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Table of contents

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The Brazilian surface freshwater framework in union-dominated rivers: challenges and prospects for water quality management

O enquadramento das águas doces superficiais brasileiras em rios de domínio da união: desafios e perspectivas para a gestão da qualidade hídrica

Vagner Alexandre Aparecido de Souza[1], *Denise Gallo Pizella*[2]

ABSTRACT

The framing of surface water bodies is an instrument present in the National Water Resources Policy that aims to outline the goal of water quality to be maintained or achieved by water bodies, according to their predominant and intended uses by society. In view of the importance of the framework for water quality planning and the difficulties and possibilities for its implementation reported in the literature, this study aimed to identify them in the hydrographic basins of rivers in the Union's domain. In this sense, it was analyzed, in the most recent Plans of the nine basins with established committees, the aspects related to the framework; and, in order to diagnose the perspectives of the management bodies on the subject, electronic questionnaires were applied to the committees of the analyzed basins and to the National Water Agency. As a result, there was a lack of framing in accordance with current regulation, namely CONAMA Resolution no. 357/05, in all situations. The main problems identified for this were: lack of fluviometric data, distribution of water quality monitoring points in the basins in such a way as to make analysis difficult, diversity of legislation applicable to the framework in the States in which they are located, water pollution, and lack of articulation institutional relationship between water management bodies, States and municipalities. On the other hand, some potentialities for achieving the framework were verified, such as the implementation of the grant for the use of water resources in all situations, the existence of charges for the use of water resources in five of the nine basins in question, and a greater interaction between the water resources management bodies, States and municipalities in two of the analyzed basins.

Keywords: water management instruments; CONAMA Resolution no. 357/05; surface freshwater classification.

RESUMO

O enquadramento de corpos hídricos superficiais é um instrumento presente na Política Nacional de Recursos Hídricos que tem por objetivo delinear a meta de qualidade hídrica a ser mantida ou alcançada dos corpos hídricos, de acordo com seus usos preponderantes e pretendidos pela sociedade. Tendo em vista a importância do enquadramento para o planejamento da qualidade hídrica e as dificuldades e possibilidades para sua efetivação relatadas na literatura, este trabalho teve por objetivo identificá-las nas bacias hidrográficas dos rios de domínio da União. Nesse sentido, buscou-se analisar, nos planos mais recentes das nove bacias com Comitês instituídos, os aspectos afeitos ao enquadramento; e, no intuito de diagnosticar as perspectivas dos órgãos gestores sobre o assunto, foram aplicados questionários eletrônicos aos Comitês das bacias analisadas e à Agência Nacional de Águas. Como resultado, verificou-se a ausência de enquadramento de acordo com a normativa vigente, qual seja, a Resolução CONAMA nº 357/05, em todas as situações. Os principais problemas identificados para tanto foram: carência de dados fluviométricos, distribuição de pontos de monitoramento da qualidade hídrica nas bacias de tal forma que dificultam as análises, diversidade de legislações aplicáveis ao enquadramento nos estados em que se encontram, poluição hídrica, e falta de articulação institucional entre os órgãos de gestão hídrica, os estados e os municípios. Em contrapartida, algumas potencialidades para a consecução do enquadramento foram verificadas, como a implantação da outorga de uso dos recursos hídricos em todas as situações, a existência de cobrança pelo uso de recursos hídricos em cinco das nove bacias em questão e uma maior interação entre os órgãos gestores de recursos hídricos, estados e municípios em duas das bacias analisadas.

Palavras-chave: instrumentos de gestão hídrica; Resolução CONAMA 357/05; classificação das águas doces superficiais.

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Introduction

The water bodies framework in classes is an instrument of the National Water Resources Policy, instituted by Law no. 9,433, of January 8, 1997, which is defined as the planning of water quality to be achieved or maintained according to the predominant and intended uses by society (BRASIL, 2005).

The water bodies subject to classification are all those of fresh, brackish and saline waters, with five classes for fresh water, six for brackish and six for saline (BRASIL, 2005). Freshwater, the object of this article, is classified according to quality grades, being more demanding in the Special Class, followed by Classes 1, 2, 3 and 4, as they are, respectively, becoming less restrictive in terms of quality.

According to Diniz *et al.* (2006), the creation of the National Environmental Council (CONAMA) Resolution no. 357, of March 17, 2005, represents a major step forward to allow the progressive planning of river basins through the establishment of progressive and final goals consistent with institutional and technological performance, such as society's aspirations and availability of resources.

The framework has some methodological procedures for preparing its proposal, defined by the National Water Resources Council (CNRH) through Resolution no. 91, of November 5, 2008, which, in summary, provides stages of diagnosis, prognosis, proposals and programs for its implementation, that should include the participation of the local community, through public consultations, technical meetings, workshops, among others (BRASIL, 2008).

The framing proposal must be prepared by the Water Agencies and, in their absence, by the water resources management body, in conjunction with the environment body (ANA, 2013A), being the committee responsible for discussing, analyzing and forwarding the proposal to the respective Council (State or National), according to the water body domain, which should analyzed it, under possible adjustments and approved it in the form of Resolution (ANA, 2009).

It should be noted that water management occurs within the Union or the States scope, which, according to the Federal Constitution of 1988, have the domain of the waters, in line with the scope defined in articles 20 and 26. In 1997, with the institution of the National Water Policy Resources and creation of the National Water Resources Management System, an institutional arrangement was formed that foresees the users and civil society participation in all federation instances (Union, States and municipalities), which Porto and Porto (2008) stand as a way of giving legitimacy to decisions and also being more efficient to guarantee the implementation of the decisions taken.

According to Brasil (2008), two aspects must be considered in the proposed framework, namely: surface and groundwater associated analysis and broad participation by the hydrographic basin community, through public consultations, technical statistics, workshops, among others. Once this process is completed, whose discussion takes place in the Hydrographic Basin Committee, the proposal must be submitted to the State Water Resources Councils (CERHs) or to the CNRH, depending of the water course domain, for appreciation, approval and deliberation (ANA, 2007).

It is important to highlight, in this context, the relationship between the instrument "framing of water bodies" and the Water Resources Plans, as they are, in their essence, planning instruments. Thus, it is necessary for these to be synergistic, since they are benchmarks for granting and charging for the use of water (ANA, 2013A).

Porto and Porto (2008) observed both in the framework of water resources and the Water Resource Plans a possibility of planning, embodied in participatory processes that involve both civil society and economic agents with individuals (public and private) interests.

The framework, according to Yassuda (1993), demands institutional mechanisms capable of respecting the political, social, economic and environmental consequences for local users and for the population affected by it. In this context, the author warns that it is difficult to reach a balanced decision in the absence of a reliable information system, and, therefore, it is assumed that the development of this instrument in river basins is essential both for the realization of the framework and for monitoring over the horizon of the idealized planning.

According to Diniz *et al.* (2006), Brandão *et al.* (2006), ANA (2007), Pizella and Souza (2007), Porto and Porto (2008), Braga *et al.* (2008), Corrêa *et al.* (2013), Silva (2017) and Foleto (2018), some of the obstacles to make the framework effective are: absence of Basin Plans and Plans without consolidation, which do not perform actions that corroborate for the framework to be achieved; deficiencies in social participation and methods used; difficulties in the institutional articulation between the Basin Committees and the municipalities; lack of a comprehensive water monitoring and inspection system, which makes it impossible to assess whether the framework is being effective; inexistence of charges for the use of water resources in several basins, making it difficult to allocate budgets to management and grant systems that disregard the reality of water quality.

In this sense, researches are needed that addresses the problems related to the implementation of this fundamental instrument for the progressive improvement of water quality in a country, in order to consider the main existing technical, budgetary and institutional limitations and ways of overcoming them. Therefore, this work aims to identify difficulties and potentialities related to the framing of river basins in the Union domain, pointed to Basin Plans, pointed out in the Basin Plans, documents that guide the instrument under study, and in the perspectives of water resources managers, who are aware of the management challenges in the basins, in order to point out improvements for their effectiveness.

Metodology

The Research had a qualitative and quantitative approach as to its nature, explanatory, in terms of its objectives and survey, as to its procedures, according to Gil (2002). It was carried out as follows.

First, an analysis was made of the most recent Basin Plans for rivers in the Union domain with Hydrographic Basin Committees in operation, namely: Piracicaba River, Capivari River and Jundiaí River; Paranapanema River; São Francisco River; Paranaíba River; Paraíba do Sul River; Grande River; Piancó-Piranhas-Açu River; Verde Grande River and Doce River, which their Basins are represented in Figure 1.

In each Hydrographic Basin Plan, the following aspects were identified:

- Committee creation data;
- General characteristics of the basin: drainage area, total population and number of municipalities;
- Quality of surface freshwater, in terms of the main factors that affect it;
- Whether or not there is a classification of surface freshwater and the main problems identified for achieving it.

Also, in order to identify the main problems and potentialities for the instrument from the point of view of the water resources management bodies (Committees and the National Water Agency), semi-structured electronic questionnaires were developed, on a digital platform, with multiple choice questions. In the presentation of the study, the participants only answer questions if they agree with the Informed Consent Term (ICF), for ethical reasons in the research.

The questionnaires were sent to the nine Interstate River Basin Committees in the country, which questions are found in Appendix 1 of the article. For each committee, a representative of a Technical Chamber qualified with the study and implementation of any of the instruments of the National Water Resources Policy was selected to answer the questions, that is, to the granting, planning, charging or framework sector of the water resources. All the committees answered the questionnaire, with the exception of the Piancó-Piranhas-Açu River, Verde Grande River and Doce River committees.

In view of the knowledge about the situation of rivers in the Union's domain by the National Water Agency, questionnaires related to each of the nine hydrographic basins under analysis were sent to this body. The respondent was a specialist who works in the area of the water resources framing, with whom the researchers had a previous contact, in order to verify its knowledge about the Water Resources Plans under analysis and the framework instrument.

The questions addressed to the managers dealt with the factors that affect the water quality in the Basins under study; the presence or not of framing of surface freshwaters and the factors that hinder or enhance the implementation of the instrument, such as the existing State legislation and its current status with CONAMA Resolution no. 357/05; the existence or not of charging and granting for the use of water resources; monitoring of water quality and fluviometric quantity and its proper spatialization, in addition to the institutional difficulties and potential of articulation between the proposals of the committees and the land use policies of the municipalities. For all questions, that was of multiple choice, it was left an opportunity for respondents to external their views on the subject addressed.

The analysis consisted of identifying the aspects related to the framework instrument present in the Basin Plans, including the questionnaires responded to the managers, making comparisons between the two contents.

Results

Hydrographic Basins of the Piracicaba, Capivari and Jundiaí Rivers

The Committee of the Hydrographic Basins of the Piracicaba, Capivari and Jundiaí Rivers (Federal PCJ) was established by the Presidential Decree of May 20, 2002. These basins have a drainage area of 15,303 km^2, distributed between the States of São Paulo (92.45%) and Minas Gerais (7.55%), covering the total and/or partially of 76 municipalities (5 from Minas Gerais and 71 from São Paulo), with 5.8 million inhabitants (PROFILL; RHAMA, 2018a).

The water quality monitoring network of the PCJ Basins comprises nine stations of the Minas Gerais Institute of Water Management (IGAM) and 94 stations of the Companhia Ambiental Paulista (CETESB), with a density of 6.70 points/1,000 km^2 (PROFILL; RHAMA, 2018b), higher than the target established by the National Water Quality Monitoring Network, whose minimum predicted is 1 point/1,000 km^2 (ANA, 2012).

In this way, this aspect does not give a weakness to the framework, since the existing stations subsidize the framework and are guiding its review. For ANA, in the response to the questionnaire, the quantity, as well as the distribution of quality monitoring points in the basins, is satisfactory. On the other hand, the perception of the PCJ Committees indicate that the frequency of surface water quality testing practiced by CETESB and IGAM are critical factors for the classification, as it would be desirable to be closer to the flow rate monitoring network.

Regarding fluviometric monitoring, the PCJ Committee considered its spatialization inadequate, which makes hydrological studies difficult, mainly for the Capivari and Jundiaí Rivers.

As for water quality, both the Committee and the PCJ addressed that its commitment is related to the uses of water for the dilution of sanitary sewage (*in natura* and treated), the receipt of rainwater in the urban environment and the release of industrial effluents.

The granting records in rivers of federal dominance correspond to 23 surface abstractions and 42 for the discharge of effluents and application in soil (PROFILL; RHAMA, 2018b). According to ANA, in the granting process, one of the analysis criteria is the quality of the water course, whose parameters are only BOD 5,20 and total phosphorus. The charge for the use of water resources was also implemented in the PCJ Basins. However, ANA is unaware if the financial resources are adequate to monitor and update the framework, while the PCJ committee reports that they are that are not enough for this purpose.

Regarding the normative and legal aspects related to the water classification in the PCJ basins, it was observed in consultation with ANA,

Figure 1 – Study area: Interstates Basins with Basin Committees installed.

through the questionnaire, that the classification is formalized only by State Decree in São Paulo. However, it is in discussion and review within the PCJ committee.

Regarding the institutional articulation for the elaboration and implementation of the framework between ANA, the Basin Committees, the States and the municipalities, ANA considered its existence in an initial phase. On the other hand, the committee assessed there is an obvious limitation in this regard, with no aligning goals between the Municipal Basic Sanitation Plans and the Basin Plans, as an example.

Hydrographic Basin of the Paranapanema River

The Paranapanema River Basin Committee was established through CNRH Resolution no. 120, of December 16, 2010. The basin has an area of 106,500 km^2, distributed between the States of São Paulo (48.60%) and Paraná (51.40%), draining water from 247 municipalities (115 from São Paulo and 132 from Paraná), with a population of 4,680,725 inhabitants (ANA, 2016B).

In relation to the fluviometric network, according to the consultation with the Basin Committee, a distribution of the fluviometric monitoring points is unsatisfactory, requiring an expansion.

Regarding water quality monitoring, there are 40 stations, 17 belonging to CETESB, in the São Paulo portion and 23 in the Paraná portion (Águas Paraná), as well as 37 stations of the Duke Energy monitoring system (used for self-monitoring of concessionaires that operate reservoirs of hydroelectric plants located on the Paranapanema River) (ANA, 2016B).

Concerning the density of monitoring points of 1 point /1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), it can be note that the density in the basin is lower than recommended.

The main aspects highlighted both in the Basin Plan and in the consultation with the Committee, which compromise the quality of surface water, refer to the uses for dilution of sanitary sewage and urban areas. However, ANA (2016B) highlights that the agricultural sector can be a relevant source of nutrient input to water courses, as it is widely observed within the limits of the basin.

As for the normative and legal aspects involved in the framing of water courses, ANA, in the answer to the questionnaire, mentioned that its formalization took place from meetings of the CEEIPEMA (Executive Committee for Integrated Studies of the Paranapanema River Basin) of 1980. In the stretches of the São Paulo side, it was used the State Decree (SP) no. 10.755/1977, and in the Paraná's stretches, the SUREHMA/PR no. 6/1991. The Resolution CERH/PR no. 100/2016 framed the surface water bodies of the Tibagi River. In this sense, the methodology adopted for the framing of water bodies was predominantly used in Ordinances and Resolutions prior to CONAMA Resolution no. 357/2005.

The granting of rights to use water resources in rivers belonging to the Union is implemented in the Basin, with the quality of the water course used for analysis, specifically to the parameters BOD5,20 and total phosphorus, according to ANA reports. Charging for the use of water resources has not been implemented in the basin. In this sense, the Basin Committee relate that the implementation of charging for the use of water resources would be a factor that would corroborate for the elaboration of studies for the framing of superficial water courses in the Basin.

Concerning the articulation between the institutions involved in water management, both ANA and the committee considered that it is necessary, but incipient.

Hydrographic Basin of the São Francisco River

The São Francisco River Basin Committee (CBHSF) was established by the Presidential Decree of June 5, 2001. The basin has an area of 639,219 km^2, covering 505 municipalities in six States of the Federation, namely: Minas Gerais, Goiás, Bahia, Pernambuco, Alagoas and Sergipe, in addition to the Federal District (CBHSF, 2016).

According to consultation with the committee, a number of points for fluviometric monitoring is considered unsatisfactory, what makes it difficult to classify water courses.

The water quality monitoring network encompasses 362 stations, including a monitoring network of ANA and the States of Minas Gerais and Bahia. Regarding the density of monitoring points of 1 point/1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), the basin density is of 0.56, lower than recommended.

The main aspects highlighted in the Basin Plan that compromise the quality of surface water in the basin refer to the uses of dilution of sanitary sewage, urbanization processes, the inadequate disposal of waste, mining and agricultural activities (CBHSF, 2016). These aspects are evidenced by both ANA and the committee, being the first highlight the lack of sanitation in the basin.

In consultation with ANA, the framework for water courses was formalized through various regulations, such as: IBAMA Ordinance no. 715/1989 for rivers belonging to the Union; CRH/DF Resolution no. 02/2014 for rivers in DF domains; COPAM Normative Resolution no. 14/1995 for stretches of affluent basins on the Paraopeba rivers; COPAM Normative Resolution no. 28/1998 and Normative Resolution COPAM no. 20/1997 in Pará, in addition to CONERH/BA Resolution no. 112/2018 for the bodies of water in the Salitre River Basin, in Bahia. In addition, CBHSF (2016) mentions the framing of the Piauí River (Alagoas) by Decree no. 3,766/1978.

In the Water Resources Plan for the horizon from 2004 to 2013, a proposal was made to reframe the water bodies. In summary, this proposal follows the CONAMA Resolution no. 357/05, except in the Middle São Francisco, where the proposal is more demanding than the provisions of this Resolution. The committee commented that such a proposal does not reflect the reality of the preferred uses in the Basin, requiring the updating of the framework and an effective Plan that affects the better management of surface.

In the São Francisco River basin, it can be seen that the grant of the rights to use water resources have been implemented and the water quality is one of the requirements for its concession, the quality parameters being only BOD 5,20 and total phosphorus, according to ANA's report. Charging for the use of water resources was also implemented in the Basin. ANA judged that the financial resources from charging are accessible for the preparation of the proposed framework and its monitoring.

Regarding the institutional articulation between ANA, the committee, the States and the municipalities on the discussion of the framework, ANA explains that it finds in the initial phase. On the other hand, the perception of the Basin Committee was diverse, indicating its inexistence and that the strengthening of this depends on actions by the Public Power.

Hydrographic Basin of the Paranaíba River

The Paranaíba River Basin Committee was established by the Presidential Decree of July 16, 2002, being installed only on July 10, 2018. The basin has an area of 222,600 km^2, covering 197 municipalities, in three States: Goiás, Mato Grosso do Sul and Minas Gerais, in addition to the Federal District.

According to the committee, the number of points for fluviometric monitoring is unsatisfactory, what brings the difficulty of the water courses frameworking.

Regarding the characterization of the surface water quality monitoring network, the Basin Plan highlights that sampling points from the hydroelectric sector, public supply concessionaires and State management agencies were used. However, the quantification of the existing network has not been presented. One of the proposals of the Basin Plan aims to expand the surface water quality monitoring network, noting that the existing network is insufficient for the dimensions of the basin, which requires standardization of the analyzed parameters and the sampling frequency (ANA, 2013b).

The main aspects highlighted in the Basin Plan that compromise the quality of surface water refer to uses for agriculture, the urban areas and dilution of domestic and industrial effluents (ANA, 2013b). These aspects were also highlighted by ANA and the committee, in the questionnaires. However, ANA has little information on interference from diffuse polluting sources, such as livestock and agriculture.

In consultation with ANA, it was observed that the framework of water courses was approved by the committee according to the current rule, requiring approval by the CNRH, whose adjustment requests will be made from 2019.

In this basin, it was observed that the grant to the rights to use water resources has been implemented and that one of the analysis criteria is water quality, whose patterns used are only DBO5,20 and total phosphorus. The charge for the use of water resources was also implemented in the basin, from the approval of Resolution CNRH no. 185/2016 (ANA, 2013b).

Concerning the institutional articulation between the water resources management bodies, States and municipalities, ANA considers that there is on an initial phase a different perspective from the committee, which points to its inexistence.

Hydrographic Basin of the Paraíba do Sul River

The Paraíba do Sul River Basin Integration Committee (CEIVAP) was established by Federal Decree no. 1,842, of March 22, 1996. The hydrographic basin has an area of 56,584 km^2, distributed between the States of São Paulo (22.73%), Rio de Janeiro (43.51%) and Minas Gerais (33.76%), comprising 184 municipalities, 39 from São Paulo, 59 from Rio de Janeiro and 88 from Minas Gerais (COHIDRO, 2014).

The number of fluviometric monitoring points are considered satisfactory, according to the Basin Committee.

The network for monitoring water quality encompasses a total of 115 stations. Regarding the density of monitoring points of 1 point/1,000 km^2 recommended by ANA (2012), the basin presents 1.87 points/1,000 km^2 (PROFILL, 2018), being considered satisfactory. On the other hand, the committee's perception indicates that the surface water quality monitoring network and the distribution of its points are unsatisfactory.

The main aspects highlighted both in the Basin Plan, as well as in consultation with the committee and ANA, that compromise the quality of surface water, refer to the uses for dilution of sanitary sewage, industry, agriculture, livestock and urban areas. However, ANA reports the weights for each of these agents should be the object of study in the review/adequacy of the framework.

Regarding the normative and legal aspects related to the framing of water courses, ANA shows that, in rivers belonging to the Union, the currently framework was defined by Ordinance Minter no. 86 of 1981; in the State of São Paulo, by State Decree no. 10.755 of 1977; and in the State of Minas Gerais, on the Paraibuna River and its tributary, by the COPAM Resolution no. 16 of 1996, all of which need to be reframed according to the current rule.

Still, ANA includes that the committee is preparing a review of the Water Resources Plan and has been discussing the possibility of preparing in sequence the complementary studies for review/adjustment of the framework.

The granting of rights to use water resources was carried out, and the committee points out that this instrument needs improvement, in order to standardize its criteria considering the natural area instead of the administrative area. The water quality parameters considered are BOD 5,20 and total phosphorus. There is the charge for the use of water resources and the committee pointed out that the resources are sufficient for monitoring the framework, but not for its implementation.

Concerning the institutional articulation between ANA, the committee, the States and the municipalities in the discussion of the framework, ANA explains that it exists in part, but without mentioning how it is being carried out. The committee already lists its presence, highlighting that the framework is a joint construction and that there must be an agreement on the quality standards adopted as a goal and the ways to achieve it.

Hydrographic Basin of the Grande River

The Grande River Basin Committee was established through Resolution CNRH no. 11, of April 13, 2010. The basin has 143,255 km^2 and its waters are distributed between the States of São Paulo (40%) and Minas Gerais (60%), with Grande River being the main water course, with an extension of 1,286 km, which drains water from 393 municipalities, 214 from Minas Gerais and 179 from São Paulo (ANA; CBH GRANDE, 2017).

The water quality monitoring network comprises 148 stations. In relation to the density of monitoring points of 1 point/1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), the density in basin is 1.03 point/1,000 km^2 (ANA; CBH GRANDE, 2017), what can be considered adequate. However, ANA considers the surface water quality monitoring network and the distribution of sampling points unsatisfactory, especially in Minas Gerais portion of the basin.

The main causes pointed out in the Basin Plan for the depreciation of water quality in the Class 4 stretches refer to the discharge of urban domestic sewage and some stretches associated with the discharge of industrial effluents (ANA; CBH GRANDE, 2017). The main aspects highlighted in the consultation with ANA that compromise the quality of surface water refer to the uses for dilution of sewage, industry, agriculture, livestock and urban areas.

ANA pointed out that there was no formalization of the water courses framework, considering the stretches of the Union domain, but in the stretches located in the State of São Paulo, which follow State Decree (SP) no. 10.755, of 1977. In compliance with the Plan, it was noted that there are only guidelines for the implementation of the reframing, mainly regarding the carrying out of complementary studies to comply with Resolution CNRH no. 91/2008, included in the Implementation Program for the Framework/Reframing of the Basin Water Bodies Program, with investment goals between 2018 and 2030 (ANA; CBH GRANDE, 2017).

The granting of rights to use water resources was instituted in the basin, and the water quality values considered were BOD5,20 and total phosphorus. According to information available in the Basin Plan, there is no charge for the use of water resources in rivers belonging to the Union. On the State level, São Paulo has the charge in place (ANA; CBH GRANDE, 2017).

Concerning the institutional articulation between ANA, CBH GRANDE, the States and municipalities in discussion of the framework, ANA lists its presence in an initial phase. The Basin Committee did not respond to the questionnaire.

Hydrographic Basin of the Piancó-Piranhas-Açu River

The Piancó-Piranhas-Açu River Basin Committee was established through the Presidential Decree of November 29, 2006 (CBH DO RIO PIANCÓ-PIRANHAS-AÇU, 2019). The basin has an area of 43,683 km^2, distributed between the States of Paraíba (60%) and Rio Grande do Norte (40%), with the Piancó River (rising until its confluence with the Piranhas River) and the Piranhas River (from confluence with the Piancó River to the Armando Ribeiro Gonçalves reservoir), the main water courses, which drain water from 147 municipalities, 100 belonging to the State of Paraíba and 47 to Rio Grande do Norte (ANA, 2018).

According to ANA, the distribution of the fluviometric monitoring points is considered unsatisfactory in the basin.

The water quality monitoring network of the Piancó-Piranhas-Açu River Basin comprises 91 stations, 69 located in dams and 22 in rivers in the basin (ANA, 2018).

In relation to the density of monitoring points of 1 point/1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), the density of the basin is 2.08 points/1,000 km^2 (ANA, 2018). However, the Basin Plan shows a lack of representativeness of the series of quality data, providing for an operation of an additional 59 monitoring points (ANA, 2018). In this sense, with a view to monitoring water quality as a limitation for the formalization of the framework, this aspect gives the instrument a weakness. ANA's perception of monitoring the quality of surface water in the basin, as well as the distribution of its points, is considered unsatisfactory.

The main aspects evidenced both in the Basin Plan, as well as in the consultation with ANA, that compromise the quality of surface water, refer to the uses for dilution of sanitary sewage, agriculture and livestock. However, ANA points out that, as monitoring is deficient, it is very difficult to accurately establish the share of pollutant contributions from each sector.

Also, through consultation with ANA, it is possible to observe that there is no framework of rivers belonging to the Union domain in the basin, with their water courses automatically included in Class 2, according to Brazil (2005).

The water use rights grant was instituted and considers as water quality parameters only DBO5,20 and total phosphorus. The charge has not been implemented.

Regarding the institutional articulation between ANA, CBH GRANDE, the States and municipalities in discussion of the framework, ANA lists its presence in an initial phase. The Basin Committee did not respond to the questionnaire.

Hydrographic Basin of the Verde Grande River

The Verde Grande River Basin Committee was established by the Presidential Decree of December 3, 2003. The basin has an area of 31,410 km^2, distributed between the States of Bahia (13%) and

Minas Gerais (87%), being Verde Grande River the main water course, which has waters from 35 municipalities, 8 belonging to the State of Bahia and 27 to Minas Gerais (ANA, 2016a).

The water quality monitoring network comprises 16 stations. In relation to the density of monitoring points of 1 point/1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), the basin has a density of 0.60 point/1,000 km^2 (ANA, 2016a), insufficient, therefore. The Basin Plan considers the need for expansion and better distribution of these points, in agreement with ANA.

The main aspects highlighted in the Basin Plan, as well as in ANA, which compromise the quality of surface water, refer to the uses for diluting sanitary sewage, agriculture and livestock.

According to ANA, the framework for water courses in the Union domain was formalized based on the MINTER/IBAMA Ordinance no. 715, of September 20, 1989. In the Basin Plan, it was observed that the framework was included only in the Investment Programs, in view of the existing surface water quality problems and because the current framework is based on instruments prior to Brazil (2005).

A water use rights grant was instituted and considers as water quality parameters only DBO5,20 and total phosphorus. The charge has not been implemented.

Regarding the institutional articulation between ANA, CBH GRANDE, the States and municipalities in discussion of the framework, ANA lists its presence in an initial phase. The Basin Committee did not respond to the questionnaire.

Hydrographic Basin of the Doce River

The Doce River Basin Committee was established by the Presidential Decree of January 25, 2002. The basin has an area of 86,715 km^2, distributed between the States of Minas Gerais (86%) and Espírito Santo (14%), being Doce River its main water course, covering 850 km from its source in the Mantiqueira and Espinhaço Mountains (Minas Gerais) to the Atlantic Ocean and draining waters from 229 municipalities, 203 of which belong to Minas Gerais and 26 to Espírito Santo (ANA, 2013c).

In relation to the quantity of fluviometric monitoring points in the Doce River Basin in its sufficiency or not for the framing of surface water bodies, ANA has shown to be unaware of the matter.

The water quality monitoring network of the Doce River Hydrographic Basin comprises 41 stations from the Minas Gerais Water Management Institute (IGAM) and the State Institute of Environment and Water Resources (IEMA) (ECOPLAN, 2010). Regarding the density of monitoring points of 1 point/1,000 km^2 recommended as a goal by the National Water Quality Monitoring Network (ANA, 2012), the density in the Basin is 0.47 point/1000 km^2 (ECOPLAN, 2010), which can be considered insufficient. For ANA, the quantity, as well as the distribution of quality monitoring points in the basins, are considered satisfactory. However, it points out that there may be some monitoring deficiencies in Doce River basins affluents.

The main aspects highlighted in the Basin Plan, as well as in ANA, which compromise the quality of surface water in basin, refer to industrial uses, dilution of sanitary sewage, agriculture, livestock, urban areas and mining activity.

Concerning the normative and legal aspects involved on the theme of framing water courses in the domain of the Union, ANA pointed to its inexistence, and its waters are considered automatically in Class 2, as recommended by Brazil (2005).

In the Basin Plan, the framing of surface waters was considered only in the Basin Management Guidelines, from the outline of desirable quality goals for the water bodies considered, once the examination of most of the data and the necessary information was insufficient to prepare a proposal for a framework compatible with the relevant environmental standards (ECOPLAN, 2010).

In this way, the Plan defines an arrangement of guidelines for the development of this instrument, considering, in addition to legal, technical and operational aspects, the local specificities of the Basin (ECOPLAN, 2010).

The granting of rights to use water resources in rivers in the domain of the Union is present and considers as water quality parameters only DBO 5,20 and total phosphorus.

The charging for the use of water resources was implemented, with sufficient raising of financial resources for the application of the water courses adjustment proposal and/or monitoring in the cases of rivers in which they have already been implemented, once it is foreseen the beginning of the application of the proposal above in early 2019, together with the revision of the Basin Plan, according to ANA reports.

According to ANA, there is a beginning of institutional articulation between the committee, States and municipalities in the basin, with no explanation of its structure. The Basin Committee did not respond to the questionnaire.

Discussion

In the responses to the questionnaires, ANA assessed the quality of surface water in the analyzed basins as regular, in general, except in the Piancó-Piranhas-Açu Rivers basin, where poor quality predominates. The committees of the hydrographic basins of the Paranapanema and São Francisco rivers presented more optimistic points of view in relation to that evidenced in their Basin Plans and by ANA, characterizing the quality of the surface waters in their basins as adequate to the quality standards of the current classes of water resources. It is important to highlight that there is better detail regarding the water quality present in the Basin Plans than in the narratives presented by ANA and committees.

In general, quality problems are related to sources of pollution, such as sewage, occasional industrial launches and diffuse loads of agricultural activities and urban drainage.

According to Diniz *et al.* (2006) and Brandão *et al.* (2006), the lack of supervision of these economic activities is a factor that leads water bodies already classified to remain in disagreement with a designated quality class, making it difficult for basin managers to propose a reframing of surface water bodies.

In the Basin Plans analyzed, 55% have a surface water quality monitoring network density of less than 1 point/1,000 km^2, as recommended by ANA (2012). ANA reported that only the surface water quality monitoring network in the PCJ Basins is satisfactory, with the others being regular, with the exception of the Grande, Piancó-Piranhas-Açu and Verde Grande rivers, which are considered unsatisfactory.

On the other hand, according to the Basin Committee that participated in the research, there is a need to expand the monitoring network and/or even improve the distribution of existing points. However, according with the Paranaíba River Basin Committee, it is necessary to improve the understanding of the committees with this respect, such as the model of bulletins generated by the management agencies.

According to Cunha *et al.* (2013), problems related to monitoring water quality make it difficult to verify compliance with the quality standards assigned to water courses. This factor is corroborated by Foleto (2018), Diniz *et al.* (2006) and Brandão *et al.* (2006), which relate the difficulties of water resource management with the deficiency of water quality monitoring, being that the points must be expanded, best distributed in space and the measurements standardized in terms of the quality parameters used.

In the Basin Plans and in the answers to the questionnaires, it was found that, in general, the quantity and distribution of fluviometric stations in the basins are in deficit, with the need to expand historical series to improve hydrological analysis. In addition, there was a need for such points to be closer to those for monitoring water quality, in order to improve the understanding of water courses and, therefore, the reframing proposal.

Regarding to the framework of watercourses, in most basins, there are federal normative prior to the PNRH, as well as different State norms prevail, without uniform rules in the same hydrographic basin.

With these factors in perspective, the Basin Committees considered that the most water courses in the Union domain are not framed, being its waters automatically in class 2, independently of the classes that are in force in the States. In fact, in spite of the Basin Plans present guidelines for the revision of the framework, until its proposal is made in accordance with the current rules, the water courses under analysis are non-compliant.

In all cases studied, therefore, it is necessary the review of the framework, so that water courses are classified based on current rules, in terms of requirements for defining water quality standards and their processing in the appropriate institutional instances, as recommended by CNRH Resolution no. 91/2008. In this way, it is important to highlight that the basins of the PCJ and Paraíba do Sul rivers are in the process of updating the framing of superficial water bodies in the molds that determine the legal provisions currently in force.

As for the strengths for a reframing proposal, it was noted in the Basin Plans of the PCJ and Paraíba do Sul, a factor that may have acted as a facilitating agent, that is, the presence of a Delegation Basin Agencies, which ones, even if they have not elaborated the Plans and the framing proposals, has a specialized technical staff that may have helped the environmental consultancy.

A necessary factor for the creation and strengthening of Basin Agencies refers to the implementation of charging for the use of water resources, an aspect evidenced by the PCJ, Paraíba do Sul and Paranaiba committees, which considers the resources from charging in their areas of coverage sufficient to enable the elaboration of framework studies.

In this sense, stands out that the Paranapanema River Committee considers that charging, not yet instituted in the basin, is a factor that corroborates the preparation of the water framework studies. In fact, charging for the use of water resources makes it possible to collect financial resources that can be used to improve knowledge of the characteristics of hydrographic basins and in clean-up programs that help with waters framework, according to Brites (2010).

An important aspect of the framework is its relationship with the instrument granted for the rights to use water resources, especially for effluent releases for dilution in water courses, because, when considered in the mass balance for verification in the mixing zone, it will provide the regulator agent the knowledge of the absorption capacity without violating the limits of the current framework.

In this theme, the Basin Plans analyzed do not provide information about the synergy between charging, granting and water framework instruments, essential to combine water quality and quantity, considering the intended uses.

However, through the questionnaire submitted to ANA and the basin committees, it was possible to identify that granting, instituted in all the Basins analyzed, consider as a criterion for its concession the maintenance of the water body class, specifically for DBO5,20 and total phosphorus. Nevertheless, it should be noted that only two water quality parameters are an inadequate quantity to determine the quality of a water course, mainly in view of the water classification system in CONAMA Resolution no. 357/05, which quality standards refer to a set of more complex physical, chemical and biological parameters.

The agents interviewed identified a deficiency in institutional articulation between the environmental and water resources management bodies, as well as the vertical articulation between municipalities, States and the Union. According to ANA, an arrangement in an initial stage of development occurs in the Paraíba do Rio Sul and Doce basins, without, however, presented the adopted format.

In fact, according to Pizella (2015) and Oliveira-Andreoli *et al.* (2019), the municipalities are responsible for ordering of land uses, delimiting the areas of urban expansion and the establishment of different types of human activities in urban and rural areas, with their functions and limits, given by social, economic and environmental issues. The municipal policies generated, therefore, positive and negative socioenvironmental impacts with different magnitudes on water resources, in terms of their quality and quantity. However, the administrative limits of the municipalities do not coincide with the drainage area of water courses present in the hydrographic basins, whose planning takes place on a regional basis, through the Hydrographic Basin Plans, under the responsibility of the Basin Committees. In order to reduce the negative effects on water resources and the Basin Plans achieve its improvement goals on them, the authors propose that both the committees and the municipalities promote dialogue mechanisms and participation in both the public politics, that is, in plans related to land use, such as Environmental Zoning and Municipal Master Plans and Water Resources, represented by Basin Plans.

At this moment, the water resource managers responding to the questionnaires indicated that the Municipal Basic Sanitation Plans, executed by the municipalities, can align their sewage collection and treatment goals with the Basin Plans, as an example. To this end, the committees can create communication strategies and convincing the municipalities to enhance its presence in the plenary discussions of these entities. In addition, the greater involvement of diverse social actors, such as users and social groups of society present in the basins, is considered essential for the objectives outlined in the plans related to water resources are transparent, known, jointly elaborated with the residing population in the basins and, as a consequence, effective, according to Rodorff *et al.* (2015), consolidating the principle of participatory management present in the National Water Resources Policy.

Conclusion

This article identified the challenges to the framing of surface freshwaters in the hydrographic basins of the Union domain with constituted Basin Committees, in order to present the main conditions that affect the implementation/monitoring of this instrument, based on the analysis of the Basin Plans and interviews with Hydrographic Basin Committees, as well as with ANA. Thus, the main problems observed were:

- deficiencies in the inspection of polluting sources in all the analyzed basins, evidenced by the worse quality of the water courses due to occasional releases of sanitary sewage and of diffuse loads from agricultural activities and urban areas;
- problems related to water quality monitoring points, with the need to increase stations, application of criteria for their spatialization and association with fluviometric stations, and, based on a greater assessment of water quality and quantity factors, support the framework proposals;
- difficulties in fluviometric stations in terms of scope, distribution and representativeness, which make it difficult to use adequate quantitative data;
- the presence of norms used for the framework that precedes the definitions of Brasil (2005) and Brasil (2008), with the need to reframe the water courses in the analyzed basins;
- the inexistence of charges for the use of water resources in the Paranapanema, Grande, Piancó-Piranhas-Açu and Verde Grande basins, making it difficult, due to lack of financial resources, to propose and maintain the framework for water courses;
- the lack of institutional coordination between water resource management bodies, Agency, States and municipalities, hindering the synergy between water management and land uses.
- In addition to the difficulties mentioned above, it was possible to identify some opportunities in proposing and implementing the framework, which can be summarized as:
- presence of the granting for the use of water resources in all the basins analyzed, which make use of the type of water body classified for the concession of punctual releases, in order to verify its capacity for necessary uses. However, while dealing with a strong point of the framework, it can impair its effectiveness, when considering only two quality parameters to assess the situation of the water course. It is necessary that other biological, physical and chemical elements, among those present in CONAMA Resolution no. 357/05, are also employed;
- the availability of charging for the use of water resources in the PCJ, São Francisco, Paraná, Paraíba do Sul and Doce basins, which is subsidizing the hiring of consultants to update basin plans and of reframing studies;
- presence of Delegation Basin Agencies in the basins of the PCJ and Paraíba do Sul rivers, which can act with a greater focus on the needs of the committees in relation to ANA, the Basin Agency of nine committees that have personalized characteristics and is responsible for water management of a large territorial areas of the country;
- the development of mechanisms for dialogue between the various institutions responsible directly and indirectly for the management of water quality, as listed by ANA in the Paraíba do Sul and Doce River basins. In this sense, it is necessary detailed analysis in respect of the methodologies used in these basins, in order to verify their effectiveness and applicability in other territories.

The problems presented do not have a simple solution and is expected that their identification and analysis being specific research objects in order to find the best strategies for better them. In addition, it was observed the need for a reflection on how the bodies responsible for water management share with other planning instances at different basin scales, such as municipalities and States, in order to promote the framework of water courses and, therefore, a progressive improvement in water quality. Participatory methodologies involving the government, users of water resources and members of civil society are essential to guarantee the agreed quality goals.

Contribution of authors:

Souza, V.A.A.: Data curation, Formal analysis, Obtaining funding, Investigation, Project administration, Validation, Writing — original draft, Writing — review & editing. Pizella, D.G.: Conceptualization, Methodology, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing.

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APPENDIX 1 – Model of the questionnaires sent to Interstate's Basin Committees and the National Water Agency.

1. Select your role in the National Water Resources Management System (SINGREH):
   - Member of BC Piracicaba, Capivari and Jundiaí
   - Member of BC Paraíba do Sul
   - Member of BC Paranaíba
   - Member of BC Paranapanema
   - Member of BC Piancó-Piranhas-Açu
   - Member of BC Rio Grande
   - Member of BC São Francisco
   - Member of BC Verde Grande

2. Are you part of a Technical Chamber or Technical Group for framing matters?
   - Yes
   - No

   Which one?

3. What is the quality of surface freshwater in the hydrographic basin?
   - Great
   - Good
   - Regular
   - Bad
   - Unsatisfactory
   - Very unsatisfactory
   - I have no knowledge

4. What is your opinion on the availability of surface freshwaters in the hydrographic basin?
   - Great
   - Good
   - Regular
   - Bad
   - Unsatisfactory
   - Very unsatisfactory
   - I have no knowledge

5. Does the hydrographic basin have a Water Resources Plan?
   - Yes
   - No

6. How is the framework addressed in the Water Resources Plan?
   - It is not considered
   - There is a framework proposal
   - There are only guidelines to elaborate the framework (standards, priority areas, among others)

   Considerations:

7. What is the current status of the framework in the basin?
   - Nonexistent. Water curses automatically in Class 2
   - Pending in the committee
   - Approved by the committee
   - Submitted to the National Water Resources Council for deliberation
   - In the process of adjustments requested by the National Water Resources Council
   - Approved by the National Water Council

   Considerations:

8. What items are considered in the framework proposal below? (Check all that apply)
   - Preponderant uses
   - Uses intended by society
   - Social participation (local community)

9. What parameters were considered for the framing of water bodies in the watershed? (Check all that apply)
   - $DBO_{5,20}$
   - Dissolved oxygen
   - Total phosphorus
   - Nitrate
   - Nitrite
   - Total ammoniacal nitrogen
   - I have no knowledge

   If there are others, quote:

10. Was the instrument granting for the use of water resources implemented in the hydrographic basin?
    - Yes
    - No
    - I have no knowledge

    Considerations:

11. Is the water resource class considered in the grant criteria?
    - Yes
    - No
    - I have no knowledge

    Considerations:

12. What are the water standards criteria considered for granting?
    - $DBO_{5,20}$
    - Dissolved oxygen
    - Total phosphorus
    - Nitrate
    - Nitrite

- Total ammoniacal nitrogen
- I have no knowledge

If there are others, quote:

13. Has the instrument charging for the use of water resources been implemented in the hydrographic basin?
    - Yes
    - No
    - I have no knowledge

    Considerations:

14. Judge the following statement: The financial resources arising from the charging in the hydrographic basin are adequate for the elaboration of the proposed framework for water courses or for their monitoring, if already implemented.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

15. Judge the following statement: The revision of the charge for the use of water resources would be a factor that would corroborate for the realization of the framework according to Resolution CNRH no. 91/2008 or its follow-up, if already implemented.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

16. Judge the following statement: The implementation of charging for the use of water resources would be a factor that would corroborate for the elaboration of studies on the framing of superficial water courses or their monitoring, if already implemented.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

17. Judge the following statement: The quantity and distribution of surface water quality monitoring points in the watershed are satisfactory.

- I agree
- I strongly agree
- I disagree
- I strongly disagree
- I have no knowledge

Considerations:

18. In case of disagreement in the previous question, is an unsatisfactory quantity and the distribution of monitoring points a factor that makes it difficult to framework these water courses?
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

19. What are the main polluting sources of surface freshwater present in the watershed?
    - Industries
    - Sanitary sewage
    - Agriculture
    - Livestok
    - Urban areas

    Anothers:

20. Judge the following statement: The quantity and distribution of fluviometric monitoring points for surface waters in the watershed are satisfactory.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

21. What would be the appropriate amount of water and fluviometric quality monitoring points in the hydrographic basin (following on the proposal and implementation of the framework)?.

22. Judge the following statement: ANA's technical staff is sufficient and able to prepare the proposed framework (or follow-up, if already implemented) for water courses in accordance with the precepts of Resolution CNRH no. 91/2008.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

23. Judge the following statement: The wide extension (area) of the hydrographic basin is a factor that makes it difficult to execute the framework or its monitoring, considering the specificities of each water course in terms of its intended uses, predominant uses and participation of society, as advocated by CNRH Resolution no. 91/2008.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

24. Judge the following statement: There is institutional articulation between the Basin Committee and the States, as well as the municipalities that act in ordering land use in their jurisdictions, in the discussion about the framework.
    - I agree
    - I strongly agree
    - I disagree
    - I strongly disagree
    - I have no knowledge

    Considerations:

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The dynamics of knowledge about stemflow: a systematic review

A dinâmica do conhecimento sobre o escoamento pelo tronco: uma revisão sistemática

Kelly Cristina Tonello[1], Alexandra Guidelli Rosa[2], José Augusto Salim[3], Carina Julia Pensa Correa [4], Marcelle Teodoro Lima[4]

ABSTRACT

The importance of stemflow to hydrology and biogeochemistry in forest ecosystems is highlighted by the growing interest of the scientific community since the 1970s. This paper summarizes the main contributions of stemflow (SF) studies from recent years through a systematic review of the literature, including 375 scientific articles published between 2006 and 2019. Shrub SF has shown superior efficiency (11.1%) compared to tree species (3.6%). Branches, bark texture and composition, branch and leaf saturation capacity, and wind intensity were identified as factors that significantly influence SF. However, despite the increasing number of publications on the subject, most of them focus on semi-arid regions of Asia, particularly of China, and temperate regions. Thus, there is still a lack of knowledge about the role of the different species in the biogeochemical cycle concerning the SF in tropical and semi-equatorial regions.

Keywords: forest hydrology; forest restoration; rainfall repartitioning; throughfall; biogeochemical cycle.

RESUMO

A importância do escoamento pelo tronco para a hidrologia e biogeoquímica dos ecossistemas florestais é destacada pelo crescente interesse da comunidade científica desde os anos 1970. Para resumir as principais contribuições dos estudos de escoamento pelo tronco (Sf) dos últimos anos, este trabalho apresenta uma revisão sistemática da literatura, incluindo 375 publicações científicas de 2006 e 2019. O Sf em arbustos demonstrou uma eficiência superior (11,1%) ao escoamento pelo tronco em espécies arbóreas (3,6%). Galhos, textura e composição das cascas, capacidade de saturação das folhas e intensidade dos ventos foram identificados como os fatores que mais influenciam o Sf. No entanto, apesar do crescente número de publicações sobre o tema, a maioria concentra-se em regiões semiáridas da Ásia, principalmente na China e em regiões temperadas. Assim, para as regiões tropical e semiequatorial, ainda há um desconhecimento sobre o papel das diferentes espécies no ciclo biogeoquímico em relação ao Sf.

Palavras-chave: hidrologia florestal; restauração florestal; reparticionamento de chuvas; precipitação interna; ciclo biogeoquímico.

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Introduction

Research related to forest restoration stimulates reforestation involving predominantly exotic tree species, plantings with a high diversity of regional native forests (GALETTI *et al.*, 2018), and other ways of catalyzing the regeneration potential of the area to be restored. This knowledge is increasing due to the demand for the environmental regularization of productive activities and the mitigation of several environmental impacts (RODRIGUES; BRANCALION; ISERNHAGEN, 2009).

Ecological restoration is defined as the science, practice, and art of assisting and managing the restoration of the ecological integrity of ecosystems. This process includes a minimum level of biodiversity and variability in the structure and functioning of ecological processes, considering their ecological, social, economic, and environmental values (SOCIETY FOR ECOLOGICAL RESTORATION INTERNATIONAL, 2004). According to Rodrigues, Brancalion and Isernhagen (2009), this definition brings an ecosystem perspective of the ecological restoration process. However, a practical approach is still a huge challenge due to the high complexity of biological interactions between species and the relationships of species with abiotic factors in the environment. This fact highlights the lack of knowledge about the complex interactions that regulate the functioning of these ecosystems. Another major challenge is choosing between the different assessments and monitoring models required for the same type of ecosystem (BRANCALION *et al.*, 2012).

Some initiatives seek to establish standardized parameters and models for monitoring biodiversity and ecosystems, allowing comparisons between studies and simplifying the decision-making process regarding environmental conservation, preservation, and recovery. Brancalion *et al.* (2012) point out that the universe of indicators

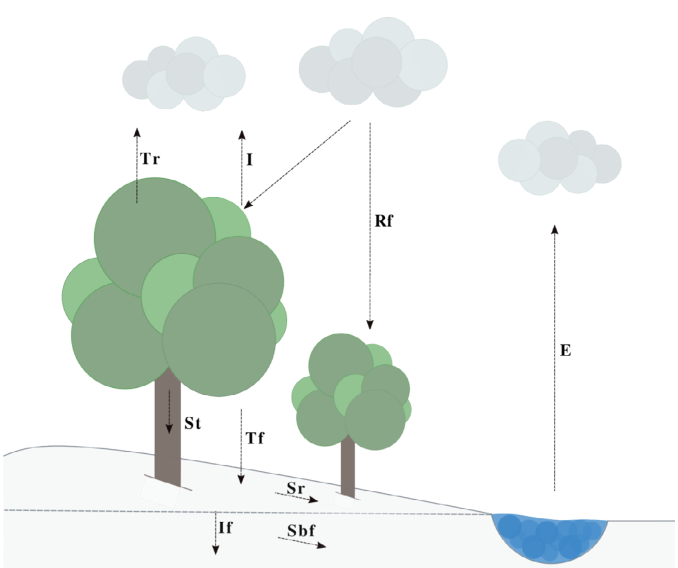

Figure 1 – Schematic representation of the hydrological cycle.
Rf: rainfall; Tf: throughfall; I: interception; Tr: transpiration; E: evaporation; Sf: stemflow; If: infiltration; Sr: surface runoff; Sbf: subsurface flow.

that can be evaluated is excessively extensive, such as the richness, diversity, and density of native species, biological invasion, rainfall, seed bank, phenology of plant species, genetic diversity of seedlings used, ecosystem services, gene flow, plant-animal interaction, and many other possibilities.

Understanding the role of forests in the hydrological cycle is fundamental to forest management practices related to hydrological and watershed conservation. Figure 1 presents the schematic representation of the hydrological cycle in the natural environment. Forest cover is one of the main responsible for the variation of the hydrological cycle in the different regions of the world. It interferes with water dynamics at various stages of the system, including transfers to the atmosphere and rivers. Some authors even report the importance of humidity and precipitation for the occurrence of certain forest and epiphytic species in riparian forests (ROCHA-URIARTT *et al.*, 2015). Others underline the necessity of analyzing precipitating weather systems, as well as the seasonal rainfall variation and its influence on the variability of litterfall production in the mangrove forest, for example (SOUZA *et al.*, 2019).

One of the main forest influences is the damping, direction, and retention of rainwater by the tree canopy, a process called interception. This retained water becomes available for evaporation. The remainder reaches the ground as throughfall and stemflow. Consequently, the water table supply is favored, and the flow variation throughout the year decreases, besides delaying the flood peaks (OLIVEIRA JÚNIOR; DIAS, 2005).

Stemflow can be defined as the intercepted rainwater collected by the stem that passively descends to the roots through gravity (BIDDICK; HUTTON; BURNS, 2018; BESSI *et al.*, 2018a; BESSI *et al.*, 2018b) and has been recognized as an essential process of water supply to spatially located areas of forest soil (TANAKA *et al.*, 2017). According to Levia and Germer (2015), many researchers recognize stemflow as an important phenomenon that can have considerable effects on ecosystem hydrology, biogeochemistry, and ecology. Throughfall and stemflow are processes responsible for precipitation and solute transfer from a vegetative canopy to the soil (LEVIA *et al.*, 2013).

However, despite representing a small proportion of gross rainfall, stemflow is an essential and poorly studied water flow in forested areas (CAYUELA *et al.*, 2018). Recent studies have highlighted its complexity and relative importance in understanding soil and groundwater recharge (SPENCER; VAN MEERVELD, 2016; MCKEE; CARLYLE-MOSES, 2017; MICHALZIK *et al.*, 2016).

Thus, this paper aims to summarize the main contributions of stemflow studies through a systematic review of the last 15 years, including country distribution, vegetation type, stemflow efficiency, research importance, and perspectives.

Materials and Methods

significant advances have been made in several related areas, such as ground-flow interactions, the effects of lichens and other epiphytes, and a deeper understanding of the influence of climate on stemflow (LE-

VIA; GERMER, 2015). Notably, the increase in the breadth and diversity of stemflow publications and the confirmation of its importance to the hydrology and biogeochemistry of wooded ecosystems is perceived by the growing interest of the scientific community since the 1970s. This assumption could be verified by the frequency of the term "stemflow" in scientific works indexed by the Scopus portal (ELSEVIER BV, 2019) (Figure 2).

However, the full understanding of the importance and influence of stemflow for plant species, soil dynamics, and the biogeochemical cycle still requires many further studies. We performed this systematic literature review to outline the area and identify general patterns and knowledge gaps in the role of stemflow. To that end, we used the databases of scientific publications Scopus and SciELO (SCIELO, 2019).

Both bases were searched for scientific articles with the terms "stemflow" and "throughfall" in the keyword field. The search was limited to return only documents in English, Portuguese, and Spanish. Also, results were restricted to works published after 2006. The SciELO database search was also limited to only scientific articles from Brazilian collections (Table 1). A total of 375 papers were retrieved — 357 from Scopus and 18 from SciELO.

The recovered works were screened considering the following criteria: studies that investigated stemflow in agricultural plants (*e.g.*, sugar cane, coffee, soybean, corn) are excluded; works that directly measured stemflow using a flow pickup ring (*e.g.*, works that used the soil moisture near the trunk for indirect flow measurement) are excluded; works limited to the study of flow and concentration of pollutants, pesticides, and other anthropogenic aerosols are excluded; mathematical modeling works and stemflow simulations are excluded; only works that could be fully retrieved are included.

This first selection of articles resulted in a total of 124 papers, and studies that investigated the concentration of radioactive isotopes in forest areas near Fukushima after the nuclear disaster and works related to the concentration of pollutants (*e.g.*, metals) and pesticides were excluded. The selected articles were thoroughly analyzed, and the extracted data are available online (GUIDELLI, 2019). We carried out the subsequent analyses with the aid of the R statistical software (R CORE TEAM, 2018), as well as the elaboration of the graphs. Geospatial analysis and graphing were performed using the R: *rgeos* (BIVAND; RUNDEL, 2018) and raster (HIJMANS, 2018) packages.

Results and Discussion

The analysis of the selected studies reveals that the proportion of stemflow concerning the total precipitation averages 4.7%. However, the variance of these data is high (35.6), indicating that several factors are acting together to determine runoff (*e.g.*, rainfall intensity and

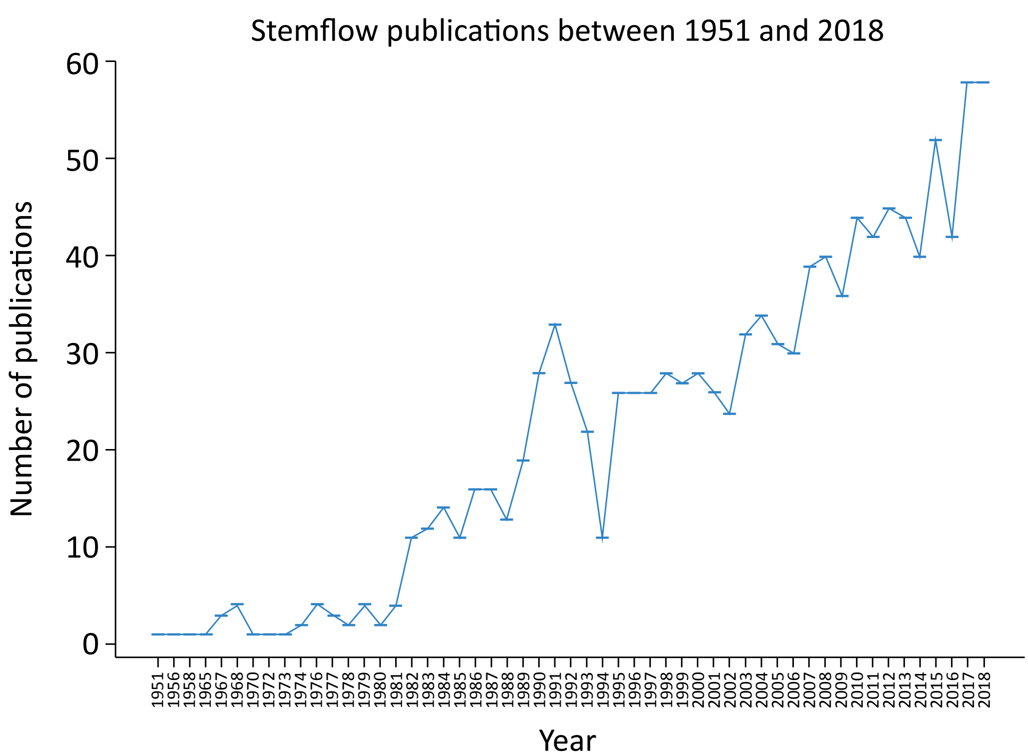

Figure 2 – Frequency of occurrence of the term "stemflow" in scientific publications between 1951 and 2018, according to Scopus (1,146 documents).
Source: Elsevier BV (2019).

amount, species morphological characteristics, wind direction, climate factors, biotic interactions). A survey of 124 studies reveals that, in approximately 70% of the observations, stemflow in different regions of the planet represents less than 5% of total precipitation (Figure 3).

Although stemflow represents a small portion of the total precipitation, runoff plays a more significant role in the water flow from the canopy to the roots than in tree habitats (Figure 4). In shrubs, approximately 70% of the observations indicate stemflow superior to 5%, with an average of 11.1% (± 9.2%). The opposite is true for trees, as approximately 80% of the data present values below 5%, with an average of 3.6% (± 3.7%). Thus, stemflow plays different roles for shrubs and trees. Although many works report morphological characteristics that could support these differences, very little has been presented to place this difference in an ecological context, even evidencing the importance of particular species for the growth in tree soil dynamics and nutrient cycling.

Some studies have proposed that precipitation intensity, number of branches (BARBIER; BALANDIER; GOSSELIN, 2009; CARLYLE-MOSES; SCHOOLING, 2015), bark texture and composition (CATINON *et al*., 2012; VAN STAN *et al*., 2016), branch and leaf saturation capacity (BARBIER; BALANDIER; GOSSELIN, 2009), and wind direction and intensity (ANDRÉ; JONARD; PONETTE, 2008) significantly influence stemflow and, consequently, the biogeochemical cycle and the ecosystems as a whole. However, few studies focus on the medium- and long-term effects of stemflow on soil dynamics and the biogeochemical cycle (LI *et al*., 2009; PICHLER *et al*., 2009).

Based on the geographical coordinates of the places where the studies were performed, it was possible to map the climatic zones according to the Köppen classification (KOPPEN, 1900). Even though microclimatic and meteorological variations may affect local precipitation, temperature processes (ABREU; TONELLO, 2015; 2017; ASSIS; SOUZA; SOBRAL, 2015; BORK *et al*., 2017; FERNANDES; VALVERDE, 2017; SILVA; VALVERDE, 2017), and, consequently, stemflow, this climatic distribution allows a larger scale view of the observations (Figure 5).

The data show a large variation in stemflow values between climatic zones and within the same climatic zone. Climate group B (dry) has the highest mean stemflow (9.3%). Climate groups A (tropical), C (temperate), D (continental and subarctic), and E (polar and alpine) present lower averages, 3.1, 2.7, 2.1, and 3.3%, respectively. Higher runoff values may be related to climate group B due to its drier nature and lower rainfall indices compared to the other groups. Thus, the various plant species might have adapted to allow higher runoff generation.

When limited only to tree species, climate group B still has the highest average runoff, but with a slightly lower value (6.0%), while the other groups show small changes in the mean (A = 4.0%, C = 2.8%, D = 2.4%, and E = 3.3%). We used the Tukey test to determine whether the differences found between the mean stemflow of the climate groups are significantly different, with 95% confidence. According to the test result considering both shrub and tree habits, the mean runoff in climate group B is significantly different from groups A ($p < 0.00001$), C ($p < 0.00001$), and D ($p < 0.04$), but not from group E. Analyzing only tree habits, the test did not find significant differences between groups.

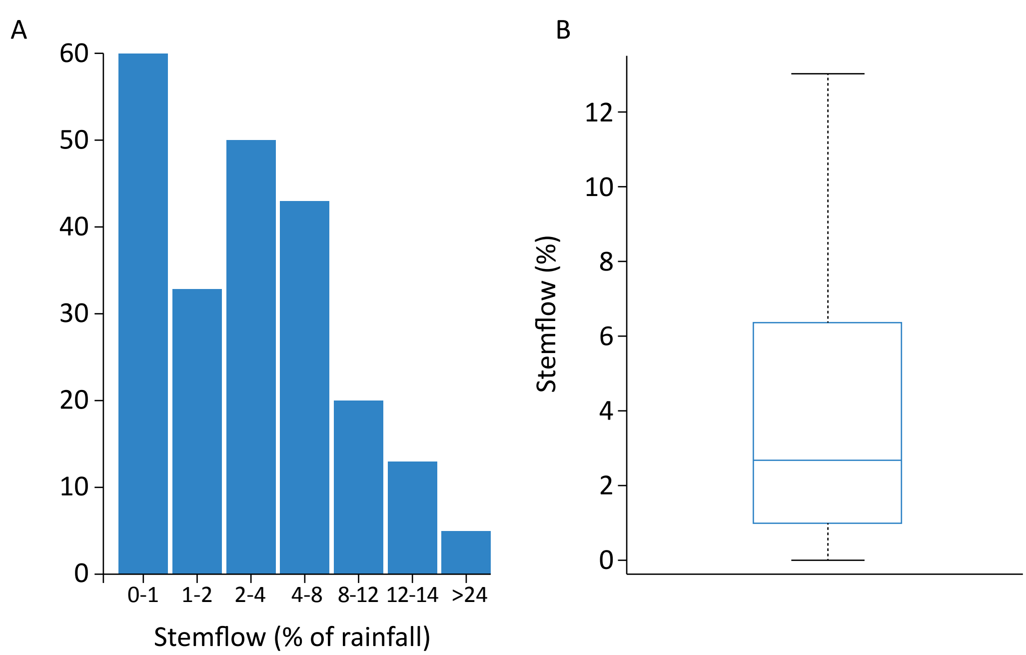

Figure 3 – (A) Number of works by stemflow class (percentage of total precipitation). (B) Distribution of stemflow values of all selected works.

This assessment could not be performed by comparing only shrub habits since, except for group B, all groups presented insufficient data for shrubs (A and C had only one study including shrubs each, while the other groups had no studies with shrubs), at least in the data collected from the 124 survey works.

As climate group B has the most significant number of shrub runoff studies (77%), the differences found indicate that the shrub habit is more efficient in the runoff generation, mainly due to morphological and ecological characteristics distinct from trees. However, the confirmation of this hypothesis needs to be tested with a more significant amount of data involving studies that encompass different climatic zones. At the same time, some studies point out that plants in dry environments might have adapted to channel water and nutrients in response to more severe rainfall pressures and developed mutualistic interactions, such as ecological facilitation or probiosis (FLORES; JURADO, 2003; SCHWINNING; SALA, 2004; NEWMAN *et al.*, 2006).

In the case of groups A and C, where rainfall regimes are more intense, especially in tropical regions, the abundance of rainfall water may not have been a determining factor for the adaptation of water uptake by stemflow. As a result, these regions present lower averages. Nevertheless, fewer studies have been conducted in climatic zones D and E, and the data available may be far from representing all variations in plant species strategies. Determining these general patterns requires further investigation and studies related to the adaptations of different plant species to environmental conditions and stemflow.

Studies on the mountainous green forest and tropical forest with a high density of ectomycorrhizal trees showed that only 2% of the rain that hits the forest floor originates from stemflow, but their contribution to nutrient replacement is important (CHUYONG; NEWBERY; SONGWE, 2004; LIU; FOX; XU, 2003). Santos Terra *et al.* (2018) identified spatial randomness of the amount of water in the soil between different stemflow classes in an Atlantic Forest area. In other words, they report that these events are independently and evenly distributed and, therefore, likely to occur anywhere and have no interaction with each other. The authors further noted that stemflow impacted soil water content in surface layers and indicated that complex interactions between rain and forest characteristics could affect local hydrology and need to be explicitly considered in reforestation projects. Stemflow acts as an entry point since its correlations suggest the potential of using stemflow to frame soil moisture patterns and induce vertical flows as well as groundwater recharge.

The fact that soil infiltration rates decrease with increasing distance between trees should not be overlooked; thus, water is absorbed in locations closest to the tree trunk, at least in arid areas (PRESSLAND, 1976). Therefore, stemflow of a particular species and rainfall events should be considered the result of a complex set of interactions between species, plant sizes, and weather conditions, suggesting that temporal variation in forest water flow may play a significant role in subsurface drainage during rain events (LEVIA; GERMER, 2015).

In addition to abiotic factors, there is also variation in water flow according to plant species, mean stemflow measured, precipitation and

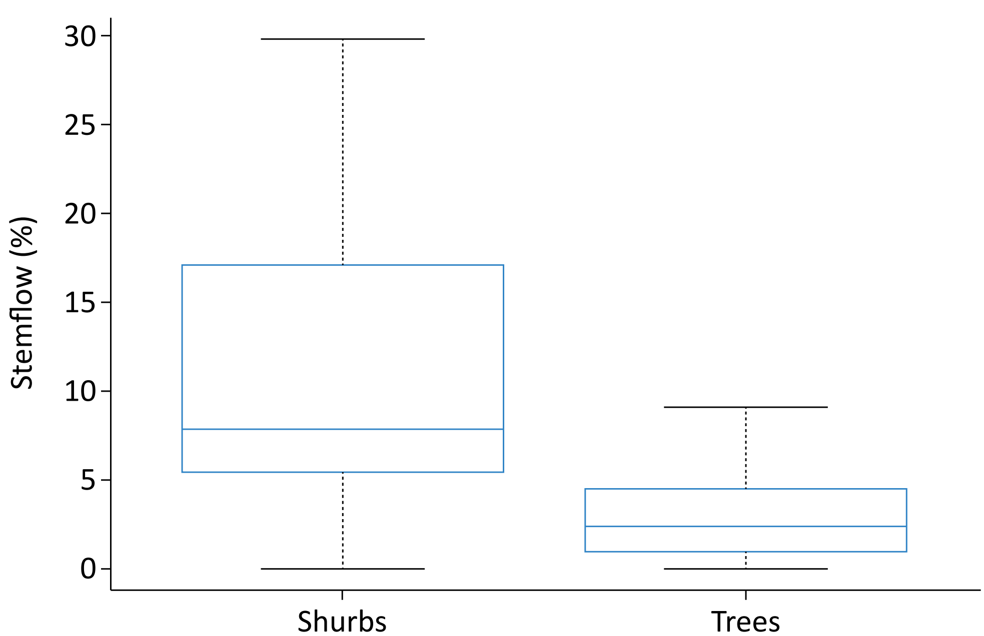

Figure 4 – Stemflow distribution values for shrub and tree habits.

interception of two species (*Grewia optiva* and *Morus alba*), and the different contributions of each species (2.5, 86.7, and 10.8% for *G. optiva* and 8.6, 76.4, and 14.7% for *M. alba*). The authors also reported that the nature of the tree canopy in *M. alba* resulted in a unique flow yield over *G. optiva*. *M. alba* channeled almost 3.5 times more flow than *G. optiva*, and the proportion of rain partitioning components differed for both trees due to their distinct morphological characteristics.

Recently, canopy area (or canopy volume/basal area), stem area index, and stem diameter have been identified as the most influential factors for the amount of stemflow in the *Caragana korshinskii* (family: Fabaceae) species (ZHANG *et al*., 2017). Nonetheless, it is not safe to say that the same is true for other species in the family, and few of these parameters can be adopted as part of the general stemflow pattern, although other studies have found similar results with other species (BARBIER; BALANDIER; GOSSELIN, 2009; CARLYLE-MOSES; SCHOOLING, 2015). A general pattern needs to be elaborated; however, it would require the construction of a database that includes stemflow data from different species and regions of the planet. At present, the contributions and data produced, with rare exceptions (SCHMID *et al*., 2011; TU *et al*., 2013; ZOU *et al*., 2015), are not readily available, so review work is a vital instrument, as it summarizes the results obtained in the area (VAN STAN; GORDON, 2018).

The funneling ratio (FR) is a characteristic that also influences stemflow. Introduced by Herwitz (1986), it quantifies the contribution of peripheral portions of a tree canopy to rain interception and stemflow generation. While stemflow represents the total flow to the ground, FR expresses the efficiency of individual trees in capturing rainwater and generating runoff. For small trees, although the volume is minimal, FR values are typically greater than those of higher trees, evidencing a competitive advantage (SIEGERT; LEVIA, 2014). A study by Raich (1983) in a mature rainforest in Costa Rica attributed high stemflow to total rainfall (9%) to the abundance of palm trees in the area, as they are efficient at tapering stemflow (92% of total flow).

In another study, Zimmermann *et al.* (2015) reported that palm trees had little influence on total stemflow, but emphasized that a closer look revealed that all monitored palm trees were relatively small, and therefore contributed only slightly higher volumes than other trees. Due to the abundance of palm trees, not only in mature open tropical forests but also in pastures and succession forests, their effects on water and nutrient cycling deserve further research (GERMER; WERTHER; ELSENBEER, 2010), as they may work as "gutters" in the interception and runoff of rainwater. Besides, some studies have shown that tree size affects the stemflow bottleneck in tropical (GERMER; WERTHER; ELSENBEER, 2010) and temperate (LEVIA *et al*., 2010; SIEGERT; LEVIA, 2014) forests.

Nonetheless, FR alone is not enough to explain the differences observed in water flows through the stem. For example, in the study by Yuan, Gao and Fu (2017), the percentage of total stemflow for the *Caragana korshinskii* species averaged 8%, while its FR was 173.3. The

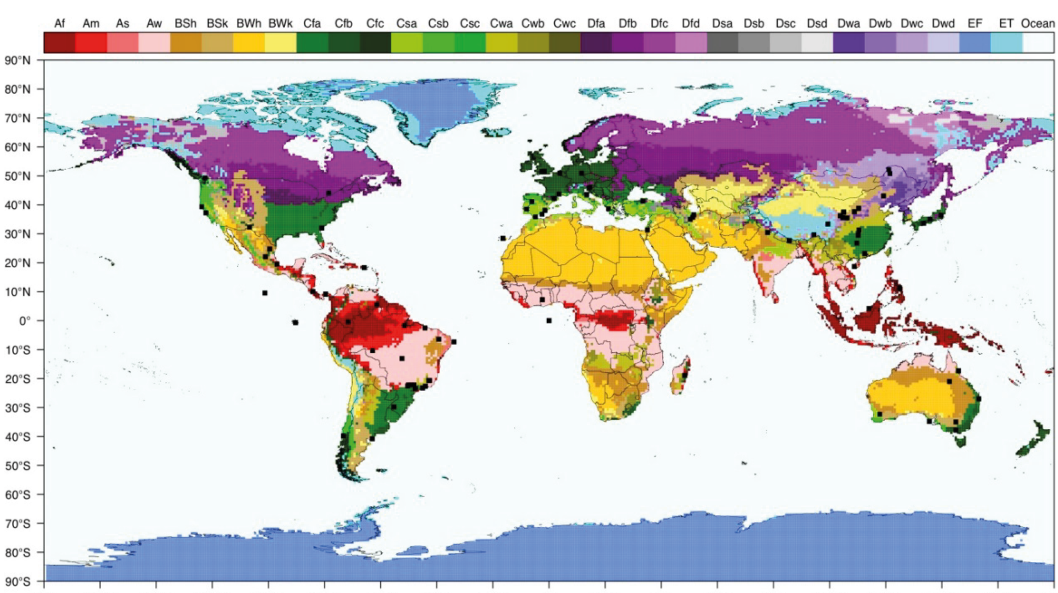

Figure 5 – Selected studies in the literature review distributed into climatic zones according to the Köppen classification. The sampled locations are represented by black dots on the map (squares).
Source: Kottek *et al.* (2006).

work by Garcia-Estringana, Alonso-Blázquez and Alegre (2010) for the *Cistus albidus species* found an average runoff of 20.8% for an FR of 194. Several studies have reported FR values, and they vary significantly according to the species considered.

Carlyle-Moses and Price (2006) identified a range of 7 to 26 for some deciduous tree species in Canada, while Li *et al.* (2008) described average FR values between 24 and 153 for shrub species in semi-arid regions of China during storm events. For individual trees, FR values exceed 100 (HERWITZ, 1986), reaching 260 for *Dorycnium pentaphyllum* (GARCIA-ESTRINGANA; ALONSO-BLÁZQUEZ; ALEGRE, 2010) and 8 for *Quercus cerris L.* (CORTI *et al.*, 2019). The linear correlation between stemflow and FR was relatively low in the selected studies (0.58). On the other hand, the amount of precipitation establishes a threshold to start the stemflow, that is, the flow varies according to the precipitation, which in turn undergoes spatial and temporal variation (YUAN; GAO; FU, 2016). Hence the difficulty in establishing a definitive stemflow contribution (Figure 6).

Several studies indicate that the stemflow contribution is around 1 to 2% of gross precipitation (AHMED *et al.*, 2017; CHUYONG; NEWBERY; SONGWE, 2004; LIMIN *et al.*, 2015; LORENZON; DIAS; TONELLO, 2015). Thus, Lorenzon, Dias and Tonello (2015) suggested that species with higher stemflow have some kind of morphological adaptation for rainwater harvesting. Several authors have found that understory trees produce more flow than emergent trees with a larger diameter at breast height (DBH) (LLOYD; MARQUES, 1988; NÁVAR; BRYAN, 1990; MANFROI *et al.*, 2004). This finding shows that some species have adapted to capture rainwater through the canopy by directing it through the trunk to the roots as a way of meeting their water needs, perhaps because they depend on too much soil moisture or have shallow roots.

Various studies have sought to relate plant morphological characteristics with the stemflow yield, showing that some general correlations can be established. Yield decreases with a basal diameter of branches, while branch architecture, more abundant leaf biomass, and larger angle are more efficient for water flow production (YUAN; GAO; FU, 2016). Shinzato *et al.* (2011) argue that the larger the canopy size, the higher the water retention capacity and the amount of incident precipitation that will initiate the stemflow process. In addition to crown size, other authors emphasize that runoff is controlled by trunk size and shape, slope and number of branches and twigs, wooded area, and the number of leaves (LEVIA *et al.*, 2015).

Still, according to the authors, straighter trunks with a higher number of sloping branches and fewer leaves would be more efficient in the stemflow. Therefore, the heterogeneous structural composition of the canopies is expected to exert differential effects on the stemflow yield, given the intraspecific and interspecific morphological variation found in natural environments, especially those with little anthropization.

Stemflow increases with the amount of precipitation (YUAN; GAO; FU, 2016). However, this increase is more related to the rise in rainfall and leaf area index than to the rainfall intensity (LIU *et al.*, 2015). Levia *et al.* (2010) summarize that stemflow is more similar in trees of the same species than between species, with the differences being due to bark texture and water storage capacity. The authors further highlight that tree size and the characteristics of rain events affect stemflow.

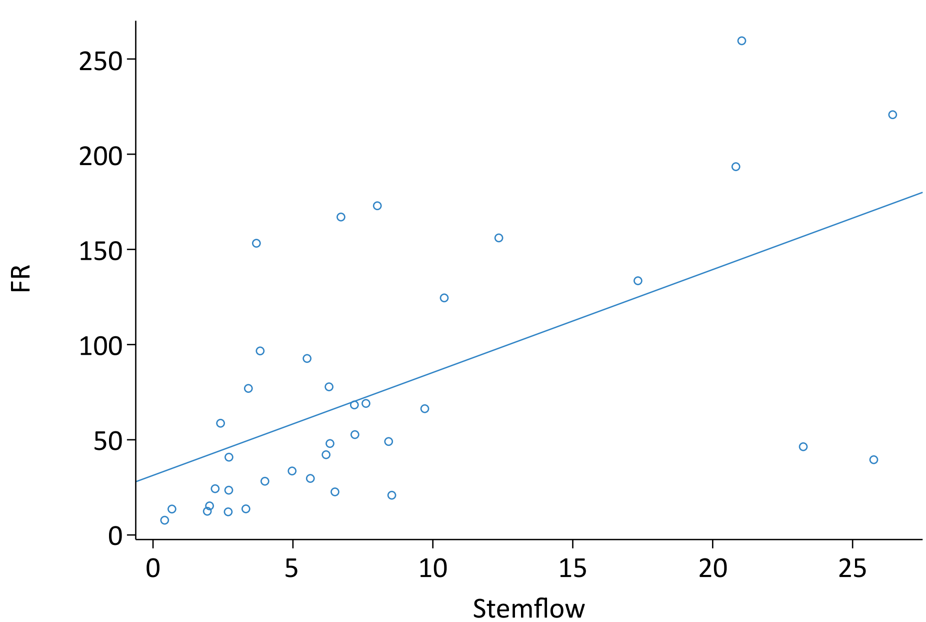

Figure 6 – Relationship between funneling ratio (FR) and stemflow efficiency (%).

Although many studies have considered the flow and concentration of nutrients in the stemflow, few have related its effects to the biogeochemical cycle more broadly. Consequently, further investigation on the relationship between stemflow and morphological characteristics of different species is necessary, as well as the various interactions of the biogeochemical cycle, enabling more assertive conservation and restoration actions.

Besides water, what else is in the stemflow?

Even though the stemflow contributes a small portion of the total precipitation in general, its chemical composition presents higher nutrient concentrations in relation to total precipitation and throughfall. Water and nutrient intake are influenced by vegetation type. Stemflow is fundamental for the biogeochemical balance, especially in forests with a diversity of tree species.

Schroth *et al.* (2001) identified phosphorus (P) and phosphate concentrations about 400 times higher in stemflow than in rainwater for Central Amazonian tree species. Liu, Fox and Xu (2003) showed that stemflow contributed about 10% of mineral nitrogen, emphasizing that this contribution should not be ignored in nutrient flow studies. At the same time, this transport is subject to several factors that can influence the concentration and flow of nutrients from the crown and stem to the soil. The volume and magnitude of rainfall, the period before rainfall, and seasonality are essential factors that can alter canopy and stem dilution and leaching processes (SIEGERT *et al.*, 2017). Carnol and Bazgir (2013), for example, reported differences in the nutrient returned to the forest floor through litter- and throughfall under seven forest species after conversion from Norway spruce. In China, Su *et al.* (2019) found that mixed evergreen and deciduous broad-leaved forests present differences between mean nutrient concentrations in throughfall and stemflow. In northern temperate forests, stemflow has been extensively studied, as demonstrated by Van Stan and Gordon (2018). Brazil has some studies about the solute concentration in the hydrological process, mostly concerning monocultures (BALIEIRO *et al.*, 2007; DICK *et al.*, 2018; DINIZ *et al.*, 2013; LACLAU *et al.*, 2010).

The concentration of chemical compounds in stemflow can also be influenced by the action of organisms that live in the treetops, creating a complex network of interactions that may change the concentration of nutrients. Michalzik *et al.* (2016) demonstrated that under aphid (insects) infestation the water chemistry was significantly altered, showing intense K (+ 139%), Mg (+ 82%), Mn (+ 93%), S (+ 86%), SO4-S (+ 62%), dissolved organic sulfur (+ 51%), and dissolved organic nitrogen (+ 62%). The authors point out that the analysis of the chemical composition can be used as a bioindicator to evaluate the impact of herbivore activity on forest ecosystems. Rosier *et al.* (2016) also detected variations in the composition of soil microbial communities in the stemflow of different plant species. Species-specific differences potentially change moisture, pH, and carbon and mineral nutrient composition near the stems contributing to greater microhabitat variability.

Another critical situation was observed by Ptatscheck, Milne and Traunspurger (2018) in Germany. The authors investigated stemflow as a vector for the transport of small metazoans from tree surfaces down to the soil. The pilot study showed for the first time that stemflow is a transport vector for numerous small metazoans. They concluded that by connecting tree habitats (*e.g.*, bark, moss, lichens, or water-filled tree holes) with soil, stemflow might influence the composition of soil fauna by mediating intensive organism dispersal. Bittar *et al.* (2018) also conducted an interesting study involving throughfall and stemflow from an oak-cedar forest in Southeastern USA. The authors identified that both hydrological processes were significantly enriched in bacteria compared to the open-area rainfall.

Runoff may also play a role in “discharging” large concentrations of nutrients under certain conditions. During periods of drought, chemical compounds from the atmosphere tend to accumulate in the canopy and stem. In a first precipitation event, this accumulation of chemical compounds will flow through the trunk, increasing their concentrations in relation to total precipitation and throughfall (ZHANG *et al.*, 2016). Therefore, the transport of nutrients and other compounds from the canopy to the soil can vary significantly according to rainfall seasonality.

Stemflow has also proven to be an important factor in the transfer of anthropogenic chemical compounds to the soil and water reservoirs, as is the case with anthropogenic nitrogenous compounds (BURBANO-GARCÉS; FIGUEROA-CASAS; PEÑA, 2014). This finding raises questions about how chemicals of anthropogenic origin that are harmful to ecosystems are being incorporated into the biogeochemical cycle, especially inert compounds such as hydrochlorofluorocarbons (HCFCs).

A study by Glinski *et al.* (2018) investigated the cumulative effect of 160 pesticides on the environment and measured the concentrations of these compounds in stemflow. The authors found similar concentrations of herbicides, fungicides, and insecticides on the surface of water bodies and stemflow, revealing the importance and indirect impact of the exposure of these environments to chemical agents of anthropic origin. Two years after the nuclear accident at the power plant in Fukushima, Japan, Endo *et al.* (2015) measured the radioactive cesium concentration (137Cs) on throughfall and stemflow. The authors pointed out that due to the defoliation caused by radioactivity in the area, the flow was significantly high, transporting 137Cs to the soil.

Therefore, stemflow and throughfall play a dominant role in biogeochemical processes through the nutrient flow of compounds deposited in the canopy, especially after long periods of drought, and their contribution can account for up to 50% of the total nutrients returned to the soil (HOFHANSL *et al.*, 2012). Like the flow of water, the chemical composition is influenced not only by environmental characteristics but also by plant species, their interactions with other organisms, and their localized effects; their contribution may not be detected, but they are certainly important to ecosystems (GERMER *et al.*, 2012).

