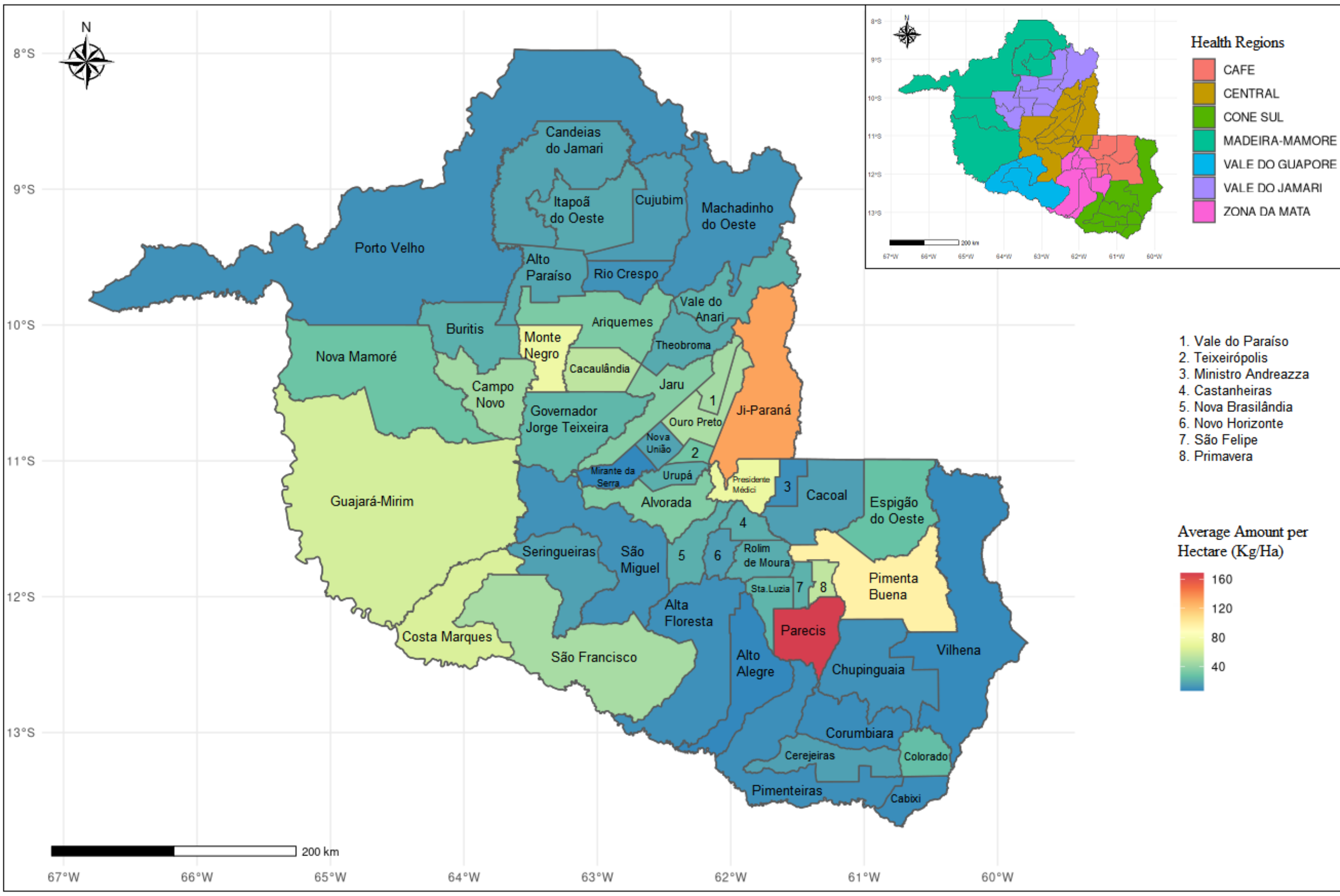


Figure 4 – Quantity of pesticides sold in kilograms per cultivated area of temporary and permanent crops (average 2015–2019) in the municipalities of Rondônia.
Source: data from IDARON/SIAFRO (2020).

When the destination of pesticides sold for pasture was evaluated, the Café region had the highest percentage (69%); the Cone do Sul the lowest percentage (10%), and the other percentages above 48%. On the other hand, when the destination was soybean cultivation, the Cone do Sul region stood out, accounting for 63% (11,174 t) of sales of these products and the Café region had the lowest percentage, 5% (172 t).

During this period, an average of 431 different products were sold in the state of RO. Among them, the 20 most commercialized active ingredients totaled 17,420 t, accounting for 38% of total consumption. They are: the 2,4-D herbicides, ametrine, atrazine, clomazone, diuron, flumioxazine, and glyphosate; the insecticides abamectin, acephate, fipronil, chlorpyrifos, imidacloprid, lambda-cyhalothrin, and thiamethoxam; and the fungicides azoxystrobin, carbendazim, chlorothalonil, flutriafol, mancozeb, and tebuconazole (Figure 5). In all health regions, Glyphosate is the most commercialized pesticide, except in the Café and Zona da Mata regions, where it ranks third.

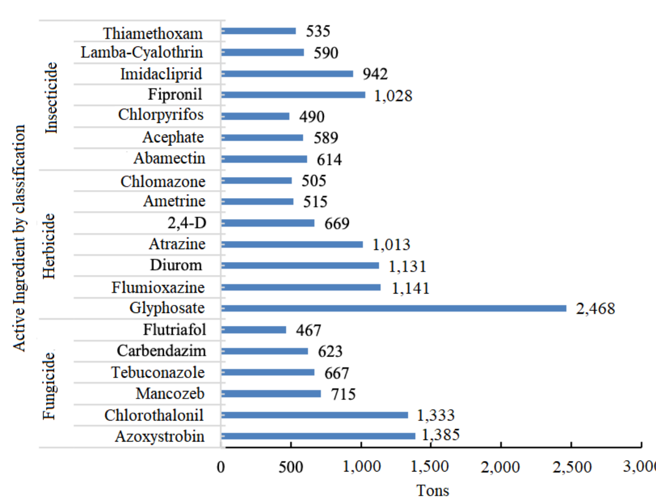


Figure 5 - Total commercialized quantity of the 20 active ingredients, by classification, in the state of Rondônia, in the period from 2015 to 2019 (in tons).
Source: data from IDARON/SIAFRO (2020).

Table 1 presents the classification of the 20 most commercialized active ingredients in RO regarding environmental hazard, following the following graduation:

- class I: extremely toxic;
- class II: highly toxic;
- class III: moderately toxic;
- class IV: little toxic.

And the toxicological classification:

- category 1: extremely toxic product;
- category 2: highly toxic product;
- category 3: moderately toxic product;
- category 4: little toxic product;
- category 5: product unlikely to cause acute damage;
- unclassified (Anvisa, 2019c; Brasil, 2020b).

Table 1 – Classification of environmental hazard potential and toxicological classification of the most commercialized active ingredients in the period from 2015 to 2019 in Rondônia.

Active Ingredients	Classification for Environmental Hazard	Toxicological Classification
2,4-D	Class I	Category 4
Abamectin	Class I	Category 4
Acephate	Class I	Category 4
Ametrine	Class IV	Category 5
Atrazine	Class II	Category 4
Azoxystrobin	Class IV	Category 5
Carbendazim	Class III	Category 5
Chlomazone	Class III	Category 5
Chlorothalonil	Class II	Category 4
Chlorpyrifos	Class I	Category 3
Diurom	Class II	Category 5
Fipronil	Class I	Category 3
Flumioxazine	Class II	Category 5
Flutriafol	Class I	Category 4
Glyphosate	Class III	Category 5
Imidacloprid	Class I	Category 4
Lambda-Cyalothrin	Class II	Category 5
Mancozeb	Class I	Category 5
Tebuconazole	Class III	Category 5
Thiamethoxam	Class III	Category 5

Source: IDARON/SIAFRO (2020).

Discussion

Agribusiness has become the protagonist of economic growth in RO, with an expressive participation in the state's economic indicators (GDP and GVA). This performance is a reflection of the expansion of agricultural frontiers over biomes, such as the Amazon forest, since the implementation of monocultures requires high productivity goals and dependence on pesticides to combat "pests" (Carneiro et al., 2012; Lobão and Staduto, 2020).

Since the implementation of monocultures, there has been a consolidation of a production model aimed at concentrating land and interfering in the way of life of traditional communities, generating an unrestrained exploitation of the environment and impacts on the health of the population (Carneiro et al., 2012; Carneiro et al., 2015; Pignati et al., 2017).

In RO, there is land concentration concomitantly with the predominance of establishments that practice family farming. According to IBGE (2017a), the relationship between the total area devoted to agriculture (in hectares) and the number of agricultural establishments results in an average area of 47 hectares in establishments classified as family farming, while those of non-family farming reached an average of 335 hectares. This was a value higher than that found in Brazil (21 hectares in family farming and 230 hectares in non-family farming).

Since 1995, the National Program for Strengthening Family Agriculture (*Programa Nacional de Fortalecimento da Agricultura Familiar* – PRONAF) has been implemented, an agricultural public policy fundamental to this type of agriculture, which provides differentiated financing conditions (Bühler et al., 2016; Dyngeland et al., 2020), providing the farmer with the opportunity to expand production and/or increase productivity. On the other hand, the resources arising from this financing are largely used in the purchase of pesticides (Grisa, 2012; Bühler et al., 2016).

The use of pesticides in family farming is a challenge to both health and environment, due to the deficiency in technical assistance, the precariousness of guidelines for their proper use, the lack of perception of the risk to which these workers end up exposed, in addition to intradomiciliary contamination and inadequate disposal of waste from the production process and empty packaging of the products used (Wahlbrinck et al., 2017; Waichman et al., 2007; Buralli et al., 2018; Ndayambaje et al., 2019; Bagheri et al., 2021).

Official data for the period 2015 to 2019 show that the sale of pesticides in the state of RO decreased from the year 2018 — 7,231 tons were sold in 2015, 9,563 tons in 2018, and 9,090 tons in 2019 (Idaron and Siafro, 2020). For Gaboardi et al. (2019), one of the hypotheses for this reduction is the supply of illegal products, given the border between RO and Bolivia, which could favor this type of crime.

The illegal importation of these products into Brazil occurs mainly across land borders and is motivated by the fact that they are cheaper than products sold nationally (despite the fact that pesticides are exempt from taxes in Brazil), by legislation that facilitates unrestricted and free sales of products in bordering countries and by the possibility of purchasing products that are prohibited in Brazilian territory, but which are legally marketed abroad (Dorfman and Rekowsky, 2011; Lemos et al., 2018).

Other alternatives to consider for this reduction would be: the incentive to reduce the use of pesticides in RO, in parallel with technical assistance and more adequate management techniques (however, it is not possible to obtain concrete information in this regard); and/or some type of inconsistency in the data collected in SIAFRO. Despite the broad incentive for the use and production of pesticides in Brazil, access to information about these substances is still precarious (Gaboardi et al., 2019).

The data obtained from SIAFRO are not an exact representation of the reality of pesticide consumption in RO. As in any database, several factors can introduce inconsistencies, including: purchases made without presenting the agronomic revenue, leading to an underestimation of the total traded; the use of pesticides in crops other than those indicated in the recipe, and possible typing and filling errors (Neves and Luiz, 2006).

Another example is the IBAMA data, which present information on production, import, export, and sales of active ingredients to Brazil; however, when the data is searched by states and regions of Brazil, only the quantification of sales is presented, without accounting for imports and exports, generating a lower value than the data collected in SIAFRO.

By analyzing the spatial distribution of the amount of pesticides sold in the health regions of RO (Figure 2), it was possible to relate it to the historical context of the agricultural movement in the state. An example is the Cone do Sul region, which, in 1980, had the municipality of Vilhena as a pioneer in soybean production in RO and later had its production spread throughout neighboring municipalities, becoming the "soy agribusiness region", with the presence of Amaggi and Cargill trading companies. There, agriculture typified as non-family predominates, increasing the importance of the region in the state's economy (Silva, 2013; IBGE, 2020b).

Until the end of the 1990s, the municipalities of Vilhena and Cerejeiras together produced practically all the soy in the state. Then, Chupinguaia and Corumbiara were also included in the production of this crop. Today, the region has the largest planted area in the state and, consequently, the largest commercialization of pesticides in relation to other health regions.

Based on the panorama of pesticide commercialization in RO and considering that excessive exposure to these substances causes several public and environmental health problems (Kim et al., 2017; Van Bruggen et al., 2018), one can speculate that greater chances of exposure to pesticides are in places where the ratio between the total amount of pesticides sold and the number of inhabitants is higher (Anderson et al., 2013; Dutra e Ferreira, 2017; Leão et al., 2018).

In this way, it is possible to scale the importance and assess the possible impacts of pesticides on public and environmental health. It is important to emphasize that the results do not consider that not all crops that use pesticides are for food (for example, cotton) nor do they consider the level of human exposure according to the proximity to rural areas (Gaboardi et al., 2019).

The absence of reliable control over the use of these products contributes to the invisibility of impacts, originating from their manufacturing stage, through their production chain, in addition to the risks of occupational exposure of rural producers, exposure of the population that resides or frequents nearby contaminated areas and the contamination of the environment by pesticide residues, until reaching the final consumer through the residues of these substances in food and water in urban areas (Belo and Peres, 2011; Kong et al., 2014; Mostafalou and Abdollahi, 2017; Pignati et al., 2017; FAO et al., 2018; Li et al., 2021).

Various health problems including cancer, diabetes mellitus, respiratory disorders, neurological disorders, reproductive syndromes (sexual/genital), and oxidative stress are caused by direct exposure to pesticides, handling pesticides or pesticide residues present in food (Mostafalou and Abdollahi, 2017; Chevrier and Béranger, 2018; Kalliora et al., 2018).

Certain groups of pesticides have the ability to modify the balance and function of the endocrine, immune, and neurological system (Cremonese et al., 2012; Pinheiro and Souza, 2017; de Araújo-Ramos et al., 2021). Therefore, fetal susceptibility to environmental exposure is even more critical if contact with these substances occurs early in the prenatal period, with risk of prematurity, low birth weight, reduced weight for gestational age, intrauterine growth retardation, reduced height and head circumference of the neonate, fetal death, poor Apgar score, and congenital malformations (CM), such as cryptorchidism and hypospadias (Cremonese et al., 2012; Carmichael et al., 2016; Froes Asmus et al., 2017; Ling et al., 2018; Toichuev et al., 2018). Prevention and investigation of risk factors for CM have been considered relevant to public health. Dutra and Ferreira (2019) analyzed the trend of CM and the use of pesticides in microregions of Brazilian states with greater production of agricultural commodities and found that the environmental exposure to pesticides suffered by the population of the studied microregions and states has increased over time, as well as the incidence of CM.

Another point to be considered is the presence of pesticide residues in water and food, which is one of the most urgent concerns in the debate on food safety in the world (FAO, 2018; Kong et al., 2014). In a study by Galvan et al. (2020) in the hydrographic basin of the São Domingos River, in Cunha Porã, Santa Catarina (SC), where the main economic activity is agriculture, it was found that 55% of the springs are contaminated with pesticides. These springs are the main sources of water to supply families, being used both "in natura" and for food preparation.

Regarding environmental impacts, pesticides can pollute the soil, water, air, fauna, and non-target vegetation (Bhandari et al., 2020; Fernandes et al., 2020; Rani et al., 2020). Nogueira et al. (2012) found nine out of 11 active principles analyzed in surface, underground and rainwater in urban and rural areas of Lucas do Rio Verde, Mato Grosso, where the use of pesticides is considered excessive.

Also in the state of Mato Grosso, Nasrala Neto et al. (2014) recorded reports of environmental impacts caused by the use of pesticides in several municipalities, such as: contamination of the water table, mortality, and reduction of fish in rivers close to agricultural production areas, inability to produce fruits and vegetables, and vanishing of birds. In addition to these factors, the destination of use of agricultural areas is an important factor to be observed, since it introduces potential risks to human health and the environment. In RO, the use of pesticides for pasture and commodity production predominates.

The livestock production chain is identified as the main cause of deforestation, fires, and the use of pesticides, which are among the biggest environmental issues in Brazil today (Almeida et al., 2017; Mello e Artaxo, 2017; Froehlich, 2019).

The conversion of forests into pastures is carried out by clearing vegetation and burning plant material, encouraging greater use of pesticides for pasture maintenance, control of pests and herbs rejected by cattle, in addition to the use of household cleaning products in corrals and control of external and internal parasites of the herd (Focus, 2010; Pequeno and Oliveira, 2015). Another important factor is animal feed with cereals, sugar cane and other sources, in whose production pesticides are also used (Cardeal and Paes, 2006).

In Brazil, the number of pesticides authorized by the Ministries of Health and Environment and registered by MAPA is growing. In 2015, there were 139 registrations, 404 in 2017, 474 in 2019, and 405 products were registered or have already been registered in 2020 (Brazil, 2020a). Parallel to IBAMA data, eight of the 20 most commercialized active ingredients in RO are among the 10 most sold in Brazil in the same period (IBAMA, 2020). A key factor to be mentioned is that, of the 504 active ingredients with authorized registration, that is, allowed for use in Brazil, 149 of them are prohibited in the European Union (EU). Among the active ingredients banned in the EU, five are the most sold in RO, namely: Acephate, Atrazine, Ametrine, Abamectin, and Carbendazin (Gonçalves, 2016; Bombardi, 2017).

In Brazil, there are 150 pesticides authorized for the cultivation of soy and, of these, 35 are prohibited in the EU. For the cultivation of coffee, 121 different pesticides are authorized, 30 of which are also banned in the EU, most of them since 2002 (Bombardi, 2017).

In RO, the most commercialized active ingredients have herbicidal action, as occurs in the rest of Brazil. Herbicides are mainly used in monocultures to avoid competition for water and nutrients with the cultivated plant, causing crop losses (Marchi et al., 2008). Among herbicides, the most commercialized active ingredient is glyphosate, which leads the ranking in RO and in Brazil, both in that period and in the last 10 years (Ibama, 2020).

In Figure 5, the quantity of glyphosate is represented only by products in which the nomenclature "glyphosate" appears. Importantly, there are several formulations that have a portion of an active ingredient, but they are of different chemical species and have different Chemical Abstract Services (CAS) registration numbers, such as: glyphosate, glyphosate potassium salt, isopropylamine salt of glyphosate, ammonium salt of glyphosate, and dimethylamine salt of glyphosate (Gaboardi et al., 2019).

In 2019, ANVISA released the new regulatory framework for pesticides (Anvisa, 2019a) in order to comply with the standards of the Globally Harmonized System of Classification and Labeling of Chemicals (GHS). This system was launched in 1992, during ECO 92, and endorsed by the General Assembly of the United Nations (UN) to strengthen international efforts related to the environmentally safe management of chemical products (Brazil, 2019). The new classification aims to match the 53 countries that adopt the GHS standards and thus strengthen the commercialization of domestic products abroad and the import of foreign products.

GHS defines the classification for product labeling purposes according to the death outcome analyzed in acute toxicological studies. The proposal is to establish scientific criteria to compare toxicity (toxic action) between products based on mortality (Anvisa, 2019b; Lopes and Padilha, 2019), which will therefore exclude all the numerous health effects that do not lead to death.

In Brazil, the registration process is carried out by three public institutions: Anvisa, which assesses issues related to human health; MAPA, which takes care of agronomic issues and is responsible for registering products for agricultural use; and IBAMA, which is responsible for environmental issues (Anvisa, 2019a).

Classifications are defined by active ingredients, without considering the inert ingredients and/or additives used in the manufacture of commercial products, nor the adjuvants used to increase their efficiency or modify certain properties of the solution. To aggravate the situation, only the active ingredients are subject to toxicological tests and not the commercial product actually used in crops.

Dutra and Ferreira (2017), when analyzing the association between the use of pesticides and congenital malformations in municipalities with greater exposure to pesticides in the state of Paraná between 1994 and 2014, cited some active ingredients that have the potential for toxic effects on the endocrine system and in the reproductive system, among which: acephate, atrazine, azoxystrobin, chlorothalonil, deltamethrin, diuron, glyphosate, and imidacloprid.

Glyphosate is a substance with potential toxic and mutagenic effects on the cardiovascular, hepatic, endocrine, and reproductive systems. It affects embryonic, fetal, and placental cells, being also recognized as an inducer of autism and depressive-like behavior (Hess e Nodari, 2018).

Atrazine, banned in the European Union since 2004 (Bombardi, 2017), has toxic properties on the immune system (Lee and Choi, 2020). In the endocrine system, it has a disruptive action on testosterone, prolactin, progesterone, luteinizing hormone, and estrogen (Zhu et al., 2021). In pregnant women, it resulted in the birth of babies with lower weight than expected, in addition to chromosomal damage in workers in atrazine-producing industries (Chevrier et al., 2011; Zhu et al., 2021).

Acephate has been banned in the EU since 2003 (Bombardi, 2017). In the analyses carried out by ANVISA's Program for the Analysis of Pesticide Residues in Food (PARA) — whose objective was to structure a service to assess and promote the quality of food that reaches the consumer in relation to the use of pesticides and the like, in the periods from 2013 to 2015 and 2017 to 2018 — Acephate had the highest rate of irregular detections, having been observed in unauthorized crops (Anvisa, 2016; 2019b).

Pesticides will continue to be part of modern agriculture and much remains to be learned about their potential exposure effects, particularly on subpopulations that may be especially sensitive. Furthermore, there are several pesticides that have been recently introduced and for which there is no data on potential toxicity.

Conclusion

The growing global demand for food intensifies concerns on food safety and the permitted levels of exposure to pesticides present throughout the production chain. In addition to the paucity of data for monitoring the marketing and use of pesticides and considering what is known to date about these substances, as well as the knowledge gaps that continue to raise concerns, it was possible to infer that current safety standards for pesticides, especially in Brazil, are outdated and may not protect public health and the environment. In this sense, this study aimed to provide a detailed overview of the marketing, destination, and use of pesticides in the state of RO. We concluded that the sale of pesticides in the state of RO decreased between 2015 and 2019. During this period, the main destinations of pesticides were application in pasture and soybean cultivation. The Café region was responsible for the highest percentage of pesticides destined for pasture, and the Cone do Sul region for soybean cultivation. The Cone do Sul region also stood out in relation to the others in the total quantity marketed and in the average per capita consumption, surpassing the national average. The main ingredients used in RO were glyphosate, chlorothalonil, azoxystrobin, diuron, flumioxazine, atrazine, and fipronil. The information generated in this work allows to identify priority areas for environmental and health monitoring in the state of Rondônia, those with greater exposure to pesticides.

Author's contribution:

Franco, T.F.: Data curation, Formal analysis, Research, Methodology, Writing – original draft and editing; Parmejiani, R.S.: Data curation, Research; Cunha, M.P.L.: Data curation, Acquisition of financing, Project administration, Resources; Miranda, A.: Data curation, Formal analysis, Methodology, Writing – review; Marques, R.C.: Conceptualization, Writing – review and editing; Guimarães, J.R.D.: Conceptualization, Acquisition of Financing, Project Management, Resources, Supervision, Writing – review and editing.

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Air pollutants associated with surface meteorological conditions in São Paulo's ABC region

Poluentes atmosféricos associados a condições meteorológicas de superfície na região do ABC em São Paulo

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ABSTRACT

Air pollution is one the main environmental problems in urban areas like the Metropolitan Area of São Paulo (MASP) in Brazil, where millions of inhabitants are exposed to pollution concentrations above the standards, with potential health impacts. Exposure is unequal throughout MASP, relying on the dynamics of local emission sources interplaying with weather and climate in a regional scale. The ABC region — ABC standing for Santo André, São Bernardo do Campo and São Caetano do Sul, the cities the area originally comprised of — is MASP's largest industrial center, sitting in its southeast border, and encloses environmental protection areas. That leads to a unique emission profile that differ from the metropolis center. This study aims to characterize the variability of atmospheric pollutants in the ABC region in 2015, investigating possible sources and associations with surface meteorological conditions. Multivariate statistical analyses were applied to data from seven air quality monitoring stations and surface meteorological variables. Results show that São Bernardo do Campo stood out, with O_3 concentrations 20% higher (43±19 $\mu g.m^{-3}$) than the other sites, while São Caetano do Sul had the highest annual mean PM_{10} concentrations (39±19 $\mu g.m^{-3}$), mostly related to vehicular emissions. Relative humidity was negatively correlated with primary pollutants, while temperature and radiation correlated with O_3. Unusually high O_3 concentrations were observed in January of 2015, concomitant with negative anomalies of precipitation and relative humidity, likely associated with the 2014/2015 summer drought event in Southeast Brazil. Overall, results show that local emission sources significantly impact air pollution loading and its diurnal variability, particularly in the case of primary pollutants. Climate modulates the seasonal concentration variability, and regional scale weather phenomena may impact air quality conditions. To reach concentration standards everywhere, policy makers must be aware of processes occurring in different spatial scales that determine air quality.

Keywords: air pollution; particulate matter; tropospheric ozone; multivariate analysis; Brazil.

RESUMO

A poluição atmosférica é um dos principais problemas ambientais em áreas urbanas como a Região Metropolitana de São Paulo (RMSP), no Brasil, onde milhões de habitantes estão expostos a concentrações acima dos padrões, com potenciais impactos à saúde. A exposição à poluição atmosférica é desigual na RMSP, dependendo da dinâmica de fontes emissoras locais e da influência do tempo e do clima em escala regional. A região do ABC — sigla originada a partir das iniciais de suas cidades originais: Santo André, São Bernardo do Campo e São Caetano do Sul — é o maior centro industrial da RMSP, localizada em sua fronteira sudeste, e inclui áreas de proteção ambiental. Essas características resultam em um perfil de emissões singular, que difere do centro da metrópole. Este estudo visa caracterizar a variabilidade na concentração de poluentes atmosféricos na região do ABC em 2015, investigando possíveis fontes e associações a condições meteorológicas de superfície. Análises estatísticas multivariadas foram aplicadas a dados de qualidade do ar de sete estações de monitoramento e variáveis meteorológicas de superfície. São Bernardo do Campo se destacou, com concentrações de O_3 20% maiores (43±19 $\mu g.m^{-3}$) do que as outras estações, enquanto São Caetano do Sul apresentou a maior média anual de PM_{10} (39±19 $\mu g.m^{-3}$), relacionada principalmente a emissões veiculares. A umidade relativa apresentou correlação negativa com os poluentes primários, enquanto a temperatura e a radiação se correlacionaram ao O_3. Elevadas concentrações de O_3 foram atipicamente observadas em janeiro de 2015 (59±19 $\mu g.m^{-3}$), simultaneamente a anomalias negativas de precipitação e umidade relativa, possivelmente associadas ao evento de seca no Sudeste do Brasil no verão de 2014/2015. Os resultados mostram que fontes emissoras locais podem impactar significativamente a carga de poluição e sua variabilidade diurna, especialmente no caso de poluentes primários. O clima modula a variabilidade sazonal das concentrações, e fenômenos meteorológicos de escala regional podem impactar a qualidade do ar. Para atingir os padrões de concentração em toda a parte, o poder público deve ficar atento aos processos que ocorrem em diferentes escalas espaciais e que determinam a qualidade do ar.

Palavras-chave: poluição do ar; material particulado; ozônio troposférico; análise multivariada; Brasil.

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Introduction

Megacities worldwide concentrate intense economic activity, high population density and high emission of air pollutants, with impacts to human health, climate and environment (Parrish and Zhu, 2009; Gurjar et al., 2010). In the Metropolitan Area of São Paulo (MASP), vehicular emission plays a major role on air quality, followed by industrial emissions (Andrade et al., 2017; CETESB, 2019). The ABC region — ABC standing for Santo André, São Bernardo do Campo and São Caetano do Sul, the cities the area originally comprised of —, located in the southeast of MASP, comprises 7 municipalities and 2.6 million inhabitants (SEADE, 2018). In the ABC region, areas of environmental protection and water reservoirs coexist with vehicular traffic and industrial activity, including the Capuava petrochemical pole, automobile, metallurgic and chemical industries, resulting on an emission profile distinct from the central areas of MASP. The combination of several air pollution sources, both anthropogenic and biogenic, results in physical and chemical interactions that lead to the formation of secondary pollutants like ozone (O_3) and secondary particulate matter.

In the ABC region, the predominant winds are from southeast (IAG-USP, 2015a), with great influence of the sea breeze and mountain-valley circulation (Ribeiro et al., 2018; Valverde et al., 2020). The southeastern winds can transport region atmospheric pollutants produced at coastal cities (such as Cubatão and Baixada Santista), marine emissions and biogenic emissions from Mata Atlântica rainforest fragments (Carvalho et al., 2012; Ribeiro et al., 2018) to the ABC. Furthermore, the southeastern winds can transport pollutants generated at the ABC region to the center of the São Paulo metropolis. Occasionally, the preferred wind direction suffers an inversion, in a way that atmospheric emissions from agricultural areas at northwest São Paulo state may be transported to the MASP, and, consequently, to the ABC region (Sánchez-Ccoyllo et al., 2005). These elements make the ABC region a unique location for the study of the dynamics of atmospheric pollutants, the contribution of various pollutants sources and the influence of meteorological conditions.

Among CETESB's (Companhia Ambiental do Estado de São Paulo, São Paulo State Environmental Agency) 24 air quality monitoring stations located at MASP in 2018, the ABC municipalities of São Caetano do Sul, Santo André and Mauá figured among the 10 stations with highest PM_{10} (inhalable particulate matter) annual mean concentrations (CETESB, 2019). In the same year, the ABC municipality of São Bernardo do Campo counted nine exceedances of the O_3 state air quality standard (140 $\mu g\ m^{-3}$, 8 h moving average), the highest among the MASP monitoring stations (CETESB, 2019). This is an indication that air quality conditions in the ABC region may differ from other parts of MASP, being influenced by local sources and regional transport of pollutants.

Studies about air pollution dynamics, variability and concentration ranges are profuse for the MASP as a whole (e.g., Carvalho et al., 2015; Kumar et al., 2016; Andrade et al., 2017; and references therein). However, despite the particularities of air pollution sources and dynamics, few atmospheric studies were dedicated to the ABC region. Most of them focused on air pollution health impacts (e.g., Chiarelli et al., 2011; Negrete et al., 2010; Silva et al., 2017), on urban climate (Valverde, 2017; Valverde et al., 2020), and a few on ambient air pollution measurements (Saiki et al., 2007; Savóia et al., 2009; Caumo et al., 2017; Guimarães et al., 2019). This study contributes to the filling of this gap, describing the variability of air pollutant concentrations in the ABC region, accounting for its particularities on pollution sources and atmospheric conditions.

In this way, the main objective of this study is to characterize the temporal and spatial variability of atmospheric pollutants at the ABC region in the year of 2015, exploring the associations with surface meteorological conditions, as well as investigating the main pollutant sources and atmospheric processes that explain the observed concentration variability.

Methodology

Characterization of the study area

The ABC region covers an area of 829 km^2 within MASP, in the Southeast region of Brazil (Figure 1). It is an urban area in the periphery of MASP, where intense vehicular traffic and industrial activity coexist with water reservoirs and areas of environmental protection. MASP is located on a 700 m plateau above mean sea level, and approximately 50 km inland from the coast. The predominant winds are from the southeast (IAG-USP, 2015a), and low level circulation is dominated by the sea breeze entrance, mountain-valley circulation and urban effects (Oliveira et al., 2003; Ribeiro et al., 2018; Valverde et al., 2020). While the sea breeze may contribute to the dispersion of the urban plume, the transport of air pollutants from industrial areas in the coastal region cannot be discarded.

The climate at MASP, including the ABC region, is classified as high elevation subtropical humid (Cwb), according to the Köppen classification (Piñero Sánchez et al., 2020). The winter at the ABC region is dry and mildly cold, with a mean temperature of 16.7°C and 74.5% relative humidity (RH) in July. The summer is wet and warm, with mean values of temperature and RH of 23.2°C and 78.8% in January. The highest monthly rainfalls occur in the summer, reaching 242 $mm.month^{-1}$ in January on average, while August is typically the month with the lowest amount of rainfall, 26 $mm.month^{-1}$ (Valverde et al., 2020). The planetary boundary layer (PBL) height at MASP shows a daytime maximum of about 1,500 m in the summer and 1,100 m in the winter, related to seasonal variations in the heat fluxes at surface (Piñero Sánchez et al., 2020). The seasonality of large-scale circulation at MASP is influenced by the dynamics of the South Atlantic Subtropical Anticyclone (SASA), which is zonally wider and closer to the continent in the austral winter and retracted to the east during the summer (Reboita et al., 2019). SASA spatial configuration can be

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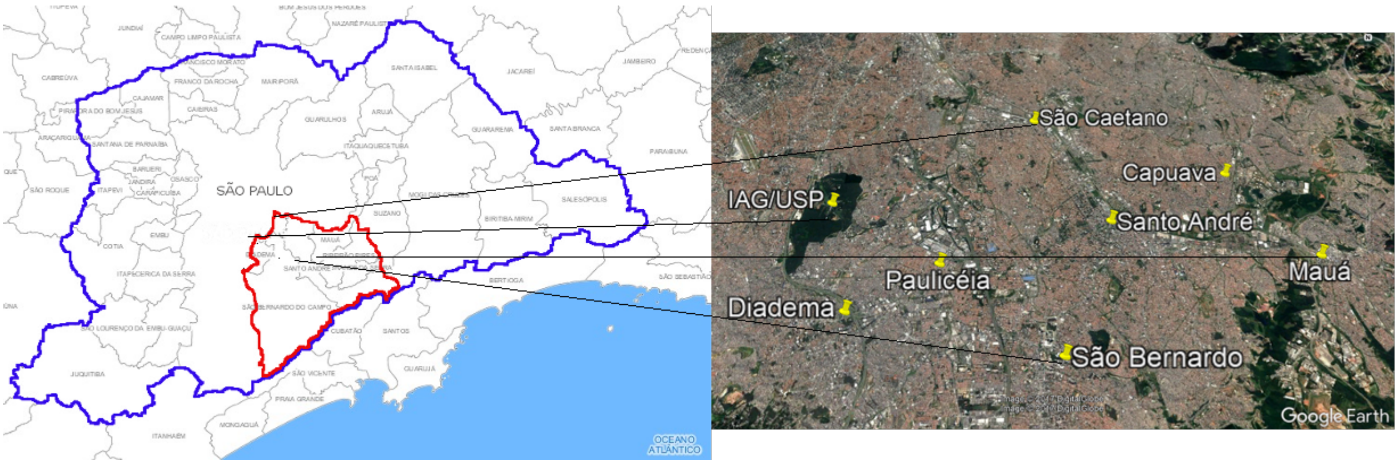

Figure 1 – Map showing the Metropolitan Area of São Paulo contoured in blue and the ABC region in red. The location of the seven Companhia Ambiental do Estado de São Paulo's air quality monitoring stations at the ABC region and the Instituto de Astronomia, Geofísica e Ciências Atmosféricas (Universidade de São Paulo) meteorological station are shown in a zoomed image (Google Earth). The distances between this ensemble of air quality and meteorology monitoring stations are in the range of 4 to 15 km.

disrupted by the influence of transient systems like cold fronts and extratropical cyclones, which are more frequent in the winter (Foss et al., 2017). Low-level jets intensify the moisture transport from equatorial South America to southeastern Brazil during the summer (Marengo et al., 2004). In the winter, surface anticyclonic circulation predominates at MASP, and postfrontal high-pressure systems moving northeast typically merge with SASA. This winter synoptic pattern inhibits cloud formation and provides increased atmospheric stability, leading to a higher frequency of thermal inversions and restrictions on the air pollutant dispersion at MASP (Piñero Sánchez et al., 2020; Gozzo et al., 2021; Oliveira et al., 2021).

Datasets of air pollution and surface meteorological variables

Hourly concentration data for ozone (O_3), inhalable particle matter (PM_{10}), carbon monoxide (CO), sulfur dioxide (SO_2) and nitrogen oxides (NOx) for the year of 2015 was obtained from seven CETESB air quality monitoring stations distributed in the ABC Region (Figure 1). Since the CETESB stations do not monitor meteorological variables continuously, surface meteorological data was obtained from IAG–USP's (Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo – Astronomy, Geophysics and Atmospheric Sciences Institute, University of São Paulo) meteorological station (World Meteorological Organization (WMO) station #83004). This is the closest available WMO meteorological station, with distances to the air quality monitoring stations ranging from 4 to 15 km (Figure 1). Previous studies have shown that measurements of temperature, precipitation and relative humidity at IAG–USP station are representative within this spatial scale (Sugahara et al., 2012; Piñero Sánchez et al., 2020). The following surface variables were used in this study: air temperature (T), relative humidity (RH), wind speed (WS), global radiation (RAD) and precipitation. The time series of pollutants and meteorological data since 1998 were used for historical data analysis. Months with less than 50% data coverage were not included in monthly statistics. Table 1 shows the configuration of the air quality stations, including its spatial representability and whether they are directly influenced by stationary sources, according to CETESB (2014, 2016a). All stations were influenced by vehicular emissions to some extent.

Data analysis procedures

For investigation of the similarity between concentrations measured at different stations, multiple comparisons of group means were performed using one-way analysis of variance (ANOVA), which has been used before in air quality spatial variability studies (e.g., Estévez-Pérez and Vilar, 2013). The assumptions for ANOVA are normality and homoscedasticity, but previous studies show that ANOVA is robust even if normality is violated (e.g., Schmider et al., 2010). Although the time series of pollutant concentration daily averages did not completely fulfill the ANOVA requirements, tests with Kruskal-Wallis and Welch-ANOVA showed similar results, and all tests rejected the null hypothesis of equal means or ranks, with 95% significance and $p<0.05$.

Principal component analysis (PCA) was applied to daily datasets of meteorological variables and pollutant concentrations at São Caetano do Sul and São Bernardo do Campo, aiming to identify pollution sources and processes that influence air quality at these sites. The choice of the stations was based on the variety of monitored parameters, as well as in the contrasting character of the stations con-

Table 1 – Characteristics of air quality stations and location of the the Instituto de Astronomia, Geofísica e Ciências Atmosféricas (Universidade de São Paulo) meteorological station. Representability scale was based on Companhia Ambiental do Estado de São Paulo (2014, 2016a) reports. The influence of fixed sources was based on the same reports, when available, and on visual inspection of aerial images in a radius of 1000 m around the stations of Santo André, São Bernardo do Campo and Pauliceia.

Name	Altitude	Coordinates	Fixed sources	Scale (km)	Variables monitored
Diadema	789 m (complex/top)	23.685 S 46.610 W	No	0.5–4	PM_{10}, O_3
Capuava (Santo André)	815 m (complex/top)	23.637 S 46.488 W	Yes	0.5–4	PM_{10}, O_3, SO_2
Mauá	775 m (complex/top)	23.669 S 46.466 W	Yes	0.5–4	PM_{10}, O_3, NOx
Santo André (Paço Municipal)	764 m (complex/valley)	23.657 S 46.530 W	Yes	0.1–0.5	PM_{10}, CO
São Bernardo do Campo (Centro)	781 m (plane/valley)	23.698 S 46.546 W	No	0.5–4	O_3, NOx, CO
Pauliceia (São Bernardo do Campo)	761 m (plane/valley)	23.670 S 46.584 W	Yes	0.5–4	PM_{10}
São Caetano do Sul	745 m (plane/valley)	23.603 S 46.572 W	Yes	0.1–0.5	PM_{10}, O_3, NOx, CO, SO_2
Instituto de Astronomia, Geofísica e Ciências Atmosféricas (Universidade de São Paulo)	800 m (complex/top)	23.651 S 46.622 W	–	–	T, RH, WS, RAD, rain

cerning air quality conditions. PCA is a multivariate analysis that identifies associations between variables in a dataset, resulting on a group of so called Principal Components (PCs), which consist of linear combinations of the original variables, reducing the complexity of the original dataset (Correia and Ferreira, 2007). PCA has been successfully applied to environmental data before (Guardani et al., 2003; Santos et al., 2018; Corrêa et al., 2019). The analysis was performed using the "principal" function in the R software, with the option of Varimax rotation. Six outliers were replaced by averages, being identified as values outside the interval $[Q1 - 3IQ ; Q3 + 3IQ]$, where Q1 and Q3 are the 1^{st} and 3^{rd} quartiles and IQ is the interquartile range. The time series of CO, NO and SO_2 were log-transformed to get conformity with normal distribution, which is a requirement for PCA. Concentration and meteorological variables were normalized by their arithmetic mean and standard deviation. The Kaiser-Meyer-Olkin (KMO) test was applied to the datasets, obtaining the values of 0.68 for São Bernardo and 0.79 for São Caetano, attesting that the data is suited for PCA. Eigenvalues above 1.0 were used as criteria to define the number of PCs.

Results and Discussion

Spatial and temporal variation of pollutant concentrations

Analysis of air pollutant concentration time series at seven sites in the ABC region in 2015 revealed similarities and discrepancies, despite the proximity of the sites. Analysis of variance (ANOVA) was applied to daily concentration averages to investigate differences in the mean concentration values and its variability among the sites. In Figure 2, circles indicate the mean concentration values for each pollutant at each site, and the error bars represent the overall variability. Differences between pairs of stations are statistically significant ($p<0.05$) when the error bars do not overlap.

São Caetano do Sul showed significantly higher concentrations for PM_{10}, CO and NOx when compared to the other sites. In 2015, the annual mean PM_{10} concentration at São Caetano do Sul was the second highest considering the whole MASP region (CETESB, 2016b). SO_2 concentrations were similar in São Caetano do Sul and Capuava, with typical concentrations in the range of 4 to 5 $\mu g.m^{-3}$. According to CETESB (2016b), in 2015, CO in the MASP was mostly emitted by light duty vehicles and motorcycles (94%), while PM_{10}, NOx and SO_2 had a significant contribution of heavy duty vehicle emissions (respectively 31%, 44% and 10%). NOx and SO_2 also had a significant contribution from industrial sources (respectively 32% and 78%). The abundance of these pollutants in São Caetano suggest greater influence of local air pollution sources at this site, both vehicular (Valverde et al., 2020) and industrial. In fact, São Caetano do Sul is surrounded by five industries within a 1.5 km radius, and sits downwind of avenues with intense vehicular traffic — Goiás Avenue and Do Estado Avenue, respectively at ~0.8 and 1.4 km eastern to the site (CETESB, 2002). Even though Mauá and Capuava are located in the vicinity of petrochemical plants, the observed PM_{10} concentrations there were significantly smaller in comparison to São Caetano do Sul. Conversely, O_3 in São Caetano do Sul was in the lower range of concentrations, similar to the Diadema and Capuava stations. Because of the prox-

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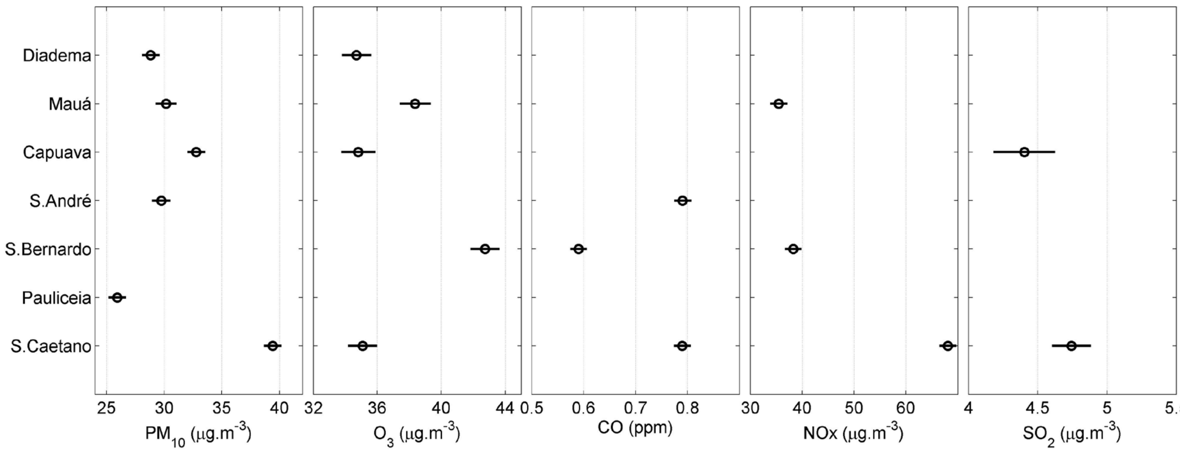

Figure 2 – Analysis of Variance (ANOVA) applied to daily mean concentrations of PM_{10}, O_3, CO, NOx and SO_2 at seven air quality monitoring sites in the ABC region in 2015. Circles indicate the mean concentration values for each pollutant at each site. Error bars represent the overall confidence level for each pollutant, considering the variability at all sites. The difference in the mean concentration of a pollutant between pairs of stations is statistically significant ($p<0.05$) when the error bars do not overlap. Note: SO_2 measurements at Capuava were available only between August and December.

imity of the stations, it is reasonable to assume that they had similar sky conditions on average, so that differences in annual mean O_3 concentrations may be explained by chemical factors related to the local availability of precursors.

In general, stations with relatively low NOx concentrations showed significantly higher O_3 concentrations when compared to the others. This fact agrees with the hypothesis of a VOC (volatile organic compounds) limited regime for tropospheric O_3 production at MASP, in which an increase on NOx concentrations leads to a decrease on O_3 net production (Silva Junior et al., 2009; Madronich, 2014; Alvim et al., 2017). São Bernardo do Campo, for example, showed low concentrations for CO and NOx, and the highest mean for O_3 (43 ± 18 $\mu g.m^{-3}$), above the national standard for O_3 (annual mean of 40 $\mu g.m^{-3}$ Brasil, 2018). In 2015, São Bernardo do Campo figured as the MASP station with the second highest number of O_3 exceedances (CETESB, 2016b), demonstrating the need for a better understanding of the dynamics and emission of O_3 precursors at this municipality.

Figure 2 reflects the spatial distribution of air pollutants in 2015, but it is important to mention that this scenario evolved along the years. Carvalho et al. (2015) reported negative PM_{10} concentration trends in the ABC region between 1996 and 2009, ranging from -2 to -3 $\mu g/m^3$ per year. The year of 2015 showed one of the lowest annual mean PM_{10} concentrations in the ABC since 1998, attributed to the combination of continuous reduction of vehicular emissions (Andrade et al., 2017) and occurrence of favorable dispersion conditions in the austral spring of 2015, associated with the influence of the 2015–2016 El Niño episode (CPTEC, 2015; Kogan and Guo, 2017; Pereira et al., 2017).

The seasonal variability observed for PM_{10} and O_3 was similar at all sites in the ABC region (Figure 3). This is an indication that the variability of pollutant concentrations at this time scale is modulated by the climate, which reflects the seasonality of atmospheric circulation in regional and large scale. The variability of PM_{10} concentrations in 2015 was in agreement with previous reports at MASP, with highest concentrations during the austral winter (Figure 3D), when the atmosphere is typically more stable (Piñero Sánchez et al., 2020) and the accumulated precipitation is lower (Figure 3B), leading to a meteorological scenario that favors the retention of PM_{10} in the surface layer (Carvalho et al., 2015; Valverde et al., 2020). The concentration of NOx, CO and SO_2, which are mostly of primary origin, followed the same seasonal pattern as PM_{10}, with higher concentrations during the winter. During the austral summer, PM_{10} and primary pollutant concentrations decreased, likely due to the influence of typical summertime convection systems that promote atmospheric instability, wind gusts and rainfall (Marengo et al., 2004; Valverde et al., 2020), favoring the dispersion and removal of aerosols.

PM_{10} concentrations peaked in August of 2015 at all ABC stations, and exceeded the 1998–2015 mean in São Caetano do Sul (Figure 3D). This month was characterized by surface wind velocities (not shown) and relative humidity (Figure 3C) below the 1998–2015 average. It is likely that these surface weather conditions were associated with the occurrence of a high pressure system that restrained frontal activity in the Brazilian southeast region (CPTEC, 2015), and resulted in the absence of precipitation at MASP between July 26 and August 19, 2015 (IAG-USP, 2015b). This meteorological scenario possibly inhibited the dis-

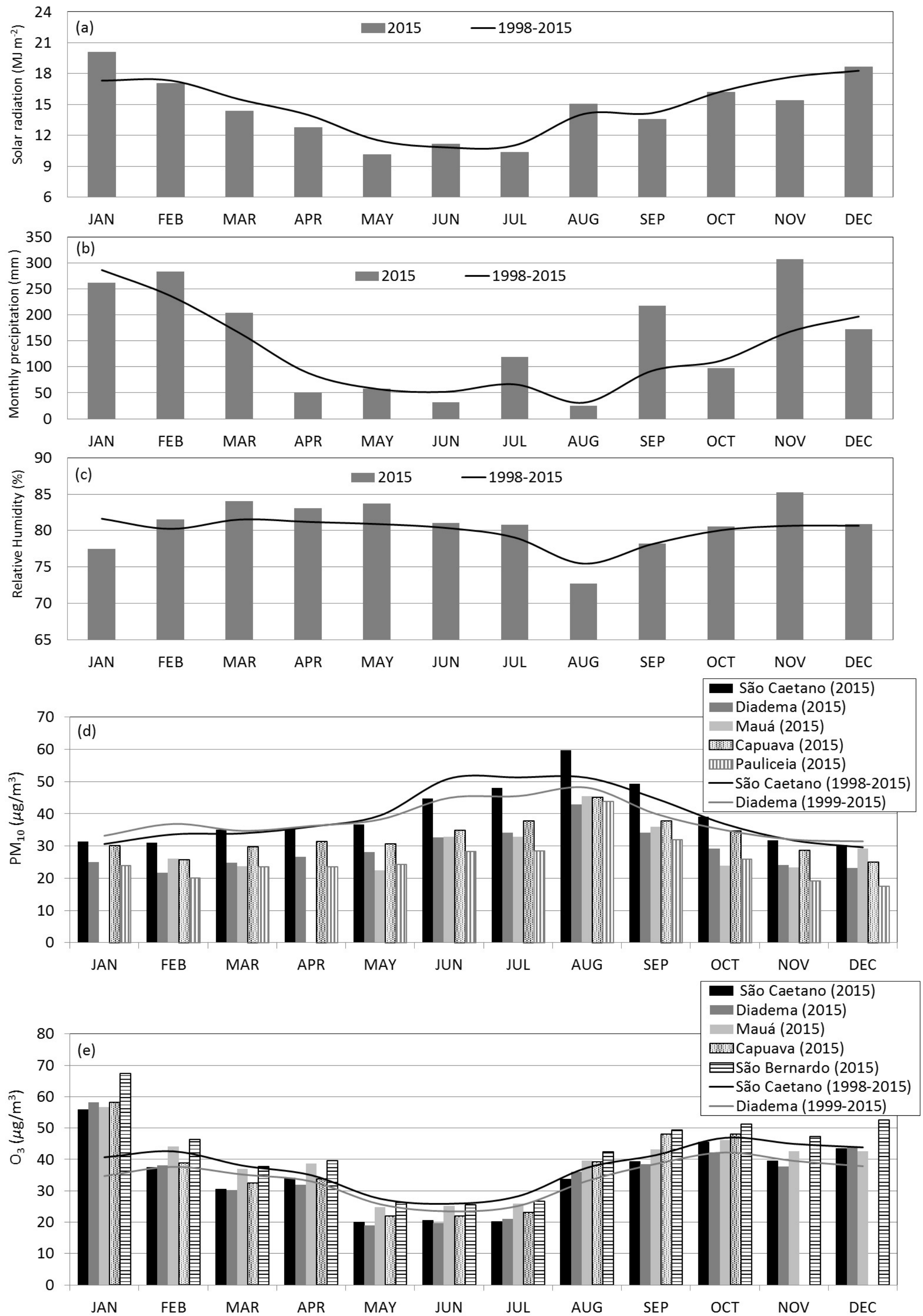

Figure 3 – Monthly means for 2015 and for the historical time series (1998–2015) for surface meteorological variables measured at the Instituto de Astronomia, Geofísica e Ciências Atmosféricas (Universidade de São Paulo) meteorological station: (A) global solar radiation, (B) monthly accumulated precipitation, (C) mean relative humidity and pollutant concentrations: (D) PM_{10}, (E) O_3.

persion of air pollutants at MASP, although a detailed characterization of the active synoptic systems and atmospheric thermodynamic conditions in August of 2015 would be necessary to support this hypothesis.

While the seasonal behavior was very similar for PM_{10}, significant concentration differences were observed between the stations. PM_{10} concentrations at São Caetano do Sul's station stood out throughout the year (Figure 3D), once more suggesting the influence of local sources of the pollutant at this site. At Diadema, PM_{10} concentrations were, most of the time, well below the 1999–2015 average, and the same holds for Mauá and Capuava. Particularly, the Pauliceia site showed an intense reduction in PM_{10} levels over the years, with concentrations 50% lower in 2015 when compared to 1998, when PM_{10} concentrations in Pauliceia used to be similar to the São Caetano site. The year of 2015 was relatively rainy (Figure 3B), with precipitation rates above the climatology, especially during the austral spring (IAG-USP, 2015a), possibly related to the influence of the 2015–2016 El Niño (CPTEC, 2015; Kogan and Guo, 2017; Pereira et al., 2017). This scenario certainly contributed to the dispersion and removal of PM_{10} at the ABC region, leading to the observed concentrations below the average at most stations, except in São Caetano do Sul.

Contrary to PM_{10}, O_3 concentrations peaked in the austral spring and summer (Figure 3E). São Bernardo do Campo stood out, with O_3 concentrations significantly higher when compared to other stations, in agreement with the ANOVA analysis (Figure 2). Observed O_3 concentrations in 2015 were similar to the 1998–2015 averages at all stations, except in January, when an anomalous concentration peak was observed. Previous studies at MASP report highest O_3 concentrations at austral spring, when the combination of increased solar radiation input and decreased nebulosity favors the production of this secondary pollutant (Silva Junior et al., 2009; Carvalho et al., 2015; Carvalho et al., 2020).

The high O_3 concentrations observed in January 2015 (Figure 3E) were concomitant with positive anomalies in global solar radiation (8% above the 1998–2015 mean value for January) and negative anomalies in precipitation and relative humidity (Figures 3A–3C). It is very likely that this meteorological pattern at the surface was associated to an atypical high pressure system established over Southeast Brazil at the end of December 2014. This episode is well documented in the literature, since it resulted in an extreme drought event, with shortages in water supply at MASP (CPTEC, 2015; Marengo et al., 2015; Coelho et al., 2016; Nobre et al., 2016; Cavalcanti et al., 2017). Based on detailed synoptic analysis for the austral summer of 2014/2015, the authors show that a mid-tropospheric blocking high inhibited the development of the South Atlantic Convergence Zone (SACZ) and of typical summertime rainfall events. Changes in circulation were associated with a large-scale teleconnection wave train (Coelho et al., 2016).

The unusual high O_3 concentrations observed at the ABC region in January 2015 were also reported for other CETESB stations at the MASP (CETESB, 2016b). On 17 January 2015, 14 out of 19 CETESB monitoring stations at MASP had maximum O_3 (8 h moving average) above the state standard (140 μg m^{-3}), including all stations at the ABC region. Particularly, three ABC stations, Diadema, Mauá and São Bernardo do Campo, reached the attention level for O_3 (>200 μg m^{-3}, 8 h moving average) between January 13 and 20. Since this air pollution event was observed in a regional scale, it is possible that the synoptic conditions during the 2014/2015 summer drought may have affected O_3 photochemical production at the ABC region in January of 2015. However, to confirm this hypothesis, further studies should be conducted, including a detailed case study on atmospheric circulation and thermodynamics in a synoptic scale. Also, since O_3 formation relies on the relative proportion of precursors in a non-linear way, the impact of possible changes in the emission patterns of NOx and VOCs cannot be ruled out. To investigate the role of atmospheric chemistry on the observed O_3 peak, monitoring of VOCs would be necessary at the ABC region, particularly for species with high O_3 yield, like aldehydes and isoprene (Alvim et al., 2017).

While the seasonal variability of pollutant concentration was very similar between the monitoring stations, the diurnal pattern showed significant differences from one station to another (Figure 4), reflecting the influence of local emission sources and processes. O_3 diurnal cycle behaved as expected, with highest concentrations observed between 2 PM and 4 PM local time (LT) (Figure 4B), a period of high solar incidence and elevated temperatures, which favors the formation of the pollutant. The diurnal peak, considering all ABC stations in 2015, was 74±4 μg/m^3 (average±standard deviation), compatible with previous reports for the MASP (Carvalho et al., 2015; Schuch et al., 2019). The diurnal variability and O_3 concentrations were similar at most stations, due to the fact that it is a secondary pollutant and thus has a weaker dependence on local sources. São Bernardo do Campo was the only station that stood out, with higher O_3 concentrations when compared to the other sites. It is reasonable to assume that the average sky conditions were similar between the monitoring stations considered in this study, since they are up to 14 km apart from each other. So, the significantly higher O_3 concentrations at São Bernardo do Campo (Figure 2) are likely related to the relative proportion of the precursors NOx and VOCs near the site, favoring O_3 photochemical production (Alvim et al., 2017).

The diurnal pattern of PM_{10} (Figure 4A), NOx (Figure 4C) and CO (not shown) showed concentration peaks in the morning (between 7 AM and 10 AM LT) and evening (between 5 PM and 8 PM LT), associated with periods of intense vehicular traffic and low mixing layer height, in accordance with previous observations at MASP and other cities worldwide (Laakso et al., 2003; Zhao et al., 2009; Muñoz and Alcafuz, 2012; Carvalho et al., 2015; Valverde et al., 2020). The morning peaks were usually concomitant, while, in the evening, PM_{10} peaks typically occurred two hours earlier than CO and NOx

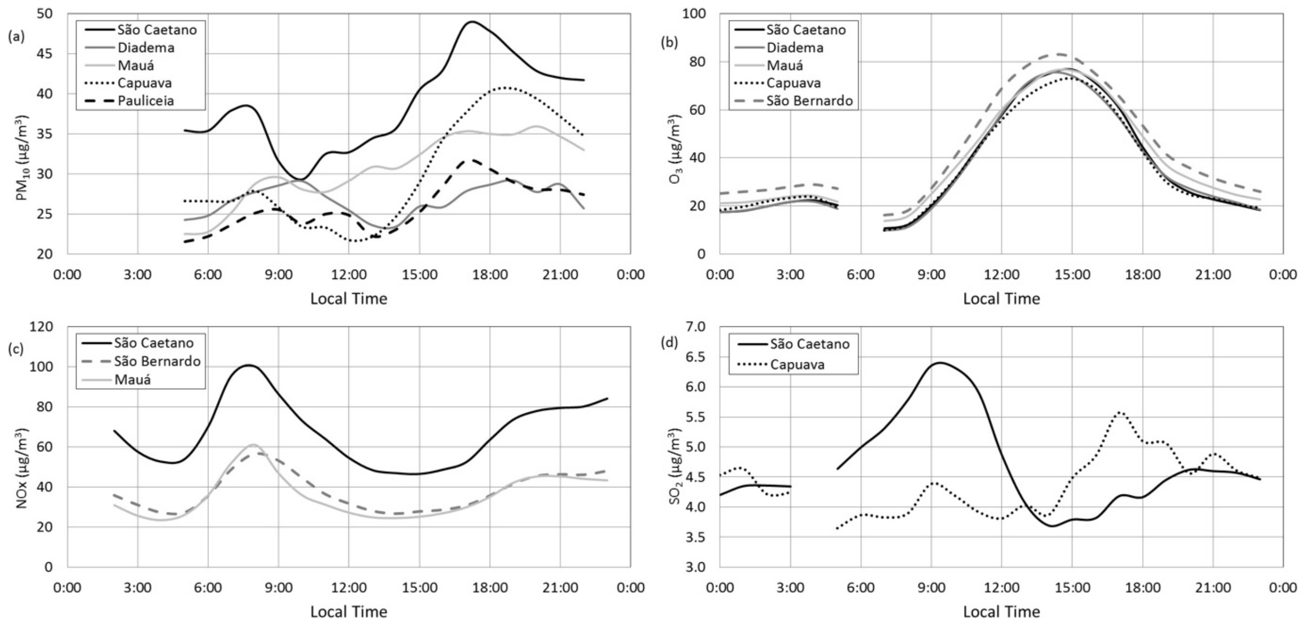

Figure 4 – Mean diurnal cycle for (A) PM_{10}, (B) O_3, (C) NOx and (D) SO_2 at five ABC stations in 2015. There is a lack of data at certain hours of the day because of automated instrumental checks in the monitoring stations. Note: SO_2 measurements at Capuava were available only between August and December.

peaks. The similar diurnal variability of PM_{10}, CO and NOx in São Caetano suggest common emission sources, as will be discussed in the next section.

Another aspect shown in Figure 4A is that the PM_{10} diurnal pattern differed between the stations. Around noon, PM_{10} concentrations decreased in most stations, in response to the dilution caused by the development of the mixed layer. Mauá station was an exception, with PM_{10} concentrations rising steadily between 10 AM and 8 PM LT. This station sits nearby industrial plants and at the top of complex topography landscape (Table 1), which can affect the local wind circulation (Valverde et al., 2020), influencing the PM_{10} diurnal variability. Different variability of pollutant concentrations at Mauá station has been reported in a previous study, although for O_3 (Guardani et al., 2003). Considering that about 75% of PM_{10} at MASP are of primary origin (CETESB, 2016b), its diurnal pattern can be strongly influenced by the variability and strength of local sources.

The diurnal variability of SO_2 (Figure 4D), which is considered a tracer for industrial emissions at MASP (CETESB, 2016b), also showed morning and late afternoon peaks, but they were not always concomitant with CO and NOx. However, the analysis for SO_2 and the contribution of industrial emissions was undermined by the lack of observations, since it was monitored only at two stations.

Air pollution sources and processes

Aiming to identify air pollution sources, processes, and their relative importance, PCA was applied to daily databases of pollutant concentrations and meteorological variables at São Bernardo do Campo and São Caetano do Sul. These stations were chosen based on data availability and diversity of local conditions. In São Bernardo do Campo, three principal components (PCs) were found, responding for 84% of total variance (Table 2). The first component was identified as photochemical production of pollutants, since it includes O_3, temperature and radiation, while the second component was associated with vehicular emissions due to the presence of CO, considered a tracer for light duty vehicle emissions (Guardani et al., 2003; CETESB, 2019). PC1 and PC2 showed similar contributions to the total variance, explaining 36% and 35%, respectively. Relative humidity had negative loadings split between the PCs 1 and 2, indicating a negative correlation with pollutant concentration. Previous studies reported associations between increased O_3 concentrations, high temperatures and low relative humidity at MASP (Santos et al., 2018). A third component, less relevant in terms of explained variance, had only wind speed as a main variable, isolated from the other variables.

In São Caetano do Sul, PCA resulted in three components, explaining 78% of total variance (Table 3). Contrary to São Bernardo do Campo, the first PC, which explained 37% of the variance, was associated with vehicular emissions. PC2 explained 30% of the variance, being associated with photochemical formation of pollutants, similarly to São Bernardo do Campo. Once again, relative humidity had negative loadings split between the PCs 1 and 2 and wind speed was isolated in the third PC. The fact that PM_{10} had a high positive loading in PC1 suggests that, in São Caetano do Sul, most of PM is from primary ve-

Table 2 – Principal component analyses applied to São Bernardo do Campo's daily dataset of pollutant concentrations (CO, NO, NO and O_3) and surface meteorological variables in 2015: RAD (global radiation), T (air temperature), RH (relative humidity) and WS (wind speed).

Principal Components (PCs)			
Variables	1	2	3
CO	0.11	**0.86**	0.34
NO	-0.28	**0.88**	0.08
NO_2	0.05	**0.94**	0.13
O_3	**0.87**	-0.23	0.04
RAD	**0.90**	0.04	-0.02
T	**0.86**	-0.01	0.15
RH	**-0.69**	**-0.52**	0.27
WS	-0.06	-0.29	**-0.92**
Eigenvalues	2.87	2.8	1.07
% variance	36%	35%	13%

Table 3 – Principal component analyses applied to São Caetano do Sul's daily database of pollutant concentrations (CO, NO, NO_2, O_3, SO_2, PM_{10}) and surface meteorological variables measured at the Instituto de Astronomia, Geofísica e Ciências Atmosféricas (Universidade de São Paulo) meteorological station in 2015: RAD (downward global radiation), T (air temperature), RH (relative humidity) and WS (wind speed).

Principal Components (PCs)			
Variables	1	2	3
CO	**0.85**	-0.07	0.14
NO	**0.87**	-0.33	-0.06
NO_2	**0.93**	-0.03	0.06
SO_2	**0.52**	0.29	0.24
PM_{10}	**0.83**	0.27	0.24
O_3	-0.19	**0.85**	0.24
RAD	0.09	**0.90**	-0.08
T	-0.02	**0.83**	-0.06
RH	-0.57	**-0.67**	0.27
WS	-0.24	0.05	**-0.92**
Eigenvalues	3.72	2.95	1.14
% variance	37%	30%	11%

hicular emissions. The presence of SO_2 in PC1 suggests an influence of heavy duty vehicle emissions at this station. Nevertheless, the relatively low SO_2 loadings in the PCs 1 and 2 indicate that this pollutant has a distinct behavior when compared to the others, and possibly a different source, likely related to industrial emissions. Unfortunately, no other tracers for industrial emissions were available in a daily timescale for inclusion in the PCA analysis.

Conclusion

This study described the spatial and temporal variability of atmospheric pollutants at MASP's ABC region in 2015, and its associations with meteorological conditions. Climate regulated the seasonal variability of pollutant concentrations at all monitoring stations. Local processes influenced the loading of primary pollutants like PM_{10}, CO and NOx and their diurnal cycles, which were different across the monitoring stations. Higher PM_{10} concentrations were observed at the São Caetano and Capuava sites, reflecting the proximity to industrial areas and traffic of heavy duty vehicles. In the case of O_3, which is a secondary pollutant, local processes had a weaker influence, and only the station of São Bernardo stood out with significantly higher concentrations. Vehicular emissions and photochemical production were identified as the main processes explaining the observed concentrations. It is possible that insufficient data on industrial emission tracers prevented the identification of fixed sources as a major contributor.

Overall, results have shown that air quality is unequal in the ABC region, relying on the magnitude and dynamics of local emission sources. Expansion of the air quality monitoring network is important in order to improve knowledge on local processes, or, at least, increase the variability of atmospheric parameters monitored at the existing stations. In addition to the impact of local processes, weather events may lead to extreme events of air quality deterioration, with likely health impacts for the population. In order to attain air quality concentration standards at all parts of the ABC region, policy makers should consider the proximity to emission sources and be aware of the variability of atmospheric dispersion conditions. The development of policies and mechanisms for provisory restriction of emissions during episodes of unfavorable dispersion conditions are recommended to minimize impacts on human health and environment.

Future studies could expand the analysis for other years, investigating long term trends in air pollutant concentrations at the ABC regions and its spatial differences. Detailed case studies on synoptic meteorological conditions during extended periods of air quality deterioration are recommended to evaluate the direct impact of regional weather phenomena on air pollution at MASP. The investigation on local air pollution sources could be improved by the inclusion of other pollutant species in the analysis, as well as proxies to the emission strength of industrial and vehicular sources. Measurements of hydrocarbons would be crucial to unveil the relative roles of atmospheric chemistry and meteorological conditions in episodes of high O_3 concentrations.

Contribution of authors:

Silva, M.D.: Conceptualization, Methodology, Formal analysis, Writing – original draft. Oliveira, M.C.Q.D.: Validation, Visualization, Writing – original draft. Drumond, A.: Validation, Supervision, Writing – review & editing. Rizzo, L.V.: Conceptualization, Writing – original draft, Supervision, Project administration.

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Geographic Information Systems supported by multi-criteria decision analysis to indicate potentially suitable areas for construction and demolition waste disposal

Uso do SIG auxiliado pela análise multicritério de tomada de decisão na indicação de possíveis áreas aptas para a disposição em solo de resíduos de construção civil

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ABSTRACT

In Brazil, the disposal of construction and demolition waste (CDW) quite often occurs in inadequate places, resulting in social, economic, and environmental problems. This reflects the need for selecting appropriate areas for the disposal of this type of waste. These areas must follow local standards and regulations to protect human health and the environment. Considering that, this study is intended to indicate potentially suitable areas for CDW landfill deployment, known as Class A landfill in Brazil, supported by a GIS-MCDA based model. The GIS-MCDA technique, used as a basic tool to identify potentially suitable areas, has several advantages, such as low cost, reduced spatial data subjectivity, and fast decision-making process. The place chosen for this study is the Urban Central Core of the Metropolitan Area of Curitiba. By integrating GIS with MCDA techniques in this research study, it was possible to indicate potentially suitable areas for CDW disposal in this region.

Keywords: construction and demolition waste; waste management; environmental planning; environmental protection; landfill.

RESUMO

No Brasil, a disposição dos resíduos de construção e demolição é frequentemente efetuada em locais inapropriados, resultando em problemas sociais, econômicos e ambientais, o que demonstra a necessidade de áreas aptas para a sua correta disposição final. A área adequada deve estar de acordo com as regulações e normas locais. Considerados esses fatos, o objetivo do presente trabalho é indicar possíveis áreas aptas para a construção de um aterro classe A, apoiado por um modelo baseado em SIG-MCDA. O SIG-MCDA, que é utilizado na identificação de possíveis áreas aptas, apresenta diversas vantagens: baixo custo, redução da subjetividade do dado espacial e processo de tomada de decisão mais ágil. O local de estudo escolhido foi o Núcleo Urbano Central de Curitiba. A integração do SIG com as técnicas de MCDA nesta pesquisa resultou na indicação de possíveis áreas adequadas para o descarte dos resíduos de construção de demolição para essa região.

Palavras-chave: resíduos de construção e demolição; gerenciamento de resíduos; planejamento ambiental; proteção ambiental; aterros sanitários.

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Introduction

The illegal disposal of construction and demolition waste in Brazil is considered a matter of public concern and may result in several disadvantages for society as a whole, such as high costs for public drainage and health systems, because waste sedimentation may increase the chances of flooding, contributing to soil and surface water contamination and obstruction of urban drainage systems (Ferreira and Pinto, 2010; Pinheiro et al., 2019). Among the various approaches developed for municipal solid waste management, landfills continue to be the main final destination of waste (Costa and Silva, 2011). When properly segregated, construction and demolition waste (CDW) in Brazil is deployed as construction and inert waste in landfills (ABNT, 2004).

When selecting CDW disposal sites, it is extremely important to adopt a prevention policy to ensure environmental integrity and the well-being of the population. Site selection requires the collection and processing of a wide range of information on environmental aspects, socioeconomic status, and operational location. In addition, it should consider the interaction between planning and waste management (Geneletti, 2010). Moreover, the criteria established and used to indicate potentially suitable sites for landfill construction need to be technically defined and analyzed. This is a complex process because its evaluation requires time devoted by the parties involved. In addition, it is an expensive decision-making process since it involves different criteria for site selection (Rikalovic et al., 2014).

It is important to consider other methods that accelerate and minimize the costs of area selection. For example, we can mention the Geographic Information System (GIS) and Multi-Criteria Decision Analysis (MCDA) techniques. This combination has been widely used in site selection and urban planning studies, as mentioned by Ramos (2000), Dalmas et al. (2011) and Geus et al. (2019). Regarding spatial analysis, several decision-making problems give rise to the MCDA technique combined with GIS (Boroushaki and Malczewski, 2008). Contribution and research progress in terms of integration between GIS and MCDA derives from the synergy between these two distinct sets of decision-support tools. GIS technique can improve MCDA capabilities by exploring the decision situation and supporting the learning and discovery process, while MCDA integration into the GIS can improve GIS limited capabilities in data storage and analysis, according to the decision maker's preference (Malczewski and Rinner, 2015). This technique has been useful to indicate suitable areas to receive different types of developments, when different criteria are related to the decision-making process (Demesouka et al., 2013; Koc-San et al., 2013).

Therefore, this study is intended to indicate potentially suitable areas for the disposal of CDW in the Urban Central Core of the Metropolitan Area of Curitiba, using Spatial Analysis tools in a Geographic Information System environment, supported by the MCDA technique and pre-established criteria. GIS-MCDA integration has never been used to manage CDW in this region and can contribute to decision-making processes in waste management. Thus, it can help protect human and environmental health, considering Brazil's current CDW standards and applicable specific legislation.

Material and Methods

Several methods can be adopted for the selection of landfills. In this study, GIS software known as ArcGIS® associated with MCDA tools was used. Research development was supported by the following MCDA techniques: Delphi, Boolean, Analytical Hierarchy Process (AHP), and weighted linear combination to analyze criteria related to the spatial problem. The choices of these tools were due to the difference between the criteria and the need for convergence among them, but also to reduce subjectivity during decision-making to indicate potentially suitable areas (Biju, 2015).

The selected assessment criteria must be measurable — spatialized — and have compatible formats, so that they can be processed together in the GIS environment. The criteria used to indicate potentially suitable areas were defined according to the Brazilian Standard No. 15.113/2004 (ABNT, 2004). This standard establishes the basic requirements and criteria for CDW landfill site selection, which is the main objective of this research. Moreover, this standard is in accordance with the Brazilian regulation for waste management, such as The National Policy of Solid Waste — Law No. 12.305 of 2010 and CONAMA resolution No. 307 of 2003 — National Environmental Council (Brasil, 2002, 2010). Therefore, the criteria selected, which were based on the mentioned standard, are: Distance from urban centers; Water resources; Road distances; Land use and land cover; Zoning; Soil classes; Geology; Slope and; Environmental protection areas. Some criteria require more than one set of geospatial data to be analyzed in the GIS and comply with different legislations, as observed in Table 1.

After criteria selection, inadequate parcels of the study area needed to be excluded, e.g., water bodies, protected areas, urban areas. Moreover, Geus et al. (2019) state that the adequacy models with Boolean overlapping are useful, for example, to eliminate environmental protection areas, parks, and squares, 30-meter strips on both sides of urban streams and rivers, or even places subject to landslides or floods. The GIS technique allowed a logical operator (*Boolean*) to be used to carry out intersections between the layers of geographic data, represented by the selected criteria and their respective restrictions. Therefore, the study performed the logical operations of types A and B, resulting in all elements contained in the intersection between A and B. Mitchell (2012) describes the Boolean adequacy model as one of the most used models to assess areas for a particular use. According to him, this type of adequacy model divides a site into two distinct groups or sets: those that are adequate (value 1) and those that are not (value 0). The model assesses whether each site meets each criterion. The answer must be "yes" (value 1) for all criteria assigned so that a site can be included in the set of suitable places. The benefit of the Boolean approach is its simplicity and easy application, with a logical combination of maps, in a GIS environment directly analogous to the traditional method of overlapping employed in light tables. Thus, a map for constrained/not suitable areas was created.

Also, it may not be appropriate to treat each of the combined criteria as equally important (Câmara, 1995). Usually, criteria have different levels of importance, which may hinder the decision process difficult. That is why it is necessary to define which of these criteria have a greater degree of importance in accordance with the decision-makers' view. According to Malczewski (1999), these difficulties can be reduced when all the criteria are standardized and classified through weighting assignment. For this reason, this study decided to draft and send a questionnaire based on Delphi techniques associated with the AHP to several experts on the subject. The questionnaire is intended to facilitate formal discussion among experts, especially when they cannot get together in one place (Wakefield and Watson, 2014). According to Gupta and Clarke (1996), this method aims to reach the most reliable consensus in a group of experts through a series of questionnaires interspersed with feedback. The Delphi process is characterized by a set of surveys and it is necessary to have two to three rounds of questionnaires. This technique is widely used to access expert's opinion and to enhance clarity of the subject (Page et al., 2021).

As stated before, combined criteria should not be handled equally. In fact, to reduce bias, criteria must be standardized and prioritized. MCDA aims to structure, design, and assess decisions according to the stakeholders' views, and to transform this into a decision. Therefore, the AHP method developed by Saaty (1987) was chosen because the method is intended to assist the decision-making process based on qualitative and quantitative criteria, aiming to analyze the expert's judgment in the decision process, transforming complex problems into simpler ones by decision hierarchy. The AHP consists of a pairwise comparison, followed by the construction of a comparison matrix on a fundamental scale from 1 to 9 to rank the selected criteria (Saaty, 1990). Moreover, the AHP is widely used in environmental decision-making (Görener et al., 2012), which demonstrates that AHP is a methodology that fits the purpose of this research.

Therefore, a survey was designed according to the Delphi method, two rounds of questionnaires were sent to a set of experts, who were chosen due to their expertise in CDW management. As the minimal number of experts required by the method is 10, an invitation to

Table 1 – Sources of spatial data and normative references used.

Spatial data	Standard established by
Urban area (Urban Central Core)	State Law No. 139/2011 (Paraná, 2011) and Laws from each of the Municipal governments involved
Slope	ABNT 13896/1997 (ABNT, 1997)
Roads and Highways	ABNT 15.113/2004 (ABNT, 2004) and DER-PR
Geology	NAPA – National Asphalt Pavement Association
Water Resources	Federal Law No. 12.651/2012 (Brasil, 2012); Paraná State Law No. 5.305/1998 (Paraná, 1998)
Rivers	Federal Law No. 12.651/2012 (Brasil, 2012), Paraná State Law No. 5.305/1998 (Paraná, 1998)
Soils	EMBRAPA, 2013 and 2014; Ross, 1994
Conservation Units	Federal Law No. 9.985/2000 (Brasil, 2000)
Land use and occupation	Laws from each of the Municipal governments involved (Rio Branco do Sul, 1998; Campo Magro, 2000, 2012; Curitiba, 2000; Quatro Barras, 2000; Itaperuçu, 2001; Campina Grande do Sul, 2004; Colombo, 2004; São José dos Pinhais, 2005; Almirante Tamandaré, 2006; Fazenda Rio Grande, 2006; Campo Largo, 2007; Piraquara, 2007; Pinhais, 2009; Araucária, 2010)
Land use and land cover	Laws from each of the Municipal governments involved (Rio Branco do Sul, 1998; Campo Magro, 2000, 2012; Curitiba, 2000; Quatro Barras, 2000; Itaperuçu, 2001; Campina Grande do Sul, 2004; Colombo, 2004; São José dos Pinhais, 2005; Almirante Tamandaré, 2006; Fazenda Rio Grande, 2006; Campo Largo, 2007; Piraquara, 2007; Pinhais, 2009; Araucária, 2010)
Zoning	Laws from each of the Municipal governments involved (Rio Branco do Sul, 1998; Campo Magro, 2000, 2012; Curitiba, 2000; Quatro Barras, 2000; Itaperuçu, 2001; Campina Grande do Sul, 2004; Colombo, 2004; São José dos Pinhais, 2005; Almirante Tamandaré, 2006; Fazenda Rio Grande, 2006; Campo Largo, 2007; Piraquara, 2007; Pinhais, 2009; Araucária, 2010)

answer our survey was sent to 26 experts with relevant expertise in the area. In these questionnaires, the AHP technique was applied to compare, rank, and standardize the criteria. Also, there was an open question within the survey, where the experts could suggest changes in the set of criteria. After that, the first round of responses of the pairwise comparison was processed, and the criteria were normalized and staggered. Moreover, according to the experts, the criteria were enough and in accordance with the purpose of this research.

While the first round of questionnaire responses was processed in Expert Choice, the geographic data in vector format of the criteria were converted into raster data in a GIS (ArcGIS®) environment, whose objective is to create adequacy maps from algebra calculations between variables. Subsequently, all raster data were standardized (reclassified) on a common scale from 1 to 5, with 1 being the least adequate and 5 being the most adequate. According to Esri (2015) resources, reclassification is considered an adequacy model done by assigning values of preference, sensitivity, priority, or similarity, thus creating a common scale of values. After response processing, the second round was sent to experts within the feedback responses, and another open question was sent to verify if they agreed with the results of the analysis.

For the criterion "Distance from the urban center", the study considered a buffer with intermediate values, starting with 1 (less suitable) as 100 meters, 2 as 200 meters, 3 as 300 meters, 4 as 400 meters, and 5 and above as 500 meters (more suitable). From 200 meters onwards, suitability increases since areas around urban centers are less suitable. The study chose the values according to the municipal laws (land use and zoning law) of the 14 cities studied. Based on the criterion "Distance from highways and roads" and according to Associação Brasileira de Normas Técnicas (ABNT) 15.113 (ABNT, 2004), a landfill should not be located too far from highways, streets, and roads. In fact, the same rule defines the minimum distance between roads and the selected area. According to the Department of Roads and Transportation of the State of Paraná, the extent of disused areas is 15 meters, but there is still the field range of the highway, and it can reach 70 meters on both sides of the highway (DER-PR, 2012). Therefore, the study created a multiple buffer of roads and highways with the following distances: 100 meters, 200 meters, 250 meters, 300 meters, and 350 meters. Considering that 250 meters is an intermediate value (not near and not far from the main roads), it is considered the best distance (value 5). The greater the distance, the less suitable the area is; the distance of 350 meters was reclassified as 2, and distances above this value were reclassified as 1. Distances lower than 100 meters were constrained using Boolean operator, since these areas were not suitable.

The land use and occupation criterion for assigning pre-defined values was based on each city's zoning laws. In many municipalities, protected areas, such as parks, reserves, conservation units, and other areas, are already included in their zoning map. Therefore, these protected areas were classified as restricted, being assigned value 0. Values from 2 to 4 were assigned according to the zoning regulation. In some municipalities, industrial and/or rural areas were assigned value 5 (more suitable). Moreover, in some municipalities, this type of work implantation is allowed in their industrial and rural areas, so value 5 was assigned to both places.

Soils were reclassified according to their fragility: 1 (less suitable) for Gleysols and 5 (more suitable) for Latosols, according to the Brazilian Agricultural Research Corporation (Embrapa Solos, 2013) and Ross (1994). Geologically, value 1 was assigned to sedimentary rocks and value 5 to igneous rocks, according to the mechanical resistance of rocks, defined by the report "Hot Mix Asphalt Materials, Mixture, Design, and Construction" published by NAPA. The geotechnical criteria, generated from various spatial data, refer to a set of factors related to the susceptibility of a site, such as erosion susceptibility. In this case, water, slope, and geology data integrated this factor to scale, hence all data were compiled and the suitable areas were defined considering the geotechnical criterion. Slopes between 1 and 30% of the study area were considered the most appropriate (value 5), that is, the higher the slope, the lower the adequacy. The values were based on the Brazilian Landfill Standard ABNT 13896/1997. In addition, in restricted areas protected by law (for example, parks and watercourses), a 100-meter buffer was established for these areas (value 1), considering that the greater the distance, the greater the site adequacy. In some cities of the Urban Central Core, such as Curitiba, minimum distances from rivers vary, as defined by the Special Sector of Health, Environment, and Conservation, specified in the law of land use and occupation. However, there are also different distances established in Federal Law No. 12.651/2012. A 400-meter buffer for water resources was defined as an intermediate value between those described in the Federal Law; thus, the greater the distance, the greater the area adequacy.

To verify area adequacy according to the proposed objective, a map was prepared with all data previously reclassified, integrated, and analyzed. The output data was the final suitability map of the study case. After prioritizing the criteria defined by the results from the first round of the Delphi questionnaire, along with previously treated geographic data, this study determined the Equation 1 and the weighted linear combination that could compose the final map. According to Estoque (2011), it is the most used equation for MCDA. ArcGIS® has a tool based on Equation 1, called Weighted Overlapping, which was used to assign weights to the criteria, with subsequent multiplication among them, as recommended by Equation 1.

$$S = \sum WiXi \times \prod Cj \quad (1)$$

Where:
S = area suitability;
X_i = staggered factors;

W_i = weights assigned to each criterion;
C_j = restrictions (or Boolean factors),
Σ = sum of weighted factors;
Π = restriction product (1 – suitable, 0 – constrained).

In the following step and based on Equation 1, the map of constrained areas is multiplied by the suitability map, using Map Algebra in ArcGIS. With the output data, a map was generated to indicate potentially suitable areas for CDW waste disposal. For the area to be considered adequate, its size must be at least 12,000 m². This value was determined from a literature review on CDW landfills, based on the estimated population of the Metropolitan Area of Curitiba and the CDW data obtained from the ABRELPE (2014) survey. Using the data extracted from ABRELPE (2014) report and the population of the Metropolitan Area of Curitiba — 3,223,836 inhabitants, according to the Brazilian census (IBGE, 2010) — this study estimated the total CDW generated daily in the Urban Central Area, resulting in less than 200 tons/week. This would be close to what happens in New York, where CDW landfills with 12,000 m² (about 3 acres) or less can receive up to 200 tons per week (New York State, 1989).

As a result, the study created the final map, indicating potentially suitable areas for CDW disposal. Two areas located in the municipality of São José dos Pinhais were chosen by the authors for an on-site visit to verify whether the areas were suitable — according to criteria established — for a landfill, validating the agreement between data output and the proposed methodology. São José dos Pinhais municipality was selected because it is close to Curitiba and has many potentially suitable areas. Nevertheless, the objective of this research was not to define a specific area, but to indicate suitable areas in the Urban Central Core of Curitiba.

Study area

The study area is the Urban Central Core of Curitiba, in the State of Paraná, Brazil. The determination of this area (Figure 1) — which contains 14 municipalities — considered the integrated relations of municipalities, such as commercial and employment relationship, and high population density. Additionally, the capital of the state of Paraná, Curitiba, is inserted in this area.

Results and Discussion

To design the map of constrained areas, the areas were divided into two classes — suitable and unsuitable. The creation of a Buffer, in combination with the "Is Null" operation, plus the Raster Calculator tool with GIS usage, allowed the areas to be classified as suitable and unsuitable. According to Malczewski and Rinner (2015), the approach operation (Buffer) generates limits around objects, having the same distance in all directions, thus resulting in a binary buffer, where the inner area inside this limit is assigned a value equal to zero (0) and the remaining areas, a value equal to 1. Within the areas considered to be unsuitable (0) (Figure 2), there were water resources, protected areas, and streets/roads, showing that GIS was effective in excluding these areas. Following the procedure described in Chang et al. (2008), the first landfill implementation analysis was effective, excluding sensitive areas, while maintaining suitable areas for further assessment.