Final Considerations

The growing number of studies on the subject in the most diverse regions, especially in the last two decades, has contributed to answering several questions about the importance and role of stemflow in ecosystems and the biogeochemical cycle. However, new questions arise as our knowledge of the topic deepens, revealing not only its complexity but also its diversity. Future works should seek to explore multidisciplinary aspects involving biotic and abiotic components and the impact of their interactions, seeking to quantify stemflow concerning plant morphological, physiological, and biochemical characteristics, as well as qualify the flow outcome in spatial and temporal scales.

With the stemflow contribution to the input of nutrients and microorganisms in the soil, would it be better to explore this relationship as a function of forest species in recognized diversity biomes? We believe that linking stemflow and soil recovery is necessary. Perhaps we could identify species with higher nutrient inputs to the soil and eventually explore them, positively, for the recovery of degraded soils, especially when it comes to forest restoration.

Contribution of authors:

Tonello, K.C.: Project administration, Supervision, Conceptualization, Review & editing. Balbinot, L.: Investigation, Formal analysis, Data curation, Writing – First draft; Pereira, L.C.: Investigation, Formal analysis. Matus, G.N.: Investigation, Formal analysis. Lima, M.T.: Investigation, Formal analysis.

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ABES

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Evaluation of freshwater benthic communities: a case study in an urban source in the Northeast of Brazil

Avaliação da comunidade meiobentônica de água doce: estudo de caso em um manancial urbano no Nordeste brasileiro

Suelen Nascimento dos Santos[1], *Jonathas Barbosa de Araújo Freitas*[2], *Jaime Joaquim da Silva Pereira Cabral*[3], *Anderson Luiz Ribeiro de Paiva*[4], *Caroline Cibelle Correia Clemente*[5]

ABSTRACT

The environmental damage suffered by urban water bodies and the need for public water supply result in a greater interest in techniques that enable water treatment in an efficient and ecological way, such as River Bank Filtration (RBF). This technique uses the soil as a filtering medium, as well as the biological activities of organisms that dwell in the Hyporheic Zone (HZ), the zone of interaction between the surface water body and its underlying aquifer. Knowledge of sediments and hyporheic organisms is indispensable to study RBF. The present paper aimed to characterize the HZ of the middle section of Beberibe river (Pernambuco State, Brazil) in its sedimentological and biological aspects, with sampling druing the rainy and dry seasons, in two distinct sampling sites, one in a conserved area and the other in a highly urbanized area. Biological characterization was performed at the level of large taxonomic groups of meiofauna, accounting for 982 individuals, with the three most abundant taxa being Nematoda, Annelida, and Rotifera. Permutational Analysis of Variance (PERMANOVA) statistical tests were performed, showing significant differences for the season and point factors ($p < 0.05$) in relation to abundance. The highest concentration of individuals and total organic matter were seen in the rainy season, especially at the point located in the urbanized area. With sedimentological characterization by grain size tests of the hyporheic sediments, the predominance of silt was observed during the rainy season, and sandy during the dry season. It

RESUMO

Os danos ambientais sofridos pelos corpos hídricos urbanos e a necessidade de suprir o abastecimento público das cidades resultam em um maior interesse por técnicas que possibilitem o tratamento de água de maneira eficiente e ecológica, como a Filtração em Margem (FM). Essa técnica utiliza o próprio solo como meio filtrante, além das atividades biológicas dos organismos que ocupam a Zona Hiporreica (ZH), zona de interação entre o manancial superficial e o aquífero subjacente. É indispensável o conhecimento acerca dos sedimentos e dos organismos hiporreicos para o estudo da FM. Este artigo objetivou caracterizar a ZH do trecho médio do rio Beberibe (Pernambuco, Brasil) em seus aspectos sedimentológicos e biológicos, com coletas nos períodos chuvoso e seco, em dois pontos distintos, um em uma área conservada, e o outro em área altamente urbanizada. A caracterização biológica foi realizada em nível de grandes grupos taxonômicos da meiofauna, contabilizando-se 982 indivíduos, sendo os três *táxons* mais abundantes o Nematoda, a Annelida e a Rotifera. Realizaram-se testes estatísticos de Análise Permutacional de Variância (PERMANOVA), constatando-se diferenças significativas para os fatores período e ponto ($p < 0,05$) em relação à abundância. A maior concentração de indivíduos e de matéria orgânica total ocorreu no período chuvoso, sobretudo no ponto localizado na área urbanizada. Por meio da caracterização por ensaios granulométricos dos sedimentos hiporreicos, observou-se a predominância arenosa no período seco, e de silte durante o período chuvoso. Concluiu-se que o

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was concluded that the main factor that influenced the structure of the meiofauna community was the release of domestic effluents. The information obtained by the present work helps to understand some features of the HZ, which is essential for RBF or other techniques that use the interstitial matrix.

Keywords: meiofauna; riverbank filtration; Beberibe river; hyporheic zone; sedimentology.

principal fator que influenciou na estrutura da comunidade da meiofauna foi o lançamento de efluentes domésticos. As informações obtidas com o presente trabalho auxiliam a compreensão de algumas características da ZH, a qual é essencial para a FM ou outras técnicas ambientais que utilizem a matriz intersticial.

Palavras-chave: meiofauna; filtração em margem; Rio Beberibe; zona hiporreica; sedimentologia.

Introduction

A problem currently observed in Brazilian urban centers is the pollution of their water sources, mainly due to irregular urban occupation and lack of basic sanitation (GUGLIELMELI; SILVA; STRAUCH, 2018), contributing to the degradation of water resources and making water supply more expensive (SILVA; FIGUEIREDO; MORAES, 2015).

In this context, alternative water treatment techniques, such as Bank Filtration (BF), are being increasingly studied and applied in developing countries to obtain water efficiently at a reduced cost, even from degraded urban sources (PHOLKERN *et al*., 2015; HU *et al*., 2016; FREITAS *et al*., 2018).

BF consists of the indirect abstraction of water from a surface source with pumping wells close to the river (or lake), causing an increase in the difference of hydraulic head between the source and the water table, which induces the passage of water through the porous medium to the well (RAY, 2002). In this technique, physical, chemical, and biological processes occur (FREITAS *et al*., 2018), mainly during the passage of water through the Hyporheic Zone (HZ), which is the transition zone between the surface environment and the underground environment (VERAS *et al*., 2017). The HZ plays a fundamental role in the river-aquifer interaction, acting as a regulator in the water flow and as a natural filter (MUGNAI; MESSANA; DI LORENZO, 2015). The water percolating through the hyporheic sediments undergoes several biogeochemical processes (LIU *et al*., 2017) and reaches the well installed on the bank with better quality water than water collected directly from the superficial source (RAY, 2002). Figure 1 illustrates the relation between a BF system and the HZ.

Thus, knowledge of the hyporheic zone is important for BF understanding. Similarly, the analysis of their physical and biological characteristics, with textural and grain-size analysis of hyporheic sediments, the content of sedimentary organic matter, and the evaluation of hyporheic fauna are fundamental to characterize the HZ. In addition, these biotic and abiotic parameters analysis are also important for assessing the vulnerability of underground and surface water bodies, commonly used in environmental studies (BORN; OLIVEIRA; CUBAS, 2014; JUNQUEIRA *et al*., 2018).

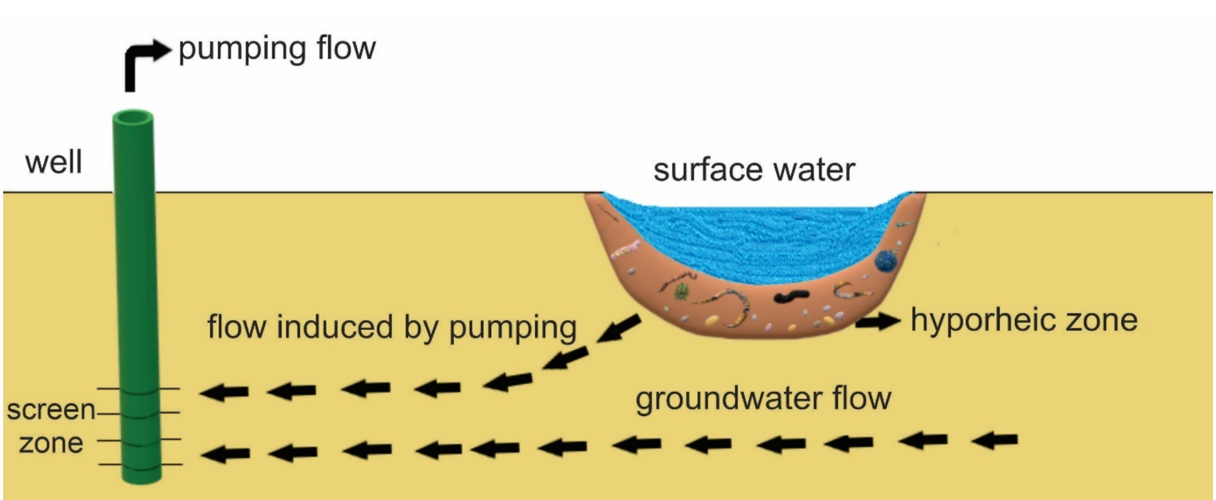


Figure 1 – Scheme of a bank filtration system and the hyporheic zone of the surface water source.

Among the organisms belonging to the hyporheic fauna, meiofauna organisms (or meiobenthos) stand out, which are small benthic organisms capable of interacting with different types of substrates and are distinguished by the opening of the mesh in which they are retained: between 500 and 42 μm (MARE, 1942).

These organisms have representatives that occupy aquatic and terrestrial ecosystems, which can inhabit the substrate of streams, trunks, and roots, in addition to coral reefs and several sedimentary matrices (GIERE, 2009). Meiobenthos have a short life cycle, facilitating observations in environmental studies (JUNQUEIRA *et al.*, 2018; VERAS *et al.*, 2018), act on nutrient cycling (ZEPPILLI *et al.*, 2015) and favor the formation of biofilms (LIU *et al.*, 2017). They play an important role in the river-aquifer interaction (FREITAS *et al.*, 2019), with highlights for studies with meiofauna in recent years. Despite the increase in the number of research on meiofauna, most of them have been developed in marine and estuarine environments (MARIA *et al.*, 2016). Thus, focusing on the study of meiofauna in freshwater environments is needed, which requires a greater number of studies. The use of organisms as biotic indexes of water quality is not largely widespread in Brazil, even though there are some adaptations for macrozoobenthos, for example (JUNQUEIRA *et al.*, 2018).

Sedimentological characteristics of the HZ are important for directly determining the spatial and structural conditions and indirectly determining the physical and chemical environment of the sediment (MUGNAI; MESSANA; DI LORENZO, 2015). In addition, meiofauna is important to influence the spatio-temporal distribution of the hyporheic meiofauna (VERAS *et al.*, 2017).

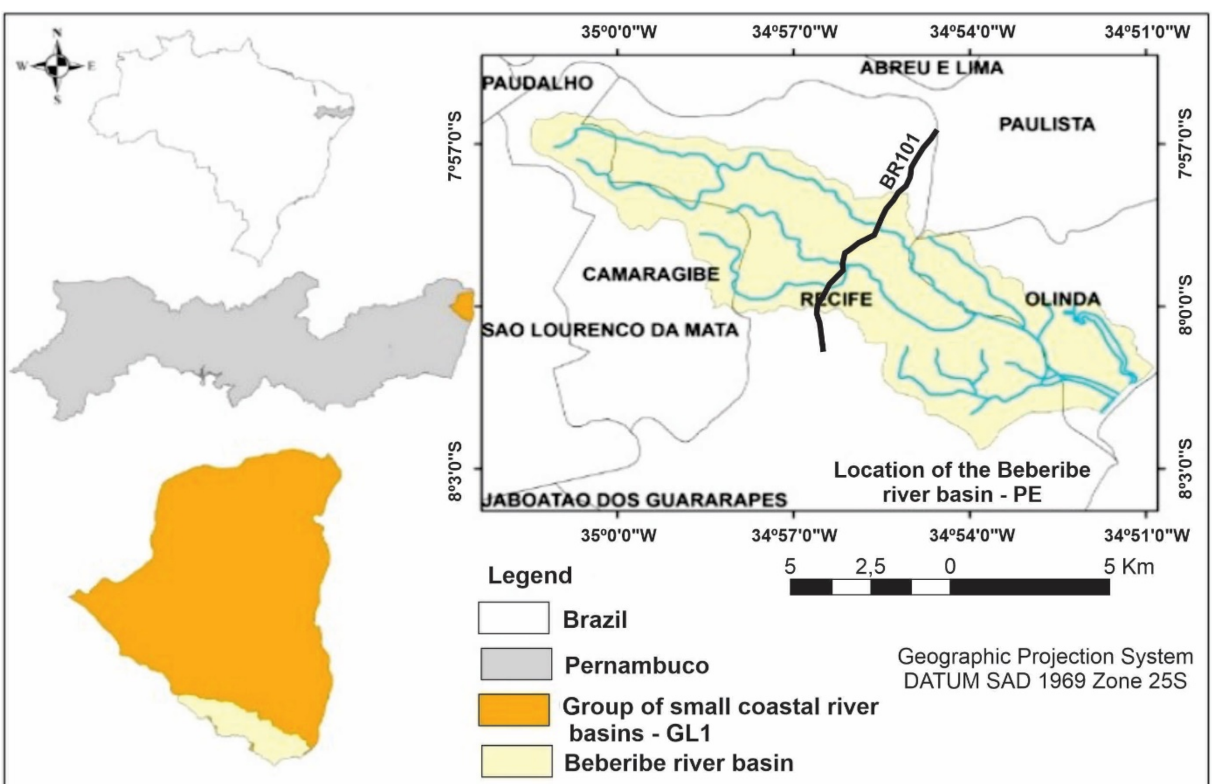
In this context, knowing the sedimentological and meiofaunal compositions of the HZ is relevant, since these factors interact and provide a basis for an effective analysis of the river-aquifer interaction. Thus, the present paper aims to evaluate the HZ, in terms of its sedimentological characteristics (grain-size and total sedimentary organic matter content) and biological (abundance of meiofauna organisms and their interaction with several factors), aiming to contribute to the understanding of the processes that occur in BF.

Materials and Methods

Study area

Hyporheic Zone (HZ) was studied on Beberibe river, located in Recife Metropolitan Region (RMR), Pernambuco State (Figure 2). Beberibe river has its source in Camaragibe municipality, its hydrographic basin is 81 km^2, and it includes portions of the municipalities of Recife, Olinda, and Camaragibe (SIRH, 2019).

It is one of the most polluted rivers in Pernambuco State, because there is a high population density along its length, especially defined by



Source: Silva and Barbosa Neto (2016).

Figure 2 – Location of Beberibe river's basin (PE).

their low income and no adequate basic sanitation, besides the industrial activities in its basin (CAMPOS, 2003; SIRH, 2019).

In terms of land use and occupation, Beberibe river's basin is divided into two distinct sectors by the BR-101 highway, one to the west of this highway, a sparsely urbanized area with preserved fragments of Atlantic forest, and the other to the east of the highway, with a high rate of urbanization (CAMPOS, 2003).

Beberibe river's basin is represented by areas of slopes with exposed soil, characterized by sandy-clayey sediments from Barreiras Formation. These areas are subject to water erosion during rainfall periods (CAMPOS, 2003).

With a hot and humid climate, Beberibe river's basin is part of the Humid Tropical Climate (AS'), with a great amount of rainfall during the autumn-winter period, according to the Köppen classification (1948). Given that the annual thermal variability is very low, there are two distinct seasons related to rainfall levels: the rainy season (winter), and the dry season (summer).

Rainfall data from the last ten years (2007 to 2017) were obtained from Pernambuco Water and Climate Agency (*Agência Pernambucana de Águas e Clima* — APAC) from Olinda 199 rain station near the study area. Figure 3 shows that the rainfall in the study area was higher in May, June, and July; and lower in October, November, and December (APAC, 2019).

The research samples were obtained with different samplings, which were carried out in the middle section of Beberibe river in RMR, on the border between the cities of Recife and Olinda.

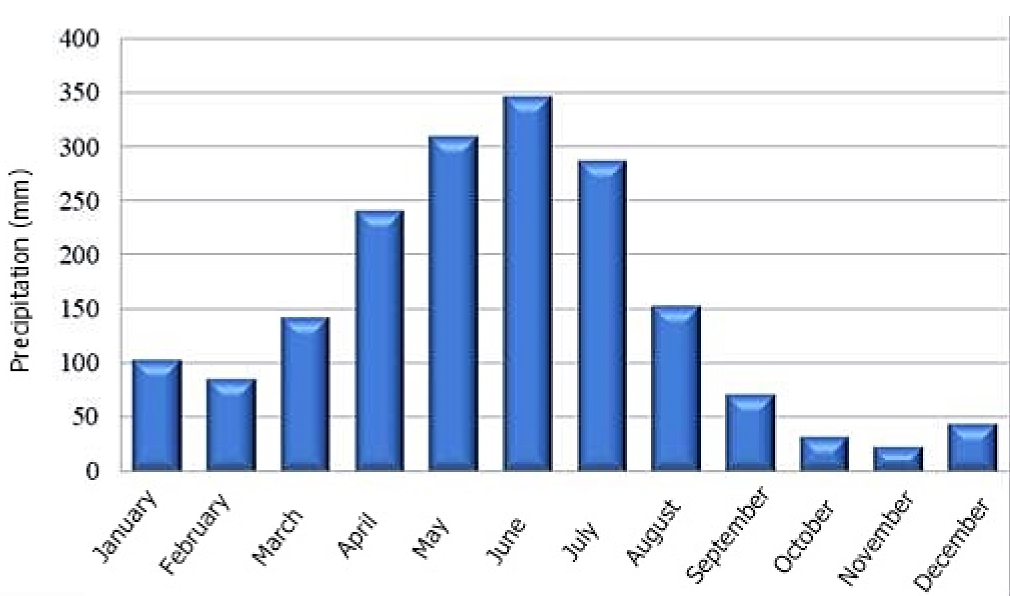
Two different sampling sites were selected (Figure 4): Sampling Site 1 (SS1) and Sampling Site 2 (SS2). SS1 is located close to BR-101 in Guabiraba neighborhood, in Recife, in an area with traces of the remaining Atlantic forest vegetation and without upstream urbanization. SS2 is located 3.5 km downstream of SS1, in a section where an experimental Bank Filtration (BF) station is located, in an area highly urbanized by low-income settlements and with a large supply of domestic sewage.

Field methodology

All samples presented in this paper were extracted from the Hyporheic Zone (HZ) of Beberibe river at Site 1 (SS1) and Site 2 (SS2) on July 27th, 2018 (rainy season) and December 21st, 2018 (dry season).

For the analysis of meiofauna, the number of samples collected during the summer season was carried out in three replicates for SS1 and three replicates in SS2. During winter, the number of replicates remained three for SS1 and three for SS2. After being collected, each replicate was stored in a plastic pot, later preserved in formaldehyde 4%, so that it could later be transported for screening in the laboratory. Recent authors also use formaldehyde 4% in their work (COSTA; VALENÇA; SANTOS, 2016; SARMENTO *et al*., 2017).

For the grain-size analysis, a sediment sample (from 0 to 10 cm deep) was collected in SS1, and another sample from SS2 during summer, repeating the sampling in the winter. The granulometric samples were packed in plastic bags and transported in styrofoam until they were stored in a freezer for later analysis. The sediments collected for both granulometry and meiofauna were obtained with a corer (cylindrical sampler of smooth and transparent acrylic) with a cross-sectional area of 11.33 cm^2. The corer was marked with different depth stratifications: 0-5 cm and 5-10 cm, as illustrated in Figure 5. The depth stratification was present for both meiofauna and granulometry.



Source: APAC (2019).

Figure 3 – Average monthly rainfall (mm) at Olinda 199 station in the last ten years (2007-2017).

Laboratory methodology

Particle size and total organic matter analysis

The grain-size analyses were performed at Universidade Federal de Pernambuco (UFPE), in the Oceanography Department (DOCEAN), Laboratory of Geological Oceanography (LABOGEO). These grain-size analyses were made using the sieving and pipetting technique described by Suguio (1973). Besides that, the contents of total organic matter (TOM) were also obtained, using the methodology described by Muller (1967).

The sediments were removed and placed in Becker for drying in the oven for 24 hours at 60°C. After that, the TOM analysis was performed with a 30 g aliquot of the post-drying sediments, in which a 10% H_2O_2 solution was used for the oxidation of organic matter. Subsequently, the TOM contents were acquired from the difference in weight before and after the oxidation process after determining the TOM. The fine and coarse particles were separated with wet sieving to remove the fines with the aid of distilled water. The finer particles, which are difficult to quantify by sieving, were subjected to the pipetting process.

The weighing results were placed in the SYSGRAN 3.0 software to identify the granulometry and plot the data of the granulometric fractions, using parameters such as average diameter, classification and degree of selection, according to the equations by Folk and Ward (1957).

Meiofauna

The characterization of meiofauna organisms was carried out with a quantitative survey and identification of large taxonomic groups. The samples were subjected to elutriation and wet sieving (washed in running water and filtered), in sequence, with the aid of geological sieves nested with 500, 200, 100, and 45 μm mesh openings. This methodology was chosen because the Flotation method is not highly recommended for this work, considering that the solution of NaCl or sucrose (most commonly used) has a very high osmotic potential, for example, thus damaging part of the fauna and spoiling the data. Therefore, it is more appropriate to use the nested sieve separation method. Thus, in the sieves of greater opening, the thicker sediments and some other material of larger size are retained: pieces of leaves, small stones, among others. This avoids clogging the mesh opening sieve (45 μm) and possible damage to the retained fauna (SOMERFIELD; WARWICK; MOENS, 2005).

The material retained in the 45 μm sieve was placed in a plastic pot and stained with Rose Bengal. The main taxonomic groups of meiofauna were counted with the aid of a stereomicroscope. Authors, such as Castro (2003) and Veras (2015), also used similar methodologies for meiofauna quantification in an estuary area and in a river, respectively.

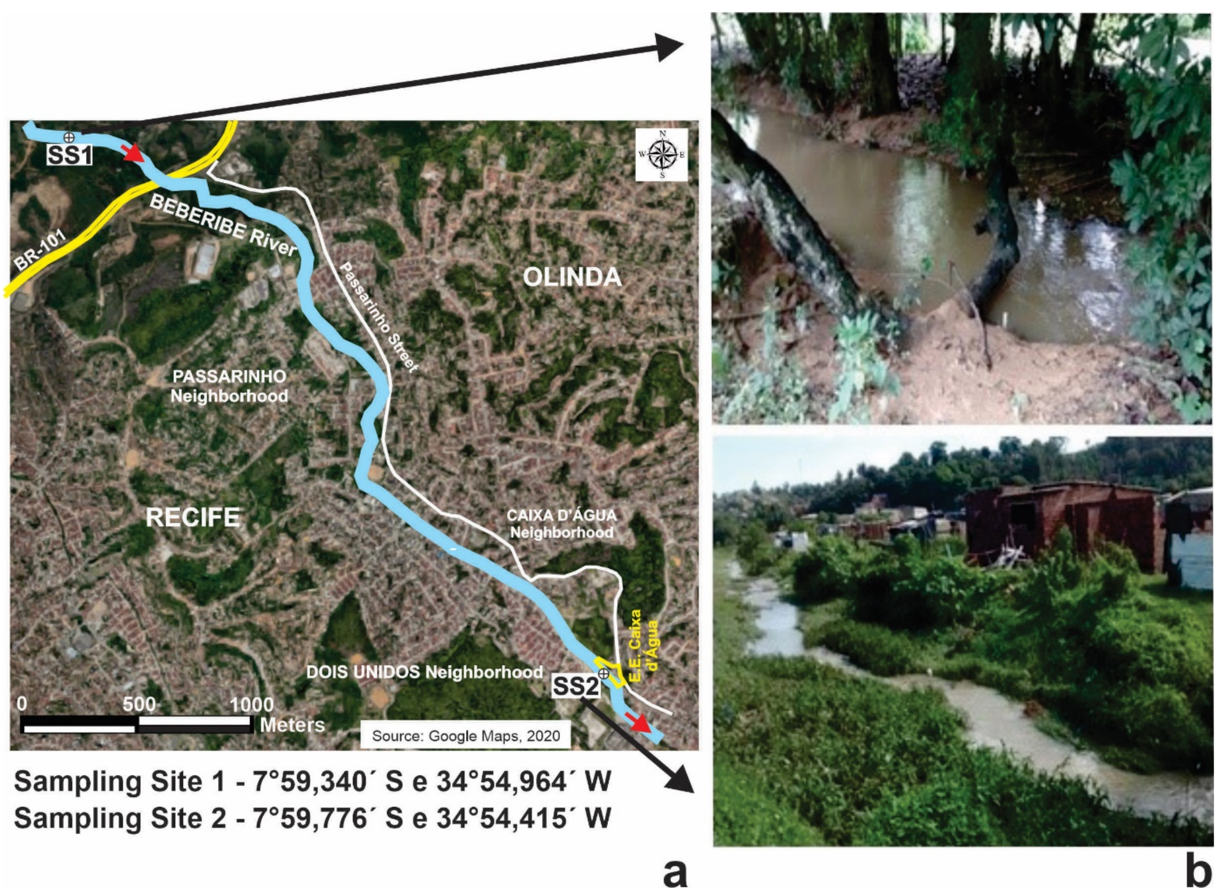


Figure 4 – Location of study sampling sites (SS1 and SS2) in the middle section of Beberibe river (PE).

The density of meiofauna is calculated by the cross-sectional area of the corer used (11.33 cm^2). Then, the density was standardized to values corresponding to individuals/10 cm^2 from Equation 1:

$$D = (N / V) \times 10 \quad (1)$$

In which:
D: the density;
N: the total number of organisms present in the samples;
V: the sample volume (cm^3).

Based on the similarity matrix of Bray Curtis, the analysis of the meiofauna community structure was performed with the representation on a multidimensional scale (MDS), in which it is used to graphically express the similarities (groupings) between replicates and factors (CLARKE; WARWICK, 2001). Significance between clusters was tested using Permutational Analysis of Variance (PERMANOVA) (ANDERSON, 2005); in case of significance, Tukey's posterior test was applied to the pairs of levels of each factor.

Three factors were adopted for data analysis: Period (winter and summer), Space (P1 and P2), and Depth (0-5 and 5-10 cm). All analyzes were performed using the software Primer® v.6 + PERMANOVA (Plymouth Routines in Multivariate Ecological Research).

Results and Discussion

Hyporheic sediments

Table 1 describes the data found with granulometric analyses and Total Organic Matter (MOT) in summer and winter periods. All samples presented in this paper were extracted from Beberibe river Hyporheic Zone (HZ) at Sampling Site 1 (SS1) and Sampling Site 2 (SS2) on July 27th, 2018 (rainy season) and December 21st, 2018 (dry season).

According to Xavier *et al*. (2016), a greater number of fines may be linked to organic manure of anthropic origin. This can be seen in SS2, which is the most urbanized and probably receives a greater discharge of domestic waste.

The MOT values did not show relevant differences between the two depths studied. During summer, the MOT contents were 1.67 and 1.56% in SS1, 4.53 and 5.08% in SS2, respectively for depths 0-5 cm and 5-10 cm. During winter, these values were 11.44 and 11.70% in SS1, 9.95 and 9.03% in SS2. Furthermore, there was no clear distinction between the MOT levels between SS1 and SS2. According to Junqueira *et al.* (2018), the domestic effluent can cause the excess of organic matter in waters, consisting of an important fact for evaluation and the use of improvement techniques capable of identifying the integrity of rivers.

On the other hand, SS2 obtained contents of fine sediments (silt and clay) considerably higher than SS1, in which the vegetation cover in its surroundings contributes to a smaller contribution of fines. These results differ from the observation made by Barcellos *et al.* (2016), who stated that fine particles are associated to a larger surface area of the sediment, which allows a greater accumulation of organic matter, because it is adsorbed by finer sediments. However, it must be considered that the entry of MOT in the system may have occurred by natural processes, especially in the rainy season (winter) due to the carrying of organic matter from the vegetation in SS1.

When comparing the rainfall seasons, an increase in clay contents in winter was seen when compared to summer in all respective sampling sites and their depths. The most expressive values of clay in winter possibly occurred due to the period's rainfall, causing a greater runoff and carrying fine particles to the riverbed.

This result is similar to those obtained by Resende, Craveiro and Pereira (2016) in sediments from stretches of the river Capibaribe, where the predominance of fine particles was observed, and the authors related this fact to the influence of the rainy season.

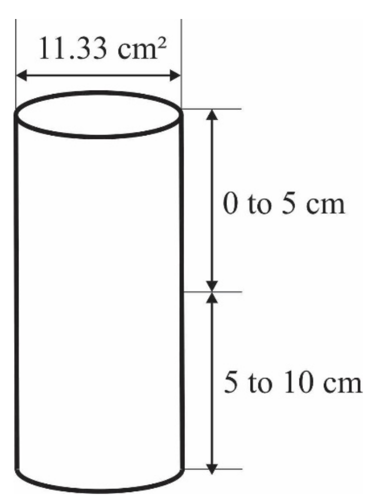


Figure 5 – Corer sampler used in sampling of meiofauna and sediment.

Regarding the selection degree of samples, this degree is a statistical parameter of dispersion classified from the standard deviation (σ) (FOLK; WARD, 1957). Given the above, the smaller the standard deviation the better the sediment that will be selected, that is, the grains will have sizes with less dispersion. Only one sample was classified as poorly selected, with all the others being very poorly selected. Samples predominantly indicated dispersion of their granulometric values, with the size of their grains varying expressively, with very large and very small grains distributed throughout the sedimentary matrix. This fact contributes to a lower hydraulic conductivity in the bed, considering that the empty spaces between the larger grains are filled by grains of smaller diameters.

Table 1 – Granulometric analyses of sediments collected in Beberibe river (PE) during summer (December 21st, 2018) and winter (July 27th, 2018) periods in SS1 (7º59,340 'S 34º54,964'W) and SS2 (7º59,776 'S 34º54,415'W).

Point and Depth	Parameters in summer period						
	% Gravel	% Sand	% Silt	% Clay	% TOM	Selection degree	Classification
SS1 0-5 cm	2.03	81.13	9.14	7.70	1.67	VPS	Thin sand
SS1 5-10 cm	3.8	79.40	4.04	12.77	1.56	VPS	Thin sand
SS2 0-5 cm	3.08	53.55	11.88	31.49	4.53	VPS	Thick silt
SS2 5-10 cm	3.31	71.72	12.14	12.83	5.08	VPS	Very thin sand
Point and Depth	**Parameters in winter period**						
	% Gravel	**% Sand**	**% Silt**	**% Clay**	**% TOM**	**Selection degree**	**Classification**
SS1 0-5 cm	1.87	35.97	38.36	23.81	11.44	VPS	Medium silt
SS1 5-10 cm	3.58	41.26	34.86	20.30	11.70	VPS	Thick silt
SS2 0-5 cm	0.09	17.29	25.40	57.22	9.95	VPS	Thin silt
SS2 5-10 cm	0.03	14.86	45.09	40.02	9.03	PS	Thin silt

TOM: total organic matter; VPS: very poorly selected; PS: poorly selected.

Table 2 – Total abundance of meiofauna collected in Beberibe river (PE) during summer (December 21st, 2018) and winter (July 27th, 2018) periods in SS1 (7º59,340 'S 34º54,964'W) and SS2 (7º59,776 'S 34º54,415'W).

		Summer	Winter	Total
Sampling Site 1	Nematoda	68	108	176
	Annelida	83	58	141
	Rotifera	8	19	27
	Others	2	3	5
	Subtotal	161	188	349
Sampling Site 2	Nematoda	142	200	342
	Annelida	120	125	245
	Rotifera	0	31	31
	Others	4	11	15
	Subtotal	266	367	633
	Total	427	555	982

Hyporheic meiofauna

In total, 982 individuals were counted: 427 during summer and 555 during winter. The highest percentage of individuals was from group Nematoda (53%), followed by Annelida (39%), Rotifera (6%), and others (2%). Thus, taxonomic diversity was very low, in which 92% of the total abundance was concentrated in just two taxa. The other organisms found were mostly insects and amphipod larvae. Table 2 shows a summary of the abundance of phyla found.

Table 3 shows the difference in organism abundance between periods (summer and winter) compared to different depths (0-5 and 5-10 cm, respectively).

The results of PERMANOVA showed that there were significant differences between the sampling site factor (Pseudo-F = 13.547; $p < 0.05$) and the period factor (Pseudo-F = 13.547; $p < 0.05$). However, no significant difference was detected for the depth factor (Pseudo-F = 10.161; $p > 0.05$). In addition, significant differences were also observed in the interaction between the point and period factors (Pseudo-F = 7.255; $p < 0.05$).

Figures 6 and 7 show the MDS graphical representations for better visualization of the clusters with greater similarity. The figures present the MDS for the factors that had a significant difference: analyzed points and time periods.

These MDS representations presented two distinct clusters in Figures 6 and 7, respectively for sites SS1 and SS2 and for the summer and winter periods, validating the significant differences previously found with PERMANOVA. Variations in the values of parameters such as rainfall, sediment content, organic matter, and hydrodynamics were important for these differences.

The abundance in SS2 was higher than SS1, even though it is a totally degraded site in relation to the organic supply, greater abundance was observed when compared to the other less impacted site. Chemical pollution, due to domestic waste, can cause eutrophication of the surface water source, contributing to the resistance of several individuals to this pollution, although the taxonomic diversity is less.

In view of this, the organic enrichment caused by the greater potential sanitation deficit in the SS2 area is likely to also increase the density of meiofauna organisms. However, if the organic enrichment continues, the density of the organisms may decrease gradually or until the group disappears completely, a fact known as the "enrichment paradox" (TOWNSEND; BEGON; HARPER, 2009; RANA *et al.*, 2013), caused by a subsequent decrease in oxygen dissolved in water (FOTI *et al.*, 2014).

During the winter period, rainfall enriches the environment, and, according to Dalto and Albuquerque (2000), organic matter increases the temporal variability of meiofauna with this enrichment. The same occurred in the present study, in which a greater abundance and quantity of MOT was obtained in the rainy season.

Probably, the greater abundance of meiofauna in winter was due to the contribution of total organic matter (MOT), which, as shown in Table 1, presented the highest levels in this period. Organic matter can be obtained with different forms and anthropogenic sources (BUENO *et al.*, 2018), and even changes in sediments as a deposition environment can increase the contribution of MOT (OLIVEIRA *et al.*, 2014; XAVIER *et al.*, 2016). The seasonal rainfall variation influences the distribution of meiofauna organisms: rainfall can enrich the benthic environment with its organic contribution, increasing the availability of food (DALTO; ALBUQUERQUE, 2000; GHOSH; MANDAL; CHATTERJEE, 2018), including driving diffuse pollutants present in effluent networks and rainwater drainage to water bodies (CAMELO, 2019).

Thus, the statistical differences observed between a more degraded site and another site in a preserved area, and the influence of the rainy season with processes of sedimentation and organic matter input by washing urban drainage devices show that domestic effluent is the main source of organic matter in Beberibe river, which can lead to different behaviors in the meofaunistic community in such river.

This great influence of domestic effluents was also observed in studies of meiofauna in the most diverse habitats, such as in estuaries

Table 3 – Abundance of meiofaunistic organisms collected by stratification at Sampling Site 1 and Sampling Site 2 during summer and winter.

		Summer	Winter	Total
SS1	0–5 cm	117	82	199
	5–10 cm	64	106	170
	Subtotal	181	188	369
SS2	0–5 cm	141	145	286
	5–10 cm	105	222	327
	Subtotal	246	367	613
	Total	427	555	982

(VANAVERBEKE *et al*., 2003; FRASCHETTI *et al*., 2006) and in rivers (HEWITT; MUDGE, 2004; VERAS *et al*., 2018).

Despite not indicating significant differences for the depth factor alone, PERMANOVA indicated that there were significant differences in the interaction between the period and depth factors (Pseudo-F = 7.255; $p < 0.05$). The Pair-wise a posteriori test helped to better understand these differences and, gathering the information generated from the representation in MDS and relating them to Table 3, the abundance was more concentrated in the superficial layers (0-5 cm) with few organisms in the 5-10 cm layers during summer. This result is convergent with the vertical distribution found in other studies on meiofauna (DALTO; ALBUQUERQUE, 2000; HUANG *et al*., 2014; FREITAS *et al*., 2019).

On the other hand, during winter, this vertical distribution occurred so that the organisms were more distributed in the 5-10 cm layer, with great dispersion and few organisms in the superficial layers. This fact is possibly related to the rains in the winter period, which, as previously seen, can redistribute the organisms in the sedimentary matrix and the water column.

From this calculation of meiofaunistic density (D), SS1 obtained an average density of 87.82 ind./10 cm^2 in the 0-5 cm layer, whereas the average density was of 75.02 ind./10 cm^2 in the 5-10 cm layer.

Authors such as Kotwicki *et al*. (2005) and Giere (2009) identified the decrease in meiofaunistic density according to depth and, in the case of limnic environments, Albuquerque (2015) and Freitas (2018) also observed this distribution of organisms by stratification, that is, the decrease of these with depth. For SS2, the average density obtained was 126.20 ind./10 cm^2 in the most superficial layer studied, and 144.33 ind/10 cm^2 in the deepest layer.

As for the fact of a lower density of organisms on the surface during winter, this may have occurred because of a higher flow in the rainy season, as it is known that hydrodynamics can influence the structure of different benthic communities (FREITAS *et al*., 2019). The rainiest period may have caused the meiofaunistic redistribution of the most superficial layers due to sedimentation. The increase in hydrodynamics in the rainy season can be a determining factor in the concentration of organisms in the most superficial sedimentary layer, which may lead to a decrease in them, as was the case in the present study and other studies previously carried out in hyporheic environments (VERAS *et al*., 2018; FREITAS *et al*., 2019).

Thus, the migration of organisms from more superficial layers of the sediment to deeper layers (5-10 cm) may have occurred by resus-

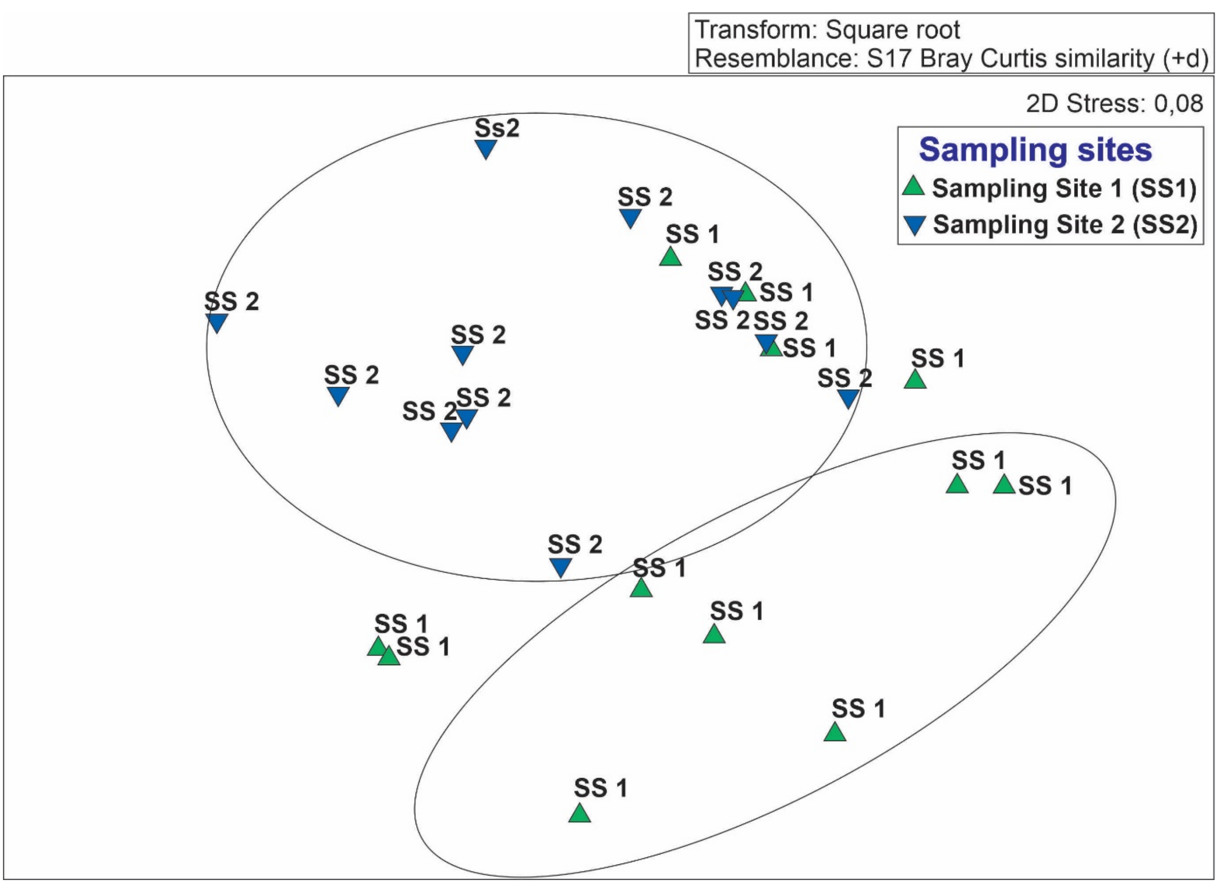


Figure 6 – Representation in MDS of the meiofaunistic structure related to the Sampling Site Factor (SS1 and SS2) during the seasons (winter and summer).

pending them to the water column, due to the hydrodynamics of the system being greater in the rainy season.

This influence was observed not only in the present study in a hyporheic environment, but also in studies carried out in estuarine environments in Brazil, such as in Porto de Galinhas City, Pernambuco State, by Maranhão (2003), and in the Biological Reserve of Lago Piratuba, Amapá State, by Venekey, Melo and Rosa Filho (2019), in which factors such as resuspension and hydrodynamics affected the pattern of the vertical distribution of the studied organisms.

Conclusions

This study encompassed several fields of knowledge. In addition to the middlebentology, data related to sedimentology (granulometry and sedimentary organic matter), rainfall and biostatistics were collected. This interdisciplinary approach is essential for the study of hyporheic meiofauna.

A low taxonomic diversity was found, in which 92% of the organisms found to belong to only two taxa: Nematoda and Annelida. With statistical analysis using PERMANOVA, there were significant differences in the structure of the meiofauna community regarding the factors sampling site (location) and period (time). Meiofaunistic abundance was greater in the most qualitatively degraded site, located in a densely urbanized area. From the low diversity found, the higher content of organic matter obtained at this site and the local socio-environmental characteristics, it was concluded that the main responsible factor for the characterization of community is the organic contribution through domestic effluents.

In addition, the statistical differences between summer and winter periods also have rainfall as an explanatory variable. Rainfalls act in the washing of the urban drainage systems, which in low-income communities in Brazil commonly function as mixed systems, thus transporting domestic effluents. This explains the increase in the organic supply in spring during the rainy season and its consequent influence on the meiofauna community.

However, it is important to infer that the increase in organic matter input can cause the increase in the density of certain taxonomic groups. Oxygen may not be enough for all organisms after this initial populational growth, later causing a dramatical reduction in population. This process is called the "enrichment paradox" (CRANFORD; BRAGER; WONG, 2017).

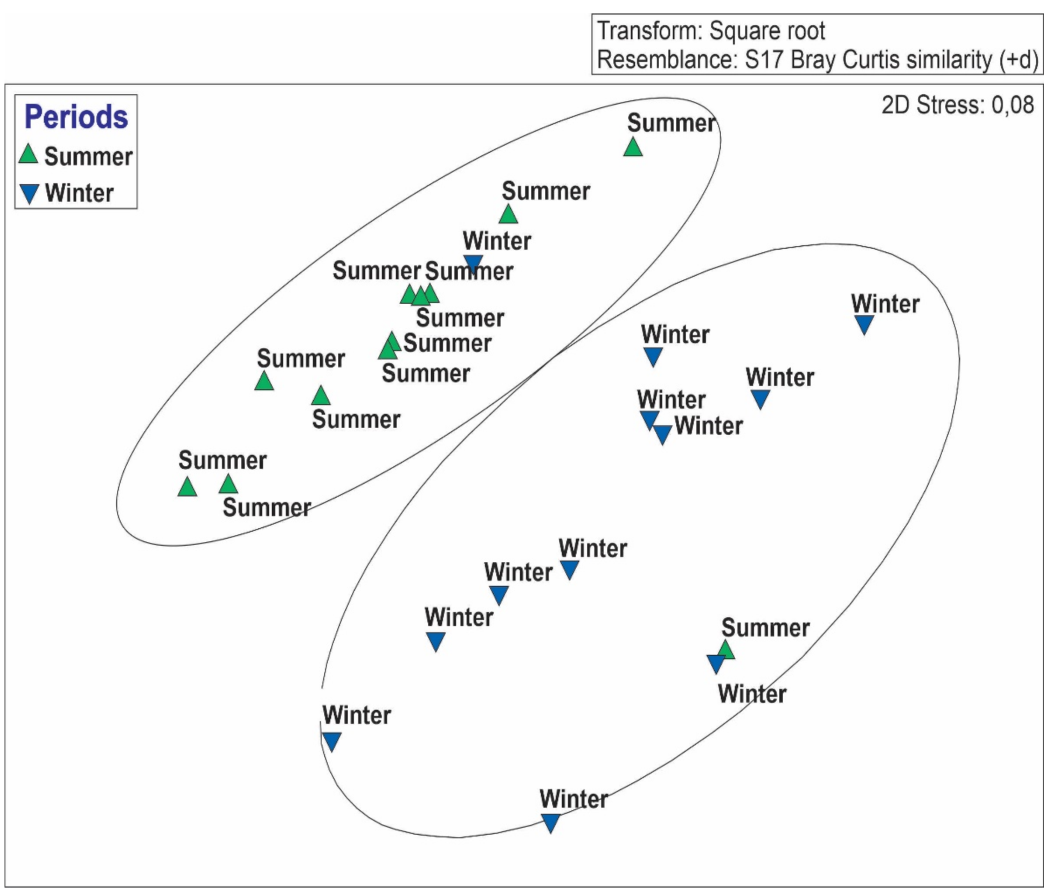


Figure 7 – Representation in MDS of the meiofaunistic structure for sampling sites (SS1 and SS2) relating to the Period Factor (winter and summer).

As to granulometry, the relation between a larger amount of fine sediments and the abundance of meiofauna was verified, since these sediments are more likely to adsorb organic matter.

The summer period had more abundance of meiofauna in the upper layer (0-5cm), which was convergent with several studies, since the more superficial layer has a higher level of dissolved oxygen. On the other hand, the opposite occurred in winter. This can be explained by the greater hydrodynamics that occurs during the rainy season, which causes a disturbance in the superficial layers, causing some of these organisms to be resuspended to the water column, and others to seek refuge in the deeper layers (migration between layers).

Therefore, the characterization of meiofauna in its interdisciplinary aspects in Beberibe river is needed for a better understanding of this environment, including for the understanding of the biogeochemical processes that occur in the hyporheic zone. However, this study should be continued, and expand further studies in freshwater environments within an urban and tropical context are encouraged, in view of the complexity of the relationships between environmental conditions in the hyporheic zone.

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Contribution of authors:

Santos, S.N.: Formal analysis, Conceptualization, Methodology, Data curation, Software. Freitas, J.B.A.: Formal analysis, Conceptualization, Methodology, Writing – First Redaction. Cabral, J.J.S.P.: Formal analysis, Conceptualization, Methodology, Review & editing, Obtaining Financing. Paiva, A.L.R.: Formal analysis, Conceptualization, Methodology, Writing – First Redaction. Clemente, C.C.C.: Formal analysis, Conceptualization, Methodology, Data curation, Software.

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A study on the reuse of ash from sugarcane bagasse

Estudo da reutilização das cinzas do bagaço da cana-de-açúcar

Monique Carrer Hobold[1], *Alex Hahn Matos*[2], *Karen Amorin da Silva*[2], *Glaucea Warmeling Duarte*[3]

ABSTRACT

The generation of large amounts of ash from sugarcane bagasse by its producing countries is becoming a worldwide-problem. Its irregular application, such as in fertilizers, contaminates soil and water, causing a great environmental problem. Studies show it is possible to apply ash in some specific areas, such as replacement of portland cement, replacement of clay, as an adsorbent, in the treatment and stabilization of soils, in the pavement of road asphalt, among others. The objective of the present article is to evaluate which are the most promising areas for the use of sugarcane bagasse ash. The work was developed with a bibliographic search, using the bibliometrics technique. The results obtained show that it is possible to use ash in several different areas. However, having a detailed study of the characteristics of the ash obtained is important, because they are directly related to the regions and climates where sugarcane is cultivated, besides its granulometry, collection time the ashes in the boilers, pHs, curing time, etc. In conclusion, results can be very different for the same application area, depending on the properties of the ash obtained.

Keywords: waste recovery; soil stabilization; portland cement replacement; adsorber; red pottery.

RESUMO

A geração de grandes quantidades de cinza do bagaço da cana-de-açúcar por países produtores está se tornando um problema no âmbito mundial. Sua aplicação irregular, como em fertilizantes, contamina solos e águas, ocasionando um grande problema ambiental. Estudos mostram que é possível aplicar cinzas em algumas áreas específicas como substituição do cimento Portland, substituição da argila, como adsorvente, no tratamento e estabilização de solos, na pavimentação de asfalto rodoviário, entre outros. O objetivo deste artigo é avaliar quais são as áreas mais promissoras para a utilização da cinza do bagaço da cana-de-açúcar. O trabalho foi desenvolvido por meio de uma pesquisa bibliográfica, utilizando a técnica bibliométrica. Os resultados obtidos comprovam que é possível a utilização das cinzas em várias áreas diferentes. Entretanto, para cada aplicação é importante haver um estudo detalhado das características da cinza obtida, pois estão diretamente relacionadas às regiões e climas onde a cana é cultivada, granulometrias, tempo de coleta das cinzas nas caldeiras, pHs, tempo de cura etc. Em suma, para a mesma área de aplicação, os resultados podem ser muito diferentes, dependendo das propriedades das cinzas obtidas.

Palavras-chave: valorização de resíduos; estabilização do solo; substituição de cimento portland; adsorvente; cerâmica vermelha.

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Introduction

When seeking sustainable development, new approaches emerge in the chemical industry, with the concept of green chemistry, which promotes more economical and environmentally correct methodologies. Among them, there are those focused on the production of more efficient and cheaper inputs. In this way, contributing to reduce the environmental impacts of the production chain with industrial ecology, which consists of the integration of the principles of Science, Engineering and Ecology in industrial systems so that the generation of products and services provided minimize the environmental impacts and optimize the use of resources, energy and capital (VARGAS *et al*., 2017).

Sugarcane is grown in approximately 110 countries, with Brazil being its largest producer in the world, followed by India, China and Thailand. It is estimated that in Brazil production exceeds 600 million tons / year (FARIA; HOLANDA, 2013). The annual production of sugar cane in Brazil contributes about US $ 43.8 billion in gross domestic product. About 80% of Brazil's biomass electricity is generated from sugarcane bagasse. However, the process of generating energy from bagasse leads to a by-product residue, sugarcane bagasse ash, which requires disposal (ANDREÃO *et al*., 2019).

Sugarcane production is one of the main agricultural activities in Brazil, and one of the by-products generated in sugar and ethanol producing plants is the sugarcane bagasse ash sand (SBAS) (ALMEIDA *et al*., 2015). As the authors Faria and Holanda (2013) add, this sugarcane bagasse is normally reused in the industry itself as a fuel source in boilers, in energy cogeneration and, as a result, an enormous amount of ash is generated throughout the world. Roughly 2.5% of the mass from the cane is transformed into ash, of which most of its reuse is in the form of fertilizers.

The sugarcane bagasse that is collected during processing has a good calorific value and is used for supplementary energy production. However, the ash generated in the process must be dumped in landfills (CHOPPERLA *et al*., 2019), which normally does not happen.

The ash, removed from the boilers, is usually stored in the open air when not used as a source of raw material in other processes, waiting for indefinite periods until it has a destination, usually in the crops as fertilizers (ALMEIDA *et al*., 2015), in the form of a mixture of vinasse (distillation remains) and bagasse ash, which can alter the physical and chemical characteristics of soil (FARIA; HOLANDA, 2013).

The use of industrial and agricultural waste in a controlled manner, such as ash from sugarcane bagasse, has been the focus of recent research due to economic, environmental, and technical issues (MOHAN; NARAYANASAMY; CHANDRASEKAR, 2018), because this by-product harms the environment when handled in an irregular way, such as the contamination of soils and water bodies (IMRAN *et al*., 2016).

Thus, the technically controlled use of industrial waste to replace natural resources to produce new products with comparable quality has a major economic and sustainable contribution (DAL MOLIN FILHO *et al*., 2019). Thus, studies that evaluate the possibilities of reusing the ash are promising, given that this material will have a more correct and profitable destination.

In addition to contributing to the conservation of the environment, by reducing waste disposal and the extraction of natural resources, it also results in minimizing costs with the final destination and management of waste, as well as economic gains with the production of materials of reduced costs (BRAGAGNOLO *et al*., 2018).

Studies by Joshaghani, Ramezanianpour and Rostami (2016) show that parts of the ash can be used to replace Portland cement. The proper use of bagasse ash in cement mortar can provide the ideal solution for environmental issues (REZA, 2019).

The authors Schettino and Holanda (2015a) present the use of sugarcane ash in the ceramic industry. The manufacture of bricks using waste presents better performance and low production cost, leading to a more sustainable construction (SANTHOSH; JAGAN; PRIYANGA, 2018). On the other hand, Ferreira, Fageriae and Didonet (2012) evaluate its use in soil treatment. The article by Hasan *et al*. (2016) made a publication for the use of ash in the road asphalt pavement.

Some papers have proved the feasibility of insertion in infrastructure works, such as in the use of materials for grounding, reinforcement for road construction and production of asphalt mixtures (BRAGAGNOLO *et al*., 2018).

The considerations pointed out in the literature can serve as a starting point for the development of new specific studies on the possibilities of using the ash from sugarcane bagasse in an effective and efficient manner, thus reducing the disposal of this residue in the environment.

Based on this premise, there is a need to investigate the state of the art of scientific production related to the theme, so that future studies can be grounded. Thus, the main objective of the present study is to analyze, from the point of view of bibliometric theory, the scientific productivity regarding the main uses of sugarcane ash.

Methodological procedures

Research presented in this article was developed using the procedures of a bibliographic study, with the collection of data using the bibliometrics technique, which is traditionally used in some areas to evaluate scientific research on a given topic, (SACARDO, 2012). Depending on the results obtained and the methodology used to analyze them, research can also be classified as quali-quantitative and, regarding the objectives, as descriptive research, it has the function of describing the characteristics observed in the selected papers.

The articles used for this bibliographic search were selected from three databases, namely: Science Direct, Scopus, and Web of Science. The search term used in the three cited bases was "Sugarcane bagasse ash", and a total of 488 articles were found. It is important to note that the searches were made considering articles published by December 2019.

Of this total, 163 articles were duplicate, that is, published in more than one evaluated database, with 325 articles remaining for further research.

After applying this first filter, all titles and abstracts of the papers were evaluated to verify if they were related to the objective of the proposed article, which is to evaluate the possible applications of ash from sugarcane bagasse.

After reading the items, 102 articles were not within the context, with a total of 223 articles used for the development of this paper.

To obtain these results in the databases, research was carried out considering only the original articles. The keywords should also appear only in the title, abstract, or keywords of the articles. The articles selected for research sought to evaluate items such as year of publication, main authors, and countries of affiliation, in addition to the objectives, methods, and results of each selected article. Moreover, we sought to classify the themes discussed in the articles to make the discussion of results easier.

Results and Discussion

The articles used for the development of the present paper were classified according to their year of publication, as shown in Figure 1. It can be seen from the results presented that those papers that deal with the possible uses of sugarcane bagasse ash are relatively recent, with publication dates after 2006. In addition, there has been a significant growth over the last five years, which makes the growing concern to find a viable application visible, both economically and environmentally, for this type of by-product.

As for the countries where these publications were developed, there is a total of 22 countries, among which Brazil stands out for the number of publications with 50 articles, followed by India, with 45 articles. Figure 2 shows the countries most cited in the evaluated publications. Both Brazil and India account for approximately 70% of all papers. This can be explained by the fact that these two countries are the two largest sugar cane producers in the world (LEITE *et al*., 2018), leading to the generation of a large amount of ash from sugar cane bagasse and, consequently, the need to seek viable alternatives for its use.

Other pieces of information extracted were regarding the authors of each country, as well as the number of articles published by each researcher. In Brazil, among the evaluated publications, the researcher who most published papers on the topic was Holanda JNF, with 12 published articles, followed by Faria KCP, with 7 articles, Sales A., with 6 articles, and authors Akasaki JL, Melges JLP and Tashima MM, with 5 articles each. In India, the researchers who most published works on the topic were Madurwar M., with 7 articles, Ralegaonkar M., with 6 articles, Bahurudeen A., with 5 articles, and Santhanam M. with 4 articles. In the other countries with published articles on the topic, the authors participated in less than 4 papers, therefore not cited.

It is noticed that, unlike other topics, there are not many authors with large amounts of publications on the topic studied. This is indicative of the novelty of the topic in the technical and scientific world. Much of the knowledge is acquired empirically during the processing of ash, such as during its use as a fertilizer, which is developed, usually without control, by the big producers or processors of this material.

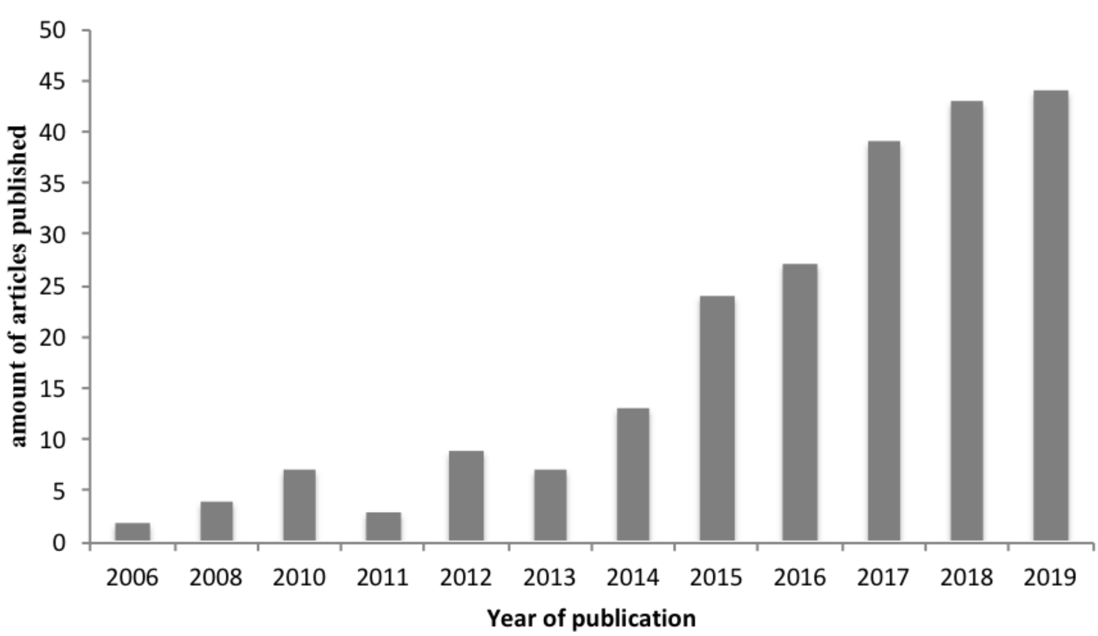

Figure 1 – Classification of publications by year.

To assess the main axes used in research on the possible applications of sugarcane ash, the papers found were categorized according to the evaluated application. Most of them, approximately 60% of all articles evaluated, studied the application of ash from sugarcane bagasse in joint applications or as a substitute for Portland cement. The second most common theme was the use to replace components used in the manufacture of red ceramics, accounting for almost 20% of all articles. Some studies have also dealt with the use of by-product for soil treatment and stabilization and as adsorbent material, making up 7 and 3.2% of the papers, respectively. The other papers evaluated varied applications, with 1 or at most 2 papers per theme, not addressed in the discussions.

Substitute in formulations of Portland cement concrete

Ash from sugarcane bagasse is promising in the partial replacement of Portland cement, showing that this material may have pozzolanic activity. In several studies, the influence of different methods of processing sugarcane bagasse ash as to pozzolanic properties are observed (BAHURUDEEN; SANTHANAM, 2015).

Some studies have evaluated the replacement of Portland cement for sugarcane bagasse ash in the proportions of 10 to 30%, together with rice husk ash. The resistance of mixtures increased by 5% after 90 days, compared to the reference sample, but when ash rates increased to 25 and 30%, there was a reduction in the compressive strength. In relation to electrical resistivity, the replacement of 20% of Portland cement for sugarcane bagasse ash promotes a 159% increase in electrical resistivity with a 90-day cure time. (JOSHAGHANI; MOEINI, 2018).

A study carried out in 2018 investigated the potential of sugarcane ash to make concrete mixtures. The economic analysis showed that the incorporation of this by-product can reduce the total cost of 1 m^3 of concrete by more than 40% compared to conventional concrete (SINGH *et al*., 2018).

Another study evaluated the substitution of fine aggregate with substitutions of 5 to 20% for ash, showing results very similar to pure cement. It shows that the best performance of the trace is with 20% ash from the sugarcane bagasse in relation to the reference concrete (FERNANDES *et al*., 2015).

Another study investigated the possibility of the combined use of agro- and industrial waste in the development of concrete. Characteristics of self-compacting concrete made from cement mixed with ash from sugarcane bagasse and common Portland cement were examined in an experimental program. The results of the tests indicated that the substitution for sugarcane bagasse in mixtures resulted in less fluidity and increased levels of sulfate (LE; SHEEN; LAM, 2018). Some results indicate that 10% of the mixture of sugarcane bagasse ash with cement is the ideal percentage to obtain efficient and, consequently, more ecological self-compacting concrete (KHATUN; SINGH; SHARMA, 2018).

An experimental study with sugarcane bagasse ash replacing cement in 5, 10, 15, 20, and 25%, by mass, was carried out in common, light and self-compacting concretes. The mechanical properties, such as compressive strength, tensile strength, impact resistance, workability, water absorption, and ultrasonic pulse speed were performed on the samples. The results indicated improvements in strength and impact resistance at light weight, as well as durability and quality of cement with mass substitution at 5%. The tests were carried out on fresh and hardened concrete.

The partial substitution of lightweight cement for ash improved the performance of lightweight concrete, more than other types of con-

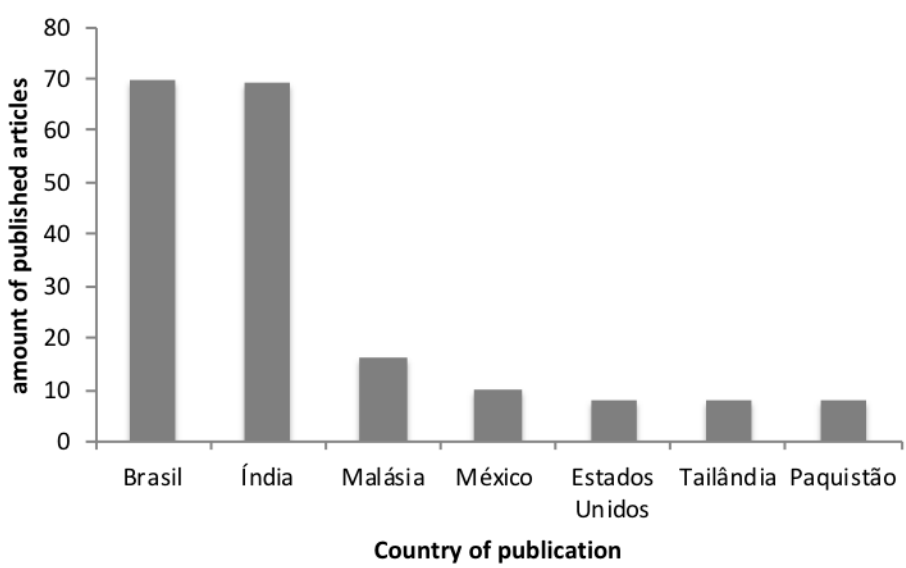

Figure 2 – Classification of publications according to the authors' country of affiliation.

crete. With the addition of 5% of sugarcane bagasse ash, the strength properties of light cement improved. The demand for water increases in the same proportion of the added ash, due to the carbon content and the porous irregularities of ash. When replacing 5% of cement for ash, there was also an increase in durability and impact. Tests show that the optimal replacement of cement is in the percentages of 5% in normal weight (ZAREEI; AMERI; BAHRAMI, 2018).

The results obtained for partial replacement of Portland cement in concrete, in the proportions of 0, 10, 15, and 20%, by weight, also indicated that the strength of the concrete increased with the replacement of 15% of cement for ash from sugarcane bagasse sugar (SIREESHA; RAO; RAO, 2013).

Red ceramic replacement

The use of sugarcane bagasse ash in the production of ceramic tiles, containing up to 2.5% by weight of ash is a partial substitute for quartz. The test results, in terms of strength, flexion, apparent density, linear shrinkage and water absorption, indicated a great potential of ash for its industrial application (SCHETTINO; HOLANDA, 2015a).

A study developed in 2017 reported that the thermal conductivity of bricks is an important parameter, because it directly influences the heat loss of buildings and, therefore, increases energy consumption. Thermally burnt clay bricks were developed, incorporating agricultural residues (sugar cane bagasse ash and rice husk ash) on an industrial scale. It was observed that lighter bricks can be produced with agricultural by-product, which helps to reduce the cost and the overall weight of the structure (KAZMI *et al*., 2018).

Faria and Holanda (2013) studied the replacement of up to 20% of natural clay mass for sugarcane ash. The results in water absorption showed only a small variation (22.76–27.40%). At 1,100ºC, there was a significant decrease in water absorption (14.45–19.50%), caused by partial closure of open pores. For an addition of 20% of sugarcane bagasse ash, the ideal temperature is 1,100ºC. For burning without ash, the ideal temperature is between 700 and 1,100ºC.

For the replacement of up to 60% of natural clay for ash in the manufacturing process of tile, technological tests show that at temperatures up to 1,000ºC, the ash from sugarcane bagasse have little influence on the properties of clay, and after 1,200ºC, X-ray diffraction data and thermal analysis showed that ash undergoes a sintering process and the formation of new phases. The addition of 60% of ash from sugarcane bagasse showed little resistance to flexion; on the other hand, the replacement of ash at 20% had very good results, staying within acceptable standard measures (SOUZA *et al*., 2011).

The flexural strength gradually decreased with the addition of sugarcane bagasse ash by-products, this result may be related to the porosity of pieces. The apparent density was essentially unchanged after the addition of sugarcane bagasse ash by-products. The incorporation of larger amounts of ash by-products tend to decrease the rate of densification of porcelain stoneware tiles. With the addition of sugarcane bagasse ash there was a variation in porosity, in which the permissible percentage is found in the substitution of 5% of the mass weight. The results showed that the replacement of the ceramic mass for sugarcane ash in 2.5% of the weight can be used as a partial substitute for stoneware porcelain, maintaining excellent technical properties. The flexural strength gradually decreased with the addition of sugarcane bagasse ash by-products, result which may be related to the porosity of pieces. The incorporation of larger amounts of ash by-products tend to decrease the rate of densification of porcelain stoneware tiles (SCHETTINO; HOLANDA, 2015b).

Another study evaluated the influence of adding ash from sugarcane bagasse on the performance in red ceramics as well. Two methods were evaluated: conventional sintering in an electric oven and microwave sintering. The results indicate that microwave sintering, when compared to sintering in an electric oven, promoted an increase in compressive strength and reduced adsorption water for the ceramic masses, probably due to the microstructure refinement. The addition of ash from sugarcane bagasse led to a reduction in the density of samples, especially those synthesized in the microwave (LYRA *et al*. 2019).

Soil treatment and stabilization

A major challenge for road contractors, as to the manufacture of paved roads, relies on expansive soils. Expansive soils undergo volume changes, depending on the humidity and weight of the mass that travel over soils or roads. Engineers are looking for a satisfactory, low-cost solution for the ash from sugarcane bagasse to solve this problem. In laboratory tests, percentages of ash and hydrated lime of up to 25% of the dry mass of the soil were used. Some tests developed show that the longer the curing time, the better the results obtained. (HASAN *et al*., 2016).

Very satisfactory results are obtained regarding the use of sugarcane bagasse ash in the construction of paved roads. The study evaluated the use of ash mixed with cement, replacing hydrated lime, in the proportions of 3, 6, and 9%, with the best mixture content found in the application of 9%, with a cure of forty days (KHAN; KAMAL; HAROON, 2015).

Moreover, with the addition of 9% cement to the ash from sugarcane bagasse, there was a double increase in resistance to compression and maximum dry density, after 40 days of curing. The ash from sugarcane bagasse had very positive results, regarding environmental protection, appropriate waste management and the saving of raw materials. In short, the use of sugarcane ash is a great alternative in the application of road construction (KHAN; KAMAL; HAROON, 2015).

The tests show that the percentages of ash application vary, according to the application and the desired results for each application, being quite satisfactory and collaborating with the environment, and reducing financial resources (MALATHY *et al*., 2018).

The use of sugarcane bagasse ash was also evaluated in peat stabilization. Studies show that the partial replacement of peat stabilized at 20% of ash from sugarcane bagasse mass has very positive results. The pre-consolidation pressure increased with the curing period. In short, the results were quite significant, and the applications can be improved (ABU TALIB; YASUFUKU; ISHIKURA, 2015).

A study was carried out to evaluate the effects of adding sugarcane bagasse ash to the development of the strength of an expansive soil stabilized with lime. The results revealed that the addition of sugarcane bagasse increased the immediate, early, and late resistance of the stabilized soil (JAMES; PANDIAN, 2018).

Other studies have also been carried out with mixtures of different types of ash, such as rice husk ash, cattle manure ash, and sugar cane bagasse ash. The mixtures were used in weight percentages from 0 to 12.5% in soils. For each type of soil application, as well as its variables, such as microscopic properties and temperature, there is a need of collecting information, both of the soil variables and the desired purpose, so that it is possible to apply sugarcane bagasse ash and other organic materials to stabilize soils (JUN, 2011).

The natural, dry clay, after stabilization, increased the natural moisture. The results showed the optimum content of the substitution, in mass, of the ash with 7.5% with significant improvements in the natural humidity and volume (JUN, 2011).

In the case of its use for soil treatment, it is known that depending on the source of ash, it can present nutrients for the cultivation of annual plants. In Brazil, considering that there is a large area of oxisol, which unfortunately has little fertility and a lot of acidity, such by-product can be used for treatment and fertilization of these areas. Ash application raises the nutritional status of the soil to a sufficiently satisfactory level, guaranteeing adequate nutritional conditions for the growth and yield of most crops. The ash was effective in reducing acidity and improving soil fertility (FERREIRA; FAGERIAE; DIDONET, 2012).

It is known that sugarcane bagasse ash is also used for soil biofertilization, without protocol. This indicates the need to develop studies and create methods for the use of these by-products with a focus on the correct management and application in the soil without causing damage to the environment (XAVIER *et al*., 2019).

Other studies carried out by Lima (2011) evaluated the availability of Phosphorus (P) for soils treated with organic materials rich in silicon for the cultivation of sugarcane. Five compounds were studied, among which are sugarcane bagasse and sugarcane bagasse ash. The results showed a reduction in phosphorus (P) fixation by the soil but contributed to the absorption of this element by the sugarcane culture. The compounds containing sugarcane bagasse ash did not contribute to the increase in the levels of Si available in the soil.

Adsorbent material

A study undertaken in 2019 showed that silicon dioxide (SiO_2) nanoparticles were synthesized via sol-gel using sugarcane bagasse ash as a source of silica. The results showed that this synthesis is a viable alternative method for obtaining silica xerogel (adsorbent material) using ash with a high content of impurities (FALK *et al*., 2019).

The activated carbon extracted from the ash from sugarcane bagasse at a temperature of 900ºC was tested in the adsorption of lead (Pb^{2+}). In the process, the heating was 10ºC/min, with a residence time of three hours. The lead adsorption test using sugarcane bagasse ash was dependent on pH and dosage. The tests showed that the maximum efficiency of Pb^{2+} was 87.3% (SALIHI *et al*., 2016a).

Activated, unburned and steam-activated coal has its properties compared to commercial coal. The study was carried out on two by-products of distilleries, namely, melanoidins and unburned carbon, both extracted in the distillery process. According to the studies, the two carbons are suitable for the adsorption of melanoidins with the addition of 25% pyridine (KAUSHIK *et al*., 2017).

The results of using the sugarcane bagasse ash as an adsorbent were very satisfactory, because the optimal removal efficiency was achieved at a pH of 6.0. The ideal equilibrium time required for zinc adsorption was found in 180 min. Given that the ash dosage increased, the number of active sites for adsorption of zinc ions also increased. The results showed an excellent efficiency in the removal of zinc, in the percentage of 89.7% obtained in a dose of 10 g/L of the ash from the sugarcane bagasse. The ash was proved to be useful as an adsorbent for the removal of metal ions from aqueous solutions (SALIHI *et al*., 2016b).

The adsorption of melanoidins on both carbons (activated carbon from sugarcane bagasse ash and commercial activated carbon). Both carbons are suitable for the adsorption of melanoidins followed by desorption by 25% pyridine solution. Yield of melanoidins obtained from sugarcane ash was like that obtained with commercial activated carbon. Therefore, ash residues from sugar cane factories can be an alternative material to produce activated carbon with properties similar to commercial activated carbon (KAUSHIK *et al*., 2017).

Final considerations

The disposal of ash from sugarcane bagasse is a problem that has been gaining prominence in the world, considering it can cause, in addition to other problems, the contamination of soils and water. Thus, scholars are trying to find an efficient and legal way to dispose of this by-product.

Several applications can be considered to correctly dispose of this by-product, some with a higher incidence of studies, and others with only previous evaluations. Among the applications that are highly evaluated and in which this material has good efficiency, we can mention the use in Portland cement composites, either as a partial replacement for cement or fine aggregates, with the objective of increasing their mechanical resistance.

The second most studied topic was the replacement of clay in the ceramic industry. In this application, there are many variables, as the substitution of clay depends on some variables, from applied temperatures to the granulometry of the material.

Besides that, the sugarcane bagasse ash can be efficiently used to stabilize soils with expansive properties or to correct some compounds in the soil, as fertilizing in this case.

In short, the application of sugarcane ash is not an easy task. There are many variables to be considered, such as the region, the cane specimen, the time the bagasse burns, the granulometry of ash, the curing temperature, the pozzolanic reaction with other substances, among others, which requires the researcher to pay special attention to its application.

The results of this paper show that it is possible to apply ash in several areas. On the other hand, there is no standard model to be followed. For each application, a study related to the properties of the available ash should be made.

Contribution of authors:

Duarte, G.W.: Conceptualization, Methodology, Project administration, Writing — Review & Editing. Hobold, M.C.:Data curation, Formal analysis, Writing — original draft. Matos, A.H.: Data curation, Formal analysis, Writing — original draft. Silva, K.A.: Data curation, Formal analysis, Writing — original draft. Duarte, G.W.: Data curation, Formal analysis, Writing — original draft.

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Legal Amazon, sustainable use and environmental surveillance "systems": historical legacy and future prospects

A Amazônia Legal, uso sustentável e "sistemas" de vigilância ambiental: legado histórico e perspectivas futuras

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ABSTRACT

Tropical rainforests are among the most endangered biomes on the planet. They have become the new frontiers for capital expansion, both for the production of agricultural commodities and the exploitation of their natural resources. This article seeks to analyze how the command and control system is being practiced on one of such tropical rainforests, namely the Brazilian Amazon. To achieve the objectives set in the research, exploratory/descriptive methods of qualitative and quantitative approach were carried out through field research and literature review on the subject. In addition, we evaluated the publications that best described the "state of the art" of the theme, always aiming at the quality and comprehensiveness of research by bibliometric mining and field survey through questionnaires administered to military police corporations. While examining the environmental protection agencies and law enforcement agencies, both from Union and the states that make up the Legal Amazon, the conclusion was that all of them devote very little material resources to effective forest protection, and that human resources are infinitely smaller than those recommended by other international nature protection organizations. Moreover, the structure in charge of investigating environmental crimes in the states is either poor or non-existent, and distant from the main regions of deforestation and other environmental crimes, something which favors impunity. It is concluded that the lack of structure of command and control bodies in the Amazon threatens the sustainability of the ecosystem, the economy and the society on local, regional, and global levels.

Keywords: military police; environmental security; environmental inspection; command and control; public policies.

RESUMO

As florestas tropicais úmidas estão entre os biomas mais ameaçados do planeta. Elas se tornaram as novas fronteiras de expansão do capital, tanto para a produção de *commodities* agrícolas quanto para a exploração de seus recursos naturais. Este artigo procura analisar como está sendo praticado o sistema de comando e controle sobre uma dessas florestas tropicais úmidas: a Amazônia brasileira. Para alcançar os objetivos traçados na pesquisa, foram empregados métodos exploratórios-descritivos de abordagem qualitativa e quantitativa, realizados por meio de pesquisa de campo e revisão da literatura sobre o assunto. Ainda se avaliou as publicações que melhor descrevessem o "estado da arte" do tema, sempre visando a qualidade e abrangência das pesquisas por mineração bibliométrica e levantamento de campo por meio de questionários administrados às corporações policiais militares. Examinando-se as agências e organizações policiais responsáveis pela proteção ambiental da União quanto aos estados que integram a Amazônia Legal verificou-se que todas elas dedicam poucos recursos materiais para uma proteção efetiva da floresta, bem como os recursos humanos são infinitamente menores do que o recomendado por organizações internacionais de proteção na natureza. Além disso, a estrutura responsável por investigar nos estados os crimes ambientais é pobre ou inexistente e distante das principais regiões de desmatamento e outros crimes ambientais, o que favorece a impunidade. Conclui-se que a falta de estrutura dos órgãos de comando e controle na Amazônia ameaça a sustentabilidade do ecossistema, da economia e da sociedade local, regional e global.

Palavras-chave: polícia militar; segurança ambiental; fiscalização ambiental; comando e controle; políticas públicas.

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Introduction

Tropical rainforests are the most ecologically diverse biomes on the planet. They are found in more than half of all species of biomes in the world, although they comprise only 7% of the Earth's surface. They are distributed around 10º latitude north and south of Ecuador and are found in three main regions: the Indo-Malaysian regions of Borneo and New Guinea; the Congo, Niger, and Zambezi watersheds in Central Africa; and the Amazon and Orinoco watersheds in South America (KORMONDY; BROWN, 2002; ODUM; BARRETT, 2007).

These biomes are among the oldest on Earth and have global ecological importance. Rainforests do not merely influence the climate through ecoclimatic teleconnections, but are also responsible for capturing and storing huge amounts of carbon dioxide and other greenhouse gases, as well as other air pollutants. However, researchers have indicated that such capture capacity has declined by around 30% in recent decades (BRIENEN *et al.*, 2015; GARCIA *et al.*, 2016).

In addition, they are potential sources of new types of foods, materials, active medicinal ingredients, among others yet to be learned. However, rainforests are being threatened by the new frontiers of capital expansion. Vast areas are cleared for the implementation of large agricultural and livestock production projects (KORMONDY; BROWN, 2002; FARIA; ALMEIDA, 2016). In the last 20 years, the planet's rainforests have lost 10% of their areas, mainly in the Amazon and Central Africa (WATSON *et al.*, 2016).

Economic pressures for new agricultural commodities, however, are not the only vectors that threaten tropical forests. Environmental damage and crime are also serious threats to humanity. Environmental degradation and climate change may increase competition over natural resources, accentuating economic inequalities, worsening social dissatisfaction, and promoting human displacement within and between nations, thus impacting human security (COATS, 2019).

Environmental crimes are also transnational. Associated with them are other crimes such as poaching and illegal trafficking of animals, predatory fishing, as well as illegal mining, consequently causing water contamination, and deforestation. There are crimes related to falsifying public documents, corruption, and usurpation as well. These associated crimes promote the evasion of currency from the very same states where such crimes occur, as well as damage to the environment. Such crimes were formed in a branch of an extensive network of organized crime, to the extent of becoming the fourth largest illegal activity in the world, trading between $ 91 and 258 billion (US dollar) per year (NELLEMANN, 2016; COATS, 2019).

The main objective of the research was to evaluate how the command and control system is being exerted on one of these tropical rainforests, namely the Brazilian Amazon. It is conjectured that the personnel deployed for command and control are undersized, and that the several existing bodies act in an uncoordinated, disconnected, and discontinued manner. The study was limited to the analysis of the military police of Legal Amazon's states, whose mission is to prevent environmental crimes from being committed in this biome and to ensure that its resources are exploited sustainably.

Methodology

The methodological aspects were underpinned by an exploratory research through a census conducted among the environmental military police (PMAm for its acronym in Portuguese) of the Legal Amazon states, in which we ran a questionnaire with open, closed and dependent questions, between January and February 2019.

The questionnaire focused on the following: the number of headquarters and sub-offices that the environmental military police had; what they were called; the staff of each headquarters and sub-offices; how many police stations specialized in the investigation of environmental crimes the state counted on, what they called themselves, where they were located, and what their opening hours were; if the PMAm employed remote sensing or other geotechnology in order to monitor crimes against the flora, and, in doing so, who performed this processing and where it was carried out (in the headquarters itself or in the headquarters of another body); in the case of employing another geotechnology different from remote sensing, what would be the other one, and for what purpose it was employed; if there was some kind of official technical cooperation agreement between the state environmental agency and the PMAm, and if so, what it covered, what the counterparts would be and what their duration was; and finally, what was the opinion of the PMAm in relation to the state environmental agency in order to exercise its responsibility for environmental protection and supervision effectively.

The primary data from the questionnaires were tabulated and interpreted both qualitatively and quantitatively. Following the analysis, 18 variables were raised, which due to their characteristics, had the power to impact more directly the activities of environmental surveillance by the PMAm.

The analysis variables (Table 1) were organized in four dimensions by their socio-geographic, logistic, geotechnological, and administrative characteristics.