The design of suitable maps, as in most multi-criteria decision-making methodologies, requires criteria to be weighted. Then, the criteria map must be standardized for an analysis to be performed (Demesouka et al., 2019). Subsequently, the group of experts answered a two-round questionnaire and returned it, allowing Delphi method validation. The "core" of the Delphi method is its structure, which lists all con-

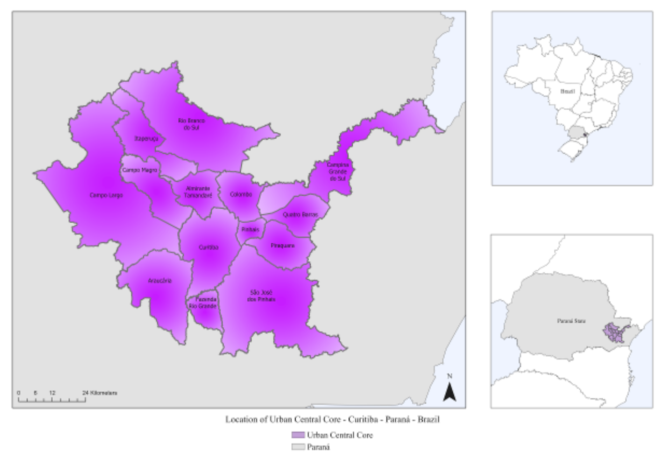

Figure 1 – Location of the Urban Central Core of the Metropolitan Area of Curitiba.

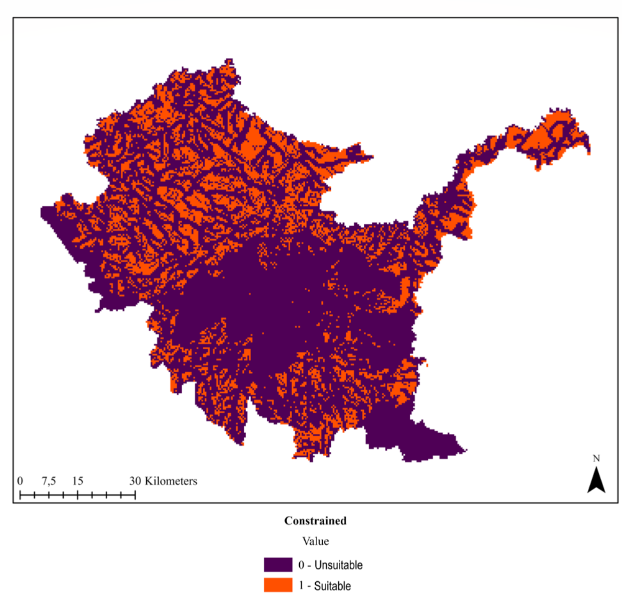

Figure 2 – Constrained areas for the Urban Central Core.

tributions made by individuals who offer a perspective or view of the group. For this reason, this technique is feasible for the decisions made (Malczewski, 1999). Software "Expert Choice" performed the analysis of the first round of questionnaires, in which the criteria were hierarchized reducing data analysis time. As observed in Figure 3, weight was also assigned to the criteria. They were ranked from 0 to 1 according to the AHP method, in which distance from water resources and vegetation (green areas) was considered the most important criterion to be considered during site selection. These results were sent to experts, in a second round of questionnaires, in accordance with the method proposed. Most of the experts agreed with the result, only one did not approve it completely. However, the expert disagreed with the criterion 'vegetation' having higher importance — for other experts — than soil, not with the 'water resources' criterion. More importantly, the inconsistency level of a pairwise comparison according to Saaty (1987) should be lower than 10%, and in our survey, inconsistency was 2%, meaning that we did not need to contact the expert again and repeat the survey.

After area adequacy escalation for each criterion was completed, the suitability map was prepared by multiplying the criteria among themselves. Moreover, to assign the weights defined by the experts for each criterion through the Delphi questionnaire responses, the operation Weighted Overlay in a GIS environment was used to create the final suitability map (Figure 4). This tool facilitates data compilation because, in addition to assigning weights to the criteria, the user can also classify (if the map is not reclassified) the criteria before performing the spatial analysis (Esri, 2015). Another advantage is that the tool does not work if the user does not assign the weights; this reduces the chances of errors in the algebra map implementation.

Subsequently, the constrained and suitability maps were multiplied, by using Map Algebra "Times" tool, resulting in the constrained and suitable area map where areas were classified from 1 (constrained/lowest suitability) to 5 (highest suitability) (Figure 5).

After the map of constrained and suitable areas was designed, the minimum size of 12,000 m^2 for the landfill area (approximately 3 acres) was delimited. Meaning that any area greater than this value was used to indicate the most suitable areas; this identification was made in GIS software, with the use of the 'Set Null' operation for all other values. Then, using the spatial data of the constrained and suitable areas output, classes lower than 5 were excluded and defined in GIS software as "No Data", resulting only in potentially suitable areas with the highest value, fulfilling the main objective of the study. Suitable areas are shown on the map as "potentially suitable areas" (Figure 6). Areas with a value equal to 5 (more suitable) are rural or industrial areas, according to the city's zoning law. Not all rural areas of the Urban Central Core can be used for this type of project, like sites located in the Karst aquifer area, in the city of Almirante Tamandaré, Paraná.

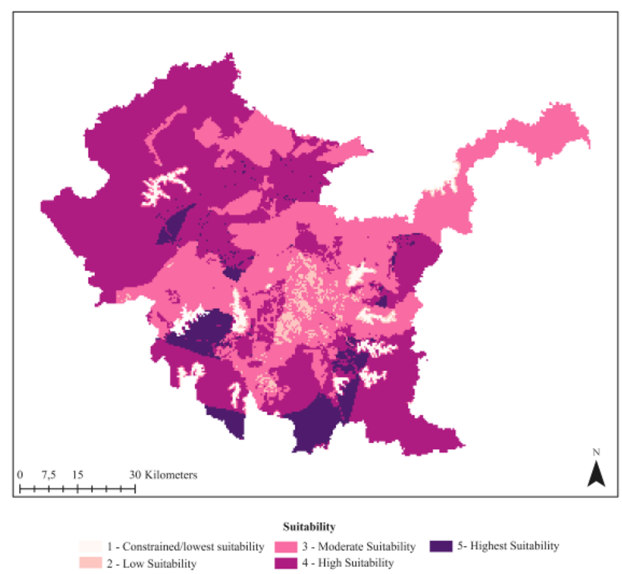

Figure 4 – Suitability map of the Urban Central Core.

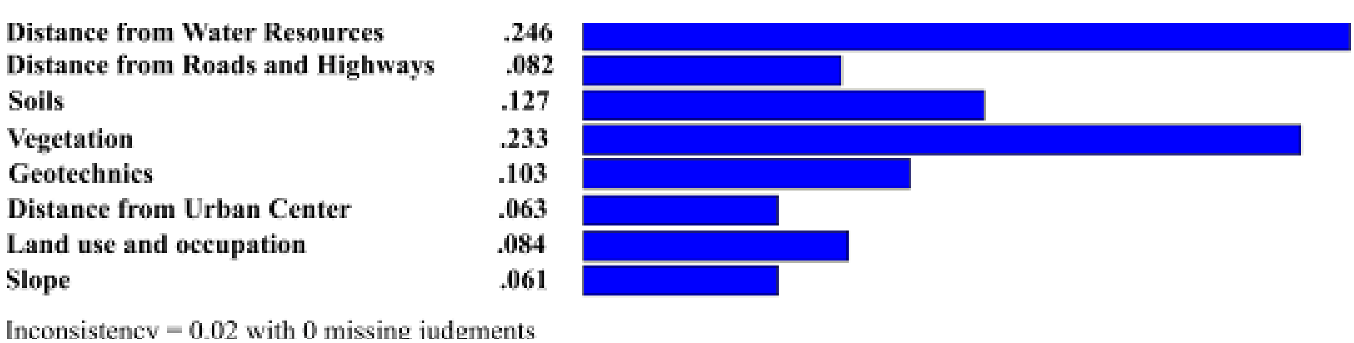

Figure 3 – Questionnaire Responses: weighted and hierarchized criteria for site selection.

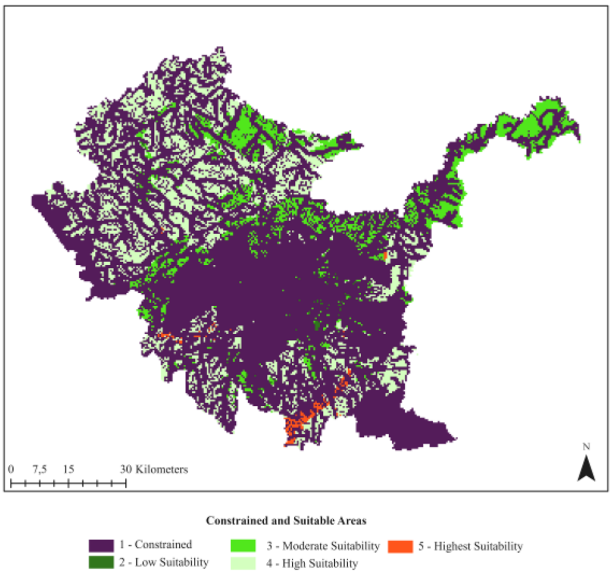

Figure 5 – Final suitability map.

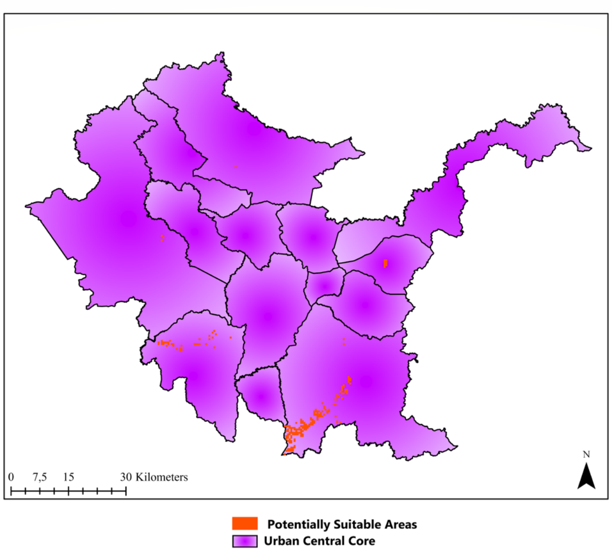

Figure 6 – Map of potentially suitable areas for landfill class A deployment.

As it can be noted, most of the areas are located in the municipality of São José dos Pinhais, some in Araucária, while others are more widespread throughout the Urban Central Core. According to the municipal zoning law of many municipalities, occupation of some protected areas is restricted, e.g., the city of Campina Grande do Sul,

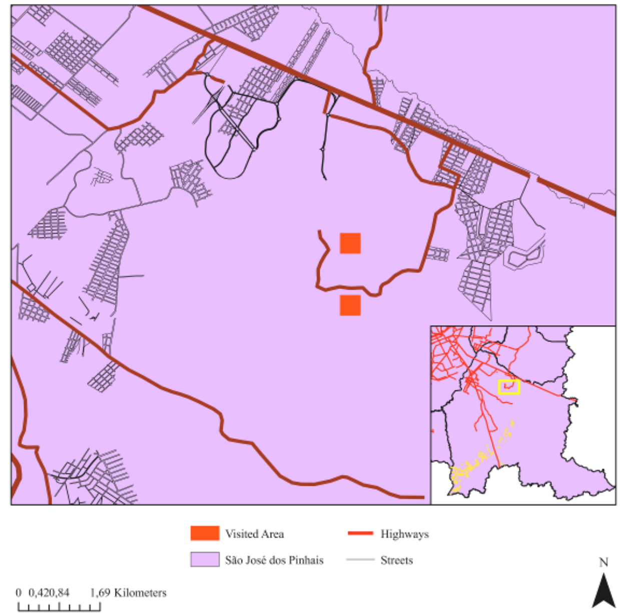

Figure 7 – Area location for on-site observation.

where most of the area is constrained, and land use and occupation are controlled. The municipalities of São José dos Pinhais and Araucária have extensive industrial and rural areas and, consequently, have a larger number of suitable areas. In addition, access to these two municipalities occurs through federal and state highways, facilitating access to certain areas of the municipalities. However, a verification through on-site observation to confirm the findings and verify methodology adequacy was conducted only in two areas located in São José dos Pinhais (Figure 7). Visiting all areas would be costly and time-consuming, especially in places where access is difficult due to different factors, i.e., unpaved roads, privates areas, distance, etc. Additionally, these areas were chosen mainly because of their proximity to the State Capital and are located in an area known for its high concentration of industries, an important place for the metropolitan region of Curitiba.

On-site observation was carried by the authors only to verify if the methodology was adequate to the main objective of this research, that is, indicate potentially suitable areas for a Class A landfill, and not to choose adequate sites. During on-site observation, the authors identified some interesting characteristics in these areas. For instance, the areas are close to BR-277 highway, which facilitates access to construction and demolition waste disposal locations. They are predominantly rural areas, occupied by country houses, with small-cultivated areas. There are some residences nearby, located at a safe distance from the indicated areas. In "area 01", access is via a partially paved road; the area has a small portion of planted forest and has no steep relief. In the second location, called "area 02", there is no steep relief; access occurs through an unpaved road up to a certain point and then through a paved road. After that, road access is reduced, but this can be modified. The area is also private, with little to no vegetation, with only agricultural areas of low commercial value. After all, the chosen sites (in relation to the adopted criteria) agree with the analysis previously performed in the GIS environment and show how this tool supported by the MCDA technique can be very useful in solving decision-making problems where a geographical component is of great importance.

Conclusion

The greatest difficulty during the study was obtaining spatial data for the criteria established for the study area. Insufficient data may limit GIS application at different stages of solid waste management. However, it was feasible to evaluate the study area, despite the existence of some limitations. During an on-site visit, it was possible to verify the importance of GIS software to organize, process, and analyze geographic data, and to create maps indicating potentially suitable areas. Both the GIS and the MCDA method were efficient in restricting, prioritizing, and weighting spatial data, helping reduce subjectivity and uncertainties related to data integration and criteria analysis, as well as considering those selected by the decision-makers. CDW landfills should be implemented to reduce environmental impacts and protect human health. According to the Brazilian legislation, this type of landfill should be used for material storage and future use, including the future use of the area, rather than just disposing of waste in landfills, reducing its useful life. Therefore, the correct indication of suitable areas for this purpose must be made considering these aspects, especially in developing countries, where this type of waste is a significant environmental issue.

Additionally, the main point of this study was to indicate potentially suitable areas rather than select them. Other relevant information on landfill location, including standards and installation, should also be considered if the selection of an appropriate site was to be performed. Then, further studies are required to select one of the areas for the disposal of construction and demolition waste. Furthermore, private companies and government agencies can use the proposed methodology for integrated waste management — not only for the municipalities covered by the study case. If adapted accordingly, the proposed method can be applied in other locations. Moreover, it can not only be used to indicate potentially suitable areas for Class A landfills, but also for landfills of other categories. Ultimately, it can be adapted and implemented in other stages of solid waste management, especially when the objective is to reduce costs, time, and social and environmental impacts arising from illegal solid waste disposal.

Contribution of authors:

Biju, B.P.: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing — Original Draft. Nagalli, A.: Conceptualization, Validation, Supervision, Project Administration. Moura, E.N.: Conceptualization, Methodology, Software, Validation, Supervision, Writing — Review & Editing.

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Spatial-temporal evolution of landscape degradation on the Guamá River Basin, Brazil

Evolução espaço-temporal da degradação da paisagem da Bacia do Rio Guamá, Brasil

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ABSTRACT

The goal of this study was to determine the anthropization evolution of the Guamá river basin in the years 2000, 2008 and 2018 by means of the Anthropic Transformation Index. Land use and cover maps were obtained from two databases, Project Mapbiomas (Brazilian Annual Land Use and Land Cover Mapping Project) and PRODES (Project for the Satellite Monitoring of the Brazilian Amazon Forest). The main classes defined in the mapping process are: forest, natural non-forest vegetation, agriculture and livestock farming, secondary vegetation, urban infrastructure, water and others. Secondary vegetation was considered as the area where the forest classes of Mapbiomas intersects with the deforested areas of PRODES, as determined by the map algebra operator. The expansion of agriculture and livestock farming achieved an increase of about 10%, while the forest was reduced in almost 10%. The Guamá river basin obtained an Anthropic Transformation Index of 4.44 in 2000, 5.04 in 2008 and 5.09 in 2018, going from a regular to a degraded state in 18 years. The occupation process caused major alterations in the natural components of the landscape over the course of 18 years, notably in the amount of forest. Protection of 35% of the remnant primary forest in the Guamá river basin is vital for the conservation of water resources vulnerable to changes in land use.

Keywords: PRODES; Mapbiomas; land use change; geoprocessing; Amazon.

RESUMO

Este estudo teve como objetivo determinar a intensidade da antropização da bacia hidrográfica do rio Guamá nos anos de 2000, 2008 e 2018 por meio do Índice de Transformação Antrópica. Os mapas de uso e cobertura da terra foram obtidos em duas bases de dados: Projeto Mapbiomas e PRODES. As classes majoritárias definidas no mapeamento são: floresta, formação natural não-florestal, agropecuária, vegetação secundária, infraestrutura urbana, água e outras. A vegetação secundária foi classificada como a área das intersecções entre as classes de floresta do Mapbiomas e a área desmatada do PRODES, utilizando o operador de álgebra de mapas. O processo de ocupação resultou na expansão da agropecuária, que cresceu cerca de 10%, ao passo que a floresta apresentou uma redução de quase 10%. A bacia do rio Guamá obteve um Índice de Transformação Antrópica de 4,44 em 2000; 5,04 em 2008 e 5,09 em 2018, passando de um estado regular para degradado em 18 anos. Esses resultados estão relacionados à expansão da agricultura e da pastagem, especialmente em áreas de ocupação antiga. O processo de ocupação provocou grandes alterações nos componentes naturais da paisagem, ao longo de 18 anos, principalmente na quantidade de floresta. A proteção dos 35% da floresta primária remanescente na paisagem da bacia hidrográfica do rio Guamá é vital para a conservação dos recursos hídricos vulneráveis às mudanças no uso do solo.

Palavras-chave: PRODES; Mapbiomas; mudanças de usos da terra; geoprocessamento; Amazônia.

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Introduction

In Brazilian Amazon, human activities have irreversibly changed many ecosystems, especially the forest (Vieira et al., 2018). Many studies have demonstrated that the main drivers of those changes are large-scale deforestation, forest fires and the shifts in land use and cover (Asner et al., 2009; Arima et al., 2014; Shimabukuro et al., 2019; Santos et al., 2020). Particularly in the last five decades, agriculture and livestock farming have been the main economic activity associated with such changes (INPE and EMBRAPA, 2014; EMBRAPA, 2018) and are responsible for 80% of the deforestation in the region (INPE and EMBRAPA, 2014). From the perspective of land use and cover in Amazonian environment, many studies are being carried out, in different time and spatial scales, to analyze landscape degradation patterns looking for actions and adjustments to be adopted by rural activities (Gouveia et al., 2013; Rodrigues et al., 2014; Almeida and Vieira, 2019).

In a broader scale, landscape degradation refers to changes in the configuration and quality of land-cover patches, disturbing the functioning of ecosystems in a given region (Ghazoul and Chazdon, 2017). Degradation at a landscape level encompasses deforestation, forest fragmentation and changes in land use, which modify landscape composition, its connectivity, and the ecosystem functions, such as nutrient cycling, climate regulation and the water cycle of the river basins (Sartori et al., 2012; Rosa et al., 2017; Almeida et al., 2020). The Anthropic Transformation Index (ATI) was developed in order to analyze the levels of change and transformation in the landscape (Gouveia et al., 2013), and it is applied in Brazil to determine landscape degradation at river basin scale (Gouveia et al., 2013; Ribeiro et al., 2017; Almeida and Vieira, 2019), as it better reflects the impact caused by human actions on the original vegetation and on land use in river basins. The latter are a natural system that is well defined in space, comprising land masses topographically drained by a watercourse and its tributaries (Rodrigues et al., 2014). River basins are considered units of environmental management and planning, as they are technically and legally established under the Brazilian legislation (Brasil, 1997).

The disordered process of occupation of the river basin causes innumerable environmental losses, such as the deforestation of areas with native and secondary vegetation in favor of expanding relatively intense agricultural activities (Tamasauskas et al., 2016). Deforestation is usually associated with the use of fire (Santos et al., 2020), and its indiscriminate application becomes a serious socioenvironmental problem (Gonçalves et al., 2012). Planning of land use and occupation in the basin is necessary in order to reconcile productive activities and limited natural resources (Tucci, 2002; Zacchi et al., 2012).

This is the case of the Guamá river basin (RGHB), which shows great anthropic pressure on the forests, from the headwaters (in the municipality of Nova Esperança do Piriá, State of Pará) to the river mouth (in Guajará Bay, State of Pará), responsible for a water supply of about 75% in the Metropolitan Region of Belém (COSANPA, 2015), which serves a population of approximately 676,510 inhabitants (IBGE, 2010).

The RGHB is located in a region of ancient occupation that underwent intense deforestation due to the construction of a railroad in the late 19th century, its effects being intensified with the opening of the Belém-Brasília highway (Silva and Silva, 2008). The RGHB is highly urbanized, with extremely concentrated economic activities, poverty increase, non-resolution of social problems, and low sustainability (Rocha and Lima, 2020).

In this study we evaluated the intensity and evolution of anthropization of the RGHB in the years 2000, 2008 and 2018 by means of the ATI, and examined how the new dynamics of land use affects the areas of native forest and secondary vegetation under the hypothesis that the intensity of landscape degradation in the RGHB, increased along eighteen years (2000-2018) is associated with the expansion of agriculture and livestock farming.

Methodology

Study area

The RGHB is located in the East of the State of Pará, between parallels 1º 10' 57" S and 5º 04' 30" S and meridians 48º 36' 47" W and 47º 41' 39" W; it encompasses an area of 80,412.34 km² within the Northeastern Atlantic Coast Hydrographic Region, as established in the State Water Resources Policy (Pará, 2001). This river basin occupies 6.2% of the State of Pará and includes 33 municipalities, as well as 2.6% of the State of Maranhão, with three municipalities (Figure 1).

Temperatures range from a minimal 22 to 23°C to a maximal 30 to 34°C, with relative air humidity between 85 and 91%. Rain is abundant in the region: rainfall index is 2.250 to 2.500 mm/year (Cordeiro et al., 2017). Vegetation comprises floodplain dense forest in lowland areas, broadleaf secondary forest in uplands and dense forest in low plateau and terraces (IDESP, 2013).

The RGHB is in the fifth-order category, with a course of 490,660 km in the main canal, divided in three zones: Lower Guamá (LGm), Middle Guamá (MGm) and Upper Guamá (UGm). Guamá river begins in the municipality of Nova Esperança do Piriá, above Paragominas, runs through Capitão Poço and Garrafão do Norte (UGm) and arrives at the municipality of Ourém. From there, it runs through São Miguel do Guamá and other three municipalities (MGm). Then, it joins river Capim in the city of São Domingos do Capim, widening forward until it opens into Guajará bay in Belém (LGm). Its main tributaries, on its left bank, are Capim, Acará and Moju rivers (Figure 1).

The UGm zone comprises the municipalities of Capitão Poço, Garrafão do Norte, Ourém and Santa Luzia do Pará, with a population of 1,814,334 inhabitants (Table 1) and only 9% of primary forest. Overall, this region harbors 26.18% (3,505,310) of the livestock heads in the RGHB and is an exponent in citrus production, with 87.56% (11,389,197 tons) of the yield (IBGE, 2017). In the 1980s, citrus culture had a strong boost and turned the municipalities of Capitão Poço,

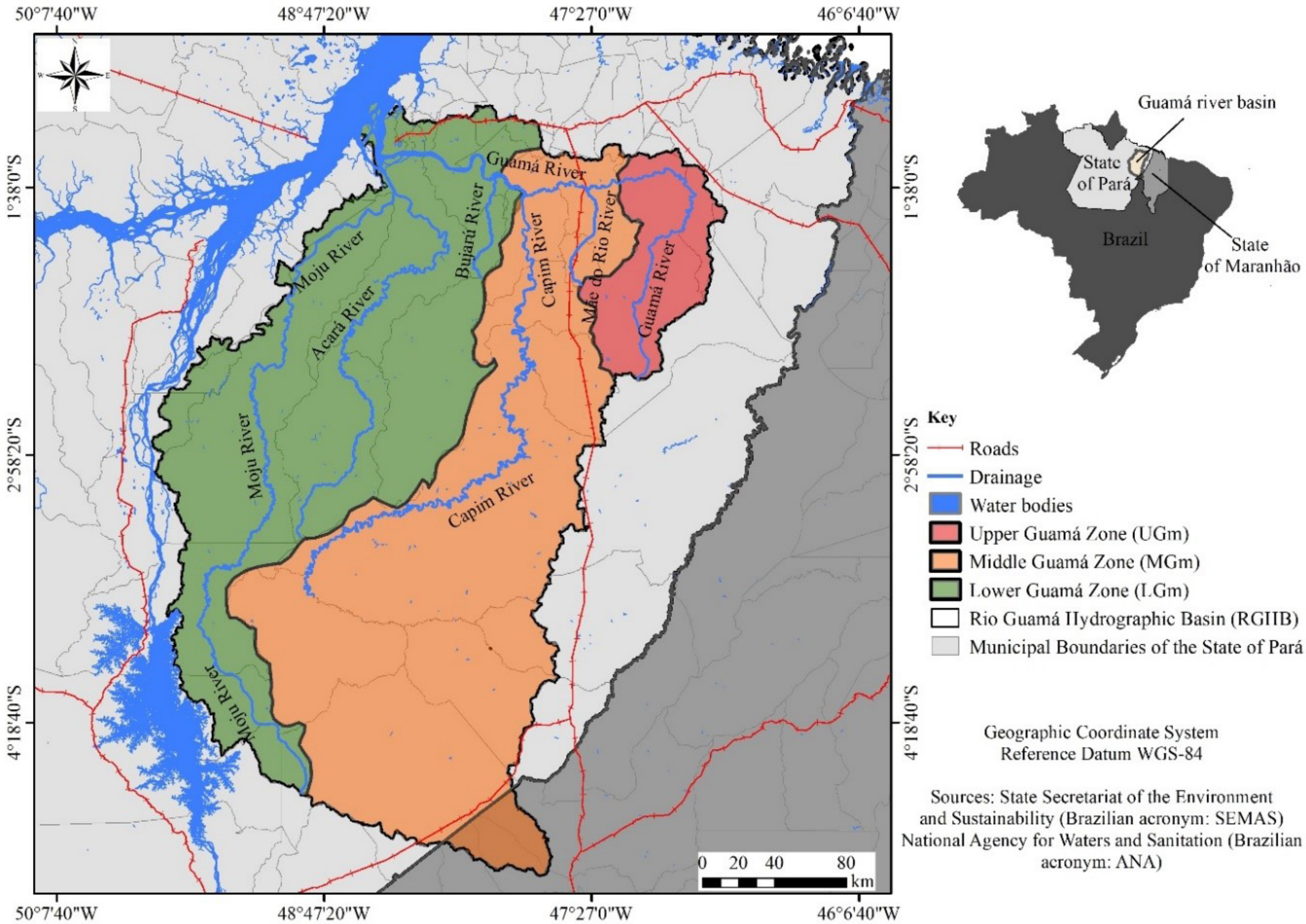

Figure 1 – Spatial location of the Guamá river basin (RGHB) and the Upper (UGm), Middle (MGm), and Lower zones of Guamá river (LGm), Brazil.
Source: prepared by the authors with information from the State Secretariat of the Environment and Sustainability (SEMAS, 2018) and the National Agency for Waters and Sanitation (ANA, 2018).

Ourém and Irituia into the greatest producers of citrus in the State of Pará (Rebello and Homma, 2017).

In the MGm zone, the municipalities of Aurora do Pará, Dom Eliseu, Goianésia do Pará, Ipixuna do Pará, Irituia, Mãe do Rio, Paragominas, Rondon do Pará, São Domingos do Capim and São Miguel do Guamá sum up 25.03% of the livestock farming in the Guamá basin and a population of 6,978,846 inhabitants; it dominates the production of soy, 98.21% (4,203,409 tonnes) of the yield in the basin (IBGE, 2017).

The LGm zone, comprising the municipalities of Acará, Ananindeua, Belém, Benevides, Breu Branco, Bujaru, Castanhal, Concórdia do Pará, Inhangapi, Marituba, Mocajuba, Moju, Santa Izabel do Pará, Tailândia and Tomé-Açu, concentrates most of the RGHB population with 82.55% (41,593,736 people) of the state residents. Agriculture is headed by the cultivation of oil palm, with a production of 17,869,270 tons (98.62%) of the total state yield.

Data processing

Data on land use, cover and deforestation for years 2000, 2008 and 2018 were obtained respectively from two databases: Mapbiomas — Brazilian Annual Land Use and Land Cover Mapping Project (Mapbiomas, 2019) and PRODES — Project for the Satellite Monitoring of the Brazilian Amazon Forest (INPE, 2019) — the latter being under the responsibility of the INPE (the National Institute for Space Research).

Mapbiomas is based on images of the Landsat satellite series (i.e., 5 — TM, 7 — ETM+ and 8 — OLI), with 1985 and 2019 data, in partnership with Google: all processing is done in the Google Earth Engine (GEE) platform and the data are stored in Google Cloud (Moore and Hansen, 2011; Ribeiro et al., 2019; Souza Junior et al., 2020).

The Mapbiomas project, now in its version 5, works with the concept of data collection. It employs a process of automatic classification of Landsat image mosaics, pixel by pixel, in scales of up to 1:100,000, analogous

Table 1 – Socioeconomic information on the Guamá River basin subdivisions, Pará, Brazil.

Sub-divisions	Population (Inhabitants)	Oil palm (tons)	Manioc (tons)	Soy (tons)	Citrus (tons)	Livestock (heads)
UGm	1,814,334	49,704	4,062,926	9,895	11,389,197	3,505,310
MGm	6,978,846	199,537	22,374,632	4,203,409	900,695	3,351,324
LGm	41,593,736	17,869,270	19,440,483	66,829	716,773	6,530,094
Total	50,386,916	18,118,511	45,878,041	4,280,133	13,006,665	13,386,728
Sub-divisions	**Population (%)**	**Oil palm (%)**	**Manioc (%)**	**Soy (%)**	**Citrus (%)**	**Livestock**
UGm	3.60	0.27	8.86	0.23	87.56	26.18
MGm	13.85	1.10	48.77	98.21	6.92	25.03
LGm	82.55	98.62	42.37	1.56	5.51	48.78

Source: IBGE (2017).

to a minimum area of 900 m² (30m x 30m), by means of Random Forest decision-tree algorithms available in the GEE platform (Ganem et al., 2017). All 13 classes presented by Mapbiomas were considered within the Guamá river basin and regrouped into the six major classes defined for the mapping process: forest, natural non-forest vegetation, agriculture and livestock farming, urban infrastructure, water and others (Chart 1).

The deforestation identification process in Project PRODES was entirely done by means of visual photo interpretation by a team of specialized interpreters using the TerraAmazon geographic information system, developed by INPE (2019). It employs Landsat images in color composition associating the medium-infrared (1.560–1.660 µm) spectral band, where dense vegetation is shown in deep red – and the near-infrared (0.845–0.885 µm) and red (0.630–0.680 µm) spectral bands, respectively, in green and blue. Visual identification of target areas takes into account the main elements of photo interpretation, such as color, tone, texture, shape and context.

Annual mapping of PRODES is applied to deforested areas larger than 6.25 ha by interpreting approximately 210 images from Landsat (spatial resolution, 30 m), with the production and disclosure of the rate of clear-cut deforestation in Legal Amazonia and related maps (INPE, 2019). PRODES utilizes the concept of cumulative mask, accruing deforestation mapped in previous years into an integrated base including all detected clear-cut deforestation areas. The PRODES mask prevents the possibility of previously detected deforestation areas being identified and mapped again, so as to keep a consistent historical series over the years (INPE, 2019).

The secondary vegetation class was obtained by crossing the forest class from the Mapbiomas Project and the deforestation class from Prodes, using the tool of map algebras of the software ArcGIS 10.2.2., which allowed mapping the area of intersections between these two classes. We consider secondary vegetation as a type of vegetation cover derived from natural regeneration following the abandonment of an agricultural area, which is considered an indicator of forest landscapes that underwent man-made alterations (Vieira and Almeida, 2013).

Chart 1 – Regrouping of land use and cover classes of Project Mapbiomas for the purposes of this study.

ID#	Mapbiomas Classes	Regrouping
3	Forest Formation	Forest*
4	Savanna Formation	
5	Mangrove	
12	Grassland Formation	Natural Non-Forest Vegetation
13	Other Natural Non-Forest Formations	
32	Hypersaline Tidal Flats	
15	Pasture	Agriculture and Livestock Farming
19	Annual and Perennial Crop	
24	Urban Infrastructure	Urban Infrastructure
33	River, Lake, Ocean	Water
23	Beach and Dune	Others
30	Mining	

#Key codes for pixel values in Mapbiomas Collection 4; *Mapbiomas considers Mangrove and Savanna Formations as Forest, in sublevels 2 and 3 (Mapbiomas, 2019), but these formations are not representative in BHRG. Source: Project Mapbiomas (2019).

Classification validation

The MapBiomas Project assesses the overall accuracy for each use and cover class through estimates based on the evaluation of a pixel sample (reference database), composed of ~75,000 samples. The number of pixels in the reference database was predetermined by statistical sampling techniques. For each year, every pixel of the sample is evaluated by technicians trained in visual interpretation of Landsat images (Pontius Jr. and Millones, 2011).

To validate the Secondary Vegetation class in 2018, field work collected 200 samples to ensure the accuracy of the secondary vegetation data, since it is practically impossible to have an error-free mapping. Therefore, procedures were taken to determine commission and omission errors. A commission error derives from the interpretation of points or pixels that do not exist in the field (digital media classification); while an omission error occurs when points or pixels existing in the field (reference or real data) are ignored (Silva, 1999).

For that matter, for more elaborate evaluations on the veracity of spatial classification of secondary vegetation, the Kappa index (Hudson and Ramm, 1987) was calculated, as it measures the accuracy of spatial data by using an error matrix correlating the classes identified in the mapping to those identified in the field work. Values above 0.8 are considered excellent (Landis and Koch, 1977; Almeida and Vieira, 2019; Silva and Vieira, 2020).

Determination of the anthropization degree

In this study, ATI was used to quantify anthropic pressure on the Guamá river basin for the years 2000, 2008 and 2018. That index, proposed by Lemechev and modified by Mateo (1984), is calculated from percentage values corresponding to the area of each land use and cover class quantified for the basin and its respective weights (Rodrigues et al., 2014), as shown in Equation 1:

$$ATI = \Sigma(\%USE * WEIGHT)/100 \quad (1)$$

Where:
USE = the percentage of area of each class of land use and cover;
WEIGHT = the value given to the classes of land use and cover with respect to their degree of anthropic alteration.

To calculate ATI, weight values for each class of land use and cover were defined from studies carried out in the area of influence of the RGHB and from specialists in the field (Mateo, 1984; Perim and Cocco, 2016), on a scale of weight variation from 1 to 10, lower to higher pressure exerted by a given class on the landscape (Chart 2). This is a numerical determination of the anthropogenic burden applied to the landscape (Ortega, 2017).

The results obtained in this study were categorized in four anthropization intervals (Cruz et al., 1998), as shown on Table 2.

Results and Discussion

The quantification of land use and cover classes in the RGHB (Table 3) showed that the forest class shrank over the years under

Table 2 – Classification of Anthropic Transformation Index (ATI) intervals.

Classification	ATI Intervals	Anthropic Pressure
Little Degraded	0–2.5	Lower
Moderate	2.5–5	-
Degraded	5–7.5	-
Highly Degraded	7.5–10	Higher

Source: Cruz et al. (1998).

Chart 2 – Weights attributed to land use and cover classes in the Guamá river basin, Pará, Brazil.

Class	Weight	Characteristics
Forest (F)	2	Includes the physiognomies of Ombrophilous Dense Forest (alluvial, lowland, and submontane) and Ombrophilous Open Forest (IBGE, 2013). The weight of 2 is justified for including primary forests that were eventually disturbed by fire or timber extraction.
Natural Non-Forest Vegetation (N-NFV)	2	Type of land cover associated with areas of campinaranas and lavrado with shrub and undergrowth vegetation and some points with Rocky Outcrop. This class is not subject to intense disturbance, which justifies weight 2.
Secondary Vegetation (SV)	3	This vegetation cover is the result of a process of succession of areas where, in the past, there was clear cutting of primary forest (IBGE, 2013). It is associated with the agriculture production system, which justifies weight 3.
Agriculture and Livestock Farming (AL)	9.5	This land use class is associated with pasture and it has the presence of grass and/or abandoned pastures with weed plants, and annual and perennial culture (the latter with a cycle above eight years), in accordance with the classes established in Mapbiomas. Weight 9.5 denotes anthropic areas that are constantly modified.
Urban Infrastructure (URBI)	10	This class referred to urban areas, such as towns, communities, villages, roads and narrow side roads. Weight 10 means lack or death of natural or planted vegetation.
Water (W)	1	Rivers and other water courses: the justification for weight 1 was that this class showed no significant alterations in landscape.
Others	9.5	Class associated with areas of mining, and those with beaches and dunes (Mapbiomas, 2019). Weight 9.5 denotes anthropic areas that are constantly modified.

Table 3 – Quantification of land use and cover classes and Anthropic Transformation Index (ATI) in the years 2000, 2008 and 2018 in the Guamá River basin, Pará, Brazil.

Land Use and Cover Classes	Weight	Areas						ATI		
		2000		2008		2018		2000	2008	2018
		km²	%	km²	%	km²	%			
Forest (F)	2	36,952.97	45.96	30,334.27	37.73	28,510.91	35.46	0.92	0.75	0.71
Natural Non-Forest Vegetation (N-NFV)	2	414.68	0.52	523.45	0.65	792.81	0.99	0.01	0.01	0.02
Secondary Vegetation (SV)	3	18,353.64	22.83	18,411.85	22.90	19,687.72	24.48	0.68	0.69	0.73
Agriculture and Livestock Farming (AL)	9.5	23,509.78	29.24	29,917.80	37.19	30,131.61	37.47	2.78	3.53	3.56
Urban Infrastructure (URBI)	10	251.96	0.31	293.02	0.36	340.02	0.42	0.03	0.04	0.04
Water (W)	1	901.12	1.12	914.47	1.14	865.22	1.08	0.01	0.01	0.01
Others	9.5	28.19	0.04	17.47	0.02	84.05	0.10	0.00	0.00	0.01
Total		**80,412.34**	**100%**	**80,412.34**	**100%**	**80,412.34**	**100%**	**4.44**	**5.04**	**5.09**

study. In 2000, the forest occupied 45.96% (36,952 km²) of the basin area, while in 2018 it comprised 37.73% (30,334.27 km²), and in 2018 only 35.46% (28,510.91 km²), which represents a loss of almost 10% (8,442.06 km²) of forests over 18 years. On the other hand, agriculture and livestock farming increased in the same proportion, with an expansion of 8.23% (6,621.83 km²) in the same period. From that we can deduce that the forest area was deforested to give way to agricultural and livestock farming activities (Walker et al., 2009) and infrastructure projects encouraged by public policies of occupation of upland areas in Amazonia.

The overall performance of secondary vegetation classification was 0.87% for the Kappa index. This high value indicates a satisfactory rating (Landis and Koch, 1977). Regarding the MapBiomas classification, the global accuracy was 91.2% on the scale of 1:100,000, and considered excellent (Congalton and Green, 2019).

The result of forest loss (10%) caused major changes in the natural components of the landscape, implying an increase in agricultural activity (8.23%), secondary vegetation (1.66%), and urban infrastructure (0.11%) over 18 years. In fact, the Amazon region became the stage of various landscape transformations that gave way to the deforestation of wide areas, with landscape-level consequences that can be disastrous. Among the main effects, we can mention the loss of biodiversity and changes in the structure of the landscape, with a high intensity of forest fragmentation (Almeida et al., 2020).

Secondary vegetation had little variation over the years. In 2000, it corresponded to 22.83% (18,353.64 km²), increasing to 24.48% (19,687.72 km²) in 2018. Carvalho et al. (2019) found the same pattern and suggested that the decrease of secondary vegetation in Pará is associated with changes in the dynamics of land use and land cover in relation to the decrease in deforestation, being converted into other types of land uses. In general, secondary forests are associated with recently abandoned pastures or agricultural fallow stages and are highly dynamic in the landscape. These dynamics can be seen in Figure 2, where secondary vegetation begins concentrated in the northern part of the basin (year 2000), extends into the areas taken over by agriculture and livestock farming (year 2008), and arrives at the southeastern portion of the basin (year 2018). Overall, the average time secondary vegetation thrives in the landscape is only five years (Aguiar et al., 2012), and this land cover is quite vulnerable to deforestation (Pereira e Vieira, 2001; Coelho et al., 2018; Wang et al., 2020).

Agriculture and livestock farming class showed the greatest variation in terms of land use area. There was an increase from 2000 (29.24%, or 23,509.78 km²) to 2018 (37.47%, or 30,131.61km²), representing an expansion of almost 9% (6,621.83 km²) of this land use class.

Occupation and alteration of landscape in the RGHB began at the edges (limits), where the main roads and highways are concentrated, reducing the forest area into many fragments in the central part of the basin (Figure 3). It should be noted that the more deforested areas are located along highways BR-010, BR-222 and PA-150, PA-252 and PA-256 (Figure 3), matching the same phenomenon detailed by Soares-Filho et al. (2004) on the impacts of the expansion of the agricultural border, unleashing potential changes in land use and cover and high rates of deforestation.

The development of agriculture and livestock farming in the RGHB in the 1970s was the main trigger for the expansion of deforestation, a complex activity involving many social players. A portion of this region was cut by the Belém-Brasília highway and, during its occupation, squatters, farmers, and loggers got involved in forest felling to exploit timber and open areas for agriculture and pasture. Indeed, the intense anthropization associated with the occupation was a determining fac-

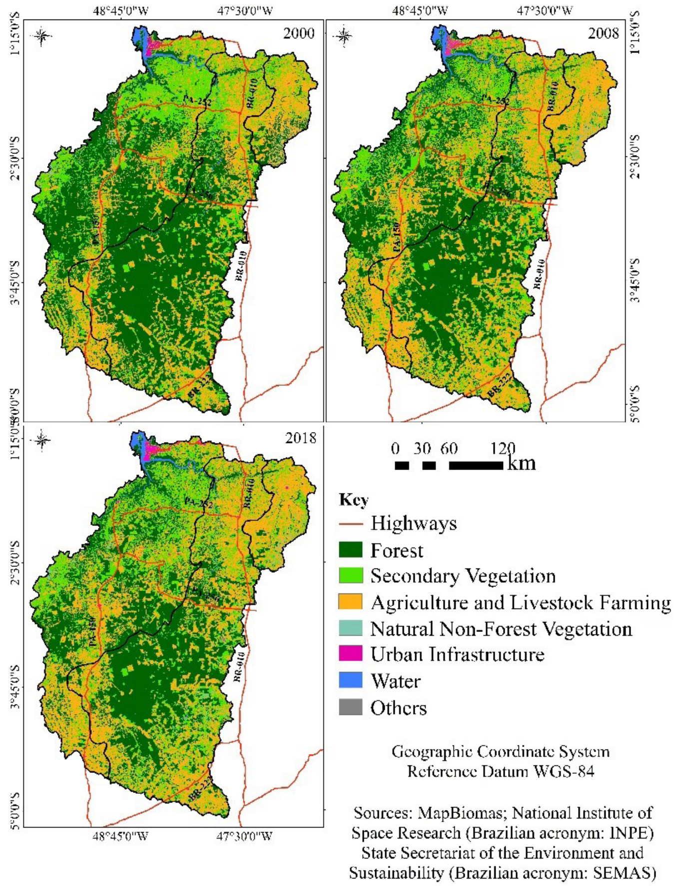

Figure 2 – Vegetation cover and land use in the years 2000, 2008 and 2018 in the Guamá River basin, Pará, Brazil.
Source: prepared by the authors with information from the Mapbiomas Project (2019), INPE (2019) and SEMAS (2018).