Subsequently, the variables were compared with data from secondary sources obtained from documentary and bibliographic researches, latter by the bibliometric method using the data mining technique. Thus, an indexed search was performed for the keywords of the article (Amazon; military police; environmental security; environmental surveillance) and their thesauri and terms that represented them in English. The keywords were searched individually, and subsequently, a combinatorial analysis was performed two by two, three by three, and finally all together, using the Boolean operators of the Scopus database (Elsevier). The search was limited to the most cited peer-reviewed journals of the last five years (REDONDO *et al.*, 2017).

Finally, the analysis was performed. The data obtained were gathered, tabulated, treated according to statistical principles and related to each other. Furthermore, they were organized according to the

Table 1 – Variables of analyses.

Dimension	Variable	Description	Type	Category / Unit of measure
Socio-geographic	1. State territorial area	shows the territorial area of the state	Discrete quantitative	km^2
	2. Conservation unit area	shows the conservation unit area of the Amazon biome	Discrete quantitative	km^2
	3. PMAm staff	shows the amount of military police officer (PM) in the environmental military police unit	Discrete quantitative	number of PM
	4. Active force of military police corps	shows the active personnel of the state military police corps	Discrete quantitative	number of PM in active service
	5. Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) staff	shows the number of IBAMA agents applied in environmental surveillance	Discrete quantitative	number of IBAMA agents
	6. Chico Mendes Institute for Conservation of Biodiversity (ICMBio) staff	shows the number of ICMBio agents applied in environmental surveillance	Discrete quantitative	number of ICMBio agents
	7. Geospatialization of PMAm's headquarters and sub-offices in the state territory	shows the location of PMAm headquarters and sub-offices in state	Nominal qualitative	headquarters and sub-offices address
Logistics	8. Number of vehicles	shows the number of vehicles that the PMAm had to perform its environmental inspection activities	Discrete quantitative	number of vehicles
	9. Number of vessels	shows the number of vessels that the PMAm had to perform its environmental inspection activities	Discrete quantitative	number of vessels
Geotechnological	10. Use of remote sensing or other geotechnology	shows whether the PMAm used remote sensing or other geotechnology	Dichotomous nominal qualitative	yes / no
	11. Place where monitoring was carried out	shows the address of the geoprocessing sector	Nominal qualitative	address
	12. Purpose of using the data	shows the operational use of geoprocessed information	Nominal qualitative	use of information
Administrative	14. Existence of technical cooperation	shows the existence of official instrument of cooperation between the PMAm and the state environmental agency	Dichotomous nominal qualitative	yes / no
	15. Existing co-responsibility	shows the existing co-responsibilities in the technical cooperation instrument established between the PMAm and the state environmental agency	Nominal qualitative	description of co-responsibilities
	16. Number of police stations specialized in the investigation of environmental crimes	shows the number of police stations specialized in the investigation of environmental crimes	Discrete quantitative	number of specialized police stations
	17. The hours of the police station specialized in the investigation of environmental crimes run	shows the hours which police stations specialized in the investigation of environmental crimes run	Continuous quantitative	run hours
	18. Opinion of the effectiveness of the state environmental agency (sectional) in the protection of nature	shows the PMAm's opinion regarding the state environmental agency's action in order to protect nature	Nominal qualitative	ineffective, low effective, high effective, does not know how to inform

Brazilian state political-administrative division and their frequencies were calculated following the most widely used descriptive measures of central tendency, mean and mode. Therefore, it allowed an accurate analysis of environmental surveillance in the Legal Amazon, as it can be observed in the next section.

Results and discussion

Environmental security and sustainable use of natural resources in Amazon

The colonization of the Amazon

In the early years of colonization, the Amazon was characterized by actions aimed at maintaining Portuguese sovereignty over newly discovered lands. However, this sovereignty was only ensured if the possessor or discoverer colonized the territory. Portugal founded the city of Belém in 1616 after expelling the English, French, and Dutch, thus assuring sovereignty over the entire Amazon River basin and the Brazilian north coast, initiating the process of colonization of the Amazon (PICOLI, 2006; FURTADO, 2007; DEAN, 2007; BECKER, 2016).

In the second half of the eighteenth century, the engine of development was gold mining activities. The discovery of deposits in Minas Gerais, Cuiabá, and Goiás promoted the dream of the discovery of the Brazilian "El Dorado", also in the Amazon, the place where all the great rivers and forests inhabited by warrior women – the Amazons – originated. The Amazons, who held treasures of precious stones, remained in the imagination of explorers — so-called Bandeirantes. The search for these treasures led the Paulistan Bandeirantes to reach the headwaters of the São Francisco, the Paraguay, and the Amazon rivers, also generating a new European migratory wave for the region (DEAN, 2007).

The nineteenth century was marked not only by the Cabana Revolution, but also by the great migratory waves, the rubber trees latex extractive activities, and the trafficking of their seeds. Large numbers of northeastern peasants migrated to the region fleeing the drought scourge in search of wealth resulting from the exploitation of rubber. In the same period, the British trafficked thousands of rubber tree seeds to London acclimatized them and developed commercial plantations in their colonies in Ceylon, Singapore, and Malaysia, breaking the Brazilian monopoly (PICOLI, 2006; FURTADO, 2007).

Extensive latex production in Asian countries not only caused the price of rubber to fall by more than 80%, but also quickly spread misery. As a result, it turned the rubber tappers to their own most primitive subsistence economy: hunting, fishing, and extrativism, similar to their native forefathers. Rubber was the most sought-after commodity in the world market between the last years of the nineteenth and early twentieth centuries, especially in industrialized countries (FURTADO, 2007).

Although the price of latex has devalued due to oversupply, the region has developed adversely. The major beneficiaries of the profits were the agents of the rubber sector and the large landowners, while the rubber tappers were subjected to a regime of semi-slavery or servitude, which reduced their life expectancy due to exposure to the dangerous and unhealthy forest environment (BECKER, 2016).

Until the early twentieth century, the occupation of the Amazon was shy, since Portuguese colonization concentrated on the Brazilian Atlantic coast. Paradoxical though it may seem, World War II promoted a new cycle of economic development for the Brazilian hylean. Japan ruled over the Malaysian and Burmese rubber groves. As a consequence, the Americans resorted to Brazil as the main source of latex, formerly exploited from the two English colonies. However, production was again compromised by the lack of workforce. The option was once again the northeastern people, who were left with two options: to become "rubber soldiers" in the Amazon or "Brazilian soldiers" on the Italian battlefront during World War II (PICOLI, 2006; BECKER, 2016).

In the second half of the twentieth century, the Amazon benefited from the development of coffee-industrial culture in the Southeast region, which began to absorb all rubber production allowing the opening of new production lines, such as jute (FURTADO, 2007). From this period on, the region has been occupied in three manners:

- through spontaneous colonization;
- government direction through land distribution;
- promotion by private real estate speculation companies (companies of colonization) (PICOLI, 2006).

The process of colonization of The Amazon, however, has intensified within the last 50 years, due to the development of large infrastructure projects, such as the construction of hydroelectric power stations and federal highways. The highways promoted the integration of the Amazon with the rest of the country, becoming the engine of this process (PICOLI, 2006). They have changed the pattern of regional mobility dynamics. The connectivity between the regions, which was previously performed by waterways, is now centred on the road axes (paved roads and roads opened by loggers), facilitating the creation of settlements along these axes (Figure 1). The three main frontiers of colonization in recent times were: the municipality of São Félix do Xingu, in Pará; BR-163, the Cuiabá-Santarém highway further north of Mato Grosso; and the northern part of Mato Grosso and Rondônia towards the southern region in the state of Amazonas (BECKER, 2016).

The pattern of colonization contributed to the increase in deforestation in the region. These works reached an area of influence around 50 km from each bank. In other words, they have impacted even specially protected areas within this distance (BRASIL, 2018c).

More than colonizing expansion fronts, these new frontiers have tended to consolidate settlements due to the significant economic development and technological transformation of *agribusiness*. Soybean and cotton crops grew in production in southern Pará (PA), while agriculture advanced in southern PA and Mato Grosso (MT). The degradation and deforestation that has occurred in the south-southeastern regions of PA, extending to the west through the north of MT and Rondônia (RO), and southern Amazonas (AM) has been so intense that it has become known as “Fire Arch” or “Deforestation Arch” (Figure 2) (BECKER, 2016).

The colonization projects delivered by the government to the private sector were another vector of Amazonian penetration. They were developed on unoccupied Union land that would be primarily intended for land reform. However, colonization companies benefited few rural workers. The criterion of land distribution used was the purchasing power of the interested parties, which favoured those with greater financial resources (PICOLI, 2006; BECKER, 2016).

During the process of land distribution, large numbers of migrants, either unemployed or underemployed workers, moved in search of occupation. However, the process was not peaceful or fair. Invariably, landless workers and squatters arrived after the giant landlords or even after domestic or foreign businesspeople, carrying out an agrarian reform inside out. The tactic used was the expropriation of the lands of their original inhabitants, the Indians, and the squatters, who did not have documentation to legitimize rightful ownership of the land. Holders of capital and political power, farmers and landowners, land grabbers, gunmen and *jagunços* spread terror and violence in the region in order to appropriate land (PICOLI, 2006; TOLLEFSON, 2015).

Projects such as agriculture and the woodworking industry thrived, thanks to the high profitability of the commercialization of rich and noble timber. Moreover, logging was associated with agriculture, since deforested areas quickly became cattle pasture. These activities gave the region a boost and became its economic base until the present day (PICOLI, 2006).

One of the consequences of this process in the Amazon was the slumming of cities. Throughout human history, the cities have been centers of economic and political power. On the one hand, cities were modernizing in structures and services in order to attend necessity demanded by both the ruling economic and political classes. On the other hand, large estates could not absorb all the available labour. Thus, idle labor migrated to large urban centers, giving rise to slums and stilts, the “human clusters of exclusion”, especially in those cities that had rural *commodities* and were export corridors. These spaces became belts of poverty and misery, bringing huge social costs to those who inhabited them. Since the individuals inhabiting these spaces were ostracized and placed in the outskirts of town less supplied by basic public services, they did not create an emotional link with that new territory. In other words, they became *deterritorialized* (COSTA, 2004, p. 278; PICOLI, 2006; RICHARDS; VANWEY, 2015).

The last decades of the twentieth century brought new challenges to the Amazon. It was the region with the highest urban growth rates in the country, according to the 2000 Census. Although, the cities within the Amazon still lack basic public services despite such growth. Furthermore, environmental awareness has sprouted a sense of unity in

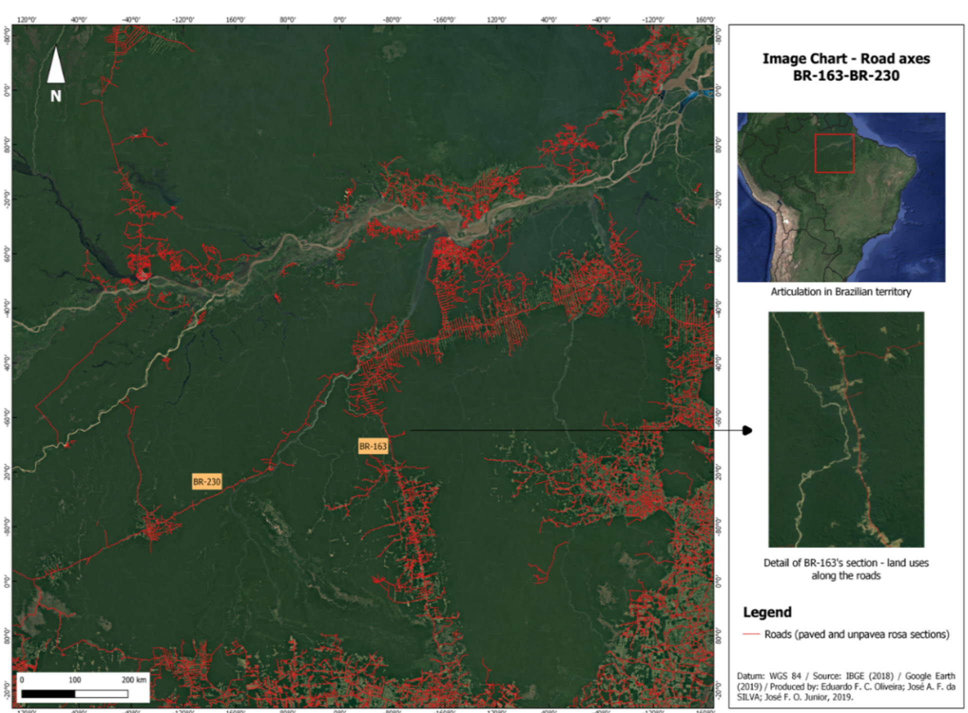

Figure 1 – BR-163 and BR-230 Road Axes.

the world and Brazil, thanks mainly to the advancement of geotechnologies. These conditions were adequate for the proliferation of several civil society organizations. By this time, the environment was already the second biggest concern of young people in big cities (SVIRSKY; CAPOBIANCO, 1997; DEAN, 2007; BECKER, 2016).

In this regard, Becker (2016) noted that the Amazon had become an “urban forest” due to its significant urban growth in the last two decades of the twentieth century. Although this development has generated high social and environmental costs, it was thanks to it that the region has achieved the level of progress it currently has, even with social indicators still lower than the rest of the country. However, socio-environmental conflicts emerged in the 1990s between policymakers and those who wanted to protect the environment, advocating economic development through the sustainable exploitation of the forest and its natural resources. The defence of the forest and its resources killed in Brazil about 622 activists between 2002 and 2017 (MIDDELDORP; LE BILLON, 2019).

Today, the Amazon is no longer a frontier for migratory expansion, but a region with its production structure and multi-stakeholder projects. Civil society is a key player in this movement, both in rural and urban areas. Faced with the economic and political crisis of the central government, the Amazon states assumed the political responsibility to develop their own regions. These states adopted different strategies, such as extensive land use in the cases of Mato Grosso and Pará, and industrial development, as was the case of Amazonas, with the establishment of the “Manaus Free Zone” (BECKER, 2016; NOBRE *et al*., 2016).

Forest preservation is directly related to the development of sustainable products that can compete in terms of economic value with livestock and logging. This involves a scientific and technological revolution of the Amazon Forest, based on the techno-productive chain and biodiversity, as well as transforming forest communities into centers of advanced technology (BECKER, 2016).

Geotechnologies and the Geopolitics of the Amazon

According to Becker (2016, p. 16), geopolitics “is a field of knowledge which analyzes relations between power and geographical space”. Thus, the development of geotechnologies remote sensing, brought two important changes in perspectives on the Amazon region.

First, a supported by geotechnologies. Satellite imageries have heightened awareness of the Amazon by highlighting the role it plays as a forest in capturing and storing greenhouse gases, so crucial to mitigating the effects of global warming and preserving biodiversity. The result of this change has been that nature-provided ecosystem services have been re-evaluated and revalued (COSTANZA *et al*., 2014; BECKER, 2016).

Geotechnologies have made it possible to observe the planet as a whole and in a systemic way, giving rise to a common sense of respon-

Figure 2 – Burn in the Amazon, in the municipality of Altamira (PA).
Source: Figueiredo (2019).

sibility for its protection to a large portion of mankind. However, technological development and popularization in the production of *web* maps have promoted negative externalities, thanks to mobile mapping on portable devices and the development of free and open source software, such as deforestation in smaller areas than satellite imagery could capture (TSOU, 2011; MENEGUETTE, 2012). Therefore, between 2002 and 2009, the amount of small deforestation increased from 30 to 73% of all deforested areas in MT, PA, and RO, which makes remote surveillance difficult (ROSA; SOUZA JR.; EWERS, 2012; BECKER, 2016).

Second, the development of geotechnologies increased the need for governmental presence in the Amazon in order to maintain national sovereignty. From an economic point of view, the different sensors of satellite images facilitated and promoted the discovery of huge mineral riches in the underground of the Amazon, increasing international greed for the region. There was a strategic need for preservation of national sovereignty over the Amazon region by the Brazilian government through the thickening of the military presence in the region with the installation of multiple bases. The consequence of this process was the increase of areas under special protection, such as conservation units (UC for its acronym in Portuguese) and indigenous lands, comprising an area of more than 30% of the Amazon, equivalent to the territory of Spain (BRASIL, 2008b; PICOLI, 2006; BECKER, 2016).

Cunha e Menezes (2015, p. 210) found out that the creation of protected areas was part of this defence strategy, since protected areas "prevent land grabbing, restrict uncontrolled deforestation… direct migratory movements, and encourage development according to preconceived vectors".

The scarcity of the government's presence in the Amazon has happened for years. While the strategy of creating UC as a tool for maintaining sovereignty, seemed to be good in theory, on the other hand, it has been proven ineffective in recent years. Between May 2017 and May 2018, deforestation in the Amazon advanced 73%. Most of them in areas under the special protection regime, such as UC (30%), land reform settlements (13%), and indigenous lands (1%) (FONSECA *et al*., 2018). The impunity of criminals is also associated with deforestation in the areas that they operate. Only 10% of all administrative fines imposed by federal command and control agencies were paid (BARRETO *et al*., 2009). The creation of UC and the installation of military bases were not enough to stop the environmental crimes that plagued the Amazon.

Environmental security in the Amazon

Environmental security is the branch of scientific knowledge that studies how dynamics and connections between the environment, society and the economic engines influence the stability both local and regional. Yet it analyzes the role that natural resources play in promoting, preventing, mitigating, and resolving conflicts in all its dimensions. For this reason, environmental security plays a key role in the promotion and preservation of national security of any country (UNITED NATIONS ENVIRONMENT PROGRAM, 2009; INSTITUTE FOR ENVIRONMENTAL SECURITY, 2019).

The Legal Amazon has its largest portion inserted in the Brazilian northern region. In addition, this region was the most vulnerable from environmental monitoring by the environmental military police (PMAm for its acronym in Portuguese). Although it has the largest territorial extension, it has the smallest contingents of environmental military police and the smallest number of vehicles and vessels intended for surveillance. The region also uses less technological resources, such as aircraft and drones, and it is the region that employs least geotechnologies for remote sensing (CABRAL DE OLIVEIRA, 2018).

Environmental problems in the Amazon are not limited to deforestation; in reality, they have only become another branch of organized crime. There was a wide variety of crimes connected to a well-organized chain of diverse actors, from the humblest individual doing manual work to the leaders with great economic and/or political power, as well as public officials. In addition to deforestation, they included crimes such as hunting, for sporting purposes, meat consumption ,and the capturing of animals for trafficking; illegal mining activities; tax evasion; predatory fishing and catching ornamental fish for export; drug trafficking; smuggling of forest and biological products; money laundry; active and passive corruption, etc. (VAN VLIET *et al*., 2015; BECKER, 2016; UNGAR, 2017).

There were several negative externalities associated with these crimes. Among them, we could cite loss of soil productivity, changes in the hydrological system, loss of biodiversity, global warming, acculturation of indigenous and traditional communities, tax evasion, water and soil pollution, siltation of watercourses, and violence (UNGAR, 2017).

The interconnection between violence and environmental crimes in the Amazon has never been so clear. Following the work of Waiselfisz (2015) concerning the outbreaks of violence by municipalities, he identified that in addition to those outbreaks already traditionally located in urban centers and metropolitan regions, new ones appeared. Among them, the municipalities that make up the Amazon "Deforestation Arc", which accounted for about 65% of all deforested areas in the Amazon in 2016 (BRAZIL, 2018c). Especially in these places, crimes are associated with slave labour, illegal logging, land grabbing, the extermination of indigenous communities or the appropriation of their land, and large unproductive landlords — all with the goodwill of politicians and financial groups.

The importance of the Amazon for social and environmental balance

The Amazon and its concepts

The noun "Amazônia" refers to at least three geographically well-defined and diverse concepts. First, the biogeographic features the Amazon within biome perspective, i.e., a large continuous area with similar characteristics to biotic and abiotic (KORMONDY; BROWN, 2002; ODUM; BARRETT, 2007). In this light, the Amazon biome extends beyond Brazilian borders and extends over 7 million km^2, 60%

of them in Brazil and the rest distributed in eight other countries: Bolivia, Peru, Ecuador, Colombia, Venezuela, Guyana, France (French Guiana), and Suriname. The sheer size of the Amazon has influenced some authors to call it the South American or International Amazon (PICOLI, 2006; SANTOS, 2015).

According to the political-administrative concept, by derivation, it deals with the state of Amazonas as one of the 27 federative units that make up the Brazilian state as well as one of the seven states in the northern region of the country (Brazilian federative units and its abbreviation: Acre – AC, Alagoas – AL, Amazonas – AM, Amapá – AP, Bahia – BA, Ceará – CE, Distrito Federal – DF, Espírito Santo – ES, Goiás – GO, Maranhão – MA, Minas Gerais – MG, Mato Grosso do Sul – MS, Mato Grosso – MT, Pará – PA, Paraíba – PB, Pernambuco - PE, Piauí – PI, Paraná – PR, Rio de Janeiro – RJ, Rio Grande do Norte – RN, Rio Grande do Sul – RS, Rondônia – RO, Roraima – RR, Santa Catarina – SC, Sergipe – SE, São Paulo – SP, and Tocantins – TO).

Finally, the third approach defines the Amazon under the socioeconomic aspect. This approach was defined as of 1953 with the creation of the "Amazon Economic Recovery Plan" (BRASIL, 1953). However, the term "Legal Amazon" was only adopted from 2009 when the government attempted to regularize land occupations on land under the Union's domain and was later adopted in more recent legislation (BRASIL, 2009). Currently, the Legal Amazon comprises the area corresponding to the states of Acre (AC), Amazonas (AM), Amapá (AP), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR), Tocantins (TO), and part of Maranhão (MA) (BRAZIL, 2007). Figure 3 presents geographically the various concepts of the word "Amazon".

The Amazon as a biome, nonetheless, has its survival threatened firmly in its strengths: the forest, biodiversity, and water resources. It is estimated that around 20% of all vegetation in the Amazon rainforest has already been destroyed (NOBRE, 2014). The realization of these threats can impact Brazil and the world in several ways: on climate change at local, regional, and global levels; in the economy; and on biodiversity. These are the topics that will be covered in the next sections.

The Amazon and the climate change

The international community has drawn its attention to the Amazon, and the importance of this broad region is getting known around the world. If the Amazon were a country, it would be the 9th largest in the world. Since it comprehends a large mass of land, it has implications for the survival of *homo sapiens*, who as a species relies fundamentally on the preservation of the forest. It captures and stores 120 tons of carbon year^{-1}, mainly by large trees (diameter at breast height - dap ³ 60 cm), which accumulate almost half of all aboveground biomass. This represents more than 17 times the amount of carbon that the United States expels annually (SIST *et al.*, 2014; UNGAR, 2017). Thus, the Amazon plays a key role in global warming, capable of enhancing or mitigating its effects according to its use (BECKER, 2016; PHILLIPS; BRIENEN; THE RAINFOR COLLABORATION, 2017).

Moreover, rainforests promote life-critical ecosystem services. Approximately 90% of all moisture that reaches the atmosphere from terrestrial ecosystems did so through evapotranspiration (JASECHKO *et al.*, 2013). The recycling of water that the Amazon performs is essential for the water balance of the entire South American continent. It is estimated that only the Amazon transpires somewhere around 20 trillion litres of water a day^{-1}, forming true "flying rivers". These "rivers" are responsible for moisture in the Southeastern and Southern regions of Brazil, the Pantanal, the Chaco, and the agricultural areas of Bolivia, Paraguay, Uruguay, and Argentina, where it is discharged by rain, which also promotes an energy gradient, reducing atmospheric pressure and accelerating ocean winds inland.

Other factors that favour the occurrence of the "flying rivers" are the atmospheric circulation combined with the geological formation of the Americas. The distribution of deserts and wetlands on Earth are established by the largest latitudinal climate belts. They ensure that there is not merely a predominance of forests along equatorial latitude, but also the dominance of arid regions around the Tropics of Cancer and Capricorn. This phenomenon is known as Hadley's circulation. However, the geological formation of the Americas has caused the Andes to dominate the entire western portion of the continent, forming a barrier that directs the "flying rivers" to its south-central portion. This combination of factors caused the region to become an exception to the rule. Otherwise, it would be a true desert, such as those of Atacama, on the other side of the Andes; Namibia and Kalahari in southern Africa; and the Great Victoria Desert in Australia; all at the same latitude (NOBRE, 2014; RICKLEFS; RELYEA, 2014). Thus, decimating the Amazon forest would incur the interruption of this supply of moisture.

These true "Wooden geysers" not only perspire water, but also the evapotranspiration carry biogenic volatile organic compounds (BVO-Cs for its acronym in Portuguese), such as isoprene and monoterpenes, are essential for formation of clouding nuclei and rainfall production (SINDELAROVA *et al.*, 2014; CSETTKEY, 2015; WANG *et al.*, 2016). However, such phenomena neither are completely known, nor is synergy between them entirely understood. Also, forest evaporation and transpiration occur even during drought periods, although in pastures, the volume is much lower than those produced by forests (LOVEJOY; NOBRE, 2018).

Another worrying and little-known fact are how climate change and the indiscriminate use of fire to clean and eliminate trees, grass, and weeds can contribute to changes in the hydrological cycle. This concern worsens even more during the occurrence of the La Niña phenomenon, when the risk of fire is increased (SODRÉ *et al.*, 2018). The first mathematical models presented as a forest tipping point a deforestation rate of 40%. When the variables of climate change and indiscriminate use of fire are added, computer modelling indicated an even lower tipping point, around 20–25% of deforestation.

These changes would promote "*savannization*" of the region, with canopy loss, grass invasion and biomass loss, as well as it has already occurred in some areas of the same latitude. Scientists have suggested that severe droughts in 2005, 2010, and 2015-16 were the first signs of these changes in the region's hydrological cycle (BRANDO *et al*., 2014; DOUGHTY *et al*., 2015; ROWLAND *et al*., 2015; LOVEJOY; NOBLE, 2018).

However, these same scientists stressed that developing the Amazon can transform the paradigm of development worldwide.

The economic importance of the Amazon

The Amazon region has riches still little explored. The mapping of the Amazon underground demonstrated a potential that can raise Brazil to a new economic level in the region and the world. Globalization and the fall of most trade barriers have aroused concerns about the need to maintain sovereignty over this territory (CUNHA; MENEZES, 2015).

However, the challenge is how to exploit this potential under a new sustainable development paradigm. This can be accomplished through the combined use of digital, biological, and material technologies from the 4th Industrial Revolution, thereby creating high value-added advanced products, services, and platforms (BECKER, 2016; NOBRE *et al*., 2016).

Becker (2016) noted in his research the existence of three challenges that science and technology must overcome to reconcile economic development and conservation of natural resources:

- the new global geopolitical significance of the Amazon as a vast natural capital frontier;
- the new role of the Amazon in Brazil;
- the urgency of a new development policy and basic strategies for implementing them.

However, at the regional level, it is necessary for this development to be inclusive, sustainable, and sustained, and based on five pillars: social, environmental, territorial, economic, and political (SACHS, 2008).

From a national perspective, the Amazon has a major impact on the water sustainability of other Brazilian regions, particularly the South and Southeast. Both are those with the highest economic potential, accounting for 20 and 50% of Brazilian GDP, respectively (IBGE, 2019). At this point, a controversial idea arises: does it seem likely that a severe change in the hydrological cycle of these regions would have the potential to promote political, social, and economic consequences such as migration, conflict over natural resources, and loss of productive capacity? The answer is yes. The depletion of resources can lead to a social and public order collapse of the Amazon region, Brazil, and the planet in the short term.

The Amazon on a global scale is a huge carbon store, notably 120 tons of carbon a year^{-1}. Conservation of the region is essential to an effi-

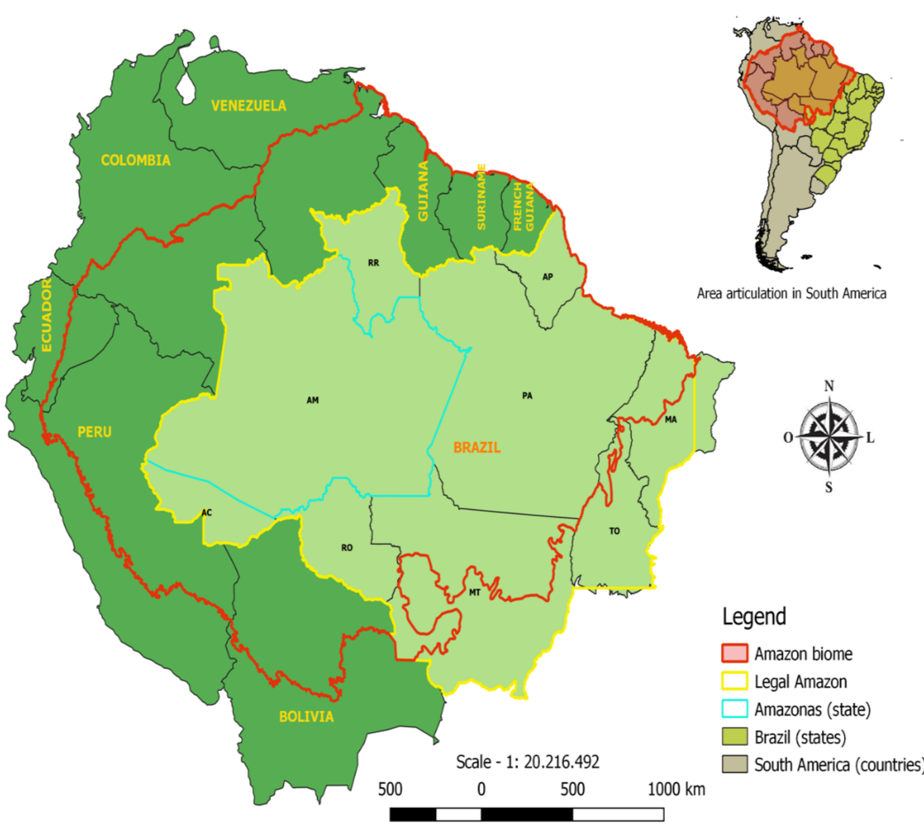

Figure 3 – The geospatialization of the various concepts of the word "Amazon".

cient global carbon cycle for its ability to store carbon, thereby mitigating the effects of global warming by reducing the amount and intensity of extreme climate phenomena, which affects contemporary humanity, endangers the climate and human security, and its biodiversity (ABRIL *et al*., 2014; UNGAR, 2017).

Amazon biodiversity

Brazil is considered to be the most biodiverse country on the planet, having in its different biomes 13% of all species of living beings. Hence, Brazil is recognized as the most megadiverse nations in the world. The Amazon is not simply the largest biome and the most extensive tropical rainforest in the world, but also the biome with the largest number of fauna species, totalling 5,250 taxa (BRASIL, 2018b).

Nevertheless, this megadiversity is associated with the current intangibility of some of its areas. The westernmost portion of the Amazon biome is the least inhabited, the best-preserved, and where the largest border strip in the country is located (BECKER, 2016). This part of the biome is among the last five wilderness regions on the planet. The Amazon, along with the forests of northern Russia, the boreal forests of Canada, the arctic tundra in Alaska, and the Australian desert, make up 70 percent of all the world's wilderness (WATSON *et al*., 2018).

However, all these biological heritages are threatened. Worldwide 3.3 million km^2 of all wildness areas have already been lost, 30% of them in the Amazon (WATSON *et al*., 2016). Like other tropical forests, the sustainability of the Amazon biome is being threatened through activities that are potentially harmful to the environment. Some of them are associated with organized crime, which compromises the sustainability of the use of its natural resources, expropriating resources of its population, sometimes with the use of violence, as well as plundering the government of taxes and fees on the exploitation of natural resources.

Deforestation, burning, damming of watercourses for power generation, waterways, predatory fishing, mining, and pollution are among the main vectors that endanger the sustainability of the Amazon as a biome (NEPSTAD *et al*., 2014). Furthermore, these anthropogenic interventions can double the loss of biodiversity in the region, including ichthyological fauna (LOBÓN-CERVIÁ *et al*., 2015; BARLOW *et al*., 2016; BETTS *et al*., 2017). Some social and environmental initiatives have been taken to reduce deforestation and protect biodiversity. The creation of the Amazon Fund was one of them.

Amazon Fund

The Amazon Fund was an initiative by The United Nations aiming at reducing greenhouse gas emissions from deforestation in the Amazon biome. It is regulated by Decree No. 6,527/2008 (BRAZIL, 2008a) and raised between 2009 and 2017 more than R$ 3 billion (three billion reais), being 93.3% of this amount from the Norwegian government, 6.2% of the German government, and 0.5% of Petrobras, a Brazilian oil company. During this period, 95 projects were financed for a total amount of more than R$ 1.5 billion (one and a half billion reais). Most of the projects (52) involved third sector organizations, which absorbed 38% of these resources, followed by the Legal Amazon states that benefited from 34% of that amount. The Union was the third most benefited from the use of 24% of the fund values in eight projects (BRASIL, 2018a).

The projects also favoured some federal and state operative command and control agencies. the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA for its acronym in Portuguese) was awarded funds for renting cars and helicopters (R$ 56 million) and to structure the National Center for Forest Fire Prevention and Fighting (Prevfogo for its acronym in Portuguese) and environmental education (R$ 14 million). The Mato Grosso Military Fire Department funded the installation of a forest fire fighting airbase, as well as the acquisition of aircrafts (R$ 12.5 million). The National Force of Public Security (FNSP for its acronym in Portuguese) structured its company of environmental operations with those resources (R$ 30 million). The state of RO acquired equipment for the installation of the Air and Ground Operations Base of its Military Fire Department in Porto Velho, its capital (R$ 15 million) (BRAZIL, 2018a).

However, the vast majority of PMAms of the Legal Amazon's states has never directly benefited from resources of this fund. It was not known whether for lack of submission of projects or their non-approval, and the only exception was the MT PMAm. The Amazon Fund supported the construction of an integrated center for environmental operations in the northern municipality of Colniza. This center would be attended not only by PMAm from MT, but also by members of FNSP, Federal Police (PF for its acronym in Portuguese), and IBAMA. The goal would be to increase the presence of state command and control agencies to prevent deforestation in a region where it occurs most intensely (BRASIL, 2016). Even though this center has already been built, PMAm of MT has not yet integrated it due to a lack of staff.

Future prospects of environmental protection in the Amazon

The strategy of promoting the thickening of the military presence in the Amazon to guarantee Brazilian sovereignty over the region seems to have been successful. That is more that can be said of the creation of areas under special protection, such as indigenous lands and UC. Although these areas would be under a stricter special protection regime than in other areas, they were the ones that suffered the most from illegal deforester actions. Approximately 45% of all deforestation in the Amazon between May 2017 and May 2018 occurred in UC (30%), land reform settlements (13%), and indigenous lands (1%) (FONSECA *et al*., 2018).

Moreover, what prevailed in the practice of these environmental crimes was impunity. Only 10% of all administrative fines imposed by IBAMA to environmental offenders in protected areas were received (BARRETO *et al*., 2009), as well as those applied only for deforestation had a payment rate of around 1% (UNGAR, 2017). These data support the case study conducted in Rio de Janeiro that found that only 4% of all environmental criminals arrested by PMAm in that state in 2014 were convicted in court (CABRAL DE OLIVEIRA; ALVES; FERREIRA, 2018).

Concerning UC, the data collected suggest that they are unprotected. The Chico Mendes Institute for Conservation of Biodiversity (ICMBio for its acronym in Portuguese), for example, had around 288 inspectors to oversee 118 conservation units in the Legal Amazon, which together amounts to about 605,000 km² (CABRAL DE OLIVEIRA, 2018; ICMBIO, 2019). The UCs of the Legal Amazon are unprotected, not merely owing to the absence of inspection agents, but also because of the validity of a Forest Code (BRASIL, 2012) much less rigid in the preservation of natural resources than the previous one (NICOLAU *et al*., 2018).

The PMAms of the member states of the Legal Amazon together total 1,229 members and are responsible for a policing area of more than five million km². These amounts are proportional to one inspector per each 2,100 km² block in the case of ICMBio, and one environmental military police officer (PM) per each 4,097 km² block in the PMAm. However, the average ICMBio inspector was calculated, taking into consideration only the area of federal UCs, while in the case of the PMAm, the calculation was based on the area of the entire Legal Amazon region.

In addition, the data maintain that these averages are much lower than those recommended by international nature protection bodies and those practiced in other countries of the Americas. The International Ranger Federation (IRF), for example, proposed that the ideal for adequate protection of an area under special protection regime, such as UC, would be that of a park ranger for a block of 100 km² (1/100). The International Union for Conservation of Nature (IUCN) advised that, according to the risk of extinction of species, the park ranger relationship by km² protected should be even lower, ranging from 1/10 and 1/30 km². Guatemala, Panama, Nicaragua, and the USA have an average of rangers very close to that recommended by the IRF, ranging from 1/74 to 1/125 per km² (EMSLIE; BROOKS, 1999; CUNHA; MENEZES, 2015).

As for the PMAms, the data found in the survey indicate that the average of environmental military police per km² in the Legal Amazon is also much lower than the national average. While the national average is one environmental military policeman for every 1,173 km², in the Legal Amazon, this ratio has been reduced to one PM for an area of 4,097 km². The averages also vary considerably across states, such as in RO where it is found the best proportion, with an average of 1 PM/914 km², and in AM where the average is 1 PM/11,902 km² (Table 2).

IBAMA agents are responsible for overseeing the entire territorial extension of the states, and in many of them, the proportion of agents per km² was lower than the PMAms. In the state of PA, for example, the proportion was from an inspector to an area of 7,998 km², while in AM, this proportion was even lower. In 2014, there were only 47 agents to oversee its more than 1.5 billion km², equivalent to the average of one inspector for every 33,100 km² of the area to be inspected (SEVERIANO, 2014; UNGAR, 2017).

The PMAms of the states that make up the Amazon have so much diversity among themselves, as its fauna. Take the case of personnel that they devote to environmental policing. The percentage ranges from 1% to almost 5% of its active staff (Table 3).

They also have most of their headquarters and sub-offices concentrated in the capital of their respective states, such as the states of AC, AM, AP, and RR. The state of MT has its headquarters in the capital, Cuiabá, and concentrates its subdivisions on the south. PA does further east and southeast. RO does it close to its borders. MA has its subdivisions located in the capital, São Luís, and one in each of its western and eastern limits. TO is the state with the largest number of nodes between headquarters and sub-offices, with a balanced distribution throughout its territory.

The interaction between the PMAms and the territory is directly related to this spatialization. In other words, the larger the nodes of this network formed between the headquarters and their subordinate sub-offices, the greater their interaction with the territory, and the greater the effectiveness of environmental overview.

Moreover, they are also different to their socio-geographic characteristics, its logistics structures, the forms as they are used in geotechnology, and finally, the administrative support they receive for environmental policing activities. One of the most striking socio-geographic characteristics that directly influence environmental surveillance is the intentional violent death rate (MVI, for its acronym in Portuguese, refers to the sum of the victims of intentional homicide, murder, bodily injury followed by death, and deaths resulting from police interventions on and off duty, in some cases). They impact these activities since in Brazil, there is a tendency for the higher the MVI rate, the lower the percentage of the staff devoted to environmental policing. Thus, most states show MVI rates above the national average of 30.8 per 100,000 inhabitants (Table 4).

Legal Amazon's PMAms are among the most logistically deficient. They have the lowest absolute numbers of personnel, vehicles, and vessels when compared to their counterpart of the rest of the country, and they also have poor use of geotechnologies. Only two states use drones (AP and RR), two have a geoprocessing sector at their headquarters (AC and MT), three use remote sensing for environmental surveillance purposes (AC, MT, and AM), and two employ thematic maps for operational planning (AM and TO).

When it comes to administrative support, the differences stand out even more. The states of MT, RO, and RR are the only ones that have a delegation of competence regarding the environmental administrative police power to carry out their activities. The role of the state environmental agency (sectional) is considered effective or very effective to only four states (MA, MT, PA, and TO), while others consider the performance to be of little effect or an ineffective body. Interestingly, the PMAms of the states of MT and PA, even considering the work of the state agency as effective or very effective, is among states with the highest deforestation rates in the region.

Police stations specializing in the investigation and prosecution of environmental crimes also act poorly. Although the states, except AC, have at least one station of this nature, all the others are located in the capitals of their respective states, distant from the main areas of illegal deforestation, and run only on weekdays during business hours or part-time. The lack of adequate investigation, with robust evidence to identify and punish violators of environmental law, favours impunity and inequalities in the Brazilian Amazon region are accentuated.

Without coordinated and integrated action between the command and control bodies and adequate logistical resources, it will be very difficult to achieve effective results in the environmental supervision of a region as vast and complex as the Legal Amazon.

Final considerations

The protection of the Brazilian Amazon demands a tremendous challenge and effort from state command and control agencies, not merely for its continental extent, but also for the inaccessibility of some areas. The colonization of the region took place *sui generis* because it went through periods of long stagnation and successive migratory waves to exploit its natural resources. However, the most striking fact was the tactic of expropriation of the lands of their original inhabitants: the Indians and the settlers. Without documentation assuring them of legal ownership of the land, they were expelled from it by both the dominant political elites and those most economically privileged. Sometimes, these elites were from both categories, and they used land grabbers, gunmen, and *jagunços* to spread fear and cruelty upon the early inhabitants of these lands. This is a tactic that unfortunately endures to the present days.

However, the technological advance brought a new perspective to the Amazon, attracting the attention of the world and giving rise to a sense of oneness and common responsibility for the region. Nonetheless, environmental problems in the Legal Amazon are not just about

Table 2 – Average proportion of environmental military police per km² protected.

State	AC	AP	AM	MA	MT	PA	RO	RR	TO
Average of Environmental Military Police per km²	1/3,492	1/992	1/11,902	1/3,688	1/5,221	1/5,356	1/914	1/8,627	1/2,222

Source: The Authors (2019).

Table 3 – Percentage of the environmental military police (PMAm) personnel in relation to the active force of the Military Police in 2016.

State	AC	AP	AM	MA	MT	PA	RO	RR	TO
PMAm personnel in relation to the active force of the Military Police in 2016 (%)	1,93	4,28	1,42	1,01	2,19	1,57	4,94	1,36	3,31

Source: adapted from IBGE (2016).

Table 4 – Rate of intentional violent deaths per 100 thousand inhabitants (2017).

State	AC	AP	AM	MA	MT	PA	RO	RR	TO
Rate of intentional violent deaths per 100 thousand inhabitants (2017)	63,9	55,8	31,3	29,4	31,5	53,4	28,1	44,0	26,6

Source: Fórum Brasileiro de Segurança Pública (2018).

agrarian problems and deforestation. The Amazon region has become a stage in an extensive and well-diversified network of organized crime that threatens local, regional, and global environmental security.

Amazonia performs ecosystem services that are not only essential for mitigating the effects of climate change globally, but also for maintaining the water sustainability of the Southern and Southeastern regions and part of the South American cone, as well as for conserving local biodiversity. In this light, command and control bodies play a key role in mitigating these problems.

It was evaluated how these state command and control systems responsible for the protection of the Brazilian Amazon rainforest are developing. This assessment comprised four discussions. The first aimed to identify how many agents (inspector or PM) were designated for this protection. Survey data showed that the average IBAMA, ICMBio, and PMAm agents per km^2 are infinitely lower than recommended by international nature protection bodies, such as IRF and IUCN. Furthermore, the average of environmental military police officers per km^2 in the Legal Amazon is about a quarter of the average of the other states of the federation, as well as the percentage of active personnel that each state military police corporation devotes to environmental policing varies greatly.

The second analyzed how the headquarters and subdivisions were geospatialized in the territory of each state. It was found that most of the PMAms have their headquarters and subdivisions located in the capitals of their states. This contributes negatively to the effectiveness of overseeing activities since the more dispersed, the greater their interactions with the territory.

The third discussion was about their socio-geographic characteristics. It was revealed that the higher the state's MVI rates, the lower the percentages of active personnel that military police corporations will devote to environmental policing.

Finally, the fourth argument was about the logistical and administrative structure that PMAms have to perform their services. The information obtained from the research clarified and confirmed that they are among the most deficient, also in terms of the logistic point of view of vehicles and vessels. Moreover, most of them consider the performance of the state environmental agency to be ineffective or inefficient. Surprisingly, the PMAms of the states of MT and PA consider the performance of those agencies to be effective or very effective, although they are among the states with the highest deforestation rates in the region. Also, the form of policing commonly used in law enforcement is motorized, and deforestation occurs along the axes of paved roads or roads opened by loggers. This fact suggests that motorized policing is not being carried out effectively.

Another fact revealed by the research is that, except for AC, all other states have only one civil police station specialized in the investigation and repression of environmental crimes. However, these public offices are not only located in their state capitals, which are away from areas where illegal deforestation occurs and far from other environmental crimes, as well as these public offices are only open during business hours or part-time.

The lack of structure of the command and control systems and their uncoordinated, disconnected, and discontinued performance compromises the ecosystem, economic, and social sustainability of the Legal Amazon. In the medium to long term local impacts, they will have the same consequences at the regional and global level. Thus, the findings of this paper should be viewed as opportunities for improving environmental inspection in general.

This research also presents the possibility of precious points to be investigated in future research, such as the assessment of how other biomes and their ecosystems are being protected, thus obtaining an overview of the entire national territory. Another research opportunity presented by this study is the possibility of verifying the viability of the use of PMAms in the policing of UCs, which keep relevant and valuable biotic and abiotic representatives of Brazilian nature.

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Sewage treatment efficiencies estimation for urban areas located in the River Pardo's watershed by associating nonlinear programming and water quality modeling

Estimativa de eficiências de tratamento de esgotos para os núcleos urbanos da bacia hidrográfica do Rio Pardo a partir da associação de programação não linear e modelagem de qualidade de água

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ABSTRACT

Estimating efficiencies required for sewage treatment plants within a river watershed, where there are usually multiple sewage discharges and water withdrawals points in watercourses, presenting different quality conditions and sewage assimilation capacities, is a complex task. In this context, combined optimization techniques and water quality modeling can be important tools to support sewage treatment efficiencies appropriation processes. In the present paper, QUAL-UFMG water quality model and Nonlinear Programming (NLP) are jointly applied to sewage treatment levels selection for the river Pardo's (watercourse located in Espírito Santo State, Southern region, Brazil) watershed different urban areas. Four different optimization models were tested for estimating the minimum organic matter removal efficiencies. The results indicate strong dependence between the estimated minimum organic matter removal efficiencies within the watershed and equity measures incorporated in the optimization models.

Keywords: optimization; optimization model; water quality; domestic sewage.

RESUMO

A estimativa de eficiências requeridas pelas estações de tratamento de esgoto constitui tarefa complexa no âmbito de uma bacia hidrográfica, onde habitualmente existem múltiplos lançamentos e captações em cursos d'água com diferentes condições de qualidade e capacidades de assimilação de despejos. Nesse contexto, as técnicas de otimização e a modelagem da qualidade de água, quando aplicadas de maneira combinada, podem constituir importante ferramenta de apoio ao processo de apropriação de eficiências de tratamento de esgotos. Neste trabalho, o modelo de qualidade de água QUAL-UFMG e a Programação Não Linear (PNL) foram conjuntamente aplicados para a seleção de níveis de tratamento de esgotos para os diferentes núcleos urbanos da bacia hidrográfica do Rio Pardo, curso d'água da porção sul do estado do Espírito Santo. Quatro diferentes modelos de otimização foram testados, quando da estimativa das eficiências mínimas de remoção de matéria orgânica. Os resultados indicaram a acentuada dependência entre as eficiências mínimas de remoção de matéria orgânica estimadas no âmbito da bacia e a incorporação de medidas de equidade nos modelos de otimização.

Palavras-chave: otimização; modelo de otimização; qualidade de água; esgotos domésticos.

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Introduction

In the last century, the world population has grown rapidly in a disorderly manner, resulting in agglomerations without infrastructure and quality of public services. Most Brazilian cities still release their sewage directly into watercourses, causing significant impacts on the receiving water bodies and imbalances to local ecology, posing risks to human health (CHO *et al.*, 2013).

Sewage treatment systems processes choice should be based on technical, economic, and environmental criteria analysis, considering each treatment system alternative characteristics (VON SPERLING, 2005). Usually, the main considered factors are treatment systems installation land costs, systems' operational costs, load of raw effluents and water quality standards to be attended by effluents (SOUZA, 1998). Other important environmental factors in the effluent treatment systems selection process are related to the receiving water bodies capacities. Proper water bodies organic matter assimilation capacities consideration allows selection of simpler (constructively and operationally) and treatment plants which are economically more viable. Minimum pollutant removal efficiencies determination is the starting point for sewage treatment systems selection processes.

Sewage treatment efficiencies estimation, when observed from the watershed point of view, is often complex, due to numerous discharge points, with different loads in water bodies presenting varied assimilation capacities and water quality conditions (REIS; VALORY; MENDONÇA, 2015). In this context, water quality simulation models can help in water resources management and sewage treatment systems selection processes (TEIXEIRA; PORTO, 2008; CALMON, 2015; ARRUDA; RIZZI; MIRANDA, 2015; MATEUS *et al.*, 2015; CORRÊA *et al.*, 2019; ROCHA; MESQUITA; LIMA NETO, 2019; FORTUNATO *et al.*, 2020).

However, water quality mathematical simulation does not, necessarily, involve the analysis of the ideal solution to sewage treatment efficiencies within a watershed estimation problem, because the multiple releases may require very large sewage treatment efficiencies combinations analysis. In this context, the association between water quality models and optimization techniques can allow the determination of the optimal treatment efficiencies combination to be adopted within a watershed (ANDRADE; MAURI; MENDONÇA, 2013). In this research line, different studies (VALORY *et al.*, 2013; MANSHADI; NIKSOKHAN; ARDESTANI, 2015; SANTORO; REIS; MENDONÇA, 2016; FANTIN; REIS; MENDONÇA, 2017; BRINGER; REIS; MENDONÇA, 2018; AGHASIAN *et al.*, 2019; SÁ *et al.*, 2019) have prioritized the association between water quality models and Genetic Algorithm (GA) metaheuristic optimization technique. According to Lacerda and Carvalho (1999), GAs have been employed in complicated problems (where other optimization methods fail) and have several advantages, such as the possibility to work both with continuous and discrete parameters (or a combination of them), several optimization variables, and complex optimization functions.

These authors note that GAs are not efficient for many problems and can be quite slow depending on values assumed for the initial population and options assumed for operators.

The present study's main objective is to estimate minimum sewage treatment efficiencies within a watershed, with water quality mathematical modeling and conventional Nonlinear Programming (NLP) optimization technique combination. According to Cirilo (2002), the main advantage of NLP is its comprehensiveness, given that once the mathematical model that describes the system to be optimized is elaborated generally, no formulation simplification is needed, increasing the accuracy of obtained results. Cirilo (2002) notes that the uncertainty about obtaining the optimal solution weighs against NLP (possibility of determining local optimal solutions values instead of the global optimum).

What is relevant to note in the present study is that water quality modeling and NLP are conducted in a Microsoft Excel® spreadsheet environment, a popular software usually more accessible than other software available for applying metaheuristic optimization techniques such as GA. Water quality mathematical model QUAL-UFMG, whose use has been popularized in Brazil, is employed and was introduced in an expeditious procedure, which aims to overcome, without significant computational demands, the difficulty arising from eventual optimal solutions appropriations.

Materials and methods

Study area

The study area considered in research is the river Pardo's watershed (Figure 1). This river is an important tributary of Itapemirim River. Itapemirim is the main watercourse located in the Southern region of Espírito Santo State. The river Pardo's watershed drainage area is approximately 611 km², distributed in the Ibatiba, Irupi, Iúna and Muniz Freire, all located in Espírito Santo State, and Lajinha, in Minas Gerais State.

The river Pardo's watershed presents three cities (Ibatiba, Iúna, and Irupi), and two villages (Santíssima Trindade and Nossa Senhora das Graças). The watershed does not have any sewage treatment plants being operated. Although the cities and towns in the hydrographic basin that are the focus of the present study may have unitary treatment systems and final effluent disposal, reducing the organic load released into the water bodies, the authors chose to consider that the entire organic load produced in the basin reaches the water bodies, modeling the most critical scenario. The river Pardo is the main raw domestic effluents recipient, receiving the sewage produced in Ibatiba and Iúna Cities. The river Pardinho and Ribeirão da Perdição stream are two tributaries of the river Pardo that also receive sewage discharges. The river Pardinho receives the sewage produced in Irupi City. Ribeirão da Perdição stream receives the sewage produced in Santíssima Trindade and Nossa Senhora das Graças villages. Ribeirão São José constitutes a Pardo's tributary that does not receive any sewage.

Water quality model

QUAL-UFMG water quality computational-simulation model, developed in the Microsoft Excel® spreadsheet computational environment, was applied to the studied water system. In the present paper, water quality was described exclusively as a function of biochemical oxygen demand ($BOD_{5,20}$) and dissolved oxygen (DO) parameters modeling. These parameters are usually used for water bodies qualitative characterization after sewage discharges. For simulating these parameters spatial variation, first order differential equations were considered, covering deoxygenation and atmospheric reaeration phenomena. The equations that describe DO and $BOD_{5,20}$ parameters variations, considering deoxygenation and reaeration phenomena, are presented in detail by Von Sperling (2007).

Kinetic constants, hydrodynamic, and water quality information

The kinetic constants, hydrodynamic data, and water quality parameters adopted in this paper were obtained from research conducted by Calmon *et al.* (2016), when analyzing the use of water quality permanence curves to support the definition of water quality classes of the river Pardo's watershed rivers.

In their study, Calmon *et al.* (2016) determined kinetic constants and hydrodynamic variables values for the river Pardo from the records available for Terra Corrida Montante fluviometric station, installed and operated on the river Pardo by the Brazilian Water Agency (*Agência Nacional de Águas* — ANA).

Due to the small drainage areas associated to the springs of water courses located in the study area, the flow rates of the first segments of the water courses considered in the modeling were zero. Calmon *et al.* (2016) estimated the incremental (diffuse) flows to Pardo river watershed watercourses by mass balance, considering the differences between the flows in the final simulated section and the respective headwater flows. Simulations performed in the river Pardo's watershed assumed incremental flow of 3.53 $Ls^{-1}km^{-1}$, and DO and $BOD_{5,20}$ concentrations of 5 and 2 mgL^{-1}, respectively. These DO and $BOD_{5,20}$ concentration values were assumed from Von Sperling (2007) propositions.

The functional relations between flow (Q, m^3s^{-1}), velocity (U, ms^{-1}), and depth (H, m), potential functions in the QUAL-UFMG model, were established from flow measurement records carried out at the cited fluviometric station. Equations 1 and 2, established by Calmon *et al.* (2016), made it possible to estimate watercourses velocities and depths as functions of flows.

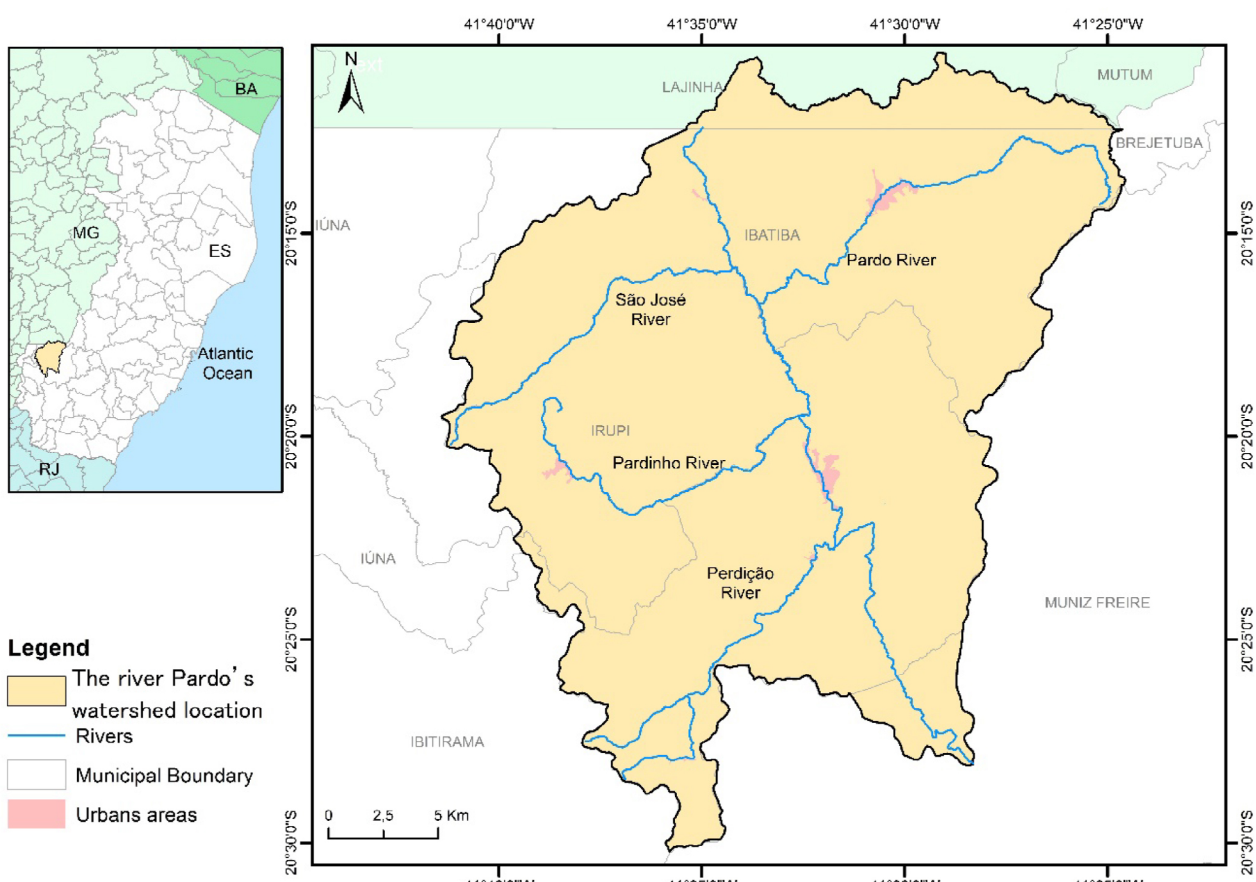


Figure 1 – The river Pardo's watershed location.

$$U = 0.1433.Q^{0,6305} \quad (1)$$

$$H = 0.6076.Q^{0,2566} \quad (2)$$

The average domestic effluents flow rates relative to the river Pardo's watershed urban population and the corresponding organic loads are presented in Table 1.

For urban domestic sewage, a concentration of 400 mgL^{-1} for $BOD_{5,20}$ was adopted, as well as 145 $Lhab^{-1}d^{-1}$ *per capita* yield, and return coefficient of 0.8. The adopted $BOD_{5,20}$ concentration corresponds to the upper limit for the raw domestic sewage concentration range indicated by Von Sperling (2005), and Jordão and Pessôa (2009). Raw domestic effluents DO concentrations were considered null.

Zero concentration for DO in raw and treated sewage was adopted in order to simulate discharges under more conservative conditions, by ignoring that certain sewage treatment systems may incorporate some DO in the treated sewage.

As proposed by USEPA (1985), and Thomann and Mueller (1987), Calmon *et al.* (2016) defined K_d (in d^{-1}) as a function of watercourse hydraulic characteristics (depth and flow), according to Equation 3.

$$K_d = 0.3 \cdot \left(H/_{2.5}\right)^{-0.434} \quad (3)$$

Equation 4 defines the kinetic constant that regulates the atmospheric reaeration process (K_2), according to the original proposition by O'Connor and Dobbins.

$$K_2 = 3.73 \cdot U^{0.5} \cdot H^{-1.5} \quad (4)$$

Substituting Equation 1 and Equation 2 in Equation 4, the result is the equation used to determine K_2 in each river stretch (Equation 5).

$$K_2 = 3.73.(0.1433.Q^{0.6305})^{0.5}.(0.6076.Q^{0.2566})^{-1.5} \quad (5)$$

Effluent disposal scenario

In the river Pardo's watershed watercourses, the point sources are composed by the river Pardo's tributaries (Ribeirão São José, Pardinho, and Ribeirão da Perdição, presenting extensions of 17.5, 19.9 and 18.5 km, respectively) and domestic effluents from five urban areas (Ibatiba, Irupi and Iúna cities, and Santíssima Trindade and Nossa Senhora das Graças villages). The distributed sources are composed by incremental flows and $BOD_{5,20}$ loads from the sewage produced by the rural population located in the river Pardo's watershed, evenly distributed throughout the water system.

Optimization models

The objective functions employed to estimate minimum sewage treatment efficiencies for the river Pardo's watershed were selected from the study developed by Santoro, Reis and Mendonça (2016), and considered the following aspects:

- $BOD_{5,20}$ removal efficiencies sum minimization referring to the different treatment systems proposed for the river watershed;
- inequity minimization between different proposed treatment systems, imposing higher $BOD_{5,20}$ removal levels for those receiving higher organic loads;
- conformity with environmental quality standards established for water bodies by the Brazilian Environmental Council Resolutions (*Conselho Nacional do Meio Ambiente — CONAMA*) 357/2005 and 430/2011 (BRASIL, 2005; 2011).

Considering the above guidelines, the following optimization models were used:

- Model 1, originally proposed by Valory, Reis and Mendonça (2016), seeks to minimize the sum of efficiencies (Ei) within the watershed (Equation 6);
- Model 2 introduces an equity measure in the objective function (Equation 7), as established by Mulligan (1991), seeking to ensure that the efficiency in each station is proportional to its raw organic load ($load_{lanc}$);
- Model 3 employs an objective function that enforces an inequity between treatment systems measure minimization (Equation 8), as originally established by Marsh and Schilling (1994);
- Model 4 uses an objective function that imposes another inequity between treatment systems measure minimization (Equation 9), as proposed by Burn and Yuliant (2001).

Table 1 – The river Pardo's watershed urban population mean domestic sewage flow rates.

Cities and Villages	Average domestic sewage flow (Ls^{-1})	Urban population (inhabitants)	Raw Organic Load (kgd^{-1})
Ibatiba	24.33	18,125	840.84
Irupi	5.24	4,918	181.09
Iúna	19.90	14,821	687.74
Santíssima Trindade	0.32	301	11.06
Nossa Senhora das Graças	0.64	600	22.12

Source: Calmon *et al.* (2016).

$$\text{Minimize } f(E) = \sum_{i=1}^{n} E_i \quad (6)$$

$$\text{Minimize } f(E) = \sum_{i=1}^{n} \left[\left| \frac{\text{load}_{\text{lanc},i}}{\text{load}_{\text{lanc}}} - \frac{E_i}{E} \right| \right] \quad (7)$$

$$\text{Minimize } f(E) = \sum_{i=1}^{n} \sum_{i=j}^{n} \left| \left(\frac{\text{load}_{\text{lanc},i}}{E_i} \right) - \left(\frac{\text{load}_{\text{lanc},j}}{E_j} \right) \right| \quad (8)$$

$$\text{Minimize } f(E) = \sum_{i=j}^{n} \left| \left(\frac{\text{load}_{\text{lanc},i}}{E_i} \right) - \left(\frac{\overline{\text{load}_{\text{lanc}}}}{\overline{E}} \right) \right| \quad (9)$$

All optimization models incorporate, as restrictions, the environmental quality standards set for DO and $BOD_{5,20}$ (minimum DO 5 mgL^{-1} and maximum $BOD_{5,20}$ 5 mgL^{-1}) for class 2 rivers. Class quality 2 as assumed for the Pardo river watershed watercourses due to legal framework absence, according to the guidelines established by CONAMA Resolution No. 357/2005 (BRASIL, 2005). Additional restrictions aimed at ensuring efficiencies non-negativity (Ei ≥ 1%) and the establishment of a limit for $BOD_{5,20}$ removal by treatment systems (Ei ≤ 95%).

Nonlinear Programming application

NLP is suitable for problems that have nonlinearity in their objective function or constraints. The solution, in general, is a vector of decision variables that optimizes the nonlinear objective function subject to nonlinear constraints (CIRILO, 2002). NLP is characterized by not presenting a general method for solving all problems. In the present study, for obtaining treatment efficiencies from the different optimization models selected, the Generalized Reduced Gradients Method (GRG), available in the Microsoft Excel® spreadsheet Solver macro, was employed. The GRG Method, originally proposed by Lasdon *et al.* (1978), deals with the solution of nonlinear optimization problems, in which the objective function and constraints can present nonlinearities if the function is differentiable.

According to Cirilo (2002) and Albertin, Mauad and Daniel (2006), the main limitation in applying NLP to water management problems is that the technique does not necessarily provide the overall optimum, often reaching a partial optimum value. In research, seeking to circumvent this limitation and maximize global optimum obtaining chances, a total of 150 initial efficiencies sets was randomly generated for each optimization model. These efficiencies set established the initial values from which the established NLP search process was conducted. The search process operationalization occurred with the implementation of a computer program developed in Visual Basic for Applications (VBA) in the Microsoft Excel® spreadsheet environment, the code integrated with the Solver macro and the QUAL-UFMG model. This integration allowed search process automation.

Results and Discussion

Control scenario: raw effluent discharges

This section presents the results from raw effluents final disposal in the different river Pardo's watershed watercourses simulations. Considering the river Pardo's watershed does not present any sewage treatment plants installed and in operation, the results gathered in this section represent the currently expected condition for the watershed, establishing a control scenario for subsequent discussions.

Ribeirão Perdição stream receives domestic effluents discharges from Santíssima Trindade and Nossa Senhora das Graças villages (with discharge rates of 0.3 and 0.6 Ls^{-1}, respectively). These discharges are small and have little impact on Ribeirão Perdição water quality. In this watercourse, DO and $BOD_{5,20}$ concentrations invariably respect the limits established by environmental quality standards.

Figure 2 shows the DO and $BOD_{5,20}$ profiles for the river Pardinho river, which receives in kilometer 5 the domestic effluents from Irupi City. Although not among the largest organic loads produced in the river Pardo's watershed, Irupi City domestic effluents disposal effect is relevant due to the river Pardinho's low flow (0.18 m^3s^{-1}) in the final disposal point. This condition gives the river Pardinho low organic loads assimilation capacity, leading to non-compliance with the $BOD_{5,20}$ environmental quality standard downstream effluent discharge point.

Along the Pardo river, the largest watershed cities (Ibatiba and Iúna) are located. Consequently, it is in this water system portion where the highest DO and $BOD_{5,20}$ concentrations variability occurs (Figure 3). The large parameters variation observed in kilometer 16 of the river Pardo is due to Ibatiba City's domestic effluent final disposal (corresponding to the largest pollutant load in the watershed, with 24.3 Ls^{-1} raw sewage discharge rate), and the limited river flow at the discharge point (0.60 m^3s^{-1}). Thus, $BOD_{5,20}$ concentration exceeds the environmental quality standard imposed for class-two rivers, reaching a 18.1 mgL^{-1} peak.

Ribeirão São José stream flows into the river Pardo approximately 7 km downstream Ibatiba and provides a 0.62 m^3s^{-1} flow increase to this river, improving water quality downstream the affluence point. This affluence increases the main river dilution capacity for the remainder of its course, decreasing its $BOD_{5,20}$ concentration, attenuating Ibatiba effluent final disposal impact. The same happens for the river Pardinho, which flows into the river Pardo at km 30, with a 0.71 m^3s^{-1}flow. Although this flow increase is greater than the corresponding to São José stream, the reduction in $BOD_{5,20}$ concentration for the river Pardo is smaller due to the higher main river flow on the river Pardinho's affluence and the higher river Pardinho's $BOD_{5,20}$ concentration (4.9 mgL^{-1}) when compared to the corresponding Ribeirão São José stream (2 mgL^{-1}).

At the kilometer 35 of the river Pardo, Iúna City's domestic effluent is discharged, increasing $BOD_{5,20}$ concentration to a maximum value of 9.5 mgL^{-1}, and reducing DO levels to a minimum value of 6.77 mgL^{-1}. Downstream Iúna, Ribeirão Perdição stream flows into the river Pardo, and as it happens for the other tributaries, main river water quality conditions improvement occurs.

Minimum sewage treatment efficiencies

Optimization Model 1 (Equation 6) seeks exclusively to comply with watercourses environmental quality standards and minimize the treatment efficiencies sum within the watershed. The main purpose of its application was to evaluate the difference between the estimated efficiencies considering models with and without equity measures incorporation.

The lack of an equity measure in the pursuit of sewage treatment systems efficiencies, within the watershed sum minimization, may mean that users located in the watershed downstream stretches need to treat their effluents with higher efficiencies, because the river Pardo's water reaches their disposal locations with lower quality, as a result from upstream discharges. There is also the possibility that the river presents much higher flow downstream than upstream, due to incremental flow and tributary affluences. Consequently, sewage produced closer to headwater would require higher treatment efficiency even if its discharge load is like that discharged downstream (ALBERTIN, 2008).

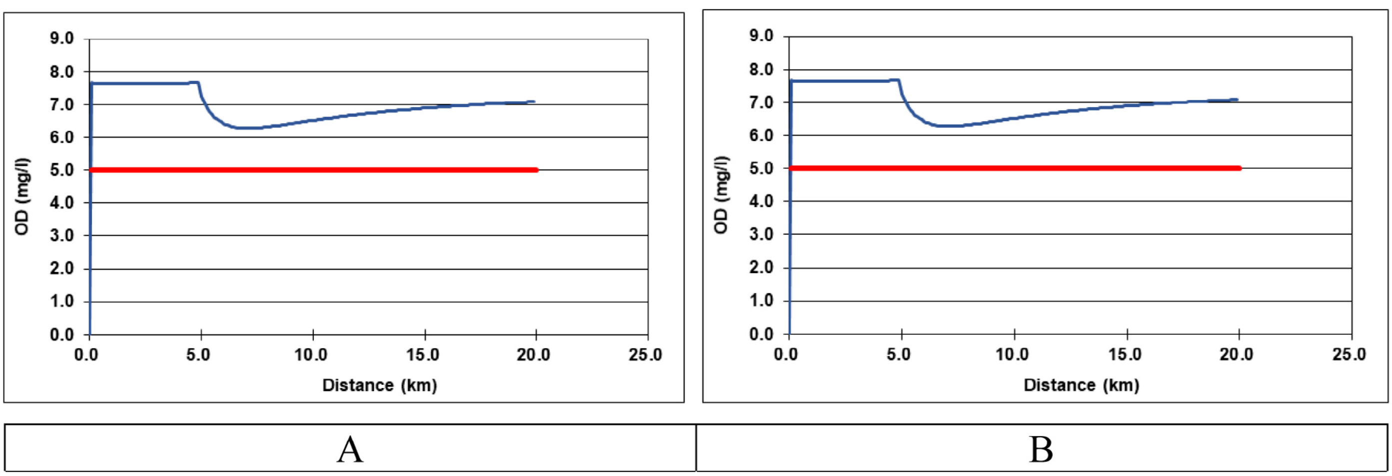


Figure 2 – DO and $BOD_{5,20}$ concentration profiles for the river Pardinho, considering the raw effluent final disposal.
DO: dissolved oxygen; $BOD_{5,20}$: biochemical oxygen demand.

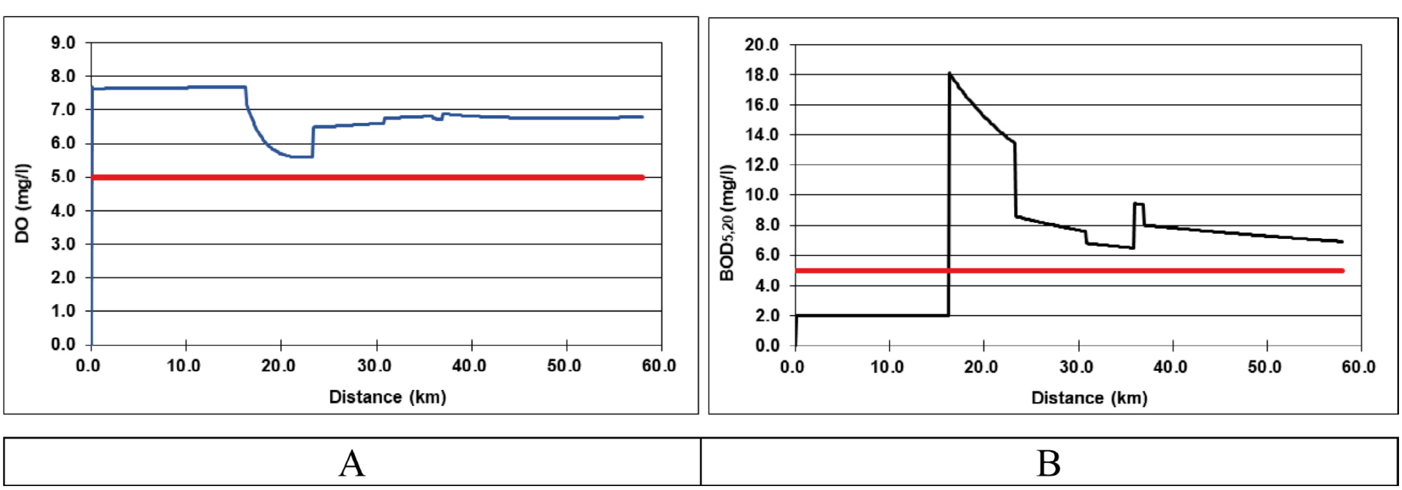


Figure 3 – The river Pardo's DO and $BOD_{5,20}$ concentration profiles for the considered raw effluent final disposal.
DO: dissolved oxygen; $BOD_{5,20}$: biochemical oxygen demand.

Primary sewage treatment systems present minimal BOD removal efficiency, usually of 25% (VON SPERLING, 2007). From this perspective, all estimated efficiencies with values lower than 25% are shown in parentheses in the following tables, next to the symbol < 25.

Table 2 shows the estimated minimum $BOD_{5,20}$ removal efficiencies values for the treatment systems associated to the river Pardo's watershed urban areas, according to optimization Model 1.

Effluent discharges from Irupi City occurs near the river Pardinho's headwater, where flow is still low. Hence, a more rigorous treatment for this effluent than the necessary for similar organic loads is required. The $BOD_{5,20}$ peak concentration, when the treated effluent is discharged, reaches the limit value acceptable for class-two rivers. In this context, treatment efficiency was 73% (Table 2), defined for Irupi effluent, which is the minimum required to maintain the river Pardinho's water quality parameters respecting class-two rivers limits under the boundary conditions that conformed the simulations performed.

Considering that effluent discharges from Santíssima Trindade and Nossa Senhora das Graças villages in Ribeirão Perdição stream are small, they can be assimilated by the river without affecting maintenance of quality standards even if disposed without treatment (minimum allowable efficiency of 1%, imposed to guarantee non-negativity).

Ibatiba effluent is released into a river Pardo's section that presents low flow, a condition that imposes high treatment efficiency to the city effluents (95%, according to Table 3). For Iúna City, where Pardo river presents higher flow, the required efficiency is considerably lower than that imposed for Ibatiba effluent (approximately 13%, according to Table 3), allowing simpler sewage treatment systems adoption.

Optimization Model 2 (Equation 7) sought to minimize the difference that point organic loads and estimated efficiencies for treatment systems present among themselves. Table 3 presents the five best results related to optimization Model 2.

Optimization Model 3 (Equation 8) aimed to minimize inequities between adjacent discharge points, so that the relation of organic load over efficiency ratio between two adjacent points would be as close as possible, seeking to establish a common efficiency that was related not only to the organic load, but also consistent with its neighborhood, where the discharged effluent presents greatest influence. These results are summarized in Table 4.

The results of Model 3 indicate that the inequity measure proposed by the model established a pattern similar to that obtained previously, with the urban areas that produce largest organic loads charged with applying the highest efficiencies in their effluents treatment.

Table 2 – Estimated minimum efficiency: optimization model 1.

Treatment efficiency (%)					Σ efficiency
Ibatiba	Irupi	Santíssima Trindade	Nossa Senhora das Graças	Iúna	
95	73	< 25 (1)	< 25 (1)	13	184

Table 3 – Minimum estimated efficiencies: optimization model 2.

Solution	Treatment efficiency (%)					Σ efficiency
	Ibatiba	Irupi	Santíssima Trindade	Nossa Senhora das Graças	Iúna	
1	90	73	< 25 (1)	< 25 (2)	20	186
2	81	73	< 25 (2)	< 25 (2)	30	188
3	81	73	< 25 (7)	< 25 (2)	30	193
4	95	73	< 25 (20)	< 25 (2)	< 25 (13)	203

Table 4 – Minimum estimated efficiencies: optimization model 3.

Solution	Treatment efficiency (%)					Σ efficiency
	Ibatiba	Irupi	Santíssima Trindade	Nossa Senhora das Graças	Iúna	
1	95	73	< 25 (1)	< 25 (2)	95	266
2	95	73	< 25 (1)	< 25 (6)	95	270
3	95	73	< 25 (1)	< 25 (7)	95	271
4	95	73	< 25 (1)	< 25 (9)	95	273
5	95	73	< 25 (1)	< 25 (10)	95	274

In this model, however, greater rigor was observed for urban areas that contribute with higher loads, reducing the variations observed for optimization Model 2. $BOD_{5,20}$ high removal levels suggested for Iúna effluent treatment was due to the fact that the inequity measure associated with optimization Model 3 considers discharges in the vicinity. By the fact that Iuna presents higher sewage load than the adjacent urban areas (Irupi and Nossa Senhora das Graças villages), NLP sought to minimize the ratio between loads discharges and treatment efficiencies for these locations, increasing Iuna treatment efficiency.

Model 4 (Equation 9) aimed to minimize the relation between organic load and efficiency for each discharge point in relation to the ratio between average load and efficiency in the watershed. The results from the application of this model are presented in Table 5.

The DO and $BOD_{5,20}$ profiles produced considering the efficiencies estimated with optimization Model 4 help are presented in Figures 4 (the river Pardinho), 5 (Ribeirão Perdição stream), and 6 (the river Pardo), and were conformed with the use of efficiencies referred to the solution presenting lowest efficiencies sum. These figures exemplify the profiles produced from the incorporation of efficiencies estimated by the optimization model. Similar figures were produced considering efficiencies estimated by other optimization models. Regardless of the efficiencies set for their production, these profiles present DO and $BOD_{5,20}$ parameters variations that are established in accordance with the environmental quality standards, since the environmental quality standards constituted optimization models restrictions.

When comparing only the efficiencies sum obtained by the different optimization models, optimization Model 1 produced the lowest $BOD_{5,20}$ removal efficiencies sum for the watershed. Optimization Models 2, 3, and 4, however, usually imposed considerably more efficient treatments than those established with the aid of optimization Model 1.

Recurrently, sewage treatment efficiencies associated to the smaller urban areas (Nossa Senhora das Graças and Santíssima Trindade villages) were not significant, being lower than the efficiencies normally achieved by primary sewage treatment systems. Ibatiba and Irupi Cities, regardless of the optimization model employed, demanded higher

Table 5 – Minimum estimated efficiencies: optimization model 4.

Solution	Treatment efficiency (%)					Σ efficiency
	Ibatiba	Irupi	Santíssima Trindade	Nossa Senhora das Graças	Iúna	
1	95	73	< 25 (2)	< 25 (3)	95	268
2	95	95	< 25 (2)	< 25 (3)	95	290
3	95	73	< 25 (2)	46	95	311
4	95	73	63	< 25 (4)	95	330
5	95	73	< 25 (2)	85	95	350

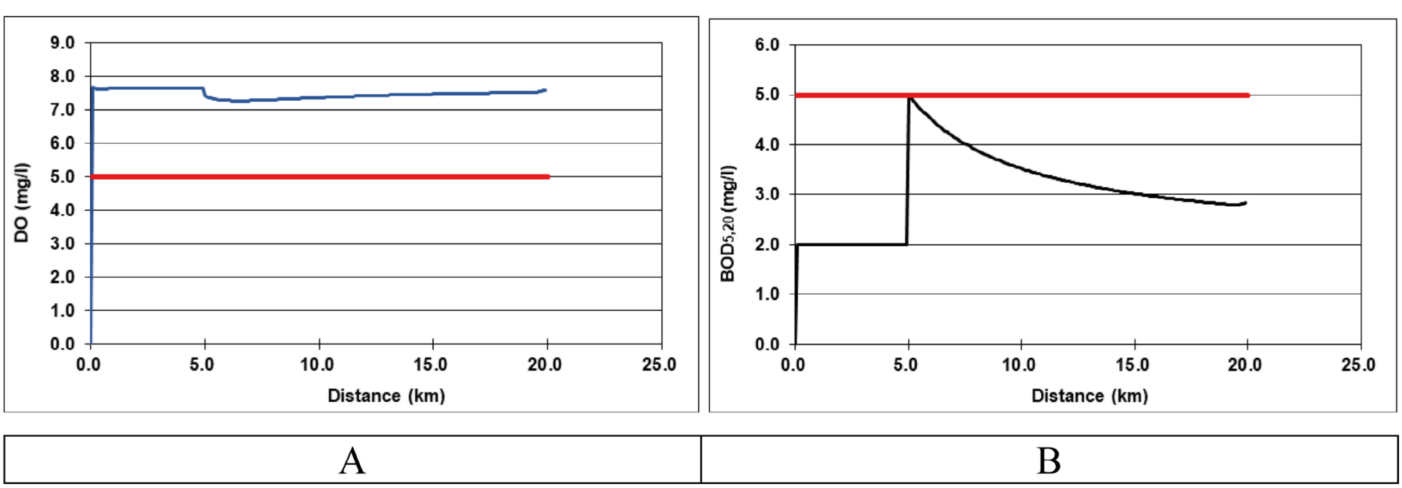
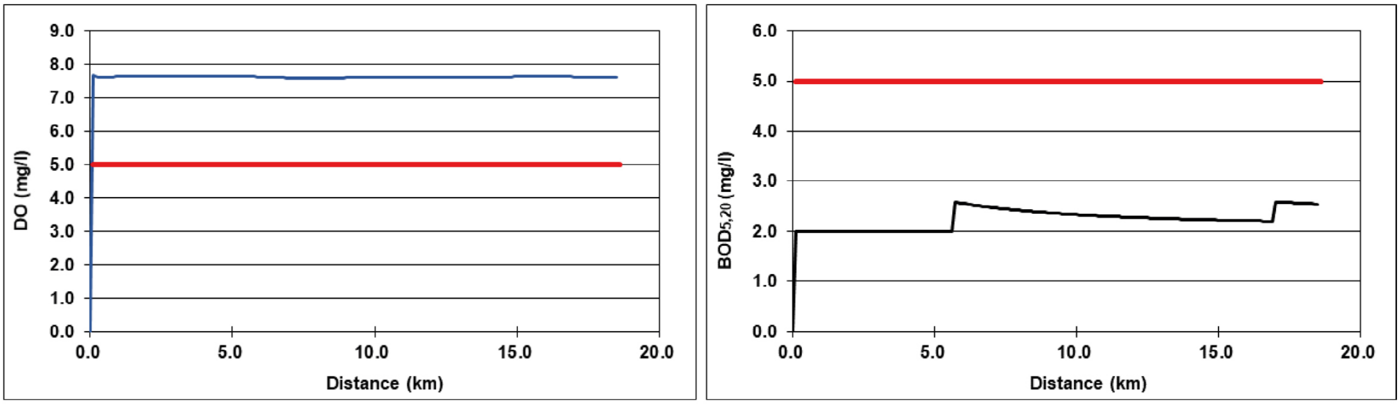


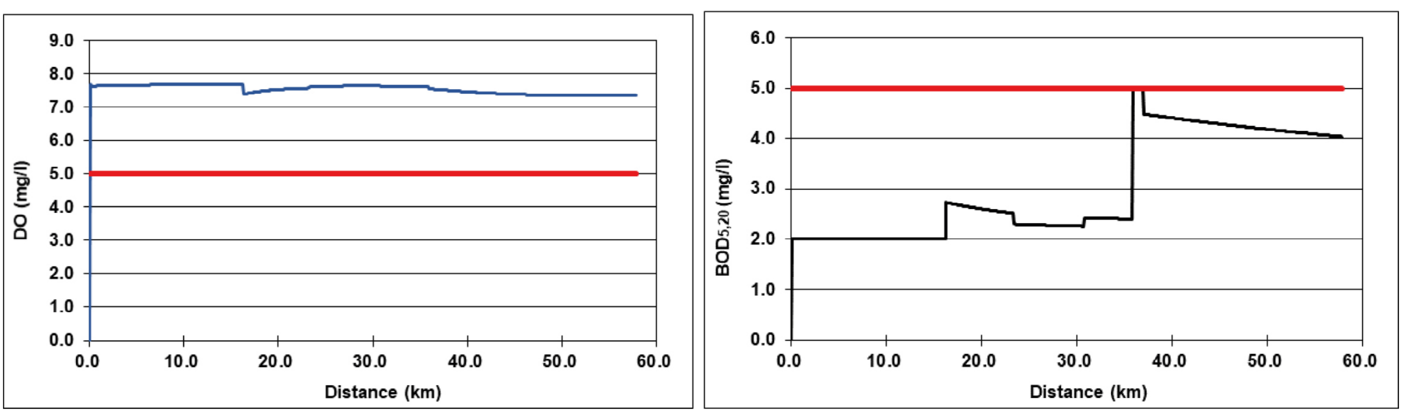
Figure 4 – The river Pardinho's DO and $BOD_{5,20}$ concentration profiles after minimum treatment efficiencies incorporation: optimization model 4.

DO: dissolved oxygen; $BOD_{5,20}$: biochemical oxygen demand.



A	B

Figure 5 – Ribeirão Perdição stream's DO and $BOD_{5,20}$ concentration profiles after minimum treatment efficiencies incorporation: optimization model 4.
DO: dissolved oxygen; $BOD_{5,20}$: biochemical oxygen demand.



A	B

Figure 6 – The river Pardo's DO and $BOD_{5,20}$ concentration profiles after minimum treatment efficiencies incorporation: optimization model 4.
DO: dissolved oxygen; $BOD_{5,20}$: biochemical oxygen demand.

treatment efficiencies, compatible with secondary or higher-level treatment systems. These urban areas are substantially more populous than Santíssima Trindade and Nossa Senhora das Graças villages, making their final sewage disposal in the upper portion of the rivers Pardo (Ibatiba) and Pardinho (Irupi) stretches, in sections that present low flow rates for sewage dilution.

Model 2, among the optimization models that incorporated equity measures in the objective functions, was the only one to present efficiencies sums close to those established by optimization Model 1.

The results achieved in the present study are similar to those found in Santoro, Reis and Mendonça (2016), Fantin, Reis and Mendonça (2017), and Bringer (2017), who used GA as an optimization tool to determine minimum sewage treatment efficiencies for the river Pardo's watershed. In this context, NLP has produced consistent and similar results to those obtained from the use of a metaheuristic optimization technique, which usually requires higher computational demands.

Conclusion

qUAL-UFMG water quality mathematical model and NLP combined use is a versatile alternative for minimum sewage treatment efficiencies within a watershed determination, allowing different optimization models and agile results.

The estimated efficiencies for the river Pardo's watershed with the aid of NLP were similar to those obtained with the use of the Genetic

Algorithm, a metaheuristic optimization technique that usually requires computational demands substantially higher than those associated to conventional optimization techniques use.

The estimated minimum organic matter removal efficiencies within the river Pardo's watershed were highly dependent on the incorporation of inequity measures into the optimization models. Sewage treatment efficiencies associated to Nossa Senhora das Graças and Santíssima Trindade villages were not significant, and were usually lower than primary sewage treatment systems organic matter removal efficiencies. Estimated efficiencies for Ibatiba and Irupi cities were usually high, regardless of the optimization model employed. These efficiencies are compatible with secondary or higher-level treatment systems.

Contribution of authors:

Rocha, L.G.: Conceptualization, Data curation. Almeida, K.N.: Formal analysis, Investigation, Methodology, Writing — original draft. Reis, J.A.T.: Formal analysis, Investigation, Methodology, Validation, Writing — review & editing, Supervision. Mendonça, A.S.F.: Formal analysis, Investigation, Methodology, Validation, Writing — review & editing. Braga Silva, F.G.: Validation.

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ABES

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An analysis of energy efficiency in multicampi higher education institutions and a novel environmental labeling proposal

Análise de eficiência energética em instituições de ensino superior multicampi e uma nova proposta de rotulagem ambiental

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ABSTRACT

The expansion of Brazilian higher education institutions (HEIs) organized in multicampi structures brought a significant complexity to the academic and administrative management. In this context, environmental management strategies become quite relevant, especially when considering the low effectiveness of the Brazilian Labeling Program (BLP) for the classification of buildings in practice. The main objective of the present paper is to evaluate the BLP efficacy as applied to HEI buildings, aiming to develop a new environmental labeling model for multicampi HEIs. For this purpose, the BLP was applied to the labeling of Instituto Federal de Educação, Ciência e Tecnologia do Piauí (IFPI), employing data obtained from electricity bills between 2016 and 2018. The energy diagnosis was performed considering distinct indicators, performance indexes, levels and rankings of relative energy efficiency, from which energy efficiency labels could be developed. The results allow the verification of the low efficiency of the BLP, especially in the environmental labeling of HEIs. From the detailed analysis of bills, it is possible to develop environmental labels inspired by the BLP, resulting in a different approach. A novel type-II environmental labeling methodology is then introduced based on the breakdown of electricity bills and statistical methods.

Keywords: buildings; energy management; labeling.

RESUMO

A expansão das Instituições de Ensino Superior (IES) brasileiras organizadas em estruturas *multicampi* trouxe uma complexidade significativa à gestão acadêmica e administrativa. Nesse contexto, as estratégias de gestão ambiental tornam-se relevantes devido à baixa eficácia do Programa Brasileiro de Etiquetagem (PBE) na rotulagem de edificações. Assim, o principal objetivo deste trabalho foi avaliar a eficácia do PBE na etiquetagem de eficiência energética das edificações de IES e desenvolver um novo modelo de rotulagem ambiental para a eficiência energética de IES *Multicampi*. Para tanto, o PBE foi aplicado à etiquetagem do Instituto Federal de Educação, Ciência e Tecnologia do Piauí (IFIPI), empregando dados coletados nas faturas de energia nos anos de 2016 a 2018. O diagnóstico energético foi realizado considerando indicadores distintos, índices de desempenho, níveis e classificações de eficiência energética relativa, a partir dos quais as etiquetas de eficiência energética poderiam ser desenvolvidas. Os resultados permitem verificar a baixa eficiência do PBE, sobretudo na rotulagem ambiental da eficiência energética em IES. A partir das análises detalhadas das faturas, pode-se sintetizar rótulos ambientais inspirados no PBE, resultando em uma abordagem diferente. Uma nova metodologia de rotulagem ambiental tipo II é então introduzida, baseada na desagregação de faturas de energia e métodos estatísticos.

Palavras-chave: etiquetagem; gestão energética; edificações.

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Introduction

In the 2030 Agenda published by the United Nations (UN) in September 2015, member countries were committed to 17 main sustainable development goals (SDGs) and 169 other goals to be pursued in the subsequent 15 years (UN, 2015b). The seventh SDG is defined in terms of accessible and clean energy policies, aiming to provide universal access to energy, increase the share of renewable energies, double the global energy efficiency rate, as well as to strengthen international cooperation in research and technology transfer (UN, 2015a). In the context of electricity, the energy efficiency of residential, commercial, and public buildings becomes relevant, which also comprises higher education institutions (HEIs). This aspect is of major concern, especially because the consumption of electricity in buildings accounted for 42.6% of overall Brazilian consumption in 2018 (EPE, 2019, p. 40). Energy efficiency can then be regarded as a set of measures aiming at the development of activities or product and service supply with low energy consumption (PÉREZ-LOMBARD; ORTIZ; VELÁZQUEZ, 2013).

The Brazilian higher education scenario has faced a significant geographical expansion since the 1960s, thus requiring improved academic and administrative management policies to ensure good performance in terms of a multicampi structures (NEZ, 2016). This expansion has become more expressive in federal HEIs since 2007 with the introduction of the Support Program for Restructuring and Expansion Plans of Brazilian Federal Universities (*Programa de Apoio a Planos de Reestruturação e Expansão das Universidades Federais* — REUNI). This program counted with the participation of all federal institutions since its first year of implementation, which led to a significant increase in the existing infrastructure (LIMA; MACHADO, 2016). Since the use of energy is the input with the highest environmental risk index (ERI) in HEIs (SENNA *et al.*, 2014), it is important to consolidate the environmental management taking into account energy efficiency policies (SILVA *et al.*, 2016). This aspect is expected to allow HEIs to promote significant changes in social reality, not only with its core activity, but also with the proper application of management strategies to the buildings in order to consolidate them as sustainable educational spaces.

According to distinct energy balance reports, *e.g.*, the ones presented by the International Energy Agency (IEA, 2018) at the global level and by the Energy Research Company (EPE, 2019) at the national level, energy statistics are generally compiled and presented on a sectoral basis, where consumers are grouped according to the economic activity, *i.e.*, industry, transportation, services, agriculture, and residential consumers. However, the sector in which HEIs are inserted is the most heterogeneous one. Although energy consumption data for the whole sector are available, specific reports for the subsectors are not easily found. In this context, the energy labeling becomes relevant as an environmental management instrument, which can be adopted as a benchmark strategy and encourage the continuous improvement of energy management in HEIs.

According to the Brazilian Association of Technical Standards (ABNT, 2002), environmental labels are statements that indicate the environmental performance of general-purpose products, or even products related to specific environmental aspects, among which the use of energy is included. Energy labels can be employed in the form of text, symbols, or graphic elements added to packages, technical bulletins, or advertisement material to allow a fair comparison among products of the same type, aiming at promoting conscious consumption. Such labeling can also be classified in three categories: type I, which refers to third-party labeling, according to the fulfillment of specific requirements (ABNT, 2004); type II, which corresponds to environmental self-declarations presented by product and service suppliers without independent certification (ABNT, 2017); and type III, which refers to the labeling of products or services while presenting environmental information on the life cycle, also comprising several stages from the acquisition of raw material to their final disposal (ABNT, 2015).

The first milestone in environmental labeling was established in 1977, when Germany created the Blue Angel label. Since then, similar strategies have been adopted in several countries worldwide, e.g., the Green Label in the United States of America (USA), the EcoMark label established in Japan in 1989, and the EU Ecolabel created by the European Union in 1998 (PRIETO-SANDOVAL *et al.*, 2020). According to Spengler *et al.* (2020), the Blue Angel label is still in force and can be classified as type I. This label is applied to distinct products to reduce impacts during the utilization stage, whereas other stages of the product life cycle are covered to a lesser extent.

Figure 1 shows a timeline comprising regulatory frameworks that led to the current state of energy consumption labeling in Brazilian buildings. In order to develop a benchmarking strategy in Brazil, the Brazilian Labeling Program (PBE) was created in 1984. Under the supervision of the National Institute of Metrology, Quality and Technology (Inmetro), which was created in 1973, and the Ministry of Mines and Energy (MME), this program is dedicated to provide consumers with information on energy efficiency of distinct products. Thus, it intends to encourage a more conscious purchasing process through the National Energy Conservation Label (ENCE), which can be classified into two types: voluntary or compulsory certifications (EPE, 2020). The social benefits of voluntary labeling increase proportionally with the market demand for certified products, the relevance of labeling issues, and the consumer ability to understand, trust, and interpret the provided information on the label. On the other hand, compulsory labeling is associated to several negative aspects, e.g., high social and production costs; extremely rigid production patterns; increase in size and complexity of the supply chain; sudden changes in production patterns or techniques; and market distortions with reduced competition (ROE; TEISL; DEANS, 2014).

The BLP is supported by the National Electricity Conservation Program (*Programa Nacional de Conservação de Energia Elétrica* – Procel), which was created in 1985 with the subprogram named Procel Seal (*Selo Procel*). This practice was instituted in 1993 to classify distinct equipment according to a given efficiency index (ELETROBRAS, 2019). Therefore, the National Label for Energy Conservation (*Etiqueta Nacional de Conservação de Energia* – ENCE) is regarded as the certification provided by Inmetro to several products, whose energy efficiency performance can be classified according to proper levels. Procel Seal is then used to identify the best products in a given category according to a type-I environmental label, highlighted at the end of the timeline shown in Figure 1.

In addition to Procel Seal, Procel Energy Efficiency in Buildings (*Procel Edifica*) subprogram was created in 2003 for the development of activities that promote the energy efficiency improvement in buildings. It is responsible for coordinating the Brazilian Building Labeling Program (*BLP Edifica*), which aims at the environmental labeling of energy efficiency in Brazilian buildings (EPE, 2020). The creation of the Energy Efficiency Program (EEP) for Electricity Distribution Companies (BRASIL, 2000) and the enactment of the Energy Efficiency Law (BRASIL, 2001) must also be highlighted. As from the introduction of this policy, electric energy distribution companies are expected to employ a minimum percentage of the net operating revenue (NOR) for the development of energy efficiency programs and Procel. Besides that, it also represents an important source of funds for the program. On the other hand, the Energy Efficiency Law establishes the minimum energy efficiency requirements for machines and devices powered by electricity, which are manufactured or marketed in the country, as well as a program of goals for improving this classification (BRASIL, 2001). It is directly associated to the BLP and Procel, given that such mechanisms tend to encourage the acquisition of energy-efficient products.

As a direct consequence of such policies, an energy saving of 21.2 billion kWh was reported in 2017, corresponding to an amount 39.89% greater than that of the previous year. It is also equivalent to 4.57% of the overall electricity consumption in Brazil during 2017, as associated with the annual consumption of 11.25 million households. This reduction accounts for the emission of 1.96 million tons of CO_2 into the atmosphere, i.e., 675,000 cars over one year (ELETROBRAS, 2018). However, in order to increase the effectiveness of the energy efficiency policies, Nogueira *et al.* (2015) underline the need for marketing campaigns to inform the general public about regulation benefits; constant review of efficiency limits; increase in the amount of regulated equipment; and increase in the number of equipment compulsorily withdrawn from the market due to low energy efficiency, similarly to what occurred with incandescent lamps.

The BLP initiatives have contributed to the efficient use of energy in the country. However, this certification can also be applied to buildings in Brazil since 2009 with the ENCE within the scope of the BLP Edifica as a result of the interaction between the BLP and Procel Edifica. The Management Committees for Energy Efficiency Indicators and Levels (*Comitê Gestor de Indicadores de Eficiência Energética* — CGIEE), which were established by the Energy Efficiency Law (BRASIL, 2001), joined the Technical Building Commission (*CT-Edificações*) together with Inmetro in 2005, considering that it also established the regulatory frameworks of BPL Edifica. The Technical Quality Requirements for

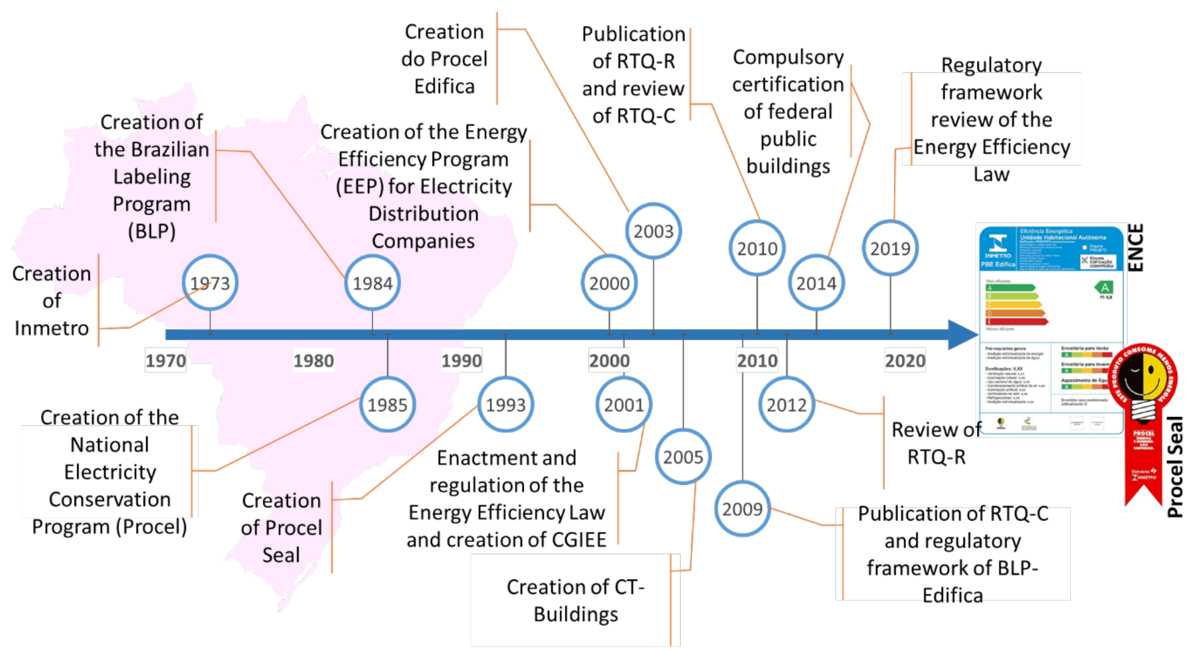


Figure 1 – Regulatory framework of energy efficiency labeling in Brazilian buildings.
Source: prepared by the author with images provided by ELETROBRAS (2019).

the Energy Efficiency Level of Commercial, Service, and Public Buildings (RTQ-C) were published in 2009 and modified in 2010 (INMETRO, 2010). The Technical Quality Regulation for the Energy Efficiency Level of Residential Buildings (RTQ-R) was also published in 2010. This regulation and its complementary documents were properly modified two years later (INMETRO, 2012).

The aforementioned regulations use engineering calculations and computer simulations from three individual building systems, *i.e.*, envelope, air conditioning, and lighting to determine the energy performance of a part or the whole building during the design or conclusion stage of the facility. It considers a set of mandatory requirements, *e.g.*, insulation of air conditioning system pipes, as well as bonus issues corresponding to photovoltaic generation systems for supplying at least 10% of the overall energy consumption, for instance.

Borgstein, Lamberts and Hensen (2016) could identify 17 examples of energy performance classification systems and projects in non-residential buildings in five countries (Brazil, the United States, the United Kingdom, China, and Australia), among which BLP Edifica is included. In this study, the program was characterized as a labeling system with asset classifications, which are applicable to new buildings and major renovations based on prescriptive or simulation methods for a comparison with national buildings. With a focus on comparing the energy consumption of buildings, these assessment techniques are used to classify, tax, and rank the energy performance of buildings on a compulsory or voluntary basis. In most cases, it also aims to ensure good performance levels and reduction of energy consumption in buildings, in addition to providing a proper classification according to the type (simple labeling or benchmarking, for example), application, and benchmarking methodology.

There are several methodologies for assessing the energy performance of buildings, which can assume several classifications based on the adopted techniques. According to Hong *et al.* (2013) and Burman *et al.* (2014), such strategies can be classified as top-down or bottom-up. In the first approach, the benchmarks are obtained based on the energy performance indices of the building. The second one considers that the indices can be obtained from the theoretical analysis of a building. According to the control level of the determination processes, Li, Han and Xu (2014) state that methodologies can be classified into white, gray, or black box type. In the first model, the techniques are purely statistical, with little information required for each building. In the second model, a limited physical analysis of the building is mixed with statistical methodologies. The last model relies strongly on the physical structure of buildings and is highly dependent on input data provided by the user. The choice of a given methodology must be performed according to the objective of the study, which is limited by the availability of data and cost-benefit ratio of data acquisition.

Among the existing techniques, it is possible to identify and classify some of the most common methodologies for determining the energy performance of non-residential buildings: engineering calculations (bottom-up and white box) (FUCCI *et al.*, 2016); statistical methods (top-down and gray or black box) (LI; TAO, 2017): simulations (bottom-up and gray or black box) (PLANAS; CUERVA; ALAVEDRA, 2018); machine learning (top-down and black box) (CHENG *et al.*, 2019); dynamic methods and real-time analysis (top-down and black box) (SCHIBUOLA; SCARPA; TAMBANI, 2018); load curve analysis and energy bill breakdown (top-down and black box) (NIEDERBERGER; CHAMPNISS, 2018); energy audit (bottom-up and white box) (MATHIOULAKIS *et al.*, 2017); post-occupation, comfort, and environmental quality analysis (bottom-up and gray or black box) (GHAHRAMANI *et al.*, 2018). According to the purpose of the study, the methodologies can be independent or complementary.

Public assessment systems for energy performance can be used in new and existing buildings for distinct purposes, which include mandatory compliance with minimum requirements; conception of policies to penalize low energy performance, or reward good energy performance; mandatory or voluntary labeling of the energy performance of buildings; transparency and disclosure programs; voluntary internal benchmarking; and evaluation of improvement opportunities (BORGSTEIN; LAMBERTS; HENSEN, 2016). BLP Edifica is characterized as one of the systems, which is an important instrument to ensure the good energy efficiency performance of buildings in Brazil. However, there is the need for a simplified, more accurate and efficient model for the labeling process (MELO *et al.*, 2012). Thus, for achieving the full implementation of this program, there is a need for developing methodologies to calculate realistic values; creating awareness campaigns for the general public; providing training and support to increase the number of energy assessors; applying sanctions in case of non-compliance with the existing regulation; conducting post-certification monitoring and evaluation measures; establishing and maintaining a central recording system for collecting relevant certification data (WONG; KRÜGER, 2017).

From the comparison of the Brazilian labeling model with those used by other countries, e.g., the United States and Portugal, it is clear that motivating the conception of zero energy consumption buildings, which are totally self-sufficient; informing CO_2 emission reductions; expanding its coverage to the industrial sector; and making certification mandatory is required (LOPES *et al.*, 2016). It is also worth mentioning that labeling buildings is still voluntary in Brazil. However, compliance with ENCE became mandatory since June 2014 for purchasing or renting electric equipment and devices, as well as for new building projects for federal institutions, which are facilities subject to retrofit with federal public resources for the exercise of administrative activity, or for the provision of public services (BRASIL, 2014). Therefore, federal public facilities can be regarded as any property built or adapted with federal public resources for the exercise of administrative activity or for the provision of public services. Even with such mandatory requirements, BLP Edifica is ineffective in labeling the energy efficiency of buildings.

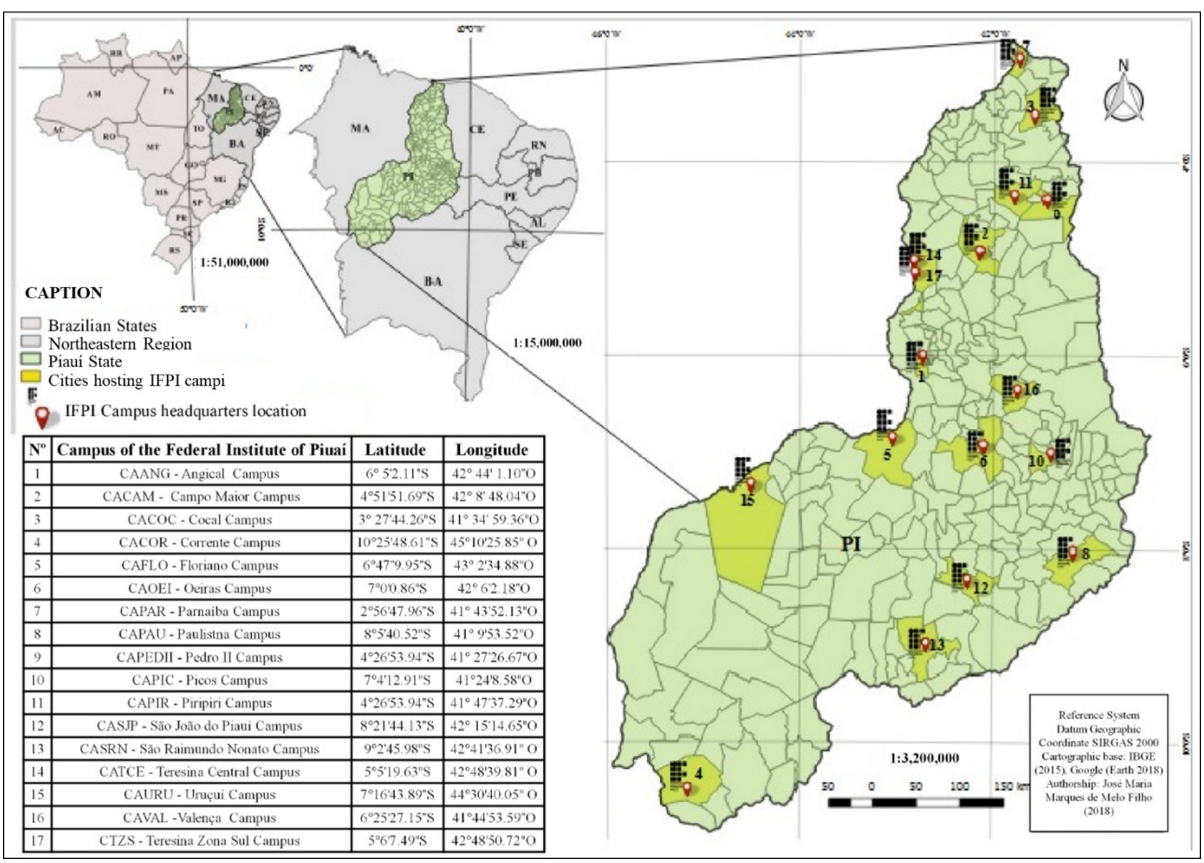
Six years after the program's creation, considering a period until 2015, during which the expansion of federal institutes of education, science and technology occurred, only 84 commercial, public, and service buildings were labeled throughout the country in a few states, which do not include Piauí State, as stated by Silva *et al.* (2015) and Wong and Krüger (2017). In this context, the present study aims to provide answers to the following question: How is it possible to develop an energy efficiency label for compliance with environmental management in multicampi HEIs in a reliable and effective manner? The main hypothesis is that energy diagnosis may rely on the detailed analysis of electricity bills, as well as productivity indicators for the conception of energy efficiency indices and levels that can be summarized in environmental labels inspired by the BLP, which is a different methodology than that of standardized by Inmetro (2010). Therefore, a type-II environmental labeling methodology is introduced in this paper, based on the breakdown of electricity bills, as well as top-down and gray box statistical methods.

For this purpose, the general objective of this study consists in evaluating the effectiveness of the BLP applied to the energy efficiency labeling of HEI buildings for developing a new environmental labeling model especially dedicated to multicampi HEIs. IFPI, which is held by the Brazilian Federal Government, was chosen as the analyzed scenario (SILVA *et al.*, 2018).

Materials and Method

Research started with the assessment of the BPL applied to HEIs. An extensive search was performed in Inmetro website (INMETRO, 2015) to identify and classify the ENCE regulations issued for buildings in Brazil, specifically comprising HEIs. Then, a general characterization of IFPI was obtained based on the available bibliography and the institution website. Relevant documents such as the institutional development plan and management reports were used for the energy diagnosis.

According to the methodology used by Silva *et al.* (2016; 2018) and Silva *et al.* (2017), a census survey was carried out and, considering the multicampi organizational structure, an extensive analysis of electricity bills of all campuses was developed for the period between 2016 and 2018. Created by the Brazilian Federal Government in 2008, in agreement with the Federal Law No. 11,892, IFPI (2014) aims to "be consolidated as a center of excellence in professional, scientific, and technological education, ranked among the best educational institutions in the Northeastern region". It currently encompasses 17 campi and 19 energy consuming units, which are distributed over all regions of Piauí State, as shown in Figure 2. All campi are the subject of research, except for ad-



Nº	Campus of the Federal Institute of Piuaí	Latitude	Longitude
1	CAANG - Angical Campus	6° 5'2.11"S	42° 44' 1.10"O
2	CACAM - Campo Maior Campus	4°51'51.69"S	42° 8' 48.04"O
3	CACOC - Cocal Campus	3° 27'44.26"S	41° 34' 59.36"O
4	CACOR - Corrente Campus	10°25'48.61"S	45°10'25.85" O
5	CAFLO - Floriano Campus	6°47"9.95"S	43° 2'34.88"O
6	CAOEI - Oeiras Campus	7°0'0.86"S	42° 6'2.18"O
7	CAPAR - Parnaíba Campus	2°56'47.96"S	41° 43'52.13"O
8	CAPAU - Paulistna Campus	8°5'40.52"S	41° 9'53.52"O
9	CAPEDII - Pedro II Campus	4°26'53.94"S	41° 27'26.67"O
10	CAPIC - Picos Campus	7°4'12.91"S	41°24'8.58"O
11	CAPIR - Piripiri Campus	4°26'53.94"S	41° 47'37.29"O
12	CASJP - São João do Piauí Campus	8°21'44.13"S	42° 15'14.65"O
13	CASRN - São Raimundo Nonato Campus	9°2'45.98"S	42°41'36.91" O
14	CATCE - Teresina Central Campus	5°5'19.63"S	42°48'39.81" O
15	CAURU - Uruçuí Campus	7°16'43.89"S	44°30'40.05" O
16	CAVAL -Valença Campus	6°25'27.15"S	41°44'53.59"O
17	CTZS - Teresina Zona Sul Campus	5°6'7.49"S	42°48'50.72"O

Figure 2 – Description of IFPI campi.
Source: adapted from Silva et al. (2018).

vanced campi and the main administration building, whereas the analysis considers indicators measured from 2016 to 2018.

With the breakdown of 684 electricity bills, a preliminary energy diagnosis was performed while identifying three relevant aspects: manageable costs; avoidable loss and other issues; and proposal of strategies for the energy efficiency evaluation of HEIs. The breakdown of electricity bills is typically used in similar studies, which include those developed by Ketchman *et al.* (2018) and Niederberger and Champniss (2018). Partial results were then presented to the administration board of IPFI to establish a continuous flow of information in the subsequent months and enable the continuity of studies. In addition, based on the percent participation of cost centers in the total electricity bill, the indicator of avoidable loss (IndAL) was defined as the ratio between manageable costs and the sum of costs associated to avoidable loss.

In order to establish the energy efficiency labels for the campi, an environmental indicator matrix was compiled using the pressure-state-response (PSR) framework (OECD, 2003) based on the pressure (energy use) and state (number of civil servants, infrastructure, and educational aspects) variables, just like recommended by Silva *et al.* (2018). Such variables were chosen based on the end activity of the institution and on the following qualitative and quantitative criteria: data reliability, relation with the addressed problem, usefulness to the user, data availability, relevance, redundancy, and measurability. Primary data associated with the indicators were used in all campi between 2016 and 2018 in a formal request forwarded to the administration board, in addition to secondary data collected from Nilo Peçanha Platform. This virtual environment is available to the IFPI community since 2017, containing official statistics from the Brazilian Federal Network for Professional, Scientific and Technological Education, which also comprises IFPI (BRASIL, 2019b).

From such data used for classifying the campi in different scale categories, statistical software SPSS was employed to perform a multivariate analysis; and a dendrogram was plotted, which is a graph obtained with the cluster analysis to aggregate different observations. The Euclidean distance was used as an evaluation criterion and the centroid of each cluster of observations was considered. The value of each observation corresponds to the arithmetic mean of the values for the indicator considering 2017 as a reference for all campi (MANLY, 2008). Besides that, in order to prevent a given variable from dominating the analysis, the data were previously normalized based on the difference between the minimum and maximum values (KILKS, 2015).

According to the recommendation provided by Silva *et al.* (2018), the data envelopment analysis (DEA) (CHARNES; COOPER; RHODES, 1978) was employed with the analysis model (Charnes, Cooper and Rhodes — CCR or Banker, Charnes, and Cooper — BCC), which is based on the homogeneity of samples (CHARNES; COOPER; RHODES, 1978; BANKER; CHARNES; COOPER, 1984). Thus, new efficiency indices were determined: the general indicator of manageable costs (IndMC), which was obtained with the DEA using the BCC model; and the clustering IndMC, which resulted from the DEA based on the CCR model. In addition to this, given the number of observations, the DEA golden rule, as defined by Banker *et al.* (1989), was applied to the third version of the Integrated Decision Support System (SIAD) (ANGULO MEZA *et al.*, 2005) software. This methodology was used by Blum and Okwelum (2018), Borgstein and Lamberts (2014), and Domingos *et al.* (2018) in the energy efficiency evaluation based on DEA, aiming at the analysis of household appliances, buildings, and public policies, respectively.

From the aforementioned indicators, the general relative energy efficiency index (REEI) was created and clustered using the arithmetic mean of IndAL and IndMC. By using such new data, the campi were classified according to five levels of relative energy efficiency with equal lengths, based on the difference between the highest and lowest indicators. A general ranking was then established in terms of energy performance while estimating the benchmarks for increasing energy efficiency. The main goal was defined as the elimination of avoidable loss. The DEA models were then used to provide inputs and outputs for establishing energy consumption and demand benchmarks, and for teaching activities, as well as the best efficiency energy level, as observed in Figure 3.

According to the diagram shown in Figure 3, a new type-II environmental labeling model is proposed for energy efficiency evaluation, *i.e.*, a self-declaration approach that is supposed to be employed by the HEIs without independent certification while following general and specific requirements provided by ABNT (2017). For this purpose, the model standardized by BLP Edifica, *i.e.*, the traditional paradigm, was used as a starting point. A new energy efficiency label was presented for each of the campus containing relevant information for the energy efficiency analysis, such as indicators, indices, levels, rankings, and diagnostics aiming at a benchmarking strategy.

Results and Discussion

From data provided by Inmetro (2015), it was possible to identify only 96 non-commercial buildings with the energy efficiency labeling in the scope of the BLP until June 10th, 2019, corresponding to 18 additional units when compared to the amount reported by Wong and Krüger (2017). The Southeastern and Northeastern regions stand out with the highest percentage of issued labels (50 and 24%, respectively), mainly in São Paulo and Bahia States, which were the states with the highest number of ENCE certifications, *i.e.*, 27.1 and 20.8%, respectively. A total of 12 other states with no energy efficiency certification for non-residential buildings were also found, *i.e.*, Acre, Alagoas, Amapá, Goiás, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, Rondônia, Roraima, and Tocantins. From the percent analysis of each energy efficiency level applied to the buildings according to BLP Edifica, it was possible to verify that most of the systems have good performance. Moreover, the percentage of the assessed buildings ranged from 66 to 100%, as observed in Figure 4. This variation is due to the possibility of providing partial certifications to the buildings. However, the envelope analysis was carried out in all buildings considering that this is a mandatory requirement for obtaining general or partial ENCE labels.

Only two HEI buildings received the ENCE label: the School of Architecture of Universidade Federal de Minas Gerais (UFMG) in November 2013; and the University Restaurant of Universidade Federal de Santa Catarina (UFSC) in October 2012. The building envelope and lighting at UFMG were classified with energy efficiency levels C and B, respectively, which are considered low. On the other hand, the building envelope at UFSC was classified with energy efficiency level A, the highest rank.

It is important to highlight that, even if more than one system is certified, only one ENCE certificate is issued. This result proves that even with the requirement of ENCE in federal HEIs (BRASIL, 2014), the BLP Edifica is quite ineffective in the certification of buildings as evidenced by Silva *et al.* (2015) and Wong and Krüger (2017), mainly in the case of HEIs, which should be an example of sustainability to the entire community. However, this study does not take into account the implications of the Energy Efficiency Law (BRASIL, 2001) and the mandatory purchase of products with energy efficiency level A (BRASIL, 2014), which may be the scope of future work.

Considering the multicampi organizational structure of IFPI, electricity costs were estimated based on the breakdown of electricity bills of all campi in 2016, 2017, and 2018, according to Table 1. An annual average value of R$ 232,668.59 was determined, *i.e.*, 4.68% of the total cost, which is higher than the amount spent individually on electricity by six of 17 campi, as shown in Figure 2 (CACAM, CACOC, CAPAU, CAPEDII, CASJP, and CAVAL). In this context, such loss should be promptly eliminated. The amount transferred to the local utility in the form of fines due to delay in the payment of bills is equal to 37%; 35% corresponds to excessive consumption of reactive power, *i.e.*, the amount of energy supplied by the utility that does not result in useful work; and 28% is due to the higher energy consumption than the contracted demand.

Additionally, the annual average manageable costs of R$ 5,060,994.66 must be reduced with the proper execution of energy efficiency projects (EEPs), also comprising environmental education strategies aiming to reduce energy consumption during the more expensive period, *i.e.*, the peak hours between 5:30 p.m. and 8:30 p.m. (ANEEL, 2010). During this interval of only three hours, the amount spent on energy consumption corresponded to 33% of the overall cost. During the three-year period under analysis, there has been a growing trend involving all components associated to manageable costs, as well as in all other components related to avoidable loss, except for the exceeding demand. This component faced a drastic decrease from 2016 to 2017, but it increased again from 2017 to 2018 according to Figure 5A, thus reflecting a specific action taken by the HEI administration board.

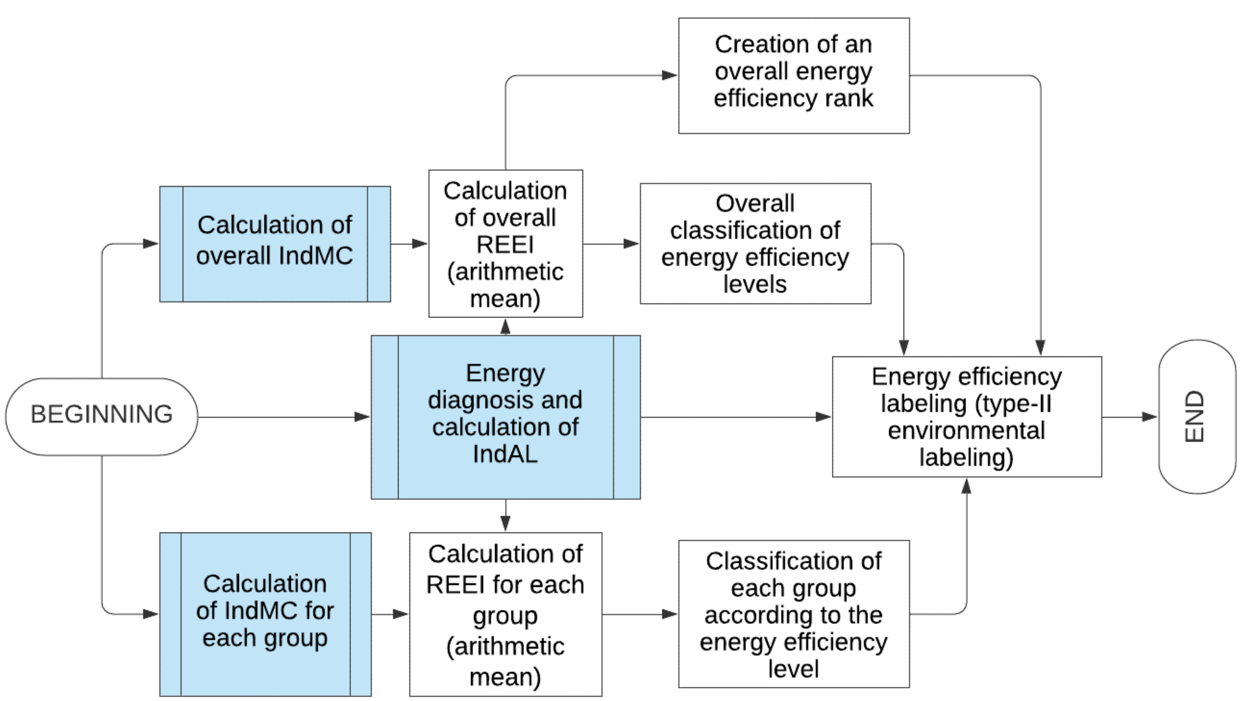


Figure 3 – Environmental energy efficiency labeling of multicampi HEIs.

The preliminary analysis of energy supply contracts suggests that there was a reduction in the amount paid on the exceeding demand from 2016 to 2017, as a result of the review of the contract terms of all consumer units at the beginning of 2017. However, the increase in this cost in the subsequent year suggests that even though it is a concrete and efficient action, this was a one-off action that should be maintained to ensure good results. The increase in electricity costs also reflects the annual tariff adjustment, which varies significantly. Thus, the energy management, especially in terms of energy efficiency, must consider the variation in consumption and demand of the facilities. However, the analysis in monetary terms is relevant due to the multidisciplinary nature of the study, which is a specific aspect of environmental sciences and involves the impact of costs on the management of organizations.

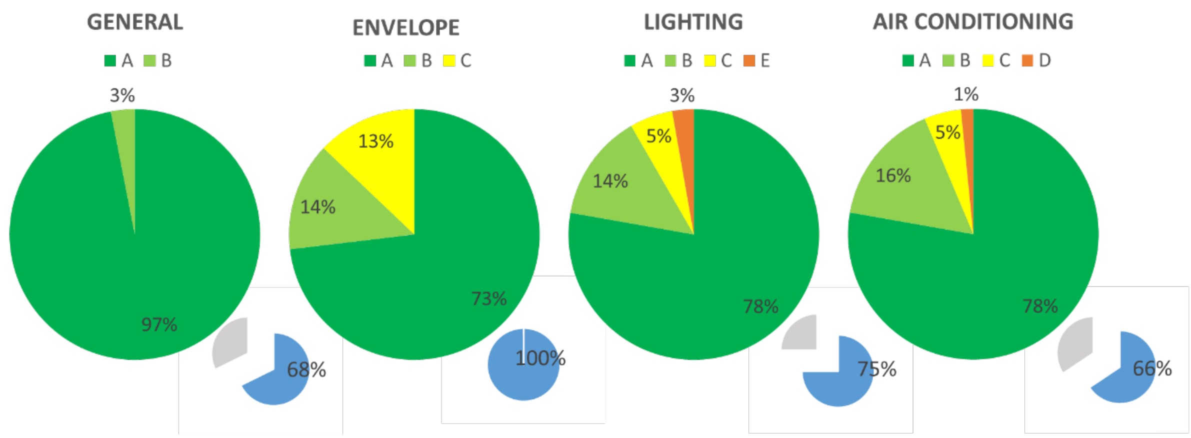


Figure 4 – Percentage of labels issued by the BLP to non-residential buildings until June 2019.
Source: prepared by the author from data provided by Inmetro (2015).

Table 1 – Electricity costs of IFPI between 2016 and 2018.

INPUTS	2016	2017	2018	Annual Average	
	R$	R$	R$	R$	%
Total bill	**R$ 4,330,125.85**	**R$ 4,624,818.04**	**R$ 5,921,169.26**	**R$ 4,958,704.38**	**100.00**
Total manageable costs	**R$ 4,360,863.56**	**R$ 4,762,192.47**	**R$ 6,059,927.94**	**R$ 5,060,994.66**	**102.06**
Demand	R$ 708,753.53	R$ 648,530.82	R$ 779,652.78	R$ 712,312.38	14.36
Peak consumption	R$ 1,279,736.25	R$ 1,650,506.04	R$ 2,099,384.28	R$ 1,676,542.19	33.81
Off-peak consumption	R$ 2,289,969.22	R$ 2,348,814.02	R$ 3,045,944.65	R$ 2,561,575.96	51.66
COSIP	R$ 82,404.56	R$ 114,341.58	R$ 134,946.23	R$ 110,564.12	2.23
Total avoidable losses	**R$ 266,582.22**	**R$ 170,546.17**	**R$ 259,057.56**	**R$ 232,061.98**	**4.69**
Exceeding demand	R$ 121,474.48	R$ 27,761.74	R$ 44,475.81	R$ 64,570.68	1.30
Exceeding reactive power	R$ 69,234.70	R$ 76,354.14	R$ 102,183.25	R$ 82,590.70	1.67
Fine	R$ 58,466.57	R$ 54,879.87	R$ 81,991.74	R$ 65,112.73	1.31
Default interest	R$ 9,951.10	R$ 10,721.37	R$ 15,447.24	R$ 12,039.90	0.24
Monetary correction	R$ 8,260.70	R$ 1,325.42	R$ 15,477.63	R$ 8,354.58	0.17
Other costs*	**-R$ 297,319.94**	**-R$ 307,920.60**	**-R$ 397,816.24**	**-R$ 334,352.26**	**-6.74**
*Additional costs and eventual invoice discounts were not analyzed in the project.					

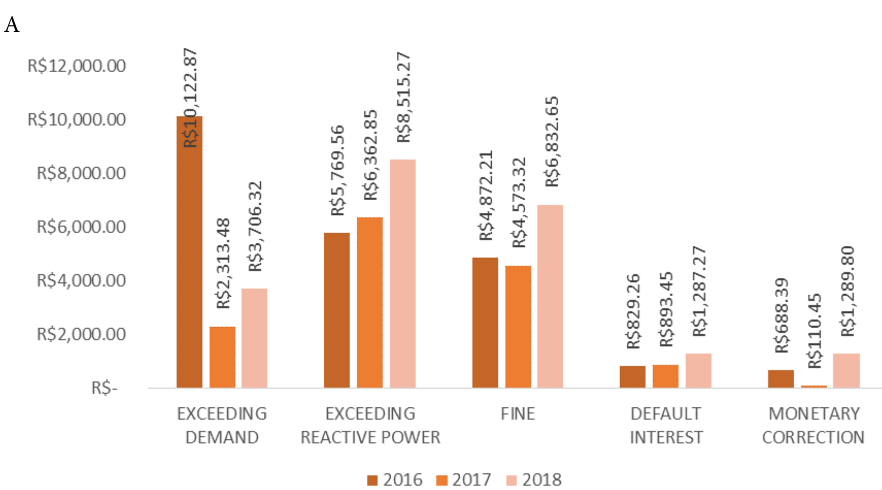
Source: prepared by the author employing data from electricity bills between 2016 and 2018.

Breaking down electricity bills was also essential to calculate IndAL, which measures the percentage of avoidable loss in the amounts paid to the utility and corresponds to half of the weight of the REEI as proposed in the present study. The variation of IndAL in the IFPI campi from 2016 to 2018 is also shown in Figure 5B, in which the green and red colors are used to represent units with improved and worsened performances from 2016 to 2018. It seems that even with the significant reduction of loss associated to the exceeding demand, nine out of 17 campi presented the worst performance in terms of such indicator, thus suggesting the need for an improvement in the energy management strategies of the HEI, especially with respect to electricity costs.

All the actions proposed to eliminate avoidable loss can provide average monthly savings of R$ 19,338.49. They should be considered in an economic analysis as prominent advantages of the proposed interventions, considering important aspects such as the on-time payment of invoices, installation of capacitor banks, and review of the electric energy supply contracts with the local utility. However, the manageable costs represent the largest portion of the electric energy expenses, *i.e.*, almost 21 times higher than the cost of avoidable loss. This aspect requires the implementation of an efficient energy management system. For this purpose, data for the elaboration of an indicator matrix, as defined by Silva *et al.* (2018) between 2016 and 2018, were used. From the previously normalized state indicators of 2017, a clustering analysis was performed, and two clusters could be formed based on the multivariate distance of the campi, thus denoting that they are all similar to each other, except for CATCE, as shown in Figure 2.

Thus, based on productivity concepts, it was possible to determine IndMC using the measurements related to energy use (inputs) and education (outputs) in 2016, 2017, and 2018, according to Silva *et al.* (2018). Such data represent a measure of the demand relative efficiency and use of active power, which is associated to the energy used to perform useful work. The DEA BCC model was used to determine the general IndMC, because this model considers different returns depending on the scale of the decision-making unit (DMU). On the other hand, the DEA CCR model was used to determine the clustering IndMC, because it considers constant returns regardless of the DMU scale. The annual variations of this indicator are presented in general terms in Figure 6A and by clusters in Figure 6B, in which the green and red colors denote the campi with worsened and improved performances from 2016 to 2018, respectively. Floriano Campus (CAFLO) could not be included in the analysis because its respective efficiency was not determined in 2016. The utility energy meter installed in the facility could not measure the peak and off-peak energy consumption separately, which are essential variables for calculating IndMC.

It is observed that there is no regular pattern in the variation of IndMC in the general or in the clustering analysis, given that it increased or decreased randomly in some campi. In addition, there are inconsistencies in the comparison between indicators due to the differences between the DEA BBC and DEA CCR models, which were used for determining the general IndMC and clustering IndMC, respectively. DEA BBC considers that the scale returns vary, but DEA CCR provides constant values to such quantities. However, the variations in the indicators related to energy use and education at Angical Campus (CAANG) from 2016 to 2018 can be highlighted, since the general IndMC and clustering IndMC varied -0.23 and -0.24, respectively. Variations of inputs and outputs were also found in Paulista-



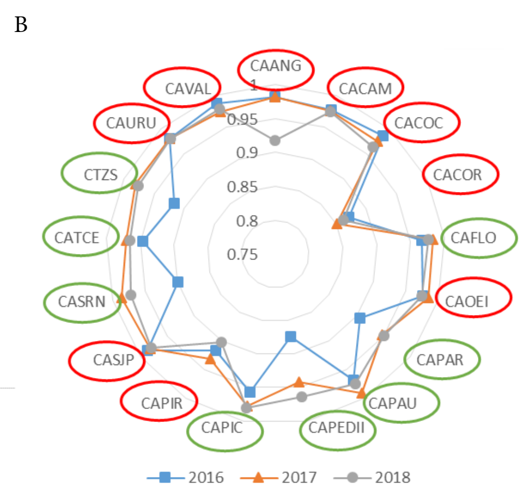


Figure 5 – (A) Profiles of avoidable loss in all IFPI campi and (B) avoidable loss per campus between 2016 and 2018.

Source: prepared by the author employing data from electricity bills between 2016 and 2018.

na (CAPAU) and Cocal (CACOC) campi for the same period, with the highest increase in general IndMC and clustering IndMC corresponding to 0.31 and 0.40, respectively.

As previously discussed, the DMU with higher efficiency consequently has the best productivity, being possible to define this concept as the ratio between outputs and inputs. Thus, when analyzing the variation of the IndMC in CAANG, which is the campus with the largest decrease, it is observed that this indicator reflects the variation in productivity. There was an increase in inputs in Figure 7A and a decrease in outputs in Figure 7B. Such aspects cause a decrease in productivity and efficiency. Considering the campi in which IndMC increased, the direct impact on the increased productivity and efficiency is noticeable.

After calculating IndAL, general IndMC, and clustering IndMC, it was possible to determine the REEI in terms of general and clustering values using the arithmetic means of the aforementioned indicators for all campi from 2016 to 2018, except for CAFLO in 2016. In general, an increase in this indicator over the years for both representations can be noted due to the improvement of IndAL. However, the positive impact on this indicator is due to a one-off action, which should be maintained.

Analogously to the indicators that compose it, there was no defined pattern in the variation of the REEIs in IFPI, whereas some units presented improved or worsened performance in the clusters. The results are shown in Figure 8 for all campi in 2018. São Raimundo Nonato campus (CASRN) and CAFLO present the lowest and highest REEIs, respectively, which is also reflected by the existence of a grid-connected photovoltaic system installed in CAFLO (MORAIS *et al.*, 2019.

In order to achieve the maximum energy efficiency level in all campi, the maximum level is required for both IndAL and IndMC. The maximum performance in the first indicator can be obtained only if avoidable loss is completely eliminated, which include important actions, such as the on-time payment of bills, revision of energy supply contracts, eventual installation of capacitor banks, and the consequent elimination of excessive reactive energy consumption. There are two possible solutions to maximize IndMC: reduction in consumption and demand for active energy; or increase in the number of students. Both actions should be developed simultaneously. The goals for decreasing inputs and increasing outputs include the application of DEA to inputs and outputs of campi with low performance in this indicator, as stated by Silva *et al.* (2018). This action is supposed to bring additional benefits, such as the increase of monetary resources received by the HEI; reduction in the socioenvironmental impacts related to the power system expansion; and establishment of a benchmark model for other HEIs in Brazil.

The campi with the lowest IndMC have more ambitious goals toward an efficient energy management strategy. Considering environmental statements can be presented in different ways (ABNT, 2017), relative energy efficiency labels (REELs) were developed as shown

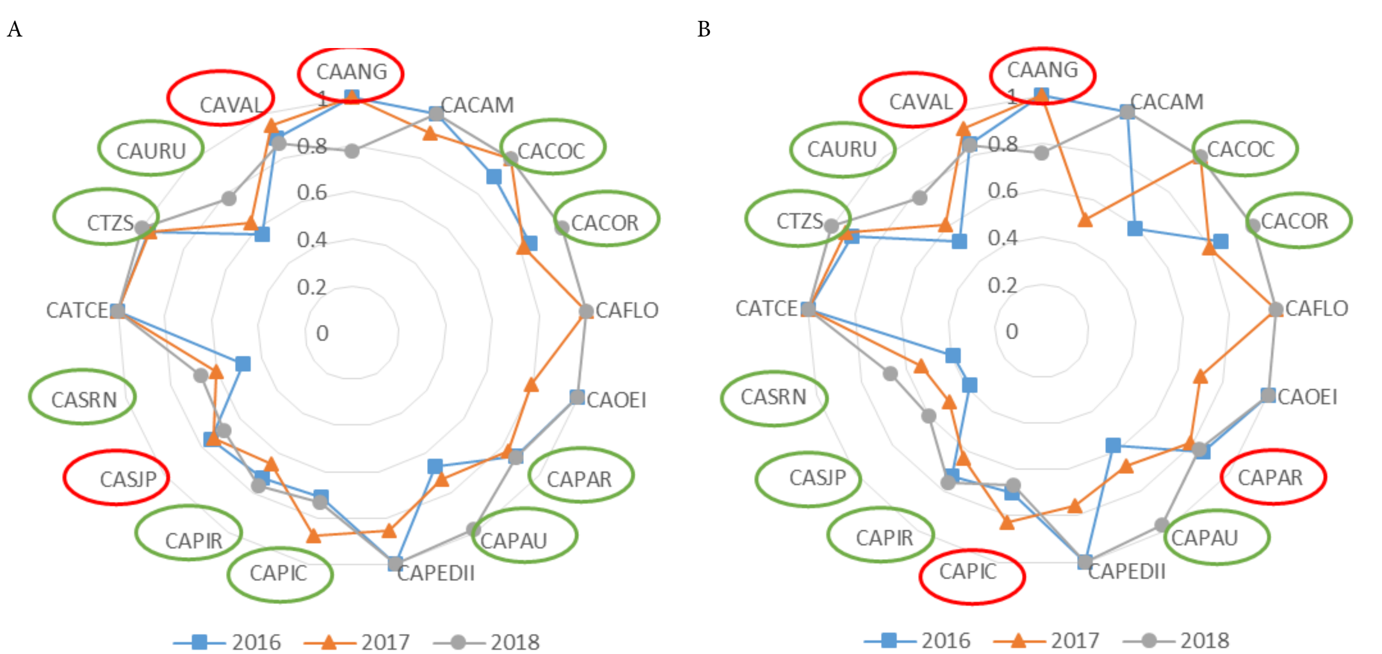


Figure 6 – Behavior of (A) general IndMC and (B) clustering IndMC in each IFPI campus between 2016 and 2018.
Source: prepared by the author with data from electricity bills between 2016 and 2018, also considering primary data provided by IFPI (2014) and Brasil (2019b).

in Figure 9. This approach can be regarded as a clear, transparent, sound, and documented type-II environmental labeling proposal, which also comprises some essential characteristics to ensure the self-declaration reliability.

In addition to socioenvironmental benefits, the implementation of energy saving strategies also contributes to mitigating the impacts of contingency of funds. This scenario is currently faced by Brazilian HEIs, which have struggled to reduce operating ex-

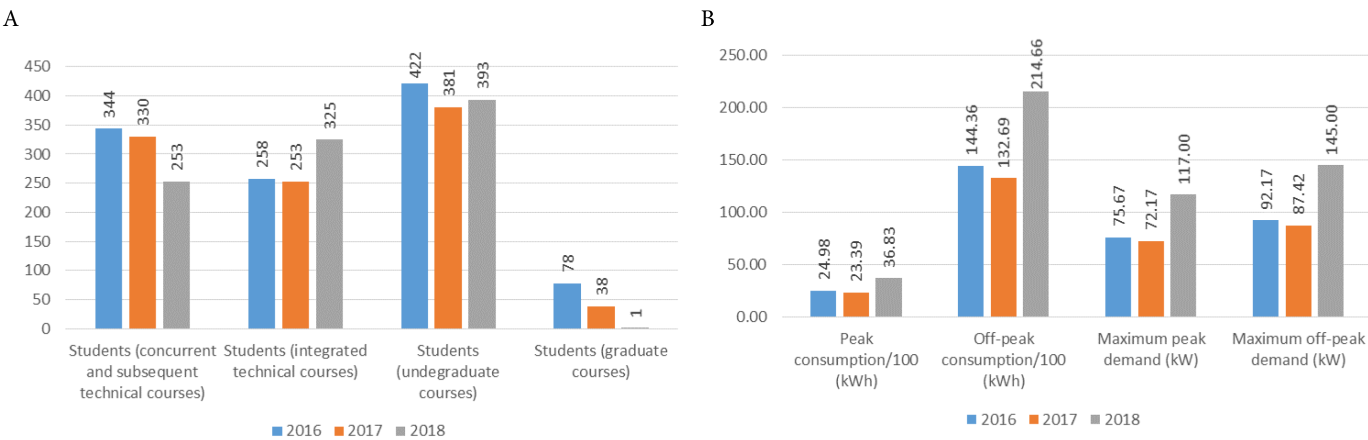
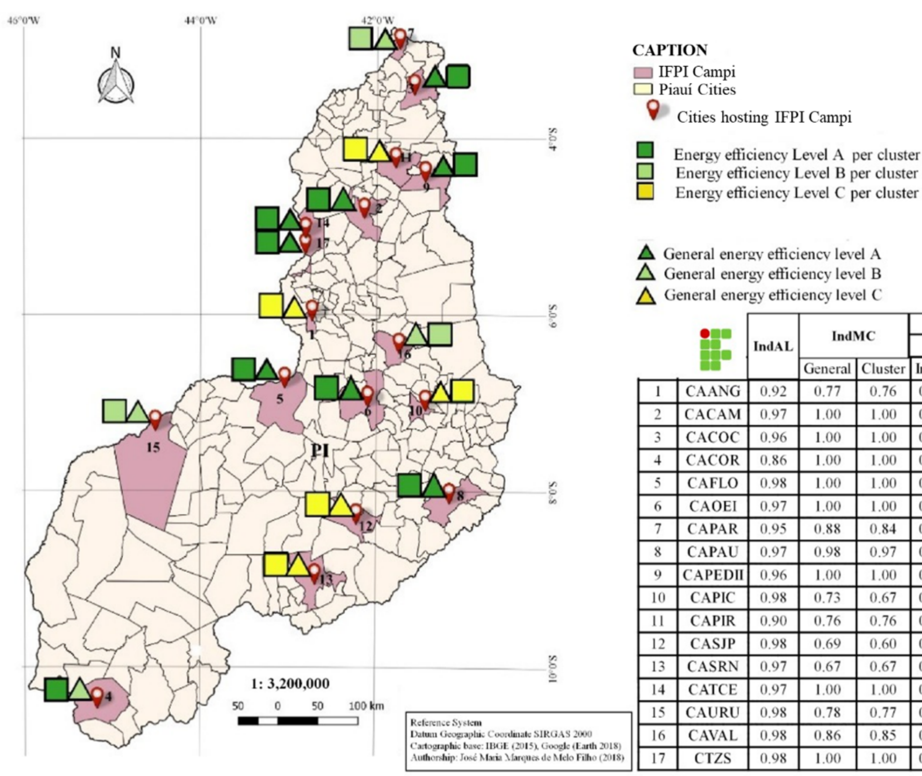


Figure 7 – Behavior of (A) energy indicators – inputs and (B) education indicators – outputs of CAANG between 2016 and 2018.

Source: prepared by the author employing data from electricity bills between 2016 and 2018, also considering primary data provided by IFPI (2014) and Brasil (2019b).



		IndAL	IndMC		REEI			
					General		Cluster	
			General	Cluster	Index	Level	Index	Level
1	CAANG	0.92	0.77	0.76	0.84	C	0.84	C
2	CACAM	0.97	1.00	1.00	0.99	A	0.99	A
3	CACOC	0.96	1.00	1.00	0.98	A	0.98	A
4	CACOR	0.86	1.00	1.00	0.93	B	0.93	A
5	CAFLO	0.98	1.00	1.00	0.99	A	0.99	A
6	CAOEI	0.97	1.00	1.00	0.99	A	0.99	A
7	CAPAR	0.95	0.88	0.84	0.91	B	0.89	B
8	CAPAU	0.97	0.98	0.97	0.98	A	0.97	A
9	CAPEDII	0.96	1.00	1.00	0.98	A	0.98	A
10	CAPIC	0.98	0.73	0.67	0.86	C	0.82	C
11	CAPIR	0.90	0.76	0.76	0.83	C	0.83	C
12	CASJP	0.98	0.69	0.60	0.83	C	0.79	C
13	CASRN	0.97	0.67	0.67	0.82	C	0.82	C
14	CATCE	0.97	1.00	1.00	0.98	A	0.98	A
15	CAURU	0.98	0.78	0.77	0.88	B	0.87	B
16	CAVAL	0.98	0.86	0.85	0.92	B	0.91	B
17	CTZS	0.98	1.00	1.00	0.99	A	0.99	A

Figure 8 – IndAL, IndMC, and REEI of each IFPI campus between 2016 and 2018.

Source: prepared by the author from data provided by IBGE (2015) and Google (2018).

penses in the last years (SANTOS, 2020). Thus, the composition of the proposed labels for the multicampi HEIs can be used as an important tool to develop benchmarking strategies and guide the actions toward the conception of an efficient energy management system, in terms of energy efficiency indexes, levels and ranking, as well as energy diagnosis.

Conclusion

Even without considering the implications of the Energy Efficiency Law (BRASIL, 2001) and the mandatory purchase of products with the energy efficiency index class A (BRASIL, 2014), the survey carried out on the Inmetro website has proven the ineffectiveness of the BLP applied to the environmental energy efficiency labeling of buildings in Brazil. This fact is especially true in the case of HEIs, since only two buildings were certified even after ten years of regulation.

The energy diagnosis performed at the IFPI proves that the institution does not adopt an adequate energy management strategy. It was found that 4.68% of the total amount paid to the local electricity company in 2016 to 2018 are due to loss, corresponding to a value higher than that paid for the electric energy consumption in six out of 17 campi in 2018.

The development of research activities in energy efficiency can lead to positive impacts on the energy management in HEIs, which may include review of energy supply contracts, for instance. However, if there is no continuous monitoring of energy consumption in terms of the adoption of an accurate energy management system, sometimes these one-off actions may lead to poor results in the long term.

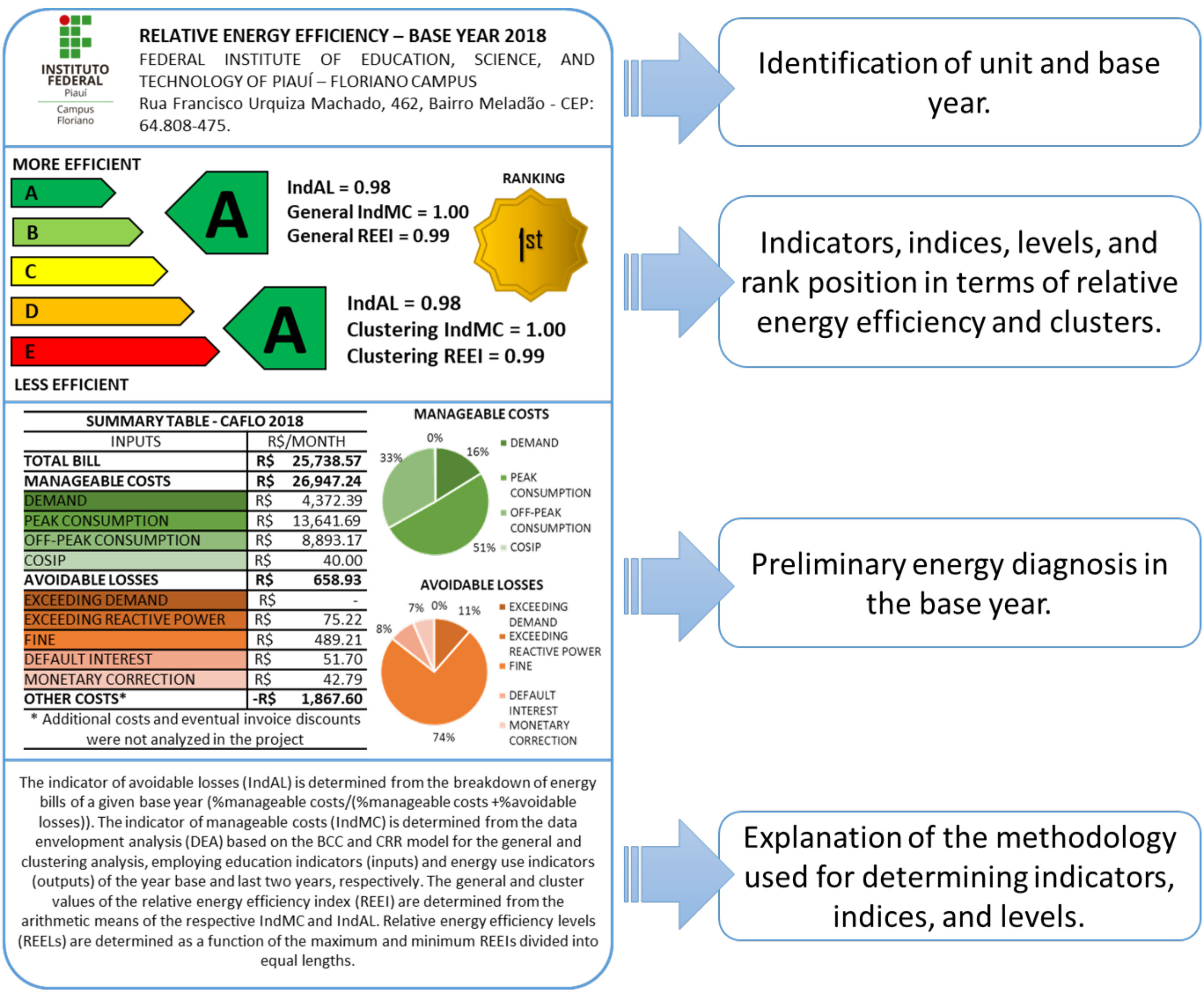


Figure 9 – Proposed energy efficiency environmental labeling for multicampi HEIs.

The breakdown of energy bills can be used in the energy diagnosis of multicampi HEIs, thus allowing the identification of cost centers, which include avoidable loss, manageable costs, among others. From the definition of an indicator of avoidable loss (IndAL), it was possible to determine the campi that have the highest and lowest contributions to the existing expenses. In addition, an environmental indicator matrix using the PSR model could be designed to characterize all campi, making it possible to cluster them with multivariate statistics and to define an indicator of manageable costs (IndMC) using the general and clustering DEA.

Therefore, the matrix data can be used as inputs and products, such as in the form of education and energy use indicators, respectively, aiming at an analysis of productivity and efficient energy use associated with the breakdown of electricity bills. This study resulted in IndAL, which was used to define the general REEI and clustering REEI. From such data, the traditional CCR and BCC DEA models could also be used to determine goals for reducing energy consumption and demand and or increase the education indicators in multicampi HEIs, considering that both actions should be carried out simultaneously.

By using benchmarking, this methodology can be employed to rank the campi and monitor energy consumption in various measurement cycles, thus promoting the continuous improvement of this environmental aspect. In fact, this is the main objective of an energy management system, which may also contribute to the guidelines provided by Agenda 2030. Such results can also be summarized in terms of a REEL, which is classified as a type-II environmental labeling approach applied to each campus. Therefore, this can be regarded as a top-down and black box methodology, which is simpler and more effective than that standardized by Inmetro, i.e., the traditional paradigm. Besides that, the latter approach is sometimes limited given the high complexity, intersubjectivity, and instability of the environment, which confirms the main hypothesis investigated in this study.

Research results are expected to lead to positive impacts on the environmental performance of HEIs. The promotion of awareness of the academic community to environmental issues is also intended, considering that energy consumption is only one of many manageable environmental aspects. Within this context, the development of sustainable spaces in HEIs is highly encouraged. The present study aims to motivate the development of similar studies in other institutions, and the proposed methodology can be used as a benchmark in the energy management of HEIs. Finally, given the flexibility of the introduced techniques, this strategy is expected to be applied to other multisite organizations and aggregate other environmental aspects.

Contribution of authors:

Silva, O.A.V.O.L.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Writing — original draft, Writing — review & editing. Moita Neto, J.M.: Funding acquisition, Project administration. Lira, M.A.T.: Supervision, Validation, Visualization, Writing — review & editing.

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ABES

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Effect of toxicity in *Folsomia candida* by the use of fungicide and insecticide in subtropical soil

Efeito da toxicidade em *Folsomia candida* pelo uso de fungicida e insecticida em solos subtropicais

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ABSTRACT

Pesticides are widely used for control and prevention against agricultural pests and diseases. The use of these products can negatively affect non-target organisms with important role in soil such as springtails. The present study aimed to evaluate the toxicity of two commercial formulations of pesticides on soil fauna using the springtail Folsomia candida. A natural soil classified as Inceptisol, characteristic of the western region of the Santa Catarina State, was used. The treatments in both tests consisted of six concentrations of the fungicide Comet® (a.i. pyraclostrobin) (0.35; 0.70; 1.40; 2.10; 2.80 and 4.00 mg kg^{-1} of soil) and of the fungicide + insecticide Standak®Top (a.i. pyraclostrobin + thiophanate-methyl + fipronil) (0.20; 0.60; 1.20; 1.80; 2.40 and 3.00 mg kg^{-1} soil), plus the control treatment. Acute and chronic tests were carried out following ISO guidelines. Both products proved to be toxic to the evaluated species. Lethality effects were observed in relation to the control of the organisms exposed to low concentrations of the fungicide (0.35 mg kg^{-1} soil); while for the fungicide + insecticide formulation, lethality was observed at higher concentrations, from 2.40 mg kg^{-1} soil (LC50 > 3.00 mg kg^{-1} soil). The reproductive rate was affected only in organisms exposed to the fungicide, with a reduction in the number of juveniles at concentration from 4.00 mg kg^{-1} soil, with EC_{20} of 3.38 mg kg^{-1} soil (2.79–3.96). The results indicate that springtails are sensitive to the tested products, especially to the fungicide that contains the highest concentration of pyraclostrobin in the composition.

Keywords: springtails; pesticides; Inceptisol; edaphic fauna; terrestrial ecotoxicology.

RESUMO

Os agrotóxicos são amplamente utilizados para o controle e a prevenção de pragas e doenças agrícolas. O uso desses produtos é capaz de afetar de maneira negativa organismos não alvos de papel significante no solo, como os colêmbolos. O presente estudo teve como objetivo avaliar a toxicidade de duas formulações comerciais na fauna do solo utilizando o colêmbolo Folsomia candida. Foi utilizado um solo natural classificado como Cambissolo Húmico, característico da região oeste do Estado de Santa Catarina. Os tratamentos nos dois testes consistiram em seis concentrações do fungicida Comet® (i.a. piraclostrobina) (0,35; 0,70; 1,40; 2,10; 2,80 e 4,00 mg kg^{-1} de solo) e do fungicida + inseticida Standak®Top (p.a. piraclostrobina + tiofanato metílico + fipronil) (0,20; 0,60; 1,20; 1,80; 2,40 e 3,00 mg kg^{-1} de solo), acrescidos do tratamento controle. Testes agudos e crônicos foram realizados de acordo com protocolos ISO. Ambos os produtos demonstraram ser tóxicos para a espécie avaliada. Efeitos de letalidade foram observados em relação ao controle dos organismos expostos em baixas concentrações do fungicida (0,35 mg kg^{-1} solo), enquanto para a formulação do fungicida + inseticida a letalidade foi observada em concentrações mais altas, a partir de 2,40 mg kg^{-1} solo (CL50 > 3,00 mg kg-1 solo). A taxa de reprodução foi afetada somente nos organismos expostos ao fungicida, com redução no número de juvenis em concentração a partir de 4,00 mg kg^{-1} solo, com CE_{20} estimado de 3,38 mg kg^{-1} solo (2,79–3,96). Os resultados obtidos indicam que os colêmbolos apresentam sensibilidade aos produtos testados, especialmente ao fungicida que contém maior concentração de piraclostrobina em sua composição.

Palavras-chave: colêmbolos; pesticidas; Cambissolo Húmico; fauna edáfica; ecotoxicologia terrestre.

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Introduction

Pesticides are widely used in the agricultural sector for the control or prevention against the onset of pests and diseases, and the expansion of agricultural frontiers has increased their use (MAJOLO; REMPEL, 2018; NASCIMENTO; NAVAL, 2019; LORENZATTO *et al.*, 2020). Their continuous and frequent use has allowed Brazil to become the largest consumer of agrochemicals since 2008, consuming about 20% of the total marketed in the world (CARNEIRO *et al.*, 2015; PELAEZ *et al.*, 2015). According to data from the institute that protects and monitors the environment and renewable resources (IBAMA, 2019), it is estimated that, in the year 2017, consumption in Brazil reached 540,000 tons of active ingredients (a.i.). Among the categories of pesticides most sold in the national market, fungicides (13.4%) and insecticides (10.4%) are widely used (IBAMA, 2019). The climate change observed in recent years, as well as an agriculture often based on a low diversity of species, are directly related to an environment that makes crops a favorable scenario for fungal diseases and pest attack (YOUNG *et al.*, 2019). This fact causes a large consumption of fungicide and insecticide products in a preventive way or for the control of the pest itself. The toxicity of pesticides can pose a risk to non-target organisms of soil fauna.

In agricultural crops, a wide variety of commercial formulations are used, among them Comet® (a.i. pyraclostrobin) and Standak®Top (a.i. fipronil + pyraclostrobin + thiophanate-methyl). Pyraclostrobin is a strobilurin fungicide, recommended for agricultural and forestry crops (BRASIL, 2020). Thiophanate-methyl is a benzimidazole fungicide with indication for agricultural crops (BRASIL, 2020). Fipronil is a pyrazole insecticide, recommended for agricultural crops (BRASIL, 2020). These substances are commonly marketed with formulations composed of a single active ingredient, or through multiple mixtures of active ingredient, although there is little knowledge about the possible synergistic and antagonistic effects between these multiple mixtures found in commercial and field-applied products (YANG *et al.*, 2017). The toxicity effect depends on each mixture, even if the molecules present in the formulations have the same mode of action (KOUTSAFTIS; AOYAMA, 2007; YANG *et al.*, 2017). However, it is recommended that tests be carried out on the combined effects of pesticides that are found in the environment (EC, 2012). Some adverse effects on non-target organisms have been reported, such as negative influence of fipronil (ZORTÉA *et al.*, 2018a; 2018b) and pyraclostrobin (MA *et al.*, 2019; ZHANG *et al.*, 2019) in pesticide formulations with only one active ingredient. However, no other studies were found testing the hazard of these commercial formulations evaluated in the present study for soil organisms, such as *Folsomia candida*.

Due to the frequent and repeated use of pesticides applied in agricultural areas, such products may directly or indirectly affect edaphic fauna. Although the application of agrochemicals is often not carried out directly in the soil, pesticides are sprayed on the plants and part of the spray reaches the soil (BERTRAND *et al.*, 2015). It has been estimated that 99.9% of pesticides used move into the environment (PIMENTEL, 1995) where they adversely affect soil organisms. The use of these products is capable of causing irreversible damage to the soil ecosystem (DABROWSKI; SHADUNG; WEPENER, 2014), mainly through the use of substances that may indirectly affect the important role played by organisms in this environment.

Although they represent a small proportion of the soil biomass, springtails participate in the process of organic matter decomposition and nutrient cycling, and stimulate the activity of bacterial and fungal colonies, being fundamental for soil fertility (BUCH *et al.*, 2016). The *F. candida* species is recommended for ecotoxicological tests (ISO, 1999). These organisms are considered bioindicators because of their sensitivity to contaminants, as well as the ease of sampling and cultivating them under laboratory conditions. Recent studies show the sensitivity of these organisms to the application of fungicides and insecticides, which affect the survival, reproduction and gene expression, also causing effects of genotoxicity and cytotoxicity on the species (JEGEDE; OWOJORI; RÖMBKE, 2017; GÜNDEL *et al.*, 2019; SIMÕES *et al.*, 2019).

The present study aimed to evaluate the ecotoxicity of different concentrations of two commercial formulations of fungicide (a.i. pyraclostrobin) and fungicide + insecticide (a.i. pyraclostrobin + thiophanate-methyl + fipronil), on the survival and reproduction of *F. candida* through standardized tests in subtropical natural soil.

Material and Methods

Test organisms

The tests were performed with springtails of the species *F. candida*, with age synchronized between 10 and 12 days, cultivated in plastic pots containing a mixture of gypsum and activated charcoal in the proportion of 11:1 and deionized water, fed weekly with yeast (*Saccharomyces cerevisiae*), according to the recommendations of the reference protocol ISO 11267 (ISO, 1999), obtained from the establishment in the Soil Laboratory of Universidade Comunitária da Região de Chapecó (Unochapecó). The cultures of organisms and tests were conducted in a controlled environment with a temperature of 20 ± 2ºC, with photoperiod of 12:12 h (light:dark).

Soil test

The soil used for the tests was the Inceptisol, chosen for its ecological relevance and presented as a highly representative soil class in Brazil and in the State of Santa Catarina. The soil was collected at 0–10 cm depth in the city of Guatambú, Santa Catarina [27º05'574" S and 52º49'177" W], with no history of agricultural use, sifted and dried. Soil pH was adjusted to 6.0 ± 0.5 with addition of $CaCO_3$ and its moisture was corrected at the beginning of the test to 60% of the maximum water retention capacity (WRC). The physical-chemical parameters of the natural soil were determined according to the methodology described by Tedesco *et al.* (1995) and Embrapa (2011). The soil characterization was: clay 26.0%; sand 48.7%; silt 25.3%; cation exchange capacity pH 7.0 13.84 $cmo_c\ dm^{-3}$; pH (H_2O) 5.4; organic matter 2.8%; P 15 mg dm^{-3}; K 160 mg dm^{-3}; Ca 7.8 mg dm^{-3}; Mn < 50 mg dm^{-3}; Cu 4.7 mg dm^{-3}; Zn 22.1 mg dm^{-3}; Fe > 5 g dm^{-3}; Al 0.5 $cmo_c\ dm^{-3}$; Mg 1.3 $cmo_c\ dm^{-3}$.

Test substances and concentrations

The treatments consisted of increasing concentrations of the commercial formulations of the fungicide Comet® (BASF), containing: Methyl N- {2- [1- (4-chlorophenyl) -1H-pyrazol-3-yloxymethyl] phenyl} (N-methoxy) carbamate (pyraclostrobin) 250 g L^{-1} (25% m/v), and the fungicide + insecticide Standak®Top (BASF), containing: Methyl N- {2- [1- (4-chlorophenyl) -1H-pyrazol-3-yloxymethyl] phenyl} -methoxy) Carbamate (pyraclostrobin) 25 g L^{-1} (2.5% w/v); Dimethyl 4,4 ‘- (o-phenylene) bis (3-thioallophanate) (thiophanate-methyl) 225 g L^{-1} (22.5% w/v) and (RS) -5-amino-1- (2,6- dichloro-α, α, α-trifluoro-p-tolyl) -4-trifluoromethylsulfinylpyrazole-3-carbonitrile (fipronil) 250 g L^{-1} (25% w/v) applied to Inceptisol. The pesticides were diluted and homogenized in deionized water before the start of the test, and applied to the soil during the correction of moisture.

The final concentrations were calculated from the results obtained by the acute pre-tests and were determined by the commercially recommended doses of the products (predicted environmental concentrations — PEC), adjusted to values above and below these. The PEC of the application of the product in its commercial recommendation was extrapolated from the values obtained by multiplying the recommended volume per hectare (ha), assuming soil density of 1 g cm^{-3} and 0.10 m depth layer (label directions of pesticide Comet®); and the recommended volume per kilogram of seed used per hectare (ha) (label directions of pesticide Standak® Top). For both products, soybean (*Glycine max*) was used as reference crop and the number of seeds per hectare was calculated using 0.50 m spacing and 12 seeds per linear meter (50 kg of seeds ha^{-1}). These procedures followed the methodology described by Alves *et al.* (2013).

The tested concentrations of fungicide were 0.35, 0.70, 1.40, 2.10, 2.80 and 4.00 mg kg^{-1} soil, and for the fungicide + insecticide were 0.20, 0.60, 1.20, 1.80, 2.40 and 3.00 mg kg^{-1}. The control treatment did not receive the products and only had its moisture corrected using deionized water. The environmentally predicted concentrations of the active ingredients present in pesticide formulations are described in Table 1.

Acute and chronic toxicity tests

The toxicity effects of the tested products on springtails were evaluated following the methods described by the protocol ISO 11267 (ISO, 1999), by means of lethality and reproduction tests. The experiment was conducted in a completely randomized design with six replicates. Each experimental unit consisted of plastic pots, which received 30 g of the natural soil contaminated with the different concentrations of the pesticides tested. During the test period, soil moisture was corrected weekly, and the organisms were fed at 14-day interval with 2 mg of dry granulated yeast (*S. cerevisiae*).

At 28 days, the contents of the plastic pots were transferred to a larger container containing water and a few drops of black paint. The contents were mixed so that the organisms could rise to the surface. Each experimental unit was photographed for subsequent counting regarding adult survival and number of juveniles generated (differentiated by body size) using ImageJ 1.5 software (SCHNEIDER; RASBAND; ELICEIRI, 2012).