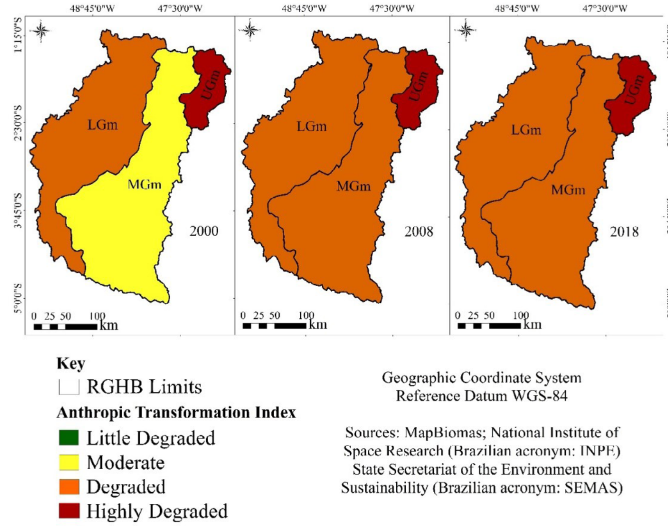

Figure 3 – Distribution maps of the Anthropic Transformation Index for years 2000, 2008 and 2018 for the Upper (UGm), Middle (MGm) and Lower Guamá (LGm) in the Guamá River basin, Pará, Brazil.
Source: Authors, with information from Project Mapbiomas (2019), INPE (2019) and SEMAS (2018).

tor for changes in the Amazonian landscape, as only about 35% of the original primary forest still exist in the region (Cordeiro et al., 2017).

The urban infrastructure, natural non-forest vegetation, water and others (mining, beaches and dunes) classes encompass places with high populational density, open areas and lakes, weirs and levees, homogeneous reforestation and exposed soil, which amounted to 2.59% in 2018, not showing any significant variation over the years.

Table 4 shows the relative area occupied by land use and ATI values in each zone of the RGHB in the years 2000, 2008 and 2018. There is clearly a differentiation of land use in the three RGHB subdivisions: forests predominate in Middle Guamá river and Lower Guamá river, while agriculture and livestock farming occupy about 65% of Upper Guamá river.

The ATI values had a slight increase between 2000 and 2018, except for UGm, in which ATI stayed above 7.8, indicating a situation of high degradation or under high anthropic pressure. In 2000, the ATI values for MGm and LGm were respectively 5.96 (moderate) and 5.01 (degraded). In 2008, however, ATI in MGm was higher, indicating a degraded state (5.59), while LGm continued as degraded (5.52). In 2019, the ATI values changed substantially but the three regions kept the same pattern (Figure 3).

The high value of ATI in the UGm zone occurs because it has the largest area occupied by agricultural and livestock farming activities, characterizing an intense process of anthropization, dominating over 50% of the region.

In a study conducted in the northeastern region of the State of Pará, it was ascertained that, in a period of only four years, the degree of anthropic transformation shifted from moderate to degraded (Almeida and Vieira, 2019), which seems to happen often in this old region of agricultural border. High anthropic pressure is mainly attributed to opening pastures for agricultural introduction, such as the cultivation of citrus, responsible for its impact on the landscape of the UGm zone, comparable to clearing the way for highways such as PA-124, PA-127, PA-136 and PA-140; this allowed for wider circulation of people, goods, and services. Thus, the anthropic action in the region involves wide extensions of land, making up a special arrangement formed by crops of different ages, areas of expansion and reserve, nurseries, roads, and agro-industrial infrastructure (Nahum and Santos, 2016).

The greatest loss of forest (12.86%) between 2000 and 2008 took place in the MGm zone and contributed to the highest level of anthropic transformation and the acceleration of the environmental degradation processes. This loss was caused by livestock farming, responsible for 88% of the economy in the region (IBGE, 2017). In the last decade,

Table 4 –Anthropic Transformation Index for the Guamá River basin zones, Pará, Brazil in the years 2000, 2008 and 2018.

Land use and cover classes (area in %)								
Zones	F	SV	AL	N-NFV	URBI	W	Others	ATI
Year 2000								
UGm*	8.23	21.85	66.25	3.39	0.12	0.15	0.00	7.89
MGm**	52.66	18.08	28.45	0.22	0.05	0.53	0.00	4.86
LGm***	44.12	27.99	24.68	0.47	0.67	1.99	0.08	5.01
Year 2008								
UGm	7.60	19.65	68.90	3.54	0.14	0.16	0.00	8.00
MGm	42.01	19.78	37.18	0.40	0.06	0.53	0.04	5.59
LGm	37.80	27.06	31.95	0.45	0.75	1.98	0.00	5.52
Year 2018								
UGm	9.01	23.23	64.64	2.80	0.20	0.13	0.00	7.82
MGm	39.80	21.04	37.37	1.16	0.08	0.47	0.08	5.66
LGm	34.85	28.73	33.04	0.46	0.86	1.92	0.15	5.69

*Upper Guamá Zone; **Middle Guamá Zone; ***Lower Guamá Zone.

the expansion of soy in the State of Pará had a huge increase in area, totaling 433,813 ha in 2016, representing 29% of the agricultural area of Pará (Fapespa, 2017). According to the Soy Moratorium, an initiative aimed at ensuring that the soy produced and marketed in the Amazon biome is not associated with the suppression of forest, out of the 66 municipalities that have soy plantations in disagreement with the Moratorium, 14 of them are in the State of Pará, including Altamira, Novo Progresso and Paragominas, which had the largest deforested areas in the period between 2009 and 2018; among these, Paragominas had the largest area of soy planted over deforested areas (8.7%). This explains why the MGm zone, as the region with the largest soy production, with the municipality of Paragominas accounting for 25.84% of the total crop in Pará (Fapespa, 2017), lost more than 12% of forest in the last 18 years, while agriculture and cattle raising now occupy about 9% of the region. In addition to forest conversion, pastures increase the risk of fire and are a significant degrader of riparian and aquatic ecosystems in the Amazon region.

The greatest increase in agriculture and livestock farming in a decade (2008-2018) and a slight expansion of secondary vegetation were observed in the LGm zone and could be associated with the abandonment of pastures, which, due to natural regeneration processes, resulted in the forest regrowth (Silva et al., 2019). More recently, this region has been featuring extensive monoculture of oil palm (Nahum and Malcher, 2012), following the flow of deforestation in northeastern Pará, as confirmed by Almeida et al. (2020), and more recently by the TerraClass project (INPE and EMBRAPA, 2014). Nevertheless, although agriculture and livestock farming were predominant in the study area and in the Guamá river basin zones, secondary vegetation has expanded over time. Homma (2015) mentions that government policies related to deforestation and fires are promoting the increase in secondary vegetation and the advance of agriculture and livestock farming. Insofar as the occupation of a region is consolidated, deforestation, use and abandonment of the land are intensified, and secondary vegetation thrives (Almeida et al., 2010).

It is important to highlight that in 2008 there was a recovery of secondary vegetation, which may be associated with regularization measures implemented in consolidated rural properties, forcing the restoration of marginal strips in Permanent Preservation Areas and the recovery by compensation in areas destined to be Legal Reserves, as established in Ordinance 7830/2012, which regulates the Environmental Register System. Furthermore, Normative Instruction 08, of October 28, 2015, protects secondary vegetation areas in advanced stages of succession (Vieira et al., 2014). These areas have been considered important repositories of biodiversity in anthropic landscapes (Lenox et al., 2018; Almeida and Vieira, 2019) and provide high-value ecosystem services available through natural regeneration.

Lastly, it should be emphasized that, considering the region's carrying capacity, the expansion of inadequate forms of land use could result in serious environmental impacts (Ribeiro et al., 2017), such as the decrease in availability of water resources, the intensification of degradation processes, soil compaction and elimination of plant and animal species. Thus, studies focused on the more anthropized areas of a basin (Coelho et al., 2018) could be useful to define priority areas in projects of environmental restoration of river basins, enabling the protection and conservation of their integrity.

Conclusion

The high intensity and dynamics of anthropization in BHRG in the years 2000, 2008 and 2018 revealed great diversification in the three zones of the basin, with emphasis on the decrease in forest cover and a greater intensity of landscape degradation associated with the expansion of agriculture, confirming the initial hypothesis.

The ATI allowed for the qualification of the levels of environmental degradation due to land use. Thus, only the Upper Guamá river was found to be highly degraded in 2018, despite having the lowest rate of area occupied by agriculture and livestock farming and being the farthest from any urban infrastructure.

Considering the human pressure on the environment, the conservation of native forests becomes more and more dependent on strong economic and political incentives. Land value and the expansion of the agricultural frontier, among other factors, have put forward new pressures on Amazonia, even in anciently colonized, well-established regions. These changes in landscape, associated with the decrease of native forests, require quite a lot of attention from public authorities.

Protection of the remnant primary forest, covering 35.46% of the RGHB landscape, is vital for the conservation of water resources vulnerable to changes in land use: accordingly, the use of ATI to monitor anthropic transformations proved to be an alternative to quantifying and overseeing these changes. The study of indexes related to the spatialization of landscape degradation contributes to monitor regions with a history of changes in forest cover and land use. River basins are study units that ensure a better management of decision-making to prioritize areas for forest conservation and for the expansion of agriculture and livestock farming without the need to open further new areas.

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Martins Silva, T.C.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. Vieira, I.C.G.: Conceptualization, Formal analysis, Investigation, Resources, Funding, Review & Editing. Thales, M.C.: Methodology, Software, Formal analysis, Investigation, Visualization, Review & Editing.

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Connecting environmental education, science–technology–society and ecological theory: possible pathways to reduce socioenvironmental problems

Conectando educação ambiental, ciência-tecnologia-sociedade e teoria ecológica: caminhos possíveis na redução de problemas socioambientais

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ABSTRACT

Social practices influence the production, application, and values of modern Science and Technology (S&T). The epistemological integration of science, ideology, and politics produces a complexity that is able to restore the capacity of science to deal with complex problems from several levels. Therefore, it is arguable that scientific education should be effectively committed to instrumentalization for citizenship, as well as to avoid misinterpretations, distortions, and social exclusion. This theoretical study aims to provide a useful guideline for teachers, scientists, and decision-makers focusing on the importance of education and general scientific training on conservation efforts, as to encourage the teaching classes to expand the conceptual framework by encompassing the sociopolitical outspread of S&T. The theoretical foundation was conducted based on two dimensions of Science, Technology, and Society (STS) within scientific education. We created some examples based on phytoplankton biogeochemical dynamics and coral reef conservation to fetch the integration of STS with ecological theory, which can be easily transposed into other subjects or disciplines. The discussion follows the logic that science popularization is a valuable tool for environmental education and a strategy for social inclusion in Brazil. However, the curriculum is an important mechanism driving scholar practices that demands further improvements, besides the academic training of the teachers and the support of the didactic textbooks. Finally, we encourage a policy of science popularization, designed to enlarge individual comprehension of our modern world, to stimulate public participation in decision-making, likewise, to reduce social exclusion and combat structural racism.

Keywords: social inclusion; environmental problems; conservation; socio-scientific controversy.

RESUMO

As práticas sociais influenciam a produção, aplicação e os valores da ciência e tecnologia moderna. A integração epistemológica da ciência, ideologia e política produz uma complexidade que é capaz de restaurar a capacidade da ciência de dialogar com problemas complexos de vários níveis. Por essa razão, argumenta-se que a educação científica deveria ser efetivamente engajada à instrumentalização para a cidadania, bem como para evitar falsas interpretações, distorções e exclusão social. O presente estudo teórico tem por objetivo fornecer um guia útil para professores, cientistas e tomadores de decisão, focando na importância da educação e formação científica em geral nos esforços de conservação, assim como encorajar as salas de aula a expandirem o corpo teórico conceitual pela incorporação dos desdobramentos sociopolíticos da ciência e tecnologia. A fundação teórica foi conduzida baseada nas dimensões da ciência, tecnologia e sociedade na educação científica. Alguns exemplos, baseados na dinâmica biogeoquímica do fitoplâncton e conservação de corais, foram criados buscando a integração de CTS com a teoria ecológica, os quais podem ser facilmente transpostos em outros assuntos e disciplinas. A discussão segue a lógica de que a popularização da ciência é uma ferramenta valiosa para a educação ambiental e uma estratégia para inclusão social no Brasil. Contudo, o currículo é um importante mecanismo na condução das práticas escolares e demanda melhorias, juntamente com a formação acadêmica dos professores e o suporte dos livros didáticos. Finalmente, defende-se uma política de popularização da ciência, desenhada para alargar a compreensão individual do mundo moderno, estimular a participação pública nas tomadas de decisão, reduzir a desigualdade social e combater o racismo estrutural.

Palavras-chave: inclusão social; problemas ambientais; conservação; controvérsias sociocientíficas.

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Introduction

Improving scientific teaching has been a major concern in Brazil (El-Hani and Greca, 2013). The traditional practices have been based on contents and concepts that are memorized, decontextualized, or disconnected from reality due to the lack of articulation with the other disciplines of the middle school curriculum (Teixeira, 2003). Science has thus far been a misinterpreted and mistreated body of knowledge wherein complex deep aspects, such as processes, values, interests, and aims, remain neglected or even lost throughout the didactic process (Camino and Calcagno, 1995). Thus, the outcome is likewise an idealization of science disengaged from the real praxis or scientist's labor, implying a mischaracterization of historic battles, contradictions, conflicts, and problems. As a result, a vision of an altruistic, uninterested science arises produced by individuals equally carrying those qualities (Leal and Selles, 1997; Owen et al., 2012, p. 751); whereas, modern Science and Technology (S&T) play fundamental roles in the organization of social practices, social relationships likewise have "great importance in the production, applications and implications of technology and scientific knowledge" (Campos, 2010, p. 25).

Both the movement and studies on Science, Technology, and Society (STS) originated around the 1970s as a result of efforts to reflect on the impacts that S&T has on society (Santos and Schnetzler, 1997; Ribeiro et al., 2017). From such a perspective, "war" served as a motto to rethink the euphoria caused by scientific and technological developments adjoined to environmental problems and the advancement of S&T as a contrary response to the current idea of a neutral and linear scientific progress (González García et al., 1996; Auler and Bazzo, 2001), instead of recognizing the multiscale effects of political decisions on sustainability for a balanced development (Andriantiatsaholiniaina et al., 2004).

The issue of sustainable economic development arises from the ecological movement and the political, economic, and socioenvironmental theme in which humankind and nature theoretically establish harmonic relationships. However, the aforesaid education for sustainability has been criticized regarding its developmental character in which it favors "predatory economic growth," as well as it has overlooked modern global society constraints (Girault and Sauvé, 2008, p. 17; McFarlane and Ogazon, 2011). The original concept of sustainable development, that is, "development that meets the needs of the present generation without compromising the capacity of future generations to meet their own needs" was introduced by the World Commission on Environment and Development (Brundtland, 1985, p. 26; Hanss and Böhm, 2012). The main criticized conceptual issue is that the need for sustainable education goes back to the emergence of environmental problems, because "the world is not as broad and unlimited as we thought" (Vilches et al., 2011, p. 176). Nonetheless, social expressions, such as politics and economics, influence the application of science (Aikenhead, 2006; Camino and Calcagno, 1995), sometimes posing controversial aspects. The importance of such a perception within environmental education relies on the economic aspect of conservation shaped by a sustainability model, along with the production of goods and services that directly affect the environment.

In this context, interdisciplinarity stems as "a logical bridge among fields that converge on the resolution of a given problem" instead of a simple sum of disciplines (Bursztyn and Drummond, 2014, p. 9). The epistemological integration of science, ideology, and politics produces a complexity that is able to restore the capacity of science to deal with complex problems (Morin, 1980; Broggy et al., 2017, p. 81). Several studies on biodiversity conservation within schools adduce a conceptual lag besides a high variety of proposals, methodologies, and practices. Grace and Ratcliffe (2002) observed that the students guide themselves based on their own conceptions, even though biological concepts had been offered with regard to decision-making about conservation scenarios. Grace (2009) introduced biological conservation shedding light onto the social-scientific sphere as a premise toward sustainable development and pedagogical work. Cachelin et al. (2010) attended a textbook-based activity concerning ecology and conservation and indicated that language is one of the main obstacles in the perception of humans acting on ecosystems. Martins and Halasz (2011) analyzed the mangrove conservation of an indigenous area through environmental education within the "Escola no mangue" program.

An alternative to emancipatory and democratic teaching in Brazil originates in Historical-Critical Pedagogy, which establishes connections with the STS movement. These theoretical strands "are excellent instruments of reflection to support change in the focus of scientific education, progressively abandoning the canonical teaching of sciences [...] to build a scientific education approach that is effectively committed to instrumentalization for citizenship," (Teixeira, 2003, p. 179) as for a broader sociopolitical commitment in the application and production of scientific knowledge (Aikenhead, 2006). Studies of STS are crucial to understand and problematize the relationships between STS in the real social practice, as well as to propose forms of informed citizen participation concerning techno-scientific problems.

In this study, we presented a theoretical discussion with the aim to provide a useful guideline for teachers, scientists, and decision-makers by recognizing the importance of education and general scientific training on conservation efforts, as well as to encourage the teaching classes to expand the conceptual framework by encompassing the sociopolitical outspread of S&T within environmental education. Additionally, we proposed some illustrative examples based on marine ecological communities, whose model can be easily transposed into other formal contents and disciplines.

Methodology

In order to contemplate the STS framework, the discussion related to scientific education will be carried out alongside the proper epistemological domain over the varied dimensions that STS can denote.

The first dimension refers to the educational parameters of STS, which "synthesize different perspectives of STS, and may serve to support the insertion of discussions belonging to the field of STS in scientific education" (Strieder and Kawamura, 2017, p. 32). The other dimension is related to the purposes of STS education, which "synthesize different educational perspectives and their meanings in STS education" (Strieder and Kawamura, 2017, p. 32).

Considering the inherent potential of coral reef conservation and phytoplankton ecology in generating multidisciplinary outbreaks, we created several themes, each one accompanied by an introductory text, with the seek to remodel environmental questions from those interconnected dimensions of Science, Technology, Society, and Environment (STSE). These themes also involve different social layers with diverse actors and evoke different potentially controversial problems. The first text introduces the biological entities involved, their role on the ecosystem's properties, and the effects of anthropogenic activities *via* the degradation or destruction that leads to unbalanced ecosystem functioning. Thus, the proposed examples seek to fetch the integration of STS with coral reefs and phytoplankton ecology as an illustrative background, based on the assumption that the STSE model should incorporate the political component, deconstruct the developmental model, and provide social inclusion.

Results: possible themes and approaches in light of STS

Why are coral reefs and phytoplankton so important?

The marine environment is actually the largest ecosystem on Earth. Approximately 70% of the planet's surface is covered by brackish waters, whose importance is related to reserves of food, oil, natural gas, minerals, and other bioactive substances (Mitra and Zaman, 2016). The oceans hold, among other things, coral reefs and phytoplankton microalgae, which play a crucial role in the biosphere. In the first case, coral reefs account for one-sixth of the world's coastal zone (Birkland, 1997; Chen et al., 2015) and shelter hundreds of thousands of animals and plants species (Reaka-Kudla, 1997).

Anthropogenic activities are responsible for threatening 58% of coral reefs worldwide (Bryant et al., 1998; Yu, 2012). The main sources of ecosystem disturbance are agriculture, deforestation, and urban development, which introduce high amounts of sediments, nutrients, and pollutants into coastal waters and can lead to eutrophication and habitat destruction (Ginsburg, 1994). During the last few decades, notwithstanding, conservation of coral reefs has been a global concern as those ecosystems are directly affected by climate change (Brandini et al., 2001), which in turn poses a threat to important ecosystem services and ecological dynamics. More than a quarter of coral reefs have already been affected, destroyed, or severely degraded due to problems caused by rising global temperatures (Goreau et al., 2000). For this reason, tropical coral reefs demand high priority for conservation actions (Roberts et al., 2002).

Phytoplankton communities likewise play a crucial role in marine ecosystems and have also been suffering from anthropogenic impacts and neglect from conservation efforts. Anthropogenic activities degrade the phytoplankton ecosystem through excessive exploitation, habitat destruction, and pollution (Lotze et al., 2006; Gunkel et al., 2015), phenomena related to the occupation of coastal areas, where more than 60% of the global human population is concentrated between the coastline and 100 km inland (Vitousek et al., 1997). Although representing only 1% of the Earth's photosynthesizing biomass, the microscopic unicellular organisms that compose this community are responsible for up to 45% of annual primary productivity (Falkowski et al., 2004). Thus, these organisms are considered a source of energy that sustains trophic chains in pelagic zones, which reflects their importance in global nutrient cycling and dynamics (Cloern and Dufford, 2005).

As a consequence of human development for ecosystems, there has been an inflection pattern in species depletion, destruction of coastal habitats, degradation of water quality, and bioinvasion in coastal ecosystems of North America, Europe, and Oceania over the last 150–300 years (Lotze et al., 2006). The social actors related to the problem are coastal communities and consumer society in general. However, agriculture makes a considerable contribution to the degradation of estuarine systems and reservoirs due to the suppression of native land and the introduction of pollutants (Wiegand et al., 2020).

Coral reefs and acidification of coastal waters

Acidification of coastal waters is one of the factors reported by the scientific community in reference to safe planetary boundaries for global sustainability concerning critical issues arising from human occupation of Earth (Artaxo, 2014). This process is basically caused by carbon dioxide (CO_2) enrichment of the atmosphere (Hoegh-Guldberg et al., 2007). This increase has not been occurring naturally, since approximately 25% of the CO_2 produced by all human sources enters ocean systems (Canadell et al., 2007) where it reacts with water and produces carbonic acid (Hoegh-Guldberg et al., 2007). This phenomenon decreases carbonate ion concentrations leading to a direct impact on marine organisms that morphologically and physiologically depend on carbonate to build their cells, walls, skeletons, and shells and on ecosystems (Lohbeck et al., 2012; Artaxo, 2014). Although society as a whole contributes to the problem of acidification, some sociotechnical actors are particularly problematic, such as the growing fleet of vehicles powered by fossil fuels and agricultural production with ruminant animals, among other processes that significantly exacerbate the problem.

The relationship between coral reef and acidification of coastal waters, a field of global concern, allows not only environmental classes to summarize empirical concepts of science but also to reflect on how society has related to marine ecosystems historically. This includes the occupation of the Brazilian coast by settlers to the present day during which the Anthropocene is by far the most discussed. We proposed an activity consisting of some questions to be discussed after reading a newspaper article about the worldwide threat to coral reefs due to ocean acidification. The questions are as follows:

- What current global phenomena cause ocean acidification?
- Who is responsible for protecting the ocean?
- What human practices contribute to the degradation of marine environments and the consequent death of coral reefs?
- Perform an Internet search of possible toxic effects of sunscreen on marine ecosystems. In brief, report the results and indicate the source of your research.
- What measures should be taken to effectively protect coral reefs? Indicate at least one for each category listed below and their respective associated actors:
- Social responsibility: (e.g., correct disposal of trash – citizens);
    - Political responsibility: (e.g., efficient law proposals – politicians);
    - Environmental responsibility: (e.g., oversight of threatened areas – environmental police);
    - Technological responsibility: (e.g., high-scale monitoring software – scientists).

The fundamental role of the teacher is to guide the students to think of their realities and actions outside of school. Teachers are encouraged to transform the class into a conversation wheel by exploring the news while reminding students about our social, political, and philosophical responsibilities in the face of environmental problems. Similarly, the activity could be extended with participation in a public legislative assembly session on the occasion of debating local issues or law projects.

Technology is also arranged in this way since it is strictly correlated with the transformation of energy and human development. Therefore, the role of the teacher in this example is to lead the students toward a comprehension of the connection between ecological elements and possible STS relationships to be made. Several examples illustrate such relationships, like the discharge of phosphorus *via* sewage, land use, the effect of sunscreen on coastal waters, and other toxic compounds dumped into the marine environment, pesticide use, conversion of virgin land for agriculture in estuarine ecosystems, and damage to mangroves. Additional possibilities involving different social actors and techno-scientific processes depend on the theme and the specific realities of the school. In our case, examples include industry, ranchers, farmers, fishermen, and the general population that occupies beaches in the summer and introduce high concentrations of chemical compounds from sunscreen that pose a threat to water quality and coastal marine fauna.

Ocean warming

Global warming is, in fact, one of the main threats that oceans have been facing. In a broad sense, humankind has historically affected, or at least altered, ecosystem functions and/or ecological dynamics since prehistory (Doughty et al., 2010). Nielsen (1960) argued that temperature does not significantly affect marine organic production. However, studies in recent decades have shown that climate change impacts phytoplankton communities by increasing the number of cells and possibly causing the so-called harmful algae blooms (Hallegraeff, 1993). Climate change also poses a threat for coral reefs due to the loss of zooxanthels — photosynthesizing microalgae located in the gastrodermal tissue of coral where they interact symbiotically. Such “abandonment” by zooxanthels leads to coral bleaching and consequent death due to carbonate deficiency likely from acidification or other environmental disturbances (Kikuchi et al., 2004).

Notably, this object of investigation offers a potential background to discuss interdisciplinary implications in terms of the role of STS in environmental issues and how we could solve controversial problems, mainly when they evoke different types of interpretations. For example, market-based relationships between technology and the production of goods and services can be considered from the perspective of the effects of industry on the pollution of the atmosphere, the increasing number of cars that burn fossil fuel, the warming of the planet, and so on.

From another angle, as subjects, coral reefs and phytoplankton may also be efficient at guiding students toward a comprehension of the biosphere as a complex interconnected system, and how sociotechnical actions impact marine life. A student that does not live near the sea or in a coastal region may assume that these marine themes are not common issues to think about. The science teacher is thus entrusted to plan or design environmental classes that dialogue with different social and political spheres enlarging local realities. Furthermore, students may be able to state how human actions impact terrestrial and marine systems on broad scales, especially those derived from economic activities related to consumerism and the production of goods and services (Bursztyn and Drummond, 2014).

Nonetheless, there is a barrier separating citizen participation from the construction of sustainable ideals: the naïve statement or view that environmental changes are linear and slow and thus would allow human adaptation. Apart from such common sense, temperature shifts of around 2°C can actually have drastic and irreversible effects on the planet, even though those changes seem to be negligible or of less significance (Pearce, 2007). Such a statement is not always clear or intuitive due to the difficulty of accessing information, as well as the paradoxical character science sometimes achieves. In this example, increased temperature leads to the thawing of the Arctic’s permafrost, which implies a release of methane gas and a consequent enhancement of temperature (Vilches et al., 2011). Within our suggested approach, we proposed an activity based on local news regarding coral reef losses over the last 50 years in the Northeast Region of Brazil. Students can be invited to discuss, in pairs or groups, some topics related to the problem mentioned in an STS context. The discussion can then be wide open and mediated by the teacher. The main objective of the teacher should be to articulate the activity without personal meddling, yet guide contextualization in order to allow the students to think without losing central information.

Terrestrial runoff and coral reef ecology

Land use is undoubtedly a major ecological and conservation concern. Coastal regions are being increasingly affected worldwide due to deforestation and the use of fertilizers (Vitousek et al., 1997). More than two decades ago, Bryant et al. (1998) called attention to the increasing nutrient, sediment, and allochthonous pollutant levels to which coastal coral reefs are exposed. Furthermore, the terrestrial runoff was considered an augmenting concern for the majority of 104 countries where coral reefs occur (Bryant et al., 1998).

Discussion

We presented a narrative that can be applied to any educational reality because the problems addressed are global and emergent, in addition to evidence an unsustainable development increasing chain-based socioenvironmental problems (Andriantiatsaholiniaina et al., 2004). Camino and Calcagno (1995) discussed the same patterns of social implications and controversy in scientific education in Italy and proposed role-playing to solve controversial issues and introduce inter-disciplinary themes of STS. The main argument developed targets the obsolete programs of some countries, where teachers have "little professional preparation to tackle inter-disciplinary themes and are reluctant to introduce environmental issues at school." Hwang (2009, p. 697) addressed "the possibility and practice of environmental education in schools," wherein "the gaps between policy discourse and practice in environmental education have remained significant over the past 20 years". Additionally, the study indicates strict curriculum division and timetable as institutional barriers to environmental education in Korea.

In the light of STS, the acquisition of knowledge and traditional skills cultivated inside science curricula is not enough to be scientifically aware. This may imply the development of attitudes, values, and new skills that support the capacity of formulating and debating responsibly a personal point of view related to scientific–technological problems. (Cachapuz et al., 2002). Such new skills rely on the ethics of responsibility, such as learning how to learn and openness to change. Aside from this, such new skills would sustain "more informed judgments on the merit of certain subjects and situations with personal and/or social implications; participation in the democratic decision-making process; and a better understanding of how ideas of Science/Technology are used in specific social, economic, environmental and technological situations" (Cachapuz et al., 2002, p. 45).

Similarly, teachers should encourage students to think about the scientific content of the curriculum as social-scientific issues by deconstructing the traditional reasoning that S&T should solve everything, as scientists are responsible for proposing miraculous solutions (Auler and Delizoicov, 2006). Such common sense "encourages the citizenship to delegate to others (the specialists) the responsibility of solutions, justifying its inhibition. This distorts STSE relationships by posing difficulties on solutions to problems" (Vilches et al., 2011, p. 4-5). An example to illustrate this distortion is currently happening in relation to the coronavirus disease-2019 pandemic, due to the public pressure received by scientists, who have been charged with miraculously producing a cure for the virus. Such behavior not only ignores complex scientific processes but also poses unidirectional responsibility, contributing to scientific misinterpretations and assigning values that should be broadly distributed with other important social actors, such as politicians, businesspersons, civil society, large companies, etc.

Popularization of STS as a tool for environmental education

The history of Conservation Biology illustrates the impossibility of monitoring biodiversity in its entirety, much less when considering its dynamic character. For this reason, ecologists work with indicators or proxies (Williams and Gaston, 1994). Therefore, the term "charismatic" appears in the conservation literature as a specific mark in the identification of emblematic species – in its original definition "popular, charismatic species that serve as symbols and points of a union to simulate conservation actions and consciousnesses" (Heywood and Watson, 1995, p. 23). In spite of their importance, phytoplankton communities have been neglected with regard to conservation efforts. In Brazil, dinoflagellates (unicellular microscopic organisms responsible for toxic or harmful blooms, also called red tides) have remained far less studied than in other countries in the last 50 years, especially when compared with Japan, China, Germany, the United Kingdom, and the United States (Noga and Gomes, 2018).

In this regard, scientific literacy and STS integration raise the possibility of facing environmental issues as interdisciplinary themes, instead of splitting concepts or taxa to study. Such an approach should be applicable to any environmental problem. In fact, the claim is not related to coral reefs or phytoplankton exclusively, but to how responsible science or environmental classes should be performed in order to empower people to be part of scientific and environmental issues, to be capable of decision-making related to STS themes, and to be active and aware toward one's own reality, for example, through political choices. Environmental education has been valued as an educational action that should be present throughout the entire life of a student, in a transversal and/or interdisciplinary way, articulating a set of knowledge and forming attitudes or values and environmental sensitivities (Carvalho, 2017). Therefore, phytoplankton dynamics ecology and coral reefs conservation are good examples to explore the dimensions of STS, but not the point, especially in a developing country where social exclusion historically leads people to be uncommitted to important decisions due to a lack of formal education and literacy and misinformation or negligence. Importantly, Brazil has been facing the worst environmental crisis so far due to deforestation (Aragão et al., 2018), fire, lack of public environmental policies, negligence, international disengagement, traditional native communities' abandonment, and ecosystem destruction (Paiva et al., 2020). The Brazilian agency for space research (INPE) has called attention to the increasing fire points and deforestation areas as never seen before and an area up to 3 million acres recently burned in the Wetland-Amazon region during the wettest season, probably caused by illegal occupation to set cattle breeding. Such examples reinforce the necessity of public participation in scientific issues not as a regular student only, but as a citizen able to intervene, understand, and charge politicians to propose better laws and inspections, in addition to consider the scientific information available, instead of denying the problems (i.e., global warming, Amazon fire and deforestation, hundreds of kilometers of coastal areas contaminated by oil in 2019, etc.).

The set of social practices focused on different aspects of the relationship between society and the environment can be denominated in the environmental field (Carvalho, 2017). The importance of incorporating the social aspect into what is meant by nature or environment is to remove the reductionist character to which some pedagogical practices are subjected. Notwithstanding, teaching practices that enunciate an exclusively naturalistic conception, restricted to fauna, flora, and natural resources conservation are criticized due to the lack of social aspects in their conception. Vilches et al. (2011, p. 171) argued that

> it was environmental educators who claimed the protection of the environment – in the broader sense of the human environment, which does not limit their attention to the physical environment, but extends to other social, ethical, cultural, political and economic dimensions – as a basic requirement to make the continuity of the human species possible.

The question remaining is how these dimensions can be efficiently and broadly applied in scientific education in order to achieve a better understanding regarding the human–nature relationships? In this sense, we suggested that scientific popularization should begin in the life of an elementary student and evolve gradually throughout their life. Additionally, scientific academic language should be more accessible to avoid social exclusion and to allow science to dialogue with different dimensions of knowledge, not only the formal dimension. In this sense, "specialization divided the academic world into hundreds of isolated and self-centered fields" (Bursztyn and Drummond, 2014, p. 4) when, in fact, Science should be the bond to integrate complex epistemological fields in order to restore its capacity to deal with complex problems.

Science popularization as a strategy for social inclusion

The emergence of the environmental agenda since the 20th century has required efforts from various areas and research programs. In the case of scientific education, efforts need to be based on educators to whom appeals are directed toward forming "a citizenship capable of participating in decision-making" (Vilches et al., 2011, p. 4-5). Such an appeal generated positive impacts on an STS educational model and on environmental education "which resulted in an approximation between both currents but led to some misconceptions that need to be undone" (Vilches et al., 2011, p. 5). From this confluence arises an integrated movement involving STS and environmental education, which can be defined, generically, as "educational efforts to make clear to all citizens the seriousness of the problems humanity has to face today and the necessary and possible measures to contribute to their solution" (Vilches et al., 2011, p. 5).

The current context of advances in S&T is linked to the idea of society's technoscientific illiteracy. Reflections have been generated on the importance of the democratization of acquired knowledge. The label "Scientific and Technological Literacy" encompasses a fairly broad spectrum of meanings translated through expressions such as "popularization of science, scientific dissemination, public understanding of science, and democratization of science" (Auler and Delizoicov, 2001, p. 123). The guiding objectives rely on authentic participation of society in S&T problem-solving or likewise the endorsement of societal support of the dynamics of current technoscientific development (Auler and Delizoicov, 2001).

Thus, scientific literacy, in addition to science popularization, not only enables critical environmental education but also the entrance into other fields of citizenship that are essential to modern and inclusive life. Lima et al. (2008) argued that a policy of science popularization, designed to enlarge individual comprehension of our modern world, could stimulate public participation regarding choices and directions of S&T. Consequently, policies of S&T popularization may contribute to including interests of social groups (i.e., black people, original people, marginalized society, etc.) traditionally left on the sidelines and out of the benefits that scientific and technological development can provide. In this sense, actions to promote the popularization of science can also be understood as strategies to promote social inclusion (Lima et al., 2008).

Notably, the concept of sustainability as the preservation of natural resources for future generations does not include current discrepant socioeconomic realities, especially in Brazil where social inequalities, in addition to structural racism, have led to marginalization, dropping out of school, violence, etc. The World Commission on Environment and Development (1987) mentions a concern for a sustainability that considers social equity, stating that "sustainable development requires the satisfaction of the basic needs of anyone, and extends to all the people the opportunity to satisfy their aspirations for a better life."

Furthermore, environmental education, the STS movement, and education for sustainability have common objectives, based on the improvement of the quality of life for all, as well as the conservation of the environment in current and future emergencies (Sequinel and Caron, 2010; Vilches et al., 2011). Therefore, the epistemological domain and clarity about the assumptions and articulations of each of these areas are necessary, especially in science classes.

Considering such sociopolitical factors, the science teacher, therefore, has the mission of leading their students under the aegis of the transformation of the reality in which they live, by deconstructing the "scientism" character that "neutralizes/eliminates the subject from the scientific–technological process" and that conveys the idea that "the expert (expert/technician) could solve social problems in an efficient and ideologically neutral way" (Auler and Delizoicov, 2001, p. 124). The critical participation of a student in science, especially in politics and decision-making issues, potentially allows them to ascend as a citizen and provide the social protagonism necessary to reduce social exclusion (Santos, 2012).

Environmental education and curriculum: theoretical basis

Discussions encircling science curriculum focused on scientific literacy began in the United States of America in the 20th century after changes in the sociocultural scenario (Sasseron and Carvalho, 2011), whereas, an interest was manifested toward a curriculum contemplating impacts on the progress of life, culture, and society, and the rethought programs and curricula worldwide aimed at generating scientists (Hurd, 1998). It was well after that the curriculum began to be thought of according to the need for personal training that accompanies sociohistorical change (Sasseron and Carvalho, 2011). Such conceptual change led to the review of curriculum structure for all students, but not only for those who may want to pursue a scientific career (Hurd, 1998).

The selection of content that integrates the curriculum at the elementary school level seems to have an arbitrary basis when the epistemological foundations to support this selection are not discussed. The State Curriculum Guidelines of Paraná (SCGP) for science teaching propose a discussion related to prescriptive curricular structuralism that does not dialogue with the selection of knowledge historically. Thus, this perspective does not highlight "the way this knowledge is organized and related in the curricular structure and, consequently, the way people can understand the world and act in it" (Paraná, 2008, p. 17).

Based on this criticism, the SCGP document cites three curriculum characterizations, namely:

- academic/scientific curriculum, in which socialized knowledge is "derived from science and the applicability of the scientific method as a teaching method." This type of curriculum, however, makes school subjects hostage to the fragmentation of knowledge, and thus, it does not dialogue and loses the dimension of totality;
- curriculum linked to subjectivity, the main premise of which is the interest or experience of students. This perspective originates in the ideals of the New School and the neoliberal education project implemented in the National Curriculum Parameters. The problems concerning this type of curriculum are that it relies on empirical bases through which the school is reduced to a socializing role, as well as being destitute of the historical character of human knowledge construction;
- curriculum linked to critical theories, i.e., "curriculum as a configurator of practice, a product of broad discussion among the subjects of education, based on critical theories and disciplinary organization."

This perspective considers the various dimensions of knowledge and considers the internal and external factors intrinsic to teaching. Moreover, this disciplinary format allows an interdisciplinary perspective for human knowledge, precisely because of the dialogue-based character it offers (Paraná, 2008).

Of these conceptions, environmental education, sustainability, and conservation are best aligned with the critical theories of the curriculum. However, if elementary school is based on a critical curriculum, then why have some practices not been consolidated therein? We argue that the answer may lie in the teacher through their pedagogical training that, when insufficient, does not correspond to the theoretical curricular foundations on which the school curriculum is rooted. Another possible answer is the textbook in that it may not be in dialogue with the curricular model provided by the official guidelines. The lack of studies concerning methodological issues for addressing biodiversity conservation, such as approaches in the didactic textbooks (Louzada-Silva and Carneiro, 2013), hampers the access and the applications of this agenda on real teaching practices. As a result, the aforesaid critical character of the curriculum is neglected or ineffective. In this case, the textbook becomes a book of texts with general concepts, empty exercises, and a lack of emergent important issues heuristically. Notwithstanding, the formalization of problems related to content and concepts is essential, otherwise "there is no rigorous or scientific discourse about teaching because we would be talking about an empty activity or one with meaning outside the scope of what is it for" (Sacristán, 2000, p. 120).

Thus, environmental education and conservation actions, as scientific knowledge, should start in the school, but they need to transcend its limits, materializing in the daily lives of students, becoming an effect in society, locally where the subject is inserted and where real problems demand public intervention.

Final Considerations

Science education based on the discussions of STS plays a fundamental role in the conception of critical teaching, citizenship, and environmentally conscious participation. However, there are several methodological deficiencies to overcome, whether due to the obsolete academic background of some teachers in relation to the subject or the teaching practice rooted in obsolete textbooks. Therefore, the needs that emerge from these factors are mainly theoretical investments in discussions based on the STS relationships in the teacher training courses (both in graduate academic programs and in continuous pedagogical training) and improvements in textbooks, which should be highly encouraged to include a more coherent look at technoscientific aspects concerning environmental education or STSE.

Research agendas addressing the political and social character of S&T need to be stimulated, especially in present situation when access to information is increasing. Teacher training courses should also expand discussions on STSE beyond the walls of schools and universities, so as to allow the community, in general, to participate, engage, or make decisions on aspects related to local demands. Demonstrating these relationships is the way that the ecology of coral reefs and phytoplankton can be helpful, in addition to contributing to their biological conservation and showing how to handle controversial social-scientific problems.

Contribution of authors:

Noga, P.M.B.: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing — Original Draft, Project Administration, Writing — Review and Editing. Antiqueira, L.M.O.R.: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Supervision, Writing — Original Draft, Project Administration, Writing — Review and Editing. Jacinsky, E.: Conceptualization, Visualization, Writing — Review and Editing.

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Use of HAND terrain descriptor for estimating flood-prone areas in river basins

Uso do descritor de terreno HAND na estimativa de áreas suscetíveis a inundações em bacias hidrográficas

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ABSTRACT

The flood hazard mapping in a river basin is crucial for flooding risk management, mitigation strategies, and flood forecasting and warning systems, among other benefits. One approach for this mapping is based on the HAND (Height Above Nearest Drainage) terrain descriptor, directly derived from the Digital Elevation Model (DEM), in which each pixel represents the elevation difference of this point in relation to the river drainage network to which it is connected. Considering the Mamanguape river basin (3,522.7 km²; state of Paraíba, Brazil) as the study location, the present research applied this method and verified it as for five aspects: consideration of a spatially variable minimum drainage area for denoting the river drainage initiation; the impact of considering a depressionless DEM; evaluation of hydrostatic condition; effect of incorporating an existing river vector network; and comparative analysis of basin morphology regarding longitudinal river profiles. According to the results, adopting a uniform minimum drainage area for the river network initiation is a simplification that should be avoided, using a spatially variable approach, which influences the amount and spatial distribution of flooded areas. Additionally, considering the depressionless DEM leads to higher values of HAND and to a smaller flooded area (difference ranging between 3% and 99%), when compared with the use of DEM with depression, despite 3.1% of the pixels representing depressions. The use of the depressionless DEM is recommended, whereas the DEM pre-processing by incorporating a vector network (stream burning) generates dubious results regarding the relation between HAND and the morphological pattern presented in the DEM. Moreover, the estimation of flooded areas based on HAND does not guarantee the hydrostatic condition, but this disagreement comprises a negligible area for practical purposes.

Keywords: geomatics; digital elevation model; floods.

RESUMO

O mapeamento de áreas inundáveis em uma bacia hidrográfica é fundamental para o gerenciamento do risco de inundações, estratégias mitigadoras e sistemas de previsão e alerta, entre outros benefícios. Uma abordagem para esse mapeamento é com base no descritor do terreno HAND (*Height Above Nearest Drainage*), derivado diretamente do Modelo Digital de Elevação (MDE), no qual cada pixel apresenta a diferença de elevação desse ponto em relação ao ponto da rede de drenagem ao qual ele se conecta. Considerando a bacia do rio Mamanguape (3.522,7 km²; Paraíba) como área de estudo, esta pesquisa adotou esse método e verificou sua aplicabilidade quanto a cinco aspectos: consideração de uma área mínima variável espacialmente para denotar o início da drenagem; impacto de considerar o MDE sem depressões; avaliação da condição hidrostática; efeito de incorporação de uma rede vetorial existente; análise comparativa à morfologia da bacia em termos do perfil longitudinal dos rios. Os resultados indicaram que adotar um valor uniforme de área mínima de contribuição para início da rede de drenagem é uma simplificação que deveria ser evitada, adotando-se a variação espacial de tal parâmetro, que influi no total e na distribuição espacial das áreas inundadas. Além disso, considerar o MDE sem depressões leva a maiores valores do HAND e menor área inundada (diferença variou de 3% a 99%), comparativamente ao MDE com depressões, embora apenas 3,1% dos pixels representem depressões. É recomendado considerar o MDE sem depressões, ao passo que o pré-processamento por incorporação de rede vetorial (*stream burning*) gera resultados incoerentes quanto à relação do HAND com o padrão morfológico representado no MDE. Concluiu-se, ainda, que a estimativa de áreas inundáveis pelo HAND não garante a condição hidrostática, mas esse desacordo abrange uma região de extensão desprezível para fins práticos.

Palavras-chave: geomática; modelo digital de elevação; cheias.

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Introduction

Flood is a natural process that has occurred worldwide, even before human existence itself, and has been a decisive factor in the rise and development of civilizations and the decadence of others (Goerl et al., 2017). Flood events result from multiple and dynamic factors such as intense rainfall, low soil infiltration capacity or changes in land cover and land use patterns (Ali et al., 2020). This has motivated several studies to be carried out such as on the trend of occurrence of extreme events (Lira and Cardoso, 2018; Paprotny et al., 2018), the resilience to these events (Fernandes and Valverde, 2017; Heinzlef et al., 2020), and concerning climate change projections related to flood risk (Alfieri et al., 2017; Bork et al., 2017).

The association of urbanization with the intense soil impermeabilization and the reduction of vegetation cover, in addition to river drainage network modifications, leads to runoff increase, infiltration reduction, and a consequent decrease in groundwater recharge (Benini and Mendiondo, 2015). These aspects, associated with the greater occupation of high vulnerability areas, intensify the occurrence of disasters, such as floods (Speckhann et al., 2018), with a higher number of victims and higher damage costs of different types (Meyer et al., 2013). Floods are pointed out as the second most frequent extreme event in Brazilian municipalities between 1991 and 2012, with drought occupying the first place (CEPED/UFSC, 2013).

The analysis of land use and land cover in river basins is crucial for flood risk management, for supporting decision-making, flood forecasting and early warning systems, and for studying mitigating alternatives, among several other benefits (Paul et al., 2019; Ali et al., 2020). Flood risk mapping is a basic element for the design of mitigating strategies, justifying the regulation of this instrument by legislation as in the case of the USA and European countries (Degiorgis et al., 2012; Caldas et al., 2018). This type of mapping may also be adapted for evaluating flash floods, caused by the occurrence of rainfall with large volumes highly concentrated in time, or even due to the rupture of hydraulic structures such as dams (Arabameri et al., 2020).

Hydrological modelling is considered the most recommended approach to estimate flood areas, as it enables to mathematically represent the hydrological and hydrodynamic processes in the surface runoff generation and flood wave propagation, among other aspects, depending on the considered models. Thus, ideally, a distributed hydrological model can be combined to simulate the rainfall-runoff transformation process in areas contributing to the drainage network, and a two-dimensional hydrodynamic model to simulate the flood wave routing and floodplain inundation (Paz et al., 2011; Zambrano et al., 2020), or analogously for urban areas (Prakash et al., 2020), but there are several variants of this approach (Bravo et al., 2012; Pontes et al., 2017; Hdeib et al., 2018).

However, these mathematical modelling approaches require a considerable amount of field data and effort to process these data, to prepare and adjust the models (Lin et al., 2020), even with the availability of automation tools and the existence of graphical user interfaces (Siqueira et al., 2016). In addition, these approaches require considerable expertise in hydrological modelling that becomes incompatible with fast applications and expeditious surveys (Morelli et al., 2014). Alternatives have been developed by combining multiple layers in a geographic information system and using statistical analysis techniques, such as analytic hierarchy process, logistic regression and fuzzy logic, and machine learning methods such as artificial neural networks, decision trees and support vector machine (Degiorgis et al., 2012; Tehrany et al., 2015; Paul et al., 2019; Ali et al., 2020; Lin et al., 2020). At the same time, these approaches require in-depth knowledge of such methods, with a level of complexity that can discourage users and hinder their further application (Zheng et al., 2018a).

A more simplified alternative is the estimation of flood areas in a more expedient way, based on the processing of Digital Elevation Models (DEM) such as the method based on the terrain descriptor called HAND (Height Above Nearest Drainage) (Rennó et al., 2008). The proposal of this method is to produce reasonable estimates in a fast way, such as those required to prioritize evacuation areas during extreme events (Afshari et al., 2018), with an easy application procedure and requiring free widely available data for any area, taking advantage of the availability of DEM data (Garousi-Nejad et al., 2019). In fact, freely and globally available DEM, such as those from the SRTM Mission (Shuttle Radar Topography Mission) (Van Zyl, 2001), have been crucial for flood studies in places with low data availability (Hawker et al., 2018).

HAND is an information plan directly derived from DEM, involving two other products also extracted from DEM, namely the flow directions and the drainage network (Rennó et al., 2008; Nobre et al., 2011). The HAND concept, initially discussed in Rodda (2005) and named and presented as such by Rennó et al. (2008), is simple: each pixel or point of this information plane presents the altitude difference of this point in relation to the point of the drainage network to which it connects, according to the flow paths extracted from the DEM processing. To estimate flood areas based on HAND, according to the most simplistic approach, a certain height of this flood is assumed, and the HAND analysis is performed: all points of this layer that present attributes lower than the established flood height are considered flooded (Nobre et al., 2016). This method identifies flood areas assuming, therefore, that the water level equally rises along the entire river course, maintaining the unevenness along with the drainage network – that is, the water level rises parallel to the bottom of the river course.

Another benefit of the use of HAND as a flood area estimator is the continuous increase of available topographic data acquired by remote sensing, either showing improvements in terms of more refined spatial resolution, regarding the quality of the acquired information, or the removal of errors in already existing data (Hawker et al., 2018). For example, there are data available from new orbital sensors with increasingly refined spatial resolution and other improved features such as the ALOS AW3D (Tadono et al., 2015), the ALOS PALSAR DEM (Niipele and Chen, 2019) and the TanDEM-X WorldDEM (Krieger et al., 2007). Another advantage is the availability of data resulting from improvements of already used DEM, such as MERIT (Yamazaki et al., 2017) and BEST (O'Loughlin et al., 2016), both proposed aiming at reducing the effect of vegetation and other noise on SRTM data, and EarthEnvDEM90, proposed as a fusion of SRTM and ASTER data (Robinson et al., 2014). Conversely, there is the increasing availability of data obtained from aerial or unmanned remote sensing, such as LiDAR survey data, which are already freely available for the entire state of Pernambuco, Brazil (Cirilo et al., 2014), or aerial photogrammetry data, such as those available for the state of Santa Catarina, Brazil (Momo et al., 2016), both with a refined spatial resolution of 1 meter.

In addition to applications for multiple purposes (Gharari et al., 2011; Nobre et al., 2011; Cuartas et al., 2012; Rahmati et al., 2018), several research studies have estimated flood areas based on HAND, comparing such studies with flood delineations estimated by remote sensing (Mengue et al., 2016; Garousi-Nejad et al., 2019) and analyzing them against field data indicating flood location and heights (Momo et al., 2016; Nobre et al., 2016; Goerl et al., 2017; Speckhann et al., 2018) or comparing them with estimates made by hydrological-hydrodynamic models (Momo et al., 2016; Afshari et al., 2018; Zheng et al., 2018b). Clement et al. (2018) and Landuyt et al. (2019) also report the use of HAND to mask and restrict areas estimated as inundated in studies on synthetic aperture radar images, either previously or as a post-processing step.

The effect of the channel initiation on the results of flood area estimates using HAND has also been evaluated (Mengue et al., 2016; Goerl et al., 2017; Speckhann et al., 2018) as well as the influence of the source of the DEM data (Zheng et al., 2018b) and the spatial resolution of the DEM (Goerl et al., 2017; Speckhann et al., 2018). Some studies have estimated flooded areas by proposing modifications to the HAND-based method, such as combining it with rating curves and streamflow forecasts (Liu et al., 2018; Zheng et al., 2018b; Garousi-Nejad et al., 2019) or with streamflow frequency analysis (Speckhann et al., 2018).

Despite the simple concept and the wide use of the HAND-based method, there are issues involved in the estimation of flood areas that require further study, which are addressed in this research:

- the effect of considering a spatially varying minimum area threshold to denote channel initiation, as this identification of the headwaters is one of the most challenging aspects in the DEM processing and has a strong influence on the extracted drainage network (Li et al., 2020), but no previous research considered such spatial variation in the computation of HAND;
- the impact of considering or not the depressionless DEM, taking into account that the removal of depressions is necessary to establish continuity in flow paths and constitutes the main motivation in the improvement of DEM processing algorithms, although there are authors who used the DEM without depressions (Garousi-Nejad et al., 2019) and others who used the DEM with depressions (Zheng et al., 2018b) in the HAND calculation;
- evaluation of the hydrostatic condition of the flood area, preliminarily mentioned by Momo et al. (2016);
- the effect of incorporating an existing vector network as a DEM pre-processing procedure (Lindsay, 2016), deepening the related discussion as the one presented by Mengue et al. (2016);
- comparative analysis of HAND-based results to the basin morphology in terms of the longitudinal profile of rivers.

This study aims to verify the applicability of HAND in estimating flood areas, covering the five raised issues and deepening the understanding of such approach. The Mamanguape River basin, located in the state of Paraíba (Brazil) and subject to a historical record of flash floods and serious consequences (Aagisa, 2004), is considered as the study area.

Materials and Methods

Study area and data

The study area, the Mamanguape River basin, is located entirely in the state of Paraíba, in Northeast Brazil, in the mesoregions of Zona da Mata and Agreste, and with a drainage area of 3,522.7 km² (Governo do Estado da Paraíba, 2006; Figure 1). A warm and wet climate predominates in the region, with the main rainy period between March and August and annual precipitation ranging from 700 to 1,600 mm (Barbosa, 2006; Santos et al., 2015). The Atlantic Forest biome predominates in this basin, with the presence of *restinga* and mangrove vegetation (Rodrigues et al., 2005).

The Mamanguape River basin is the third largest basin in the state of Paraíba in terms of area and has a fundamental role in economic, social, and environmental aspects, especially for over 42 municipalities totally or partially inserted in this area. Ten of these municipalities are in areas prone to the occurrence of river flooding (Aagisa, 2004; Barbosa, 2006), with a total population of over 450,000 inhabitants (Santos et al., 2015).

The topography varies from sea level at the river mouth in the east region to 750 m in the Borborema Plateau region (Marques et al., 2015). Topographic variation, characteristics of the rainfall regime, and geomorphological characteristics of the basin increase the occurrence of flash floods, in response to intense precipitation events, with rapid runoff and large destructive power. In 2004, one of these flash flood events occurred, with major socioeconomic losses (Aagisa, 2004). A field survey during the flood identified more than 150 critical points in the basin (Aagisa, 2004; Figure 1).

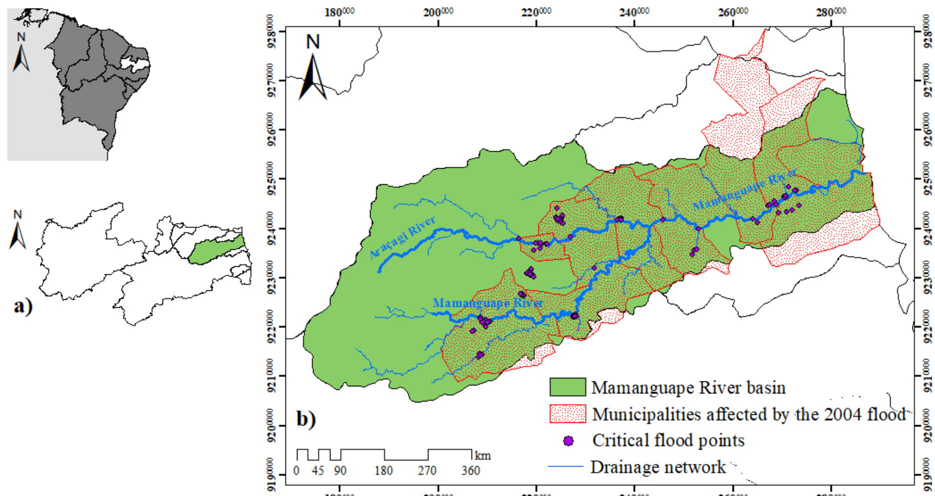

Figure 1 – (A) Location of the Mamanguape river basin in the state of Paraíba, Brazil and (B) Delimitation of the basin with the indication of the drainage network and critical flood points raised for the 2004 event according to Aagisa (2004).

In addition to this field survey of the critical flood points in the 2004 event, the materials used for the present research were: DEM with spatial resolution of 30 m from SRTM data (Farr et al., 2007); vector river drainage network available from the geographic data portal of the Paraíba State Water Resources Management Executive Agency (*Agência Executiva de Gestão das Águas do Estado da Paraíba* – AESA); and satellite images available from Google Earth.

Basic Digital Elevation Model processing

The DEM of the study area was initially processed to derive basic information layers for estimating flood areas. Depressions were removed and flow directions were defined, i.e., the flow direction for each pixel was established in the direction of one of its eight neighbors (D8 method –Deterministic Eight-Neighbor; Mark, 1984; Jenson and Domingue, 1988). Depressions that were removed can be either real, such as areas of the terrain lower than the neighborhood, or artefacts caused by noise and other interference during DEM data acquisition (Barnes et al., 2014). This removal of depressions is necessary to achieve flow path continuity from the headwaters to the basin mouth (Mark, 1984; Jenson and Domingue, 1988).

The main rule for defining flow direction is to set this direction toward the neighboring pixel that provides the highest slope, but with specific rules for the treatment of situations of depressions and flat areas according to each algorithm, usually involving operations of elevation increase or decrease (Barnes et al., 2014). The TerrSET software was used, whose algorithm for removing depressions and defining flow directions is of the Priority First Search type (PFS; Sedgewick, 1992; Jones, 2002), described by Buarque et al. (2009) and Siqueira et al. (2016) with results evaluated as of superior quality in relation to other algorithms, such as the one used in the ArcGIS software, which tends to present unreal parallel drainage lines (Paz and Collischonn, 2008).

The accumulated drainage areas were determined based on the flow directions. These areas consist in a raster layer whose attribute of each pixel represents the upstream contribution area (sum of the areas of the pixels whose flow paths drain into the pixel in question). Based on the definition of the Mamanguape River basin outlet into the ocean, the river basin was delimited by the automatic identification of all pixels whose runoff drains into this point.

Drainage network determination

The drainage network was determined based on the accumulated drainage areas, initially following the procedure of adopting a uniform minimum threshold (Amin) of accumulated area (Fan et al., 2013; Momo et al., 2016; Goerl et al., 2017; Speckhann et al., 2018). In other words, all pixels in the river basin that have drainage area greater than Amin become representatives of the drainage network. Different Amin values were adopted to represent the sensibility of the drainage network obtained to this parameter: 5, 10, 25, 50, 75, and 100 km², resulting in their corresponding drainage networks.

This procedure is simplified, considering that physical (soils, vegetation cover, relief, geology, etc.) and climatic (precipitation) characteristics imply that each headwater formation corresponds to a specific upstream accumulated area. Hence, a second procedure was adopted, considering a spatially variable Amin value, following the approach suggested by Fan et al. (2013). Based on satellite images available from Google Earth, 25 headwaters of the drainage network were visually identified and the drainage area value derived from the DEM corresponding to each of these points was surveyed. Based on these values, the basin was divided into three regions considered relatively uniform regarding the upstream drainage area of the surveyed headwaters. For each region, a specific Amin value was adopted (20.54 km², 39.92 km², and 78.75 km²), established by the average of the accumulated area identified for the headwater points in the region.

Incorporation of the existing vector drainage network

Considering the river vector drainage network provided by AESA and assuming that one intends to determine flow paths from the DEM in a compatible way with such vector network, the DEM pre-processing procedure known as stream burning was performed (Lindsay, 2016; Wu et al., 2019). The vector network was converted to a raster format, with the same spatial resolution of the DEM, and them the decrease of the elevation of DEM pixels located exactly along the representative pixels of the vector network was performed. This burned DEM was processed to remove depressions and derive flow directions, accumulated areas, river basin delimitation, and drainage network, as described in the previous items for the DEM without stream burning.

Extracting the longitudinal profiles of the drainage network

A computational routine in FORTRAN language was developed to elaborate longitudinal profiles of the entire river drainage network, with the following algorithm:

- starting from each headwater, the downstream flow path is followed pixel by pixel according to the flow directions;
- the accumulated distance travelled (Dacum_i) is counted, where each incremental step between pixels has summed the size of a pixel (dx) or the value of √2dx, if the step is orthogonal or diagonal, respectively;
- the elevation of the visited pixel (Z_i) is recorded;
- after following all flow paths, the distance of each pixel relative to the basin outlet (Dexu_i) is calculated as the difference between Lmax and Dacum_i, where Lmax is the full river length relative to the outlet.

The pairs of points (Dexu_i, Z_i) are considered to construct the longitudinal profiles. As the distances in each profile were calculated in relation to the basin outlet, it is possible to graph all points of the drainage network together, increasing the potential of the analysis.

HAND determination

For determining the HAND terrain descriptor, another computational routine was developed in FORTRAN language, having as input the DEM, the flow directions, the basin delimitation, and the drainage network in the raster format. For each pixel of the basin that is not part of the drainage network, its elevation (Zp) is registered and the downstream flow path until reaching the drainage network is traced, registering the elevation of this pixel of the drainage network (Zr) that was reached. HAND is calculated by the difference between Zp and Zr, that is, the topographic referential of HAND varies (Nobre et al., 2016), and each pixel has its corresponding referential (Zr).

The routine execution was repeated, and several HAND layers were obtained, varying one or more of the input data (Table 1), to provide three main focuses of comparative analyses. For the first analysis, HAND was determined considering the drainage network obtained from the uniform Amin rule, but testing different values (HANDu5 to HANDu100), and considering the drainage network obtained from the spatially heterogeneous Amin (HANDhet). All other input data for HAND remained unchanged for this first analysis.

The second analysis was performed with two configurations for obtaining HAND that only differs to the input DEM: one configuration uses the original DEM, from SRTM-30m data, which presents depressions as any DEM without pre-processing (HANDdep); the other configuration uses this DEM after having the depressions removed for generating continuous flow paths (HANDhet). In the third analysis, the difference between both configurations for obtaining HAND is only the flow directions and, consequently, the derived drainage network: in one configuration, the flow directions were obtained by applying the PFS algorithm of TerrSET to the depressionless DEM determined from SRTM-30m data (HANDhet); in the other configuration (HANDburn), this same algorithm for determining the flow directions is employed, but firstly the SRTM-30m DEM is pre-processed with the incorporation of the drainage vector network made available by AESA (stream burning procedure).

Estimation of flood areas

For each HAND configuration, the estimation of flood areas was performed in the standard way, by adopting an inundation height threshold. In other words, once this threshold (Hlim) is established, all pixels with HAND attribute lower than Hlim are part of the flood area. Different arbitrarily chosen Hlim values were tested to denote a variation of the flood height, and the Hlim value of 1.5 m was also specifically evaluated based on information reported for the flood height that occurred in the 2004 event (Folha de S. Paulo, 2004).

For estimating the flood areas obtained from the HAND configuration adopted as reference (HANDhet), the inclusion of a post-pro-

Table 1 - Configurations used for the determination of the different HAND layers and an indication of the main focus of each comparative analysis.

Pre-processing the DEM to obtain flow directions (stream burning)	Input DEM for HAND	Amin's criterion for obtaining drainage network		HAND	Comparative analysis
No	DEM without depressions	Uniform Amin	5 km²	$HAND_{u5}$	Influence of the drainage network initiation ($HAND_{u5}$ to $HAND_{u100}$ vs. $HAND_{het}$)
			10 km²	$HAND_{u10}$	
			25 km²	$HAND_{u25}$	
			50 km²	$HAND_{u50}$	
			75 km²	$HAND_{u75}$	
			100 km²	$HAND_{u100}$	
		Heterogeneous Amin		$HAND_{het}$	
	DEM with depressions	Heterogeneous Amin		$HAND_{dep}$	Effect of considering the removal of depressions ($HAND_{het}$ vs. $HAND_{dep}$)
Yes	DEM without depressions	Heterogeneous Amin		$HAND_{burn}$	Stream-burning effect ($HAND_{het}$ vs. $HAND_{burn}$)

cessing step was additionally evaluated to impose the hydrostatic condition in the immediate neighborhood of flood areas.

In a situation of a flood area in which the velocity of water can be neglected, pressure at any point of this region follows the hydrostatic approximation. Considering that the variation in water density is also negligible, according to this hydrostatic approximation, pressure is a function of the height of the water level above the considered point. In this study, it was verified whether, for each pixel integrating the flood area, there was a valid hydrostatic equilibrium condition concerning the neighboring pixels.

The procedure was carried out as follows: for each flooded pixel, the authors identified which of its eight neighbors in a 3x3 window were not flooded; for each non-flooded neighbor, it was checked whether its elevation was lower than the sum of the elevation and the height of the water level in the central flooded pixel. If this was the case, the hydrostatic condition was not satisfied, and the neighboring pixel was considered flooded.

Results and discussion

Estimation of flood areas: configuration of the reference HAND

With the HAND configuration considered as reference (HANDhet), the terrain descriptor varied over the Mamanguape River basin as illustrated in Figure 2A, with a predominance of lower values near the drainage network, mainly in the middle and lower parts of the basin, as expected. By assuming a 5-m HAND threshold, the corresponding flood areas are predominantly in the margins of the watercourses, with greater spreading in the final stretch of Mamanguape River near the basin outlet. Nevertheless, there are also regions in the upper and middle parts of the basin, including marginal areas toward the Araçagi River and, in lower proportion, in smaller tributaries (Figure 2B).

The total flood area obtained ranged from 10.7 km², for the 1-m HAND threshold considered as flood height, to 404.7 km², when considering 15 m for such threshold (Figure 3A). An increase in flood area as a function of the increase in flood height based on HAND is noted, approximately following a third-degree polynomial function, a pattern similar to that found by Goerl et al. (2017) for another study area. The result presented in Figure 3A refers to the spatially variable Amin threshold condition for obtaining the drainage network (Figure 3B), as described by the HANDhet configuration in Table 1.

Influence of the definition of the drainage network initiation

By varying the criteria for defining the drainage network initiation, a direct effect is produced on the total flood areas estimated based on HAND, for the same flood height threshold of 5 m (Figures 3B and 4).

With a uniform minimum area equal to 5 km², there is an estimate of 166.7 km² of flood areas, a total that exponentially decreases to 77.3 km² (54% reduction) when considering a uniform minimum area of 100 km². This result pattern of inundated area reduction as a function of increasing Amin parameter was also obtained by other authors (Mengue et al., 2016; Goerl et al., 2017; Speckhann et al., 2018) for other study areas. This may be generalized and expected for any area considering that, conceptually, there is a reduction of the drainage

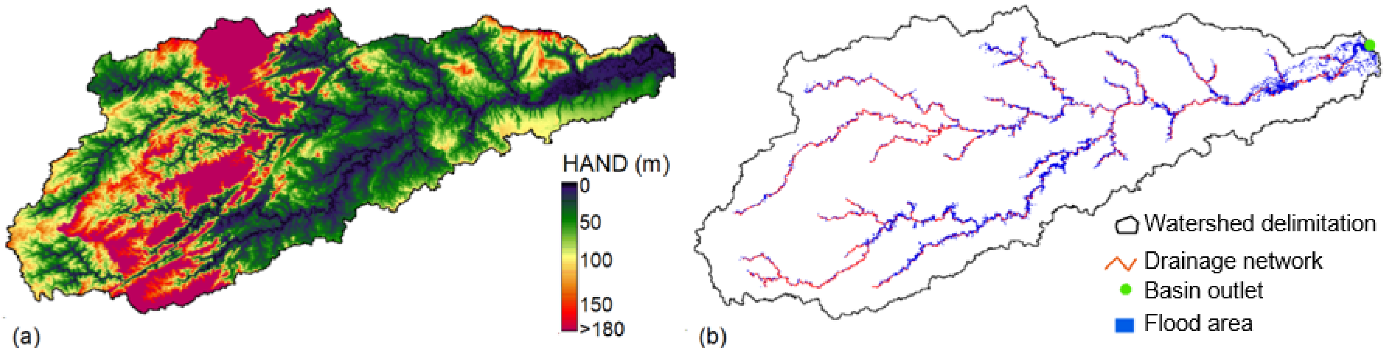

Figure 2 – (A) HAND terrain descriptor obtained for the HANDhet configuration; (B) Flood area assuming a 5-m HAND threshold and the HANDhet configuration.

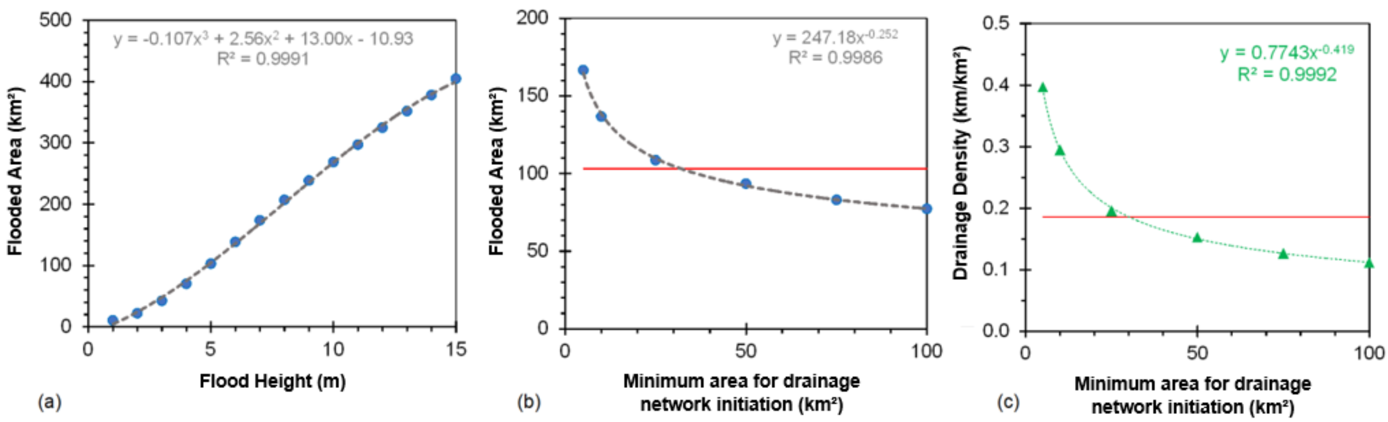

Figure 3 – (A) Flood height used as HAND threshold and the corresponding obtained inundated area (HANDhet configuration); (B) Minimum area for drainage network initiation and the corresponding obtained inundated area, considering a 5-m HAND threshold; (C) Minimum area for drainage network initiation and the resulting drainage density; the red line indicates the value on the y-axis for a spatially variable minimum area, whereas the dashed curves and equations indicate the trend curves fitted to the points.

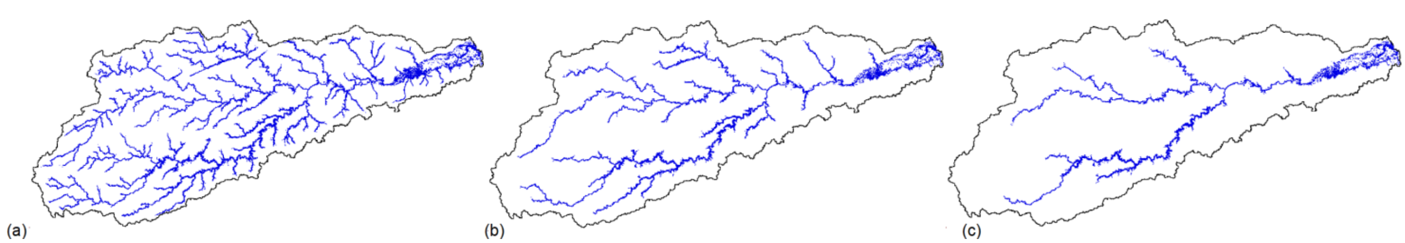

Figure 4 – Mapping of flood areas for a 5-m HAND threshold, considering a uniform minimum contributing area for drainage network initiation with values of (A) 5 km² (HANDu5); (B) 25 km² (HANDu10); and (C) 100 km² (HANDu100).

network extension with the increase in the minimum area and, consequently, the drainage density. In the Mamanguape River basin, for a minimum area of 5 km², there is a total of 1,311 km of rivers in the basin (drainage density of 0.40 km/km²), whereas the total extension is only 371 km (drainage density of 0.11 km/km²) when considering a minimum area of 100 km².

In the study conducted by Mengue et al. (2016), the comparison of the results obtained from HAND considering different values of

Amin with the estimate of the inundated area from LANDSAT satellite images allowed identifying which Amin value provided the better agreement. However, it is understood that the estimate based on HAND could be further improved if the spatial variability of Amin was incorporated. The consideration of a spatially variable minimum area for the drainage network initiation is a more reasonable way for obtaining the drainage network and it has greater resemblance to reality than assuming a uniform value, as there is no uniformity in the drainage area of each river headwater.

In the study by Liu et al. (2018), the location of the identified headwaters of a reliable vector network representative of the river course was used as the definition of the DEM-derived drainage network initiation. This ensures not only the issue of each headwaters with their specific contributing area, but also increases the reliability of this DEM-derived drainage network, proportionally to the quality of the available vector network. But this approach is clearly limited to the availability of this vector network of acceptable quality. Meanwhile, McGrath et al. (2018) adopted the criterion of applying HAND only considering the reaches of the drainage network with higher order according to the hierarchy of the Strahler method. However, this approach does not disregard the effect of the Amin choice to denote the drainage network initiation. In fact, the channel initiation influences the hierarchy of the network according to the Strahler method. Furthermore, there is the subjectivity of which minimum hierarchical order of the drainage network to be adopted for HAND determination.

An alternative would be to identify the drainage network initiation from the combination of the contribution area (A), the local slope (S), and a parameter k by the expression AS^k, as adopted by Degiorgis et al. (2012). This method would also lead to spatial heterogeneity of the contributing area at each of the headwaters, but with the disadvantage of involving an additional parameter (k), in addition to the decision of which threshold to adopt for the AS^k term denoting the channel initiation.

With the Amin parameter spatially varying as performed in this study, a total river length equal to 615 km was obtained (drainage density of 0.19 km/km²) and the inundated area for the 5-m HAND threshold was 103.1 km² – results that are close to those obtained for the uniform condition of the minimum area equal to 25 km². However, the spatial occurrence of the flood areas presents considerable differences between the two cases. This is because, when considering the spatially variable minimum area, there is a change in the positioning of each headwater concerning the drainage generated by considering a constant minimum area. This variation is even greater when comparing the results obtained from the variable minimum area with those obtained for the other minimum area values (Figure 4).

Effect of the removal process of DEM depressions

In order to obtain the continuous flow paths downstream from any pixel of the basin up to the outlet, depressions that reached 3.1% of the river basin pixels were removed. Most of them (84% or 2.6% of the river basin total) resulted from elevation lowering; and the remaining (16% or 0.5% of the river basin total), from elevation raising. Most of the removed depressions are located along with the drainage network and are associated with the effect of the vegetation marginal to the river on SRTM data (O'Loughlin et al., 2016). This leads to the difference among the longitudinal profiles drawn along the Mamanguape River considering the original DEM (with the presence of depressions) and the depressionless DEM (Figure 5A).

The removal process of depressions tends to generate lower elevations than there were in the original DEM along the main river, in addition to smoothing the elevation variations. Considering that the effect of vegetation on the elevations in the SRTM data and the abrupt

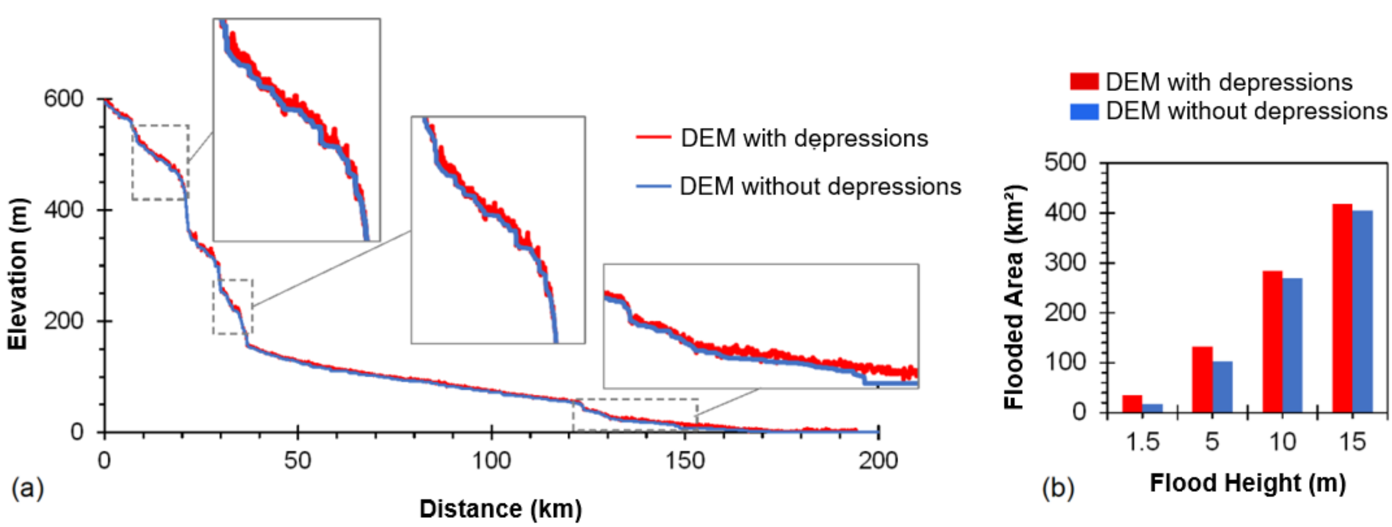

Figure 5 – (A) Mamanguape River longitudinal profile considering DEM with and without depressions; (B) Inundated area in the basin for different flood heights considering DEM without and with depressions, in the HANDhet and HANDdep configurations, respectively.

variations in elevation along the main river are not consistent with reality, it is more reasonable to consider the DEM without depressions as input for the HAND calculation, as used by Garousi-Nejad et al. (2019), than the original DEM with depressions (adopted by Zheng et al., 2018b). However, to minimize the effect of the removal of depressions, Garousi-Nejad et al. (2019) adopted a procedure that relies on elevation information from another data source, with higher spatial resolution. This is a methodological alternative, though limited to the availability of such auxiliary data. Zheng et al. (2018b) evaluated, as an advantage of using the DEM with depressions, the fact of correctly identifying local flood areas, such as small lakes not connected to the drainage network, from the comparison with estimates made by hydrological modelling.

In this research, the lower elevations present in the depressionless DEM along the main river induced higher HAND values for other points in the basin and the reduction of flood areas for the same HAND threshold, compared with the use of the original DEM (Figure 5B). This reduction ranged from 3% to 99% according to the HAND threshold, with greater difference the lower the considered flood height. This indicates a greater impact of considering DEM with or without depressions on the estimation of flood areas corresponding to smaller floods. In this type of event, flood areas are predominantly in the parts of the floodplain closest to the river channel, precisely the regions most subject to vegetation height bias on the SRTM data. This is because vegetation affects the elevations of the SRTM DEM (O'Loughlin et al., 2016; Yamazaki et al., 2017), and there is greater presence of vegetation in areas marginal to the rivers in the studied basin.

This pattern of results becomes clearer when observing the map with values concerning differences between the HAND obtained for the DEM with depressions (HANDdep) and that without depressions (HANDhet). Negative values are predominant (Figure 6A), indicating that HANDhet presents higher values than HANDdep. In the comparison of the flood areas corresponding to the 5-m HAND threshold, the consideration of the DEM with depressions leads to the identification of more areas subject to flooding in the lower part of the basin than the DEM without depressions, but this also occurs in a lower proportion in the middle and upper parts (Figure 6B).

Comparative analysis of the morphology of the basin concerning the longitudinal profile of the rivers

When generating the drainage network from the accumulated areas, by considering the criterion of a spatially variable minimum contributing area to denote the drainage network initiation, that is, considering the value of the parameter Amin variable in the basin, 31 headwaters were obtained (Figure 7A). For each drainage headwaters, the area directly contributing to the continuous river reach downstream of that point was also identified, whereas the longitudinal profiles of these reaches are presented in Figure 7B, maintaining the basin outlet as a reference of the distances in the x-axis.

Headwater 1 represents the channel initiation of the main river of the basin, which is the Mamanguape River, whose points every 10 km of distance are indicated in Figure 7C. In the longitudinal profile of this river there is an abrupt variation in slope around 165 km from the outlet. This has a direct impact on the occurrence of larger flood areas downstream to this point than along upstream reaches of this river (Figure 7D). The figure illustrates the extent of incremental flood areas (i.e., not cumulative) directly connected to each point along the Mamanguape River. An abrupt change is verified around the 165-km position, with greater occurrence of flood areas than in previous positions. This is a coherent result, as this abrupt change in the longitudinal slope of the river drastically alters its hydraulic conveyance, resulting in a lower capacity of the river to convey the flow, which facilitates the overflow of the river channel onto the floodplain. In fact, in the field survey carried out for the 2004 flood (Figure 1), several points of the overflow of the channel and floodplain inundation were observed along this river reach.

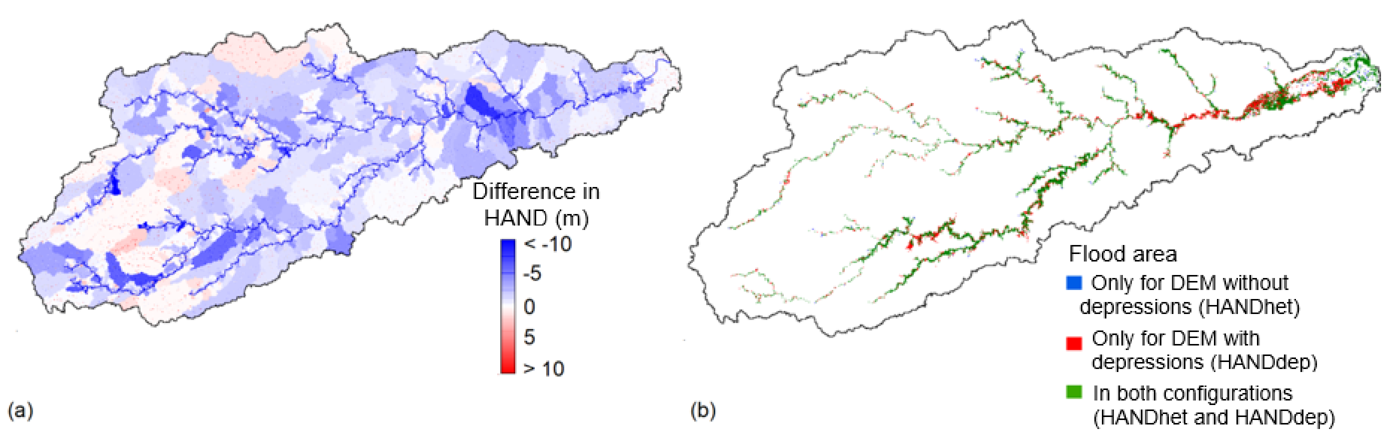

Figure 6 – (A) Difference in HAND obtained from the DEM with depressions and the DEM without depressions; (B) Analysis of flood-prone areas obtained only from the DEM without depressions, only from the DEM with depressions, and those simultaneously obtained from both.

Around the 55-km position, an increase in riverbed slope reduces the occurrence of flood areas, whereas around the 40-km position there is another remarkable reduction in slope, once again increasing the occurrence of flood areas.

Effect of the stream burning procedure

The vector drainage network provided by AESA presents some divergences compared with the drainage network obtained in this research from the SRTM DEM data, mainly in the lower part of the basin near the outlet (Figure 8A). The AESA vector drainage network was used for pre-processing the SRTM DEM data by the stream burning procedure, in such a way to obtain the flow paths and the raster drainage network. With these data, HAND (HANDburn) was obtained, whose difference in relation to the reference HAND of this study (HANDhet) indicates that the DEM pre-processing by stream burning has resulted in the decrease of the HAND in most of the basin (Figure 8B). As a result, there is an increase in the flood areas obtained from HANDburn in relation to HANDhet, and such increase is distributed throughout the extension of the drainage network, but with a higher concentration in the lower part (Figure 8C).

The procedure used for HANDburn was similar to the procedure adopted by Mengue et al. (2016), and aims at producing results compatible with an existing river drainage network. This is indeed the benefit reported in the literature when using the stream burning procedure (Lindsay, 2016; Wu et al., 2019). But such compatibility occurs in terms of the river drainage network as such, i.e., the network derived from the DEM modified by stream burning approximates the existing vector network. It is understood that this is valid if the existing vector drainage network is representative of the actual river flow paths, at least in higher quality than the flow paths resulting from the DEM processing, as in the case of the application of HAND made by Garousi-Nejad et al. (2019). If there are no elements to measure the quality of the available river vector network, the performance of the stream burning processing is deemed unreasonable.