Data analysis

Survival and reproduction results were tested for normality and homogeneity by the Kolmogorov-Smirnov and Levene tests, respectively. The data were submitted to analysis of variance (One-way ANOVA), and the means were statistically compared by the Dunnett test ($p < 0.05$). Data that did not meet the assumptions were submitted to the Kruskal-Wallis test, followed by the Bonferroni post-test, using Statistica Software 7 (STATSOFT, 2004). EC_{20} values (estimated concentration to cause one or more specific effects capable of affecting 20% of the organisms) were estimated by regressions through the Hormesis model using Software Statistica 7.0 (STATSOFT, 2004). The values of non-observed effect concentration (NOEC) and lowest observed effect concentration (LOEC) were also determined. LC_{50} values (lethal concentration) were determined by PriProbit® *Software* 1.63 (SAKUMA, 1998).

Results

Test validation

Acute and chronic toxicity tests met the validation criteria according to ISO 11267 (ISO, 1999). Adult survival in the control treatment

Table 1 – Description of commercial formulations of tested pesticides and their active ingredients (a.i.) at predicted environmental concentrations (PEC) at commercial doses for soybean cultivation.

Commercial name	a.i. name	a.i. content (g L^{-1})	PEC (mg a.i. kg^{-1} dry soil)
Comet®	Pyraclostrobin	250	0.0875
Standak®Top	Pyraclostrobin + thiophanate-methyl + fipronil	500	0.05

was 83.3%. In the reproduction tests, the number of juveniles in the control treatment was higher than 100 individuals per replicate (mean of 278 juveniles), with coefficients of variation of 15.9 and 23.1% for the lethality and reproduction tests, respectively.

Effects on the survival of Folsomia candida

Both commercial formulations of pesticides were lethal to *F. candida*, causing a reduction in the survival of the individuals ($p < 0.05$). The significant lethality of springtails was found from the first tested concentration of fungicide (a.i. pyraclostrobin) (0.35 mg kg^{-1} soil) (Figure 1A), but the LC_{50} values could not be calculated. For the formulation of the fungicide + insecticide (a.i. pyraclostrobin + thiophanate-methyl + fipronil), significant mortality was found when the organisms were exposed to concentrations equal or higher than 2.40 mg kg^{-1} soil ($LC_{50} > 3.00$ mg kg^{-1}) (Figure 1B).

Effects on the reproduction of Folsomia candida

Although both formulations had an effect on survival, reproduction was little affected by the concentrations of the commercial formulations of the tested pesticides. The effects of reduction in the reproductive rates of the species were observed only at the highest concentrations of the fungicide. The formulation of the fungicide containing pyraclostrobin was able to significantly affect the reproduction rate of the organisms ($p < 0.05$), causing a reduction at the concentration of 4.00 mg kg^{-1}, with EC_{20} values of 3.38 mg kg^{-1} soil (2.79–3.96) (Figure 2A). The NOEC and LOEC values were 2.80 and 4.00 mg kg^{-1}, respectively. The values of EC_{20} for fungicide + insecticide could not be calculated because the product was not able to cause significant reduction in reproduction at the concentrations tested (Figure 2B).

Discussion

Both formulations caused a lethal effect on the organisms, especially the fungicide containing the active ingredient pyraclostrobin, which

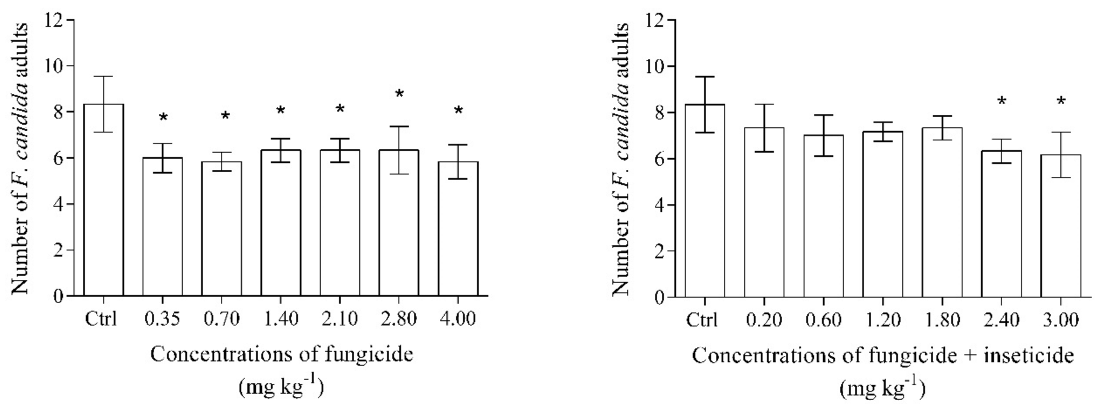

Figure 1 – Mean number of live adults of *Folsomia candida* in Inceptisol treated with concentrations of (A) fungicide and (B) fungicide + insecticide.

*A significant reduction in the number of adults compared to control ($p < 0.05$), by the (A) Dunnett test and the (B) Bonferroni test; ┬: standard deviation (n = 6).

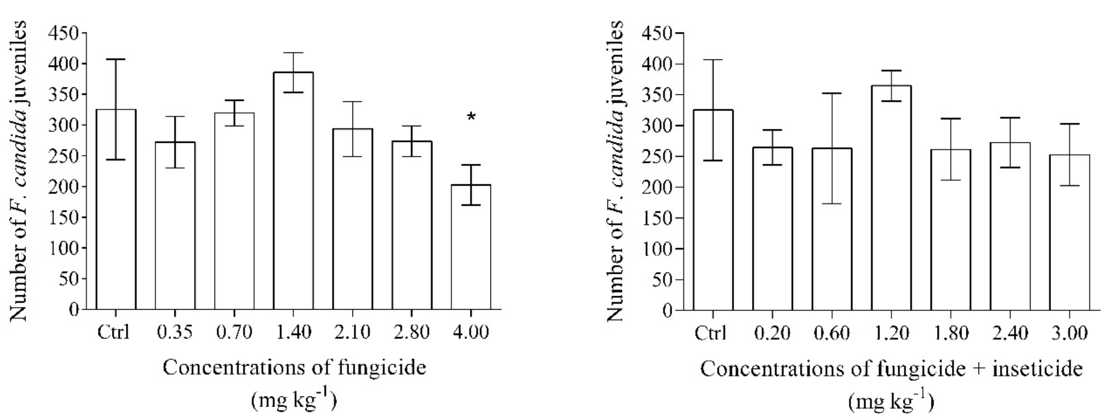

Figure 2 – Mean of *Folsomia candida* juveniles in Inceptisol treated with concentrations of (A) fungicide and (B) fungicide + insecticide.

*A significant reduction in the number of juveniles compared to control ($p < 0.05$), by the Dunnett test; ┬: standard deviation (n = 6).

even at the lowest concentration caused the lethality of the organisms, demonstrating greater toxicity than the formulation of the fungicide + insecticide, containing pyraclostrobin, thiophanate-methyl and fipronil, which caused lethality at higher concentrations. The results obtained in our study differ from those of other studies that observed that springtails were less sensitive to fungicides than to insecticides (DAAM *et al.*, 2011; ALVES *et al.*, 2014). However, there are studies that also indicate lower rates of reproduction of springtails when exposed to fungicides (JÄNSCH *et al.*, 2006; GÜNDEL *et al.*, 2019).

Only the fungicide caused a reduction in the reproduction of springtails, an effect observed only at the highest concentration (4.00 mg kg^{-1} soil). The lower sensitivity to the formulation of the fungicide + insecticide may be related to the lower concentration of the active ingredient pyraclostrobin in its formulation (2.5%), which corresponds to 0.005 mg kg^{-1} soil at the lowest concentration tested when compared to the commercial formulation in which pyraclostrobin has no effect combined with other substances, and has a concentration of 25% of active ingredient (0.0875 mg kg^{-1} soil at the lowest concentration tested).

No other studies have been found demonstrating the effect of the active ingredients thiophanate-methyl and pyraclostrobin on springtails. The more severe effect of pyraclostrobin on survival than on the reproduction of organisms in laboratory tests may be related to the reduction in food sources, considering these organisms mainly feed on fungi (SEGAT *et al.*, 2018). These organisms are mostly mycophagous, consuming any kind of fungi, lichens, bacteria and organic material available in the environment (SEGAT *et al.*, 2018). Under environmental conditions, the application of fungicides affects many organisms, including bacteria, fungi, yeasts and arbuscular mycorrhizal fungi, which can serve as a source of food for springtails (JANSA; WIEMKEN; FROSSARD, 2006; BENDING; RODRÍGUEZ-CRUZ; LINCOLN, 2007; CAMPOS *et al.*, 2015).

Therefore, the decrease in food availability can lead to the lethality of these individuals. At first, the application of these pesticides may not affect the ability of these organisms to reproduce, allowing the survivors to continue reproducing normally. However, the intensification of this effect (mortality by the use of pesticides) can determine in the medium and long term whether or not survivors will be able to reproduce, depending on the applied concentrations of the pesticides, even if the surviving springtails still remain able to reproduce (VAN GESTEL *et al.*, 2017).

No LC_{50} and EC_{50} values were found for the *F. candida* species obtained from the validation and registration of pyraclostrobin and thiophanate-methyl. For earthworms of the *Eisenia fetida* species, pyraclostrobin was able to cause oxidative damage at concentrations of 0.1 mg kg^{-1} soil, and damage to DNA at concentrations of 1.0 and 2.5 mg kg^{-1} soil (MA *et al.*, 2019). In the present study, the LOEC on the reproduction of springtails was 0.60 mg kg^{-1} soil and the EC_{20} value calculated was 3.38 mg kg^{-1} soil (2.79–3.96), which were below the concentrations that caused effects on worms in other studies performed with pyraclostrobin as the only active ingredient.

Regarding the effect of the other active ingredient present in the tested products, fipronil caused toxicity to *F. candida* species, affecting its survival and reproduction, with estimated LOEC value of 1.0 mg kg^{-1} soil and EC_{50} of 0.18–0.35 mg kg^{-1} in natural soil, Oxisol (ZORTÉA *et al.*, 2018b). In the present study, even at the highest concentration tested (3.00 mg kg^{-1} soil), which corresponds to 0.75 mg kg^{-1} soil of the active ingredient fipronil, no effects were observed on the reproductive rates of the organisms. Although it is within the range estimated by Zortéa *et al.* (2018b), capable of causing effects on the reproductive rates of *F. candida*, such work is related to the active ingredient fipronil in veterinary drug formulations and does not present the interaction of active ingredients as in the present study. The mixtures of pesticides may exhibit synergistic or antagonistic action, which still needs to be better explored (YANG *et al.*, 2017). The same authors, studying combinations of insecticides and herbicides, observed that such effects depend on the proportion of the active ingredients in the mixtures, taking as an example the insecticides chlorpyrifos and clothianidin, which had either a synergistic effect or an antagonistic effect.

The effect of the interaction between the active ingredients pyraclostrobin, thiophanate-methyl and fipronil, present in the formulation of the fungicide + insecticide, is not known. These results may also vary depending on the type of soil tested, considering that the toxicity of the molecules can vary in the natural soils, being related to the physicochemical characteristics and the organic matter content present in the soil (NATAL-DA-LUZ; RÖMBKE; SOUSA, 2008).

Under natural conditions, the reduction in the abundance of springtails can affect the rates of decomposition of organic matter and consequently the cycling of nutrients performed by these organisms. As demonstrated by Brooks *et al.* (2005), exposure to insecticides promoted an 80% reduction in springtails in agricultural areas. This reduction caused by exposure to pesticides resulted in a 45% reduction in soil organic matter degradation, demonstrating that, although the effects are acute and do not affect the perpetuation of the species in the surrounding environment, the reduction in the number of such organisms in their natural environments can affect important processes that occur in the terrestrial ecosystem. The decomposition of organic matter and nutrient cycling performed by springtails (BUCH *et al.*, 2016) may be impacted by the use of such substances that cause both acute and chronic effects on such organisms.

The effect of pesticides may still be noticeable over generations due to the persistence of substances in the soil. Mortality and reduction in the reproductive rates of *F. candida* were observed after exposure to insecticides such as imidacloprid and thiacloprid even over several generations, due to the persistence characteristics of the molecules in the soil (VAN GESTEL *et al.*, 2017). Pyraclostrobin, thiophanate-methyl and fipronil have half-life values (DT_{50}) of 12–101 days, 0.48–0.74 days and 120–308 days, respectively (EC, 2004; 2005; 2011), and may have a cumulative effect on the soil, especially if we consider that the products are often reapplied in the same crop, so these substances are able to reach high concentrations. Pesticides are used intensively and inadequately in many agricultural areas, contributing to high concentrations in the soil.

Studies on natural soils are particularly important because the effects of toxicity can vary when compared to the artificial soils standardized by Organisation for Economic Co-operation and Development (OECD), where the sorption capacity of the organic matter present in them can influence the toxicity of pesticides, especially when applied to the field. As an example, the insecticide dimethoate showed higher EC_{50} values for springtails in OECD artificial soil with 10% of total organic matter and 8.6% of humified organic matter than in the same soil with only 5% of total organic matter and 1.8% of humid organic matter (MARTIKAINEN; KROGH, 1999). The subtropical soil, classified as Inceptisol, has buffering agents such as clay and significant organic matter contents in its composition and, when the pesticides are applied, they can remain adsorbed on the organic material and thus remain available to the soil organisms for many years after the application to the field, varying according to the persistence of the molecules of the active ingredients present in the commercial formulations of pesticides, prolonging the period of exposure of these organisms to these substances (SÁNCHEZ-BAYO, 2011).

Studies on natural soils are particularly important in the field of terrestrial ecotoxicology. Authors report that the physicochemical characteristics, as well as the organic matter content and high clay content present in natural soils are directly related to the toxicity of the molecules (NATAL-DA-LUZ; RÖMBKE; SOUSA, 2008; ZORTÉA *et al.*, 2018a). The active ingredient molecules present in pesticide formulations may remain adsorbed on organic matter, with a tendency of pesticides to cause a lower toxicity effect on natural soils, when compared to artificial soil tests (MARTIKAINEN; KROGH, 1999). Even in natural soil, both products demonstrated toxic potential for the *F. candida* species, corroborating the need for the use of natural soils in pesticide toxicity tests.

Conclusion

The organisms of the species *F. candida* were sensitive to both tested substances. The variation in the concentrations of fungicide (a.i. pyraclostrobin) and of the commercial formulation of the fungicide + insecticide (a.i. pyraclostrobin + thiophanate-methyl + fipronil) cause higher acute toxicity effect when compared to the chronic effect on springtails in natural soil. The reproduction of *F. candida* was affected only when exposed to higher concentrations of the fungicide, with no effect of the product containing fungicide + insecticide. The results showed that exposure to such products may represent a threat to the functionality of the services performed by these soil organisms in subtropical natural soils. However, we recommend that other non-target organisms (such as plants, invertebrates, and microorganisms) must be evaluated, because they may be more sensitive to these products than springtails.

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Economic evaluation of the impacts of water quality on fishery production in the Estuary Complex of Santos, São Vicente and Bertioga cities, in southeastern coast of Brazil

Avaliação econômica dos impactos ambientais na qualidade da água estuarina

Victor Carrozza Barcellini[1], *Ângela Tavares Paes*[2], *Simone Georges El Khouri Miraglia*[3]

ABSTRACT

The present study proposes a diagnosis of water quality and fishery production in the Estuarine Complex of Santos, São Vicente, and Bertioga Cities as a requirement for economic valuation of water pollution impacts on fishing production. In the study period (2009–2014), three water quality parameters were identified (dissolved oxygen, total phosphorus, and nitrate), which occurred more frequently in non-conformity with Brazilian water standards, according to reports released by the Environmental Company of São Paulo State (*Companhia Ambiental do Estado de São Paulo* — CETESB). For data collection of fishery production, data from the monitoring of Institute of Fisheries of Santos City (*Instituto de Pesca de Santos*) were used, and 15 species were identified with higher occurrence in the study area. The relation between water quality parameters and fishery production was analyzed with mixed linear models, in which significant values for dissolved oxygen parameters, total phosphorus (positive relation), and nitrate (negative relation) were found. Environmental valuation considered only the direct use values (DUV) component of the valuation of fishery production variation in relation to water quality variation. For this purpose, the Marginal Productivity Method (MPM) of the dose-response function was used, which resulted in a range of monetary loss between US$ 24,760,550.22 and US$ 60,635,978.78. The obtained values represent only a portion of the valuation of economic and environmental loss in the fishing activity (part of DUV). Therefore, economic value calculated is conservative, and although it did not reached the total amount corresponding to all the impacts caused by poor water quality, given the limitations of methods and study period, the obtained values represent the minimum environmental monetary loss.

Keywords: marginal productivity method; direct use values; environmental valuation; water pollution; fishing

RESUMO

O estudo propõe um diagnóstico da qualidade da água e da produção pesqueira do Complexo Estuarino de Santos, São Vicente e Bertioga, como subsídio à valoração econômica dos impactos da poluição da água na produção pesqueira. No período do estudo (2009–2014), foram identificados três parâmetros de qualidade da água (oxigênio dissolvido, fósforo total e nitrato) que ocorreram com maior frequência em não-conformidade com as normas brasileiras, segundo os relatórios divulgados pela Companhia Ambiental do Estado de São Paulo (CETESB). Para a coleta de dados da produção pesqueira, foram utilizados os dados do monitoramento do Instituto de Pesca de Santos, sendo identificadas 15 espécies com maior ocorrência na área de estudo. A relação entre os parâmetros de qualidade da água e a produção pesqueira dessas espécies foi analisada através de modelos lineares mistos, resultando em valores significativos para os parâmetros de oxigênio dissolvido, fósforo total (relação positiva) e nitrato (relação negativa). A avaliação ambiental considerou apenas a componente VUD (Valor de Uso Direto) por meio da variação da produção pesqueira em relação à variação da qualidade da água. Para tanto, utilizou-se o Método de Produtividade Marginal (MPM), a partir da função Dose-Resposta, permitindo observar a variação nas perdas monetárias, entre US$ 24.760.550,22 e US$ 60.635.978,78. Ressalta-se que os valores obtidos representam apenas uma parcela da valoração da perda econômico-ambiental na atividade de pesca (parte da VUD) e, portanto, a avaliação econômica é subestimada. Cabe apontar que, embora não tenha chegado ao valor total correspondente a todos os impactos ocasionados pela baixa qualidade da água, tendo em vista as limitações dos métodos e período de estudo, entende-se que os valores obtidos representam uma perda monetária ambiental mínima.

Palavras-chave: método de produtividade marginal; valor de uso direto; valoração ambiental; poluição da água; pesca.

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Introduction

The interest in the study of ecosystem functions and services to understand the negative impacts of ecosystem degradation on the human populations' well-being and how these changes can affect the ecosystem services' flows is increasing within the scientific community (DE GROOT; WILSON; BOUMANS, 2002; COSTANZA *et al*., 2014; MARTINEZ-HARMS *et al*., 2015; ROSA; SÁNCHEZ, 2016; YOSKOWITZ *et al*., 2017; HACKBART; LIMA; SANTOS, 2017; ENRIQUEZ-ACEVEDO *et al*., 2018; TANNER *et al*., 2019; ARMOSKAITE *et al*., 2020). The analysis of relations, aiming to estimate the impact of an anthropic action on a service's supply, presents a more feasible and viable alternative in practical terms when carried out from a particular ecosystem function directly associated to the service itself (DE GROOT; WILSON; BOUMANS, 2002).

Ecosystem services that are directly related to water can be relevant indicators of disturbances caused by human actions, given that water is the best connectivity element within a landscape, leading to matter and energy flow (GERGEL *et al*., 2002; HACKBART; LIMA; SANTOS, 2017). Moreover, water reveals a momentary state of disruption, because mobility and its renewal dynamics are intense. In addition, it offers numerous uses for society, such as: raw material in various productive activities, sports, and leisure practices, beyond receiving and recycling matter and even aspects cultural, spiritual experiences and contemplation of nature (ARMOSKAITE *et al*., 2020).

Throughout the world, coastal waters, widely used for recreation, are also important for the fauna and flora of the marine ecosystem (ARMOSKAITE *et al*., 2020; FREIRE *et al*., 2020). Coastal and estuarine ecosystems provide critical services to humans (TOKUNAGA *et al*., 2020). Waters near the coast are the most productive in the ocean because they receive the contribution of nutrients carried by rivers (MIRANDA; CASTRO; KJERFVE, 2002; ROMERO *et al*., 2016). The maintenance of these waters' quality is essential to guarantee population's leisure, and to preserve aquatic life and fishing productivity (HUNTINGTON *et al*., 2017; VISBECK, 2018; ARMOSKAITE *et al*., 2020).

In Abessa *et al*. (2018), the authors warn that the chemical pollution status of most of the marine protected areas around the world is unknown. This is aggravated, once many fish and invertebrates present in estuaries and coastal waters are valuable fishing resources, serving as a quick and accessible source of food to humans, forming the basis for the development of a wide range of fisheries. In developing countries, fishing is often the main source of food and income for people living along the coast. Small-scale fisheries are very important food producers, especially because they often bring a higher diversity of fish to the table when compared to the few species that are the focus of industrial fisheries (CANTARELI; RAMIRES; BEGOSSI, 2016; HUNTINGTON *et al*., 2017). In this way, the direct or indirect introduction of substances and energy by humankind, which can reach high concentration levels, can contaminate estuarine waters leading to adverse effects on living resources, endangering human health, forming obstacles to marine and fishing activities, and reducing its natural attractiveness (MIRANDA; CASTRO; KJERFVE, 2002).

In Brazil, the coastal zone is one of the largest areas under environmental stress due to over-exploitation of natural resources, land use, and low water quality, influenced by the sanitation conditions existing in coastal cities (CETESB, 2016). Many of Brazilian capitals are located on the seafront; in most cases, they do not have enough sanitation infrastructure for their population (ROTH *et al*., 2016). Thus, dumping domestic sewage on beaches becomes a routine occurrence. This release of untreated domestic effluent makes many uses of aquatic ecosystems unfeasible and may pose serious health threats to local residents and tourists (ROTH *et al*., 2016; GONÇALVES *et al*., 2020).

In the Estuarine Complex of Santos, São Vicente, and Bertioga Cities, located along the Brazilian southeastern coast, the industrialization process and development became a source of income, generating migration cycles and potential risks of pollution, considering that the industrial activities of this region were responsible for releasing several potentially toxic substances in the aquatic environment (CETESB, 2016). In addition, the disordered land use and its effects, in terms of sedimentation of the bodies of water, increase in the sedimentation rate and flood, coupled with water pollution due to domestic effluent releases, reflect the currently high eutrophic character of the region, showing no improvement over time (BRAGA *et al*., 2000; CETESB, 2016; MOREIRA *et al*., 2018; PERINA *et al*., 2018; GONÇALVES *et al*., 2020).

In this context, several studies have used the analysis of chemical parameters to evaluate the alteration of water quality of rivers and lakes (WU *et al*., 2018; ESCHER *et al*., 2019; LONGLEY *et al*., 2019; FONTES; MARANHO; PEREIRA, 2020), and estuaries (ROMERO *et al*., 2016; SANTOS *et al*., 2018; DUARTE *et al*., 2019; FONTES; MARANHO; PEREIRA, 2020; GONÇALVES *et al*., 2020), where there is a decrease in fish production, associated to the destruction of habitats, overfishing, and water pollution. Additionally, economic values of ecosystem services are an important tool to support ecosystems management (CARRILHO; SINISGALLI, 2018). Several other studies have identified marine and coastal services, estimated their economic value (TADEU; SOSA, 2010; COSTANZA *et al*., 2014; TANNER *et al*., 2019; TOKUNAGA *et al*., 2020), or even estimated their economic and socio-cultural values (QUEIROZ *et al*., 2017; CARRILHO; SINISGALLI, 2018). Therefore, considering the possibility of increasing the efficiency of environmental management with the complementary use of an economic criterion, the purpose of this study was to economically value the influence of changes in water quality parameters on fishery production and, consequently, local economy.

Materials and Methods

Study area

The study area is the Estuary Complex of Santos, São Vicente, and Bertioga Cities, which is located in the central coastal region of São

Paulo State, in Brazil's southeastern coast, covering the estuarine area of São Vicente Island (Santos and São Vicente) and Santo Amaro (Guarujá City), as well as Piaçaguera (Cubatão City) and Bertioga Channel (Figure 1). The region is formed by an extensive plain, limited to the north by *Serra do Mar* and to the south by the Atlantic Ocean. It has a network of meandering channels, interconnected to the Bay of Santos, with opening to the ocean located to the south, through two main channels that surround São Vicente Island.

The study region presents a great heterogeneity in relation to biotic and anthropogenic abiotic factors, considering the presence of the most important port in Latin America, the port industrial pole with more than 23 industrial complexes, 111 factories, and more than 300 pollution sources. It also experiences transit of large vessels carrying several types of chemicals (DUARTE *et al.*, 2019). Despite all these obstacles to aquatic biota, there are also abundant living resources in the region. They have been commercially exploited for many decades and constitute an important economic activity, especially for the communities of local artisanal fishermen (SEVERINO-RODRIGUES; PITA; GRAÇA-LOPES, 2018).

Data

Data on surface water quality

Historical data on surface water quality in study areas are scarce. In 2009, the Environmental Company of São Paulo State (*Companhia Ambiental do Estado de São Paulo* — CETESB) started monitoring the quality of the coastal and estuarine waters of Santos, São Vicente, and Bertioga Cities in 9 samples points: 3 in Santos channel (P01-ST, P02-ST and P03-ST), 3 in São Vicente channel (P01-SV, P02-SV and P03-SV), and 3 in Bertioga channel (P01-B P02-B and P03 -B) (Figure 2).

This monitoring, carried out by CETESB, aims to evaluate water quality with 34 parameters (physical, chemical, and biological), at pre-established sampling points and frequencies. In the study region,

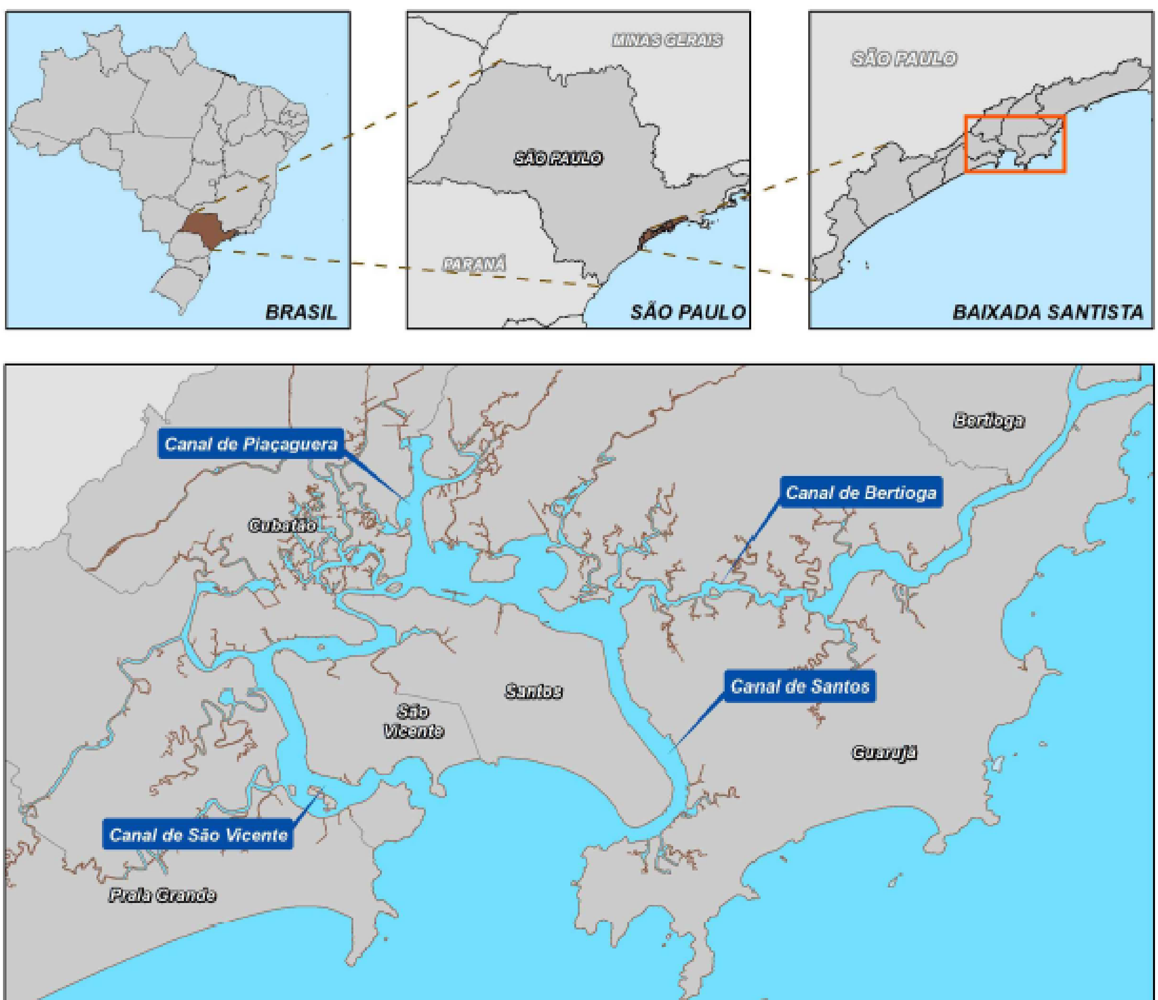

Figure 1 – Geographical location of the study area.

three parameters (dissolved oxygen — DO, total phosphorus, and nitrate), frequently were in non-conformity with the Brazilian standards established by the National Environment Council in Brazil (CONAMA).

Between 2009 and 2014, 11 semi-annual sampling campaigns were carried out at these 9 points, totaling 99 samples for each parameter. The time series of analyzed parameters in the study period are shown in Figure 3. The Resolution no. 357/05 by CONAMA establishes as a quality condition for DO values greater than 5.0 mg/L, and as a standard condition for total phosphorus those values under 0.124 mg/L, and nitrate, under 0.40 mg/L (BRASIL, 2005). The parameters systematically decrease along the period in all regions.

Fish community

The areas with the largest fishing activities in the Estuary Complex (Figure 2) and the main species fished in the region were described in Togni (2013) and used in this study. In all, 15 fish species were identified with higher occurrence in the study area (Table 1).

In order to obtain the fishery production data of these 15 fish species, the annual fishery production monitoring reports of Santos Fishing Institute (IP, 2020) were consulted. Data were tabulated in an Excel spreadsheet. Subsequently, Catch per unit effort (CPUE) of each region (Santos, São Vicente, and Bertioga Cities) were calculated by the total Kg landed divided by Productive Units (fishing boats) (Table 2).

The present study has limited coverage due to the fact of water quality collection having started only in 2009 (resulting in a limited database of water quality indicators), making it difficult to proceed to a sensitivity analysis with scarce data. In this sense, data on fisheries for the same period regarding water quality were used, since such data are available from 1998. If we analyze the historic time series of fisheries data, there is a decreasing trend of fishing stock in the region (Figure 4).

Integrated data analysis: statistical analysis

Given that water sampling points within regions are similar, and the main observed dependent variable corresponds to the whole region, data from the three points were summarized as means. Therefore, there were 33 sampling units for each parameter (11 semesters and three regions).

The relation between water quality parameters and fishery production (CPUE) was analyzed with mixed linear models, with fish production as a dependent variable, and water quality parameters as independent variables. These models were chosen to consider the correlation between longitudinal measures of the same region. As a first step, simpler models were fitted into only one of the parameters. Those with $p < 0.05$ in the first step were selected to a multiple model. All models included region as a control variable, and the covariance structure was first-order autoregressive. Pearson's correlation was computed to analyze collinearity between independent variables. Assumptions were verified by residual analysis.

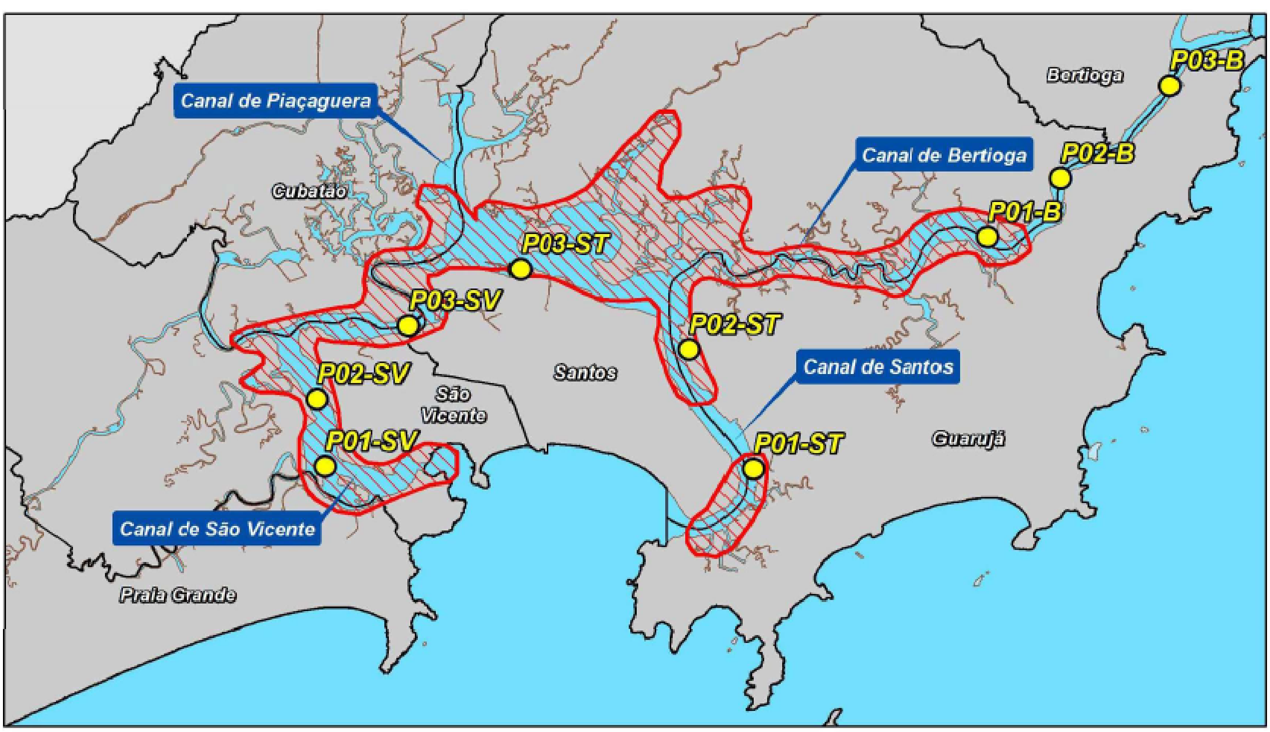

Figure 2 – Location of surface water monitoring points (yellow dots) superimposed on the distribution area of fishing activities identified in Togni, 2013 (hatched in red).

Figure 3 – Results of dissolved oxygen, total phosphorus, and nitrate concentrations in water samples during the 11 semi-annual sampling campaigns, between 2009 and 2014.

From: adapted from CETESB (2016).

Table 1 – List of ichthyofauna species identified with higher occurrence in the study area.

Groups	Scientific name
White mullet	*Mugil curema Valenciennes*, 1836
Caitipa mojarra	*Diapterus rhombeus Cuvier*, 1829
Brazilian mojarra	*Eugerres brasilianus Cuvier*, 1830
Lebranche mullet	*Mugil liza Valenciennes*, 1836
Whitemouth croaker	*Micropogonias furnieri Desmarest*, 1823
Largehead hairtail	*Trichiurus lepturus Linnaeus*, 1758
Snooks	*Centropomus undecimalis Bloch*, 1792
	Centropomus parallelus Poey, 1860
Sea catfishs	*Cathorops spixii Agassiz*, 1829
	Genidens barbus Lacepède, 1803
	Genidens genidens Cuvier, 1829
Weakfishs	*Cynoscion acoupa Lacepède*, 1801
	Cynoscion leiarchus Cuvier, 1830
	Cynoscion microlepidotus Cuvier, 1830
	Cynoscion guatucupa Cuvier, 1830

Table 2 – Mean catch per unit effort (CPUE) ratio (kg/units) by study region in the sampled period (2009 to 2014).

	Santos	São Vicente	Bertioga
CPUE (Kg/units)	880.27	252.29	57.73
Standard deviation (±)	124.05	74.70	23.15

Environmental valuation

The Marginal Productivity Method (MPM) was used as the method to value the Direct Use Value (DUV) considering the decline in fish production due to the decrease in water quality of the Estuary Complex. In this sense, the MPM method was used to attribute a value to the use of biodiversity by directly relating the quantity or quality of an environmental resource (estuarine water) to the production of another product (fishery production) with a defined market price. The role of environmental resources in the production process will be represented by a Dose-Response function, which relates the level of environmental resource provision to the respective level of production in the market. This function will measure the impact on the productive system, given a marginal variation in the provision of the environmental good or service and, from this variation, an estimation of the economic value of use of estuarine water is estimated (MOTTA, 2006).

The construction of the Dose-Response function involves two basic steps. The first requires the elaboration of a physical function of damage, relating the dose of pollution or degradation to the response of polluted or degraded environmental assets in production. The second corresponds to the formulation of an economic model that measures the financial impact of these changes in the productive process (MAIA; ROMEIRO; REYDON, 2004).

The valuation of the direct use (DUV) of the variation of fishing production in relation to the variation of the estuary's water quality was based on the Dose-Response function presented on Equation 1.

$$DUV = DR_{CPUE} * \text{Average value}_{CPUE}$$

Caption:

DR_{CPUE} = Dose-Response Function of Fishing Production represented by CPUE (Equation 2):

$$DR_{CPUE} = CI * \Delta \text{ (parameter)}$$

Caption:

CI = 95% confidence interval (coefficient $|\beta| \pm 1.96$ * standard error);

$|\beta|$ = linear mixed-effects models coefficient;

Δ (parameter) = variation of the parameters' maximum and minimum values.

The DR adopted in this study are those that relate to the level of water pollution (Q) that affect water quality (E), which, in turn, affects fish production (Z). Given this DR, damage variation in terms of good variation or environmental service that affects the production of a good can be estimated, in this case fishing.

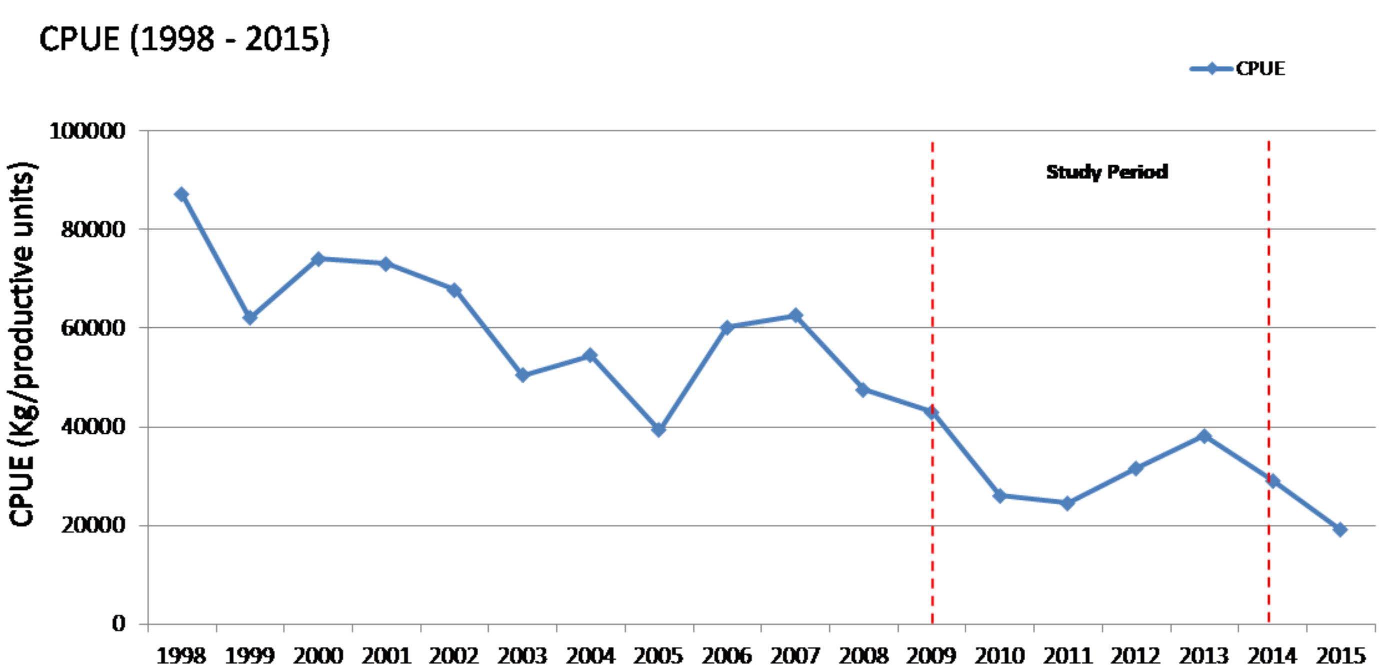

Figure 4 – Catch per unit effort (CPUE) of fishery production of all landed species during the monitoring period conducted by Santos Fishing Institute (1998-2015). Highlighted in the figure, the study period of this paper (2009 to 2014).

Source: adapted from the report by Santos Fishing Institute (IP, 2020).

Data on water quality were cross-referenced with those of fishery production to verify some relation between those variables throughout the study period. The purpose of MPM was to observe the impact value on fishery production, based on the variation of the Ecosystem Service (Fisheries) to which water quality contributes.

Results

Integrated analysis of data (statistical analysis)

The relation between water quality parameters and fishery production (CPUE) was analyzed with mixed linear models, with fish production as a dependent variable, and water quality parameters as independent variables. Based on mixed linear models, significant values ($p < 0.05$) were obtained for dissolved oxygen, total phosphorus (positive relation), and nitrate (negative relation) parameters, demonstrating that these parameters, may negatively influence fish production in the study region at certain concentrations (Table 3).

Environmental valuation

In order to obtain the Dose-Response (DR) function of CPUE production, according to each of the statistically significant parameters (DO, total phosphorus, and nitrate) the values of each parameter's confidence intervals (CI) were obtained from mixed linear models coefficient modulus, summed, and subtracted (±) from the standard confidence coefficient (1.96), and multiplied by the standard error. Table 4 shows the results of confidence interval (CI) and concentration variation (Δ) of each parameter over the study period.

Applying these results into the formula DR_{CPUE}:

Dissolved oxygen:

$DR_{CPUE\ (min.)}$ = 1,547.12* 5.72 = 8,849.50

$DR_{CPUE\ (max.)}$ = 1,645.38* 5.72 = 9,411.58

Total phosphorus:

$DR_{CPUE\ (min.)}$ = 4,276.90* 2.62 = 1,1205.49

$DR_{CPUE\ (max.)}$ = 4,429.53* 2.62 = 1,1605.37

Nitrate:

$DR_{CPUE\ (min.)}$ = 19,602.26* 1.09 = 21,366.46

$DR_{CPUE\ (max.)}$ = 19,882.11* 1.09 = 21,671.50

This shows a variation between the maximum and minimum DO values in the study period. The impact found on fish production was between 8,849.50 and 9,411.58 CPUE. For the impacts on total phosphorus, CPUE interval was between 11,205.49 and 11,605.37; for nitrate, between 21,366.46 and 21,671.50.

For appraising damage, fish production values provided by the Institute of Fisheries were used as reference, which were converted into American dollars in the study period and an average value taken by CPUE (Table 5).

As estimated in Table 5, the average value of CPUE obtained in the period was US$ 2,797.96. In this way, the values found in the DR function of each of the parameters and the mean value by CPUE resulted in DUV:

- Dissolved oxygen:
  $DUV_{(min.)}$ = 8,849.50* US$ 2,797.96 = US$ 24,760,550.22
  $DUV_{(max.)}$ = 9,411.58* US$ 2,797.96 = US$ 26,333,234.51
- Total phosphorus:
  $DUV_{(min.)}$ = 11,205.49*US$ 2,797.96 = US$ 31,352,508.03
  $DUV_{(max.)}$ = 11,605.37 * US$ 2,797.96 = US$ 32,471,353.62
- Nitrate:
  $DUV_{(min.)}$ = 21,366.46* US$ 2,797.96 = US$ 59,782,512.08
  $DUV_{(max.)}$ = 21,671.50* US$ 2,797.96 = US$ 60,635,978.78

Table 3 – Results of mixed linear models, relating water quality parameters and CPUE. Estimates adjusted by region.

Parameter	coef	Std. Error	Hypothesis Test		
			Wald Chi-Square	df	Sig.
Dissolved oxygen	63.677	25.068	6.452	1.00	0.011
Total phosphorus	111.807	38.935	8.246	1.00	0.004
Nitrate	-276.543	71.389	15.006	1.00	0.000

Dependent variable: CPUE_SEM; Model: (Intercept), region, Dissolved oxygen, total phosphorus, and nitrate.

Table 4 – Results of confidence intervals and variation of each parameter's maximum and minimum values.

Parameter	Confidence interval of 95% (coef ± 1,96 * std. error)		Parameter variation
	Lower	Upper	
Dissolved oxygen	1,547.12	1,645.38	5,720
Total phosphorus	4,276.90	4,429.53	2,620
Nitrate	19,602.26	19,882.11	1,090

The values obtained refer to the estimated loss of fishery productivity as a function of each parameter's variation. In relation to the dissolved oxygen, obtained values resulted from monetary loss between US$ 24,760,550.22 and US$ 26,333,234.51 for total phosphorus values between US$ 31,352,508.03 (lowest value obtained) and US$ 32,471,353.62 (highest value obtained), and as a function of nitrate, loss values between US$ 59,782,512.08 and US$ 60,635,978.78).

Discussion

We do not intend to discuss here the source of alteration of dissolved oxygen in the study area's water, or even the origin of excess nutrients (total phosphorus and nitrate) in the aquatic environment of the study region, even considering its importance. However, based on the obtained results, the region presents high concentrations of these nutrients in its surface water, introduced by anthropic sources, that lead to a hypereutrophic state of aquatic ecosystems. This contribution of higher concentrations of nutrients to the estuary may be related to the emission of effluents (domestic and industrial); activities related to the port (such as accidental spills of substances in the aquatic environment, transport of solid waste, generation of liquid effluents, and dredging); and the port industrial center, which has several large companies. This assertion is not only based on data observed in research, but also on information generated by several authors and papers carried out in the study region, which also considered surface water and sediment. (BRAGA *et al.*, 2000; MOREIRA *et al.*, 2018; PERINA *et al.*, 2018; DUARTE *et al.*, 2019; GONÇALVES *et al.*, 2020).

All these changes in water quality parameters can lead to loss, in an ecological analysis based on the Ecosystem Function, Nutrient Regulation, and Ecosystem Services derived from this function, such as primary production, biodiversity maintenance, biogeochemical cycles, habitat impairment, and others (DE GROOT; WILSON; BOUMANS, 2002). The number of ecosystem services affected shows the high degree of dependence between environmental variables, as well as the high degree of complexity underlying the ecosystem analyzed.

The relation between water quality parameters and fishery production was analyzed with mixed linear models. Significant values were obtained for dissolved oxygen, total phosphorus, and nitrate parameters, indicating a relation between these parameters and fish production. In the analysis, significant values were obtained for dissolved oxygen, total phosphorus (positive relation), and nitrate (negative relation), that is, the increase in dissolved oxygen concentration in water can positively favor fish production, whereas a high concentration of nitrate can negatively influence the region's fishing productivity. For the total phosphorus parameter, caution is required to analyze this positive relation, given that this parameter is an essential nutrient for many life forms. At certain concentrations,

Table 5 – Fisheries Production and Marketed Values, Dollarized and Average Values per CPUE. (Average quotation of the US dollar versus the Brazilian real in: http://economia.uol.com.br/cotacoes/cambio/dolar-comercial-estados-unidos/?historico).

Period	Kg	No. productive units	CPUE	Value in the period	Average dollar value in the period	Dollarized value	Average value US$ / CPUE
2009 (1st)	1,368.599.2	1429	957.732	R$ 4,716.740.92	1.95	$2,418.841.50	$2,525.59
2010 (1st)	1,079.619.5	1316	820.380	R$ 5,419.894.38	1.81	$2,994.416.78	$3,650.04
2010 (2nd)	1,671.983.6	2026	825.263	R$ 4,074.728.00	1.68	$2,425.433.33	$2,938.98
2011 (1st)	1,156.393	1305	886.125	R$ 3,695.272.05	1.59	$2,324.070.47	$2,622.73
2011 (2nd)	1,327.106.2	1940	684.075	R$ 3,899.926.16	1.82	$2,142.816.57	$3,132.43
2012 (1st)	941,559.2	1392	676.407	R$ 4,426.245.63	2.05	$2,159.144.21	$3,192.08
2012 (2nd)	1,404.440.4	1379	1,018.448	R$ 5,745.358.59	2.09	$2,748.975.40	$2,699.18
2013 (1st)	980,711.1	1036	946.632	R$ 4,144.875.30	2.16	$1,918.923.75	$2,027.11
2013 (2nd)	1,318.071.3	1489	885.206	R$ 7,206.390.12	2.35	$3,066.548.99	$3,464.22
2014 (1st)	1,128.796.8	1053	1,071.982	R$ 5,304.501.73	2.20	$2,411.137.15	$2,249.23
2014 (2nd)	1,166.689.0	1281	910.764	R$ 5,410.138.43	2.61	$2,072.849.97	$2,275.95
						Total	$30,777.54
						Average	$2,797.96

(1st): first semester /(2nd): second semester it can enrich the environment and favor the increase of the algal community, which can positively influence the diet of some specimens of ichthyofauna (SILVA-NETO, 2012). However, at higher concentrations, it becomes toxic to the aquatic environment, which can lead to a state of eutrophication (THOMAS; CALLAN, 2015; LONGLEY *et al*., 2019; ROCHA; MESQUITA; LIMA NETO, 2019). Thus, further studies on the dose-response effects of this parameter in aquatic environments, in addition to fauna, are needed to evaluate the threshold between positive and negative effects, according to their concentration.

Regarding economic analysis, environmental assessment was applied to the Fisheries Ecosystem Service associated to Food with the evaluation of impacts resulting from the low water quality condition on this Ecosystem Fisheries Service. Although the total value corresponding to all the impacts caused by the poor water quality was not reached, considering the limitations of the methods and time of study, establishing statistical associations and relations between the variation of water quality and fish production of the selected fish species was possible. With the dose-response relations, variation in the marginal productivity of fishery production was reached. This allowed the variation in monetary loss as a function of the variation of water quality parameters, during the study period, to be observed.

Determining the dose-response relations between estuarine water quality and fish production is a pioneering effort in the study region, as well as the use of this methodology for the integrated analysis of results. This is the first study to establish a relation between water pollution and fishery production; additionally, it estimates an economic value on the ecosystem service deterioration. Our results are preliminary and have limitations, such as the non- guarantee about possible non-observed confounders. Besides that, the aim of the present study was not to establish rules nor to determine a fixed economic valuation to be adopted. Therefore, this analysis is expected to be feasible for replication in other environments to allow a comparative analysis, as well as a temporal evolution. Seen that, this approach consists of an important tool for environmental monitoring, in view of the possibility of increasing the efficiency of environmental management with the complementary use of an economic criterion.

In this sense, economic valuation of the impact obtained presented values of monetary loss that varied between US$ 24,760,550.22 and US$ 60,635,978.78 in the study period, considering the parameters analyzed. These values represent a portion of the value of environmental loss in the fishing activity in the region, caused by the decrease in water quality, evaluated by dissolved oxygen, phosphorus, and nitrate parameters. Therefore, we assume that this economic valuation is underestimated. We encourage further studies to enrich the valuation approach proposed herein. However, we consider it a first value for discussion and improvement for the environmental management of the studied estuarine complex.

In other studies, such as in Costanza *et al*. (2014), loss of ecosystem services worldwide between 1997 and 2011 is estimated to have ranged from US$ 4.3 to US$ 20.2 trillion per year. Yet, they believe that these estimates are conservative, as well as the values obtained in this paper, given the difficulty in evaluating all ecological interactions.

Tanner *et al.* (2019) presented the first economic valuation of multiple ecosystem services for Ecuador, using Galapagos mangroves as a case study. They focused on three ecosystem services of high value and policy relevance: carbon storage, support for small-scale fisheries, and mangrove-based tourism. Their data suggested that over 778,000 metric tons of carbon are stored in Galapagos mangroves, with mean belowground carbon being 211.03 ± 179.65 Mg C/ha, valued at $2,940/ha or $22,838/ha, depending on the valuation methodology. They identified mangrove-dependent fish targeted by the local finfish fishery, with net benefits of $245/ha, making this fishery the second most profitable in the Archipelago. The value of mangrove-based recreation was estimated at $16,958/ha, contributing with $62 million to the industry.

In Brazil, economic valuation of environmental damage is not frequent. Tadeu and Sosa (2010), with the Marginal Productivity Method, observed economic and environmental impacts resulting from the reopening of Valo Grande on the Cananéia-Iguape-Paranaguá Estuary-Lagunar Complex (CEL-CIP) located on the southern coast of São Paulo State. With data on fishing and based on the analysis of water quality, direct relations between the flow of the river Ribeira de Iguape and the region's fishery production were found. A correlation between the "flow" variation and variation in the fishery production of some species of the local ichthyofauna were observed. In this sense, economic valuation of the impact resulted in a marginal variation in economic gain, of US$ 641.03 for each variation of 1.0 m^3/s of the flow.

Carrilho and Sinisgalli (2018) identified and evaluated, with economic and socio-cultural perspectives, the ecosystem services provided by Araçá Bay (in the southeastern coast of Brazil) . The sum of the estimated (annual) economic value of the ecosystem services in 2014 was US$ 340,610.29, and the most valued service was effluent depuration. In turn, the food supply service was the most important in the socio-cultural valuation. The authors also point out that, although economic and socio-cultural values were able to reveal certain contributions of Araçá Bay to humans' well-being, they couldn't represent all of them, because the Bay's contribution to the subsistence of local families.

Environmental economic valuation of the impact of the alteration of water quality on the supply of the Ecosystem Service Fisheries presents limitations. It considered only a few species (15), culminating in a reductionist analysis, which disregarded a series of other factors (ecological and human) that are important to evaluate or assess environmental impacts.

An aspect to be considered is the variability in fisheries production over time, due to changes in global ocean cycles or other factors that could influence productivity. Some studies concerning fisheries production and operational variables in commercial fishery in São Paulo State (ROLIM; SILVA, 2018; SILVA *et al*., 2019) warn about the possibility of production variations due to overfishing. Togni (2013) show that fisheries in the Santos Estuarine present a high degree of technique diversity applied to capture. This diversification may mean an alternative to supply the diminish of both numeric and biomass abundance related to pollution and other resources aimed by fishers. Artisanal and recreational fisheries that use small- or medium-sized boats are performed with no employment bond. As shown in estuaries from São Paulo State (BARCELLINI *et al*., 2013; MOTTA; MENDONÇA; MORO, 2016; FREIRE *et al*., 2020; SILVA *et al*., 2020), these studies demonstrate the need for conducting long-term studies about these activities to gather more knowledge of this dynamics and its interactions with other activities that support resources management.

As previously mentioned, this is an exploratory pioneer study, which presents some limitations concerning the beginning of data collection, their frequency, and quality. In this sense, once data collection started in 2009 in a 6-month basis, some discrepancies may be found due to the season of the year, such as the associated meteorological conditions of the period of the collected sample's year. Moreover, additional studies must be conducted to identify these patterns and enable a confirmation of this behavior.

In addition, obtaining a larger number of samples and analyzes would be interesting, so that nutrient behavior and the influence of water quality on fish production could be observed in depth. Another aspect to consider is the season of the year in which collections were made, because there may be differences in-between dry and humid seasons, mainly in relation to nutrient contents carried to the estuary, as well as particulate matter in suspension.

Nonetheless, as shown, establishing the influence of the parameters analyzed in fish production in a statistical way was possible. Thus, the valuation obtained in this paper is considered a first value to be discussed and improved for the purposes of environmental management of the studied estuarine complex. Other estimates that represent the other environmental values, such as indirect and existence values should be considered for appropriate management and environmental valuation, aiming at improving the understanding of how ecological changes have consequences on economic activities.

Conclusion

Based on the survey of historical data on water quality, a reduction in water quality due to the increase in concentrations of some of parameters was observed, leading to a state of anthropic hyper eutrophication. The contribution of higher concentrations of nutrients to the estuary is related to the emission of domestic and industrial effluents, and activities related to the port and the industrial pole.

In relation to the main fish species landed in the region, 15 species were identified with higher occurrence. The highest values of catches per unit of effort (CPUE) were observed in Santos City. When relating data on water quality to data on fishery production, and using mixed linear models, significant values were obtained for dissolved oxygen, total phosphorus (positive relation), and nitrate (negative relation).

Data show that environmental degradation of the impacts caused by changes in water quality directly influences fish productivity. Besides that, considering only the study period, these changes have resulted in an estimated monetary loss of US$ 24,760,550.22 to US$ 60,635,978.78. Therefore, from an economic point of view, the reduction of water quality may cause negative impacts on the region's fishing productivity. Consequently, economic impacts due to changes in this environmental matrix can also be seen.

Hence, the values obtained in this study demonstrate a minimum environmental monetary loss, because, even underestimated, these values reflect how the pollution of these aquatic environments can lead to monetary loss and negative externalities to the population and the environment. The achievement of a dose-response relation and this economic-environmental result are important factors to sensitize public managers in decision-making to promote initiatives for the prevention and environmental improvement of this ecosystem.

Finally, this study has the pioneering character of obtaining a dose-response function of the estuary's quality in the region, besides the application of the methodology of environmental economic valuation to estimate damage to the aquatic environment. This also intends to contribute to the discussion and improve of the use of this tool for environmental management of water resources in Brazil.

Contribution of authors:

Barcellini, V.C.: Conceptualization, Methodology, Data collect, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Writing — review and editing. Miraglia, S.G.E.K.: Conceptualization, Validation, Writing — review. Paes, Â.T.: Statistical analysis, Writing — review.

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ABES

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Benthic macroinvertebrates as bioindicators of environmental quality of Pará River estuary, a wetland of Eastern Amazon

Macroinvertebrados bentônicos como bioindicadores da qualidade ambiental do estuário do Rio Pará, uma área úmida da Amazônia Oriental

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ABSTRACT

The study characterized and evaluated the use of the benthic macroinvertebrate community as an indicator of impacts in different estuarine environments around the Industrial Port Complex (IPC) of Vila do Conde (Pará State, Amazon region). Fauna of beaches and rivers, in sectors of the estuary under different degrees of environmental impact (high, medium, and low), was compared in different seasonal periods. Macrofauna was composed of typically fresh-water and estuarine groups. Beaches presented sediment with a texture ranging from medium to coarse sand, with a less rich macrofauna ($\bar{X}$ = 4.5 ± SE 0.3 taxa/sample) and dense ($\bar{X}$ = 1,838.1 ± 164.8 ind./m^2) of organisms when compared to rivers ($\bar{X}$ = 5.9 ± 0.3 taxa/sample, and 3,248.9 ± 77.0 ind./m^2), which were environments more muddy. For both environments, sites in the high-impact sector were less rich ($\bar{X}$ = 4.7 ± 0.3 taxa/sample) and dense ($\bar{X}$ = 2,812.9 ± 232.7 ind./m^2) when compared to those in the low-impact sector ($\bar{X}$ = 7.6 ± 0.4 taxa/sample, and 3,314.3 ± 230.1 ind./m^2). Richness ($\bar{X}$ = 6.4 ± 0.3 taxa/sample) and density ($\bar{X}$ = 3,859.4 ± 190.2 ind./m^2) were higher in the rainier season when compared to the less rainy season ($\bar{X}$ = 4.8 ± 0.3 taxa/sample, and 1,933.0 ± 172.1 ind./m^2). However, there were no significant seasonal changes in composition. Results indicated that the structure of the benthic macroinvertebrate community surrounding the IPC responds to the loss of environmental quality, with extreme effects of a drop in abundance and diversity. Taxa that are more tolerant (*Namalycastis caetensis*, *Cirolana* sp., *Pseudosphaeroma* sp., Tubificidae, and Chironominae) and sensitive (Hydropsychidae and *Eteone* sp.) to impact conditions were identified and evaluated as potential bioindicators.

Keywords: macrofauna, environmental impact; industrial pole; Amazonian estuary.

RESUMO

O estudo caracterizou e avaliou o uso da comunidade de macroinvertebrados bentônicos como indicadora de impactos em diferentes ambientes estuarinos na área do Complexo Portuário Industrial (CPI) de Vila do Conde (Pará, região amazônica). A fauna de praias e rios, em setores do estuário sob diferentes graus de impacto ambiental (alto, médio e baixo), foi comparada em distintos períodos sazonais. A macrofauna foi composta por grupos tipicamente dulcícolas e estuarinos. As praias apresentaram sedimento com textura variando de areia média a grossa, com macrofauna menos rica ($\bar{X}$ = 4,5 ± SE 0,3 táxons/amostra) e densa ($\bar{X}$ = 1.838,1 ± 164,8 ind./m^2), quando comparados aos rios ($\bar{X}$ = 5,9 ± 0,3 táxons/amostra e 3.248,9 ± 77,0 ind./m^2), os quais foram ambientes mais lamosos. Para ambos os ambientes, locais no setor de alto impacto eram de menor riqueza ($\bar{X}$ = 4,7 ± 0,3 táxons/amostra) e densidade ($\bar{X}$ = 2.812,9 ± 232,7 ind./m^2), quando comparados ao do setor de baixo impacto ($\bar{X}$ = 7,6 ± 0,4 táxons/amostra e 3.314,3 ± 230,1 ind./m^2). A riqueza ($\bar{X}$ = 6,4 ± 0,3 táxons/amostra) e densidade ($\bar{X}$ = 3.859,4 ± 190,2 ind./m^2) foram mais altas no período mais chuvoso, do que no período menos chuvoso ($\bar{X}$ = 4,8 ± 0,3 táxons/amostra e 1.933,0 ± 172,1 ind./m^2). Contudo, não ocorreram modificações sazonais significativas na composição. Os resultados indicaram que a estrutura da comunidade de macroinvertebrados bentônicos no entorno do CPI responde à perda da qualidade ambiental, com efeitos extremos de queda na abundância e diversidade. Táxons mais tolerantes (*Namalycastis caetensis*, *Cirolana* sp., *Pseudosphaeroma* sp., Tubificidae e Chironominae) e sensíveis (Hydropsychidae e *Eteone* sp.) às condições de impactos foram identificados e avaliados como potenciais bioindicadores.

Palavras-chave: macrofauna, impacto ambiental; polo industrial; estuário amazônico.

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Introduction

Roughly 30% of the Amazon's territory is protected by humid areas, which are highlighted for providing environmental services that guarantee the maintenance of biodiversity and the sustenance of human communities (BARROS; ALBERNAZ, 2014; CARVALHO; PIMENTEL; LIMA, 2019). These areas form the basis of aquatic food chains, for they have a high primary and secondary production, as well as a great diversity of plant and animal species, including invertebrates and vertebrates, many of which are valuable fishing resources (JUNK *et al.*, 2011). Besides that, they are essential for recharging aquifers, containing floods and soil erosion, retaining nutrients, and contaminants (CAVALCANTE *et al.*, 2015).

The use of environmental indicators which assess and provide data for quality management and conservation of environments is recommended for ecosystems with a high degree of sensitivity, such as those found in humid areas (JUNQUEIRA *et al.*, 2018; CHANAMÉ-ZAPATA *et al.*, 2019; MEHROTRA; BARDHAN; RAMAMRITHAM, 2019). An organism, or assembly of organisms, is considered a bioindicator when it presents a response that can be identified in the face of differences (natural variations), or changes (anthropic impacts) in its surroundings. (LIJTEROFF; LIMA; PRIERI, 2009).

Benthic macroinvertebrates are animals that have an average size of 0.5 mm and live all or part of their lives inside or on the bottom of aquatic environments (CAMARGO, 2019). They are one of the most recommended groups in literature for diagnosis and environmental monitoring, due to some attributes, such as:

- presence in practically all aquatic systems, favoring comparative studies;
- sedentary nature and relatively short life cycle, which allows a more effective spatial and temporal analysis of the effects of impacts;
- and a large number of species present therein, offering a wide range of responses to environmental stress;
- the numerous methods in the community studied, which have been used at the level of community monitoring and individual responses (FERREIRA; PAIVA; CALLISTO, 2011; JUNQUEIRA *et al.*, 2018).

The Industrial Port Complex (IPC) of Vila do Conde, in Barcarena City, Pará State, is one of the largest industrial centers in the Amazon region. The complex was created in 1976 and has, in addition to the port area, several mineral processing outsourced companies, associated with the mineral sector and general trade (QUEIROZ *et al.*, 2019). As a result of these activities, the region had its economy modified, which caused an intense and disordered population growth (BORDALO; SILVA; SANTOS, 2012; HAZEU; COSTA; NASCIMENTO, 2019). Given this scenario, recurring accidents and environmental crimes were recorded in the region, which includes: leakage/spillage of petroleum-based fuels; spillage of ores and live cargo; overflows of waste from mineral tailings dams, and releases of urban and mineral effluents (IEC, 2018; FAIAL *et al.*, 2009; FERREIRA, BELTRÃO, 2016; LIMA *et al.*, 2018; PINHEIRO *et al.*, 2019).

Effects of environmental impacts on aquatic biota at the Vila do Conde Industrial Pole were evaluated by some studies addressing plankton (phyto- and zooplankton) and ichthyofauna. Regarding plankton, changes in density of organisms, and a higher frequency of impacting species were observed in the areas closest to the port system (SENA *et al.*, 2015; COSTA *et al.*, 2016a; 2016b; PINHEIRO *et al.*, 2019). In the ichthyofauna, in places close to the IPC, there was a reduction in the diversity of species and food guilds (VIANA; FRÉDOU; FRÉDOU, 2012; VIANA; FRÉDOU, 2014), in addition to a higher incidence of individuals with histopathological damage (VIANA *et al.*, 2013). So far, only quick inventories have been carried out on the benthic community of the area,, with a view to environmental authorizations for the implantation of port and industrial enterprises.

Given the environmental vulnerability of aquatic resources in the area, the present study aims to characterize the community of benthic macroinvertebrates in different aquatic environments and seasonal periods, assessing possible changes in their structure, as well as their use as bioindicators of environmental quality.

Materials and Methods

Study site

The industrial complex of Vila do Conde has an area of 1,316.299 km^2 and is located on the right bank of the Pará River estuary (CDP, 2010), in Pará State, on the Brazilian Amazon coast. The region's drainage network is formed by rivers of small orders and by the river Pará, a water body of great spatial extensions, with 30–40 km of distance between its banks, and 300 km of longitudinal extension, until its mouth in the Atlantic Ocean (PRESTES *et al.*, 2017). The study site (Figure 1) is an estuarine region with a greater influence of fresh water, classified as a tidal freshwater estuary (ELLIOTT; MCLUSKY, 2002). On the banks of the river Pará, sand strips exposed during low tides are called beaches.

Sampling network

Quarterly collections were carried out from February to November 2012, covering two samples in the rainy period (February and May) and two in the less rainy period (August and November). A total of 10 collection stations were established (Figure 1) to cover the main drainages surrounding the industrial complex. Six of the stations were located on small rivers' stretches under the influence of tides: the river Arrozal (ARZ), the river Murucupi (MUR), the river São Francisco (SF), the river Curuperê-Dende (DEN), the river Arienga (ARI), the river Arapiranga (ARA); and four on the beaches of the river Pará: Caripi Beach (CAR), Itupanema Beach (ITU), Conde Beach (CON), and Beja Beach (BEJ).

The collection stations were distributed in three sectors with different potential impacts, according to secondary data on water quality, land use, and history of environmental impacts in the area. The sectors were:

- high impact sector (DEN, MUR, CON, and ITU), in the IPC area, including the port of Vila do Conde, in addition to large companies in the mineral sector, such as Hydro Alunorte and Imerys Rio Capim; the presence of sewage discharges and industrial effluents (BRABO *et al*., 2003; LIMA *et al*., 2009);
- medium impact sector (ARZ, SF, CAR), downstream from the IPC, with urban occupation and close to areas of companies in the mineral sector, with events for the discharge of solid materials, and of domestic and industrial effluents (FAIAL *et al*., 2009; LIMA *et al*., 2009);
- low impact sector (ARA, ARI and BEJ) upstream of the IPC, with riparian forests relatively preserved compared to other drainages nearby; and good water quality (LIMA *et al*., 2009; COSTA *et al*., 2016a; 2016b).

Field activities and laboratory

Two collection points (about 100 m apart) were established for rivers to distribute the sampling along the impacted stretch. On beaches, only one collection point was established. At each point, three biological samples were taken with the aid of a Van Veen dredge

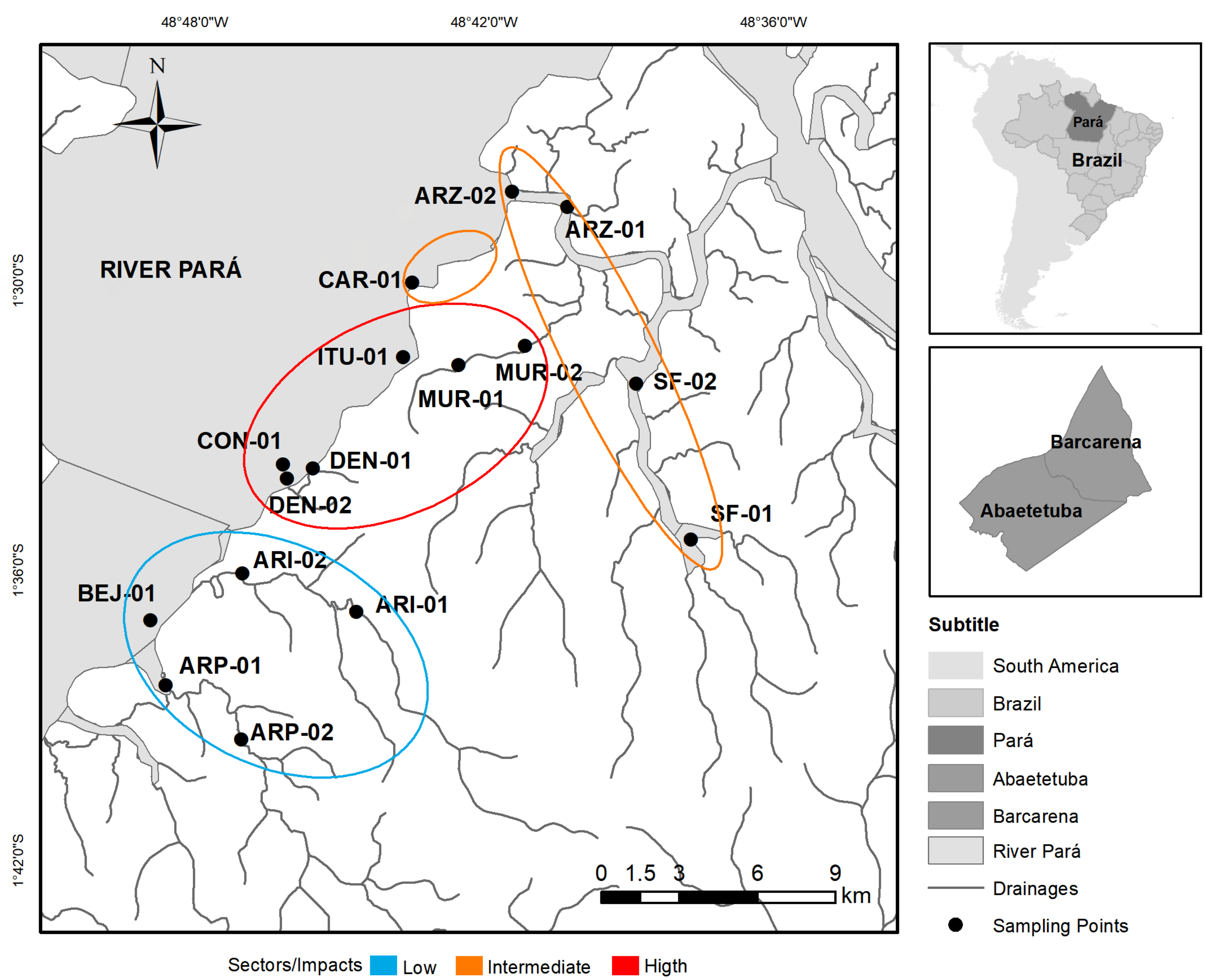

Figure 1 – Sampling network for benthic macroinvertebrates around the Industrial Port Complex of Vila do Conde (Barcarena City, Pará State, Brazil). Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), Arapiranga (ARP); Estuarine beaches on the river Pará: Itupanema (ITU); Conde (CON), and Beja (BEJ).

RBCIAMB | v.56 | n.1 | Mar 2021 | 111-127 - ISSN 2176-9478

(20 × 20 × 20 cm), at a depth of about 2 m. On each occasion and location, a sediment sample was collected for granulometric and total organic matter analysis. Biological samples were passed with a 0.3 mm opening mesh; retained material was preserved in a 5% formaldehyde solution. Sample for abiotic analysis was cooled in the field and frozen in laboratory.

In the laboratory, biological samples were screened, and organisms counted, identified at the lowest possible taxonomic level, and preserved in 70% ethyl alcohol. For sediment samples, granulometry was determined by sieving the coarse and pipetting the fines (SUGUIO, 1973). Organic matter content was determined by the muffle calcination method at 550°C for four hours (adapted from Davies, 1974). Statistical parameters (mean grain diameter, textural classification, and proportions of sand, silt, and clay) of the sediment were calculated using the equations proposed by Folk and Ward (1957).

Data analysis

Regarding sediment data, a principal component analysis (PCA) was applied to identify similarity and the most important variables for grouping locations, environments, and climatic periods. For analysis, data were first standardized and normalized; the Euclidean Distance was used to calculate similarity.

For each biological sample, biological descriptors were calculated: total abundance (number of individuals), average density (individuals per m^{-2}), richness (by simply counting the number of taxa), and diversity (Shannon-Winner index). To verify spatial variations of these descriptors, the three-way ANOVA was applied for the following treatments: climatic period (less rainy and rainy), environment (river and beach), and seasons (nested to the environmental factor). ANOVA was followed by Tukey's test whenever null hypothesis was rejected. Before ANOVA, normality of data distribution (Kolmogorov-Smirinov test), and homoscedasticity of variances (Levene's test) were tested, and, when needed, transformed.

For comparison of the structure of communities in different treatments, permutational multivariate analysis of variance (PERMANOVA) was applied (ANDERSON, 2005), following the same model applied in ANOVA. Grouping analysis (CLUSTER) was used to identify spatial patterns, according to the average distance method. For both analyzes, a similarity matrix constructed from Bray Curtis similarity index was used, calculated based on data on density. Similarity Percentage (SIMPER) routine was applied to identify the most important taxa for group similarity. Finally, indicator species index (IndVal) (DUFRÊNE; LEGENDRE, 1997) was applied to associate the taxa with types of environment and impact sectors. IndVal ranges from 0 to 100%, in which zero is equivalent to the non-indication of species for a given environmental status, and 100 indicates that the occurrence of a given species is characteristic of that environment. In conjunction with IndVal, the Monte Carlo test (with 1,000 randomizations) was performed to confirm the indication value significance. For all analyzes, a significance level of 5% was used.

Results

Precipitation

In general, rainfall rates for Barcarena City during the study period showed clear seasonal patterns and followed the climatological normal of the last 30 years (Figure 2). However, in the rainy season, rates much higher than those expected were recorded in March, June, and July 2012. For the less rainy period, September and October 2012, total precipitation was above and below the expected, respectively.

Sediment parameters

The sediment parameters of collection sites are shown in Table 1. Comparatively, beaches presented essentially sandy sediment, whereas rivers were predominantly muddy. For rivers, sediment ranged from fine silt (the rivers Murucupi, Curuperê-Dende, and Arienga) to medium silt (the rivers Arrozal, São Francisco, and Arapiranga), with organic matter above 5%. In both periods, the highest organic contents were observed in the rivers Arienga, Curuperê-Dende, and Murucupi. The presence of leaflets was observed predominantly in sediment samples from rivers (Table 1).

On beaches (Beja and Caripi) of relatively less impacted sectors, sediment was classified as medium sand, in both periods, and organic percentage varied from 3.5 to 5.1% (Table 1). In the sectors with the greatest impact (Itupanema and Conde), classification was of coarse (rainy season) and medium (less rainy) sand, always with a larger average grain size compared to the other beaches. Organic percentage on beaches under high impact ranged from 3.4 to 4.6% (Table 1). PCA analysis classified the environments as river and beach, according to their textural characteristics. However, concerning the periods, identifying seasonal patterns was not possible (Figure 3).

Benthic macroinvertebrates

General composition

A total of 2,024 organisms was collected, classified into 30 different taxonomic units (Supplementary material). The phylum Annelida was the most abundant, representing 54.8% of the total organisms collected, followed by Arthropoda (35.1%), Nematoda (7.3%), Mollusca (2.5%), and Platyhelminthes (0.4 %). In general, Polychaeta, Oligochaeta, and Insecta were the most abundant groups in rivers. Nonetheless, some distinctions were observed in-between seasons (Figure 4). In the high-impact sector, the river Curuperê-Dende was dominated by Nematoda, followed by Oligochaeta. On the river Mucurupi, highlights were Insecta and Oligochaeta. In the intermediate impact sector, polychaete worms (Rice) and insects (São Francisco) were the most representative. In the low impact sector, although polychaetes and oligochaetes were also dominant, there was greater participation of crustaceans and mollusks (Figure 4).

On beaches, polychaete worms dominated in Beja and Caripi, low and medium impact sectors, respectively; whereas crustaceans and oligochaetes were the most representative groups in Conde and Itupanema (Figure 4). Mollusks were not very representative and presented greater abundance in the river Arienga and the beaches Beja and Caripi.

Descriptors of benthic assemblies

ANOVA indicated significant variation in density, richness, and diversity, considering the different environments, collection seasons, and seasonal periods (Table 2). In general, macrobenthic assemblages of rivers were significantly denser and more diverse (number of taxa and diversity index) than those of beaches (Figure 5), although these descriptors showed low values in some rivers. In-between seasonal periods, significant variations were identified for density and total richness, without interaction with other factors. In general, the highest values of density and richness were recorded in the rainy season.

Regarding rivers, the macrofauna observed in the river Arrozal (intermediate impact sector) had the highest average density, with values significantly different from all other locations, except for the river Arapiranga in the rainy season (Figure 5). On the other hand, in the rivers São Francisco, Curuperê-Dendê, and Murucupi, the macrofauna was of lower density. For beaches' macrofauna, Caripi and Beja were significantly denser than Itupanema and Conde during the rainy season. In the less rainy season, assemblies on Itupanema and Conde were significantly more abundant than those on Beja.

As to richness and diversity, a similar pattern of abundance was observed; however, the highest values of the indices were observed in the rivers Arapiranga and Arienga (low impact sector), which, as well as Arrozal, differed significantly from the rivers São Francisco, Curuperê-Dendê, and Murucupi (Figure 5). In turn, among beaches, Beja and Caripi were richer than Conde and Itupanema in the rainy season. In the less rainy season, only Beja was richer than Conde beach.

Spatio-temporal variability of the macroinvertebrate community structure

PERMANOVA indicated that the structure of macrobenthic associations is dissimilar when comparing rivers and beaches, just as there are differences between locations within each type of environment (Table 3). There were no significant changes in-between seasonal periods. All rivers had a significantly dissimilar fauna structure, except for

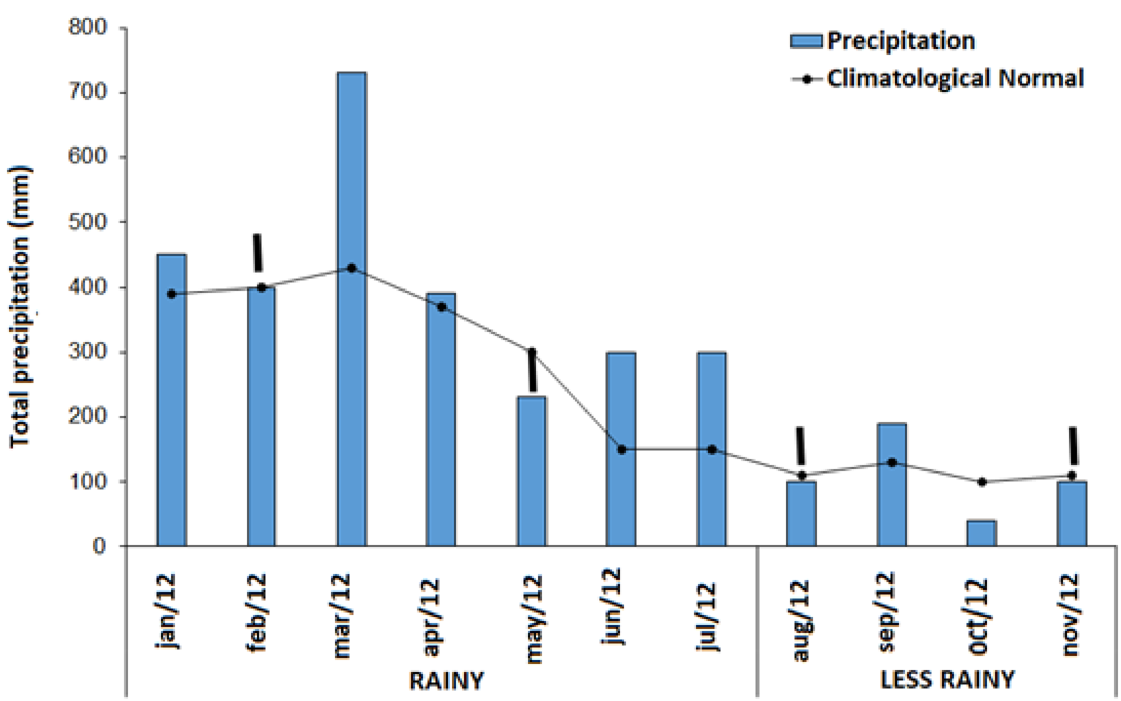

Figure 2 – Total monthly precipitation (bars) for the study period, and normal climatology (lines) for the last 30 years (1989-2019). The arrows indicate collection months.

Source: Based on data from INMET (2012).

Table 1 – Sediment characteristics in collection stations. Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ).