Conversely, even if the quality of the available vector drainage network is guaranteed, the use of such vector network for DEM pre-processing by stream burning prior to obtaining the HAND is questionable for two reasons.

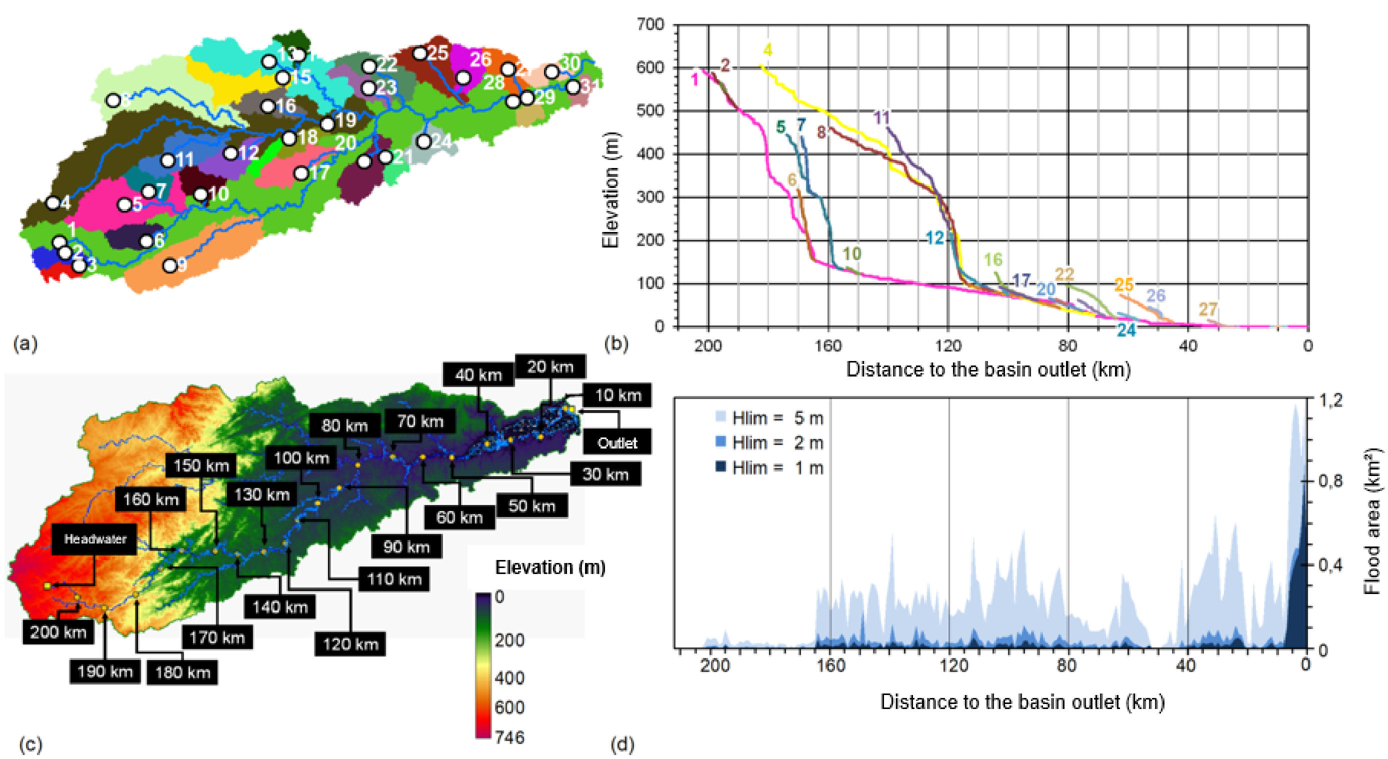

Figure 7 – (A) Identification of the 31 headwaters of the drainage network and the corresponding areas of direct contribution to the continuous downstream river reach; (B) Longitudinal profiles of each river reach downstream of the headwaters, with distance measured to the basin outlet and numerical identification of the main headwaters; (C) Digital Elevation Model with indication of the accumulated distance along the Mamanguape River, measured from the basin outlet, according to each yellow dot mark; (D) Incremental flood area at each specific point of the Mamanguape River, in HANDhet configuration and for three HAND thresholds.

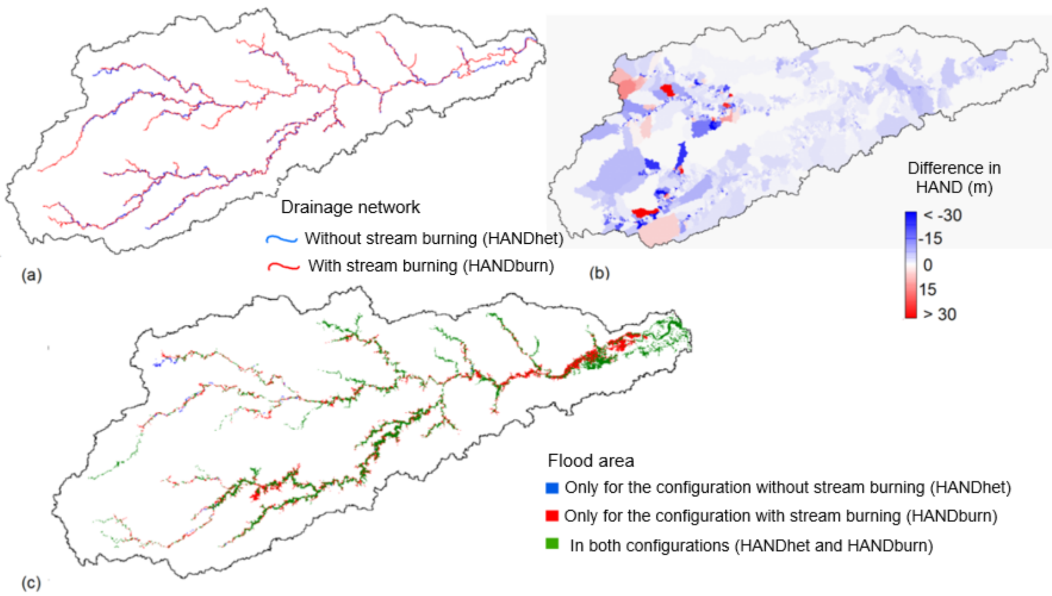

Figure 8 – (A) Comparison between river drainage networks obtained with and without stream burning; (B) Difference in HAND obtained using the DEM with and without stream burning; (C) Analysis of flood areas obtained only for HAND without stream burning, only for HAND with stream burning, and simultaneously obtained with both.

First, it is assumed that the burned DEM should not be used to calculate HAND, as it presents elevations arbitrarily lowered along with the drainage network, which was not done in this research and is addressed in the literature (Mengue et al., 2016). Garousi-Nejad et al. (2019) present another point of view, whose results showed that the lowering of the DEM according to the vector drainage network led to greater coherence of the flood area estimates compared with hydrological modelling studies. In the aforementioned study, by having a vector drainage network that is well representative of the river course and having a high spatial resolution DEM, the lowering of the DEM by stream burning prevented large areas marginal to rivers from being erroneously identified as flooded areas. The burning procedure also avoided inconsistencies in the results caused by bridge interference in the DEM, which exemplifies the high spatial resolution of the DEM used by the authors. Nevertheless, in studies such as the present one, which use DEM from SRTM data and have an available vector network whose degree of concordance with the river course is unknown, stream burning would not present this advantage.

Second, there is the conceptual issue of compatibility of the topographic information from the DEM with the available vector network. The use of flow directions and drainage network derived from the burned DEM, as input to obtain HAND, leads to results of this terrain descriptor inconsistent with the morphological pattern represented in the DEM. This occurs because the DEM was modified by stream burning only in the pixels along that vector trace.

However, by not applying the stream burning, the results of HAND and estimated flooded areas may be spatially incoherent in relation to the actual drainage network delineation. An alternative is to improve the acquisition of DEM data itself so that their processing better represents the actual drainage network, as in the case of Garousi-Nejad et al. (2019). These improvements may include the refinement of the spatial resolution of the DEM (as pointed out by Speckhann et al., 2018; Goerl et al., 2017 and Garousi-Nejad et al., 2019) and reduction of noise and other interferences such as vegetation cover. The quality of the topographic data source is pointed out as key information for estimating flood areas, including when using more elaborate methods such as hydrodynamic modelling (Zambrano et al., 2020).

Hydrostatic condition analysis

The hydrostatic condition of the flooded area, with estimation results based on HAND, is addressed in this topic, considering the HANDhet reference configuration. For instance, consider the pixels Pa, Pb, and Pc indicated in Figure 9A, whose elevation is the same (57 m). According to the flow paths illustrated in Figure 9B, pixels Pb and Pc drain into the same point in the drainage network, whose elevation is 50.9 m, which is distinct from the point to which the flow drains from pixel Pa, whose elevation is 52.4 m. As a result, the HAND of Pa is 4.6 m, whereas the HAND of Pb and Pc is 6.0 m (Figure 9C). When considering a 5-m HAND threshold for identifying the flood area, Pa is part of the flood area, but Pb and Pc are not

(Figure 9D), thus violating the hydrostatic condition of this flood area delimitation.

All green pixels in Figure 9E are not considered to be inundated by the HAND criterion, but are immediate neighbors to pixels in the inundated area and have elevation equal to or lower than those inundated. The orange pixels consist in those neighboring the immediate neighbors to the HAND-based flood area, but they also meet the elevation criterion and would thus be flooded as well. By doing this procedure for the entire Mamanguape River basin, there is an increase in the flood area of 2.18 km² and 1.19 km², respectively, for the regions of the immediate neighborhood and second neighborhood to the inundated area by the direct HAND criterion. These are small increases, representing 2.1% and 1.2%, respectively, of the flood area according to the HAND threshold. Thus, although the isolated HAND criterion does not guarantee the hydrostatic condition in the neighborhood of each pixel considered part of the inundated area, despite what Momo et al. (2016) states, the inclusion of areas to guarantee such condition increased this inundate area in a practically negligible way in this study.

Conclusions

In this research, the HAND terrain descriptor was applied to the Mamanguape river basin for estimating flood areas, obtaining the following conclusions:

- The definition of the drainage network initiation controlled its extension and density, which altered the HAND values and, consequently, the estimation of flood areas. Adopting a uniform minimum area value to denote the drainage network initiation is a simplification that continued to have a considerable effect on the estimation of flood areas based on HAND, regardless of the value of this parameter. Ideally, the spatial variation of this parameter over the basin should be adopted or the location of the headwaters should be previously identified;
- In the HAND calculation, the choice of using the original DEM or the DEM modified by the removal process of depressions impacted on the results concerning flood areas, mainly for minor flood heights. It is recommended to consider the DEM without depressions, as this leads to a smoothing of the longitudinal flood profile along the river, which is more consistent with reality, rather than there being sharp variations in flood elevation due to point variations in river bottom elevation;
- The estimate of flood areas based on HAND is coherent with the basin morphology expressed in terms of the topographic longitudinal profile of the river. Widespread occurrence of flood areas was clearly associated with sudden reductions in the river slope pattern, due to an abrupt reduction in hydraulic conveyance and greater chance of runoff overflow to the floodplain. The analysis of the total of flood areas connected by the DEM-derived flow paths to each point along the river course was essential for this type of verification;

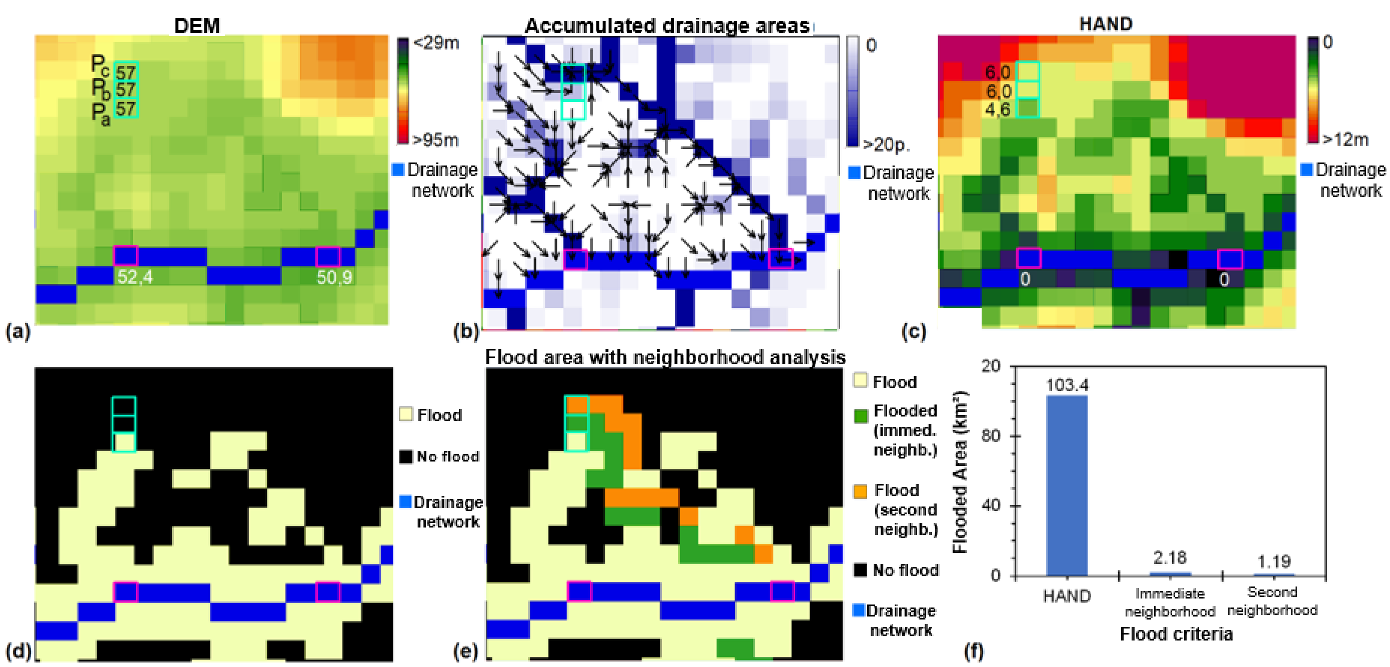

Figure 9 – Analysis of the hydrostatic condition of the flooded areas based on HAND: (A) DEM; (B) Accumulated drainage areas, with indication of the flow directions by arrows; (C) HAND – HANDhet configuration; (D) Flood area for 5-m HAND threshold; (E) Flood area with neighborhood inclusion; (F) Total flooded area obtained from the HANDhet configuration and by the additional criteria of immediate neighborhood and second neighborhood.

- The incorporation of an existing drainage network as a DEM pre-processing step (via stream burning) induced the network derived from the DEM to become more compatible with such existing network, though causing inconsistencies in the HAND method regarding the morphological pattern represented in the DEM. As a solution, there is the improvement of the DEM data acquisition, in such a way to better represents the drainage network trace;
- The hydrostatic condition did not occur in the flood areas estimated from the HAND, with sets of no flood pixels that have the same elevation or even lower elevations than neighbors integrating the flood areas. However, this occurrence was in a quantity that can be disregarded in terms of the impact on the pattern of flood estimates in this basin;
- Finally, it is recommended to validate the results of this research by applying the methods used to estimate flood areas for a specific actual flood event in the Mamanguape river basin, estimating the inundated area from field observations or, at least, via other tools such as satellite images or hydrodynamic modelling.

Contribution of authors:

Dantas, A.A.R.: Literature review, Data preparation, Methodology, Investigation, Writing. Paz, A.R.: Conceptualization, Literature review, Methodology, Investigation, Writing.

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Disaster waste: Characterization and quantification applied to an intense rain event

Caracterização e quantificação de resíduos de desastre de evento de chuvas intensas

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ABSTRACT

The amount and complexity of solid waste are intensified with the occurrence of natural disasters, compromising response and recovery actions, causing unplanned spending, environmental damage, and health impacts. The proper management of disaster waste requires knowledge of its characteristics such as quantity, composition, hazard, and management by the identified waste stream. This article aims at the characterization and quantification of disaster waste arisen from an event of intense rains, which occurred in 2013, in the municipalities of the State of Espírito Santo in Brazil. For characterization, an online survey instrument was developed and applied in institutions responsible for waste management. The survey was associated with a documentary analysis of photographic records and information obtained from the government database. Estimation of the amount of waste generated was carried out in a selected set using a method already applied in the south of the country. It was adapted to local characteristics and later compared with surveys carried out by the municipality. The characterization identified sediments, soil and mud, remains of vegetation, furniture, wood, and discarded scrap as the main generated waste. The estimated additional generation for durable consumer goods of around 1,700 tons of waste was lower than the municipal records (7,436.46 t) in the period. It was associated with the specific low weight of the considered affected goods and the inclusion of other residues in the data obtained in the city hall records. The methods used in the characterization and quantification presented application viability, through adjustments, and represented an important contribution to municipal disaster management to make cities able to face climate change, carrying out safe management of disaster waste.

Keywords: flooding; disaster debris estimation; disaster waste management; climate change.

RESUMO

A quantidade e a complexidade dos resíduos sólidos intensificam-se na ocorrência de desastres, comprometendo as ações de resposta e de recuperação e ocasionando gastos não planejados, danos ambientais e impactos à saúde. A adequada gestão de resíduos de desastres demanda conhecimento de características como quantidade e composição, e gerenciamento segundo fluxos específicos. Diante do exposto, este artigo objetivou a caracterização e a quantificação de resíduos de desastre, decorrentes de evento de chuvas intensas, ocorrido em 2013, em municípios do estado do Espírito Santo, no Brasil. Para a caracterização, um instrumento de pesquisa *online* foi elaborado e aplicado aos setores responsáveis pelo gerenciamento dos resíduos, associado a um levantamento e análise documental de registros fotográficos e de informações de banco de dados governamental. A estimativa da quantidade de resíduos gerados foi realizada em um município selecionado utilizando método já aplicado no sul do país, adaptado às características locais e, posteriormente, comparada com levantamentos feitos pela municipalidade. A caracterização identificou sedimentos, solo e lama, e restos de vegetação, seguido de móveis, madeiras e sucatas descartados como principais resíduos gerados. A estimativa da geração adicional para bens de consumo duráveis obtida, cerca de 1.700 toneladas, foi inferior aos registros municipais (7436,46 t) no período, o que se associou ao baixo peso específico dos bens sinistrados considerados, além da inclusão de outros resíduos nos dados da prefeitura. Os métodos utilizados apresentaram viabilidade de aplicação, mediante ajustes, representando importante contribuição para a gestão municipal de desastres, de modo a tornar as cidades aptas a enfrentarem as mudanças climáticas, efetuando um gerenciamento seguro dos resíduos de desastres.

Palavras-chave: estimativa de resíduos de desastres; inundação; gerenciamento de resíduos de desastre; mudanças climáticas.

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Introduction

Given the recognition of the seriousness of global warming and its relationship with extreme weather events, the international community has outlined goals and targets to address this issue. Considering the 17 Sustainable Development Goals (SDGs), which are components of the 2030 Agenda for Sustainable Development, two of them stand out: the SDG 11 —Sustainable cities and communities and the SDG 13 — Action against global climate change. Some of the goals established in these SDGs are the significant reduction of people affected by catastrophes; substantial reduction in direct economic losses, including water-related disasters (target 11.5); and strengthening of resilience and adaptive capacity to climate-related risks and natural disasters in all countries, through the integration of climate change measures into national policies, strategies, and planning, which are provided in Goals 13.1 and 13.2 (Nações Unidas Brasil, 2021a, 2021b).

Other international agreements, such as the Hyogo Framework for Action (2005–2015) and its successor, the Sendai Framework (2015–2030), reinforce the emphasis given by the international community to the impacts of disasters in order to act in the minimization of risks, improve preparedness for an effective response, and increase cities' resilience to extreme events (UNISDR, 2005, 2015).

An important disaster response action is the management of waste generated as a result of the event; such waste is called disaster waste (DW). The nature and intensity of the disaster are reflected in the quantity, quality, and danger of the resulting waste, which have different characteristics from municipal (urban) solid waste (MSW).

Estimates of DW generation show the extent of the problem. The earthquake that occurred in East Japan in 2011 generated 31 million tons of waste and a flood in the city of Joso in 2015, which affected a large part of the city and destroyed houses and generated an amount of DW equivalent to 3 years of MSW generation under normal conditions (JAPAN, 2018).

Some DR components represent a potential risk to health and the environment and should not be mixed with MSW, as their codisposition in landfills can lead to the leaching of unwanted hazardous chemical products (Agamuthu et al., 2015). García et al. (2017) reported that the large amount of debris generated after a disaster represents a risk factor for the population that have to face health problems and the need of rebuilding the city. Silveira et al. (2021) verified an increase of almost 300% in the record of waterborne diseases in the 3 months after the occurrence of flooding in an urban area in Brazil. The authors highlighted the importance of formulating and implementing policies to prevent disease outbreaks after hydrometeorological disasters.

According to Catanho et al. (2020), climate change has led to an increase in disasters in all Brazilian regions. Such disasters are often associated with hydrological factors, such as floods, wet mass landslides, strong winds, and heavy rains. Another critical aspect was evidenced in a study carried out by Souza et al. (2014) in the city of Recife, Brazil. Areas with low-income, high population density, and low Human Development Index were highlighted as more susceptible and vulnerable to disaster damages due to their social and economic conditions.

Costa et al. (2016), in a study carried out in Amazonas, identified that the efforts of public managers were focused on responses and not on the prevention of critical events, reinforcing the importance of public policies to face the risks related to climate change, attributing to local management plans the role of guiding such actions.

The DW has different characteristics depending on the type of event and the impacted environment, varying both in composition and in the potential for recyclability, hazardousness, and forms of management. When managed correctly, DW can enable reuse or sale of materials, contributing to social and economic recovery actions (Brown et al., 2011).

Crowley (2017) assessed the effects of the existence of DR management plans on disaster responses in 95 U.S. counties with major disasters declarations. He identified that the 49 locations that had such plans recycled almost two times as much wreckage as the others that required three times more Federal public assistance in financial contributions. Scatolini and Bandeira (2020) evaluated the reuse of building and demolition waste and disaster-caused displaced soil in the reconstruction of public and private works. The authors considered it a viable action once it contributes to reduce posttraumatic stress, both by the affected communities and by those who plan or execute response and resilience actions after natural disasters.

Events such as floods can generate debris, sediment, vegetation residues, ashes, wood, and waste derived from damaged furniture, electronics, and vehicles (OPAS, 2003; Günther et al., 2017). Such waste when managed in an emergency manner increases the risks of environmental contamination. It can also cause damage to final disposal plants due to the volume it occupies and make its recovery process unfeasible. Electronic equipment, for instance, can contain dangerous substances but at the same time presents the possibility of recovery (Rodrigues et al., 2015).

Seeking to comply with the precepts of the National Solid Waste Policy (PNRS), established by Federal Law No. 12,305/2010 for the optimization of structural and financial resources, as well as the mitigation of environmental impacts and the reduction of DW disposal in landfills, it is necessary to define in the disaster response and recovery actions planning several factors such as the most appropriate forms of DW destination, the infrastructure and storage logistics, treatment, recycling and final disposal of waste, and the estimation of their respective costs. Therefore, it is essential to characterize the waste in terms of typology and danger and quantify it according to each type of event (Tabata et al., 2016; Günther et al., 2017). Feil et al. (2015) highlighted the importance of prior knowledge about quantity and composition of generated waste for planning an effective management strategy.

According to the State Civil Defense and Protection Coordination—CEPDEC/ES, Espírito Santo (2019) presented a worrying scenario regarding the occurrence of disasters, especially those caused by hydrological factors, such as floods and landslides. This fact highlights the need to insert this topic on the local public agenda, seeking to mitigate losses and damage and promoting the resilience of cities.

In December 2013, the biggest hydrological disaster of the beginning of the century occurred in Espírito Santo; on that occasion, rainfall volume exceeded the average values expected for the month by up to 400%, affecting 55 of the 78 municipalities in the state, causing massive flooding and landslides. Of these 55 municipalities, 47 had an emergency situation (SE) declared. The extreme event affected 368,365 people, with more than 60,000 temporarily or permanently homeless and 26 deaths (Brasil, 2014; Espírito Santo, 2019).

As a technical support to enhance decision-making in DW management in Espírito Santo and in places with similar characteristics, the characterization and quantification of generated waste in the mentioned natural disaster in 2013 were the objectives of this study. Therefore, the study was carried out on the characteristics of the DW generated in municipalities of the state of Espírito Santo, which were affected by heavy rains, and its quantification for the Municipality of Vila Velha, ES.

Method

The critical event of heavy rains in the summer of 2013 in the State of Espírito Santo, Brazil, was selected as a study case for the measurement and characterization of disaster residues based on territorial coverage and its relevance to the region. The methodological strategy used is shown in Figure 1.

The study area was delimited based on the SE and State of Public Calamity (ECP) declarations related to rainfall in the years of 2013 and 2014 in the city. A survey of records on the website of the National Sanitation Information System (SNIS) was carried out on the disposal of waste in the period to compare the estimated values with the actual records reported by the municipalities. Municipalities that declared SE or ECP and informed the SNIS that they sent their waste to a landfill were selected as the sample of the study on the characterization of DW, which led to a total of 40 municipalities.

To quantify the waste generated in the critical event, using the generation estimation method, a representative municipality was selected due to the existence of data records and availability to participate in the study.

Disaster waste characterization

To identify the characteristics of the generated waste in the studied disaster, an instrument for the collection of primary data in simple and straightforward language was developed to facilitate and expand the participation of local management institutions. The questionnaire applied was structured in general questions about the municipality and specific questions related to the flows and procedures of DW management, registration of actions, and characteristics of the generated waste in the disaster that occurred in 2013 (Table 1).

Considering the possible lack of standardization and difficulty in recording data by the municipalities, the option "I do not have such information" was included. The instrument was submitted to a pretest with the civil defense technicians, then properly adjusted and finally made available through the platform *onlinepesquisa*, due to its remote, free, and easy access, which also includes the use of smartphones.

With the support of CEPDEC/ES, the instrument was sent through email to the Municipal Coordination of Civil Defense and Protection — COMPDEC and to the Municipal Government sectors responsible

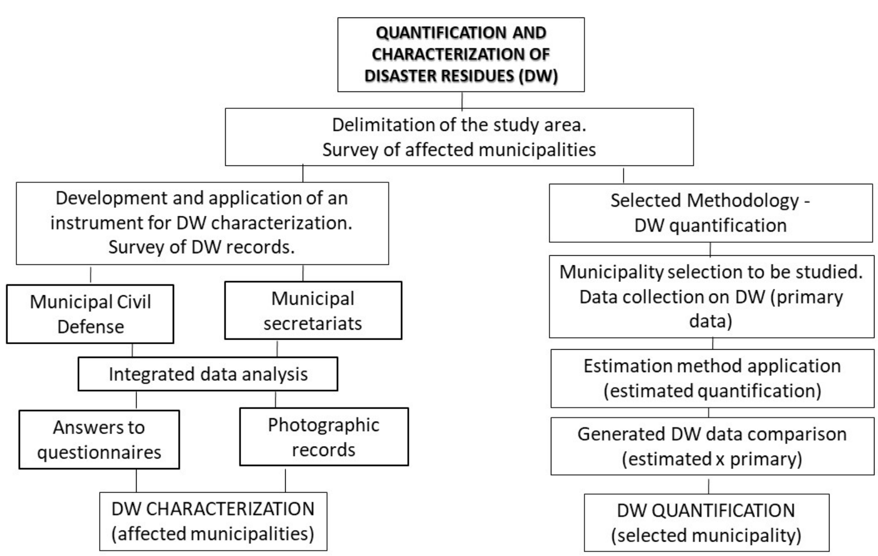

Figure 1 – Methodological strategy used in the study.

for solid waste management (Environment Department, Urban Services Department, and Department of Public Works, among others). The instrument was sent to the 40 municipalities selected for the study and was answered by municipal employees directly on the platform *onlinepesquisa* that was made available.

Additionally, photographic records of the 2013 disaster made available by the municipalities in the sample were collected and analyzed. Such records provided information about affected homes and waste disposed on the streets to qualitatively identify the types of generated DW.

Disaster waste quantification

Based on the literature review, the main methods of DW quantification were identified and evaluated concerning the data and equipment necessary for its application, as well as regarding the feasibility of using it for the event selected as a study case.

The main methods applied to quantify the identified DW generation were compared in terms of functionality and application requirements (Table 2), which led to the selection of the Durable Consumer Goods Quantification Method developed by Schreiner and Wenceloski (2016).

The durable consumer goods quantification method proposed and tested by Schreiner and Wenceloski (2016), which was chosen to estimate the DW generation in this study, is based on a calculation methodology used in Japan. This method considers the Brazilian profile in terms of consumption of durable goods and the construction pattern of buildings in the country and has been applied in another study case in southern Brazil.

The DW estimation basically considers the waste generated by the loss of durable consumer goods and civil construction waste (CCW) resulted from the destruction of homes. Therefore, the method variables were organized into two groups:

- forming variables that are predetermined, according to the context of the affected region and the characteristics of the event;
- dependent variables that arise from the mathematical relationships in the forming variables, corresponding to the result of calculations related to the prediction of the amount of generated waste, as outlined in Figure 2.

The standard house variable (SHV) is quantified as the mass, in tons (t), of generated CCW by a typical household in the region affected by the disaster. At the same time, the damaged goods variable (DGV) is provided by the quantification, also in tons, of durable consumer goods lost by a typical family in the region.

To estimate the amount of waste produced by the loss of durable consumer goods in the study selected disaster, the equations in Table 3 were adapted and used.

The quantification of lost goods in a standard house affected by a disaster was based on the minimum amount of furniture and appliances an average Brazilian family of class E has (Table 4). To estimate the values, Schreiner and Wenceloski (2016) used as a reference the Brazilian government's program *Minha Casa Minha Vida* and the established volume standards of these goods used by moving companies.

To obtain the DGV (E) in tons, Schreiner and Wenceloski (2016) used the volume of 18.30 m^3 (Table 4) and the value of 0.0075 t/m^3 for the apparent density of the waste generated by the lost goods, due to the lack of specific data on this issue applied to the Brazilian reality.

As part of the calculation, correction coefficients referring to social class and type of disaster are applied in the equations presented in Tables 5, 6, and 7.

Coefficients x and y make possible the adjustment of generated waste resulted from the loss of durable goods in a household according to social class and disaster intensity. The z coefficient, in its turn, refers to the type of natural disaster and also acts on the portion of CCW generated by an affected standard house.

To choose the correction coefficient (y) for disaster intensity, the description proposed by Castro (2010) and also adopted by Schreiner and Wenceloski (2016) was considered, in which the situation described in Level III (Table 8) was the one that most resembled the performed study case, being related to intensity 3.

As a selection criterion, it was considered that Municipal, State, and Federal governments were mobilized to face the disaster with recognition of an SE Declaration in both state and federal levels. In addition, to restore the normal situation of the region, the contribution of state or federal resources, such as the permission of Time of Service

Table 1 – Questions included in the survey sent to affected municipalities.

General questions about the municipality (n = 6)	Questions about DW (n = 12)
Municipality data Responsible person for providing information, work sector, and experience Contact number Percentage of the municipality affected by the disaster	Collection interruption and time of suspended services Municipal management body responsible for managing postdisaster DW Interruption of access and/or operation of the landfill used by the municipality Use of an emergency area for temporary storage of collected DW Extra action to the public cleaning routine to remove waste and debris after the disaster Time needed to complete the collection of DW Existence of records on the collected DW and the calculated amount. Need for an emergency contract for collection and/or final disposal of DW and/or road cleaning Occurrence of donations disposal (expired or deteriorated food, etc.) and the amount disposed Typology of collected DW

DW: disaster waste.

Guarantee Fund withdrawal, a special fund designated for workers in specific situations, and the creation of the ES Reconstruction Card, a financial assistance offered to low-income families affected by the intense rains of December 2013, is required (Espírito Santo, 2014).

Municipality selection for the study case

The Municipality of Vila Velha, located in the Grande Vitória region, was selected for the application of the quantification method on the DW generated in the intense rains of December 2013. To this end, the following criteria were considered:

- ease of contact and access to information;
- existence of information on demolitions related to the disaster;
- availability of area images from the period of the disaster;
- information on the socioeconomic characteristics of the affected area;
- records of waste destination during the disaster period.

In order to create scenarios for waste generation close to reality, in addition to contributing to the refinement of the method used, records of home destructions or demolitions as a result of the disaster were obtained from the Municipal Coordination of Protection and Civil Defense—COMPDEC. The areas of the municipality effectively affected by the disaster were delimited using images (aerial photographs) to assess their actual damage, identifying streets, affected houses, and land characteristics.

Table 2 – Methods' characteristics for estimating disaster wastes.

Method/source	Operation	Application	
		Facilities	Limitations
Ground measurement (*Debris Estimating Field Guides*) (FEMA, 2010), EUA	Calculates the DW volume from the formula for calculating the volume of a cube, using data collected in the field.	- Uses low cost and simple operation equipment; - Uses primary data; - Provides DW estimation in short time to assist in response actions; - Allows the differentiation of groups of waste to facilitate management.	- Application immediately after the disaster; - Requires field work (labor, equipment and vehicles); - Requires data and support from the local administration to delimit the area affected by the disaster according to land uses (rural, urban, and industrial).
Remote sensing (FEMA, 2010), EUA	Use of aerial photographs and/or satellite images (before and after the disaster) to estimate DW generation with the aid of formulas.	- Provides DW estimation in short time to assist in response actions; - Small demand for field data; - Suitable for areas with difficult access; - Can be applied as a complement to other methods.	- Requires specialized labor; - Requires availability of aerial photographs and/or satellite images; - Application to previous disasters only possible with photographs from the period; - Estimation method recommended with validation of results through measurements on the ground or computer models.
Computer Models (Hazus Multi-Hazard) (FEMA, 2010), EUA		- Provides DW estimation in short time to assist in response actions; - No field survey required	- Requires previous records on generated DW in similar events; - Not yet available in Brazil.
Estimation through primary data collection (Rodrigues et al., 2016), Brazil	Qualitative survey with application of a questionnaire to residents of affected areas to collect data based on the event records.	- Uses primary data; - Requires participation of affected communities in data collection; - Allows the differentiation of groups of waste to facilitate management.	- Need of application right after the disaster; - Demands community involvement and selection of volunteers; - Focuses on the typology of lost assets (families).
Typical Japanese Method (Japan, 2018), Japão	Uses an equation that relates the construction typology, risks, and local statistical data on DW generation, depending on the disaster intensity.	- Allows prior estimation of DW according to disaster type; - No field survey required; - Simplified calculation.	- Requires records on DW generation due to the disaster; - Focuses on generated DW from homes and civil constructions; - Adapted to Japanese reality and construction standards.
Quantification of durable consumer goods (Schreiner and Wenceloski, 2016), Brazil	Based on the Typical Japanese Method, it relates variables such as standard house, average family, and disaster intensity for the calculation. Uses an equation.	- Developed in the Brazilian context; - Allows you to estimate lost consumer durable goods; - No field survey required.	- Requires specific information about impacts, affected area and affected households; - Allows application to previous disasters, but requires photographs of the period; - Focuses on generated DW from homes and civil constructions.

DW: disaster waste.

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The identification of streets and houses affected by the extreme event was made using the vector format file (shapefile) of the territorial demarcation of the neighborhoods (provided by the Municipality of Vila Velha) and the geospatial data (shapefiles) developed in the research carried out by Langa et al. (2015), providing the outline for the delimitation of the flooded area in the municipality. This tracing, superimposed on the local images, with a spatial resolution of 0.25 m, in addition to information of land use and availability of public equipment included in the ES orthophoto mosaic mapping IEMA 2012-2015 and dated from the period of the disaster, made possible the manual count of households affected by the December 2013 rains.

Results

Disaster waste characterization

The characterization of the DW was based on information collected through an electronic questionnaire. In the first questionnaires sent to 40 municipalities, 17 (42.5%) responses were obtained. After a new attempt, 20 participants were reached. With incomplete information on one municipality, the final sample included 19 (47.5%) municipalities.

Results showed that in 2013, the final destinations of generated waste in the studied municipalities consisted of sanitary landfills (75%), controlled landfills (15%), and open-air dumps (10%). Even for the municipalities that had a routine to control the weight of collected waste for disposal in landfills, the amount of DW was not recorded separately but added to the total amount of MSW. Therefore, there was no specific information about the amount of generated DW as a result of the extreme event studied.

The application of the questionnaire indicated that the main residues generated from the disaster were in this order: sediments, soil and mud, and vegetation remains, followed by discarded furniture and appliances and wood/scrap, as shown in Figure 3. The percentage expressed in the graph represents the relation between the number of times each of the waste typologies was indicated by the respondents and the number of answers obtained. None of the surveyed municipalities stated the necessity to discard donations received (expired water/food or other materials damaged due to storage difficulties, etc.).

The results obtained in the characterization of waste are similar to those found by Barboza and Campos (2014), who identified mud, stone, soil, furniture scraps, large amount of paper, cardboard, household waste, bulky waste, and debris from damaged buildings as the main DW in the municipalities of Angra dos Reis, Betim, Itajaí, and São Paulo. Oliveira (2015) analyzed the impacts of a large rainy event in the city of São Paulo and registered the following types of generated waste according to reports from residents: mud, chairs, sofas, cabinets, beds, mattresses, computers, stereos and televisions, spoiled food, including grains and meat, and animal corpses. Such characterization is also in line with the findings of Günther et al. (2017) who claimed that floods can result in different types of waste, with varied composition, according to the area affected, which can generate bulky waste (vehicles, furniture, and appliances) and waste derived from clothes, shoes, food, and so on.

On the contrary, Agamuthu et al. (2015), when studying the generation and composition of types of DW generated in a flooding in Malaysia, concluded that they were heterogeneous in nature, with a predominance of CCW, which was attributed to the type of

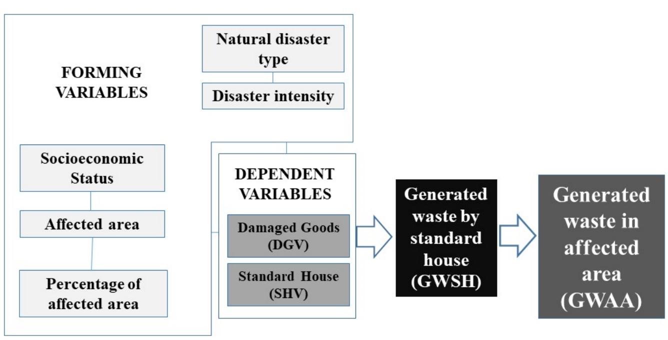

Figure 2 – Stages of the durable consumer goods quantification method.
Source: adapted from Schreiner and Wenceloski (2016).

Table 3 – Equations and variables used for disaster waste quantification.

Stage	Equation	Variables
1	DGV = $x.y$.DGV (E)	**DGV:** damaged durable consumer goods waste generated by standard house (t) **DGV (E):** damaged durable consumer goods waste generated by a standard house of social class E (t) **x:** correction coefficient for the families' social classes ***y:*** disaster intensity correction coefficient
2	GWSH = DGV + SHV	**GWSH:** total generated waste by damaged standard house (t) **SHV:** generated CCW by standard house (t)
3	GWAA = $w.z$ .GWSH	**GWAA:** total generated waste in affected area (t) ***w:*** quantity of disaster-affected houses ***z:*** correction coefficient by type of disaster

Source: adapted from Schreiner and Wenceloski (2016).

infrastructure impacted by the disaster, the intensity of the event, and the constructive pattern of the affected region. This result differs from what was found in this study, highlighting the need for specific studies applied to local characteristics to estimate DW generation.

Complementarily, the photographic records obtained from the municipalities were analyzed, and it was found that they were in accordance with the information obtained in the questionnaires (Figures 4 and 5).

Municipalities that develop predisaster management plans are more effective in DW management (Cheng, 2018). Waste management planning must consider accurate and consistent estimates regarding the quantities and types of generated waste (FEMA, 2010).

The PNRS (Brasil, 2010) established a minimum content to be included in the Municipal Plans for Integrated Solid Waste Management. Such content is composed by the diagnosis of the solid waste situation that must cover origin, volume, characterization, and forms of final disposal; besides, the definition of operational procedures to be adopted in public services of urban cleaning and solid waste management, among other requirements, is also required. Therefore, it is understood that the DW should be included in the Municipal Plans for Integrated

Table 4 – Volume of durable goods existing in a standard house of social class E.

Furniture and appliances of a social class family E	Minimum quantity (unit)	Estimated unit volume (m^3)	Total estimated volume (m^3)
Double bed	1	2.00	2.00
Bedside table	2	0.25	0.50
Wardrobe	2	2.00	4.00
Single bed	2	1.00	2.00
Full size mattress	1	0.90	0.90
Single size mattress	2	0.45	0.90
Sink cabinet	1	0.45	0.45
Medium table	1	0.80	0.80
Chair	4	0.20	0.80
Medium sofa	1	2.20	2.20
Shelf	1	1.00	1.00
Television	1	0.25	0.25
Stove	1	0.50	0.50
Refrigerator	1	1.00	1.00
Washing machine	1	1.00	1.00
Total volume of durable goods (m^3/standard house)			18.30

Source: modified from Schreiner and Wenceloski (2016).

Table 5 – Correction coefficients (x) for residues estimation according to social class.

Social class*	Correction coefficient for social class (x)
A	12.5
B	5.5
C	3.5
D	2.0
E	1.0

*Obtained based on the Socioeconomic Class stratification defined by the IBGE (A to E) based on the value of the minimum wage in 2013. Source: adapted from Schreiner and Wenceloski (2016).

Table 6 – Correction coefficients (y) for DW estimation according to disaster intensity.

Disaster intensity	Correction coefficient for disaster intensity (y)
0	0.0
1	0.2
2	0.4
3	0.6
4	0.8
5	1.0

Source: adapted from Schreiner and Wenceloski (2016).

Table 7 – Correction coefficient (z) for DW estimation according to natural disaster type.

Natural disaster type	Correction coefficient according to disaster type
Hailstorm	0.5
Flood	0.5
Windstorm	1.0
Landslide	2.0

Source: adapted from Schreiner and Wenceloski (2016).

Table 8 – Disaster intensity classification according to effects and damage to population.

Classification	Description
Level I	- Small intensity and small damages; - Easily overcome by the population affected.
Level II	- Damages of major importance; - Locally overcome (prepared and informed community).
Level III	- Large damages; - Mobilizes the three levels of the National System of Protection and Civil Defense.
Level IV	- Very large disasters, which exceed the community's capacity to overcome the disaster; - Inhabitants need external help, including international resources most of the time; - Mobilizes the three levels of the National System of Protection and Civil Defense.

Source: adapted from Castro (2010).

Solid Waste Management to guide or improve the adoption of more sustainable and viable managing practices.

It was also found that the generated DW estimation made in this study can also contribute to the inclusion of DW in the Contingency Plan — PLACON, a document that records the strategic action planning for disasters, prepared by the municipality. In order to prepare the municipality for an effective response to the disaster, it is understood that the prior direction of the logistics that involves the collection and disposal of waste during and after the disaster, involving the definition of actions, responsibilities, procedures, financial resources, equipment, and necessary personnel for the restoration of normality conditions, should be contemplated in this plan.