Parameter/Period	RIVERS						BEACHES			
	ARA	ARI	ARZ	SF	DEN	MUR	BEJ	CAR	ITU	CON
Rainy period										
Gravel (%)	4.2 ± 0.1	3.9 ± 0.2	3.6 ± 0.1	1.4 ± 0.3	4.1 ± 0.2	0.6 ± 0.2	4.5 ± 0.1	1.4 ± 0.2	2.4 ± 0.1	3.6 ± 0.2
Sand (%)	18.4 ± 0.4	23.1 ± 0.2	20.1 ± 0.1	10.2 ± 0.3	8.8 ± 0.1	24.3 ± 0.1	81.3 ± 0.1	92.3 ± 0.3	63.4 ± 0.4	91.2 ± 0.1
Silt (%)	71.1 ± 0.2	66.2 ± 0.3	71.3 ± 0.1	81.3 ± 0.2	82.1 ± 0.1	68.9 ± 0.1	8.1 ± 0.2	3.6 ± 0.3	26.4 ± 0.2	4.2 ± 0.1
Clay (%)	6.3 ± 0.3	6.8 ± 0.2	5.0 ± 0.3	7.1 ± 0.2	5.0 ± 0.1	6.2 ± 0.2	6.1 ± 0.2	2.7 ± 0.2	7.8 ± 0.1	1.0 ± 0.1
MO (%)	6.3 ± 0.5	9.1 ± 0.3	6.1 ± 0.3	5.6 ± 0.5	8.4 ± 0.3	8.9 ± 0.1	5.1 ± 0.3	3.5 ± 0.2	4.1 ± 0.2	3.4 ± 0.1
Grain size (Ø)	5.4 ± 0.3	5.4 ± 0.2	5.2 ± 0.1	5.6 ± 0.2	6.2 ± 0.1	5.1 ± 0.1	2.4 ± 0.2	2.4 ± 0.1	2.1 ± 0.2	2.1 ± 0.2
Verbal classification	Silt M	Silt M	Silt M	Silt F	Silt F	Silt M	Sand M	Sand M	Sand C	Sand C
Presence of leaflet	+	+	+	+	+	+	-	-	-	-
Less rainy period										
Gravel (%)	1.6 ± 0.1	2.8 ± 0.1	3.1 ± 0.1	3.8 ± 0.1	4.5 ± 0.1	0.5 ± 0.1	2.5 ± 0.2	0.8 ± 0.1	1.6 ± 0.2	2.9 ± 0.1
Sand (%)	10.8 ± 0.2	31.9 ± 0.4	20.2 ± 0.5	17.6 ± 0.2	18.9 ± 0.3	20.5 ± 0.4	84.0 ± 0.3	83.4 ± 0.2	90.8 ± 0.2	95.1 ± 0.3
Silt (%)	84.8 ± 0.2	57.5 ± 0.1	70.5 ± 0.1	75.3 ± 0.1	72.9 ± 0.2	69.0 ± 0.5	8.1 ± 0.2	10 ± 0.2	6.7 ± 0.2	2.4 ± 0.3
Clay (%)	2.8 ± 0.1	7.8 ± 0.1	4.4 ± 0.1	3.3 ± 0.1	3.8 ± 0.1	10.0 ± 0.2	5.4 ± 0.1	5.8 ± 0.2	0.9 ± 0.1	2.5 ± 0.3
MO (%)	5.3 ± 0.3	8.1 ± 0.3	9.1 ± 0.6	5.6 ± 0.5	8.4 ± 0.2	7.9 ± 0.2	3.9 ± 0.1	4.6 ± 0.1	4.00 ± 0.1	4.5 ± 0.2
Grain size (Ø)	5.4 ± 0.3	5.2 ± 0.2	5.3 ± 0.1	5.4 ± 0.2	5.5 ± 0.1	5.2 ± 0.1	1.0 ± 0.2	1.8 ± 0.1	2.0 ± 0.1	2.0 ± 0.1
Verbal classification	Silt M	Silt M	Silt M	Silt M	Silt M	Silt M	Sand M	Sand M	Sand M	Sand M
Presence of leaflet	+	+	+	+	+	+	+	-	-	-

MO= organic matter; Silt F = fine silt; Silt M= medium silt; Sand M= medium sand; Sand C = coarse sand; + = present leaflet; - = without leaflet

Curuperê-Dende and Mucurupi. As to beaches, Itupanema and Conde had a similar structure, whereas all the other comparisons resulted in significant dissimilarity.

PERMANOVA's results did not indicate significant seasonal variation in the structure of assemblies, or the interaction of this factor with spatial factors. Given that, ordination analyzes, SIMPER, and IndVal prioritized spatial patterns (comparisons between seasons/environments and impact sectors).

CLUSTER analysis (Figure 6) showed a separation of the samples of stations of low-impact sectors, considering rivers and beaches. These locations gather samples with greater density and species richness and presented as more common taxa, species of polychaetes (*Namalycastis caetensis*, *Eteone* sp. and *Nephthys fluviatilis*), as indicated by SIMPER (Table 4). Due to its composition and high abundance, the beach Beja exhibited a faunal structure similar to that of rivers. A group of locations (DEN, ITU, CON) of the high-impact sector was also observed. In the SIMPER analysis we noticed that the beaches in this group have *Cirolana* sp. as the most important taxon for sample similarity, and share with the Curuperê-Dende river the high frequency of Nematoda. The rivers Mucurupi and Arrozal form a group with more than 60% similarity, and SIMPER indicates *N. caetensis,* Chironominae, and Tubificidae as the most common. Caripi was also isolated from the other beaches, and its most frequent taxa were *Eteone* sp., *N. fluviatilis,* and Haplotaxidae.

IndVal values were low: only eight taxa had an indication value greater than 30% and significant (Table 5). Among these, the polychaetes *N. caetensis* and *N. abiuma* were indicatives of the rivers of the medium impact sector. For rivers of the low impact sector, only the larvae of Hydropsychidae were indicators. As to beaches, *Eteone* sp. was an indicator of low-impact beaches, *Cirolana* sp., *Pseudosphaeroma* sp. to the top, and *N. fluviatilis* for medium impact.

Discussion

Composition and spatio-temporal variations

Estuaries are environments of transition between fluvial and marine, characterized by the intense action of physical forcing, with emphasis on the entry of fresh water and tidal fluctuations (ELLIOTT; MCLUSKY, 2002). In tropical estuaries, spatial and temporal variability of salinity, which is influenced by rainfall and fluvial input, is the main macro factor to control biological processes. In Amazon's estuaries, under the influence of large rivers, such as the river Pará, penetration of saline waters from the Atlantic can be largely prevented, giving an oligohaline character (salinity between 0 and 5) throughout the entire estuary and the year (ROSA FILHO *et al.*, 2018). Accordingly, in the river Pará's stretch and the study period, surface water salinity ranged from 0.01 to 0.05 (ROSÁRIO *et al.*, 2016; COSTA *et al.*, 2016a; 2016b).

Concerning the bottom sediment, organic matter values of rivers and beaches in Pará river estuary, with percentages between 3.4 and 9.1%, are higher than those registered in other Amazonian estuaries, with muddy or sandy sediments (SILVA *et al.*, 2011; AVIZ; CARVALHO; ROSA FILHO, 2012; ROSA FILHO; AVIZ, 2013). This result may indicate enriched substrates in the surroundings of the IPC of Vila do Conde, considering that the release of untreated domestic organic effluents is one of the main contaminants of water in that area (COSTA *et al.*, 2016a; 2016b).

The area's benthic macrofauna was composed of typically freshwater groups (such as insect larvae and oligochaete) (BATZER; BOIX, 2016) and estuarine (such as polychaetes, mollusks, and crustaceans) (ELLIOTT; MCLUSKY, 2002) with numerical dominance of few taxa. This combination is characteristic of estuaries dominated by rivers (SCHUCHARDT; HAESLOOP; SCHIRMER, 1993; ELLIOTT; MCLUSKY, 2002). In the Amazon, macrobenthic communities in estuarine areas are characterized by low taxonomic diversity and dominance of a small number of taxa, attributes that probably are reflections of the stress caused by macrotidal regimes and low salinity, permanent or imposed during some months of the year (ROSA FILHO *et al.*, 2006; ROSA FILHO *et al.*, 2018).

Values of density of organisms (with averages in the collection stations between 484.8 and 3,708 ind. m^{-2}) and taxon richness (total

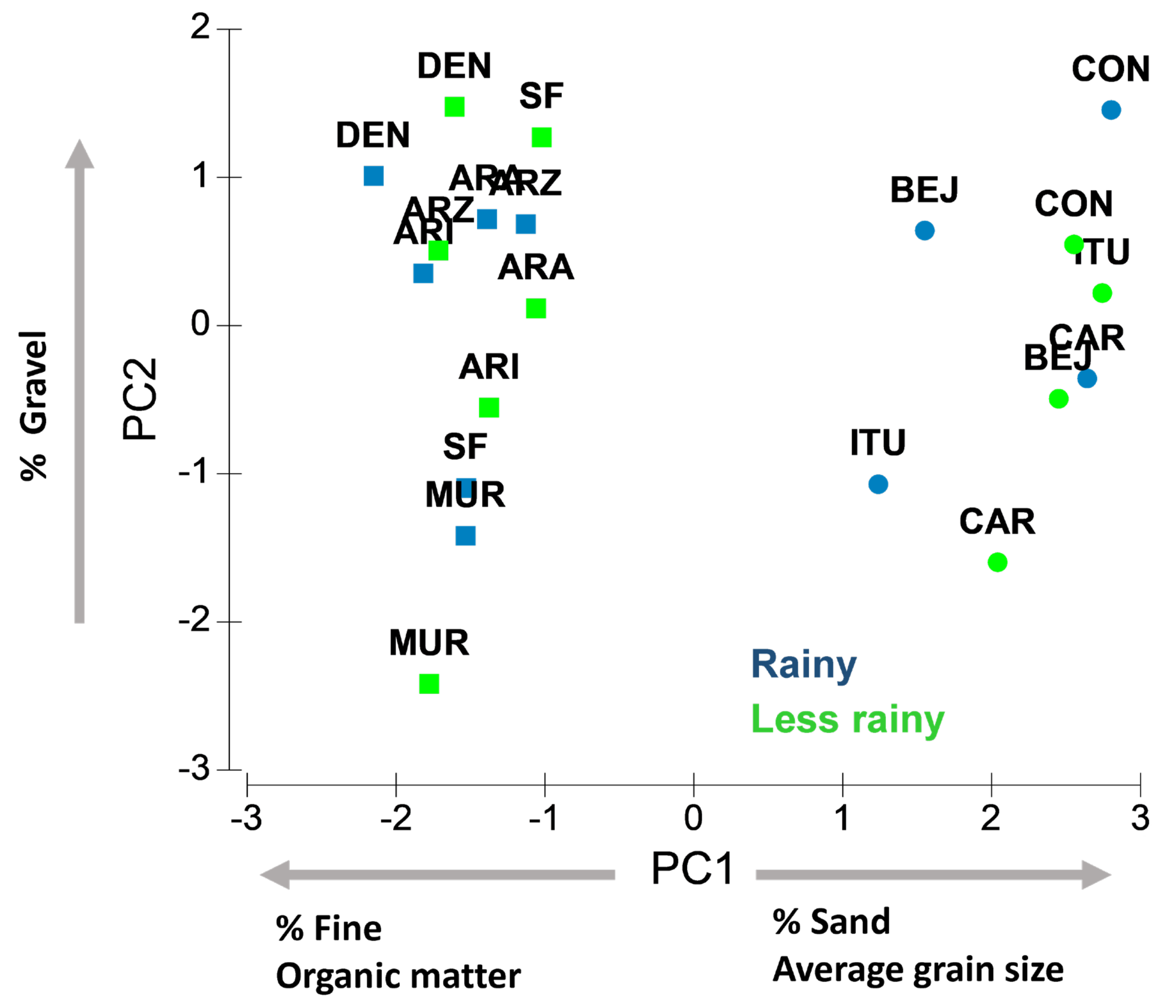

Figure 3 – Result of PCA analysis (PC1 = 62.8%, PC2 = 19.7%) for river sediment data (square) and beaches (circles) of Pará river estuary (Barcarena City, Eastern Amazon). Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ).
OM: organic matter.

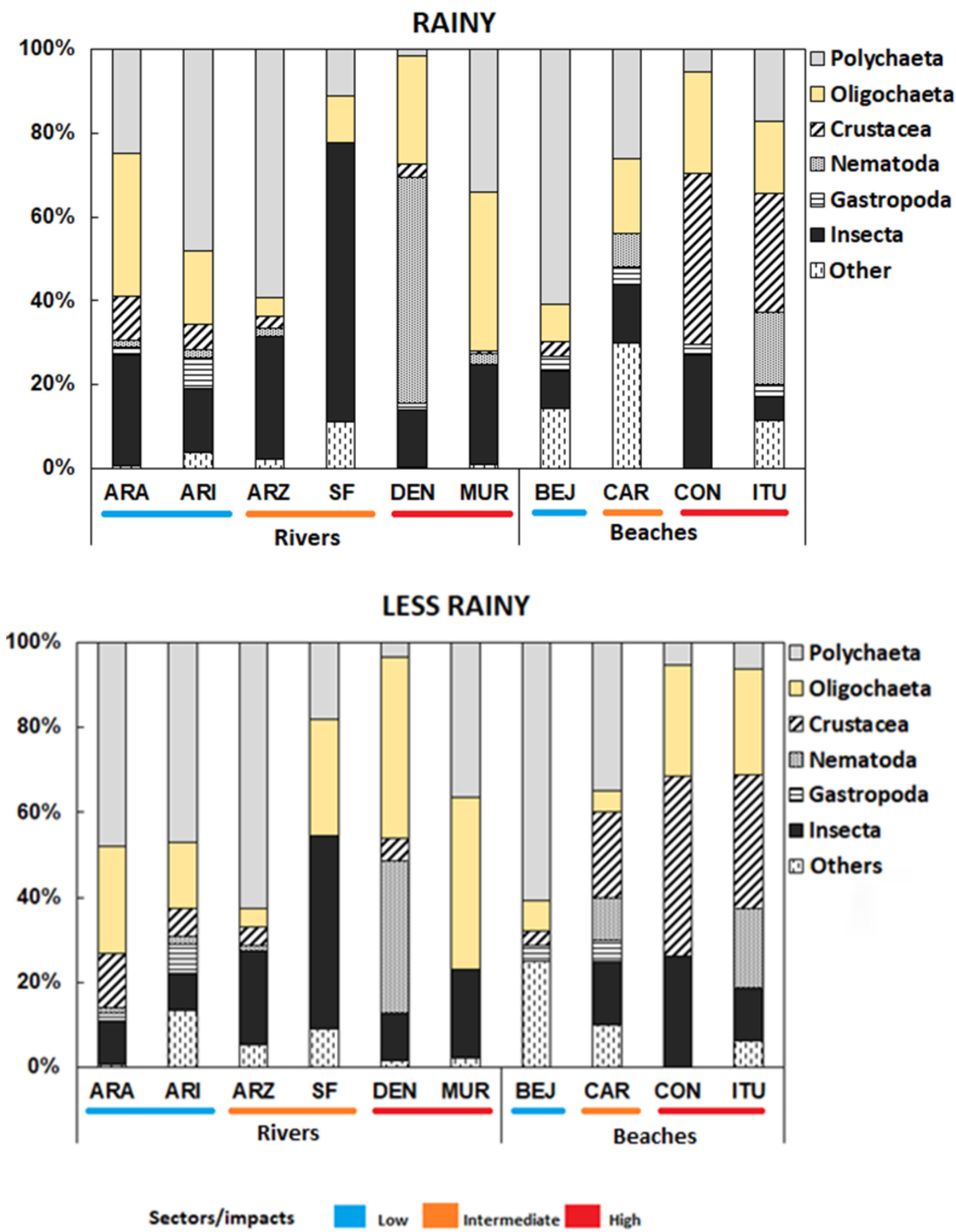

Figure 4 – Relative participation of taxonomic groups in the abundance of organisms in collection stations. Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), Arapiranga (ARA). Estuarine beaches on the river Pará: Itupanema (ITU); Conde (CON), and Beja (BEJ).

of 30 taxa) from Pará river estuary are consistent with those of other Amazonian estuaries. For example, in Guajará Estuary, with oligohaline waters (< 1), total richness was 22 taxa, and average density varied between 458.3 and 19,290.1 ind. m^{-2} (AVIZ; CARVALHO; ROSA FILHO, 2012). In the same estuary, Rosa Filho and Aviz (2013) recorded a richness of 39 taxa and densities between 403.1 and 5,181.2 ind. m^{-2}. In the estuary of the river Caeté, in a stretch with salinity between 5.1 and 26.5, the total number of taxons was 17, and density varied from 664.6 to 14,399 ind. m^{-2} (ROSA FILHO *et al.*, 2006).

The groups with the highest abundance in the area were Polychaeta, Oligochaeta, Nematoda worms, and Chironomidae larvae. Soft substrates (muddy and sandy-muddy) are especially conducive to wormlike domain, because they facilitate their movement and offer a greater amount of food, especially for deposit-eating species. In turn, Chironomidae larvae can be naturally abundant in continental environments, due to the high diversity of adult larvae in the terrestrial environment, in addition to the plasticity of habitat and tolerance of their larvae, which can use various food resources, including debris (FERRINGTON JR., 2008).

Table 2 – Results of the ANOVA analysis for the descriptors density, richness, and diversity, using the factors environment (river and beaches), collection stations, and seasonal periods.

Variation source		Density (ind.m^{-2})		Richness (No. taxa)		Diversity (H')	
	gl.	F	p-value	F	p-value	F	p-value
Environment (1)	1	35.6	< 0.01*	11.3	< 0.01*	4.6	0.03*
Station (Environment) (2)	8	88.5	< 0.01*	17.1	< 0.01*	22.2	< 0.01*
Period (3)	1	10.2	< 0.01*	20.3	< 0.01*	0.25	0.61
Interaction (1-3)	1	0.3	0,54	0.04	0.83	0.00	0.99
Interaction (2-3)	8	13.2	0,10	0.82	0.58	0.04	0.99

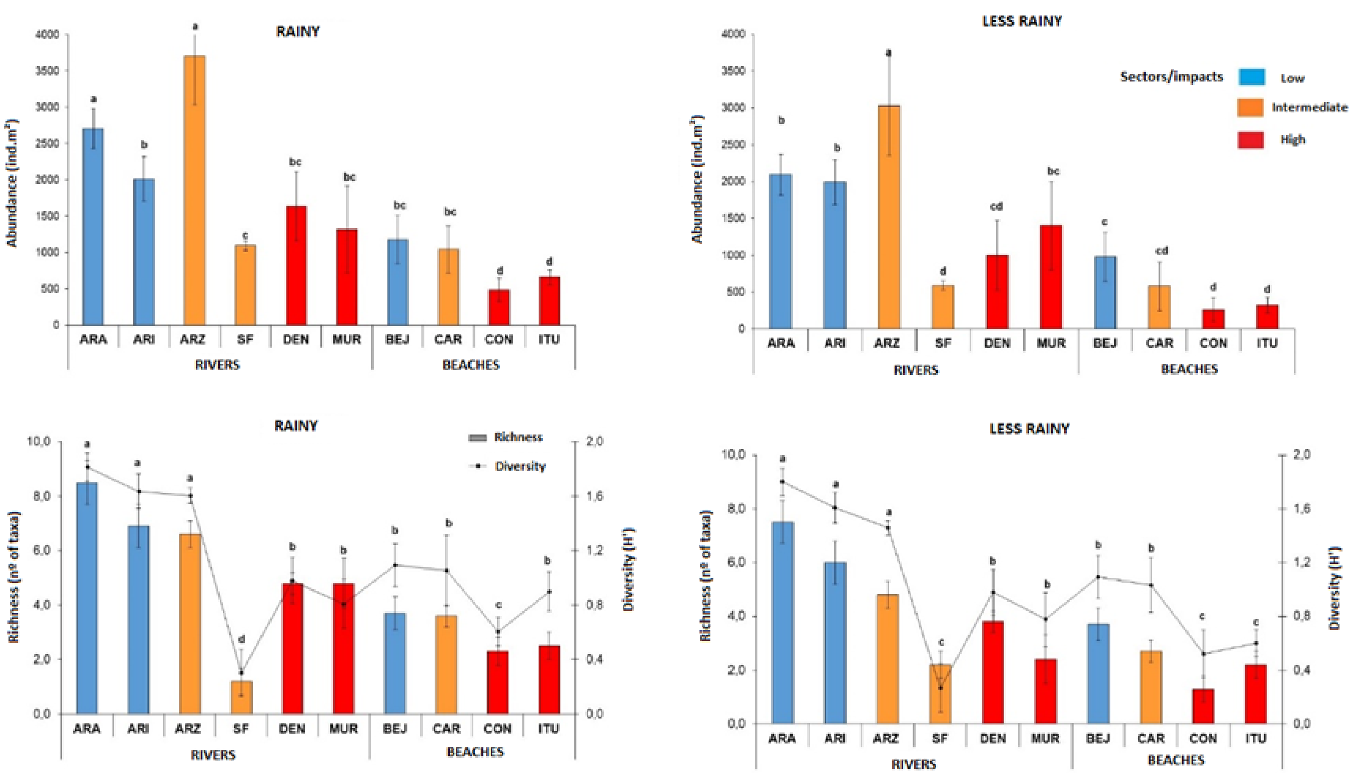

Figure 5 – Mean values (± standard error) of density, richness, and diversity of macrobenthic assemblages during different seasonal periods (rainy and less rainy). Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ). The letters above the averages represent the Tukey's test results; places that do not share letters differed significantly.

In the river Pará, estuarine beaches were environments with a different composition, lower taxonomic richness, and a lower number of macrobenthic organisms when compared to small tributaries. Those beaches are environments subject to strong tidal currents, with less deposition of fine sediments, and a substrate composed of medium and coarse sands. In turn, small rivers presented more muddy sediment and submerged litter due to low hydrodynamic activity, the influence of soils, and adjacent vegetation. High substrate stability, the greater proportion of fine grains, and the greater supply of food and shelter are factors conducive to the development of benthic organisms (SWARTZ *et al.*, 2019; BOSSLEY; SMILEY, 2019).

In beaches and rivers, the lowest values of richness and density were observed in high-impact sectors. In aquatic environments impacted by deforestation or the release of urban and industrial effluents, macrobenthic fauna tends to reduce density and taxonomic richness, due to the disappearance or decrease in the numbers of sensitive taxa (MACKINTOSH; DAVIS; THOMPSON, 2015).

In the beaches Conde and Itupanema, high-impact areas, the reduction in biological indexes was associated to more coarse and enriched sediments. In those beaches, the most abundant groups were isopods, tubificids, and chironomids. Tubificidae worms and Chironomidae larvae are known to tolerate habitat modifications, which include contamination by chemical and organic pollutants (PELLETIER *et al.*, 2010; YOSHIDA; ROLLA, 2012; MACKINTOSH; DAVIS; THOMPSON, 2015). In turn, isopods are detritivore, opportunistic organisms, and many species are relevant and useful in environmental monitoring, due to their tolerance to chemical compounds and their great capacity to store metals (GHEMARI *et al.*, 2019).

In addition to the intense urban occupation, the beaches of the river Pará are in an area of a greater influence of port facilities, which

Table 3 – PERMANOVA's results. Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dende (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ).

Variation source	df	MS	MS	Pseudo-F	P(perm)
Environment	1	19,466	19,466	12.758	0.001*
Stations (Environment)	8	1.479	18,322	12.008	0.001*
Periods	1	2,118.3	2,118,3	13.883	0.206
Environment x Period	1	123.78	123.78	8.11E+02	0.998
Station (Environment) x Period	8	1,304.5	163.06	0.10687	1.000
Res	172	2.62	1,525.8		
Total	191	4.329			
Paired tests					
Groups (Rivers)	**t**	**P(perm)**	**Groups (Beaches)**	**t**	**P(perm)**
ARZ, MUR	6.20	0.001*	CAR, ITU	1.86	0.006*
ARZ, SF	4.30	0.001*	CAR, CON	2.67	0.001*
ARZ, DEN	2.98	0.001*	CAR, BEJ	2.84	0.001*
ARZ, ARA	2.44	0.001*	ITU, CON	1.08	0.057
ARZ, ARI	3.47	0.001*	ITU, BEJ	2.50	0.001*
MUR, SF	3.67	0.001*	CON, BEJ	2. 82	0.001*
MUR, DEN	1.71	0.100			
MUR, ARA	2.88	0.001*			
MUR, ARI	5.54	0.001*			
SF, DEN	5.75	0.001*			
SF, ARA	4.71	0.001*			
SF, ARI	4.42	0.001*			
DEN, ARA	3.79	0.001*			
DEN, ARI	0.21	0.002*			
ARA, ARI	2.05	0.002*			

can affect the benthic community in different ways (MOSBAHI *et al.*, 2019). Physical facilities, such as support and mooring structures, and pipelines, can alter local hydrodynamic patterns and sediment characteristics, which can include a decrease in local sedimentation (KAWASHIMA *et al.*, 2016). Besides that, contamination of the environment can occur due to oil and fuel leaks from vessels or loss of materials (organic and inorganic) during loading and unloading these vessels (MOREIRA *et al.*, 2019).

The high-magnitude river Arrozal, is in an area of intermediate impact, and presented the highest density of organisms, without a significant drop in the richness of taxa. The site is located downstream the industrial complex and, along its course, it receives discharges of urban effluents (mainly untreated domestic sewage). *N. caetensis* and tubificids, which are deposit consumers, were dominant in this river. Biostimulation can occur in areas with moderate organic enrichment (CULHANE *et al.*, 2019) when organic supply is moderate, or sufficiently diluted; it does not compromise availability of oxygen for the biota, which contributes to increasing the abundance and the number of benthic species (ROSENBERG; RESH, 1993; AVIZ; CARVALHO; ROSA FILHO, 2012; KRUMHANSL *et al.*, 2015; CULHANE *et al.*, 2019).

Even though the river São Francisco is in an area of intermediate impact, it was the river with the least richness and abundance in the study site, in which Tubificidae, Chironominae, and *N. caetensis* were the dominant taxa. The stations on that river are the most internal to the continent, and the river drains a large continental area, including the urban area of Barcarena City. We believe that the lesser influence of the tides and less dilution of organic loads can contribute to less conducive conditions for the development of the estuarine fauna.

The main seasonal changes observed in macrobenthic assemblies were concerning the density of organisms and the number of species. The increase in the quantity of macrofauna in the rainy season may be associated to the increase in rainfall in the IPC area,

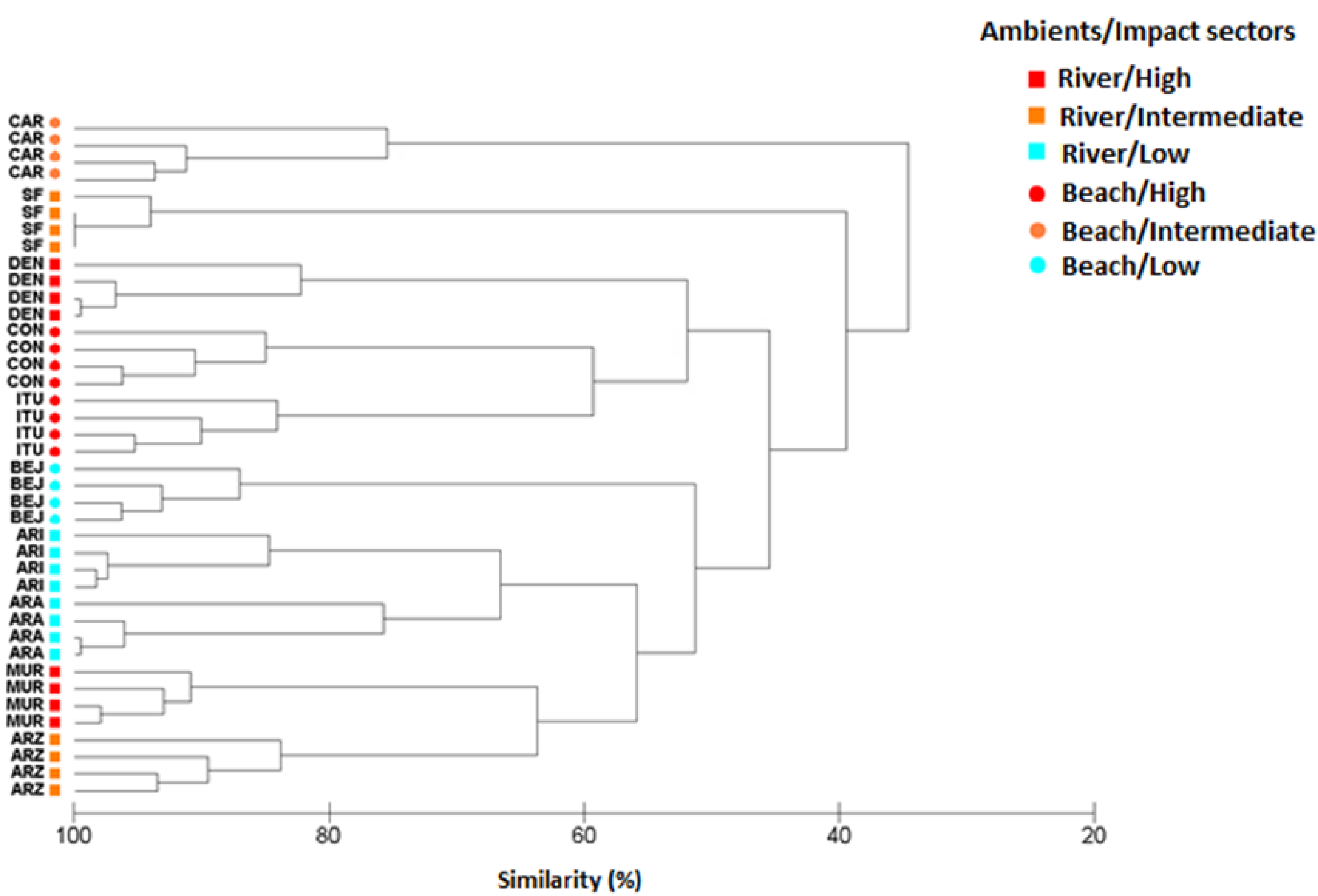

Figure 6 – Result of CLUSTER analysis for samples of benthic macroinvertebrates from Pará River estuary, in different environments and sectors of environmental impact. Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dendê (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ).

Table 4 – SIMPER results for similarity among the collection sites. Rivers: Arrozal (ARZ), Murucupi (MUR), São Francisco (SF), Curuperê-Dendê (DEN), Arienga (ARI), and Arapiranga (ARA). Beaches: Caripi (CAR), Itupanema (ITU), Conde (CON), and Beja (BEJ).

RIVERS							
Grup ARA				Grup MUR			
Average similarity: 85.1%				Average similarity: 91,4%			
Taxa	Av.S	Cont. %	Cum.%	*Taxa*	Av.	Cont.%	Cum.%
Namalycastis caetensis	12.5	14.7	14.7	*Namalycastis caetensis*	32.0	35.1	35.1
Tubificidae	10.3	12.1	26.8	Chironominae	17.6	19.2	54.3
Heleobia sp.	9.9	11.6	38.4	Tubificidae	14.8	16.2	70.5
Eteone sp.	8.2	9.6	48.0	Empididae	9.0	9.9	80.4
Hydropsychidae	7.5	8.8	56.8				
Grup ARI				Grup SF			
Average similarity: 90.1%				Average similarity: 93,9%			
Taxa	Av.S	Cont. %	Cum.%	*Taxa*	Av.S	Cont.%	Cum.%
Namalycastis caetensis	11.5	12.8	12.8	Chironominae	31.6	33.7	33.7
Eteone sp.	10.8	12.0	24.8	Oligochaeta	19.4	20.7	54.4
Nephthys fluviatilis	10.6	11.8	36.6	*Namalycastis caetensis*	12.2	13.0	67.4
Tubificidae	10.1	11.2	47.7				
Hydropsychidae	6.8	7.5	55.2				
Grup DEN				Grup ARZ			
Average similarity: 88.3%				Average similarity: 85,9%			
Taxa	Av.S	Cont. %	Cum.%	*Taxa*	Av.S	Cont.%	Cum.%
Nematoda	30.8	34.9	34.9	*Namalycastis caetensis*	17.3	20.1	20.1
Chironominae	12.2	13.8	48.7	Tubificidae	17.1	19.9	40.1
Namalycastis caetensis	7.5	8.5	57.2	Chironominae	16.8	19.6	59.6
Tanypodinae	6.1	6.9	64.1	*Nephthys fluviatilis*	10.9	12.7	72.4
BEACHES							
Grup CAR				Grup ITU			
Average similarity: 86.1%				Average similarity: 84,9%			
Taxa	Av.S	Con. %	Cum.%	*Taxa*	Av.S	Cont%	Cum.%
Eteone sp.	14.3	16.6	16.6	*Cirolana* sp.	32.0	37.7	37.7
Nephthys fluviatilis	12.7	14.7	31.3	Nematoda	11.6	13.6	51.3
Haplotaxidae	11.1	12.9	44.2	Tubificidae	11.6	13.6	64.9
Grup CON				Grup BEJ			
Average similarity: 79.5%				Average similarity: 88.4%			
Taxa	Av.S	Cont. %	Cum.%	*Taxa*	Av.S	Cont.%	Cum.%
Cirolana sp.	28.0	45.8	45.8	*Nephthys fluviatilis*	31.6	37.3	37.3
Pseudosphaeroma jackobii	10.1	16.5	62.3	*Namalycastis caetensis*	21.5	25.4	62.7
Nematoda	9.2	11.6	70.2	*Cirolana* sp.			

which significantly increases organic compounds in the water and can stimulate biota (COSTA *et al*., 2012a; 2012b). Although rains can naturally contribute to the transport of organic matter with leaching and flooding of forests, the continent's urbanization enhances the entry of nutrients into estuaries (KIMMERER, 2002).

Despite quantitative seasonal changes, the structure of assemblies, *i.e.*, their composition, and the dominant groups were similar in-between the seasonal periods, as indicated by PERMANOVA. The permanent oligohaline condition of the estuary, even with the marked variation in rainfall, seems to keep the faunal structure differently from what occurs in the estuaries furthest from the mouth of the Amazon River, where salinity throughout the year can vary from 0 to 35 (ROSA FILHO *et al*., 2018). Additionally, the little seasonal variation in sediment texture can also contribute to greater stability in the benthic communities.

Evaluation of species/bioindicator groups

IndVal obtained a low indication value for most species, due to the low degree of specificity of these species with the impact conditions (high, medium, and low impact sectors). An indicator species must have high fidelity within the assessed ecological status, which is measured by its occurrence percentage (DUFRÊNE; LEGENDRE, 1997; MCGEOCH; RENSBURG; BOTES, 2002). According to McGeoch, Rensburg and Botes (2002), only species with IndVal values above 70% are characteristic or indicative of ecological status. Species with significant IndVal values, but less than 70%, are considered detectors. Detector species are potential indicators of habitat change because they can change their preferred habitat more quickly than indicator species (VAN RENSBURG *et al*., 1999). Therefore, in the case of Pará River estuary, all taxa indicated by IndVal are detectors, and studies with longer time series are advised to confirm their use as bioindicators (MCGEOCH; RENSBURG; BOTES, 2002).

One of the most common estuarine organisms in the study site was *Namalycastis caetensis*, a species of polychaete recently described for Pará's estuaries, in sandy-muddy areas of low salinity (ALVES; SANTOS, 2016). In Barcarena, *N. caetensis* was associated by IndVal to intermediate impact rivers, but it was present in practically all collection stations (low, medium, and high impact sectors), with higher densities in rivers with a muddy-sand substrate. The genus *Namalycastis* is generally found in places severely polluted by industrial effluents (rich in heavy metals) and is relatively resistant in toxicity tests that involve hydrocarbons and bioaccumulation of heavy metals (GLASBY, 1999; SARKAR, 2018).

The isopods Cirolanidae, *Cirolana* sp. and *Pseudosphaeroma* sp., were common on the beaches of the river Pará, more frequently in the high-impact sector. Generally, isopods are considered opportunistic taxa and tolerant to environmental impacts, which include metal pollution and organic enrichment (GHEMARI *et al*., 2019). In Brazil, other species of Cirolanidae, such as *Excirolana brasiliensis*, are considered good monitors of the environmental quality of marine beaches, due to their high resistance to environmental stress, persisting in highly urbanized areas (VELOSO; NEVES; CAPPER, 2011).

Nephtys fluviatilis was a frequent species in rivers and beaches, in a medium- and low-impact sector. IndVal showed a higher frequency of the species for beaches in medium-impact sectors. The polychaete *N. fluviatilis* is an active predator of the macro and meiofauna, and an occasional eater of deposits (SILVEIRA; ORTEGA; DUMONT, 2020), usually registered in Pará's estuaries (ROSA FILHO *et al*., 2018; ROSA FILHO; AVIZ, 2013). The distribution of the species in the area reflects its preference for sandy-sandy substrates and the minor ability to colonize sandy substrates with thicker grains, such as impacted beaches.

Tubificidae oligochaetes were also a common component in rivers and beaches, with higher densities in rivers. This result is probably related to higher concentrations of fine grains, which commonly favor populations of those worms (RODRIGUEZ *et al*., 2001). Regarding environmental impacts, oligochaetes had greater participation in the abundance of rivers and beaches in sectors with the greatest impact. Tubificidae is known in literature as a tolerant and opportunistic species, with high densities recorded in places with habitat changes, such as eutrophic water and industrial pollution (ROSENBERG; RESH, 1993). Further efforts are recommended for specific taxonomic identification of the group, which still lacks specialists in the Amazon region.

When comparing polychaetes and oligochaetes, the first group of worms had greater participation in the abundance of rivers and beaches in sectors of greater impact. On the other hand, two other species of

Table 5 – Individual indication value (IndVal) for taxa of benthic macroinvertebrates from Pará River estuary in environments and sectors with different degrees of environmental impact.

Taxa	Indicating valor	p*	Environment (Impact sector)
Namalycastis caetensis	48.3	0.044	River (medium impact)
Cirolana sp.	40.9	0.003	Beach (high impact)
Pseudosphaeroma sp.	29.7	0.008	Beach (high impact)
Hydropsychidae	30.4	0.009	River (low impact)
Nephtys fluviatilis	34.8	0.011	Beach (medium impact)
Namalycastis abiuma	34.5	0.010	River (medium impact)
Eteone sp.	35.1	0.003	Beach (low impact)
Chironominae	30.9	0.021	River (high impact)

*Monte Carlos test.

polychaetes were associated to sectors of medium (*Namalycastis abiuma*) and low impact (*Eteone sp.*). Similarly, Aviz, Carvalho e Rosa Filho (2012), in an Amazon's oligohaline estuary, recorded an increase in the participation of oligochaetes and a decrease in polychaetes in areas impacted by urban effluents.

Insect larvae were highlighted in the fauna structure of rivers and beaches, with different participation according to the order. Chironomidae larvae (Chironominae, Tanypodinae, and Ortocladiinae) were present in all collection stations, with emphasis on areas of high environmental impact. In turn, in the rivers Arapiranga and Arienga, the larvae of Trichoptera and other orders (Odonata, Coleoptera, etc.) were more frequent in more preserved hydrographic units.

Traditionally, Chironomidae is considered a tolerant group, and its dominance, when associated with low diversity and the absence, and/or reduction of sensitive taxa, is a characteristic indication of environments with anthropic impacts (ARIMORO *et al.*, 2018). The group's larvae are, in general, resistant to harsh conditions to other organisms, such as waters with high acidity, high temperatures, and low dissolved oxygen levels. (FERRINGTON JR., 2008; MOLINERI *et al.*, 2019). In turn, Trichoptera larvae are considered indicators of good environmental quality, due to their sensitivity to impacts on water quality (HEPP *et al.*, 2010; CHAGAS *et al.*, 2017). Trichoptera larvae are usually more abundant in smaller rivers, with abundant vegetation and well-oxygenated waters (DE CAÍRES SOUZA; FERREIRA; MORAES, 2020), because they depend heavily on submerged leaf litter for protection, cocoon construction, and/or food. The result is that those organisms are extremely sensitive to soil use in watersheds (LECERF; RICHARDSON, 2010; COUCEIRO *et al.*, 2012).

In addition to conditions of better chemical water quality (COSTA *et al.*, 2016a; 2016b), the presence of organisms that are sensitive to impacts (*e.g.*, the Trichoptera), as well as the greater taxonomic richness of the rivers Arapiranga and Arienga, is related to the degree of preservation of marginal vegetation. Forests are not only habitat for the adult forms of insects, but also provide stability to the soils and produce large amounts of leaf litter, which increases habitat heterogeneity (LECERF; RICHARDSON, 2010; SMETI *et al.*, 2019).

Conclusion

Results indicate that the structure of the benthic macroinvertebrate community in the vicinity of the Industrial Port Complex of Vila do Conde responds to the loss of environmental quality, with events of decrease of abundance and taxonomic diversity. The groups found are typically deposit eaters, opportunistic, and adjusted to the oligohaline nature of the estuary. The low richness of the assemblies and the high dominance of few taxa are characteristics that should be considered in the area's environmental monitoring studies, as well as of another Amazon's estuaries, to differentiate the natural attributes of the macrobenthic assemblies from the effects arising from anthropic impacts. The polychaetae *Namalycastis caetensis, Nephtys fluviatilis, Namalycastis abiuma,* and *Eteone* sp., the crustaceans *Cirolana* sp. and *Pseudosphaeroma* sp., and the larvae of Hydropsychidae and Chironominae were identified as potential bioindicators. Nonetheless, in the view of their wide distribution in the area and low fidelity to the impact conditions, further studies with longer time series should be conducted.

Contribution of authors:

Pinto, A.J.A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Writing — review and editing. Tavares, V.B.C.: Supervision, Project administration. Pinheiro, S.C.C.: Supervision, Project administration. Lima, M.O.: Supervision, Project administration. Aviz, D.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Writing — review and editing. Lima, A.M.M.: Writing — revision and editing.

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ABES

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Fine root contribution to the soil carbon stock of an agroforestry system in a Caatinga-Atlantic Forest transition zone

Contribuição de raízes finas no estoque de carbono do solo de um sistema agroflorestal em zona de transição caatinga-mata atlântica

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ABSTRACT

The objective of this work was to evaluate the distribution of fine roots and its influence on the soil organic carbon stock, at a depth of 20 cm, in a *Grevillea robusta* and *Coffea arabica* agroforestry system. The study was conducted in an agroforestry system established 15 years ago in a transition area of Caatinga and Atlantic Forest biomes in Brazil. *G. robusta* trees representing the most frequent diameter class were selected, and three distances of these trees (0, 0.75 and 1.50 m) and two soil collection depths (0–10 and 10–20 cm) were defined. The root samples were scanned and quantified using a software program. There was a general predominance of roots with a diameter of 0.6 mm at the shortest distance from the surface layer, while there was a predominance of roots with a diameter of 0.4 mm in the 10–20 cm layer. The root carbon stock at a distance of 0.75 m was higher at a depth of 0–10 cm (0.60 Mg ha^{-1}). The soil organic carbon stock also showed higher results in the 0–10 cm layer compared to the 10–20 cm layer, although with significant variation only in the distance of 1.5 m. There was a higher concentration of fine roots in the topsoil, probably influenced by a greater availability of water and nutrients from plant residues. The soil carbon stock is not closely related to root density or root carbon stock. The data presented in this study do not provide a definitive conclusion.

Keywords: *Grevillea robusta*; *Coffea arabica*; root density; root diameter; organic matter.

RESUMO

O objetivo deste trabalho foi avaliar a distribuição de raízes finas e sua influência no estoque de carbono orgânico total do solo, em 20 cm de profundidade, em um sistema agroflorestal de *Grevillea robusta* e *Coffea arabica*. O estudo foi realizado em um sistema agroflorestal estabelecido há 15 anos em uma área de transição dos biomas Caatinga e Mata Atlântica no Brasil. Árvores de *Grevillea robusta* mais representativas da classe de diâmetro de maior frequência foram selecionadas e definidas três distâncias de coleta destas árvores (0, 0,75 e 1,50 m) e duas profundidades do solo (0–10 e 10–20 cm). As raízes presentes nas amostras foram digitalizadas e quantificadas com auxílio de um *software*. Na menor distância da camada superficial houve predomínio de raízes com diâmetro de 0,6 mm, enquanto, em todas as distâncias da camada 10–20 cm, houve dominância de raízes com diâmetro de 0,4 mm. Na distância de 0,75 m, o estoque de carbono das raízes foi superior na profundidade de 0–10 cm (0,60 Mg ha^{-1}). O estoque de carbono orgânico do solo também apresentou maior resultado na camada 0-10 cm em relação à camada 10–20 cm, embora com variação significativa apenas na distância de 1,5 m. Na camada superficial, ocorreu maior concentração de raízes finas, provavelmente influenciada por uma maior disponibilidade de água e nutrientes provenientes dos resíduos vegetais. O estoque de carbono do solo não está intimamente relacionado com a densidade de raízes e estoque de carbono das raízes. Os dados apresentados neste estudo não fornecem uma conclusão definitiva.

Palavras-chave: *Grevillea robusta*; *Coffea arabica*; densidade de raízes; diâmetro de raízes; matéria orgânica.

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Introduction

Agroforestry systems (AFS) are defined as any land use system that implies the deliberate introduction or maintenance of two or more plant species, where at least one of these is arboreal or other perennial species and is associated with agricultural crops, pasture and/or livestock to exploit the ecological and economic interactions of the different components (NAIR; NAIR, 2014). AFS are known for contributing to mitigating greenhouse gases (STOUT; LAL; MONGER, 2016; VICENTE; GAMA-RODRIGUES; GAMA-RODRIGUES, 2016), as they provide environmentally beneficial services and economic advantages to farmers (RODRIGUES *et al*., 2007).

Interspecific competition for water and nutrients between intercropped crops is a variable that interferes in the productivity of AFS. Tree roots can extend into the crop lines in the active crop competition zone, which occurs up to just over 1 m apart, but mainly in the surface layers (THEVATHASAN; GORDON, 2004). Thus, the choice of deeper-rooted tree species in AFS may reduce vertical competition due to their expansion by layers not exploited by crops, promoting better use of the soil profile (PADOVAN *et al*., 2015; BORDEN; THOMAS; ISAAC, 2017). On the other hand, even for deep-rooted species, it is observed that a large volume of roots is present in the surface layers, absorbing nutrients from the mineralization of plant residues. According to Defrenet *et al*. (2016), even though species in AFS exploit different soil niches, coffee roots often dominate the fine root population of the system in surface layers. It is due to higher root biomass in coffee AFS (MEIRELES *et al*., 2019).

The accumulation of organic carbon in the soil in AFS results from added and decomposing plant residues (from shoots and roots) coming from the different species that compose the system (CHATTERJEE *et al*., 2018). It is estimated that the soil organic carbon (SOC) stock in AFS differs across regions of the world and at different soil depths, ranging from 30-300 Mg C ha^{-1} (AGEVI *et al*., 2017).

Roots in general, and in particular fine roots, constitute an important carbon input into the soil (LIAO *et al*., 2014). The degree of fine root carbon (FRC) contribution to SOC depends on land use and management system, which determines the root architecture, cycling rate, root exudates and colonization by mycorrhizae (HERTEL; HARTEVELD; LEUSCHNER, 2009; POLLIERER *et al*., 2012). In addition, root distribution is influenced by edaphic characteristics. For example, Addo-Danso *et al*. (2020) reported a positive relationship between base saturation and specific root length and specific root area. Fine roots also show greater length in tropical sites where available phosphorus in the soil is low. Le Bissonnais *et al*. (2018) evaluated the effect of land use gradients (monocultures to AFS and forest) on soil aggregate stability, which was higher in surface layers than deeper layers. Aggregate stability was the main driver of SOC, cation exchange capacity and root traits.

The quantification of root biomass and its distribution in the soil may help to understand the relationship between root dynamics and SOC stock. Although many studies on this topic have already been performed with tree species, most of them are based on quantifying the total root system biomass, and the number of studies measuring the density of fine roots in different diameter classes is limited. In this work, fine roots were found in the surface layer and directly related to the higher concentration of organic matter and nutrients (WITSCHORECK; SCHUMACHER; CALDEIRA, 2003). Chatterjee *et al*. (2020) also reported that the SOC stock in coffee AFS was increased only to a depth of 10 cm after 17 years of establishment due to shade-pruned *Erytrina spp.*

Given the above, the present study aimed to evaluate the distribution of fine roots and its influence on the SOC stock, at a depth of 20 cm, in a *Grevillea robusta* and *Coffea arabica* agroforestry system. Our study is based on the fact that fine root turnover is the dominant form of below-ground carbon input (UPSON; BURGESS, 2013), with a cycle of less than one year (FREITAS; BARROSO; CARNEIRO, 2008).

Materials and methods

Study site characterization

The study was carried out in an AFS formed by the *G. robusta* A. Cunn. ex. R. Br and *C. arabica* plants planted 15 years ago, spaced 3.5 m (between trees) × 1.5 m (between trees and coffee plants) × 2.5 m (between coffee plants). The area is located in Lucaia District, Planalto municipality, Bahia State (coordinates UTM X: 334277 and Y: 8368812). The AFS was located in an area with pasture naturally formed with predominance of genus *Brachiaria* grass. Other species were not present in the AFS.

The region has an average altitude of 943 m and a tropical altitude climate (Cwb type according to the Köppen classification), with an average temperature of 19.2ºC and rainfall of 641 mm $year^{-1}$ (CLIMATE-DATA, 2012). The study area is located in a transition section between the Caatinga and Atlantic Forest biomes and has soil classified as dystrophic yellow latosol (EMBRAPA, 2013). The chemical characteristics are presented in Table 1.

Fine root and soil collection

We selected six *G robusta* trees in the most frequent diameter measurements at a height of 1.3 m (DBH) (class center = 27.95 cm) to perform the root and soil collection. The DBH measurement distribution for trees considering an amplitude of 6.14 cm is shown in Figure 1. The selection was carried out in a total area of 1.5 ha with 132 *G. robusta* tree/ha and 3530 *C. arabica* plants/ha.

Soil sampling was performed on the *G. robusta* planting line at 0, 0.75 and 1.50 m from the trunk of each selected tree at depths of 0–10

Table 1 – Chemical attributes of soil under a *Grevillea robusta* and *Coffea arabica* agroforestry system.

pH	P	K	Ca	Mg	H + Al
H_2O	mg/dm^3	--------------cmolc/dm^3 -------------			
6.2	41.5	0.5	3.8	2.6	2.7

and 10–20 cm (Figure 2). Two undisturbed soil samples to evaluate fine roots and soil density and one disturbed sample for SOC determination were taken at each distance and depth, making a total of 108 samples. The disturbed samples were taken using a Dutch auger and the undisturbed samples using a cylindrical ring auger. It was not possible to identify the origin of the roots as to whether they came from trees or coffee.

Soil density

Soil density was determined by the volumetric ring method (EMBRAPA, 2017) in samples with preserved structure and known volume (7 cm in height and 7 cm in diameter, totaling 269.3 cm^3 volume).

Fine root mass and diameter

The soil samples were placed in plastic containers and then washed with running water and collected on a 0.25 mm sieve to remove the soil mass to determine the mass and diameter of fine roots (KUMAR; UDAWATTA; ANDERSON, 2010). After washing, all roots were manually clamped and arranged on white-bottomed acrylic slides.

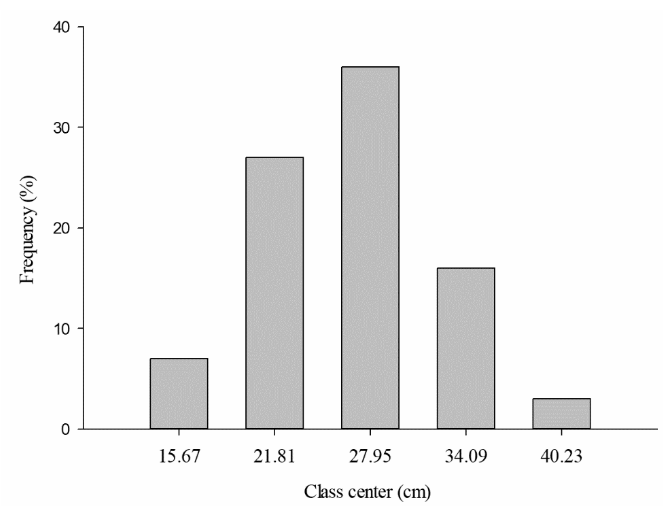

Figure 1 – Frequency histogram of the diameter classes at a height of 1.3 m from the soil of *Grevillea robusta* in an agroforestry system with *Coffea arabica*.

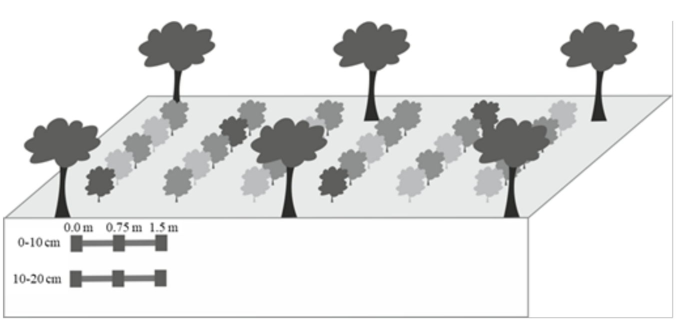

Figure 2 – Representation of soil and fine root sampling points in a *Grevillea robusta* and *Coffea arabica* agroforestry system.

The roots of each sample were scanned (Figure 3) and were distributed in ten root diameter classes (0.45, 0.63 0.81 1.0 1.18, 1.34, 1.52, 1.70, 1.87, 2.05 mm) with the aid of SAFIRA® software (JORGE; RODRIGUES, 2008) for the different studied distances and depths, according to the method described by Costa *et al.* (2014).

After scanning, the root samples were placed in aluminum containers, which were then put in a forced-air oven at 65ºC for 72 hours. The samples were subsequently weighed on an analytical balance accurate to 0.001g to determine dry mass.

Fine root density

Root dry mass was used to determine soil root density by means of Equation 1:

$$D = m/v \quad (1)$$

in which:
D = density in g cm^{-3};
m = root mass in g;
v = ring volume (269.4 cm^3);

Fine root and soil organic carbon stock

Root (after oven drying) and soil (after air drying and 2.0 mm sieving) samples were macerated in a mortar. Next, 0.02 g of roots and 0.2 g of soil subsamples were removed and submitted to chemical analysis to determine carbon content, using the wet oxidation method with $K_2Cr_2O_7$ in acid medium and titration with ammonium ferrous sulfate (EMBRAPA, 2017).

SOC was calculated on the basis of carbon content and soil density according to Equation 2:

$$SOC = T_{SOC}\ (g\ 100\ g^{-1}) \times Ds \times Slt \quad (2)$$

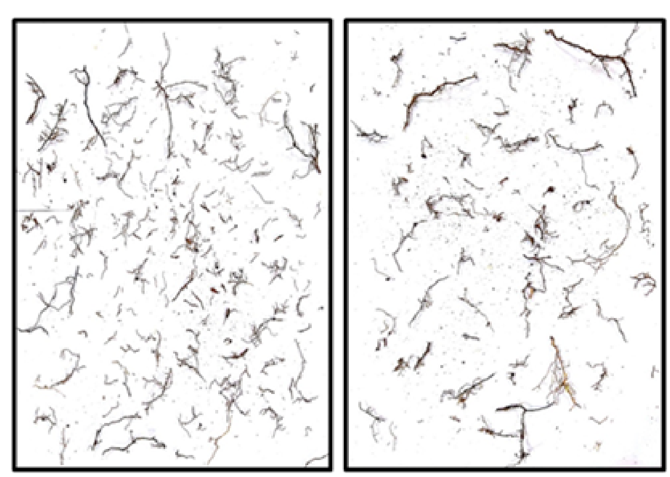

Figure 3 – Scanned images of samples utilized to determine root diameter of *Grevillea robusta* and *Coffea arabica*.

in which:

SOC = soil organic carbon stock in Mg ha^{-1};

T_{SOC} = total soil organic carbon content;

Ds = soil density (g cm^{-3});

Slt = soil layer thickness (cm).

FRC was calculated according to Equation 3:

$$FRC = C_{FRC}\ (g\ 100g^{-1}) \times Dr \times Slt \quad (3)$$

in which:

FRC = fine root carbon stock in Mg ha^{-1};

C_{FRC} = fine root organic carbon content;

Dr = root density (g cm^{-3});

Slt = soil layer thickness (cm).

Statistical analysis

The root density, SOC stock and FRC values met the parametric criteria and were then submitted to analysis of variance (ANOVA) according to a 3 × 2 factorial scheme with 6 replications (3 distances and 2 depths). Student's t-test at 5% significance was adopted to compare means between distances and depths. The analyses were performed using STATISTICA® v.10.0 software (StatSoft Inc., 1984–2011).

A descriptive frequency analysis was performed for mean root diameter values using the SIGMAPLOT® v.12.0 software program (Systat Software inc.) and the contour maps were produced using the Surfer® v.8.0 program, considering a vertical Cartesian plane formed by the spatial distribution of the soil layers and distances of the *G. robusta* trees.

Results

Fine root diameter

Root diameters ranged from 0.4 to 1.6 mm at the depth of 0–10 cm and from 0.45 to 1.34 mm at the depth of 10–20 cm (Figure 4). Roots in classes of 0.63 mm were more frequent at distances of 0 and 0.75 m and 0.45 mm at 1.5 m.

Overall, there was a predominance of roots with a diameter of 0.6 mm in the distances near the trees at the 0–10 cm depth, while there was a predominance of roots with a diameter of 0.4 mm at the distance of 1.5 m at the 0–10 cm depth, and in all distances of the 10–20 cm depth, which represented 60 to 80% of the total roots.

Root density and fine root and soil organic carbon stocks

The interaction between distance and depth produced a significant effect for the variables of root density and SOC and FRC stocks (Table 2). Significance was only observed for depth when evaluating the isolated effect of the considered factors. The results of the distance × depth interaction are presented in Table 3 and Figure 5.

The FRC and SOC stocks did not vary between the different distances studied. In the case of FRC, differences between depths were only found at a distance of 0.75 m, which showed the highest value in the 0–10 cm layer (Table 3). The SOC stock only showed variation between depths at a distance of 1.5 m, with higher results in the surface layer.

Higher root density was observed in the first soil layer (0–10 cm). However, there was only variation between distances at a depth of 10–20 cm (Figure 5). Higher values were observed in the distance 0 m, although only with a significant difference at the distance of 0.75 m.

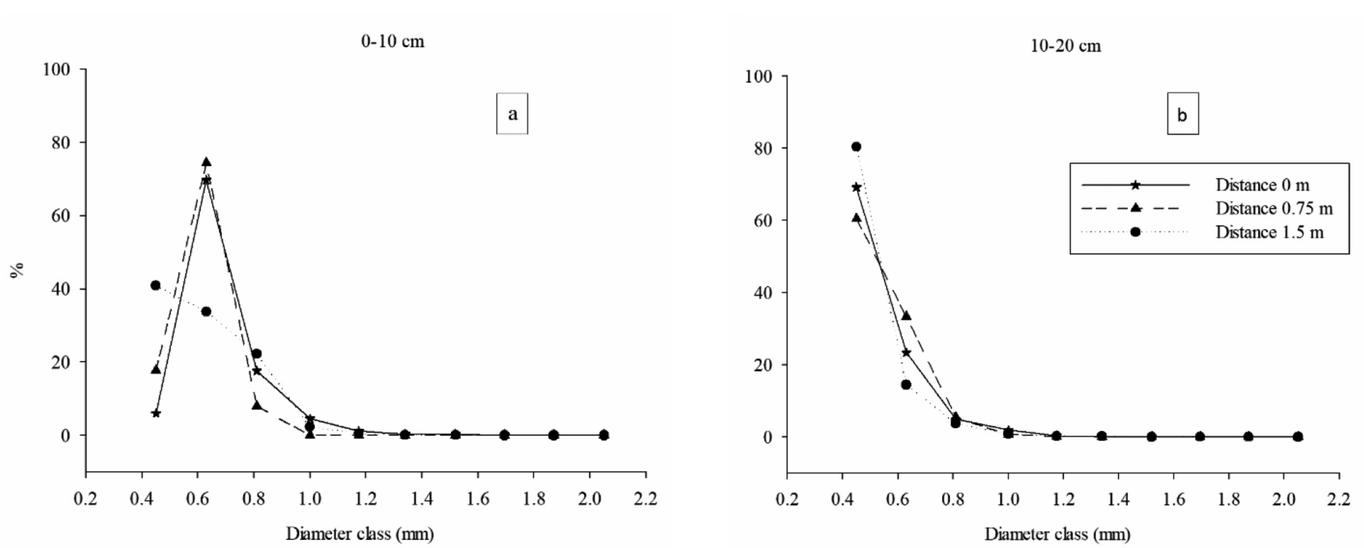

Figure 4 – Root distribution frequencies in diameter classes in the (A) 0–10 cm and (B) 10–20 cm soil layer at different distances of *Grevillea robusta* in an agroforestry system with *Coffea arabica*.

Spatial root distribution influencing soil organic carbon stock

The contours formed by the distribution of root density data and FRC and SOC stocks showed a decrease with increasing depth (Figure 6A, 6B and 6C). This means that higher values are present in the surface layer, with a slight displacement to positions closer to the *G. robusta* tree line. It was noted that the distance influenced the root density contours and consequently the FRC stock. Higher root concentration occurred in the 0-10 cm layer and specifically at a distance of 0 and 0.75 m, decreasing vertically and horizontally moving away from this region.

SOC distribution ranged from 30 to 20 Mg ha^{-1} in depth, and showed higher values according to distance (Figure 6C) in the surface layer at a distance of 1.5 m. On the other hand, lower SOC stock values were found at a distance of 0.75 m (25 Mg ha^{-1}), increasing about 2 Mg ha^{-1} close to the *G. robusta* trees. It was also possible to notice a similar distribution pattern at greater depth for all evaluated indicators.

Discussion

Fine root diameter

The predominance of roots with larger diameter in the 0–10 cm layer (Figure 4) suggests that roots close to *G. robusta* trees are associated with plant support, while the roots at increasing distance from the tree are more associated with absorption and therefore have smaller diameters. Greater amounts of subsurface roots are also associated with nutrient exploitation from plant waste mineralization (ISAAC; BORDEN, 2019). According to Mora-Garcés (2018), the distribution of fine roots generally decreases with increasing soil depth. The roots can be found in a non-standardized grouping concentrated in cracks or animal pits, showing a large amount of short branches (ZONTA *et al.*, 2006). Fine roots in AFS can also be concentrated in locations with a large agglomeration of plant residues, absorbing nutrients directly from the litter after mineralization (THAKUR; KUMAR; KUNHAMU, 2015).

Root density and fine root carbon and soil organic carbon stocks

The highest FRC values observed in the surface soil layers (Table 3) were expected, as they showed higher root concentration (PADOVAN

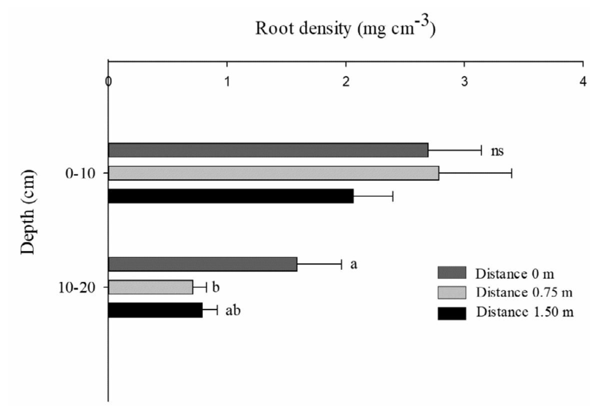

Figure 5 – Root density at three distances of *Grevillea robusta* trees at two soil depths. The same letters, which compare distances at the same depth, indicate no significant difference between values by the t-test at 5% probability*.
ns: not significant; *bars linked to histogram correspond to standard error.

Table 2 – Summary of variance analysis for fine root carbon (FRC) and soil organic carbon (SOC) stocks and root density in *Grevillea robusta* with *Coffea arabica* agroforestry system.

SV	DF	Mean squares		
		FRC	SOC	Root density
Distance	2	0.08^{NS}	10.13^{NS}	1.99E^{-5NS}
Depth	1	0.96*	263.16*	8.05 E^{-7}*
Dist × Dep	2	0.03*	15.08*	8.58 E^{-7}*
Error	30	4.13	41.09	0.85

SV: source of variance; DF: degrees of freedom; Dist: distance; Dep: depth; *significant ($p < 0.05$) by analysis of variance; ^{NS}not significant.

Table 3 – Fine root carbon (FRC) and soil organic carbon (SOC) stocks as a function of different distances and depths in a *Coffea arabica* and *Grevillea robusta* agroforestry system*.

Depth (cm)	FRC (Mg ha^{-1})			SOC (Mg ha^{-1})		
	Distance (m)					
	0	0.75	1.5	0	0.75	1.5
0–10	0.61 A (0.11)	0.60 A (0.09)	0.47 A (0.08)	26.56 A (3.03)	24.83 A (2.25)	28.36 A (1.99)
10–20	0.35 A (0.08)	0.17 B (0.03)	0.16 A (0.03)	22.36 A (4.22)	20.81 A (2.02)	20.36 B (1.00)

*The same letters in the column indicate no significant difference between values by the t-test at 5% probability. Values in parentheses represent the standard error of the mean, n = 6.

et al., 2015; ALBUQUERQUE *et al.*, 2015). This results from the greater contact of the litter (leaves, branches and bark) with the soil, which promotes greater nutrient flow in the surface layer, stimulates the development of proteoid roots and the accumulation of carbon in the soil after its turnover (PULROLNIK *et al.*, 2009). Morais *et al.* (2017) found that carbon stored in fine roots is more concentrated in the topsoil (0–10 cm). The authors also observed that fine roots store 40% more carbon than thick and medium roots in this layer.

The absence of a difference in FRC stock at distances of 0 and 1.5 m (Table 3) suggested unevenness in *G. robusta* root development. Thus, it is likely that horizontal variability in fine root distribution is being more influenced by soil resource availability than by root architecture of the species in question. In studying the distribution of *G. robusta* roots in AFS, Smith *et al.* (1999) observed great unevenness in the distribution of fine roots and argued that the root distribution complementarity of the different components in the AFS may be compromised by restrictions in the availability of water and nutrients for the tree component, which results in increased competition (BALJIT; PARAMPARDEEP; GILL, 2016).

The reduction in root concentration with increasing depth (Figure 5) can be attributed to the large amount of litter found in AFSs, which contributes to the development of fine roots in the topsoil and in the organic layer itself. Similar results were obtained by Defrenet *et al.* (2016) in evaluating the biomass and root dynamics of AFSs based on coffee planted in Costa Rica, finding higher amounts of fine roots in surface soil (12% of total roots). Fine root biomass was also twofold higher in the row compared with between rows.

The litter acts as a mulch, protecting the surface soil and providing nutrients. Freitas, Barroso and Carneiro (2008) point out that the growth of fine roots (≤ 2 mm) has a strong correlation with the availability of organic matter and soil moisture, being closely associated with litter, since it is a carbon source and favors water retention.

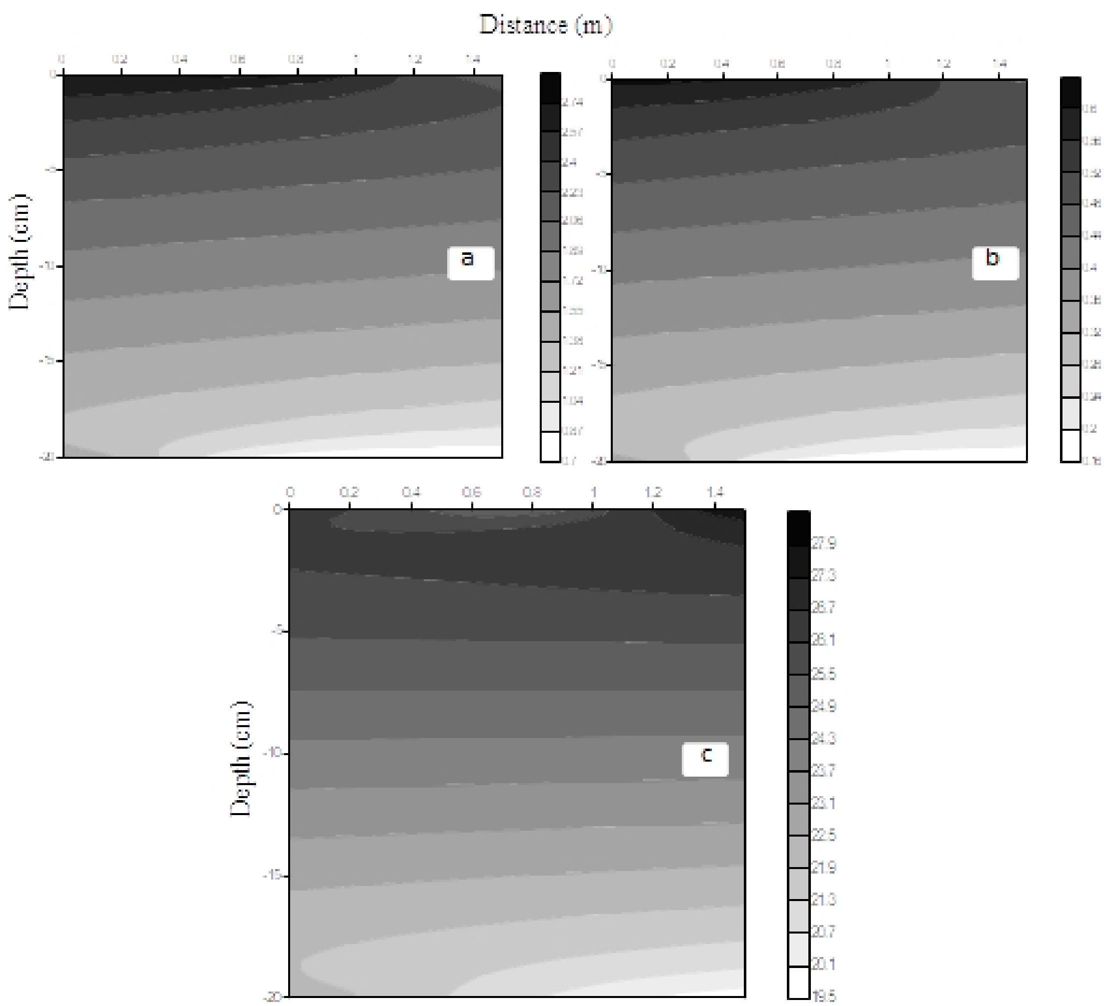

Figure 6 – Spatial distribution (A) of root density and (B) fine root carbon (FRC) and (C) soil organic carbon (SOC) stocks at different distances of *Grevillea robusta* trees associated with *Coffea arabica*.

Spatial root distribution influencing soil organic carbon stock

The results obtained did not allow us to determine the origin of the evaluated roots (of *C. arabica* or *G. robusta*), which would indicate which species would predominantly be contributing to the carbon accumulation in the soil, since the roots of *C. arabica* can develop in the middle of the *G. robusta* lines and vice versa. Some mechanisms (still little known) may alter the root growth of the intercropped crop in an AFS. For example, Livsley, Gregory and Buresh (2000) reported that corn crops showed a greater amount of fine roots and root length in an AFS with *Grevillea* sp. when compared to a monoculture. A similar pattern was observed by Duan *et al.* (2019) for oat roots, which were influenced by the presence of walnut, which caused increased root length and decreased root diameter.

Regardless of the soil carbon origin, considering the components present in the AFS, it was observed that the FRC stock had little influence on the SOC stock. On the one hand, the SOC stock did not follow a similar distribution as FRC stock in the 0–10 cm layer, on the other hand there was a high correlation between SOC stock, root density and FRC stock in the 10–20 cm layer (Figure 6). This indicated that the carbon accumulation in the 0–10 cm layer depended on more litter contribution than only the carbon originating from the fine root turnover, as in natural systems of Brazilian biomes (OZÓRIO *et al*., 2019). The influence of the FRC stock in the 10–20 cm layer was high due to a decreasing carbon incorporation rate from the surface to the deeper layer (CHATTERJEE *et al*., 2020). AFS are known to have complex relations between species which results in a heterogeneous environment, especially in the soil-plant transition.

AFSs also help to maintain the natural physical properties of the soil, especially because soil tillage is usually only done in pre-planting (FALCÃO *et al*., 2020). The conservationist character of AFS assists in natural root turnover, without harming the soil carbon accumulation.

Conclusion

There is a higher concentration of fine roots in the topsoil which decreases with increasing depth. The root density shows a homogeneous horizontal distribution from the base of *G. robusta*, probably being more influenced by litter and edaphic characteristics than by the fine roots. The SOC stock is not closely related to root density or root carbon stock. The data presented in this study do not provide a definitive conclusion. Thus, more investigations focusing on identifying the fine root origin of the different species in the AFS are necessary, including deeper layers (up to 100 cm) and evaluating other edaphic characteristics.

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Contribution of authors:

Monroe, P.H.M.: Writing – original draft, Formal analysis, Investigation, Methodology. Barreto-Garcia, P.A.B.: Supervision, Methodology, Writing – review & editing. Lima, M.C.D.: Formal analysis, Writing – review & editing. Santos, R.K.A.: Formal analysis, Writing – review & editing. Oliveira, E.P.: Formal analysis, Writing – review & editing. Silva, S.R.: Formal analysis, Writing – review & editing. Gama, D.C.: Formal analysis, Writing – review.

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Toxicological and ecotoxicological aspects of tartrazine yellow food dye: a literature review

Aspectos toxicológicos e ecotoxicológicos do azocorante alimentar amarelo tartrazina: uma revisão de literatura

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ABSTRACT

The use of the tartrazine yellow additive in food products for human consumption is permitted within the acceptable daily intake of 7.5 mg/kg of body weight per day (following the Joint Expert Committee on Food Additives standards). However, studies have described this as a toxic component. The dye, which is intensively used in the industry and commerce, enters the aquatic environment through releases of non-treated or inadequately treated effluents; however, further ecotoxicological research is needed. We addressed studies reporting the toxic effects of the exposure to this dye developed in humans, guinea pigs, and *Danio rerio* (a fish with molecular bases and genomes similar to humans). Based on this review, the doses allowed for acceptable daily intake, or even lower, toxic effects, can be evidenced for different organisms, life stages, and tested times. The reported values may not be protective to aquatic life. In a paper about the exposure of *D. rerio* from embryos to larvae kept at values lower than 0.05 and 0.5 $g.L^{-1}$ for pure and commercial tartrazine, there was ecotoxicological effect for embryos and larvae 48 hours after hatching, which implied cardiac edema, changes in the yolk sac, scoliosis, and tail distortions.

Keywords: CENO; food additive; environmental legislation; *Danio rerio*; mutagenicity.

RESUMO

O uso do aditivo amarelo tartrazina é legalizado para aplicação em produtos alimentícios para consumo humano dentro do valor de ingestão diária aceitável (IDA) de 7,5 mg/kg de peso corpóreo por dia (seguindo os padrões da *Joint Expert Commitee on Food Additives*). No entanto, estudos descrevem este aditivo como tóxico. O corante, usado intensamente na indústria e no comércio, adentra o ambiente aquático por meio de lançamentos de efluentes sem tratamentos ou tratados inadequadamente; no entanto, novas pesquisas ecotoxicológicas são necessárias. Portanto, esta pesquisa elencou estudos cujos efeitos tóxicos da exposição ao referido corante se desenvolveram em seres humanos, cobaias e *Danio rerio* (peixe com bases moleculares e genoma similares aos humanos). Concluímos, de acordo com a literatura, que mesmo em doses permitidas para a IDA, ou até menores, há evidências de efeitos tóxicos para diferentes organismos, fases de vida e tempos testados. Os valores relatados podem não ser protetivos à vida aquática. Em um trabalho de exposição de *D. rerio*, desde embriões até larvas, mantidos em concentrações de 0,05 e 0,5 $g.L^{-1}$ para tartrazina pura e comercial, observou-se que, na menor concentração, houve efeito ecotoxicológico em embriões e em larvas após 48 horas da eclosão, que implicou em edema cardíaco, alterações no saco vitelínico, escoliose e distorções na cauda.

Palavras-chave: CENO; aditivo alimentar; legislação ambiental; *Danio rerio*; mutagenicidade.

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Introduction

Colors fascinate human perception. In food, they are related to health and taste. Although these additives do not add nutritional value to the food, their use is intended, among other purposes, to intensify the natural color and extend their shelf life (FREITAS, 2012; ANASTÁCIO *et al.*, 2016). The most used dyes include those from the azo group (-N = N-), due to their high solubility, low cost, and better fixation on food. This group represents more than 65% of the commercial dyes (ZANONI; YAMANA, 2017). In Brazil, 11 artificial organic dyes are allowed, of which six are azos: tartrazine yellow, twilight yellow, amaranth, azorubin, ponceau 4R, and red 40.

The application of these additives to food must not exceed the maximum quantity allowed by the legislation: 0.5 g.1000 mL) (Resolutions 382, 383, 385, 388 e 389 – BRASIL, 1999a; 1999b; 1999c; 1999d; 1999e). However, quantitative analyzes of dye intake by the population require the identification of food products with additives in the consumer's diet, the estimation of additive concentration in these products, and the daily consumption knowledge, which should not exceed the acceptable daily intake (following the Joint Expert Committee on Food Additives – JECFA). For the tartrazine yellow dye, which is one of the most used in the food industry, the acceptable daily intake is 7.5 mg.kg of body weight per day, which would not cause health risks.

Morais (2010) studied individuals prone to allergic rhinitis, bronchial asthma, urticaria, or sensitivity to non-steroidal anti-inflammatory drugs, providing them acceptable daily intake doses of tartrazine yellow dye for seven days. The investigator observed that these individuals had a significant reduction in the peak of expiratory flow and presented angioedema, nasal congestion, rhinorrhea, wheezing, itchy skin, and urticaria, corroborating the data obtained by Doguc *et al.* (2013), Khayyat *et al.* (2017), and Bhatt *et al.* (2018).

Corder and Buckley (1995) proved in clinical respiratory studies that patients sensitive to tartrazine developed bronchoconstriction with consequent decrease in the respiratory volume. There is a group of people whose sensitivity to this dye is manifested as asthma, urticaria, and hypersensitivity to tartrazine, which occurs in approximately 3% of the population, mainly in individuals sensitive to salicylates. As the chemical structure is close to that of benzoates, salicylates, and indomethacin, allergic cross-reactions may occur. (POLÔNIO; PERES, 2009). Matsuo *et al.* (2013) analyzed the effect of tartrazine on histamine release (a hormone responsible for several allergic symptoms) in basophils (important cells of the immune system) of individuals that had chronic allergy-related conditions, such as urticaria.

Tartrazine has also been associated with behavioral changes, such as attention deficit and hyperactivity. Baterman *et al.* (2004) applied dye mixtures in the presence of sodium benzoate, in a double-blind experimental study using placebo in children at preschool age, and demonstrated that artificial dyes have a relevant influence on the hyperactive behavior of children aged about three years old.

Al-Shabib *et al.* (2017) showed that tartrazine can cause amorphous aggregation of proteins in the cationic form, which is known to cause various diseases and metabolic irregularities. Sasaki *et al.* (2002) proved the occurrence of DNA damages in mice colon in a comet assay at doses of 10 mg.kg.pc.day (mg per kilogram of body weight per day). They concluded that the azo dye, when ingested, is absorbed by the intestinal epithelium and metabolized by azo reductases elaborated by microorganisms from the intestinal flora and by hepatic reductases, which convert it into aromatic amines.

As toxicological effects were detected in humans and guinea pigs, it is likely that its release in water bodies can interfere with aquatic biota. Some papers were performed with the *D. rerio* organism, a model organism widely used in various biological, biomedical, toxicological, and ecotoxicological research, due to its 70% genetic homology with humans and to the advantages provided by its transparent embryos that permit detailed analyses of its development. These studies showed that the dye is harmful to embryos and larvae, for which development was negatively affected (JOSHI; KATTI, 2017; GUPTA *et al.*, 2019; JIANG *et al.*, 2020; SILVA; FRACÁCIO, 2020).

Despite the existence of maximum acceptable limits for daily human intake in national and international laws, there is still no specific legislation regarding the safe limits of food dyes for the discharge of effluents into water bodies aiming at aquatic life protection. Studies have indicated that approximately 12% of the synthetic dyes are lost during manufacturing and processing operations (ANUNCIAÇÃO *et al.*, 2015), which is one of the industrial sectors with increasing development. In 2019, according to the Brazilian Food Industry Association (ABIA), there was a 2.3% growth with revenues of approximately $ 700 billion.

Currently, in the state of São Paulo, regulation 333/2012 prohibits the release of dyes in rivers, lakes, dams, and other freshwater bodies without proper treatment. It includes the dyes as contaminating substances that, thus, contribute to a greater control over water quality and public health (ALSP – regulation 333/2012).

According to those pieces of information, the present paper intends, through literature data, to evaluate whether the conditions and limits of use established for the tartrazine yellow dye are safe for aquatic environments. Therefore, we intend to answer:

- the relationship between the human use of this dye and the impact on aquatic environments;
- safe exposure concentrations in the literature for aquatic life protection that can be used as a basis;
- main biological effects to test organisms.

This review aimed to contribute to further clarification on the interactions between tartrazine yellow food coloring and humans, as well as between tartrazine and aquatic life.

Methodology

A review was carried out using the PubMed database (National Library of Medicine of the United States) and CAPES journals (Coordination for the Improvement of Higher Education Personnel), in the period from 2010 to 2020. We were interested in the effects of tartrazine on both humans and aquatic life. The keywords "toxicity" and "tartrazine food" were used for analyzing their impacts on humans, whereas for aquatic life, we applied: "ecotoxicology", "tartrazine food", "ecotoxicology", "tartrazine dye" and "ecotoxicology", "tartrazine dye", "zebrafish". The searches returned 235 papers, of which only four were on aquatic life. The 231 papers on humans were analyzed to investigate selection criteria and were eliminated if they:

- dealt only with dye degradation;
- analyzed other dyes simultaneously, which could imply in synergistic processes;
- used food to analyze the toxicity (this is because foods rarely contain only one color and many foods contain other forms of additives that would require further study);
- toxicity was not significant or doubtful.

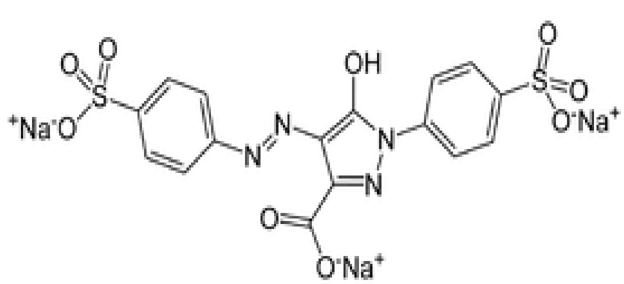
Composition and chemical structure of the tartrazine yellow dye

Tartrazine yellow is a regulated artificial organic dye used by several industrial segments. It is prepared from diazotization of 4 – amino – benzene acid with nitric acid and sodium nitrite. The diazo compound is coupled with 4,5-dihydro-5-oxo-1-(4-sulfophenyl)-1H-pyrazole-3-carboxylic acid, methyl ester, ethyl ester or a salt of carboxylic acid, which is isolated and purified as the sodium or calcium salt (FOOD AND DRUG ADMINISTRATION, 2019). As the main non-colored component, it is possible to find sodium chloride and/or sodium sulfate in its composition.

The purity degree of the dye should not be less than 85% in its total color components (calculated as sodium salt), and the remaining 15% could be composed of sodium chloride or sodium sulfate (which is never explicitly mentioned by the FDA, 2019). The water-insoluble matter must not exceed 0.2% and the subsidiary coloring, no more than 1.0% with 0.5% of organic compounds (hydrazobenzene 4-aminobenzene-1-sulfonic acid, 5-oxo-1-(4-sulphophenyl)-2-pyrazoline-3-carboxylic acid, 4,4′ -diazoaminobenzene (benzene sulfonic acid), tetrahydroxy succinic acid). Non-sulfonated primary aromatic amines can be present at levels of ≤0.01% (calculated as aniline), which were originated in the manufacturing process.

In the manufacturing process of the dye, impurities can reach 10% in the final compound (RESENDE, 2015) and many of them are metals, 4-aminobiphenyl, 4-aminoazobezene (sulfanilic acid) and benzidine (aromatic amine, formed by the oxidation of aniline). In the process of benzidine diazotization, a small part remains as free bendizine, but the majority remains in the form of subsidiary dyes, such as the diazo benzidine T-pyrazolone dye (Figure 1). According to Prival, Peiperl and Bell (1993) and Davis and Bailey Jr. (1993), if these compounds are present in the dye and mammals consume it, they will be reduced in the intestine, releasing benzidine in its free form. Compounds like benzidine are considered mutagenic and/or carcinogenic, since the electrolytes interact with DNA through their metabolism and induce mutations or generate tumors (MATHUR; BHATNAGAR; SHARMA, 2012).

The high solubility of this dye is due to the azo bond to two sulfonic groups, in addition to the functional carboxylic acid group (AL-SHABIB *et al*., 2017). They have a high standard of fixation, resistance to light and humidity, and pH and oxygen variations (HUNGER, 2003; SHORE, 2002; ZOLLINGER, 1991). The dye can be identified through ultraviolet–visible spectrophotometry (UV-Vis), with a wavelength close to 426 nm (PARLAMENTO EUROPEU, 1995). This characteristic occurs due to the presence of chromophores, carboxylic, nitro, hydroxy and amino groups that can increase the specific absorption intensity (DEL GIOVINE; BOCCA, 2003) (Figure 1).



Usual name: Tartrazine yellow.	
Chemical Name: Trisodium salt 4,5-dihydro-5-oxo-1 (4-sulfophenyl) -4-[4-sulfophenyl-azo] -1H-pyrazol-3-carboxylate.	
Synonyms: Tartrazine; FD & C Yellow No. 5, Food Yellow No.4. Class: Monoazo.	
Molecular Formula: C16H9N4Na3O = S2.	
Molar Mass: 534, 35781. CAS: 1934-21-0.	
Number Color Index: (C.I.) 19140.	
Maximum Absorption λ max. = 426nm.	
Solubility in water: 38 mg / L at 2°C, 200 mg / L at 25°C. LD 50 - 2,000 mg / kg, in mice (at this dosage, research has shown genotoxic damage).	

Figure 1 – Structure of the tartrazine yellow azo dye.
Source: Prado and Godoy (2003) and Cosmoquímica Indústria e Comércio LTDA (2009).

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Regulations on the use of tartrazine yellow dye

Human food

In 1943, the United Nations Conference on Agriculture and Food created the United Nations Food and Agriculture Organization (FAO). In 1948, it formed the first group of experts with responsibilities on human health to establish food standards, the FAO/World Health Organization – WHO, which promoted the creation of the JECFA in 1956 to:

- assess the risks of consumption by animals and humans;
- assign functional classes;
- check the identity and purity specifications;
- evaluate methods of analyses and develop standards or codes, such as labeling.

In 1961, the FAO and WHO created the *Codex Alimentarius* (CA) in an attempt to establish an international standard for the use of these additives. CA also resulted in the formation of the Codex Committee on Food Additives (CCFA), a group specialized only in food additives that establishes the maximum permitted levels of these products and acts together with the JECFA.

In 1989, CA from the FAO/WHO created the International Numbering System (INS), with the purpose of providing an international numbering system for identifying additives in lists of food ingredients and for using the specific name of the additive (name of color index – CI), based on the identification number (CI). The INS does not require toxicological approval of the substance.

In 2001, the European Food Safety Authority (EFSA) was created, providing independent scientific advice on the food-related risks, which can be existent or still emerging.

The JECFA guides the FAO and WHO on the use of food dyes, and this committee meets every two years to assess, among other demands concerning food, food additives.

In Brazil, the National Health Surveillance Agency (ANVISA) is the agency responsible for regulating the use of dyes, based on the principles of risk analyses of EFSA. ANVISA establishes the maximum limits and types of foods in which dyes can be applied without offering risk to human health. The organization also carries out surveillance activities through the Standing Committee on Food Additives – CPAA (FÁVERO; RIBEIRO; AQUINO, 2011).

In 1999, ANVISA, through Resolutions 382 (BRASIL, 1999a) to 389 (BRASIL, 1999e) of 5 August, determined the permission of only 11 artificial colors in Brazil, including the tartrazine yellow dye, which must, mandatorily, have its name declared in full on the labels of the products (Resolution No. 340 of 12/13/2002 — ANVISA/Brazilian Department of Health). The additive is listed in Appendix III of Resolution 04/88 from the National Health Council, Brazilian Department of health (BRASIL, 1988), which allows its use in food following the acceptable daily intake of 7.5 mg/kg per body weight (JECFA). Therefore, a 30-kg child can consume up to 225 mg of tartrazine per day and a 60-kg adult can consume up to 450 mg per day of the dye without a probable health risk.

In 2009, ANVISA adapted the Mercosur Group Technical Resolution GMC n. 11/2006 on food additives within the scope of Mercosur (BRASIL, 2009).

ANVISA, through Resolution No. 285/2019 (BRASIL, 2019) on May 22, 2019, prohibited the use of food additives containing tartrazine and aluminum lacquer. Lacquers are preparations of salt from the dye (Resolution No. 37 of 1977 — BRASIL, 1977). It is a combination with the basic radical of aluminum, calcium and/or sodium, which can be sold under the name aluminum, calcium and/or sodium lacquer. They are used on confectionery surfaces, processed cheeses, melted cheeses, soups, chemical yeast present in flours, pastries and pizza doughs, as well as bread and cookies, among many other food products.

Regulation for discharge of effluents with dyes

Synthetic dyes are added in the category of emerging pollutants, which are defined as any chemical substance that has not been included in monitoring programs, nor in legislation relevant to environmental quality, but is constantly being introduced into the environment due to anthropic activities (HORVAT *et al*., 2012).

Synthetic organic dyes, most of which are recalcitrant, are used universally in different manufacturing processes. The dyes are released into the environment in industrial effluents and are highly visible even at low concentrations (< 1 mg/L) (ALMEIDA *et al*., 2004).

The determination of color in liquid samples is based on the methodology proposed in the Standard Methods by the American Water Works Association (AWWA, 2005), whose principle is the determination of the color spectrophotometrically in a wavelength range between 450 and 465 nm, using a standard solution of platinum-cobalt (Pt-Co). However, effluents whose colorations of the samples are very intense, hinder the satisfactory application of the method, and in practice, they are diluted to samples with strong colors so that they can be measured on the curve scale standard of 0.005 and 0.8% of absorbance of light at predefined wavelengths – Abs (AWWA, 2005). In addition, different dyes with equal concentrations can visually present different color intensities or even completely different shades (BELTRAME, 2006).

As to Brazil, there is still no specific legislation that defines color standards for effluents. However, in CONAMA 357/2005 (BRASIL, 2005), on articles 15-III and 16-I, it is understood that, in the absence of defined standards, one should adopt those available for the class in which the receiving bodies are included. Thus, for freshwater bodies classified as Classes 2 and 3, the tolerable value of real or true color would be up to 75 mg Pt/L (platinum scale per liter). CONAMA 430/11, in its article 18, shows that effluents of any nature should not have the potential to cause toxicity in the aquatic biota.

Tartrazine toxicity

Toxicity assessment by the Joint Expert Committee on Food Additives Commission

The tartrazine yellow dye was first evaluated in 1966 by JECFA experts in food additives, and later in 1975 and 1984 by the Scientific Committee for Food (SCF), when the value of the IDA was set at 7.5 mg/kg/pc/day for humans. In a more recent meeting (WHO, 2017), the committee reassessed this value, analyzing some research produced in recent years.

The committee considered that toxicological research in recent years is insufficient to alter the value of the IDA, considering that tartrazine is not highly toxic. The analyses considered three studies as a toxicity parameter: Sasaki *et al.* (2002), who described an LD50 value greater than 2,000 mg/kg/pc/day in studies with mice; Borzelleca and Hallagan (1988a), performed with mice for 104 weeks, in which the unobserved adverse effect level (NOAEL) of 9735 mg/kg/pc/day was established, and Borzelleca and Hallagan (1988b), with rats at maximum exposure of 125 weeks, in which the NOAEL of 2,641 and 3,348 mg/kg/day were established.

A study by Axon *et al.* (2012) concluded that the dye can act as an activator of estrogen receptors (xenoestrogen), increasing the risk of primary biliary complications and cirrhosis in postmenopausal women. However, according to the committee's evaluation, it is unlikely that cosumption could reach the levels of exposure (220 and 160 nM) used in the research.

Research by Patterson and Butler (1982) reported significant increase in chromosomal aberrations in fibroblastic cells of *Muntiacus muntjak* in vitro (5 to 20 μg/mL), but it did not report cytotoxicity.

Maekawa *et al.* (1987) studied concentrations of 0, 1 or 2% administered in rats that were statistically significant, presenting mesothelioma in the abdominal cavity in males and stromal polyps of the endometrium in females, but the incidence of these tumors was not dose-dependent and was within the historical control range for these tumors and within this strain of mice.

Mpountoukas *et al.* (2010) studied human peripheral blood cells in concentrations of 0.02 and 8 mM and did not find genotoxicity, but there was cytotoxicity (which can cause cell death) in high concentrations (4.0 and 8.0 mM), and the dye also demonstrated ability to bind to DNA.

Tartrazine would have the ability to bind to human and bovine serum albumin, forming a complex with these proteins, potentially limiting their physiology and function (PAN *et al.*, 2011). However, it is poorly absorbed, and this effect would probably not have an important role; only in case of greater exposure or association with other dyes or drugs capable of binding to plasma or proteins.

Toxicity research in rats showed significant changes in some blood parameters that indicate liver and kidney malfunction (ABOEL-ZAHAB *et al.*, 1997; MOUTINHO; BERTGES; ASSIS, 2007; AMIN; HAMEID II; ELSTTAR, 2010; EL-WAHAB; MORAM, 2013; GHONIMI; ELBAZ, 2015). However, the daily intake of 8,103 and 9,735 mg/kg/day in males and females, respectively, for 104 weeks, resulted in no adverse effects (BORZELLECA; HALLAGAN, 1988b).

Another issue raised by the commission was the difficulties in the toxicity analyses of the tartrazine dye when studied in mixture with other dyes (GIRI *et al.*, 1990; POLLOCK; WARNER, 1990; COLLINS *et al.*, 1990; 1992; ABOEL-ZAHAB *et al.*, 1997; SASAKI *et al.*, 2002; MCCANN *et al.*, 2007; ELHKIM *et al.*, 2007; AXON *et al.*, 2012; EL-WAHAB; MORAM, 2013; CEYHAN *et al.*, 2013; SAXENA; SHARMA, 2014; 2015; ERICKSON; FALKENBERG; METZ, 2014), due to the interactions that can occur between chemical substances.

The committee criticized the relevance of some in vitro genotoxicity tests because the azo linkage and desulfonation in the tested metabolic products were not broken. They have also noted that the potential for tartrazine to cause mutations is in occasional cases, which, if present, would be directed to cells lining the intestine during the transit of metabolites before excretion in feces. The committee cites a personalized protocol for the reverse mutation assay, using flavin mononucleotides to accelerate azo-reduction in hamsters, with a lesser tendency to inactivate azo-reduction products, which produced negative results (PRIVAL; MITCHELL, 1982; PRIVAL *et al.*, 1988).

In assessing the reproductive parameters and offspring development, the Committee's report cites again the paper of Borzelleca and Hallagan (1988a; 1988b). It concluded that the administration of 2,641 and 3,348 mg/kg/pc/day did not affect the reproduction of rats. Tanaka (2006) also found no neurotoxic effects after providing doses of 83, 259, and 773 mg/kg/day during five to nine weeks to F0 and F1 rat lineages.

Neurological studies, in juvenile mice and rats that received tartrazine orally at doses of up to 700 mg/kg/pc/day for 30 days, revealed some neurobehavioral and neurochemical effects (GAO *et al.*, 2011). The committee, however, noted that only a small number of animals per group/dose was used and in very high doses, which prevented the use of these studies for evaluation. Ceyhan *et al.* (2013) administered tartrazine with an IDA dye mixture (7.5 mg/kg/pc/day) in female rats, before and during pregnancy, but no effects on reproductive parameters were observed.

Collins *et al.* (1990; 1992) administered doses of 60, 100, 200, 400, 600, and 1,000 mg/kg/pc/day in pregnant rats from 0 to 19 days of gestation, but no maternal toxicity or dose-related effects prevented fetal development. Subsequently, the dye was administered to rats throughout the gestational phase in doses of 0.5; 0.1; 0.2; 0.4; 0.7% diluted in drinking water and 67.4; 131.8; 292.4; 567.9 and 1064.3 mg/kg/pc/day in food, and there were also no changes in viability, size, weight, or teratogenic effects on fetal development.

In humans, many reports concluded that the tartrazine yellow dye causes intolerance or hypersensitivity reactions. However, the reports analyzed by the committee were of foods consumed by the population, which rarely contain only the dye, but a mixture of dyes. In the study carried out by Elhkim *et al.* (2007), these symptoms were observed in only 0.12% of the analyzed population, which was considered poorly relevant by the committee.

Based on studies associating the consumption of food and drinks containing tartrazine with hyperactivity in children (POLLOCK; WARNER, 1990; BATEMAN *et al.*, 2004; MCCANN *et al.*, 2007; STEVENSON *et al.*, 2010), the committee warned about the presence of the substance sodium benzoate in these products. However, these studies were considered limited due to inconsistencies in the conclusions and use of mixtures of food dyes.

JECFA (WHO, 2017) gathered studies on the exposure to food with tartrazine carried out in the European Union (EFSA, 2009); United States (DOELL *et al.*, 2015; IACM, 2015); Australia (FSANZ, 2012); France (ELHKIM *et al.*, 2007); Ireland (CONNOLLY *et al.*, 2010); Hong Kong (LOK *et al.*, 2010); India (DIXIT *et al.*, 2011); Indonesia (FIRDAUS; ANDARWULAN; HARIYADI, 2011), and South Korea (SUH; CHOI, 2012; HA *et al.*, 2013). These studies were performed using various concentrations and followed the dietary culture of each country. EFSA concluded that the maximum exposure for children aged 1 to 10 years should be 0.4 to 7.3 mg/kg/day, and exposure to tartrazine by the population, in general, does not present a health concern.

Evaluation of tartrazine ecotoxicity

Dyes have a high organic load that, in many cases, depletes dissolved oxygen and causes changes in the biological community. Its presence in water bodies affects from microalgae, which are the base of the aquatic food chain, to the top trophic level, humans. The accumulation of algae can cause eutrophication, a phenomenon that occurs when the environment receives higher concentrations of nutrients, mainly nitrogen (present in the chemical constitution of azo dyes such as nitrogen, nitrites, and nitrates), and excessive increases in algae and cyanobacteria may release toxins (MATSUZAKI; MUCCI; ROCHA, 2004).

There is little ecotoxicological research with the tartrazine yellow dye, except for those by Joshi and Katti (2017) that present values of CENO and CL50, and Jiang *et al.* (2020) that present LC50 values for the species *D. rerio*. In this context, Silva and Fracácio (2020) studied the development of *D. rerio* embryos and larvae in concentrations of 0.05 and 0.5 $g.L^{-1}$ of analytican tartrazine (100%), and commercial standard of 86% and at a concentration of 0.05 $mg.L^{-1}$. They observed loss of viability of the eggs after 24 hours of fertilization, and from 48 to 72 hpf there were no hatching and deformities, such as edema of the yolk sac, cardiac edema, distortion of the tail, lack of pigmentation and decreased heart rate, indicating ecotoxicity at the said concentrations. This paper shows ecotoxicological effects in concentrations below those presented by other papers available in the literature.

Results

Analyses of toxicological literature

After the application of the manuscript selection criteria, 29 articles were considered, in which four of them were on ecotoxicology.

The biggest concern regarding the use of tartrazine azo dye is its reduction to aromatic amines (DEMIRKOL; ZHANG; ERCAL, 2012). This mechanism is responsible for several disorders, such as anemia, pathological lesions in the brain, liver, kidney and spleen, in addition to allergic reactions, tumors, and cancer. Changes in serum albumin in humans also compromise biological functions (PAN *et al.*, 2011). In molecular toxicology studies, tartrazine has bound to the central hemoglobin cavity (BASU; KUMAR, 2016a).

Liver enzymes increased in rats administered with tartrazine, suggesting lesions and impairment of liver cells, cytoplasm, and mitochondrial organelles (AMIN; HAMEID II; ELSTTAR, 2010; HIMRI *et al.*, 2011; KHAYYAT *et al.*, 2017).

In reproductions, tartrazine induced a marked deficiency in antioxidant biomarkers (SOD, catalase and GSH) in groups of young male rats (MOHAMED; GALAL; ELEWA, 2015). Tartrazine also induced adverse effects on the memory and learning of rats (GAO *et al.*, 2011), hyperactivity, antisocial behavior, and anxiety in male rats (KAMEL; EL-LETHEY, 2011).

The largest number of studies regarding dye toxicity was carried out with rats (13 papers); cellular components or blood of human beings (four papers); mice (three papers); hamster (one paper) and others such as *Allium cepa*, calves, and horses (four papers covering these groups), as seen in Table 1.

Ecotoxicological analyses

In the bibliographic survey we found papers with the fish *D. rerio* exposed in different phases to varied concentrations of the tartrazine yellow dye. Joshi and Katti (2017) found a value of the unobserved effect concentration (CENO) and lethal concentration (CL (I) 50, 96 h) of 5 (2.67 gL^{-1}) and 29.4 mM, respectively (15.7 gL^{-1}). Jiang *et al.* (2020) found the CL (I) 50, 96 h value of 47.10 mM (25.1 $g.L^{-1}$). Of these papers, those of Gupta *et al.* (2019) and Silva and Fracácio (2020) described deformities that were found in the embryonic and larval development of *D. rerio*, suggesting that the tartrazine dye, once released into the aquatic environment, compromises aquatic life (Table 2).

Discussion

According to the literature, the tartrazine yellow dye can cause toxicity to humans in dosages considered safe, in periods of prolonged exposure. Dosages below that recommended for IDA demonstrated the ability to damage liver and kidney tissues in fetuses, in addition to other changes described (Table 1), depending on the time of exposure.

The reduction of dye into aromatic amines and benzene compounds in the digestive system of rats can trigger anemia, pathological lesions in the brain, liver, kidney and spleen, in addition to aller-

Table 1 – Research carried out in the last ten years with the tartrazine yellow dye that resulted in toxicity.

Author (s)	Objectives	Dose	Conclusions
Amin, Hameid II and Elsttar (2010)	To evaluate the toxic effects of tartrazine dye, using biomarkers of oxidative stress in the kidney and liver of rats.	15 and 500 mg/ kg/pc/day, in rats (*Rattus norvegicus*) for 30 days.	• Blood and enzymatic changes • Significant weight loss • Reduction of liver antioxidants • Increased oxidative stress • Decreased activity of superoxide dismutase (a cellular antioxidant enzyme).
Morais (2010)	To evaluate the toxic effects of tartrazine dye in people with respiratory problems and sensitivity to non-steroidal anti-inflammatory drugs.	Doses of 5, 10, and 20 mg of the additive in 77 subjects for seven days.	• Reduction in peak expiratory flow; itchy skin and hives; • Immune system reactions affecting the skin and airways.
Mpountoukas *et al.* (2010)	To evaluate the toxic effects of tartrazine dye in human peripheral blood cells with the dye.	0.02 to 8.0 mM (0.01 and 4.27 g.L-1) in vitro peripheral blood cells (for 72 hours).	• The dye changed the rates of mitotic division at high concentrations (4.0 and 8.0 mM); • High cytotoxicity (that can cause cell death); • The dye also demonstrated its ability to bind to DNA.
Gao *et al.* (2011)	To evaluate the toxic effect of tartrazine on learning and memory functions in mice and rats.	Kun ming mice and Sprague dawley 175, 350 and rats 700 mg/kg of tartrazine by body weight once daily for 30 days per gavage.	• Oxidative damage to the brain; • Decline in catalase, glutathione activities; peroxidase (GSH-Px) and superoxide dismutase (SOD); • Increase in the level of malonaldehyde (MDA), which resulted in adverse effects on learning and memory functions that can be attributed to the increase in lipid peroxidation products and reactive oxygen species, inhibiting antioxidant defense enzymes.
Kamel and El-Lethey (2011)	To address the influence of different doses of tartrazine exposure to levels of hyperactivity, anxiety, depression, and antisocial behaviors in rats.	0, 1 and 2.5% administered to male Wistar rats for 16 weeks.	• Tartrazine-treated rats showed hyperactivity; • The anxiogenic effect of tartrazine was evident; • Ingestion of tartrazine promoted significant depression, expressed by prolonged immobilization during forced swim test; • Compromised social interaction.
Kashanian and Zeidali (2011)	To address DNA interactions of the cells of a calf's thymus and its interaction with tartrazine.	10 nM of the dye	• The DNA – tartrazine interaction affected the helical structure of the DNA, in addition to showing an easier connection between tartrazine and denatured DNA. The DNA bound to the dye underwent changes.
Pan *et al.* (2011)	To test the molecular link between plasma albumin and tartrazine.	Human albumin and bovine albumin at concentrations of 5.0 x 10^{-5} $mol.L^{-1}$ and tartrazine at concentrations of 1.0 x 10^{-5} $mol.L^{-1}$.	• Tartrazine can bind to albumin spontaneously and form a complex, with Van der Walls bonds and hydrogen bonds; • Tartrazine alters the conformation of the protein.
Himri *et al.* (2011)	To address oral toxicity in Wistar rats.	7.5; 10 mg /kg/pc/day with 3.75 mg/kg/pc/ day of sulphanilic acid.	• Liver increased by 10 mg/kg/pc/day; • Changes in the kidneys; • In high doses, tartrazine can induce oxidative stress through the formation of free radicals.
Demirkol, Zhang and Ercal (2012)	To evaluate changes in oxidative stress parameters, such as glutathione (GSH), malondialdehyde (MDA), glutathione peroxidase. Activity (GPx) and catalase (CAT) in hamster ovary cells.	Chinese hamster cells (CHO) (10 x 10^3 cells) exposed in tartrazine concentrations of 10, 100, 500, 1,000, 2,000 µM (5.34; 53, 43; 267.15; 534.3; 1068 $g.L^{-1}$ – 3, 8, 12 and 24 h).	• Depletion of GSH (one of the main antioxidant cells), causing oxidative stress (that plays an important role in sclerosis, chronic lung disorders, paralysis, rheumatoid arthritis, age-related degenerations, and Alzheimer's disease).
Gomes *et al.* (2013)	To address cytotoxic effect of tartrazine on the cell cycle of *Allium cepa L.*	0.4 and 4.0 mL in Allium cepa L roots, in 24- and 48-hour exposures.	• Mitotic analyzes of the doses and exposure times evaluated were cytotoxic to the cells.

Continue...

Table 1 – Continuation

Author (s)	Objectives	Dose	Conclusions
Ghonimi and Elbaz (2015)	To evaluate histological changes in selected tissues of Wistar rats after ingestion of tartrazine with a protective effect of royal jelly and cod liver oil.	Adult Wistar rats administered at doses of 500 and 300 mg/kg/pc/day + royal jelly of 0.4 mg/kg/pc/day + cod liver.	• At 500 mg/kg/pc/day, necrosis of liver tissues; hyperplasia of interstitial connective tissue; vacuolations in brain tissues; degenerative changes in the stomach mucosa; degeneration in the renal tubules; • The curative protective effect of royal jelly and cod liver was not significant against the toxicity of tartrazine.
Mohamed, Galal and Elewa (2015)	To evaluate the possible neurotoxic effect of tartrazine, as well as to determine the potential modulating role of cod liver oil and royal jelly in protecting against dye.	Evaluate rat pups in five different groups: a) 300 mg/kg/pc/day + royal jelly; b) 0.4 mL/kg/pc/day + cod liver oil; c) 500 mg/kg/pc/day of tartrazine; d) 500 mg/ kg/pc/day + royal jelly; e) 500 mg/kg/pc /day + cod liver oil.	• Significant decrease in the concentration of brain neurotransmitters, • Marked scarcity in the level of antioxidant biomarkers; • These parameters were more recovered in the tartrazine groups with royal jelly and tartrazine with cod liver oil, which provided sufficient protection against the effects of tartrazine on function and structure of the puppies' brain tissue.
Soares et al. (2015)	To evaluate the potential effects of cytotoxicity, genotoxicity on DNA.	Human lymphocytes exposed to 0.25 – 64.0 mM dye (0.13 – 34.19 $g.L^{-1}$).	• Tartrazine did not show cytotoxicity; however it showed genotoxicity.
Basu and Kumar (2016)	To test interaction of tartrazine with human hemoglobin.	Hemoglobin concentration determined through a molar absorption coefficient of 1.79.000 $M\text{-}1cm^{-1}$ at 405 nm, where the tartrazine solution was injected.	• The dye significantly interfered with the helical stability of hemoglobin and probably the absorption of tartrazine and its metabolites in the blood plasma affected the function of hemoglobin, compromising its activity.
El Golli *et al.* (2016)	To evaluate the toxic potential of food tartrazine in different tissues of adult rats: blood, liver, kidneys, and spleen.	Tartrazine was administered orally at a dose of 300 mg/kg/pc/day in adult male Wistar rats over a period of 30 days.	• Increase in platelets, reduction in peripheral lymphocytes and TCD8 lymphocytes of the spleen; • Increased activities of hepatocellular enzymes that promoted changes in renal biomarkers; • Critical oxidative changes in all organs; • Enzymatic changes.
Al-Shabib *et al.* (2017)	To study of the interaction of tartrazine with myoglobin protein at two different pH levels.	Equine myoglobin was prepared in 20 mM and tartrazine in concentrations of 0.0 to 10.0 mM. (5.34 $g.L^{-1}$).	• The anionic sulfate group of tartrazine electrostatically interacted with myoglobin cationic amino acid residues leading to aggregation.
Khayyat *et al.* (2017)	To address the effects on hepatic-renal function, also genotoxicity in white blood cells, through the comet assay.	7.5 mg/kg/pc/day in Wistar rats for 30 days.	• Increased level of ALT, AST, ALP, urea, uric acid, creatinine; • Decrease in the total antioxidant level; • Damage to DNA in leukocytes.
Meyer *et al.* (2017)	To study the transcriptional function of the human estrogen alpha receptor in an in vitro cell model.	Transgenic mice administered at doses 50 mg/kg/pc/day.	• Increased serum alkaline phosphatase activity and mild periportal fibrosis; • Sulphotransferase in the excretion of bile acids caused periportal inflammation and liver pathology.
Abo-El-Sooud et al. (2018)	To evaluate the daily administration of dye in hepato-renal and DNA changes in rats.	Administered orally to rats, 10 times the acceptable daily dose (IDA) for 60 days.	• Significant increases in the DNA nucleus; • Histopathology of the liver and kidneys showed destructive and degenerative changes that can cause genotoxicity and hepato-nephropathy.
Bhatt *et al.* (2018)	To test the effect of the dye on the neuro-biochemistry network of Wistar rats.	7.5 mg/kg by body weight through gavage for 40 consecutive days.	• Decreased activity of Superoxide Dismutase (SOD), Catalase (CAT), considering that there was a decline in Glutathione-Stransferase (GST) Glutathione Reductase (GR); • Levels of ADI in the dye affect and alter biochemical markers of brain tissues and cause oxidative damage.

Continue...

Table 1 – Continuation

Author (s)	Objectives	Dose	Conclusions
Floriano *et al.* (2018)	To evaluate the cytotoxicity and genotoxicity of tartrazine in human leukocyte culture.	Concentrations of 5, 17.5, 35, 70, 100, 200, 300, 400, and 500 μg mL^{-1} in leukocyte cultures.	• At a concentration of 70 μg mL^{-1}, the dye induced DNA damage.
Abd-Elhakim *et al.* (2019)	To study the fibrogenic fibers of rats triggered by tartrazine, through tests with dye and chlorophyll.	The rats were administered ten times the acceptable daily intake of tartrazine or chlorophyll for 90 consecutive days.	• Increase in mRNA and immunohistochemical localization of renal fibrotic markers and liver collagen; • Differences in AST, ALP, creatinine, and urea levels; • Decline in SOD, CAT and GSH enzymes in kidney and liver.
Hashem *et al.* (2019)	To determine the effect of tartrazine dye on fetal development.	Daily administration of 0.45 and 4.5 mg/kg/pc/day tartrazine, in the fetal development of Wistar rats from the 6^{th} to the 15^{th} day of gestation.	• Liver damage; • Destroyed and necrotic renal tubules; • Absent coccygeal vertebrae; • Absence of hind limbs; • Irregular ribs.
El-Sakhawy, Mohamed and Ahmed (2019)	To evaluate the histological and immunohistochemical evaluation of tartrazine in the cerebellum, submandibular glands, and kidneys in rats.	Adult male albino rats received doses of 7.5; 15 and 100 mg/kg/pc/ day.	• Kidneys with interstitial hemorrhage and dilation of the glomerular capillaries; • Collecting tubules in the medulla with flattened epithelial cells; • Severities were higher with increasing doses.
Albasher *et al.* (2020)	To evaluate perinatal exposure of the dye in doses within the IDA range in mice, with an emphasis on neuro behavioral changes and redox imbalance.	Pregnant female mice received tartrazine; after birth, at 21 and 35 days, the mice were sacrificed and histological analyzes were performed.	• Lipid peroxidation and decreased antioxidants in different regions of the newborn's brain; • Increased hemoglobin, erythrocytes, leukocytes, and platelets; • Altered locomotor behavior as a reflex of anxiety; • Oxidative stress.

gic reactions, tumor, and cancer. Changes in serum albumin cause decreased production and malabsorption of proteins, cirrhosis, and higher liver enzymes, which compromise cells and the work of mitochondria, leading to an imbalance of oxidative stress and presence of free radicals that cause cytogenicity. The dye was able to interact with DNA, triggering mutations.

Ingestion of the dye also worsens symptoms in patients with allergic reactions, bronchial asthma, hives, and behavioral changes such as attention deficit and hyperactivity in children. Tartrazine also induced adverse effects on memory, learning and behavioral changes in rats and fish.

Research with *D. rerio* has shown that the additive alters physiological functions, not only by ingestion, but also at constant exposures, as is the case in aquatic environments. Regarding the ecotoxicity of the tartrazine yellow dye, data from Joshi and Katti (2017) indicated a CENO value of 5 mM, equivalent to a concentration of 2.67 g/L-1, in seven-day tests with *D. rerio* embryos. However, it is worth mentioning that the eggs of this species present the chorion, an acellular membrane that surrounds the embryo until the moment of its hatching, which occurs at 72 hpf (hours after fertilization). This structure has pores between 0.5 and 0.7 mm in diameter and, in this way, partially isolates the embryo from the environment (MEDEIROS *et al.*, 2017). Therefore, for this value to be considered safe, other stages of the species' development must be tested. The literature also reports that the chorion can be impervious to a good number of pollutants; however, studies have proven that the tartrazine yellow dye has overcome this protective barrier (JOSHI; KATTI, 2017; GUPTA *et al.*, 2019; SILVA; FRACÁCIO, 2020), and the dye also accelerated the embryo hatch rates (from 72 hpf to 48 hpf).

In the absence of CENO, literature recommends using the lethal concentration value to 50% of the exposed population, at a given exposure time, and dividing it by 10, as estimated safety values. Thus, the estimated CENO values would be 2.94 and 4.71 mM, corresponding to 1.57 and 2.51 $g.L^{-1}$ respectively, which is close to the reported CENO values. However, data obtained by Silva and Fracácio (2020) show that in low concentrations, compared to the values reported, there was toxicity to larvae in 48 hours after hatching at a concentration of 0.05 $g.L^{-1}$.

The concern with aquatic life protection lies in the fact that the dye can reach surface waters through large-scale production, with an

Table 2 – Ecotoxicological research carried out in the last ten years with the tartrazine yellow dye that resulted in toxicity.

Author (s)	Objectives	Concentrations	Conclusions
Joshi and Katti (2017)	To evaluate embryological development of *Danio rerio*, exposed to the tartrazine dye.	Concentrations of 0.1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 75 and 100 mM (0.053; 0.53; 1.06; 1.60; 2.13; 2.67; 5.34; 10.68; 16.03; 21.37; 26.71; 40.07 and 53.43 $g.L^{-1}$) in the gastrulation stage (5.25 hours after fertilization (hpf). Observation until the seventh day. SCENE = 5 mM (2.67 $g.L^{-1}$) CL (I) 50, 96h = 29.4 mM (15.7 $g.L^{-1}$)	• 20 to 30 mM caused tail flexion, and edema of the cardiac sac in 50% of the larvae; • At 30 to 50 mM, heartbeat declined along with tail flexion deformities, edema of the cardiac sac, causing mortality within 96 to 144 hpf; • Development has completely stopped at 75 to 100 mM concentration.
Linskens (2018)	To evaluate learning, cognitive flexibility, and the memory of adults of *D. rerio*, exposed to the dye in labyrinth tests, with different exposure times.	Concentration of 22 µM (11.75 $g.L^{-1}$) of the dye throughout its life stage (eggs to adulthood) and *D. rerio* eggs subjected to the dye and removed from the dye after 24 hours after fertilization.	• Lack of understanding and cognitive flexibility; • Exposed for 24 hpf, problems in completing the memory tasks; • Constant exposure to dye will affect the ability to learn, remember and reduce the body's cognitive flexibility, even if only exposed to an embryonic level.
Gupta *et al.* (2019)	To compare oxidative stress in embryonic phases of *D. rerio*	96 hpf embryos exposed to 0.1% tartrazine in 100 µL with the superoxide dismutase enzyme (SOD).	• Accelerated the hatch rate; • During the initial development it induces the expression of superoxide dismutase 1, inducing oxidative stress pathways; • The embryo's sensitivity to exposure resulted in significant mortality in a concentration-dependent manner, especially at higher concentrations.
Jiang *et al.* (2020)	Evaluation of *D. rerio* embrio-larval toxicity when exposed tartrazine dye	*D. rerio* subjected to a concentration of 5 to 50 mM. (2.67 $g.L^{-1}$ to 26.71 $g.L^{-1}$) LC50 = 47.10 mM (25.16 $g.L^{-1}$)	• Difficulty in hatching and developmental abnormalities, such as cardiac edema, decreased heart rate, yolk sac and spinal edema; • Scoliosis and tail distortion.
Silva and Fracácio (2020)	Evaluation of toxicity in embryos and larvae of *D. rerio* when exposed tartrazine dye	*D. rerio* subjected to concentrations of 0.05 $g.L^{-1}$ in two dye patterns (Commercial and Pure) and in concentration of 0.5 $g.L^{-1}$ of pure standard	• Coagulation in the embryos; • Deformities in the larvae such as edema (cardiac and yolk sac); • Scoliosis and tail distortion

interaction between the consumption of these industrialized foods and the quality of aquatic ecosystems – a challenge for the coming years (TEIXEIRA; PORTO, 2008). Conventional effluent treatment systems cannot effectively degrade this type of dye due to its high stability, resistance to light, and moderate oxidizing agents. Many companies, due to the peculiar characteristics of their products, dilute the dyes to cause less color impact on the environment. The dye use should be limited to the smallest amount as possible to achieve the desired effect and only when there is no other alternative, considering the lack of adequate legislation and impacts they cause to the environment and human health.

Conclusions

- Tartrazine yellow food dye is toxic even at the dose indicated for acceptable daily intake for humans. In this sense, the laws that regulate the use of the additive in food should consider the new research on the molecular interactions of the dye with animal cells to review the doses considered safe;
- There is a direct relationship between the production and use of these dyes and aquatic ecotoxicity, through the release of effluents generated in water bodies. Without adequate treatments, these chemical compounds and their by-products cause risks to biota;
- The tartrazine yellow dye crosses the protective barrier of the chorion in *D. rerio* embryos and accelerates reproduction. However, studies with other stages of the life cycle of the referred species and with other species of different trophic levels are recommended;
- The Regulation 333/2012 of the state of São Paulo should serve as a model for other areas of the national territory, and greater attention should be given to the launch of food dyes, since the azocores are freely purchased and used commercially in the food industry. This economic sector is still in need of effective regulation and implies in environmental damage and risks to human health.

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Contribution of authors:

Silva, J.: conceptualization, methodology, validation, formal analysis, investigation, writing — original draft. Fracácio, R.: resources, data curation, writing — review & editing, funding acquisition.

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ABES

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Application of machine learning algorithms to $PM_{2.5}$ concentration analysis in the state of São Paulo, Brazil

Aplicação de algoritmos de aprendizado de máquina à análise de concentrações de $MP_{2,5}$ no Estado de São Paulo, Brasil

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ABSTRACT

Air quality monitoring data are useful in different areas of research and have varied applications, especially with a focus on the relationship between air pollution, respiratory problems, and other health hazards. The main atmospheric pollutants are: ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter (PM). PM is one of the main objects of study when one intends to protect people from exposure to pollutants. This study contributes to the analysis of $PM_{2.5}$ in 21 stations in the state of São Paulo monitored by the Environmental Company of São Paulo State (CETESB). It employs cluster analysis, a prominent data mining method for detecting patterns and discovering similarities which is important for assessing air pollution, especially in a geographically vast area such as that of the state of São Paulo, which does not follow a single pattern. Another data mining technique (association rules) supports the analysis of the relationship between pollutants and meteorological variables, as it allows identifying changes between elements that occur together, in a wide variety of data. Our objectives include determining stations with similar behaviors and exploring the temporal variety of the pollutant as it relates to the dominant meteorological factors in the periods of high concentration. The clustering algorithm automatically separates stations according to their monthly averages of $PM_{2.5}$ concentration between 2017 and 2019. The clusters of stations that showed the highest pollution rates essentially included urban centers with emissions by industries and vehicles, while those with the lowest rates were located further inland. A cyclical behavior in pollutant variation was also observed in the three years under study and for both clusters. For the months with the highest concentration of $PM_{2.5}$, association rule learning was applied to connect air temperature, relative humidity, and wind speed with $PM_{2.5}$ and carbon monoxide (CO) concentrations. The obtained results are useful to analyze the temporal and geolocation profiles of pollution by particulate matter, since they identify the behavior of the meteorological factors that predominate in periods of greater concentration.

Keywords: air pollutants; particulate matter; clustering; association rules; air quality; respiratory diseases.

RESUMO

Dados de monitoramento da qualidade do ar são úteis em diferentes áreas de pesquisa e aplicações, como por exemplo, no estudo da relação da poluição do ar com problemas respiratórios e outros prejuízos à saúde. Dentre os principais poluentes atmosféricos estão: ozônio (O3), dióxido de enxofre (SO2), monóxido de carbono (CO), dióxido de nitrogênio (NO2) e material particulado (MP). O MP é um dos principais objetos de estudos quando se pretende proteger as pessoas da exposição a poluentes. O presente trabalho contribui com a análise da concentração do poluente MP2,5, em 21 estações de monitoramento, observadas pela CETESB - Companhia Ambiental do Estado de São Paulo. Este estudo emprega mineração de dados por agrupamento, um método proeminente para reconhecer padrões e descobrir semelhanças, aspectos importantes para avaliar a poluição do ar, principalmente em uma área geograficamente vasta como o estado de São Paulo, que não segue um único padrão. A técnica de mineração por regras de associação, também aplicada, oferece suporte na análise da relação de poluentes com variáveis meteorológicas, por permitir identificar associações entre elementos que ocorrem juntos, em uma grande variedade de dados. Os objetivos incluem identificar estações com comportamentos semelhantes e explorar a variedade temporal do poluente relacionada aos fatores meteorológicos dominantes nos períodos de alta concentração. O algoritmo de agrupamento, separa de forma automática as estações a partir de médias mensais de concentração de MP2,5 nos anos de 2017 a 2019. Os grupos de estações com maiores índices encontrados do poluente foram os centros urbanos, com emissões por indústrias e veículos e, as estações com índices menores foram as localizadas mais ao interior do estado. Também houve a identificação de um ciclo sazonal nas variações do poluente nos três anos para os dois grupos. Para os meses de maior concentração de MP2,5 a técnica de regras de associação foi aplicada a fim de relacionar temperatura do ar, umidade relativa do ar e velocidade do vento, às concentrações dos poluentes MP2,5 e CO. Os resultados gerados são úteis na análise do perfil temporal e por geolocalização da poluição por material particulado e identifica o comportamento dos fatores meteorológicos que predominam nos períodos de maior concentração.

Palavras-chave: poluentes atmosféricos; agrupamentos; regras de associação; qualidade do ar; doenças respiratórias.

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Introduction

In the world population, nine out of 10 people breathe polluted air, according to the annual report of the World Health Organization (WHO). Every year, seven million people die worldwide by causes directly related to air pollution, but contamination levels remain high (WHO, 2019).

According to the Environmental Company of São Paulo State (CETESB, 2019), the main air pollutants regulated by the National Environment Council (CONAMA) are: coarse inhalable particles (PM_{10}), fine inhalable particles ($PM_{2.5}$), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), total suspended particles (TSP), smoke (SMO), and lead (Pb), the latter three being monitored only in specific situations. Studies on the effects of pollution on health (POLEZER *et al.*, 2018; MACHIN; NASCIMENTO, 2018; SEINFELD; PANDIS, 2016; NODARI; SALDANHA, 2016) show that exposure to fine particulate matter ($PM_{2.5}$) can cause respiratory problems and even premature deaths, since it penetrates deeply into the respiratory system, reaching the pulmonary alveoli and the bloodstream.

Because it is associated with damage to human health and has impacts on climate and the environment, $PM_{2.5}$ was chosen as the study object in this research. PM are particles suspended in the atmosphere, solid or liquid, which can be generated by several sources, in different sizes and compositions (DIMITRIOU, 2016; ANDRADE *et al.*, 2012; QUALAR, 2019). It is classified by its aerodynamic diameter (a_d): particles with $a_d \leq 2.5$ μm are named $PM_{2.5}$ (fine inhalable particulate matter) and those with $10 \geq a_d > 2.5$ μm, as PM_{10} (coarse inhalable particulate matter). These pollutants can come from several sources, such as vehicles, industries, power plants, and fires in general. Despite the PM origin, it may be transported by air masses between cities, by atmospheric circulation (NOGAROTTO, 2019).

Meteorological variables directly interfere with the concentration of atmospheric pollutants by controlling the dispersion process of substances that are toxic and carcinogenic or that potentiate harmful effects on the environment and health (YANAGI; ASSUNÇÃO; BARROZO, 2012). The relationship between pollutant concentration and meteorological variables such as: air temperature (TEMP), relative humidity (RH), wind speed (WS), wind direction (WD), precipitation (PRE), atmospheric instability, and others that vary during the year is well known (GUERRA; MIRANDA, 2011). Given this relationship, studies such as the one by Bisht and Seeja (2018), in India, predict next-day air quality from the previous day's pollutant concentration data (PM_{10}, $PM_{2.5}$, NO_2, CO, and O_3) and meteorological variables (RH, PRE, TEMP, WS, and WD), using regression models. Gonçalves *et al.* (2005), in a research study in the city of São Paulo, proved that during summer, hot and humid days favor the decrease of PM_{10}, SO_2, and O_3 concentrations.

In winter, air quality worsens, especially regarding PM and CO concentrations, since weather conditions in this season of the year are less favorable for their dispersion (SANTOS; CARVALHO; REBOITA, 2016; MORAES *et al.*, 2019; CETESB, 2019). Therefore, the interaction between atmospheric conditions and sources of pollution defines air quality, which in turn determines the emergence of adverse effects on people's health.

A study by Abe and Miraglia (2018) shows a reduction of about 25.45% in $PM_{2.5}$ concentration in the city of São Paulo from 2000 to 2011, due to actions to contain the increase in the automotive fleet. Typically, in metropolitan regions, motor vehicles are a major cause of air pollution. A study by Andrade *et al.* (2012) states that vehicle emissions, biomass burning, and fuel combustion in industries explain at least 40% of $PM_{2.5}$ in six Brazilian states, including São Paulo.

In addition to associating air pollutants with meteorological variables, it is also possible to establish a relation between the behaviors of different air pollutants. Moisan, Herrera and Clements (2018) reported an association between car pollution and firewood burning as regards CO concentration in the atmosphere, noting that 54% of $PM_{2.5}$ concentration is composed of CO, which shows a direct relationship between these pollutants. They also found a strong negative correlation with the variables TEMP and WS, in addition to a positive relationship with RH. Saide *et al.* (2011) developed a CO forecasting system as a substitute for PM_{10} and $PM_{2.5}$, identifying a high correlation (of above 0.95) between these pollutants in Santiago (Chile), during winter nights. Therefore, by predicting CO, an estimate of PM could be obtained. The greatest benefit of the study was its ability to predict critical episodes up to 48 hours ahead. Reinhardt, Ottmar and Castilla (2011) observed that, in Brazil, the concentration levels of CO and particulate matter are correlated and that, during the burning season, CO levels in rural areas are comparable to those of urban centers, moderately polluted.

Considering this scenario, it is important to investigate the behavior of pollutants, in particular $PM_{2.5}$. Despite the fact that the problem is widely discussed in various spheres of the scientific community, the literature lacks studies whose assessment uses artificial intelligence techniques and involves knowledge about the associations between pollutants, emission sources, and their effects on air quality (AMEER *et al.*, 2019). The analysis of the sources of pollution by $PM_{2.5}$ throughout the state of São Paulo is considered a zoning problem, zoning being the discovery of different regions with similar characteristics. Data clustering technique is a prominent method for recognizing new patterns, and it is applied in exploratory data analysis. It is a suitable solution when searching for similar patterns and behaviors in different regions, which leads to the discovery of previously unknown clusters (HAN; KAMBER; PEI, 2011; KWEDLO, 2011).

Research carried out in Brazil (NODARI; SALDANHA, 2016; GUIDETTI; PEREDA, 2018) and in other countries which applied clustering techniques identified regions with similar patterns of air pollution. A study in China (XIAO *et al.*, 2020) performed cluster analysis to measure similarities in the characteristics of industrial emissions from 31 companies in different regions; results showed that pollution characteristics were similar for companies in the same cluster, which contributed to the development of specific measures for pollution control. Also in China, studies involving 13 sites with similar $PM_{2.5}$ concentration data resulted in the discovery of three clusters: two of industrial activities and another of agricultural and tourist activities (HUANG *et al.*, 2015).

In the United States, a research study clustered locations according to $PM_{2.5}$ levels and obtained clusters by regions with similar industrial activity (AUSTIN *et al.*, 2013). The study by Zou *et al.* (2014), conducted with data from the U.S. urban census, was used to investigate the population's exposure to air pollution, considering age, race, education level, and income. By applying a spatial clustering method, it was possible to show disparities in the spatial distribution of exposure to pollution throughout the territory.

Alternatively, clustering technique is also used as a preprocessing step for selecting attributes or applying other data mining algorithms. An example is the study by Du and Varde (2016), which applies association rules, clustering, and classification to identify relationships between particulate matter, pollution, and road traffic.

Another way to extract knowledge is by discovering relationships between different attributes in the database; the association rule algorithm has been efficient in this sense, given its applicability in several scenarios, such as the context of air pollution (NEIROTTI *et al.*, 2014; AGRAWAL; SRIKANT, 1994). Association rules also contribute to discovering unexpected rules with a high degree of interest in the context in which they are inserted. In our study, association rules looked for relationships between the behavior of $PM_{2.5}$ and meteorological variables, in the different clusters identified in the clustering step. They also attempted to verify whether $PM_{2.5}$ and CO were related.

Li *et al.* (2020) proposed, by using association rules, the analysis of data from various air monitoring stations in China and micro stations in the USA, considering the uneven distribution of environmental monitoring data and the characteristics of climate change, and obtained a correlation between pollutants which provides support for the treatment and prevention of air pollution. Souza and Rabelo (2016) applied association rules to identify a set of variables that often occur together: air pollutant concentrations and rates of respiratory problems. Sadat, Karimipour and Sadat (2014) explored, by association rules, the effect of air pollution on asthmatic allergies, indicating that distance from parks and roads, as well as pollutant concentrations of CO, PM_{10}, $PM_{2.5}$, and NO_2, are related to the prevalence of allergies in the most polluted month of the year, while SO_2 and O_3 have no effect on it.

This article proposes a data mining approach to analyze the air quality monitoring database provided by CETESB, between 2017 and 2019. Such analysis was carried out by applying machine learning techniques on two fronts:

- using the partitional clustering algorithm (K-medoids) to form clusters, based on the $PM_{2.5}$ concentrations of 21 stations in the state of São Paulo;
- applying the association rules algorithm (Apriori) to discover possible associations between meteorological variables that affect the increase in $PM_{2.5}$ concentration and investigate the seasonal relationship between $PM_{2.5}$ and CO.

These studies can generate knowledge that contributes to the management of air quality and provides information for an assessment of its impact on health and the environment.

Methods

The methodology used in this study will be presented as follows:

- a presentation of the places where the air pollution data were collected and how they were preprocessed so as to be used by machine learning algorithms;
- an explanation of clustering algorithms and association rules, as well as their respective validation metrics.

Study site

Diagnosis of air quality in the state of São Paulo is made by the network of monitoring stations of CETESB, which informs pollution concentrations, generating an air quality index that ranges between good, moderate, bad, very bad, and terrible. These scenarios are important in reporting the compliance with air quality standards set by law and making it possible to determine when these levels represent significant risks to human health.

Assessment is carried out based on the state's air quality standards (Table 1) established by State Decree no. 59,113 (SÃO PAULO, 2013) and by CONAMA Resolution no. 491 (BRAZIL, 2018). The national and state standards, both for air quality and critical episodes, are virtually the same.

Both the CONAMA Resolution and the State Decree define intermediate targets (IT) so that air pollution is gradually reduced based on the guidelines proposed by WHO. It can be observed (Table 1) that national values are well above the international quality standard.

To analyze the behavior of $PM_{2.5}$ in different areas of the state of São Paulo, we obtained data from all cities that have stations with pollutant monitoring. Altogether, there are 21 stations, listed in Table 2 along with their geolocation (Figure 1).

Database and preprocessing

The first database was obtained from the CETESB website, by the Air Quality platform (QUALAR, 2019), which contains data collected by automatic monitoring stations. Data on monthly average $PM_{2.5}$ concentration from January 1st 2017 to December 31st 2019 were used. They generated a set of 21 records (stations) and 36 columns (months) representing the three-year period.

On this first basis, preprocessing was carried out to identify months with missing values in $PM_{2.5}$ monitoring. To perform the study of time series, all values must be completed (CASTRO; FERRARI, 2016). Where values were missing in a given month, the last and next technique was adopted, which obtains an average between the previous and the next value of the missing attribute (PLAIA; BONDI, 2006), that is, when there is a missing value, it is replaced by the average between the previous and the next month.

In addition, the data were standardized using the Z-score technique, which modifies the original values for them to have an average of 0 and a standard deviation of 1, resulting in values that will be compared under the same scale (HAN; KAMBER, 2006; MITSA, 2010; BATISTA; CHIAVEGATTO, 2019).

To build the second database, used in the step of association rules extraction, we verified the stations that monitor $PM_{2.5}$ and that also provide monthly averages of the following meteorological variables: RH, TEMP, WS, in addition to CO concentration (QUALAR, 2019) between 2017 and 2019. Of the 21 stations

Table 1 – Comparison of international (WHO), national (CONAMA 491/2018), and state (State Decree 59,113/2013) air quality standards for $PM_{2.5}$.

Quality Standards	24 hours[1]	AAA[2]
WHO Standards	25	10
IT 1 (µg/m3)[3]	60[4]	20[4]
IT 2 (µg/m3)[3]	50	17
IT 3 (µg/m3)[3]	37	15
Final Standards (µg/m^3)[3]	25	10

[1]Average of 24 consecutive hours of sampling (should not exceed more than once a year); [2]annual arithmetic average; [3]national standards; [4]state standards; IT: intermediate targets; WHO: World Health Organization; CONAMA: National Environment Council; AAA: annual arithmetic average.Source: adapted from WHO (2019), Brazil (2018), and São Paulo (2013).

Table 2 – Cities and stations with $PM_{2.5}$ monitoring in the state of São Paulo.

City	Station
Campinas	Vila União
Guarulhos	Paço Municipal
Guarulhos	Pimentas
Osasco	Vila Quitaúna
Piracicaba	Campus FUMEP
Ribeirão Preto	Parque Ecológico Maurílio Biaggi
Santos	Ponta da Praia
São Bernardo do Campo	Centro
São José dos Campos	Jd. Satélite
São José do Rio Preto	Campo Atletismo Eldorado
São Paulo	Cidade Universitária (USP)
	Congonhas
	Grajau (Parelheiros)
	Ibirapuera
	Itaim Paulista
	Marginal Tietê (Ponte dos Remédios)
	Parque D. Pedro II
	Pico do Jaraguá (Serra da Cantareira)
	Pinheiros
	Santana
Taubaté	Parque Municipal “Eng. César A. C. Varejão”

FUMEP: Fundação Municipal de Ensino de Piracicaba; USP: Universidade de São Paulo.

whose data were obtained for the first database, seven met this new criterion (Table 3).

For this new dataset, all data must be categorical, since this is a restriction of the Apriori algorithm. Thus, each monthly average value was classified according to two categories: lower or higher than the annual average value of its respective meteorological variable or CO concentration. Table 3 represents an excerpt from the database, referring to the month of July 2018.

The algorithms applied in this study follow the unsupervised approach of machine learning, divided into two stages:

- application of the partitional clustering algorithm (*K-medoids*);
- association rules (Apriori).

The next sections discuss these algorithms.

Data clustering technique

Clustering algorithms can be either partitional or hierarchical. Their ability to cluster data based on intrinsic characteristics of the problem makes them interesting for studies. Such algorithms generate clusters formed by data samples that are similar to each other, according to some measure of similarity. Assuming, for example, a problem of clustering cities by the level of air quality, the clustering algorithms will map the cities and return clusters composed of those with similar pollution behavior. Within the cluster of partitional algorithms, the most common are K-means and K-medoids (JIN; HAN, 2017). The K-medoids algorithm uses objects from the database as the center of the clusters, called medoids, which have the lowest average dissimilarity compared to all other objects in the cluster. In the case of K-means, the centers of the clusters are calculated according to the average value of the objects in that cluster. In this case, outliers from the database can influence the formation of the clusters, since they contribute to the calculation of the central values of each cluster. This type of problem does not happen in the K-medoids algorithm, since the medoids correspond to real samples of the data and not averages (HAN; KAMBER, 2006), that is, the medoids are an element of the cluster itself and not a midpoint as occurs in K-means, which makes it less sensitive to outliers.

Both algorithms (K-means and K-medoids) were implemented in Python, using the open-source Scikit-Learn and PyClustering libraries, specific for machine learning (PEDREGOSA *et al.*, 2011).

To assess the quality of the clustering between the K-medoids and K-means algorithms, the silhouette coefficient was applied (KAUFMAN; ROUSSEEUW, 2005) to the results obtained by each algorithm. This coefficient measures the robustness of the partitions, helping to select the number of clusters, considering the internal similarity and external dissimilarity between them, that is, it combines cohesion (measures how well an element is within a cluster) and separation (measures how much the clusters are separated from each other). For example, supposing that the clustering algorithm returns two clusters, as in the previous example, the silhouette coefficient will verify whether all the elements of Cluster 1 are similar to each other and different from the elements of Cluster 2. An expected behavior would be that this hypothetical Cluster 1 would include cities with a high concentration of one pollutant and Cluster 2, cities with a low concentration of the same pollutant. Therefore, Cluster 1 and Cluster 2 would be cohesive, since they would have cities that show the same behavior, and also separated from each other for presenting an entirely different pattern.

The average value of the silhouette coefficient must be between -1 and 1, representing how well the clusters were formed. The ideal values are positive, with a silhouette coefficient close to 1. Equation 1 represents the average Silhouette calculation (S_p).

$$S_p = \sum_{1}^{n} \frac{s(x_i)}{n} \quad (1)$$

Where:

n = the number of objects in the database and the individual value of the silhouette coefficient of element x_i, given by $s(x_i)$, obtained by Equation 2:

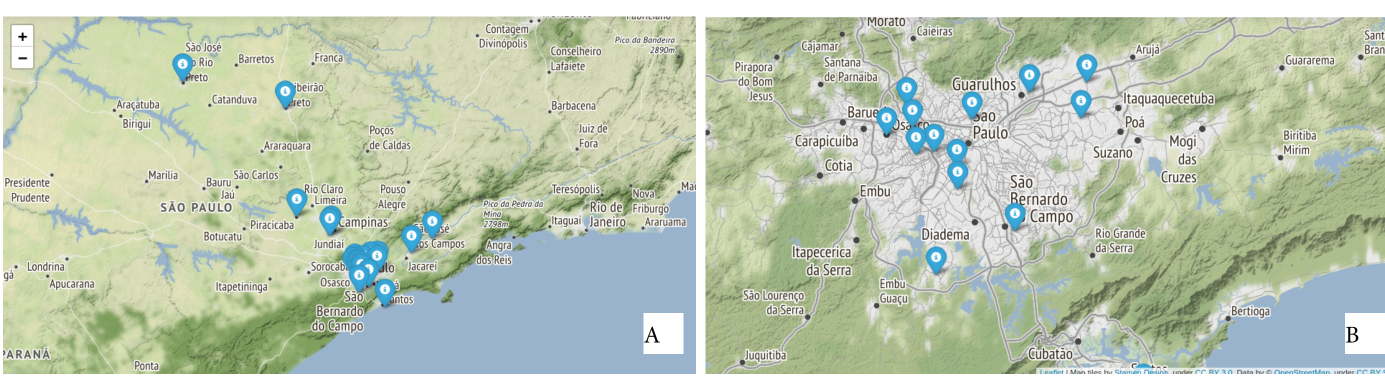

Figure 1 – (A) Map of location of the automatic $PM_{2.5}$ monitoring stations in the state of São Paulo and (B) $PM_{2.5}$ monitoring stations in the Metropolitan Region of São Paulo (MRSP).

$$s(x_i) = \frac{(b(x_i) - a(x_i))}{max\,\{a(x_i), b(x_i)\}} \quad (2)$$

Where:

the values $a(x_i)$ and $b(x_i)$ = respectively, the average distance between x_i and all the objects in its cluster and the average distance of x_i to another cluster to which x_i does not belong.

The silhouette coefficient was also the evaluation metric chosen to determine which of the two algorithms (K-means and K-medoids) would be used in this study. Therefore, the database of monthly $PM_{2.5}$ averages was used and the two algorithms were applied to carry out this evaluation. The one that presented the best silhouette result was adopted for the clustering of stations. This experiment is presented in the Results section.

Association rules

The Apriori Association Rules algorithm aims to find frequent relationships in the datasets, that is, to generate rules of type X → Y, for which X and Y are items that belong to this dataset (AGRAWAL; SRIKANT, 1994). To analyze the possible patterns found in the months with the highest concentration of $PM_{2.5}$, the Apriori Association Rules algorithm was applied to find a subset of frequent parameters related to the database of $PM_{2.5}$.

The Apriori algorithm searches, from a transactional basis, which items are related. For example, in a hypothetical database that records the monthly values of the concentration of air pollutants and the number of hospital visits involving respiratory diseases, the association rules may return {$PM_{2.5}$, PM_{10}} → {increase in visits}, indicating that a high concentration of pollutants $PM_{2.5}$ and PM_{10}, causes, with a degree of certainty, an increase in hospital visits. This degree of certainty that measures the relevance and validation of the rules is provided by: support and confidence. Given the rule X → Y, the support (or coverage of the rule) represents the percentage of transactions in the database that contain the items of X and Y, indicating its relevance (CASTRO; FERRARI, 2016). The confidence or accuracy of a rule, in turn, corresponds to the number of rules in which the consequent (term after the →) of a rule appears in transactions in which the antecedent (term(s) preceding →) is also observed, that is, it is the conditional probability $P(Y|X)$ that given the consequent X of the rule, the antecedent Y also happens (MUELLER, 1995). In this study, the Apriori algorithm was implemented in Python, using the "mlxtend" library.

Results and Discussion

In the experiment to choose the clustering algorithm, the silhouette coefficient was used as the decision criterion, as it is a measure of quality for the entire structure of the partition. It was also used to choose the number of clusters (k), and, for this, 20 different cluster sizes, related to the number of cities, were tested.

After 100 executions of the K-medoids algorithm, applied to the database of monthly averages of $PM_{2.5}$ concentration between 2017 and 2019, the average silhouette coefficient found was 0.26, while for the K-means algorithm, the average value was 0.28. Considering that the silhouette value can vary between -1 and 1, K-medoids was selected because it presents a better average silhouette value and is capable of handling outliers.

Figure 2 shows the relationship between the silhouette coefficient value corresponding to the number k of clusters. The best value corresponds to k = 2. Thus, the K-medoids algorithm was applied to obtain two clusters from the set of stations in the state of São Paulo, with $PM_{2.5}$ monitoring, and the clustering results were subsequently analyzed.

Table 3 – Example of the representation of the database in the month of July 2018, relating the stations that monitor $PM_{2.5}$ with meteorological variables TEMP, RH, WS, and CO concentration. The numerical values were transformed into a category, which may be higher or lower than the average.

	Station	TEMP	RH	WS	CO
0	Parque D. Pedro II	Below Average	Below Average	Below Average	Above Average
1	Pinheiros	Below Average	Below Average	Below Average	Above Average
2	Marg. Tietê-Pte	Below Average	Below Average	Below Average	Above Average
3	S. Bernardo-Centro	Below Average	Above Average	Below Average	Above Average
4	Guarulhos-Pimentas	Below Average	Below Average	Below Average	Above Average
5	S. José Campos - Jd	Below Average	Below Average	Below Average	Above Average
6	Taubaté	Below Average	Below Average	Below Average	Above Average
7	Ribeirão Preto	Below Average	Below Average	Below Average	Above Average

TEMP: temperature; RH: relative humidity; WS: Wind speed.

As a result of applying the K-medoids algorithm to the data, with a value of k = 2, the stations were divided into Clusters 1 and 2, shown in Table 4.

In the analyzed period, for all the stations monitored, the average annual concentrations of $PM_{2.5}$ were 16.43 μg/m^3 (standard deviation 6.45 μg/m^3) in 2017, 16.24 μg/m^3 (standard deviation 6.42 μg/m^3) in 2018, and 16 μg/m^3 (standard deviation 5.04 μg/m^3) in 2019, exceeding the annual threshold of 10 μg/m^3 established by WHO in all periods; note that the standard deviation remained constant in 2017 and 2018, and decreased in 2019. Analyzing each cluster, we can see differences:

- **Cluster 1:** 15 stations located mostly in metropolitan regions, more specifically in cities with an average annual global $PM_{2.5}$ concentration of 17.42 μg/m^3 and standard deviation of 4.72 μg/m^3;
- **Cluster 2:** 6 stations located in cities with relatively lower indexes, with an average annual global $PM_{2.5}$ concentration of 13.4 μg/m^3 and standard deviation of 4.83 μg/m^3.

Figure 3 shows that, between 2017 and 2019, higher concentrations of $PM_{2.5}$ predominate in Cluster 1 compared to Cluster 2, since the former consists of stations located in the Metropolitan Region of São Paulo (MRSP), as found in other studies (HUANG *et al*., 2015; AUSTIN *et al*., 2013). There is also a seasonal trend in the evolution of pollutant concentration and monthly peaks for both clusters in the same periods, suggesting a recurring pattern in the three years. Despite the similarity in seasonal behavior throughout the period, it is clear that in 2017 the month of greatest concentration is September, in 2018 it is July, and in 2019, June. In 2017, the peak concentration of the pollutant was lower than the peak in 2018, while in 2019, the $PM_{2.5}$ concentration level was below the one observed in previous years.

These cycles may be related to meteorological phenomena that have taken place over the period, which coincide with the data from CETESB's annual reports (CETESB, 2019), also identified in the literature (LI *et al*., 2020; BISHT; SEEJA, 2018), and which were analyzed with the association rules algorithm (*Apriori*).

Figure 4 was generated for a better assessment of the physical proximity between the stations in the clusters, showing the geographical location of the stations in each cluster. Clusters 1 and 2 were identified by the colors red and blue, respectively, in Figures 4A and 4B.

The analysis on the map shows that most of the $PM_{2.5}$ monitoring stations present in Cluster 1 are in the Metropolitan Regions (MR) of São Paulo, Campinas, and Baixada Santista. Except for the Campinas region, which is also influenced by fires, the main source of pollutants in these MRs is fuel burning by the vehicle fleet and intense industrial emissions (CARDOSO *et al*., 2017; HUANG *et al*., 2015; YANAGI; ASSUNÇÃO; BARROZO, 2012). The stations with lower concentrations, represented by Cluster 2, are located further inland in the state and are more distant from each other, except for Ibirapuera station, which, despite being located in the city of São Paulo, is located farther from intense traffic routes.

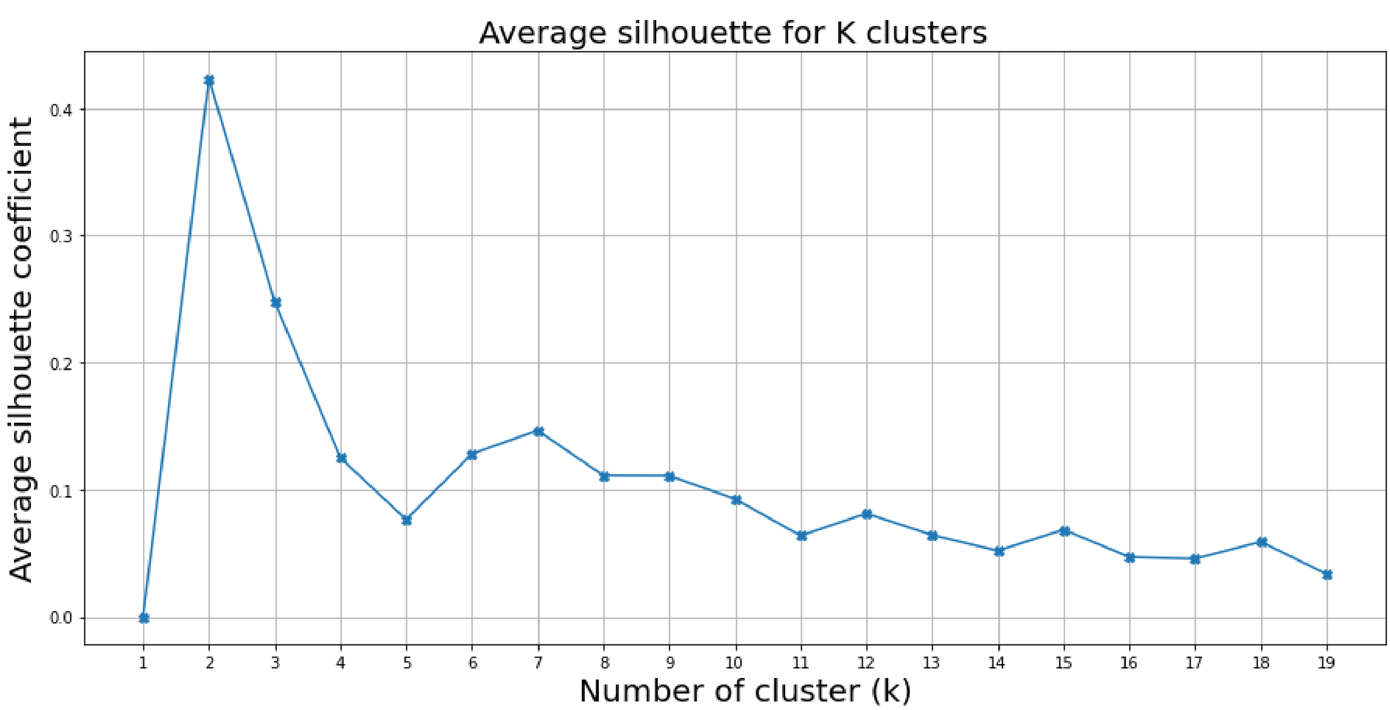

Figure 2 – Number k of clusters per silhouette coefficient value, obtained from the K-medoids algorithm, applied to the database of monthly averages of $PM_{2.5}$ concentration, between 2017 and 2019.

Comparing the results obtained, there is a correspondence between the clusters generated and other studies that investigate air pollution by $PM_{2.5}$ in the state of São Paulo: Araújo and Rosário (2020) identified from satellite data that the most polluted regions in the state are the MRs of São Paulo, Campinas, and Baixada Santista.

The analysis of the average monthly variation of $PM_{2.5}$ concentration in Clusters 1 and 2 indicates differences in pollutant concentrations between the two clusters, as can be seen in the boxplots in Figure 5. However, the interquartile ranges and maximum values (disregarding outliers) are similar.

Table 5 shows that, in 2017, the $PM_{2.5}$ concentration level increased from May to October, with a peak of about 29.8 $\mu g/m^3$ in September. Likewise, in 2018, the increase occurred from March to September, with a peak of 32.4 $\mu g/m^3$ in July, indicating an increase in the pollutant that year. The same behavior was repeated in 2019, from April to October, with a peak of 23.7 $\mu g/m^3$ in June, but with a reduction in the pollutant concentration.

Studies show that meteorological factors such as TEMP, reduction in RH, and WS can impair the dispersion of $PM_{2.5}$, increasing health-related risks (INPE, 2019; CETESB, 2019). The studies by Santos, Carvalho and Reboita (2016) and Santos *et al.* (2019) confirm a significant difference between the concentration of $PM_{2.5}$ in dry and rainy periods, indicating the association between meteorological parameters and the pollutant.

To assess such a relationship, data of the months with the highest peaks (Figure 3 and Table 5), that is, September 2017, July 2018,

Table 4 – List of monitoring stations per clusters and their annual averages (2017 to 2019) of $PM_{2.5}$ concentration.

Monitoring stations	Monthly Averages of $PM_{2.5}$ Concentration		
CLUSTER 1	**2017**	**2018**	**2019**
Osasco	28.29	21.50	20.83
São Paulo – Marginal Tietê (Pte. Remédios)	19.50	19.92	20.00
Guarulhos – Paço Municipal	18.50	16.92	15.00
São Paulo – Santana	17.92	16.25	16.33
Guarulhos – Pimentas	17.83	21.08	19.75
São Paulo – Congonhas	17.83	18.42	17.67
São Paulo – Itaim Paulista	17.25	18.50	18.50
Campinas – Vila União	17.08	15.83	19.17
São Paulo – Grajau (Parelheiros)	17.00	18.67	16.92
São Paulo – Parque D. Pedro II	16.75	17.42	17.17
São Bernardo do Campo – Centro	16.17	16.00	16.17
São Paulo – Cidade Universitária (USP)	15.92	16.00	15.00
Santos – Ponta da Praia	15.58	14.08	14.42
São Paulo – Pinheiros	14.48	16.33	16.54
São Paulo – Pico do Jaraguá (Serra da Cantareira)	12.58	15.13	15.50
CLUSTER 2	**2017**	**2018**	**2019**
São Paulo – Ibirapuera	15.75	14.83	13.08
São José do Rio Preto	15.75	14.42	14.83
Taubaté	13.08	11.08	11.08
Ribeirão Preto	13.00	13.58	14.00
Piracicaba	12.67	13.33	13.00
São José dos Campos – Jd. Satélite	12.00	11.67	11.08

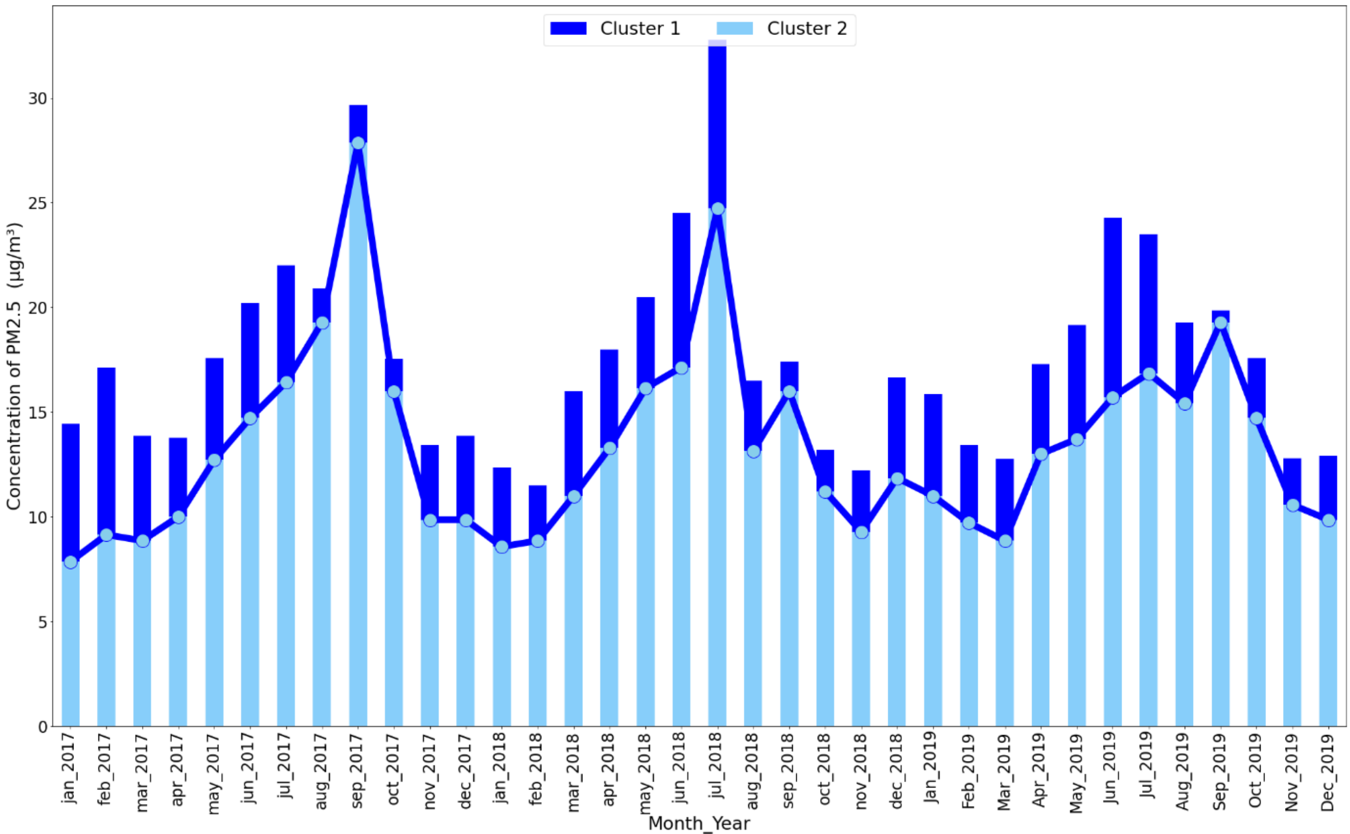

Figure 3 – Comparison of the monthly averages of $PM_{2.5}$ concentrations (µg/m³) between 2017 and 2019, in the cities of the state of São Paulo, with Cluster 1 being characterized mostly by the MRSP and Cluster 2, by inland cities.

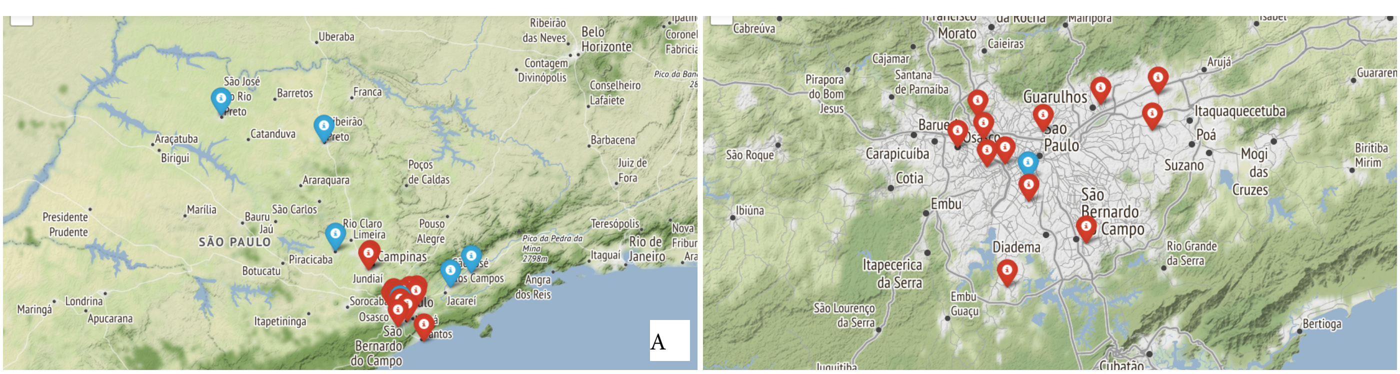

Figure 4 – (A) Visualization by geolocation of the clusters, created by the K-medoids algorithm; B) proximity of the elements of Cluster 1 on the map. Cluster 1 in red and Cluster 2 in blue.

and June 2019, were collected from the transactional base (containing the $PM_{2.5}$ concentration values for each station and the behavior of the meteorological variables) and submitted to the Apriori association rule algorithm. With that, we tried to find out which factors were more frequent in the three periods and how these meteorological factors were related.

In the first run of Apriori, using September 2017 data, nine association rules were obtained, seven of which were repeated, that is, rules that had the same meaning. This takes place because the algorithm analyzes all the possibilities between the items. Therefore, the two main rules for this period are shown in Table 6. Support corresponds to the frequency with which the patterns occur throughout the database, indicating the percentage of occurrence of the transactions. Confidence measures the "strength" of rules, that is, it assesses whether transactions that satisfy the antecedent of the rules also satisfy their consequent. The rules that meet support and confidence are called "strong rules."

It can be concluded that, for the peak month of 2017, starting from Rule 1, a high concentration of $PM_{2.5}$, below-average RH, and above average CO concentration occur together with a frequency of 85%. This rule also informs that, when the concentration of CO is above the average, RH is below the average with a certainty of 100%. For Rule 2, at the peaks of $PM_{2.5}$ concentration, the factors that occur together with a 75% frequency are above average CO and above average TEMP. Regarding confidence, when CO is above average, temperature is above average with a certainty of 100%.

In the second run of Apriori, July 2018 data were used and 44 rules were obtained, and the three not repeated rules with greater support and confidence were chosen for analysis (Table 6).

For the high concentration of $PM_{2.5}$ in July 2018, Rule 1 identifies the following factors: below-average TEMP and below-average WS occur together with 100% frequency in the database. For Rule 2, the frequency of occurrence of the two factors is 87% and the probability of low WS given the occurrence of below-average RH is 100%. For Rule 3, three factors appear together with a frequency of 87% and 100% confidence, indicating that whenever the temperature becomes predominantly colder, the CO concentration increases and WS is below average, signaling that in colder seasons there is an increase in CO concentration, stimulated by the low dispersion of this pollutant.

In the last Apriori execution, June 2019 data were used and nine rules were obtained, two of which were the most representative (Table 6). The identified rules were similar to the rules of the previous year, with the predominant variables TEMP, RH, and WS below the average. Also, the months of high concentrations tend to be close from one year to the next.

According to the winter report of CETESB (2020), the winter of 2019 presented a predominance of a hot and dry air mass throughout the state of São Paulo, with low ventilation and absence of rains, making it difficult to disperse pollutants, which corroborates the rules obtained for 2019.

Considering that the periods with the highest concentration of $PM_{2.5}$ are the ones that present the greatest risk to the population and that meteorological factors have an influence on the increase in pollutant concentration, the rules presented in Table 6 could give warning indications for the increase in pollutant concentration. In Brazil, the studies by César *et al.* (2016) and Machin and Nascimento (2018) show the influence of the 5 $\mu g/m^3$ increase in the concentrations of $PM_{2.5,}$ resulting in increases between 20 and 38% in the risk of hospitalization due to pulmonary complications.

Thus, we can conclude that when the concentration of $PM_{2.5}$ increases, the measurements show the following behaviors: low RH and above-average TEMP. The results also indicate that high concentrations of $PM_{2.5}$ may be associated with below average TEMP, milder WS, and below-average RH. We observed an increase in CO, which suggests an association with the behavior of $PM_{2.5}$ in the winter months, also reported by Moisan, Herrera and Clements (2018) and Saide *et al.* (2011).