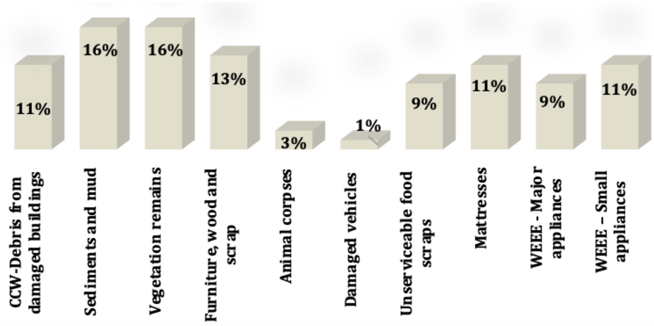

Figure 3 – Percentage distribution of generated types of waste by heavy rains in 2013, according to information from municipalities, Espírito Santo, Brazil.

Disaster waste quantification: durable consumer goods

The application of the quantification method of durable consumer goods was carried out in the Municipality of Vila Velha once it was the only municipality that reported in the questionnaire the amount of collected DW in the characterization stage. This municipality had 91 neighborhoods, and among them, 86 were affected, at different scales, by the episode of heavy rains in December 2013.

After delimiting the flooded area in the Municipality of Vila Velha by the disaster (Figure 6), the affected households were counted, and local socioeconomic characteristics information was collected.

Figure 4 – Discarded residues after heavy rain disaster in 2013, Municipality of Serra, Espírito Santo, Brazil—durable consumer goods.
Source: archive of the Municipality of Serra, ES.

The data obtained were applied to the equations of the used method. The calculation was performed by neighborhood, considering the generation variations defined in the method, according to the socioeconomic profile of each location.

The authors of the method used as reference obtained the number of affected households (w) from the population density (inhabitant/km²), determined for the evaluated region. In order to refine this type of data in this study, remote sensing was used from satellite images and aerial photogrammetry from the period studied, superimposed on the delimitation of the influence area considered in the study. Thus, the value of *w* corresponded to the number of homes affected by the disaster.

Among the affected neighborhoods, the Pontal das Garças neighborhood was selected for a preliminary study to verify the applicability of the method in the study case due to the intense damage suffered. The neighborhood has 585 inhabitants (2010 Census *apud* SEMPLA, 2013) and remained with its territory, in its entirety, immersed under water for several days, as illustrated in Figure 7. According to the local municipal administration, the cleaning, collection, and disposal of generated DW in the event occurred in the period from January to April 2014.

The occurrence of the release of Time of Service Guarantee Fund withdrawal for the inhabitants of the flooded areas guided the identification of the disaster intensity that affected the Municipality of Vila Velha in 2013. Thus, the correction coefficient referring to the disaster intensity level 3 was used once 60% of durable household goods were lost and turned into waste.

Based on the information from COMPDEC, there was no collapse or need for demolition of homes as a result of the disaster assessed in the Municipality of Vila Velha. Therefore, when applying the generated DW estimation method, the portion referring to the volume of generated CCW in the total destruction of a SHV was not considered.

According to the report of the Municipal Secretariat of Planning, Budget and Management of Vila Velha (SEMPLA, 2013), the average monthly income in the Pontal das Garças neighborhood in 2010 was R$ 911.43, so the correction coefficient for the social class E was used. For the other neighborhoods that make up the study region, the coefficient considered the following distribution between classes: C (4.6%), D (29.9%), and E (65.5%), based on the information of average monthly income for each affected neighborhood contained in the SEMPLA report.

The application steps of the generated DW estimate calculation method, selected for the neighborhood studied, are provided in Table 9.

The application of the selected and adapted method resulted in an estimate of additional 15.20 t of generated waste in Pontal das Garças neighborhood, which is a result of lost durable goods disposal. It is noteworthy that the value for the per capita mass of MSW collected that year by the municipal service of Vila Velha was 0.8 kg/inhabitant/day (SNIS, 2013). These data allowed us to estimate that the daily generation of RSU was around 0.47 tons and a monthly generation of RSU was 14.10 tons in Pontal das Garças neighborhood.

Adopting the same method for the other districts of the municipality that comprise the flooded area, the estimated global value of 1,708.85 tons of DW was obtained. It is noteworthy, however, that the method used does not include the portion of sediments, mud, and vegetation remains, which make up part of the amount of DW, as seen in the characterization carried out. According to the local municipal administration, the cleaning, collection, and disposal actions of the generated DW at the event took place from January to April 2014. In the available data, however, the DW is not separated from the other municipal collected waste. Thus, the amount registered by the municipality corresponds to household waste added to the waste collected in the cleaning actions of the DW.

Figure 5 – Discarded residues after heavy rain disaster in 2013, Municipality of Serra, Espírito Santo, Brazil—residues of vegetation, sediments, and mud.
Source: archive of the Municipality of Serra, ES.

When comparing the amount found with urban cleaning service final destination data, in the period from January to April, it was found that the amount of MSW collected in 2014 (71,733.21 t) exceeded the average for the years 2012, 2013, and 2015 (64,296.75 t), resulting in an extra difference (7,436.46 t), which was attributed to the DW. In addition to this significant increase in the collected amount, it is important to mention the presence of bulky waste demands-specific logistics, increase of transportation rides, and extra costs related to them.

In Table 10, based on the daily average of MSW collected in Vila Velha in the assessed regions, there is a comparison with the estimated generated DW by the method applied in terms of equivalent days of operation of the regular MSW collection that was needed to clean the regions affected by the disaster.

Brown et al. (2011) affirmed based on data from the time of the study that, depending on the nature and severity of the disaster, the volume of DW could reach the equivalent of 5–15 times the annual rate of MSW generation, under conditions of normality of the affected community. In an estimate carried out for the flood that occurred in 2015, in the city of Joinville, using the same method adapted for this study, Schreiner and Wenceloski (2016) found an amount of DW equivalent to 15 days of daily generation in the region lower than that obtained in Pontal das Garças (32 days) and close to the result for the total of affected neighborhoods (14 days) in the Municipality of Vila Velha.

It is worth considering that Schreiner and Wenceloski (2016) included the portion of generated CCW as a result of standard house demolitions for the estimate made in Joinville, and the study case in Vila Velha considered exclusively the portion of durable goods lost and expected that the application of the method would result in a value proportionally lower than that of the municipality in the south of the country. It is believed that the adjustment made

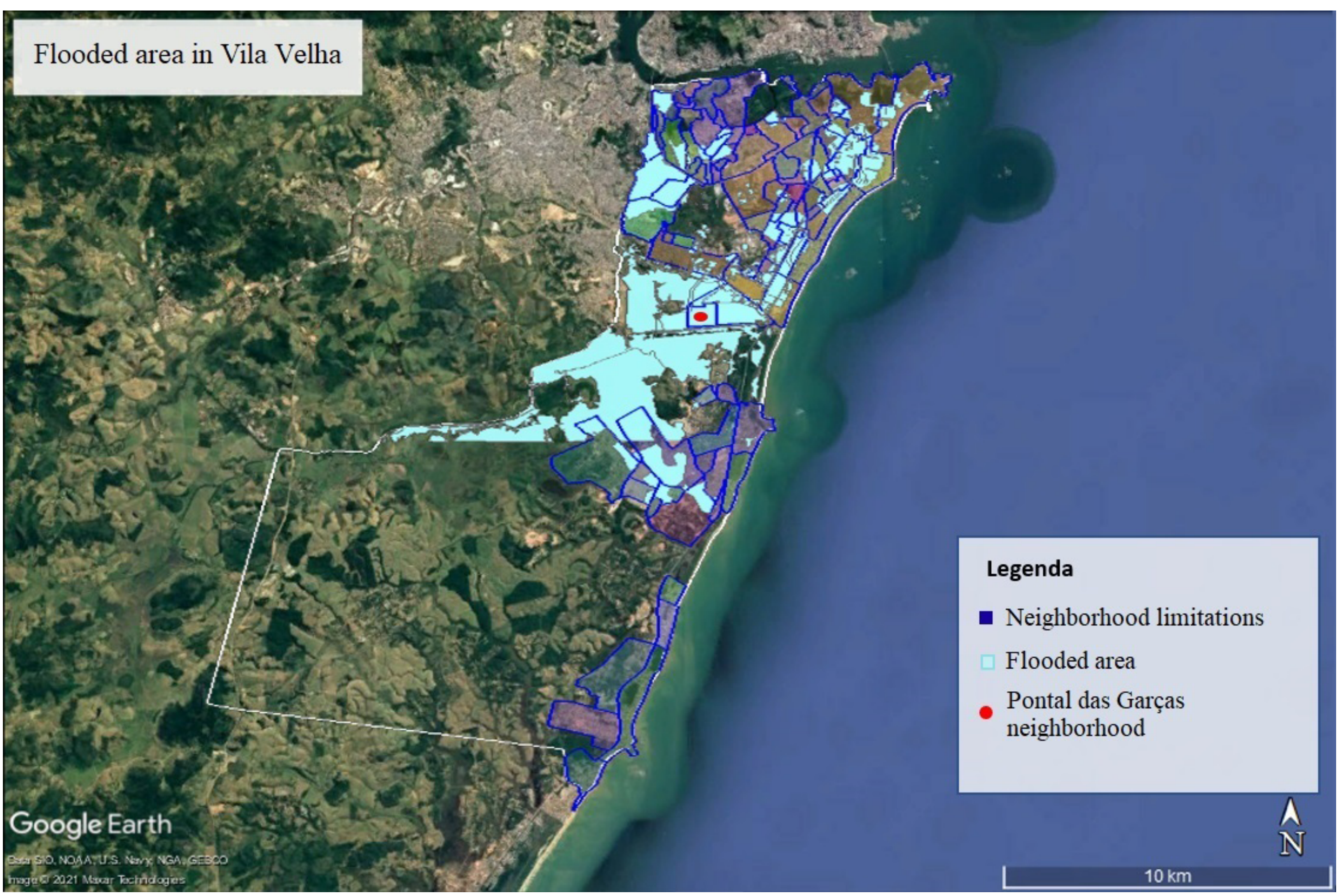

Figure 6 – Representation of affected area by the event in 2013, in the Municipality of Vila Velha.

to obtain the number of affected households may have influenced the result.

When comparing the total estimated DW for the disaster (1,708.85 t) with the increase in the amount of MSW collected and destined in 2014 (7,436.46 t), it is observed that the urban cleaning service record is about four times higher, which may be related to the long period of time required to clean and remove the DW (120 days), with the possibility of generation and disposal of several residues as a result of the postdisaster, including the CCW and residues retained in the macro-drainage system.

Table 10 – Disaster waste estimate comparison between the Pontal das Garças neighborhood and the total of regions affected by heavy rains in 2013 with the MSW daily average generation, Vila Velha, ES.

Assessed regions	Estimate DW*** (t)	MSW average (t/day)	Regular collection period of MSW (days)
Pontal das Garças	15,20	0,47*	32
Total of 86 affected neighborhoods	1708,85	535,8**	14

MSW: municipal solid waste; *estimated based on SNIS (2013); **daily MSW average collected by urban cleaning service for years 2012, 2013, and 2015; ***method adapted from Schreiner and Wenceloski (2016).

Figure 7 – Flooded neighborhoods after the December 2013 rains, Espírito Santo, Brazil.
1: Pontal das Garças neighborhood; 2: Darly Santos Highway; 3: Araçás neighborhood.
Source: Pereira (2017).

Table 9 – Application of disaster waste estimate method in Pontal das Garças, Vila Velha, Espírito Santo, Brazil.

Equation	Applied values	Criteria
DGV (E) = d.DG	***d*** = 0.0075 t/m³ **DG** = 18.30 m³ **DGV (E)** = 0.14 t	- Bulk density (*d*) proposed by Schreiner and Wenceloski (2016) - Total volume of durable goods of standard home class E (DG)
DGV = *x.y*.DGV (E)	*x* = 1 *y* = 0.6 DGV = 0.084 t	- Social class social E - Disaster intensity level 3
GWSH = DGV + SHV	SHV = 0 GWSH = 0.084 t	- No demolition of affected houses
GWAA = *w.z*.GWSH	*w* = 362 *z* = 0.5	- Quantity of affected houses in Pontal das Garças (*w*) - Flood (*z*)
Total generated DW—gwaa (t)		15.204 t

SH: standard home; DGV (E): generated residues by damaged durable consumer goods in a social class E standard home (t); DGV: generated residues by damaged durable consumer goods in standard home (t); SHV: generated CCR by damaged standard home (t); GWSH: total amount of generated residues by damaged standard home (t); GWAA: total amount of generated residues in the affected region (t).

When studying the flooding that occurred in the Municipality of São Luiz do Paraitinga, São Paulo, in 2010, Oliveira (2015) recorded reports that an amount of 2,000 trucks full of DW was removed after the disaster.

It is also noted that the value of the specific weight variable (0.0075 $t.m^3$) brought from the calculation formula of the adopted method is low and may contribute to underestimated DW values. Furthermore, the method used did not include the estimated weight of vegetation residues, sediments, and mud, and these typologies were significantly cited by the municipalities in the stage of characterization of the disaster residues generated in the event.

In the list of furniture and appliances from the Brazilian class E family (Table 2) stands out the wood and waste from electrical and electronic equipment (EEER). Bringhenti et al. (2019), when analyzing recyclables from selective collection in Brazilian condominiums, obtained the respective specific weight values: 0.296 t.m3 (wood) and 0.238 t.m3 (EEER). These values substituted in the formula (Table 9) resulted in DGV values (E), respectively, equal to 5.42 t and 4.35 t, which would be about 39–31 times higher than that used in the estimate (0.14 t), drawing attention to the importance of this parameter.

Although this work has sought to improve the calculation of the amount of waste by the method of Schreiner and Wenceloski (2016), minimizing the uncertainties in obtaining information on the number of homes affected and the amount of CCW generated, it is still verified that some aspects should be reviewed for an improvement to the method, once it has initially raised the need to adapt the value that refers to the specific weight of the waste.

Conclusions

The adaptation of the selected DW generation estimation method proved to be adequate for the study case carried out in the Municipality of Vila Velha, ES after the disaster caused by heavy rains in December 2013.

The analysis of the photographic records of the disaster in comparison with the information provided by the municipalities indicates the need for a more in-depth assessment of the real losses of durable consumer goods. There is a need to understand which goods are effectively discarded by the population and which ones continue to be used after cleaning and repairs. Therefore, a study with this objective is recommended.

The survey results pointed to the need to strengthen municipal public management regarding the registration and systematization of information related to disaster management and, specifically, waste from disasters.

It was noted that the DW was destined to landfills, while it is recommended actions that aim for its valorization and minimization, in compliance with the PNRS, favoring the reduction of costs, the extension of the useful life of landfills, and mitigating environmental impacts or even generating some revenue.

The research also revealed the need for more studies applied to the local context of DW generation and for greater dissemination of issues related to DW in order to promote the inclusion of this type of waste in the planning of disaster risk management and in the integrated management of solid waste, with a view to improve disaster preparation, response and recovery actions, and inclusion of logistics procedures and costs related to packaging, transport, and final treatment of the DW.

Contribution of authors:

Mello, D.P.P.: Data curation, Methodology, Formal analysis, Investigation, Validation, Writing — original draft, Writing — review and editing. Bringhenti, J.R.: Conceptualization, Methodology, Formal analysis, Investigation, Validation, Writing — original draft, Writing — review and editing. Bianchi, D.P.Z.: Conceptualization, Methodology, Formal analysis, Writing — review and editing. Monte, L.S.: Data curation, Investigation, Statistical analysis. Günther, W.M.R.: Conceptualization, Methodology, Writing — original draft, Writing — review and editing, Funding acquisition, Administration of projects, Resources.

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ABES

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Increased quality of small-scale organic compost with the addition of efficient microorganisms

Melhoria da qualidade de composto orgânico em pequena escala com adição de microrganismos eficientes

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ABSTRACT

Substantial quantities of solid livestock waste are potential sources of nutrients for agroecological production on small-scale farms. However, processes used to manage and dispose of this type of waste must be able to eliminate pathogenic microorganisms. This work aimed to evaluate composting and vermicomposting processes by inoculating efficient microorganisms (EMs) at the field level. Composting and vermicomposting were performed with a mixture of cattle and goat manure and sawdust (2:1:1), with the inoculation of EMs at concentrations of 0, 2, and 4 mL L^{-1}. In vermicomposting experiments, *Lumbricus rubellus* (100 g 250 dm^{-3} substrate) were inoculated. After the maturation and stabilization phases of the compost, concentrations of organic carbon, macronutrients, micronutrients, heavy metals, thermotolerant coliforms, and *Salmonella* spp. were analyzed. The composting experiments, regardless of the presence of EMs, have been shown to have higher humidity. Also, the final compost had a lower pH value. Macronutrients, such as P, K, Ca, and S, were observed to a greater extent in the composting experiments associated with 4 mL of EMs (EM4); while organic carbon and Mg were higher in vermicomposting. The vermicomposting process also allowed for more effective elimination of pathogens, such as thermotolerant coliforms, especially when associated with 2 mL of EMs (EM2). The compost products produced allowed waste with potential agroecological use to be recognized as important.

Keywords: vermicomposting; waste recovery; pathogens; organic fertilizer.

RESUMO

Quantidades substanciais de resíduos sólidos provenientes da bovinocultura são fontes potenciais de nutrientes para a produção agroecológica em agricultura de pequena escala. Os processos de tratamento e disposição desses resíduos, entretanto, devem ser capazes de eliminar os microrganismos patogênicos. Nesse sentido, este trabalho objetivou avaliar os processos de compostagem e vermicompostagem por meio da inoculação de microrganismos eficientes (EMs) em escala de campo. A compostagem e a vermicompostagem foram realizadas com esterco bovino, caprino e serragem (2:1:1), com a inoculação de EMs nas concentrações de 0, 2 e 4 mL L^{-1}. Em experimentos de vermicompostagem, *Lumbricus rubellus* foram inoculadas (100 g 250 dm^{-3} substrato). Após as fases de maturação e estabilização dos compostos, analisaram-se as concentrações de carbono orgânico, macronutrientes, micronutrientes, metais pesados, coliformes termotolerantes e *Salmonella* spp. Com os resultados obtidos, foi possível verificar que os experimentos de compostagem, independentemente da presença de EMs, apresentaram maior umidade e menor pH no composto final. Os macronutrientes como P, K, Ca e S foram observados em maior teor nos experimentos de compostagem associados a EM4, enquanto carbono orgânico e Mg foram maiores na vermicompostagem. O processo de vermicompostagem, ainda, permitiu remoção mais eficaz de patógenos como os coliformes termotolerantes, principalmente quando associado a EM2. Os compostos produzidos propiciaram a valorização dos resíduos com potencial uso para a produção agroecológica.

Palavras-chave: vermicompostagem; reciclagem e aproveitamento de resíduos; patógenos; fertilizante orgânico.

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Introduction

In order to meet growing demands for food, over-cropping and overuse of inorganic fertilizers have become common practices among farmers. However, replacing organic with inorganic inputs reduces soil quality and can lead to environmental pollution (Albiach et al., 2000; Komiyama et al., 2013). This can be avoided with the use of organic solid waste fertilizers, through composting or vermicomposting. These processes improve microbial activity (Ros et al., 2006; Knapp et al., 2010; Elbl et al., 2019), and increases soil cation exchange capacity, which favors mineralization and nutrient recycling (Nath and Singh, 2012; Domínguez and Gómez-Brandón, 2013; Yadav and Garg, 2016). On the other hand, the direct use of solid animal waste (e.g. manure) as fertilizer is not recommended because this type of waste can contain high pathogen loads (Larney and Hao, 2007; Lim et al., 2016), which can cause soil and water contamination (Ciancio et al., 2014; Ciapparelli et al., 2016). Thus, composting or vermicomposting processes must provide stable, pathogen-free, and soil-beneficial end-products. The main challenge of these processes is to control and optimize the interactions between the biological, chemical, and physical mechanisms affecting the composition and degradation behavior of heterogeneous organic matrices, such as organic waste (Hemidat et al., 2018).

The composting process involves various temperature ranges. In the thermophilic phase of humification, at ideal temperatures between 50 and 70°C, pathogenic microorganisms are eliminated (Misra et al., 2003). In the context of small-scale composting or vermicomposting, problems usually occur because the temperature is not raised and maintained at desirable values (above 50°C) in the thermophilic phase; resulting in incomplete elimination of pathogens. This results in incorrect composting and generates final products with lower quality than that required by the national and international legislation. Some studies have reported home-scale experiments with temperatures below 45°C, demonstrating the limitation of composting at this level (Ermolaev et al., 2014; Faverial and Sierra, 2014).

As an alternative, efficient microorganisms (EMs) have been used to improve microbial activity. EMs represent a consortium of beneficial microorganisms, including photosynthetic bacteria, yeast, actinomycetes, and fermenting fungi, among others (Sigstad et al., 2013; Diering, 2020). Diering (2020) observed that the majority of these microorganisms included *Zygotorulaspora florentina* (53.7%) and *Pichia nakasei* (46.0%) fungi, and *Gluconobacter cerinus* (78.5%), *Lactobacillus casei* (8.0%), and *Gluconobacter frateurii* (6.8%) bacteria. Increasing microbial load using EMs improves the chemical and physical properties of the compost, significantly affecting temperature and decomposition rates during composting, all of which contribute to a sustainable and high-quality final product (Jusoh et al., 2013; Patidar et al., 2013; Zhong et al., 2018). During organic matter composting with EMs, it was possible to verify an increase in the levels of C and N in the compost derived from fruit residues (Raja Namasivayam and Bharani, 2012) and a mixture of rice straw, goat manure, and green residues (Jusoh et al., 2013), as well as an increase in macronutrients in the compost produced from corn by-products (Hendriani et al., 2017). EMs, even when used with a reduced dose of chemical fertilizers, have been described to increase the content of humus and organic carbon in the soil, and to improve its fertility, when compared to the application of chemical fertilizers alone (Sharma et al., 2017). High efficiency in nutrient availability has also been observed in vermicomposting processes using EMs (Hénault-Ethier et al., 2016). In addition, the optimized combination of EMs allows for reduced odors released by the decomposition of organic matter, thus contributing to reduced pathogens in the compost (Calderón-Tapia et al., 2020). Nevertheless, studies are scarce, especially those focused on the removal of pathogens (thermotolerant coliforms and *Salmonella*) from agricultural waste composting in small rural properties.

Therefore, we used composting and vermicomposting methods in the present study, using organic residues with various concentrations of EMs at the field level, on small rural properties, to eliminate pathogens and generate a high-quality final compost product.

Material and Methods

Experimental design and treatments

The experiments were conducted using windrow composting, including composting or vermicomposting (with *Lumbricus rubellus*), and efficient microorganisms (EMs) were added at three concentrations: 0 mL L^{-1}, 2 mL L^{-1}, and 4 mL L^{-1}. Treatment groups were as follows:

- COMP (composting);
- COMP+EM2 (composting and 2 mL L^{-1} EM);
- COMP+EM4 (composting and 4 mL L^{-1} EM);
- VERM (vermicomposting);
- VERM+EM2 (vermicomposting and 2 mL L^{-1} EM);
- VERM+EM4 (vermicomposting and 4 mL L^{-1} EM).

The data obtained were analyzed by descriptive statistical analysis, with mean and standard deviation for data collected in triplicates.

Obtaining the microorganisms

Native efficient microorganisms were captured inside the forest area in a horticulture production farm in Erechim, Rio Grande do Sul, Brazil (-27.53301 S, -52.32665 W) and multiplied according to Bonfin et al. (2011). Boiled rice, wrapped in a shading screen, was covered with litter and maintained for 15 days in an area of virgin forest (7 m from the border), under average temperature from 15 to 20°C. After this period, the microorganisms found in the collected material were selected by staining for multiplication. Gray, white, brown, and black rice grains were discarded. The other-colored grains were multiplied by fermentation process in a culture medium containing an aqueous solution of sugarcane molasses (20%), for two months, for the development and bioaugmentation of efficient microorganisms. The mixture was kept in an expandable and air-tight container, and the gases were released when necessary.

Substrate preparation

The substrates used in all treatments were prepared with the combination of cattle manure, goat manure, and sawdust as the structuring medium. After analyzing the baseline characterization of carbon (C) and nitrogen (N) for each residue, the mass balance was calculated for various combinations, as indicated in Equation 1:

$$\frac{C}{N}\,ratio = \frac{(\%CM \times C_{CM})+(\%GM \times C_{GM})+(\%S \times C_S)}{(\%CM \times N_{CM})+(\%GM \times N_{GM})+(\%S \times N_S)} \quad (1)$$

Where:
CM = cattle manure (%);
GM = goat manure (%);
S = sawdust (%);
C = carbon (%);
N = nitrogen (%).

To achieve C/N ratios ranging from 20:1 to 35:1 (Herberts et al., 2005), the defined ratio was 50% cattle manure, 25% goat manure, and 25% sawdust.

The substrates used in the composting experiments were prepared using a 400-L concrete mixer with a 2-HP single-phase motor. After determining the baseline moisture content using reflectometry (TDR, model 6005L, MiniTRASE, Armidale, NSW, AU), the compost was added to windrow layers consisting of 30 kg of compost and 10 L of water. In experiments using EMs, these were diluted and inoculated with water. In the composting experiments, the soil was stirred up with a drill 3 times a week, until the maturation phase was reached. After this period, the soil was stirred up twice a week and, in the final fifteen days of the experiments, it was stirred up once a week.

For the vermicomposting experiments, 100 g of *Lumbricus rubellus,* commonly known as red wriggler, were added to 250 kg of substrate (0.4 g earthworms/dm^3 substrate) during compost preparation in the absence of turning.

The composting and vermicomposting experiments were conducted for 120 and 150 days, respectively. In both experiments, an aqueous solution containing EMs was replenished five times over the 150 experimental days, in the same proportion of water replenished in the experiments without EMs, considering the need for tactile analysis. Regardless of the addition of EMs, all experiments received the same total volume of water.

The experiments were carried out in windrows, made up of 1 x 1 x 0.7 m (l x w x h) wooden boxes, with a volume of 0.7 m^3, and a capacity for 250 kg of initial substrate, as suggested for small-scale uses by Faverial and Sierra (2014). The windrows were shaded and covered to prevent external effects caused by rainfall and slurry generation.

Evaluations

Substrate temperature was monitored daily using a portable thermometer with a -50°C to 200°C measuring range and accuracy of ± 0.5°C (model AK904, AKSO, São Leopoldo, Brazil). Humidity and pH were assessed at the beginning (BASELINE), before treatment (EMs and earthworms), and at the end of the experiments (after 150 or 120 days). Humidity was measured by gravimetric method, which consists of weighing the sample before and after being dried in an oven (65°C), to calculate humidity based on the dry mass. pH was determined using a laboratory pH meter (model 8650, AZ Instrument, Taichung, Taiwan).

Visual tactile analysis was done *in loco* according to Nunes (2009) to verify compost stability and humidity during testing and to determine how often water and/or EM aqueous solution should be added. The visual tactical analysis consists of manually obtaining a sample of the material from inside the windrow and pressing it firmly to verify water leakage without draining it.

At the beginning and end of the process, pH, thermotolerant coliforms, *Salmonella* spp., organic carbon, and macro and micronutrients, as well as heavy metal concentrations, were analyzed.

Thermotolerant coliforms

The number of thermotolerant coliforms was determined according to the 9221E methodology (Braun-Howland et al., 2017). Samples were initially incubated in tryptose lauryl sulfate broth (LST) at 37°C for 24 h. After confirmation of gas production, an aliquot of each culture was transferred to new tubes with a medium containing lactose, ox gall, and brilliant green at 44.5°C for 24 h. The most probable number (MPN) method was used for quantification. Only dishes at the same dilution with 30 to 300 colonies were considered for counting. The arithmetic mean of the colonies was multiplied by the respective dilution factor and the results were expressed as NMP g^{-1}.

Determination of Salmonella ssp.

The amount of *Salmonella* spp. was determined qualitatively by the presence/absence technique using VIDAS® Easy Salmonella Method (Adria Développement, Quimper Cedex, France), according to the manufacturer's recommendations. The samples were initially enriched with buffered peptone water (BPW) and maintained at 37°C for approximately 20 h. The subculture was then transferred to SX2 broth (Salmonella Xpress 2) (0.1 mL + 10 mL) and incubated for approximately 24 h at 41.5°C. Samples were then transferred to a microtube, heated to 100°C for 15 min and, after cooling, 0.5 mL was transferred to VIDAS SLM strips. Fluorescence was measured at 450 nm. The values were compared to internal references and each result was interpreted as positive or negative.

Organic carbon and mineral elements

Organic carbon (C), macronutrients (N, P, K, Ca, Mg, S), and micronutrients (Mn, Cu, Zn, Fe, B) were determined according to Brasil (2017), and heavy metals (Cd, Pb, Cr, Ni) according to USEPA (1998). All analyses were performed in triplicate.

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Results

The temperature outside the windrows was similar between the composting and vermicomposting experiments, with average temperatures of 26.0 ± 3.1°C and 26.8 ± 3.7°C, respectively (Figure 1). The maximum temperatures found inside the windrows were 49°C, 50°C, and 51°C in the experiments that did not use EMs, that used 2 mL L^{-1}, or that used 4 mL^{-1} EMs, respectively. In the vermicomposting experiments, the maximum temperatures found were 48°C (VERM), 48°C (VERM+EM2), and 47°C (VERM+EM4).

The experiments containing 2 mL L^{-1} EMs recorded temperatures above 40°C for a longer time, and the shortest time at these temperatures was recorded in the vermicomposting experiments with the highest concentration of EMs (4 mL L^{-1}) (Figure 1).

The initial substrate used in all experiments had 71.6% humidity and pH 8.1 (Table 1). After the experimental period, the substrates used for composting and vermicomposting had average pH values of 7.4 and 6.8, respectively, regardless of the addition of EMs. Humidity ranged from 50 to 67% over the experimental period.

The content of macronutrients in the substrates used for composting and vermicomposting changed at the end of the experiments compared to baseline levels. Reductions in C/N ratios and C content were observed for both composting and vermicomposting compared to the content found in the initial substrate. Amounts of N, P, Ca, Mg, and S increased in all experiments. K was found at higher values in the composting experiments only, regardless of the presence of EMs (Table 2).

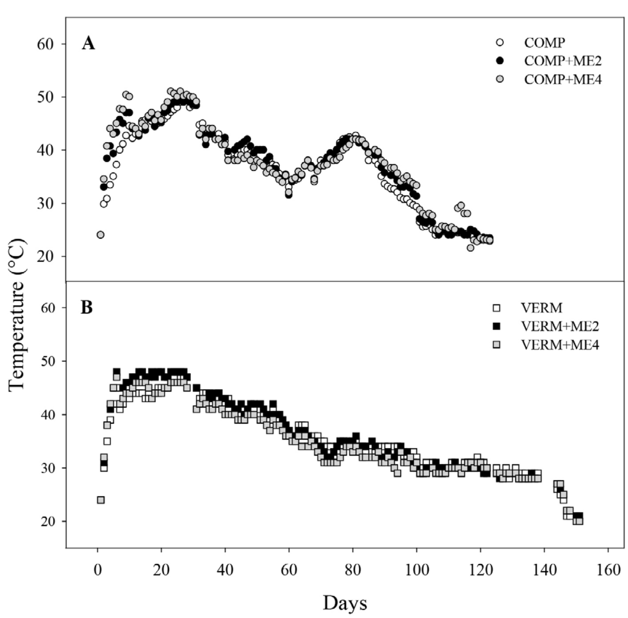

Figure 1 – (A) Windrow temperature of composting (COMP), composting with 2 mL L^{-1} of efficient microorganisms (COMP+2EM), and composting with 4 mL L^{-1} EMs (COMP+4EM); (B) vermicomposting (VERM), vermicomposting with 2 mL L^{-1} EMs (VERM+2EM), and vermicomposting with 4 mL L^{-1} EMs (VERM+4EM).

The inoculation of EMs did not influence the final C/N ratio. Nevertheless, in the composting experiments, phosphorus levels were greater for both COMP+EM2 and COMP+EM4, and levels of N, K, and Ca were greater in COMP+EM4 compared to those in the COMP treatment.

Vermicomposting allowed an increased C/N ratio, regardless of the concentration of EMs and C content, mainly in the VERM+EM4 experiment, compared to the VERM experiment. N, P, K, and Ca levels were slightly lower in the vermicomposting experiment and 4 mL L^{-1} EMs (Table 2).

The composting experiment (COMP) revealed greater availability of all micronutrients measured compared to baseline substrate contents (BASELINE) (Table 3). Similar responses were observed for Mn, Zn, Fe, and B in the VERM experiment. The micronutrients Mn, Cu, Zn, Fe, and B had higher concentrations in the composting experiments compared to the vermicomposting processes.

Adding EMs, regardless of the concentration, did not significantly influence micronutrient content in either composting or vermicomposting processes. Slight reductions in Mn and Fe levels were observed in the COMP+EM2 and VERM+EM4 experiments compared to the COMP and VERM experiments, respectively.

As observed for nutrients in general, during the experimental period in both composting and vermicomposting processes, there was greater availability of heavy metals in the substrates (Table 4). Increased Cd, Pb, Cr, and Ni levels were observed in the COMP experiment; and Cd, Cr, and Ni levels in the VERM experiment compared to baseline substrate levels. The presence of EMs resulted in lower Cr availability in composting and lower levels of Ni and Cd in vermicomposting. In general, the VERM experiments showed reduced content of the metals analyzed.

Thermotolerant coliforms were significantly lower in all processes used (Table 5). The higher concentration of EMs (4 mL L^{-1}) resulted in lower detection of thermotolerant coliforms in the composting process, compared to the intermediate concentration (COMP+EM2).

Table 1 – pH values of each experiment: composting (COMP) or vermicomposting (VERM) with the addition of 0, 2, or 4 mL L^{-1} of efficient microorganisms (EMs) at the beginning (BASELINE) and after 120 or 150 experimental days.

	Humidity (%)	pH
BASELINE	71.60	8.12
COMP	50.17	7.21 ± 0.02
COMP+EM2	55.07	7.52 ± 0.04
COMP+EM4	49.56	7.59 ± 0.01
VERM	61.90	6.72 ± 0.02
VERM+EM2	63.36	6.90 ± 0.03
VERM+EM4	66.95	6.73 ± 0.03

Table 2 – Ratio of carbon to nitrogen (C/N) and organic carbon (C, %), nitrogen (N, %), phosphorus (P, %), potassium (K, %), calcium (Ca, %), magnesium (Mg, %) and sulfur (S, %) in composting (COMP) or vermicomposting (VERM), with the addition of 0, 2 (EM2) or 4 (EM4) mL L^{-1} of efficient microorganisms (EMs) at the beginning (BASELINE) and after 120 or 150 experimental days*.

	C/N	C	N	P	K	Ca	Mg	S
BASELINE	19.26	35.50	0.52	0.50	0.32	0.39	0.11	0.11
COMP	11.62 ± 0.32	20.30 ± 0.45	0.87 ± 0.01	0.83 ± 0.01	0.43 ± 0.00	0.83 ± 0.01	0.16 ± 0.00	0.47 ± 0.06
COMP + EM2	12.33 ± 0.67	23.26 ± 0.76	0.85 ± 0.06	0.90 ± 0.05	0.56 ± 0.00	0.86 ± 0.00	0.16 ± 0.00	0.38 ± 0.05
COMP + EM4	11.51 ± 0.41	22.78 ± 0.41	0.99 ± 0.03	0.96 ± 0.01	0.61 ± 0.04	0.99 ± 0.01	0.18 ± 0.00	0.45 ± 0.04
VERM	12.12 ± 0.20	28.41 ± 1.03	0.90 ± 0.01	0.80 ± 0.01	0.28 ± 0.02	0.77 ± 0.01	0.26 ± 0.02	0.26 ± 0.01
VERM + EM2	12.78 ± 1.23	28.06 ± 0.99	0.82 ± 0.03	0.74 ± 0.04	0.30 ± 0.01	0.68 ± 0.01	0.25 ± 0.00	0.13 ± 0.01
VERM + EM4	13.12 ± 0.07	30.44 ± 0.77	0.77 ± 0.02	0.68 ± 0.03	0.23 ± 0.00	0.67 ± 0.01	0.23 ± 0.01	0.23 ± 0.03

*Data represent means ± standard deviation.

Table 3 – Content of micronutrients: manganese (Mn, mg kg^{-1}), copper (Cu, mg kg^{-1}), zinc (Zn, mg kg^{-1}), iron (Fe, mg kg^{-1}), and boron (B, mg kg^{-1}) in composting (COMP) or vermicomposting (VERM), with the addition of 0, 2 (EM2) or 4 (EM4) mL L^{-1} of efficient microorganisms (EMs) at the beginning (BASELINE) and after 120 or 150 experimental days*.

	Mn	Cu	Zn	Fe	B
BASELINE	0.027	0.004	0.008	0.561	0.003
COMP	0.079 ± 0.003	0.012 ± 0.001	0.016 ± 0.000	3.754 ± 0.161	0.008 ± 0.001
COMP+EM2	0.065 ± 0.000	0.009 ± 0.001	0.014 ± 0.000	2.678 ± 0.048	0.006 ± 0.000
COMP+EM4	0.073 ± 0.000	0.011 ± 0.002	0.016 ± 0.001	2.858 ± 0.042	0.007 ± 0.000
VERM	0.055 ± 0.001	0.007 ± 0.000	0.013 ± 0.000	1.959 ± 0.053	0.009 ± 0.000
VERM+EM2	0.054 ± 0.001	0.006 ± 0.000	0.011 ± 0.000	1.982 ± 0.012	0.009 ± 0.000
VERM+EM4	0.047 ± 0.000	0.006 ± 0.000	0.011 ± 0.000	1.572 ± 0.014	0.008 ± 0.000

*Data represent means ± standard deviation.

Table 4 – Cadmium (Cd, mg kg^{-1}), lead (Pb, mg kg^{-1}), chromium (Cr, mg kg^{-1}), and nickel (Ni, mg kg^{-1}) in composting (COMP) or vermicomposting (VERM), with the addition of 0, 2 (EM2) or 4 (EM4) mL L^{-1} of efficient microorganisms (EMs) at the beginning (BASELINE) and after 120 or 150 experimental days*.

	Cd	Pb	Cr	Ni
BASELINE	1.76	20.7	2.8	13.8
COMP	2.77 ± 0.19	53.30 ± 0.00	15.47 ± 1.02	27.56 ± 1.11
COMP+EM2	2.33 ± 0.00	53.30 ± 0.00	10.70 ± 0.00	21.50 ± 0.00
COMP+EM4	2.22 ± 0.19	57.76 ± 3.86	9.52 ± 1.02	21.79 ± 1.11
VERM	2.03 ± 0.08	21.70 ± 3.10	7.36 ± 0.98	18.54 ± 0.61
VERM+EM2	2.18 ± 0.09	21.70 ± 0.01	6.23 ± 0.98	18.90 ± 0.61
VERM+EM4	2.41 ± 0.00	21.70 ± 0.00	6.23 ± 0.98	17.83 ± 1.63

*Data represent means ± standard deviation.

Table 5 – Content of thermotolerant coliforms (NMP g^{-1}) and Salmonella spp. (in 10 g) in composting (COMP) or vermicomposting (VERM), with the addition of 0, 2 (EM2), or 4 (EM4) mL L^{-1} of efficient microorganisms (EMs) at the beginning (BASELINE) and after 120 or 150 experimental days.

	Thermotolerant coliforms	Salmonella ssp.
BASELINE	> 160,000	Absent
COMP	14,000	Absent
COMP+EM2	17,000	Absent
COMP+EM4	400	Absent
VERM	4,900	Absent
VERM+EM2	200	Absent
VERM+EM4	1,100	Absent

For vermicomposting experiments, the intermediate concentration of EMs (VERM+EM2) was more efficient in reducing coliforms. *Salmonella* ssp. were observed either in the initial substrate used in the processes or at the end of the experimental period.

Discussion

We analyzed the physicochemical characteristics and the presence of pathogens in composting and vermicomposting from cattle manure, goat manure, and sawdust associated with efficient microorganisms, under field conditions. It is important to keep the compost moist (50-75%) to allow a high-quality final product, considering that this condition ensures microbiological activity (Makan et al., 2013; Kabelitz et al., 2020; 2021), as observed in the present study. Substrate moisture, although slightly reduced in the COM and VERM experiments, probably due to greater soil aeration after turning and the action of earthworms, respectively, remained at adequate levels for the activity of microorganisms. Compost temperature is an indication of the phase of the process. The composting process begins in the adaptation or mesophilic phase, with the adaptation of microorganisms. Subsequently, at temperatures above 50°C, the process reaches the thermophilic phase, which is fundamental to ensure pathogen elimination and to assist in the elimination of invasive plant seeds from the compost (Huhe et al., 2017; Ribeiro et al., 2017). The stability of the compost is observed during the maturation or humification phase, when temperatures tend to decrease to room temperature levels. For effective elimination of pathogens and weeds, the thermophilic phase must reach temperatures above 50°C for at least 15 consecutive days, (Brenes-Peralta et al., 2021). In this sense, the maximum temperature range found and process acceleration occurred due to the presence of EMs that intensified the thermophilic phase responsible for this thermal behavior. EMs also help balance nutrient supplies by slowly releasing organically bound nutrients. They contribute to beneficial microbes that, together with native microorganisms, promote greater microbial activity (Ribeiro et al., 2017; Sharma et al., 2017; Rastogi et al., 2020) and higher temperatures, with improved efficiency and compost quality (Tran et al., 2019). The maturation phase is also affected by substrate composition. Mechanical rotation, as performed in the composting experiments, promotes greater aeration and homogenization of the compost. In the vermicomposting process, this rotation is performed exclusively by the earthworms present, which makes the process slower, thereby creating longer intervals to reach stability. In the present study, the vermicomposting processes were stabilized about 30 days after the composting processes (it took 25% longer).

Because temperature affects microbiota activity, compost pH is also regulated by the microorganisms present. They are responsible for degrading the organic matter while producing acidic or basic byproducts and CO_2 (Morales et al., 2016; Osman et al., 2020). At the end of the process, we found that more alkaline pH values were recorded in the composting experiments compared to the vermicomposting experiments. This may have occurred because the substrate was not turned in the vermicomposting experiments. Although the presence of earthworms allows for compost oxygenation, turning the substrate in the composting treatments possibly caused greater oxygenation and, consequently, a higher pH value. The addition of EMs also favored high pH, regardless of the inoculated concentration. pH values between 6 and 8 are considered suitable conditions for composting (Bustamante et al., 2013; Jerônimo et al., 2020), as observed in the present study. This represents an important advantage and suggests that the mineralization and humification reactions occurring in the present study occurred under favorable biochemical conditions, resulting in high-quality organic compost.

Biodegradation of organic matter can be assessed using the C/N ratio, which indicates the stabilization of organic fertilizers (Nafez et al., 2020; Nayak et al., 2020; Palaniveloo et al., 2020). Bioconversion of cattle and goat manure, with composting or vermicomposting, resulted in lower C/N ratios compared to baseline levels. This may occur due to the degradation of putrid organic matter, promoting nutrient mineralization. Subsequently, in the final humification and maturation phase, organic matter is formed in a stable state, in the form of complexes (predominantly humic acid, humine, and fulvic acid), which hold these nutrients in a weak link, available for and exchangeable by the plants. It results in increased bioavailability and mobility of key plant nutrients, such as K, P, and N, as facilitators of plant development, especially those that are not nitrogen fixers. On the other hand, EMs had no effect on the biodegradation of the substrate, possibly because they play a major role in increasing microbiological activity, allowing for a better nutrient stock and increasing the effect of the earthworms, among other things; and not in increasing the temperature and intensifying the thermophilic phase. In addition, the C/N ratio observed in the experiments is suitable for composting (< 20) and vermicomposting (< 14), according to MAPA Normative Instruction (Brasil, 2009). A C/N ratio between 12 and 15 at the end of the composting process indicates compost maturity and ideal conditions for fertilization (Onwosi et al., 2017; Nafez et al., 2020).

Cattle and goat manure composting and vermicomposting showed higher contents for all macronutrients evaluated at the end of the process compared to the baseline quantification of the substrate. The composting processes yielded higher contents of P, K, Ca, and S compared to the vermicomposting processes. In the vermicomposting process, intense degradation of organic compounds due to synergistic action between microorganisms and earthworms was expected, resulting in greater mineralization of organic P, for example (Eckhardt et al., 2018).

Increased macronutrients in composting and vermicomposting were expected because minerals are solubilized during biodegradation and nitrogen compounds are released. However, it was more evident in COMP+EM4 compared to COMP, where the content of P, K, Ca, and Mg was higher. A larger number of EMs has also been described as improving the levels of N, P, and K in the compost, regardless of the EM multiplication medium (Sharma et al., 2017; Nayak et al., 2020). Greater aeration in the COMP experiments may have allowed Ems to perform better, further increasing degradation. Hendriani et al. (2017) reported that EMs associated with *Azotobater* sp. in the composting of corn by-products promoted an increase in the content of macronutrients, such as N, P, and K (Hendriani et al., 2017). According to the authors, the use of the final compost as fertilizer also allowed greater productivity to pepper and tomato plants. However, the nutrient content of organic fertilizers also depends on the composition of the source material (Tratsch et al., 2019; Jerônimo et al., 2020; Wako et al., 2021). In vermicomposting experiments, macronutrient content was significantly higher when compared to BASELINE values. Vermicomposting processes can even promote residual effects for subsequent planting, as observed by Nurhidayati et al. (2018). This demonstrates the importance of adapting these processes on small farms to increase the value of residues and to reduce potential environmental contamination, all of which will reduce the need for chemical fertilizers.

Micronutrient content, such as Mn, Cu, Zn, Fe, and B, increased after composting and vermicomposting when compared to BASELINE values, regardless of EM inoculation, but were even lower in vermicomposting experiments when compared to composting. The low levels of micronutrients and heavy metals in VERM may be related to the high C levels observed in these treatments; which allowed adsorption of these elements by complexing metal ions, lowering their available concentration.

The levels of micronutrients available at the end of the process, although at a lower concentration than the ones required for crops (as compared to traditional chemical fertilizers available for sale), are important waste recovery products. This represents an economic and sustainable advantage, reducing the need for chemical fertilizers in gardening, ornamentation, and vegetable growing, especially on small farms.

The heavy metals found in the substrate tend to increase when compared to the BASELINE values because they are not degradable (Soobhany et al., 2015). However, in addition to the negative correlation with organic matter, the use of earthworm bioconversion in vermicomposting processes allowed for lower contents of Pb, Cr, and Ni compared to composting processes. This was possibly because earthworms absorbed these metals. The level of accumulation carried out by the worms will depend on the species of the earthworm and the amount of metal present; but several studies have reported that earthworms are potential bioaccumulators of metals in contaminated soils (Lv et al., 2016; Zeb et al., 2020; Xiao et al., 2021).

It should be noted that the main effect of organic fertilizers is not to enrich the soil, but rather make nutrients available slowly and continuously, which is typical of organic fertilizers produced by composting. Among other factors, they can contribute to improving soil structure by increasing porosity and gas exchange, stabilizing organic matter, and increasing microbial diversity (Rauber et al., 2018), all of which contribute to nutrient mobilization for plants. Furthermore, inoculation of microorganisms such as EMs contributes to the degradation of toxic agents (Boechat et al., 2020; Dell'Anno et al., 2020), and the control of plant pathogens (Shen et al., 2013; Alori et al., 2017; Benedetti et al., 2021). The use of these compost products for agroecological production is also environmentally friendly because excess chemical fertilizers, in addition to degrading the soil, can leach into water resources causing environmental impacts such as eutrophication (Chislock et al., 2013; Rivas et al., 2020).

Salmonella was not detected in the analyses because of the initial preparation of the compost, suggesting that the cattle and goat manure were free from contamination; *Salmonella* is often observed in chicken manure (Sheffield et al., 2014). Thermotolerant coliforms, as expected for the type of waste used, were found at high concentrations in the initial preparation of the compost. These high concentrations were drastically reduced in all experiments, with the lowest levels observed in the composting treatment and the treatment with the highest concentration of EMs (4 mL L^{-1}), and in vermicomposting inoculated with EMs (2 mL L^{-1}). These values were below the limit of 1,000 MPN g^{-1} of dry matter determined by the legislation (Brasil, 2016). Hénault-Ethier et al. (2016) studied the survival of *Escherichia coli* in different reactor scales, with and without the presence of earthworms and efficient microorganisms, and observed that a rich microbial community was the most important factor in determining the survival of *E. coli*. Lower concentrations of thermotolerant coliforms were observed in the experiments with higher concentrations of EMs. However, the role of EMs in the elimination of thermotolerant coliforms depends on the maximum temperature range in the thermophilic phase (Hénault-Ethier et al., 2016). The maximum temperature range was not significant in the present study and suggests that the effect may also be related to the increased richness of the microbial community, which stimulated the development of microorganisms antagonistic to the presence of thermotolerant coliforms.

Lower concentrations of thermotolerant coliforms were also observed in the vermicomposting experiments. Therefore, this can be considered an additional effect that also influenced reduction. During the vermicomposting process, some earthworm species may ingest and kill pathogenic microorganisms such as *E. coli*, *Salmonella* spp., and total coliforms (Soobhany et al., 2017). According to these authors, vermicomposting is an efficient technique to remove pathogenic microorganisms, especially in the mesophilic phase, as *Salmonella* suppression was more efficient at 55°C than at 70°C.

Conclusion

The composting experiments using cattle and goat manure, regardless of the presence of efficient microorganisms, allowed for higher humidity and lower pH of the final compost, probably due to substrate turning.

The percentage of organic carbon and Mg was higher in the vermicomposting treatments; while the other macronutrients (P, K, Ca, and

S) were found at greater levels in the composting treatments. The presence of EMs, mainly EM4, in the composting treatments, favored increased content of most of the macronutrients in the final compost.

Micronutrients and heavy metals were observed at a higher percentage in composting treatments, regardless of the presence of EMs. On the other hand, vermicomposting was more effective in removing pathogens such as thermotolerant coliforms, mainly when associated with EM2. Composting and vermicomposting processes have been shown to allow waste to have increased value and generate quality products that can be used in agroecological production in small rural properties.

Contribution of authors:

Panisson, R.: Conceptualization, Methodology, Conducting Experiments, Data Analysis, Writing — Original Draft; Muscope, F.P.: Methodology, Conducting Experiments, Data Analysis; Muller, C.: Conceptualization, Methodology, Data Analysis, Writing — Original Draft; Writing — Review & Edition; Treichel, H.: Conceptualization, Methodology, Resources, Supervision; Korf, E.P.: Conceptualization, Resources, Data Analysis, Writing — Original Draft, Project Administration.

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Fish consumption and consumer awareness aspects of possible mycotoxin contamination in fish in Curitiba-PR, Southern Brazil

Aspectos do consumo de pescado e da conscientização de consumidores quanto à possível contaminação por micotoxinas no pescado da região de Curitiba-PR, sul do Brasil

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ABSTRACT

The global *per capita* consumption of fish reached a record of 20.5 kg in 2018, thus demonstrating the sector's importance. A potential risk to consider when consuming fish is the indirect intake of mycotoxins by humans when consuming fish from intensive fish farming fed with potentially contaminated mycotoxins. The aim of this study was to evaluate fish consumption and consumer awareness of possible mycotoxin contamination in Curitiba, Paraná, Brazil. The information was obtained through a questionnaire applied at supermarkets in 5 different city regions, obtaining 358 respondents. Descriptive analysis was performed on the data, followed by Spearman's correlation analysis between the responses. It was observed that demographic data (e.g., age, gender, and social class) significantly influenced fish consumption frequency. Thus, 64.80% of respondents preferred tilapia meat over other fish species, 89.91% of people are unaware of mycotoxins, and 93.95% of people do not know what damage mycotoxins cause in human and animal health, and 86.17% of people did not know about any disease related to fish consumption. Schooling had a significant correlation with the aforementioned issues, demonstrating that lower educational levels negatively influence the perception of illnesses caused by food. The most consumed fish is farm-raised tilapia and the consequent possibility of mycotoxin exposure. Respondents are unaware of the possible mycotoxin presence in fish and their impact on human health.

Keywords: food safety; *Nile tilapia*; *Oreochromis niloticus*; pisciculture; toxins.

RESUMO

O consumo *per capita* global de pescado atingiu seu recorde de 20,5 kg em 2018, demonstrando a importância do setor. Um potencial risco a ser considerado no consumo de pescado é a ingestão indireta de micotoxinas pelos humanos por meio do consumo de peixes provenientes de piscicultura intensiva, alimentados com ração potencialmente contaminada por micotoxinas. O objetivo foi avaliar aspectos do consumo do pescado e da conscientização dos consumidores quanto à sua possível contaminação por micotoxinas em Curitiba, Paraná, Brasil. As informações foram obtidas com um questionário aplicado em supermercados de cinco regiões distintas da cidade, obtendo um total de 358 respondentes. Realizou-se análise descritiva dos dados, seguida de análise de correlação de Spearman entre as respostas. Observou-se que dados demográficos influenciaram significativamente a frequência de consumo de pescado (ex. idade, gênero e classe social). Um total de 64,80% dos entrevistados preferiu carne de tilápia em detrimento de outras espécies de peixes, 89,91% das pessoas desconhecem o que são micotoxinas, 93,95% não sabem quais danos as micotoxinas causam à saúde humana e animal e 86,17% não conheciam nenhuma doença relacionada ao consumo de pescado. A escolaridade teve correlação significativa com as questões citadas acima, demonstrando que níveis de escolaridade menores influenciam negativamente a percepção sobre doenças transmitidas por alimentos. O pescado mais consumido é a tilápia de cultivo, indicando a possibilidade de exposição a micotoxinas. Os respondentes desconhecem a possibilidade da presença de micotoxinas em pescado e seus impactos à saúde humana.

Palavras-chave: segurança alimentar; tilápia do nilo; *Oreochromis niloticus*; piscicultura; toxinas.

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Introduction

Fishing and aquaculture are important sources of food worldwide; this importance tends to grow since the annual global per capita consumption has increased and reached a record 20.5 kg in 2018 (FAO, 2020). These activities are considered by the Food and Agriculture Organization of the United Nations (FAO) as strategic for worldwide sustainable food security because they can provide protein sources of high nutritional quality (Bombardelli et al., 2005; FAO, 2020).

A factor contributing to the growing appreciation of this type of food is the perception by consumers regarding its positive aspects: easily digestible, high protein, and low caloric value, compared with other protein foods available in the market (Gonçalves et al., 2008).

However, as in the entire food production chain, more specifically of animal origin, this growth must occur orderly and sustainably, guaranteeing quality and origin traceability. From the quality point of view, one of the aspects to be controlled is contaminants. Among them, toxins produced by fungi present relative importance since they can be found in the production and consumption cycle (Montanha et al., 2018; Pietsch, 2020).

With the increase in the global demand for fish, intensive fish farming has been gaining space concerning fishing or extractivism (FAO, 2020). This activity is crucial because it aligns with some points of the Sustainable Development Goals developed by the United Nations (ONU, 2015) including eradicating hunger, promoting quality health, sustainable production, and consumption, and conserving and sustainably using water resources, especially marine ones.

Thus, to achieve high productivity on a large scale, the use of balanced feeds is indispensable; so, like in other intensive animal production systems, animals are fed with feeds that have potentially been contaminated by mycotoxins (Atayde et al., 2014). This is demonstrated in studies that evaluated the contaminant presence in fish feed (Barbosa et al., 2013; Olorunfemi et al., 2013; Gonçalves et al., 2016; Mohamed et al., 2017), which reported individual mycotoxin concentrations ranging from 0.04 to 341.99 μg/kg, in addition to co-occurrence, that is, contamination by more than one class of mycotoxin in the same sample (Marijani et al., 2017). If mycotoxin consumption *via* feed occurs, there is a risk of compound deposition in the final product, the so-called carry-over effect (Montanha et al., 2018), potentially exposing the final consumer to these contaminants (Abd-Elghany and Sallam, 2015).

Due to this cross-contamination possibility, countries that stand out in animal production, such as Brazil, which is the world's fourth-largest producer of *Nile tilapia* (*Oreochromis niloticus*) (ABP, 2021), must implement appropriate prevention measures to minimize or trace possible contaminations in animal feed, providing more excellent food safety and quality of the final product. Therefore, this study aimed to evaluate fish consumption and consumer awareness regarding possible food contamination by mycotoxins in Curitiba, Paraná, Southern Brazil.

Materials and Methods

This study was approved by the Research Ethics Committee of the Pontifical Catholic University of Paraná (PUCPR) under the report number 2.310.264, 2nd version.

The experimental design had a cross-sectional observational character, in which a sample of consumers from supermarkets in the city of Curitiba-PR was interviewed inside these establishments. All interviewees were above 18 years old at the time of the interview. When initially approaching consumers, the informed consent form was presented for participants' knowledge, with subsequent signatures to authorize the disclosure of the study results.

The questionnaire used in this study was adapted from Gonçalves et al. (2008) and Flores et al. (2014), and its final version contained 17 multiple-choice questions addressing aspects related to educational level, farmed fish consumption, and knowledge about mycotoxins. All questionnaires were applied to customers from previously selected supermarkets in five regions (i.e., north, south, east, west, and central) of Curitiba, Paraná.

The initial selection of supermarkets was performed through an Internet search using the Google® search platform. The terms used for the search and selection were adapted from Moutinho et al. (2015): "supermarket" + "Curitiba" + "PR" + "region."

Accordingly, the search platform returned 130 results, which were listed, numbered, and separated by region, using Excel® software. Approximately 10% of the establishments in each region were randomly selected using the "random" command. Out of the total 130 markets, 12 markets were selected for this study.

The questionnaire was applied randomly to customers inside the supermarkets in different sectors, and the manager previously approved this study. Initially, the customers were questioned about their age, and only when the interviewee was above 18 years old, the rest of the questionnaire was applied.

For the data presentation, descriptive statistics were used, with absolute and relative numbers for each alternative concerning the number of interviewees or respondents to the specific questions.

Spearman's correlation test was applied to evaluate the possible correlations between the qualitative variable responses. For the correlation analysis, the software Statgraphics Centurion, version XVI for Windows®, was used. The significance level adopted was 5% ($p < 0.05$) (Petrie and Watson, 2009).

Results

Demographic data

The questionnaire was applied to 358 participants, with the following distribution among the regions of Curitiba: north ($n = 70$), east ($n = 70$), south ($n = 71$), west ($n = 72$), and central region ($n = 75$).

Of the 358 participants, 54.19% ($n = 194$) were females and 45.81% ($n = 164$) were males. The mean, followed by the standard deviation

(± SD) of age for males was 41.85 ± 16.73 years old and for females was 39.77 ± 16.22 years old. The mean weight (± SD) for males was 79.76 ± 13.71 kg and for females 68.83 ± 12.60 kg. The mean (± SD) height of the men interviewed was 1.73 ± 0.07 m and for women was 1.62 ± 0.07 m.

Education was divided into incomplete elementary school (IES), complete elementary school (CES), incomplete high school (IHS), complete high school (CHS), incomplete higher education (IHE), and complete higher education (CHE). The results obtained from the schooling of the people interviewed (n = 358) were as follows: 9.78% (n = 35) of the interviewees had IES, 12.29% (n = 44) had CES, 3.63% (n = 13) had IHS, 36.03% (n = 129) had CHS, 6.98% (n = 25) had IHE, 5.87% (n = 21) had CHE, and 25.42% (n = 91) preferred not to answer about schooling.

The social classes of the interviewees were divided into class A, B, C, D, or E, according to the 2017 definition of the Brazilian Institute of Geography and Statistics (IBGE, 2017), which characterizes class A as people who have a monthly income equal to or greater than R$ 18,740.01, class B with a monthly income between R$ 9,370.01 and R$ 18,740, class C with a monthly income ranging from R$ 3,748.01 to R$ 9,370, class D with a monthly income of R$ 1,874.01 to R$ 3,748, and class E with a monthly income equal to or less than R$ 1,874.

Respondent distribution (n = 358) within social classes was as follows: class A = 1.12% (n = 4), B = 2.79% (n = 10), C = 20.95% (n = 75), D = 23.74% (n = 85), and E = 49.16% (n = 176), and respondents who preferred not to answer accounted for 2.23% (n = 8) of the total. Table 1 presents the respondents' education and social class data.

Regarding interviewees' occupations (n = 358), 75 different professions were registered, among which the six with the highest frequency were as follows: salesperson at 11.17% (n = 40), retiree and trader at 5.87% (n = 21), student at 4.75% (n = 17), housewife and taxi driver at 3.91% (n = 14), and others at 64.53% (n = 231) of the total responses (Table 1).

There were 50 neighborhoods in Curitiba, the ones with the highest response frequency were as follows: Cidade Industrial de Curitiba at 16.48% (n = 59), Sítio Cercado at 12.01% (n = 43), Santa Felicidade at 6.98% (n = 25), Cajuru at 5.87% (n = 21), Mercês with 3.35% (n = 12), and others at 55.31% (n = 198).

Questionnaire

In general, the questions were divided into the following three sections: consumption characteristics and preferences, the criteria for choosing fish, and the level of knowledge regarding possible contaminations and diseases acquired through the consumption of farmed fish.

Fish consumption characteristics and preference

From a total of 358 respondents, 71.23% (n = 255) stated that they were responsible for the household purchases, and the remaining 28.77% (n = 103) stated that they made sporadic purchases and did not make decisions about the products to be purchased. This variable had a significant ($p < 0.05$) positive correlation with the age of the interviewee ($r = 0.3052$), generally the older people in the house are responsible for choosing and buying the products. In addition, there was a significant ($p < 0.05$) positive correlation with the female gender ($r = 0.8362$), thus demonstrating that women are the main ones in charge of purchasing decisions in supermarkets.

Regarding the type of diet, 3.07% (n = 11) of the respondents called themselves strict vegetarians, in other words, who do not eat animal protein. These respondents did not answer the questionnaire since the other questions had to do with fish consumption and purchase.

All the remaining questions were asked for the 96.93% (n = 347) of respondents who were nonvegetarians. This definition did not show any significant correlation ($p > 0.05$) with the other results obtained in the questionnaire.

The primary motivation for consuming fish was its pleasant taste since 70.03% (n = 243) of respondents answered the alternative taste as the main reason for consumption. The nutritional quality was the reason that 12.97% (n = 45) of respondents eat fish; the easy access to fish was the reason for 2.88% (n = 10) of the respondents to consume it; 2.31% (n = 8) of respondents eat to vary their menu; 0.86% (n = 3) of respondents eat because of the affordable cost of different fish species, which represents the same proportion of people who eat fish because of religion.

Still, 6.63% (n = 23) of the people answered at least two alternatives (e.g., nutritional quality and taste of the meat, or quality

Table 1 – Distribution of respondents' answers according to education, social class, and profession.

Variable	% (total n)	Variable	% (total n)	Variable	% (total n)
IES	9.78 (35)	Class A	1.12 (4)	Salesperson	11.17 (40)
CES	12.29 (44)	Class B	2.79 (10)	Retiree	5.87 (21)
IHS	3.63 (13)	Class C	20.95 (75)	Trader	5.87 (21)
CHS	36.03 (129)	Class D	23.74 (85)	Student	4.75 (17)
IHE	6.98 (25)	Class E	49.16 (176)	Housewife	3.91 (14)
CHE	5.87 (21)	PNA	2.23 (8)	Taxi driver	3.91 (14)
PNA	25.42 (91)			Others	64.53 (231)

n: number; IES: incomplete elementary school; CES: complete elementary school; IHS: incomplete high school; CHS: complete high school; IHE: incomplete higher education; CHE: complete higher education; PNA: preferred not to answer.

and accessibility). In comparison, 0.58% (n = 2) of respondents cited a combination of three factors for consuming fish (i.e., nutritional quality, accessibility, and taste of the meat). Only 2.88% (n = 10) of the respondents were unwilling or unable to answer this question. There was no significant correlation ($p > 0.05$) of fish consumption motivations with the other questions and demographic data.

With 36.61% (n = 127) of the answers, the most significant proportion of respondents reported consuming fish only once a month, while 24.50% (n = 85) of respondents eat once a week. The option "rarely or during religious celebrations" appeared in 20.17% (n = 70) of the answers; the option "two or three times a week" appeared in 11.24% (n = 39) of the cases; 2.02% (n = 7) of the respondents eat more than three times a week, and only 0.58% (n = 2) of the respondents eat every day. Also, 4.03% (n = 14) of the people indicated that they do not consume fish. The percentage of unwilling or unable to answer was 0.86% (n = 3) (Figure 1).

The frequency of consumption correlation and age of the participants was significant ($p < 0.05$) and positive ($r = 0.1291$), indicating a slight tendency that the higher the age, the higher the frequency of fish consumption.

The data collected in the sequence were related to frequency of fish purchasing for home consumption. In this regard, 36.31% (n = 126) of the participants stated that they buy it once a month, 21.90% (n = 76) do not buy it at all, 17.29% (n = 60) buy it once a week, 15.56% (n = 54) buy it rarely or just at religious celebrations, 7.78% (n = 27) buy it two to three times a week, 0.29% (n = 1) buy it more than three times a week, and no participant replied that they buy it daily. The nonrespondents or those who did not know how to answer were 0.86% (n = 3) of the total.

The frequency of fish acquisition showed a significant ($p < 0.05$) and positive correlation ($r = 0.1142$) with interviewees' place of residence. Residents from the northern and central regions of Curitiba buy fish to consume at home more often than those who live in the other regions of the city. There was a significant correlation ($p < 0.05$) between the frequency of fish purchasing and the age of the interviewee ($r = 0.1793$), showing that the older the person, the more frequently they buy fish for home consumption, which is in line with the higher frequency of fish consumption mentioned above.

Depending on where the fish is bought, the general preference was for supermarkets, with a majority of 41.79% (n = 145), followed by 31.41% (n = 109) of people who said they prefer to buy fish from fishmongers; fish markets and fish-pond purchases had the same percentage of respondents, both at 8.07% (n = 28). It is worth mentioning that 2.88% (n = 10) of the interviewees answered that they had private suppliers such as neighbors or relatives that produce or raise fish on their property, 5.19% (n = 18) of people said they did not buy fish, and 2.59% (n = 9) were the percentages of those who preferred not to answer or did not know the answer (Figure 2). This variable did not show any significant correlation ($p > 0.05$) with other variables.

Regarding the fish preparation preference, almost half of the interviewees (44.67%, n = 155) said they prefer fried fish; 19.88% (n = 169) of the interviewees prefer baked fish; 8.93% (n = 31) of the interviewees prefer battered fish; 8.65% (n = 30) of the interviewees prefer grilled, which is the same proportion of preference for raw fish (8.65%, n = 30), and those who prefer to eat fish in stew represented 8.36% (n = 29) of the respondents. Finally, only 0.86% (n = 3) of the interviewees said they did not go for the prepared way. There was no significant correlation ($p > 0.05$) between preparation, the other questions, and demographic data.

With more than half of the answers, tilapia was the fish of preference for 64.84% (n = 225) of respondents, followed by salmon for 16.14% (n = 56) of respondents, pintado for 5.76% (n = 20) of respondents, tucunaré for 5.48% (n = 19) of respondents, and finally tambaqui for 4.90% (n = 17) of respondents The remaining 2.88% (n = 10) of respondents said that they prefer other species, such as hake, sole, and mullet, but these species are not raised in captivity and were beyond the research scope. The preference of a particular fish species did not show a significant correlation ($p > 0.05$) with any other variable evaluated. Figure 3 shows the preference distribution of fish species for consumption.

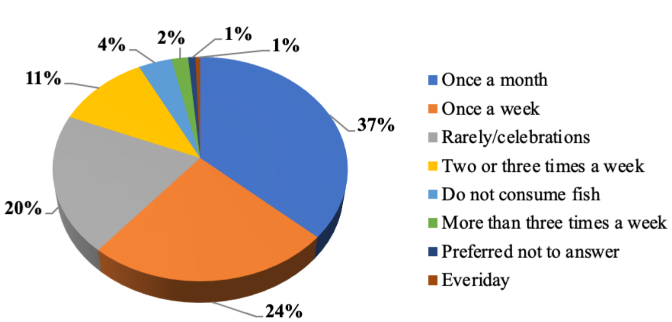

Figure 1 – Distribution of respondents' answers regarding the frequency of fish consumption.

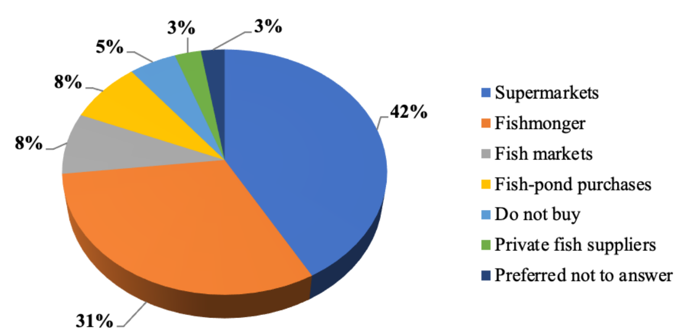

Figure 2 – Distribution of the respondents' answers regarding their preferred places to buy fish.

Criteria for choosing fish

The first item evaluated in this section was which fish species the consumer acquires at the moment of purchase; even though it is similar to the question regarding the preference for the consumption of a specific species, the consumer may decide to purchase a different species due to other factors such as price, for example.

The most frequently purchased fish was tilapia. Notably, 47.55% (n = 165) of the interviewees affirmed that it is the fish most frequently purchased; 10.09% (n = 35) of the interviewees said that they preferred to buy salmon; 3.17% (n = 11) of the interviewees preferred pintado, a proportion identical to that for tucunaré, with 3.17% (n = 11) of the answers; 2.88% (n = 10) of the interviewees preferred tambaqui; and finally, 33.14% (n = 115) preferred other species (as mentioned above) (Figure 4). The purchase preferences regarding the species were not correlated with the other variables ($p > 0.05$).

Regarding the way fish is purchased, about two-thirds of the respondents (68.88%, n = 239) stated that they prefer to buy fresh/chilled fish, 27.95% (n = 97) prefer to buy frozen fish, and 0.29% (n = 1) preferred to buy salted, canned and smoked fish. A total of 2.02% (n = 7) of the respondents stated that they do not buy fish in any form, while 0.29% (n = 1) preferred not to answer. This variable showed no significant correlation ($p > 0.05$) with the other questions and demographic data.

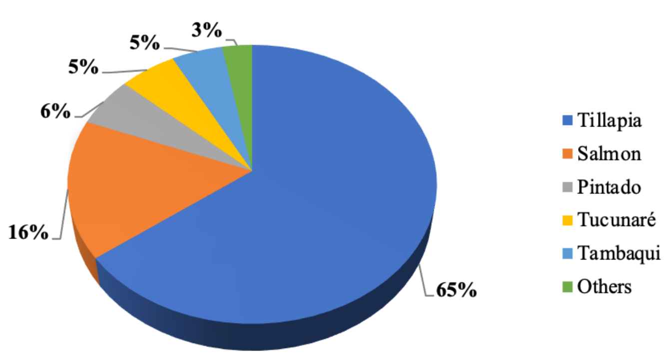

Figure 3 – Distribution of the respondents' answers regarding the preference of fish for consumption.

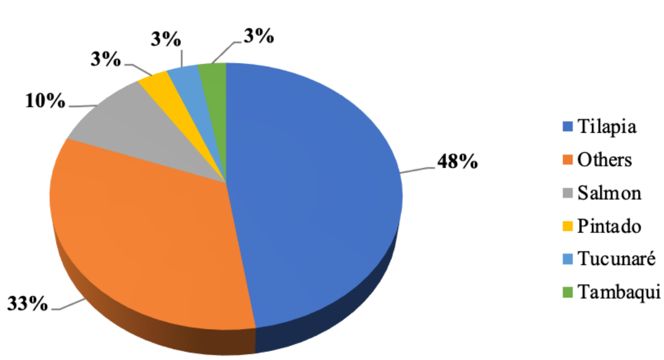

Figure 4 – Distribution of the respondents' answers regarding the acquisition of fish.

Regarding fish presentation, most of the respondents (61.67%, n = 214) stated their preference for a filet; 23.63% (n = 82) of the respondents prefer whole fish, while 9.80% (n = 34) of the respondents showed a preference for whole gutted fish, with a smaller portion of respondents (4.90%, n = 17) stating that they prefer the cut in slices. There was no significant correlation ($p > 0.05$) of presentation with the other questions and demographic data.

When asked how they evaluate the fish quality to purchase, 59.08% (n = 205) of the respondents said it is by the general appearance of the product; 19.60% (n = 68) of the respondents said it is more than one factor (i.e., by appearance and shelf life, or appearance and price, or shelf life and freshness); 12.39% (n = 43) of the respondents said it is by the expiration date on the package; 3.46% (n = 12) of the respondents answered by using factors other than the ones provided (i.e., eyes, aroma, and origin); and 1.15% (n = 4) of the respondents answered that they evaluate by shelf life. Finally, 4.32% (n = 15) of the respondents said that they do not buy fish, so they do not know how to evaluate the quality issue. There was no significant correlation ($p > 0.05$) between the other questions and the demographic data.

Regarding the perception of fish price in supermarkets, 59.94% (n = 208) of the interviewees think the price is high; 10.66% (n = 37) of the interviewees said they think it is too high; 9.22% (n = 32) of the interviewees said that the price charged by supermarkets is low; 7.20% (n = 25) of the interviewees think the price is regular; and 0.58% (n = 2) of the people interviewed think it is very cheap. In this question, 12.39% (n = 43) did not want to or did not know how to answer. There was a significant correlation ($p < 0.05$) between the perception of fish price and interviewee gender, this correlation being positive ($r = 0.1357$) with males, thus demonstrating that men, in contrast to women, tend to perceive fish price in the market as more expensive. There were no significant correlations ($p > 0.05$) between the perception of fish price and consumer education and social class/income, showing that, in general, the interviewed population considers the fish to be expensive.

Consumers' knowledge regarding possible contaminants in fish

The first question of this session was related to consumer opinion about the decrease of possible contaminants in fish after cooking; they should answer yes if they think that cooking decreases contaminant levels and no otherwise. With this, 56.77% (n = 197) of the respondents answered no that fish does not cease to present contamination risks, while 40.63% (n = 141) of the respondents answered yes that fish ceases to present contamination risks after cooking for consumption. Only 2.59% (n = 9) of the respondents did not know (Figure 5). This question also showed no significant correlation ($p > 0.05$) with the other questions and demographic data.

Regarding knowledge about possible diseases acquired by eating fish, the great majority, 86.17% (n = 299), answered that they do not know which diseases can be caught, while 12.68% (n = 44) answered that they know some diseases. Only 1.15% (n = 4) of the respondents preferred not to answer.

The knowledge of possible diseases acquired through fish consumption showed a significant ($p < 0.05$) and negative correlation ($r = -0.2039$) with the level of education of the interviewees, showing that people with lower educational levels (i.e., IES, CES, and IHS) understand this as riskless. There was also a significant correlation ($p < 0.05$) of this question with the social class of the interviewees ($r = -0.1565$), showing that people belonging to lower social classes (i.e., D and E) understand this as riskless.

The second-to-last question verifies the respondents' level of understanding of mycotoxin existence. Almost 90% of the respondents (89.91%, n = 312) did not know what mycotoxins are, while 8.93% (n = 31) said they know mycotoxins. Respondents who preferred not to answer totaled 1.15% (n = 4) (Figure 6).

There was a significant ($p < 0.05$) and negative ($r = -0.1559$) correlation between knowledge about what mycotoxins are and interviewees' educational levels, showing that people with lower educational levels tend not to know what mycotoxins are. As with the previous question, social class significantly impacts too ($p < 0.05$), with a negative correlation ($r = -0.1550$) regarding the knowledge about what mycotoxins are. In other words, individuals from lower social classes (D and E) tend not to understand what these toxins are.

The last question asked to the interviewee was about the possible toxic effects that mycotoxins can cause on humans. A total of 93.95% (n = 326) of the people said they did not know what these effects are, while only 4.90% (n = 7) of the people said they were aware of the effects caused by exposure to these toxins. Only 1.15% (n = 4) of the people preferred not to answer (Figure 7).

In this last question, there was a significant ($p < 0.05$) and negative correlation ($r = -0.1243$) with the interviewee's educational level, showing that people with lower education levels (i.e., IES, CES, and IHS) tend not to know about mycotoxins' possible deleterious effects on human health.

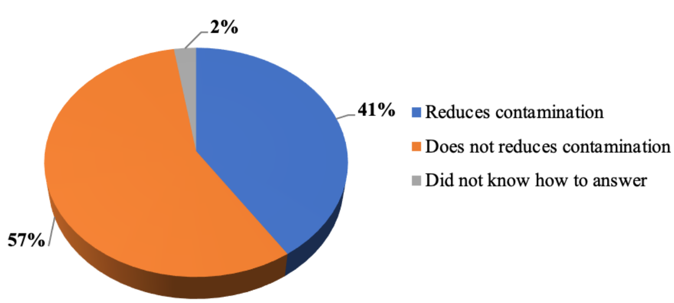

Figure 5 – Distribution of the respondents' answers regarding the perception about reducing possible contaminants by cooking the fish.

Discussion

From a consumption profile perspective, some studies have also evaluated this variable in population samples from different regions of Brazil. Maciel et al. (2013), when interviewing 1,966 people from different campuses of the University of São Paulo, reported that 27.11% of the respondents consumed fish only once a week, 25.94% from two to three times a month, 17.40% consumed it once a month, and 14.80% rarely.

Another study that characterizes fish consumption interviewed people in all Brazilian regions (Lopes et al., 2016), and the authors classified as low the average frequency of fish consumption by Brazilians, citing that 39.52% of the respondents consume from once to twice a month, while 30.65% eat at least once a week.

Both cited works differ in some point from this study regarding the frequency of fish consumption. The percentage of people who consume once a month was more than double that was found by Maciel et al. (2013), while the percentage of people who consume at least once a week was 6% points lower than that was found by Lopes et al. (2016). This shows that, in general, the characterization of fish consumption in a population tends to be complex since it involves socioeconomic factors, consumption patterns, and personal and regional preferences (Maciel et al., 2012).

The low frequency of fish consumption found in this type of work reflects the low annual per capita consumption of fish by Brazilians, which is around 9 kg/year (FAO, 2019), considered low by the FAO, which recommends at least 12 kg/person/year. The consumption of fish in Brazil is also low compared with the global average, which is 20 kg/person/year, that is, there is still room to increase the participation of fish on the Brazilian table.

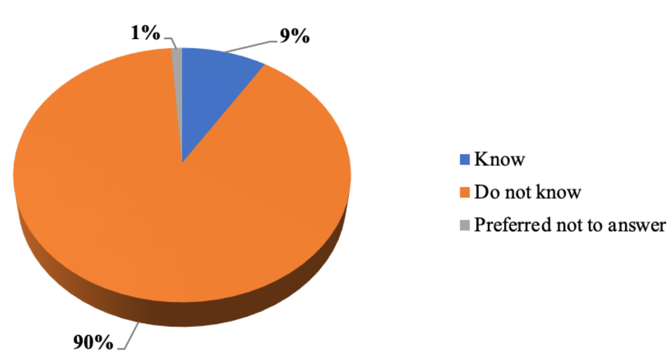

Figure 6 – Distribution of interviewees' responses concerning knowledge about mycotoxins.

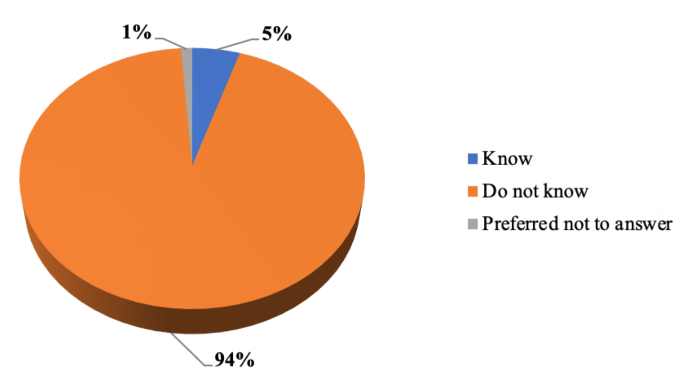

Figure 7 – Distribution of respondents' answers regarding knowledge of mycotoxins' possible deleterious effects on human health.

This low consumption seems to have a significant cultural factor in Brazilian territory since the variation among regions is significant according to the 2017 and 2018 Household Budget Survey (IBGE, 2020), which show that the per capita acquisition of fish in the Northern Region was 9.85 kg/year against 1.04 kg/year in the Southern Region. Factors such as the constant supply of fish with attractive prices, in addition to the diversity and ease of acquisition, probably influence this higher consumption in the Northern Region of Brazil (Lopes et al., 2016).

The preference for the fish species is also regionally influenced. Flores et al. (2014) conducted a preference survey in the state of Tocantins, with tambaqui being one of the most consumed species in the region. In a way, the higher tambaqui production in the Northern Region of Brazil, with 73.10% of the national total (IBGE, 2019), explains this preference, as this fish is more abundant in the producing regions. The same effect was observed in this study, since the preference was for tilapia, the most produced species in Brazil as a whole (60% of the total), with the state of Paraná as the leading producer (IBGE, 2019).

The decision to consume fish seems to be linked to the product's organoleptic characteristics, such as flavor and texture. As demonstrated by Kubitza (2002) and Silveira et al. (2012), both found the highest proportion of respondents selecting the preference for flavor as a decision for fish consumption. These data are in line with that reported in this study.

Other factors, such as protein quality, ease of digestion, and medical indication, also appear as having relative importance, but in different orders among the studies. The age of consumers seems to be involved in the decision, consumption frequency, and fish purchasing because there are reports of positive correlations between these variables (Maciel et al., 2012), probably due to the possible beneficial effects of fish meat consumption on individual health. This positive correlation between age and aspects of fish consumption and acquisition was also evidenced in this study.

In Brazil, the idea is that Brazilians do not consume fish because they are not used to it or do not have the habit due to the short supply (Pereira et al., 2003). However, the main factor cited as an impediment or disincentive to purchasing fish seems to be the price since respondents who do not consume or consume it less frequently cite this as a determining factor (Kubitza, 2002; Sonoda et al., 2012; Flores et al., 2014). Some studies cite price as an essential factor but not decisive at the time of purchase (Maciel et al., 2015), while others cite that price is irrelevant to this decision (Tavares et al., 2013).

Despite not having been directly evaluated as a possibly decisive factor in buying fish, in this study, the perception of the price charged by supermarkets was reported as being high, indicating that price can be a limiting factor for increased consumption. This perception was more significant for male consumers, a result that differs from Flores et al. (2014), who reported that women are the ones who most consider the price of fish high.

Fish filet was the most preferred by the interviewees; besides, there was a preference for purchasing these products fresh in supermarkets. Fornari et al. (2017) mentioned that the acquisition in supermarkets might be related to the concentration of food acquisition in a single place, thus avoiding trips to fairs or fishmongers. The preference for presentation in fillets is probably associated with practicality issues, for example, related to ease of preparation and the absence of thorns (Maciel et al., 2015; Lopes et al., 2016).

Gagleazzi et al. (2002) mentioned that sanitary and technological problems, in the sense of not finding fresh or good-looking products, negatively impact consumers' decision to purchase fish. Different studies corroborate the results obtained in this study regarding the evaluation of fish at the time of purchase (Silveira et al., 2012; Maciel et al., 2013, 2015); among the main attributes evaluated at the time of purchase are the odor, color, and texture, usually evaluated together; another aspect found in the literature cited, but not in this study, was the presence of the sanitary inspection seal.

From the point of view of possible contaminants and focusing mainly on mycotoxins, some studies demonstrate their presence in different fish species or cured fish. Tolosa et al. (2014; 2017) cite the presence of enniatins and beauvericins (emerging mycotoxins of the genus *Fusarium* spp.) in fresh fish from fish farms. Sun et al. (2015) found aflatoxin B_2, ochratoxin A, and zearalenone in fresh and cured fish in the Shanghai region of China. There are no evaluations of natural mycotoxin contamination in Brazil in both caught and farmed fish. The only contaminant residue evaluations are from experimental contamination.

In general, there is also a perception by consumers that the cooking process reduces the levels of chemical contaminants (Kabak, 2009; Tolosa et al., 2017). This may vary by mycotoxin type, with results showing that different heat treatment methods can reduce enniatins and beauvericins, but not more resistant mycotoxins such as aflatoxins (Tolosa et al., 2017).

Due to a bit of knowledge about mycotoxins (i.e., definitions and deleterious effects) being found in the population with up to IHS, it is possible to say that contact with fungi and mycotoxin information seems to happen only during CHS completion and later during higher education, probably because of disciplines such as biology. This, coupled with the fact that there is less information available about mycotoxin residue levels in fish and its derivatives, especially in Brazil, demonstrates the importance of greater control and investigation of this possible contamination, even if it is to demonstrate that there are no levels of these types of contaminants. Besides, it seems to disseminate information about these compounds through simple and accessible information to the less educated population because it is known that mycotoxins are present in several other types of food.

Conclusion

Tilapia is the most consumed fish by supermarket customers in Curitiba, regardless of education and social class; this preference is due to the search for practicality in acquisition and preparation, unrelated to the purchase price. In general, consumers with a lower educational level showed a lack of knowledge about what mycotoxins are, their possible deleterious effects, and the possibility of their presence in fish. This lack of knowledge and the fact that farmed fish are fed with feed that potentially carries these substances can result in a higher contamination risk to consumers through fish consumption.

Thus, it is suggested that more significant efforts should be taken to investigate and disseminate information related to this class of contaminants, providing a healthy and safe growth of this production chain.

Contribution of authors:

Anater, A.: Conceptualization, Methodology, Data acquisition, Data analysis, Writing, and Editing. Thon, B.M.: Data acquisition. Montanha, F.P.: Conceptualization, Methodology, and Data acquisition. Weber, S.H.: Methodology and Data analysis. Ribeiro, D.R.: Data analysis, Writing, and Editing. Pimpão, C.T.: Data analysis, Writing, Editing, and Supervision.

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