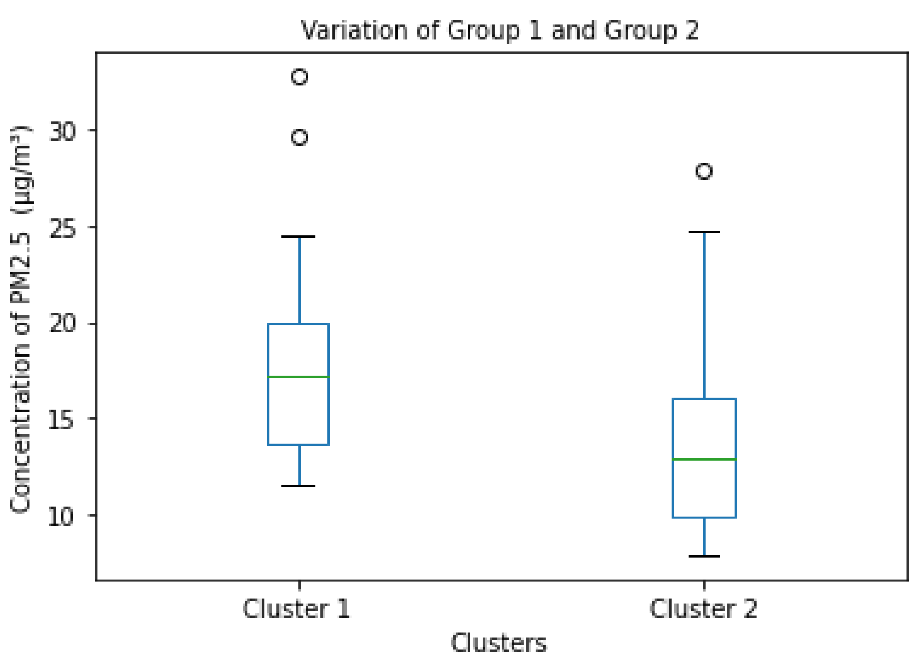

Figure 5 – Boxplots of Clusters 1 and 2, formed by the monthly averages of $PM_{2.5}$, between 2017 and 2019.

Table 5 – Monthly averages of $PM_{2.5}$ by clusters of stations and standard deviation of the clusters (in µg/m³), between 2017 and 2019. The highlighted months are the periods of greatest pollutant concentration in the three years, with emphasis on the peak months September/2017, July/2018, and June/2019.

Clusters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	2017											
Cluster 1 (C1)	14.1	16.4	13.6	13.5	17.1	19.6	21.5	20.6	29.5	17.3	13.2	13.7
Standard deviation	5.8	5.4	5.4	5.5	4.5	4.3	4.3	2.6	5.0	3.0	2.1	1.6
Cluster 2 (C2)	7.7	9.7	8.7	10.0	13.0	15.3	16.8	19.7	28.0	16.3	9.8	9.5
Standard deviation	1.6	2.1	1.5	1.3	1.5	1.5	2.5	3.7	5.6	4.1	1.9	2.3
	2018											
Cluster 1 (C1)	12.2	11.4	15.7	17.8	20.2	23.8	32.2	16.2	17.3	13.4	12.5	17.0
Standard deviation	1.5	1.5	2.1	3.2	3.1	4.9	6.3	2.2	2.1	1.4	1.9	4.8
Cluster 2 (C2)	8.3	8.7	10.8	13.0	16.2	17.7	24.8	13.3	16.2	10.5	8.2	10.2
Standard deviation	1.9	1.2	2.1	2.1	1.8	2.4	4.4	2.6	3.5	1.4	1.2	1.0
	2019											
Cluster 1 (C1)	15.9	13.7	12.8	17.3	18.9	23.7	23.0	18.9	19.5	17.5	13.0	13.1
Standard deviation	2.2	3.0	1.5	2.0	3.3	4.7	4.9	3.5	3.6	2.6	2.1	1.9
Cluster 2 (C2)	10.0	8.5	8.2	12.3	13.5	15.8	17.0	15.7	20.2	14.3	9.7	9.0
Standard deviation	1.1	0.5	0.4	0.5	1.9	2.0	1.5	3.5	6.8	3.3	1.4	1.5

Table 6 – Rules obtained by the Apriori algorithm and its respective Support and Confidence parameters*.

September 2017		
Rules (Antecedent → Consequent)	Support	Confidence
Rule 1. (Below-average RH) → (Above-average CO)	85%	100%
Rule 2. (Above-average TEMP) → (Above-average CO)	75%	100%
July 2018		
Rule 1. Below-average TEMP → Below-average WS	100%	100%
Rule 2. Below-average RH → Below-average WS	87%	100%
Rule 3: Above-average CO and below-average WS → Below average TEMP	87%	100%
June 2019		
Rule 1. Below-average TEMP → Below-average RH	62%	83%
Rule 2. Below-average WS → Below-average RH	50%	100%

*Annual averages for each meteorological variable; RH: relative humidity; TEMP: temperature; WS: Wind speed.

Conclusions

The analysis of $PM_{2.5}$ carried out in this study was done by the application of a clustering algorithm, which divided the values of measurements of $PM_{2.5}$ concentrations from 21 monitored stations, distributed over 36 months, between 2017 and 2019.

The experiments showed that the formation of two clusters is the most adequate. The results show that the stations belonging to the identified clusters have specific characteristics that lead to different pollution rates. The municipalities of the MRSP stand out as those with the highest concentration of $PM_{2.5}$, but cities inland, with a predominance of industrial and vehicular emissions, join these municipalities, forming one of the clusters. The stations of the other cluster, installed in less polluted locations, are in cities further inland, far from sources of pollution such as vehicle emissions and industrial processes.

Two very characteristic clusters were formed, with variations in pollutant concentration that followed a pattern throughout each year. A seasonal behavior was observed in the temporal study, which is repeated in every period, in both clusters. There is a higher incidence of $PM_{2.5}$ in winter, which peaked (September 2017, July 2018, and June 2019) in critical months, when the meteorological variables (TEMP, RH, WS) contribute to the increase in pollutant concentration.

From the clustering results, another algorithm was applied to meteorological data related to September 2017, July 2018, and June 2019, to find associations with the meteorological factors mentioned above in the periods of greatest concentration of $PM_{2.5}$. The results showed that, in September 2017, the predominant meteorological factors were low RH and above average TEMP. In July 2018 and June 2019, the rules showed that below average TEMP and RH and milder WS were the main meteorological factors that occurred during the period with the highest average pollutant concentration. Finally, we also observed a direct relationship between the concentrations of CO and $PM_{2.5.}$

The rules found can be useful in creating warning signs for possible increases in the concentration of PM, since the results confirm a relationship between episodes of high concentration and atmospheric conditions in the region, providing subsidies for managing air quality in the state of São Paulo.

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Environmental health indicator for the evaluation of neighborhoods in urban areas: a case study in Caruaru (PE), Brazil

Indicador de salubridade ambiental para avaliação de bairros em áreas urbanas: um estudo de caso em Caruaru (PE), Brasil

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ABSTRACT

The environment, over the years, has been subjected to strong negative impacts caused by economic policies that have promoted an uncontrolled growth of urbanization in the cities and abusive exploration of the natural resources. In this context, developing socio-environmental indicators to subsidize the formulation of municipal public policies which consider, specifically, the environmental (in)salubrity of each neighborhood or locality of municipalities is imperative. The present paper presents the construction and application of an environmental health indicator for residential neighborhoods in two localities of Caruaru City, Pernambuco State. The data adopted in research were obtained from databases of City Hall institutions, from interviews with the population of the localities and water quality analyses. The results indicated that the neighborhoods analyzed presented characteristics of medium health; water supply, the disposal of solid waste, and socioeconomic aspects require attention and priority of public policies. In conclusion, the proposed indicator can be an instrument to assist in urban planning and environmental management of Brazilian municipalities, because it can guide the performance of public managers and the civil society to identify priority actions for improving the infrastructure of the most unhealthy neighborhoods.

Keywords: healthiness; environmental health; environmental sanitation; environmental management; environmental health indicator.

RESUMO

O meio ambiente, ao longo dos anos, tem sido submetido a fortes impactos negativos gerados por políticas econômicas que impulsionaram um processo desordenado de urbanização das cidades e exploração abusiva dos recursos naturais. Nesse contexto, é imperativo o desenvolvimento de indicadores socioambientais para subsidiarem a formulação de políticas públicas municipais que considerem, especificamente, a (in) salubridade ambiental de cada bairro ou localidade dos municípios. Este trabalho apresenta a construção e aplicação de um indicador de salubridade ambiental para bairros residenciais em duas localidades de Caruaru, Pernambuco. Os dados adotados nesta pesquisa foram obtidos por meio de bancos de dados de órgãos da prefeitura municipal, de entrevistas à população das localidades e de análises da qualidade da água. Os resultados apontaram que os bairros analisados apresentaram características de média salubridade, onde foi identificado que o abastecimento de água, a disposição de resíduos sólidos e os aspectos socioeconômicos necessitam de uma maior atenção e prioridade das políticas públicas. Conclui-se que o indicador proposto pode ser um instrumento para auxiliar o planejamento urbano e a gestão ambiental dos municípios brasileiros, uma vez que pode balizar a atuação de gestores públicos e da sociedade civil na identificação de ações prioritárias para a melhoria da infraestrutura dos bairros mais insalubres.

Palavras-chave: salubridade; salubridade ambiental; saneamento ambiental; gestão ambiental; indicador de salubridade ambiental.

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Introduction

Today, around half of people live in urban areas worldwide, and this ratio is estimated to increase to two out of three people by 2050. Although the growth of urban population over the 20th century occurred on a small portion of the global Earth surface (< 3%), the impact has been significant, with 78% of the carbon emissions, 60% of the use of residential water, and 76% of the wood used for industrial purposes attributed to the cities (LUCK; WU, 2002; WU *et al.*, 2011). According to the World Health Organization (WHO), in its report on the Joint Monitoring Program in 2015 (WHO, 2015), 21% of the world population do not use safe water services (free from contamination), and 11% of the global population do not access basic drinking water services.

In Brazil, the environment has been subjected to strong negative impacts caused by economic policies, which promoted an uncontrolled urbanization process in the cities and abusive exploration of their natural resources. This process, a result from the absence of efficient public policies, generated a deficit in housing and services, causing the formation of peripheries occupied in a precarious and illegal way by urban workers, who have been attracted to cities that were not prepared for this migratory flow.

The process of urban concentration occurred mostly because of the migratory flow of field workers and their families to city peripheries, attracted by the hope of a higher quality of life, especially regarding the availability of jobs, education, and health. Nevertheless, given the cities were not prepared to receive this contingent in most cases, the integration of these people into the urban space was developed anomalously. This fact derived mainly from the speed of the process itself and by the precariousness of the urban equipment, especially in the peripheral regions of the cities.

The public power faces the challenge of prioritizing the formulation of socio-environmental public policies which adopt clean technologies, aimed at sustainable consumption, selective collection, recycling, and reduction of waste in public and private activities (BELIZÁRIO, 2012). Therefore, public policies must prioritize the environmental health of the population. Environmental health is directly related to sanitation services, appropriate housing conditions, and the existence of proper socioeconomic policies. The relation between sanitation and health is narrow; according to Law No. 11.445, which establishes the guidelines for basic sanitation in Brazil, public sanitation services are provided according to the environmental principles of waste collection and disposal of sewage (BRASIL, 2007). The concept of environmental health can be defined as the environmental quality required to prevent diseases transmitted by the environment and promote the improvement of mesological conditions favorable to the health of both the urban and rural population (CONESAN, 1999).

Brazilian investments in sanitation services and water resources are insufficient to guarantee good health conditions in a large number of cities. In this case, the adoption of criteria directed to establishing priorities for the application of the available resources, aiming at maximizing the benefits, is needed. For this, adopting efficient tools of easy application is important. The topic demands that the studies and planning of actions, both preventive and corrective, be based on reality to involve the direct and indirect actors in the analysis process. Mechanisms must be proposed to measure the health conditions of the environment, direct actions compatible with the existing reality, and contribute to define priorities in the process of public power decision and investments, especially in sanitation services.

The use of indicators and management tools contribute to the development of the functions which aim at guiding and aggregating information about the reality, so that the environmental, physical, and social aspects can be incorporated for assistance in tracking sustainable progress. In the world, the most popular among the environmental indicator systems is PSR (Pressure-State-Response). The model was developed and originally recommended by the Organization for Economic Cooperation and Development (OECD, 1993). This approach is an expanded version of the PSR model, which has been used by the United Nations Environment Programme (UNEP) on the elaboration of the series Global Environment Outlook (GEO). This project started in 1995 and aims at evaluating the conditions of the environment at the global, regional, and national levels (TAYRA; RIBEIRO, 2006).

Among the socio-environmental indicators available in Brazil, the Environmental Health Indicator (*Indicador de Salubridade Ambiental*, EHI) must be highlighted, which evaluates the services from the sanitation sector and the socioeconomic conditions of the population. The evolution of EHI over the years has been considered positive for the Brazilian technical-scientific community, and enabled the insertion and adaptation of new indicators to the original model. In this context, research by Teixeira, Prado Filho and Santiago (2018) is prominent, who identified 60 publications which adopted EHI for the evaluation of environmental health at different localities, such as: the cities of Criciúma (Santa Catarina State) (VALVASSORI; ALEXANDRE, 2012) and Mossoró (Rio Grande do Norte State) (PEIXOTO *et al.*, 2018), the neighborhood of Gargaú, in São Francisco do Itabopoana City (Rio de Janeiro State) (SANTOS; FERREIRA, 2016), and the river basin of the stream Reginaldo in Maceió City (Alagoas State) (SILVA *et al.*, 2017).

Improper occupation of soil can also increase the vulnerability of individuals and communities in relation to natural catastrophes (SANTOS; FORMIGA; FERREIRA, 2020). In this context, Bosco, Cardoso and Young (2019) evaluated the socio-environmental vulnerability to the occurrence of landslides in an area of the Metropolitan Region of Vale do Paraíba, São Paulo State, with the construction of a synthetic index of environmental and socioeconomic scope. The results showed an extremely high overall vulnerability index in the regions of Campos do Jordão and Natividade da Serra.

In this context, developing socio-environmental indicators to subsidize the formulation of municipal public policies which consider, specifically, the environmental (un)health of each neighborhood in the municipality is imperative. The present paper presents the construction and application of the Environmental Health Indicator for Residential Neighborhoods (EHIN) in two localities of Caruaru City (Pernambuco State), Brazil. EHIN is a tool to assist urban planning and environmental management of municipalities, because it can guide the performance of public managers and the civil community on the identification of priority actions for improving the infrastructure of the unhealthiest neighborhoods. The indicator proposed is expected to be adopted at different localities, given its required information is of easy acquisition and applicability.

Environmental Health Indicators

In 1999, the group of specialists that composed CONESAN/SP developed the Environmental Health Indicator (EHI) to evaluate the socio-environmental conditions of the population. The original composition of EHI is given by Equation 1, and its final score varies from 0 to 1.

$$EHI = 0.25\ IWS + 0.25\ ISS + 0.25\ ISW + 0.10\ ICV + 0.10\ WRI + 0.05\ SEI \quad (1)$$

In which:
IWS = Indicator for Water Supply;
ISS = Indicator for Sanitary Sewage;
ISW = Indicator for Solid Waste;
ICV = Indicator for the Control of Vectors;
WRI = Water Resources Indicator;
SEI = Socioeconomic Indicator.

Every first-order indicator is calculated based on associated sub-indicators (second-order indicators). The Basic Manual of EHI (CONESAN, 1999) does not establish the level of environmental health of the study place in relation to the indicator's score range. Most of the technical-scientific works adopt the values established by Dias, Borja and Moraes (2006) in the literature (Table 1). The indicators are determined by a qualitative and quantitative analysis of specific socio-environmental aspects, especially those related to environmental sanitation, with values varying from 0 to 1. The closest to the superior value, the highest the environmental health.

The variables choice by CONESAN was established according to the following principles:

- uniformity of the database and criteria and ways of calculation;
- possibility of comparison among the municipalities, which, in terms of sanitation, is limited to water supply, sanitary sewage and urban cleaning. The socioeconomic conditions are expressed by the parameters assessed by each state, related to public health aspects, income, and education. Nonetheless, for the identification of extensive or localized aspects, which differ according to the region, the comparison of EHI must be associated to the respective EHI adopted, whose variables must be in agreement;
- possibility of attributing adjusted weights to the aspects of the previous item;
- the need to limit data and information to be used, which must be available and easily tabulated.

Teixeira, Prado Filho and Santiago (2018) identified 60 publications with the use of EHI in different areas and urban occupations, with the Southern (20) and Northeastern regions (19) of the country representing the greatest numbers of studies on this topic. Research claims that unifying one EHI all over Brazil is a challenge, given the local specificities and difficulties in obtaining data from public agencies (secretariats, authorities etc.), whose reliability may be questionable. Aiming to overcome this challenge, present work proposes an easily applicable indicator, which can be adopted in other places, since it does not depend on governmental data.

Valvassori and Alexandre (2012) adapted EHI to evaluate the environmental health of urban areas in Criciúma City. The study results indicated a water supply index with good indicatives, varying from 0.8 to 1, whereas urban drainage and sanitary sewage require greater attention of the public power. Santos and Ferreira (2016) also adopted EHI as a basis to analyze the neighborhood of Gargaú in São Francisco do Itabopoana City, located near the mouth of the Paraíba do Sul river, thus adapting the model to an estuarine ecosystem. This locality is known by its important mangroves; the main income of the local population comes from the collection of crabs, shellfish, and fish. From the comparisons of results of the bacteriological and physicochemical analyses of the underground water quality with the maximum values allowed for human consumption, the community presented an unhealthy environment that needed combined actions from both the community and the public power.

Silva *et al.* (2017) developed a study in the basin of the stream Reginaldo in Maceió City, aiming at the correlation of incidence of waterborne diseases with EHI. The results indicated a correlation between EHI and the incidence of the diseases Dengue Fever, Hepatitis, and Leptospirosis. Mari *et al.* (2019) determined the EHI for municipalities of the Paraná III river basin. The data used for calculating the EHI were obtained from field surveys and research in governmental databases. As a result, defining that most of the bordering and non-bordering municipalities in the region were defined as presenting healthy conditions.

Table 1 – Environmental health level in relation to EHI score range.

Health level	Score
Insalubrity	0–25
Low salubrity	26–50
Medium salubrity	51–75
Healthy	76–100

Source: Dias, Borja and Moraes (2006).

Kobren *et al*. (2019) applied EHI in Porto Rico City (Paraná State), to characterize the potentialities and failures related to the elements which compose the indicator. The results obtained indicated the municipal health as satisfactory. Nevertheless, the global assessment does not rule out specific problems, such as the deficiency in controlling the transmitting vector of Dengue Fever and the possible future problem of water availability to supply the population.

Rocha, Rufino and Barros Filho (2019) evaluated the health conditions of Campina Grande City (Paraíba State) using an adaptation of EHI. The values of EHI/CG were associated to the census sectors of the district-headquarters of the municipality to allow, initially, an analysis of the spatial distribution of its values in the city. Santos, Formiga and Ferreira (2020) correlated socio-environmental vulnerability indicators in Goiás State with the urban drainage system. For developing indicators, the technique of exploratory factor analysis was employed. The three indicators developed (environmental fragility, infrastructural quality, and social quality) were aggregated into a single indicator. The data sets made available for the analyzes developed in research refer to the results of the 2010 Population Census by the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística*, IBGE). The results demonstrated that sectors with better drainage systems (higher proportions of households with manhole and curb) tend to present higher indicators of social and infrastructural quality, and lower values of environmental fragility.

Several studies have presented models for socio-environmental evaluation which aggregate the use of geographic information systems (GIS) (LI; WENG, 2007; PADILLA *et al*., 2016; MUSSE; BARONA; RODRIGUEZ, 2018; PEIXOTO *et al*., 2018). Li and Weng (2007) developed a methodology to integrate the remote sensing data and the demographic census performed in the United States in a GIS platform to compose a quality of life index. The study was conducted in the urban area of Marion County (Indianapolis), Indiana. The authors extracted variables from socioeconomic information obtained from data from the 2000 census and aimed at integrating the data to the Landsat Enhanced Thematic Mapper Plus (ETM+) satellite images. The index was developed from the combination of three factors, which represent different aspects of quality of life. The researchers concluded that the indicative proposed needs an incorporation of other dimensions and the combination of objective and subjective aspects.

Musse, Barona and Rodriguez (2018) presented a quantitative approach to evaluate the environment of the urban area of Cali City, Colombia, by adding more variables to the model proposed by Li and Weng (2007). The authors concluded that the environmental and socioeconomic conditions of the neighborhoods in Cali are highly correlated, which indicates that the environmental quality depends on the income capacity of the population and on urban structure, a fact observed in several cities of Latin America.

Padilla *et al*. (2016) conducted a study in Nice City, France, to identify how socioeconomic factors, such as access to health, and cumulative factors in small urban areas interfere in the inequalities and environmental health, and what is their correlation with infant and neonatal mortality. The work presented indicators for privation, proximity to high traffic roads, green spaces, and accessibility to health, by GIS. The results showed that the poorest population has a higher risk of neonatal mortality and is exposed to more air pollution, because of the approximation of high traffic roads.

Peixoto *et al*. (2018) characterized the situation of environmental sanitation of Mossoró City (Rio Grande do Norte State). For this, an EHI composed of three sub-indices was applied, with the support of a GIS: water supply, garbage collection, and sanitary sewage treatment. The study showed that there is a spatial concentration in the access to sanitation services, and sewage treatment was the most sensitive for the indicator.

When the main contributions regarding the use of socio-environmental indicators are evaluated, information sharing has a common goal, the metric of impacts on the environment and health, derived from human activities. In this sense, the contribution of each strategy adopted, both national and international, is valuable to measure these impacts and identify sectors which require major interventions to promote population health, well-being, and citizenship.

Materials and Methods

Study area

Caruaru City, located in the mesoregion of Vale do Ipojuca, encompasses a territorial area of 921 km^2, representing 0.94% of the area of Pernambuco State (Figure 1). It had a resident population of 351,686 inhabitants in 2016 (IBGE, 2017). According to the Municipal Human Development Index (MHDI), published in the Atlas of Human Development in Brazil in 2010, the city presented an MHDI of 0.677.

Caruaru is in the Brazilian semi-arid region and is placed within the domains of the basins of both Ipojuca and Capibaribe rivers, whose main tributaries are: Capibaribe river and the streams Tabocas, Caiçara, Borba, da Onça, Olho d'Água, Mandacaru do Norte, Carapotós, São Bento, Curtume, and Taquara. All water courses in the municipality have intermittent flow regime, and their drainage pattern is dendritic. The main reservoirs responsible for city supply are Jucazinho and Prata. The Prata reservoir is in Bonito City (Pernambuco State) and has a capacity of 42 million cubic meters.

Given the water crisis of the region, the population often uses the water provided by trucks, which transport containers with capacity of 1,000 liters, and tank trucks. The water provided by tank trucks may be inappropriate for human consumption. The study performed by Mendonça *et al*. (2017) indicated that the water provided in Caruaru has low potability index and high risk of contamination by pathogens (presence of the thermotolerant coliform *Pseudomonas aeroginosa* and high numbers of heterotrophic bacteria).

The neighborhoods evaluated belong to the urban area of Caruaru and were chosen based on the number of confirmed cases of Dengue Fever and Chikungunya, from 2015 to 2017. Data were obtained from the Management of Work Operation and Health Education from the City Hall (*Gerência de Gestão do Trabalho e Educação em Saúde da Prefeitura Municipal*) (PREFEITURA DE CARUARU, 2018a), and indicated neighborhoods *A* and *B* for having more cases of arboviruses. Given the nature of the topic addressed, omitting the names of the neighborhoods evaluated was a decision.

Environmental health indicator for neighborhoods

Given the need for adaptation of the EHI to the context of the Agreste region of Pernambuco State and application on the scale of neighborhood, a new indicator is proposed, named Environmental Health Indicator for Neighborhoods (EHIN), from the adaptation of the original model proposed by CONESAN (1999). The first-order indicator of EHI related to water resources (WRI) was excluded, because the evaluation of springs is not applicable at the neighborhood scale. The definition of weights and first-order indicators was performed based on Barreto *et al*. (2020), who affirmed, based on literature review (48 works published from 1999 to 2019), that states that the distribution of weights can be the same adopted by the original model; consultation with experts in the field (application of the Delphi method) was also used. In this sense, the original values of the weights of the first four first-order indicators were maintained, and the redistribution of the weight of the WRI to the socioeconomic indicator (SEI) was made, considering that the indicator SEI was underestimated in the original EHI.

EHIN was calculated by Equation 2 and has its composition according to Table 2.

$$EHIN = 0.25\ IWS + 0.25\ ISS + 0.25\ ISW + 0.10\ ICV + 0.15\ SEI \quad (2)$$

In which:
IWS = Indicator for Water Supply;
ISS = Indicator for Sanitary Sewage;
ISW = Indicator for Solid Waste;
ICV = Indicator for the Control of Vectors;
SEI = Socioeconomic Indicator.

Second-order indicators were defined based on specialized literature, with adaptations and modifications being performed according to consultations with specialists of the specific area. The changes were defined aiming at the applicability on a neighborhood scale and easiness of implementation. Except for the water quality index (WQI), which is defined by laboratory analyses, all information was obtained in interviews with the population and visits *in loco*. Thus, the application of the proposed model can be easily performed in other areas and/or

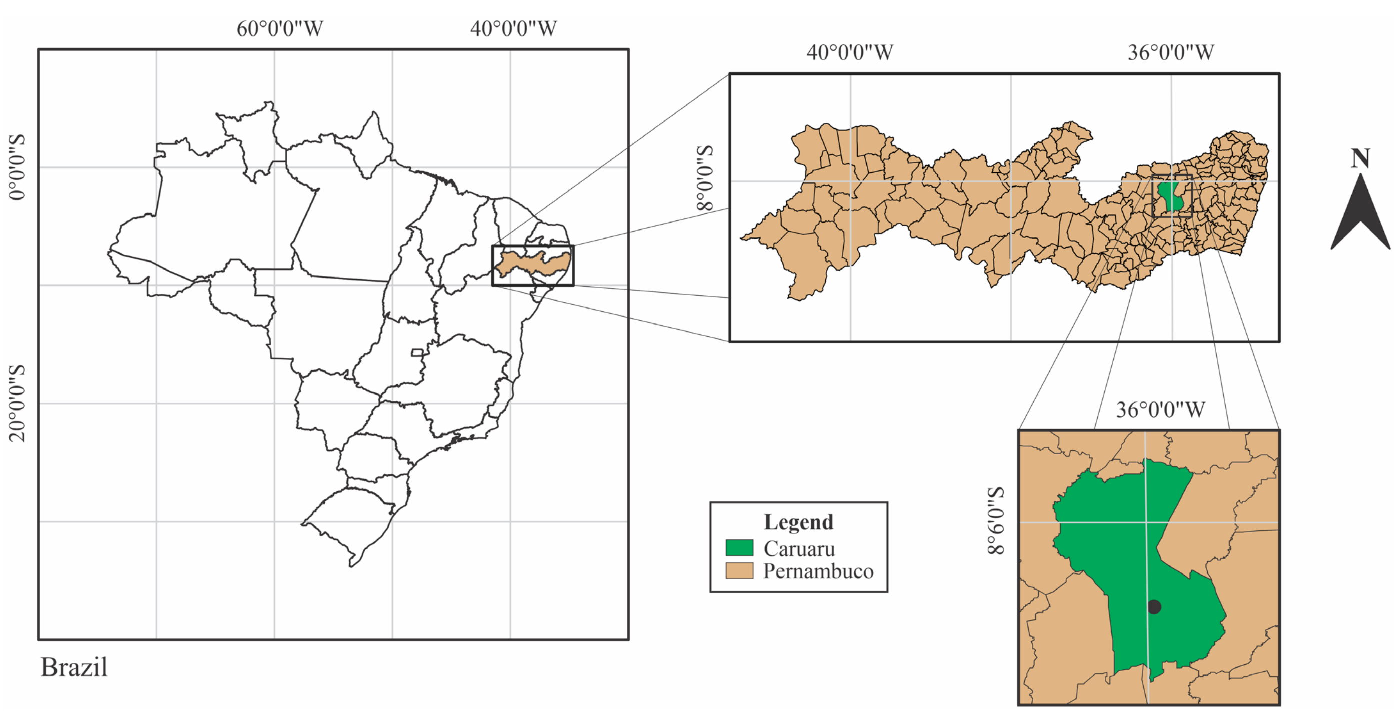

Figure 1 – Location of Caruaru City, Pernambuco State.

Table 2 – Composition of the indicator EHIN for Caruaru City, Pernambuco State.

1st order indicator	Calculation of the 1st order indicator	2nd order indicator	Goal of the 2nd order indicator	Score value
Indicator for water supply – **IWS**	IWS = (SCI + WRI + WQI) / 3	**SCI** = service coverage index	To identify whether the household is assisted by a supply network	Always = 1 Sometimes = 0.5 Never = 0
		WRI = water reuse index	To identify whether the household reuses water	Yes = 1 No = 0
		WQI = water quality index	To verify, by laboratory analyses, the percentage of households in which water sample is considered potable based on colimetry, chlorine, and turbidity.	WQI = 100% → 1 100% > WQI ≥ 95% → 0.8 95% > WQI ≥ 85% → 0.6 85% > WQI ≥ 70% → 0.4 70% > WQI ≥ 50% → 0.2 WQI < 50% → 0
Indicator for sanitary sewage – **ISS**	ISS = (SDI+ OSI) / 2	**SDI** = sewage destination index	To identify whether the household is connected to the sewage network	Network = 1 Septic tank = 0.5 Others = 0
		OSI = open sewage index	To verify whether there are places with the presence of open sewage	Yes = 0 No = 1
Indicator for solid waste – **ISW**	ISW = (WCI + SSI + WSI + WDI) / 4	**WCI** = waste collection index	To identify waste collection in the neighborhood	≥ 3 collections per week = 1 Weekly = 0.5 Rare = 0.3 Never = 0
		SSI = street sweeping index	To identify sweeping in the locality	≥ 3 sweepings per week= 1 Weekly = 0.5 Rare = 0.3 Never = 0
		WSI = waste separation index	To identify whether the household performs waste separation	Yes = 1 No = 0 No selective collection = 0
		WDI = waste disposal index	To identify where the waste is disposed for collection	Floor = 0 Collection point = 0.5 Bin = 1
Indicator for the control of vectors – **ICV**	ICV = (IPD + ICF + IPR + IPA) / 4	**IPD** = index for the presence of the Dengue virus	To identify the presence of Dengue Fever in the last six months	Yes = 0 No = 1
		ICF = index for Chikungunya fever	To identify the presence of Chikungunya in the last six months	Yes = 0 No = 1
		IPR = index for the presence of rats	To identify whether there is presence of rats in the household	Yes = 0 Rarely = 0.5 No = 1
		IPA = index for the presence of poisonous animals	To identify whether there is the presence of poisonous animals in the household	Yes = 0 Rarely = 0.5 No = 1
Socioeconomic indicator – **SEI**	SEI = (EDI + FII + UEI) / 3	**EDI** = education index	To identify the level of education of the head of the family	Illiterate = 0 Literate = 0.4 Elementary = 0.6 High school = 0.8 University education = 1
		FII = family income index	To identify the family salary range	Less than 1 salary = 0 Between 1 and 2 salaries = 0.5 Above 2 salaries = 1
		UEI = unemployment index	To identify the number of unemployed adults in the household	None = 1 1 person = 0.5 2 people = 0.4 Above 2 people = 0

cities. For the computation and tabulation of the data obtained, electronic spreadsheets of the software Excel® were employed. These data were subjected to a descriptive statistical analysis, which determined the mean value, mode, median, variance, and standard deviation for each indicator.

The questionnaire applied was structured, on a nominal scale, with the identification of each sub-indicator of EHIN, based on Menezes (2007), with adaptations performed for the conditions of local sanitation and infrastructure. The size of the statistical population was established in relation to the number of households in each neighborhood, obtained by information provided by the Treasury Department of the municipality registered in the Urban Property Tax.

Following the criteria adopted by Limeira, Silva and Cândido (2010), Nascimento, Figueira and Silva (2013), and Cunha and Silva (2014), the number of interviews was defined based on the plans of sampling and procedures presented by the standards NBR 5426 (ABNT, 1985a) and NBR 5427 (ABNT, 1985b). A total of 20 interviews was performed in neighborhood *A*, and 80, in neighborhood *B*, from the 3rd to the 24th of June, 2018.

Quality of water analysis

The procedures for the control and surveillance of the quality of water for human consumption and their potability standards are described in the Consolidation Ordinance No. 5 (BRASIL, 2017b), of September 28th, 2017, of the Brazilian Ministry of Health, that establishes acceptable values for bacteriological, organoleptic, physical, and chemical analyses. To compose the sub-indicator of water quality index, water collections were performed in the interviewed households (one per interview), during the period of application of the questionnaire in the neighborhoods (30 samples for neighborhood *A*, and 80 samples for neighborhood *B*). The samples were placed in previously sterilized flasks. For determining chlorine, a procedure was performed *in loco*, at the Laboratory of Environmental Engineering of the Agreste Campus of UFPE, with the help of a color disk kit for visual collimeter, as well as the physicochemical and microbiological analyses of the samples.

Analyses to determine turbidity, color, total, and thermotolerant coliforms were performed. The color analyses were conducted with a UV-VS spectrophotometer (Spectroquant® Pharo 300), whereas the turbidity analyses were performed using the turbidimeter model AQ3010 previously calibrated. The microbiological analyses for the determination of the most probable number (MPN) of total and thermotolerant coliforms were obtained with the Colilert test, approved by the Environmental Protection Agency and included in the Standard Methods for the Examination of Water and Wastewater. The technique of chromogenic substrate was employed, in which the culture medium is hydrolyzed by the specific enzymes of the coliforms and *Escherichia coli*, whose change in color after the incubation period determines the presence of the pathogen.

Results and Discussion

The interviews were performed the 3rd to the 24th of June, 2018. The adoption of a questionnaire with objective questions allowed the interviews to be, relatively fast, with a mean time of response of around five minutes.

For the computation and tabulation of the data obtained, and the construction of graphs, electronic spreadsheets from the software Excel® were used. The data used to calculate the second-order indicators were subjected to a descriptive statistical analysis, whose results are presented in Tables 3 and 4. In Figure 2, the conditions of the neighborhoods are shown to be similar, except for those referring to the indices of waste separation (WSI), of poisonous animals (IPA), and of unemployment (UEI). The results and the discussions for each sub-indicator are presented in the following sections.

Indicator for Water Supply

Both communities presented similar water supply coverage indices. The low values for SCI were expected because the water supply of the city has been intermittent for several years. In 2017, in the peak of the crisis, the state sanitation company (*Companhia Pernambucana de Saneamento – Compesa)* stipulated a rotation in the supply in which the population of Caruaru received water only seven days per month (SANTANA *et al*., 2019). The interviews indicated that 95% of the houses visited in neighborhood *A* received water from the company once per month.

Among those interviewed, around three fourths of the population reuses water from bath/wash for other purposes. In neighborhood *A*, the main source of drinking/cooking water were trucks with containers (60%), whereas in neighborhood *B*, 50% affirmed they bought water from trucks with containers, 43% used the sealed bottles, 5% the water from the dealership, and 2% had artisanal well (Figure 3).

In Table 5, the mean values of the concentration for turbidity parameters, color, and chlorine of the neighborhoods, determined by the laboratory analyses, are presented. The results demonstrated the precariousness of the quality used by inhabitants, the three parameters obtained values below the references established by the Brazilian Ministry of Health (BRASIL, 2017b). In Figure 4, boxplot graphs are presented, representing the distribution of the data observed.

From the analyses performed at the laboratory, 40% of the samples of neighborhood *A* presented thermotolerant coliforms, with a mean of 55.30 MPN and standard deviation of 167.22 MPN. In neighborhood *B*, this percentage was 33%, with mean of 38.85 MPN and standard deviation of 146.83 MPN. Besides that, 70% of the samples collected in neighborhood *A* had total coliforms, whereas in neighborhood *B* they were 57%. This justifies the score of zero for WQI, since the Consolidation Ordinance No. 5 (BRASIL, 2017b) establishes the absence of total and thermotolerant coliforms as the golden standard. These results can explain the high number of reported cases of diarrhea. In

2017, neighborhood *A* registered 712 cases, whereas in neighborhood *B* they were 3,117 cases (PREFEITURA DE CARUARU, 2018b). The other diseases related to water quality were not relevant to the study, namely: Hepatitis A had only one case notified in 2015, and there were no cases of cholera and schistosomiasis.

Indicator for Sanitary Sewage

For the calculation of the proposed indicator, the presence of a connection of the household to the public sewer network and the presence of a septic tank/sink were considered. In neighborhood *A*, 60% of the visited houses were connected to the sewer network, and

Table 3 – Results from the 2nd-order indicators for neighborhood *A*, Caruaru City, Pernambuco State, 2018.

Indicator	Sample mean	Median	Mode	Variance	Standard deviation
Service coverage index	0.50	0.50	0.50	0	0
Quality of water index	0.75	1	1	0.20	0.44
Water reuse index	0	0	0	0	0
Sewage destination index	0.80	1	1	0.06	0.25
Open sewage index	0.80	1	1	0.17	0.41
Waste collection index	0.57	0.50	0.50	0.04	0.19
Street sweeping index	0.27	0.30	0.30	0.06	0.24
Waste separation index	0.45	0	0	0.26	0.51
Waste disposal index	0.10	0	0	0.07	0.26
Index for the presence of the Dengue Fever virus	0.95	1	1	0.05	0.22
Index for Chikungunya	0.90	1	1	0.09	0.31
Index for the presence of rats	0.90	1	1	0.09	0.31
Index for the presence of poisonous animals	0.85	1	1	0.13	0.37
Education index	0.59	0.60	0.60	0.04	0.21
Family income index	0.23	0	0	0.12	0.34
Unemployment index	0.75	0.75	1	0.07	0.26

Table 4 – Results from the 2nd-order indicators for neighborhood *B*, Caruaru City, Pernambuco State, 2018.

Indicator	Sample mean	Median	Mode	Variance	Standard deviation
Service coverage index	0.51	0.50	0.50	0.01	0.11
Quality of water index	0.76	1	1	0.18	0.43
Water reuse index	0	0	0	0	0
Sewage destination index	0.98	1	1	0.01	0.11
Open sewage index	0.91	1	1	0.08	0.28
Waste collection index	0.50	0.50	0.50	0	0.02
Street sweeping index	0.26	0.30	0.30	0.04	0.20
Waste separation index	0.21	0	0	0.17	0.41
Waste disposal index	0.06	0	0	0.06	0.24
Index for the presence of the Dengue Fever virus	0.90	1	1	0.09	0.30
Index for Chikungunya	0.85	1	1	0.13	0.36
Index for the presence of rats	0.89	1	1	0.10	0.32
Index for the presence of poisonous animals	0.66	1	1	0.18	0.42
Education index	0.55	0.60	0.60	0.06	0.24
Family income index	0.32	0.50	0	0.11	0.33
Unemployment index	0.66	0.50	1	0.12	0.35

40% had septic tank/sink. In certain sections of the neighborhood, a big difference in the sanitary conditions of neighboring blocks was noticed: on one side, healthy conditions and, on the other side, unhealthy conditions. Neighborhood *B* presented 95% of the houses connected to the collection network and from them, 5% affirmed they had septic tank/sink. Therefore, the sub-indicator SDI was equal to 0.80 and 0.98 in neighborhoods *A* and *B*, respectively.

Indicator for Solid Waste

The waste collection system in both neighborhoods has a weekly frequency of collection. In neighborhoods *A* and *B*, 80 and 99% of the houses were served by the collection system of Caruaru City Hall, respectively. Even with the weekly frequency of waste collection, the population had the habit of disposing of their waste at a time close to the collection, to avoid that animals would touch the bags. Therefore, there was no waste close to households in both neighborhoods. Around 85 and 94% of households in neighborhoods *A* and *B* let their waste on the floor until the moment of collection, respectively. The waste observed *in loco* derived from building renovations, characterized as civil construction waste, and was found in lands without occupation.

According to the people interviewed, the sweeping of the streets was unsatisfactory, since in neighborhood *A*, 55% of streets in which

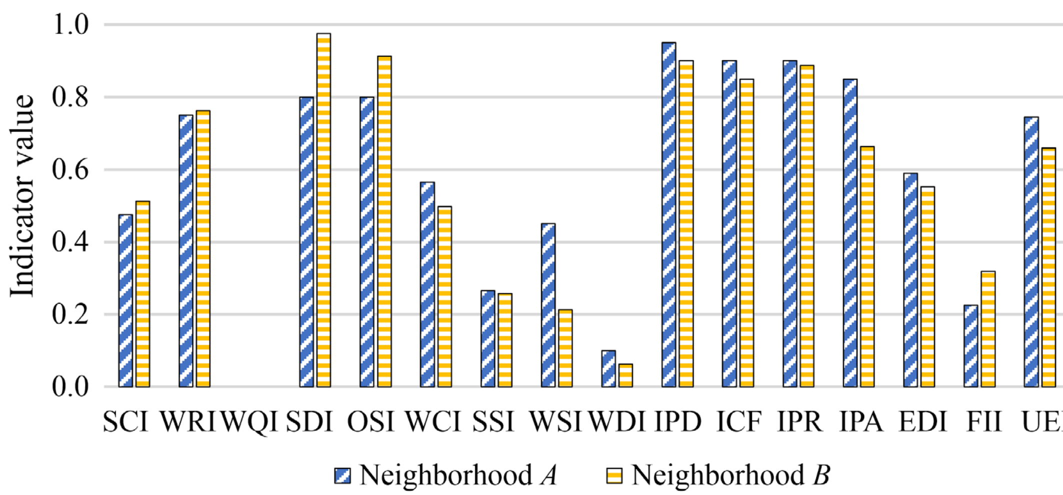

Figure 2 – Second-order indicators for neighborhoods *A* and *B*, Caruaru City, Pernambuco State, 2018.

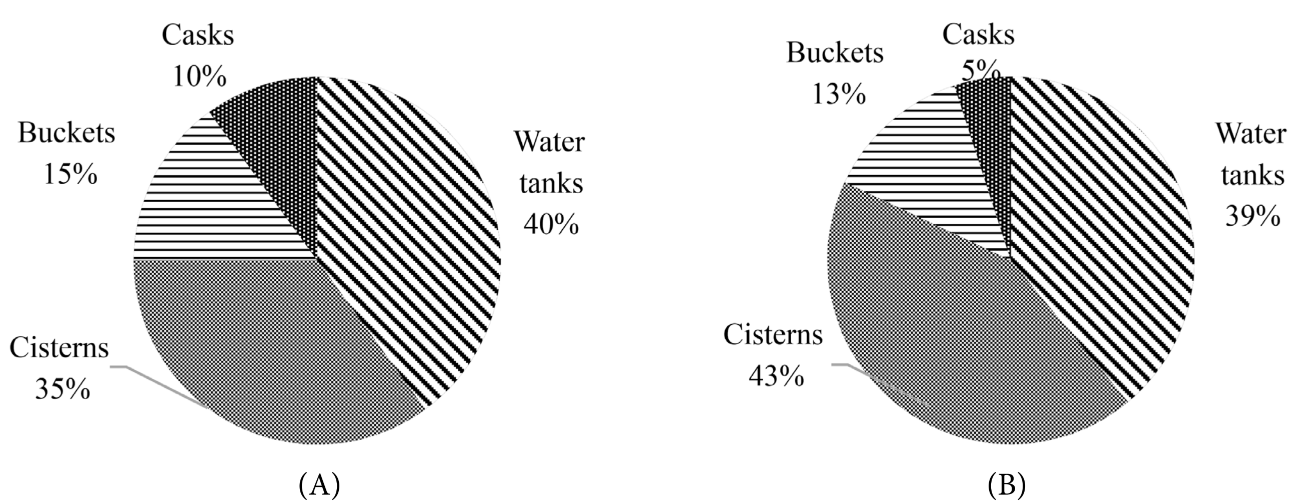

Figure 3 – Main types of storage: (A) NEIGHBORHOOD *A* and (B) neighborhood *B*.

interviews were conducted the service was rarely performed; in neighborhood *B*, it corresponded to 40%. The service was never performed in 30 and 31% of the streets in neighborhoods *A* and *B*, respectively. The reports indicated that inhabitants themselves were responsible for sweeping sidewalks. The presence of places with vacant lots and the absence of sweeping and weeding were noticed, factors which provide places favorable to the development of the mosquito responsible for the virus of Dengue Fever and Chikungunya.

Data collection for the determination of ISW indicated the need for the implementation of permanent environmental education programs aiming at population awareness, regarding the disposal of civil construction waste on lands without occupation. A partnership can be established with associations of waste collectors to encourage recycling, besides implementing voluntary delivery points for the population to safely pack the waste. Some neighborhoods in Caruaru have containerization systems to prevent the accumulation of waste on the main roads. This system has been presenting good results, and the protection of garbage from weather variations, odor elimination, and reduction in insect proliferation are among the benefits. The rise in the frequency of sweeping the streets is also indicated to avoid the proliferation of venomous animals and the mosquito that transmits arboviruses.

Indicator for the Control of Vectors

The vector infection rates in the last six months indicated that the greater proliferation of the mosquito *Aedes Aegypti* in Caruaru City occurred in neighborhoods *A* and *B*. These neighborhoods are in the range of high risk of outbreak when 2015 and 2017 are analyzed (PREFEITURA DE CARUARU, 2018a). Given the intermittence in public water supply, the neighborhoods have many household reservoirs (water tanks). Around 40% of the houses in neighborhood *A* stored water in water tanks, and in neighborhood *B*, 43% used cisterns. This strategy is used to circumvent the lack of continuous supply, which, according to Fiocruz (2016), contributes to the proliferation of the mosquito that is the vector of the diseases analyzed. Resendes *et al.* (2010) claim that the association between the risk of Dengue Fever transmission and the social conditions require attention when the municipality is analyzed together with other variables, such as: degree of population immunity, effectiveness of control measures, degree of infestation by the vector, habits and behaviors of the population.

The highest indices of the presence of the virus of Dengue Fever (DENV) were registered in neighborhood *B*. Because of the greater number of inhabitants, there was an increase from 59 cases to 105, from 2015 to 2016, and a reduction to 12 cases in 2017. From 2015 to 2016, neighborhood *A* registered a fall, from 39 cases to 14, which decreased to 7 confirmed cases

Table 5 – Parameters of water quality in neighborhoods *A* and *B*, Caruaru-PE, 2018. Sample size: 30 (neighborhood *A*) and 80 (neighborhood *B*).

Parameter	Neighborhood *A*	Neighborhood *B*	Reference from the Consolidation Ordinance No. 5/2017
Turbidity (NTU)	4.61	1.06	Maximum value of 0.5 NTU
Color (uH)	45.45	16.55	Maximum value of 15 uH
Chlorine (mg/L)	0.36	0.76	Minimum value of 0.5 mg/L

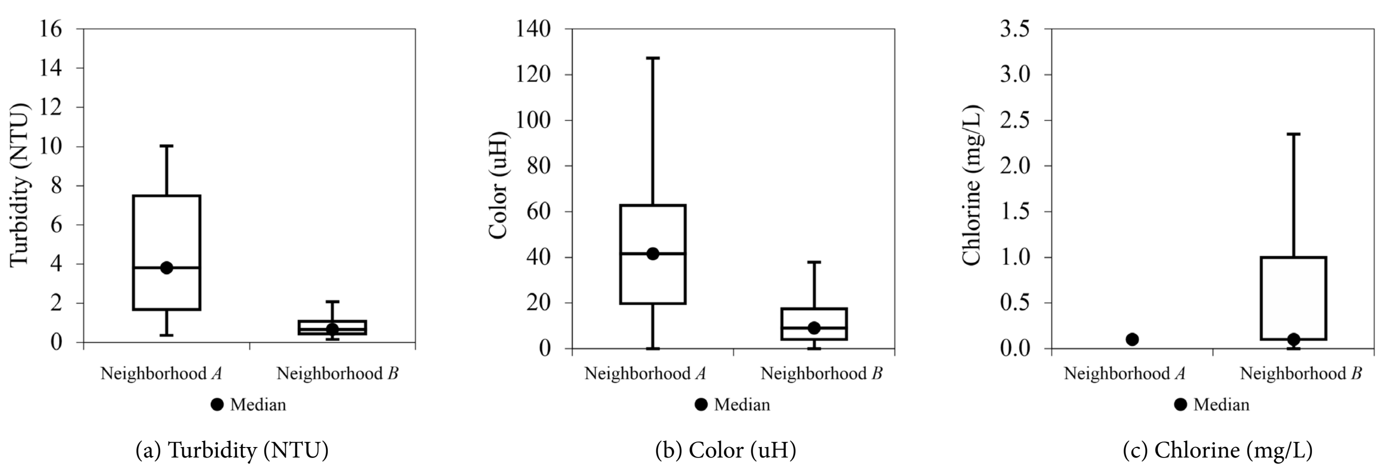

Figure 4 – Distribution of the values of the water quality parameters in neighborhoods A and B.

in 2017 (PREFEITURA DE CARUARU, 2018a). The fall in the number of cases was also verified in Pernambuco State between 2016 (57,259 cases) and 2017 (7,431 cases) (PREFEITURA DE CARUARU, 2018a). Oliveira *et al.* (2017) indicate that once the individual is primarily contaminated by the virus of Dengue Fever, a long-term immunity against the same serotype will occur. This suggests the decrease between 2016 and 2017.

The first reports of the virus of Chikungunya in Caruaru City occurred in 2015. In the period of data collection, the neighborhoods registered considerable increments in the rates of the disease during 2015 and 2016, a fact which evidences that several states of the Northeastern region presented Chikungunya fever outbreaks, which shows the increase in 2016 (277,882 probable cases), which were 20,901 cases in the country in 2015 (BRASIL, 2017a). During the research period, neighborhood *A* registered 44 confirmed cases, whereas neighborhood *B*, 47 (PREFEITURA DE CARUARU, 2018a).

The comparison of the results of the questionnaire application and the confirmed cases by the Caruaru Health Secretariat demonstrates that there is a difference between the understanding of the population and the effective confirmation by the health institution. For instance, there were 800 notified cases of Dengue Fever in Caruaru City in 2017; nevertheless, only 148 were confirmed. Similarly, for Chikungunya, 399 cases were notified, of which only 180 were confirmed. Oliveira *et al.* (2017) affirmed that the epidemiological data on the diseases caused by the viruses of Dengue Fever and Chikungunya are difficult to interpret, because the Chikungunya virus was not included in the universal notification system, and it also presents similar clinical characteristics in the acute phase.

Silva *et al.* (2017) conducted the study on the correlation between the environmental health index and indices of diseases related to sanitation services. The comparison was performed among the first-order indices obtained in 18 neighborhoods in the urban area of Maceió City (Alagoas State). With this study, the authors concluded that the major indices were: Dengue Fever, Hepatitis, and Leptospirosis. Nonetheless, when the direct correlation between EHI and the diseases was performed, the results were not satisfactory because of the linking of data between information on health (per neighborhood) and the provision of basic sanitation services (per census sector). The authors emphasized three possible causes for the low correlation: the absence of correlation between EHI and the diseases; spatial resolution determination for the correlation and the conflict between data acquisition by the neighborhoods and IBGE Demographic Census; or the indicators not being satisfactory to represent the reality of the study region.

In neighborhood *A*, only one household reported one confirmed case of Dengue Fever, and two households reported two cases of Chikungunya, whereas in neighborhood *B*, eight residences informed that there were confirmed cases of Dengue Fever, and 24 family members had Chikungunya. In 10 and 12% of the visited places, there was the presence of standing water close to the household in neighborhoods *A* and *B*, respectively.

After the analysis of other vectors of diseases, 40% of the people interviewed from neighborhood *A* had pets. In this neighborhood, around 45% affirmed there was the presence of rats, 90%, of cockroaches, and only 15%, of poisonous animals (snakes, scorpions, etc.). In neighborhood *B*, 52% of households did not have pets, 47% claimed there was the presence of rats, 64%, of cockroaches, and 24%, of poisonous animals.

Socioeconomic Indicator (SEI)

When the social aspects were analyzed, the education level, family income, unemployed adults, and the number of residents in the household were considered. 50% of the people interviewed in neighborhood *B* had complete elementary school, 23% had complete high school, and only one person interviewed claimed having higher education. In neighborhood *A*, there was the same number of people interviewed with complete elementary and high school (35%), and no residents with higher education. Regarding the income *per capita*, neighborhood *A* presented the mean value of R$ 507 per month, whereas neighborhood *B*, R$ 525. As to unemployed adults, 45% of the people interviewed affirmed that there was one adult who was not working in neighborhood *A*, and in 50% of households, there were no unemployed people. In neighborhood *B*, 44% claimed that only one person was unemployed in their household, and in 46%, there were no unemployed people. Regarding the number of residents, most households had more than two residents, in neighborhood *A* (55%) and in neighborhood *B* (68%).

Results of EHIN

The neighborhoods evaluated were categorized as medium health, according to the range established by Dias, Borja and Moraes (2006), with the values of EHIN equal to 0.56 and 0.57, for neighborhoods *A* and *B*, respectively. When the individual analysis of the first-order indicatives was performed (Table 6), both neighborhoods were classified with low health in the indices of water supply and solid waste, demonstrating the deficit in the services offered to cities inhabitants.

The water quality index, whose score was zero for both neighborhoods, is one of the items that demonstrate urgency for interventions from the public sector since it directly affects the population. The results reflect the expressive number of confirmed cases of diarrhea from 2015 to 2017, which suggests a growing trend in both neighborhoods.

Regarding the indicator for solid waste, the indices for street sweeping (SSI) and waste disposal (WDI) presented characteristics of low health. In neighborhood *A*, the waste separation index presented a score of 0.45, whereas it was 0.21 in neighborhood *B*, which demonstrates that the people interviewed perform the separation in their households, although the public power does not conduct selective collection in the city.

The indicator for the control of vectors, for both neighborhoods, was observed as healthy, considering that the questionnaire referred to sickness in the last six months. Regarding the socioeconomic conditions, a low level of education of respondents was observed and, especially, income *per capita* below a minimum wage, which reflects in a low score of the socioeconomic indicator.

Table 6 – Individual score for the indicators of neighborhoods *A* and *B*, Caruaru City, Pernambuco State, 2018.

Indicator	Individual score		Salubrity
	Neighborhood *A*	Neighborhood *B*	
Indicator for water supply	0.41	0.43	Low salubrity
Indicator for sanitary sewage	0.80	0.94	Healthy
Indicator for solid waste	0.35	0.26	Low salubrity
Indicator for the control of vectors	0.90	0.83	Healthy
Socioeconomic indicator	0.52	0.51	Medium salubrity

Final Considerations

The success of implementing public policies is directly related to the management capacity of the institutions, the strategies adopted, the budgetary and financial availability, and managers' support to the actions. In this context, the Environmental Health Indicator for Neighborhoods (EHIN) is an instrument of environmental planning and management to help public policies, which can guide the actions of public managers and the civil society.

Based on information obtained *in loco* and the water quality analyses, both neighborhoods evaluated presented characteristics of medium health. The results demonstrated that the assessment of water supply, solid waste, and socioeconomic indices require a greater attention and priority from public policies. The adoption, of actions directed to the improvement of water supply, particularly regarding the quantity and quality of water available to the population, is suggested. The quality of water consumed is low, because the population uses alternative sources for water consumption. The role of the institutions of the civil society to change the scenario described by research is highlighted, by population awareness and adoption of practices such as recycling, water reuse, among others.

EHIN presented satisfactory results and reflected the reality of the neighborhoods evaluated. It is an efficient management tool for the decision-making of public managers because it established technical criteria to prioritize sectors with worse environmental and housing conditions. Furthermore, EHIN is an efficient tool for the planning and management of structural and non-structural actions of environmental sanitation in the urban network. Integrated public policies can be formulated from the factors identified as unhealthy by the indicators in this study. Therefore, this indicator is expected to be adopted in the evaluation of environmental health of neighborhoods, initially for any Brazilian city, since the determination of the sub-indicators is based only on interviews, and in the laboratory analysis of color, turbidity, and chlorine concentration in the water.

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Contribution of authors:

Duarte, A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Writing — review & editing.
Bezerra, S.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing — review & editing, Supervision, Project administration.
Gonçalves, E.: Conceptualization, Methodology, Validation, Formal analysis, Writing — review & editing.

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Comparative evaluation of performance and usability of small-scale household composting with different geometric models

Avaliação comparativa de desempenho e usabilidade de composteiras domésticas com diferentes modelos geométricos

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ABSTRACT

The evaluation of layout influence on the operational performance and usability of small-scale composters contributes to produce compact solutions with simplified operation and sanitary safety, suitable for reduced spaces and continued use. This study aims to report the influence of different designs on the composting process and the usability of compost bins. Five composters of similar scale (3 liters) and different geometric shapes were designed, manufactured, and tested. Bench tests were carried out for 60 days, and physical, chemical, and sanitary parameters were monitored, as well as the quality of the compost, according to agronomic parameters. The composters were filled with the same proportions of organic residues (food residues, dry leaves, and lawn trimming) to obtain the ideal C:N ratio. Three geometrical layouts were tested concerning usability (hexagonal prism, cube, and parallelepiped) by volunteers for 50 days. The performed tests associated with the statistical treatment of results showed that the geometry of the prototypes interfered with the quality of the final compost and the composter operation. The hexagonal prism and the cube showed greater usability. The results represent a significant contribution to the advancement of solutions in decentralized composting.

Keywords: organic solid waste; valorization of solid waste; small-scale composting; composting bins; design.

RESUMO

A avaliação da influência do layout no desempenho operacional e na usabilidade de composteiras de pequena escala contribui para a obtenção de soluções compactas, de operação simplificada e sanitariamente seguras, adequadas a espaços reduzidos e uso continuado. Este artigo teve como objetivo relatar a influência de diferentes modelos geométricos no processo de compostagem e na usabilidade de composteiras. Cinco composteiras de escala similar (3,0 litros) e diferentes modelos geométricos foram projetadas, confeccionadas e testadas. Foram realizados testes de bancada por 60 dias, monitorando parâmetros físicos e químicos, aspectos operacionais e sanitários e a qualidade do composto segundo parâmetros agronômicos. As composteiras foram preenchidas com as mesmas proporções de resíduos orgânicos (resíduos alimentares, folhas secas e aparas de grama) para obter a relação C/N ideal ao início do processo. Três *layouts* geométricos de composteiras foram testados quanto à usabilidade (prisma de base hexagonal, cubo e paralelepípedo) por voluntários durante 50 dias. Os testes em bancada associados ao tratamento estatístico dos resultados permitiram verificar que a geometria dos protótipos interferiu na qualidade do composto final e na operação da composteira. Os modelos geométricos de base hexagonal e cubo mostraram-se de maior usabilidade. Os resultados representam contribuição significativa para o avanço de soluções na compostagem descentralizada.

Palavras-chave: resíduos sólidos orgânicos; valorização de resíduos sólidos; compostagem descentralizada; equipamentos para compostagem; *design*.

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Introduction

Minimizing and valuing domestic waste are important strategies to address the challenges of solid waste management in the cities. Several countries adopt public policies concerning organic waste, also known as food waste, which expands the discussion on issues of combating hunger and sustainability, aligned with the Sustainable Development Goals (SDGs) 1 and 11 of the agenda approved by the United Nations for sustainable development, called "Agenda 2030" (ONU, 2015).

Organic waste is part of household waste composition and has an indirect relationship with the socioeconomic conditions of its generators. On average, the percentage of organic waste generated in developed countries (34.32%) is lower than in developing countries (61.33%) and underdeveloped countries (64.21%) (FEIL; SPILKI; SCHREIBER, 2015).

Although it has great potential, organic waste has not been prioritized for recovery due to lack of specific segregation and considerable operational costs for its treatment. Once disposed of together with common waste, it represents a significant volume to be collected and transported to landfills, reducing its useful life and increasing the operational costs of these procedures. When discarded in an environmentally inappropriate manner, it can cause environmental impacts with effects on human health due to the degradation that generates leachate (an unpleasant odor) and attracts and proliferates disease vectors (GÜNTHER, 2005).

Dutra, Medeiros, and Gianelli (2019) indicate composting as an alternative to reduce negative environmental impacts resulting from the transport and final destination of organic waste. Siqueira and Assad (2015) also highlight its importance in the return of nutrients to agroecosystems. The authors point out the need for identifying and characterizing different modalities of composting municipal solid waste (MSW), as an encouragement to create new technological routes and to diversify waste management systems in municipalities.

In 2018, the destination of 62.78 million tons of MSW collected in the country registered 74.35% for proper disposal (landfills), 23.97% for inadequate disposal (controlled landfills and dumps), 1.49% for selective collection, and only 0.19% for composting. This distribution indicates the insufficiency of public policies aimed at recovering the organic portion of MSW (SNIS, 2017).

Countries concerned with sustainability in MSW management have an efficient system of waste sorting. However, the lack of organic waste segregation at source is a major problem in developing countries, considering that organics are collected as common waste and sent for final disposal with household residues through the regular municipal collection. Therefore, avoidable expenses are generated, as the organic matter could be separated at the source and sent for specific treatment (IPEA, 2018), which is the case of composting.

The National Solid Waste Policy (PNRS) is Brazil's main regulatory framework for the sector and presents composting as an alternative to the final disposal of organic waste. Waste hierarchy involves the following procedures: non-generation of waste, reduction, reuse, recycling, solid waste treatment, and environmentally appropriate final disposal of waste. Thus, composting becomes an interesting option and it is prioritized as a way of treating organic waste. In addition to promoting the recovery of organic waste and valuing it, composting is configured as an environmentally appropriate destination that avoids waste disposal in the soil (BRASIL, 2010).

The application of the composting technique is directly linked to the strategies of waste prevention, waste reduction, smart cities, and zero waste program (EUROPEAN COMMISSION, 2016). In the current environmental context, citizens play a fundamental role in minimizing waste. Individuals should decide whether or not to separate one's waste and send it to the different and specific final destinations available and focused on its recovery.

In a study carried out in the city of São Paulo, Siqueira and Assad (2015) proposed to classify composting as centralized and decentralized, with the latter subdivided into institutional, home, and community composting. Decentralized composting is still underexplored in Brazil, but presents itself as an alternative through a simplified and low-cost process (social technology).

Factors related to the practice of decentralized composting

Decentralized composting has been increasingly accepted in urban centers and can take place directly on the ground following minimum criteria or with the use of specific equipment, called compost bin or composter, that can be either homemade or manufactured (domestic/household composting). There are several models of composters on the market, from manual to automated, with or without the incorporation of earthworms or biological accelerators. It is believed that cost, operational simplicity, compatible size, aesthetics, and geometry are determining factors in the users' choice of the model (JAYAPRAKASH; LOHIT; ABHILASH, 2018).

Experience reports provided by several authors indicate that the use of the domestic composter demands dedication and knowledge of the technique for users' effective satisfaction and for the continuity of the process.

In a study carried out by Faverial and Sierra (2014), in which composters were tested by volunteers for 84 days, 32% of the participants reported difficulties in maintaining home composting due to the presence of vectors, foul odor, leachate generation, and lack of space in homes to suitably place the equipment. Most of the volunteers impacted by these factors have chosen to discontinue the use of the composter. Similar problems related to the use of composters in domestic environments have been reported in studies carried out by Bench *et al.* (2005), Smith and Jasim (2009), Lléo *et al.* (2013), Metcalfe *et al.* (2012), and Margaritis *et al.* (2018), which reinforce the need to take users' perception into account when designing equipment for composting. According to Catecati *et al.* (2018), such evaluations subsidize and impact decisions about the final product and influence the users' experience. Thus, the importance of linking composting to the concept of usability must be highlighted. This concept is used to define the ease with which people can employ a tool or object to perform a specific task (ISO, 1998).

To produce compact solutions suitable for environments with reduced space, it is essential to understand how the geometric model of the composter interferes with operational performance and usability. This aspect can improve the relationship between users and the equipment and enable the continuity of small-scale composting.

In this context, the purpose of this study was to optimize the physical characteristics of the composting bins for decentralized composting in residential and institutional environments considering the users' perception as a fundamental role to enhance the use of this sustainable practice.

Method

The research was developed in three methodological stages as illustrated in Figure 1. In the first stage (S1), the experimental apparatus, made of 5 composter prototypes, was developed. Then, in the second stage (S2), the developed models have been filled with residues and submitted to bench tests for 60 days to assess performance concerning sanitary aspects and the Normative Instruction of the Secretariat of Defense and Agriculture (SDA) of the Ministry of Agriculture, Livestock and Supply (MAPA) SDA/MAPA 25/2009(BRASIL, 2009). In the third stage (S3), the three models with the best performance were simultaneously filled up and operated by five users in a domestic environment for 50 days to assess the usability concept. In the end, an integrated analysis of results from stages S2 and S3 was carried out and discussion based on a bibliographic survey was performed.

The bench tests and analysis were carried out in the laboratories of the Federal Institute of Espírito Santo (Ifes) Campus Vitória, in the Research, Innovation and Development Center (CPID) of the State of Espírito Santo and in a specific laboratory specialized in the agronomic analysis.

Development of the Experimental Apparatus (S1)

As a result of the bibliographic review, handcrafted small-scale composters developed by 25 researchers were found, presenting different physical characteristics and the experimental design used in each study. Marketing research carried out in the first half of 2019 on websites of national and international manufacturers and resellers of domestic composters resulted in 42 models of different brands available and their respective physical characteristics. Tabulation and joint analysis of these results were the basis for the selection of five different geometries, used in the making of the experimental apparatus (the prototypes of the studied composters).

Prototypes were designed with a capacity of approximately 3 liters each, in order to maintain the scale with the use of the SolidWorks 2016 software version 9000 (SOLID WORKS, 2016). This capacity aimed to adequate studies on laboratory benches and facilitate the handling of prototypes. The prototypes were made with a 3-mm thick transparent acrylic and each model received nine 4-mm holes at the bottom for aeration and drain of any percolated liquid. A ruler was internally fixed to assist in the monitoring of the volume reduction of waste during the process, and a protection screen was installed at the top of the prototypes for insect protection. The experiment was carried out with five replicates for each of the five selected geometries, ending up in 25 geometric models (S2). The dimensions and layouts of the composter prototypes (experimental apparatus) are shown in Table 1 and Figure 2.

Bench test (S2)

To start the experiment, the composter prototypes were filled in batches using the same mixture of organic residues and prepared in order to obtain the ideal carbon/nitrogen ratio (C:N ratio) to start the process that, according to Kiehl (2004), is around 30:1. Proportions of residues were calculated by Equation 1, according to Massukado (2016), using the following equation for the calculation of the ideal C:N ratio (initial ratio of 30:1):

$$Ratio\,\frac{C}{N} = \left(Q_1 x\, RCN_1 + Q_2 x\, RCN_2 + \cdots + Q_n x\, RCN_n\right)/\left(Q_1 + Q_2 + Q_n\right) \quad (1)$$

Q = amount of waste by type;

RCN = used C:N ratio of waste.

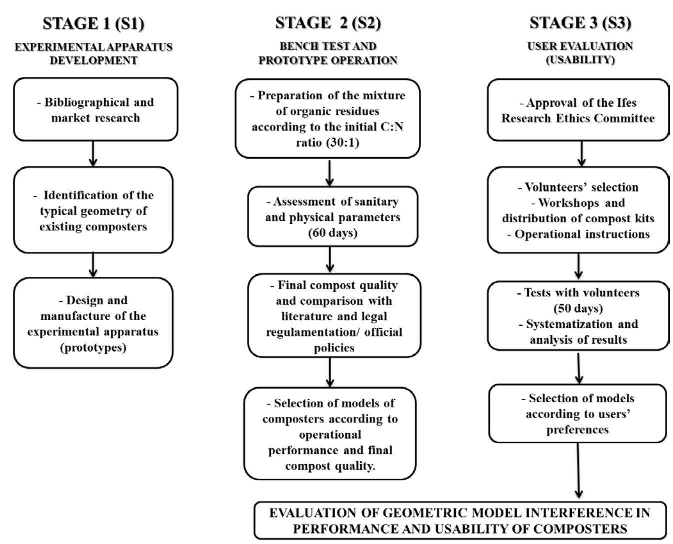

Figure 1 – Methodological stages.

Table 1 – Geometry and dimensions of the researched prototypes.

Geometry	Dimensions (m)
Cylinder (P_1)	0.075 (radius) × 0.170 (height)
Hexagonal prism (P_2)	0.080 (base edge) × 0.150 (height)
Triangular prism (P_3)	0.180 (base edge) × 0.180 (height)
Cube (P_4)	0.144 × 0.144 × 0.144 (edges)
Parallelepiped (P_5)	0.170 (width) × 0.120 (depth) × 0.150 (height)

The values of the C:N ratio used in the calculation are shown in Table 2.

The organic waste used in the experiment was collected in the restaurant of the institution that hosted the research. Dry leaves and yard trimmings were also collected in the institution. The residues were chopped, homogenized, and the used quantity and proportions are shown in Table 3. The preparation of the residues and the monitoring of the prototypes are illustrated in Figures 3 and 4, respectively.

As proposed by Arrigoni *et al.* (2018), the experiment was monitored three times a week with intervals of 48 to 72 hours. Sanitary aspects, such as the presence of vectors, leachate, foul odor, and mold, were monitored, as well as the internal and external temperature parameters, for which a thermo-hygrometer was used (Incoterm, model 7664, accuracy of 1% for moisture and 1°C for temperature). A reduction in the volume of residues was also recorded during the decomposition process, and the amount of leachate was measured with the aid of a 50-mL graduated cylinder. As proposed by Guidoni *et al.* (2018), the resulting compost was analyzed according to the references found in the bibliographic search and the Normative Instruction 25/2009 (BRASIL, 2009) at the end of 60 days of carrying out the experiments.

Table 2 – C:N ratio of residues used to calculate the proportion of organic compounds used in the sample.

Residues	C:N ratio	Reference
Vegetables scraps	25:1	Planet Natural (2018)
Fruit scraps	35:1	Planet Natural (2018)
Sawdust	132:1	Carry on Composting (2019)
Leaves	40:1	Microtack (2019)
Grass	25:1	University of Missouri (2010)

Table 3 – Proportions of organic waste used in the experiment.

Residues	Total mass (kg)	Mass per prototype (g)	Distribution (%)
Vegetable peelings	3.850	154.270	51.42
Fruit waste	1.710	68.580	22.86
Sawdust	0.210	8.550	2.85
Dry Leaves	0.428	17.130	5.71
Grass clippings	1.280	51.420	17.14
Total	7.500	300.000	≈ 100.00

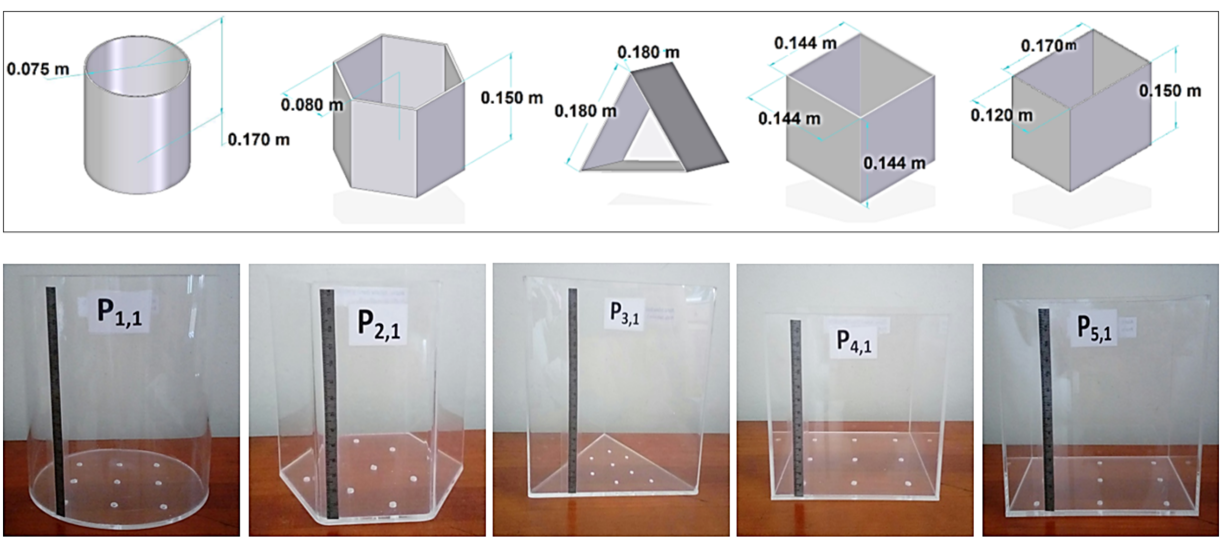

Figure 2 – Layout of the researched composter prototypes.

Figure 3 – Organic waste preparation for the assembly of experiments. (A) Chopped vegetables and fruits; (B) addition of crop residues (dry leaves and grass); (C) manual mixing of residues.

The results of variables and parameters of the final organic compound were analyzed by statistical tests performed with the Statistical Data Analysis SPSS software, version 20 (IBM, 2016). The used experimental design was completely randomized, with five treatments and five repetitions (S2). Data were submitted to variance analysis and the treatment averages were compared using the Tukey's test at a 5% probability level. The parameters analyzed during S2 are shown in Table 4.

At the end of the second stage, the researchers selected the three geometric models that presented the best results according to the legal requirements for organic compost (BRASIL, 2009) and sanitary aspects observed during the monitoring.

Users' evaluation (S3)

To identify aspects that interfere in the daily and regular use of composters and consequently be able to propose improvements, five volunteers from the Ifes academic community (Campus Vitória), including students and employees, were selected and each of them received the three best performing models defined in S2. The three selected geometric models were tested in parallel by the five volunteers for 50 days, totaling 15 prototypes tested in the S3.

To determine factors related to the insertion of composting in the daily routine of ordinary people, the volunteers' selection process prioritized participants inserted in the labor market and without training in environmental subjects. The performance of this stage was approved by the Institutional Research Ethics Committee of Ifes. The profile of the selected volunteers is shown in Table 5.

Preparatory workshops were previously carried out to answer any necessary questions and provide a composting kit and guidelines regarding the experiment to each volunteer. The delivered kit contained three geometric models of composter prototypes, monitoring sheets, standard dry organic waste (composed of earth and sawdust), water sprinkler, spoon, the base for collecting leachate, a protection net, rubber bands (against vectors), and a container for packing organic waste. The WhatsApp mobile application was used throughout this stage to support the volunteers in solving any necessary issue and providing information to researchers such as monitoring tables and photographic records. The kit delivered to each participant and the workshop are illustrated in Figure 5.

Results

Selection of geometry based on bibliographic studies and marketing research

The results of the bibliographic studies and marketing research enabled to identify the main geometric models that were being used in the design of homemade and industrial composters (Table 6).

Geometric models with a rectangular and cylindrical base were selected for the study because they were more common in both bibliographic and marketing research. On the other hand, the hexagonal model was chosen for tests due to the notoriety obtained in the marketing research. Composters with trapezoidal and spherical geometry were also identified in the survey; however, due to budget constraints, they were not tested.

Considering that five different models would be tested, the cube (square base) and the triangular prism were added to the previously three selected models, as the former results in a more compact equipment and the latter enables the modulation of equipment (fitting more than one composting unit in parallel), making it flexible to meet different types of environments.

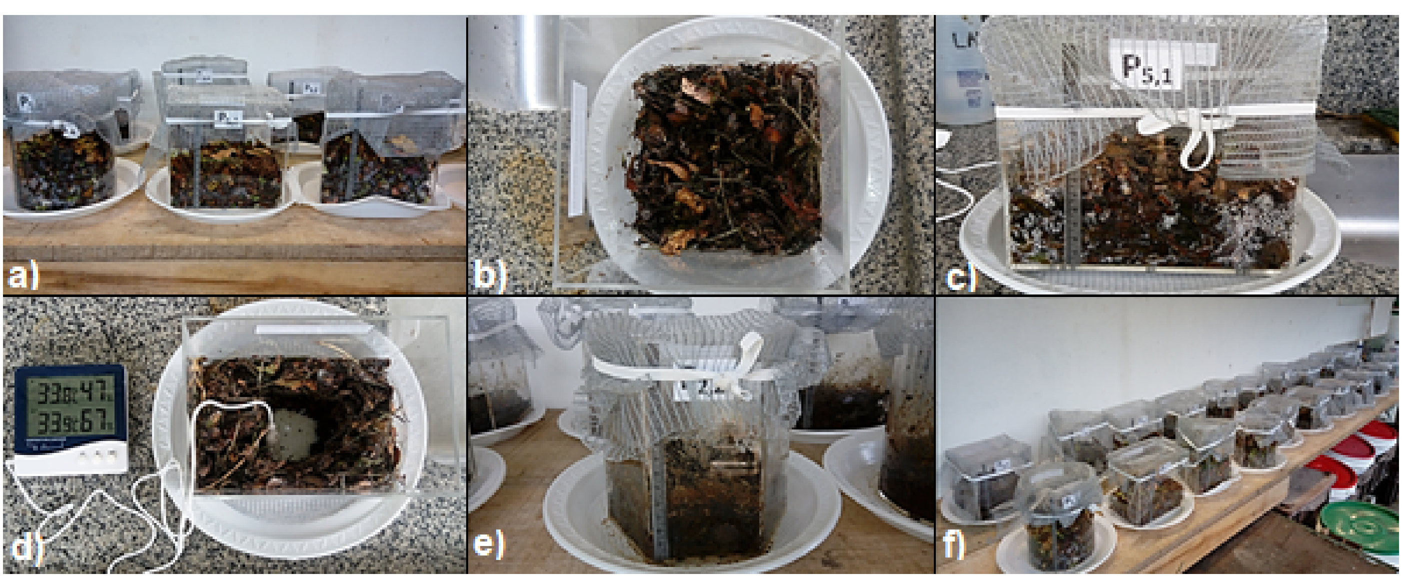

Figure 4 – Laboratory bench test monitoring. (A and F) View of the experiment installed on a laboratory bench; (B) internal view of the prototype in operation; (C and E) front view of prototypes and detail of the sanitary control screen; (D) monitoring of moisture and temperature using a thermo-hygrometer.

Table 4 – Parameters analyzed in stage 2 (S2) of the experiment.

Period	Parameters	Analysis methodology
Starting the experiment (T_0)	Mass	Scale (model SF 400, 10 kg capacity)
	Volume	Level measurement
	External (environment) and internal (prototypes) temperature and moisture	Thermo-hygrometer
	pH	*Standard Methods* (APHA, 1998)
	Conductivity	
	moisture	Gravimetric analysis (NBR 10664/1989) (ABNT, 1989)
	Total, Fixed, and Volatile Solids	
Monitoring (3 times a week)	Volume	Level measurement
	Sanitary aspects	Observation
	External (environment) and internal (prototypes) temperature and moisture	Thermo-hygrometer
60 days (T_{60}) – Compost	Mass	Scale
	Volume	Level measurement
	Sanitary aspects	Observation
	External (environment) and internal (prototypes) temperature and moisture	Thermo-hygrometer
	pH	*Standard Methods* (APHA, 1998)
	Conductivity	
	Amount of organic carbon	Handbook *Manual de Métodos Analíticos oficiais para Fertilizantes e Corretivos* (BRASIL, 2017)
	Total of nitrogen	
	C:N ratio	
	Moisture (compost)	Gravimetric analysis (NBR 10664/1989) (ABNT, 1989)
	Total, Fixed, and Volatile Solids	

Bench test stage (S2)

In stage 2, the five geometric models had their performance tested and evaluated considering the final compost achieved by each model and its sanitary and operational aspects.

The initial mass of organic waste (300 g), equally added to all prototypes, was reduced due to degradation and transformation into organic compost, which resulted in the final average mass values of compost presented in Table 7.

According to the results, the P3 model (triangular prism) presented the lowest amount of final mass, reaching the highest mass reduction (84.54%), whereas the P5 model (parallelepiped) had the lowest mass reduction (78.58%). According to Onwosi *et al.* (2017), the reduction in mass is related to the decrease in moisture content and the decomposition of organic matter.

At the end of the bench tests (S2), samples of compost (50.0 g) obtained from each prototype model were sent to a laboratory specialized in agronomic quality tests (organic carbon, total nitrogen, and C:N ratio). The results indicated satisfactory agronomic characteristics, according to Brazilian regulations (BRASIL, 2009), for all geometric models.

Regarding the pH of the final compost, most geometric models presented a basic character (variation from 8.2 to 9.9), which behavior is similar to the one observed by Guidoni *et al.* (2018) and Tatàno *et al.* (2015), who obtained results between 8.0 to 10.0, also following the Normative Instruction SDA/MAPA 25/2009 (BRASIL, 2009).

Concerning moisture levels, all 25 prototypes produced organic compost in compliance with the Normative Instruction SDA/MAPA 25/2009 standard (maximum of 50%) (BRASIL, 2009). The initial moisture of the organic mass was 71%, but it decreased over the 60 days of the experiment, resulting in final compost values that ranged from 12% to 15%.

The electrical conductivity ranged from 0.43 to 0.71 mS/cm at 25ºC, which were lower numbers when compared with those found by Arrigoni *et al.* (2018) (from 2 to 5 mS/cm), Tatàno *et al.* (2015) (from 2 to 5 mS/cm), and Lléo *et al.* (2013) (1.9 ± 0.2 mS/cm at 25ºC). This

Table 5 – Profile of volunteers for the usability test of composter models.

Participant Profile	Volunteers				
	V1	V2	V3	V4	V5
Age (years)	29	25	38	57	28
Sex	Male	Male	Male	Male	Female
Major in	Engineering	Engineering	Engineering	Physics	Chemistry
Currently working?	No	No	Yes	Yes	Yes
Type of residence	Apartment	Apartment	House	Apartment	House
Number of residents	3	3	3	3	4
Individual eating routine	Restaurant	At home	At home	Restaurant	At home
Family eating routine	At home	At home	At home	Restaurant	At home
Previous experience with composting	No	No	No	Yes	No

difference in results can be justified due to differences in the composition of the standard waste used in the prototypes and variations in the methodologies used in the studies.

Regarding the minimum value of 15% organic carbon in the final compound required by the Normative Instruction, all geometries and prototypes complied with such regulation (31.18 to 41.18%). The obtained values were similar to the ones observed by Tatàno *et al.* (2015), which ranged from 28 to 38%.

The results also showed that all tested models achieved the minimum value of nitrogen established in the Normative Instruction (0.5%), with results ranging between 2.14 and 2.77%, but did not reach the same numbers of Tatàno *et al.* (2015), who obtained values ranging from 2 to 4%. The difference can be due to the initial composition of residues and the room temperature of each location in the studies, which were not the same.

The final C:N ratio values were within expectations, with a variation between 1/14 and 1/16 under the maximum of 1/20 established by the Normative Instruction. Tatàno *et al.* (2015) obtained values of C:N ratio ranging between 5/1 and 15/1, which were close to results obtained in the present research even with considerable variation. Kumar *et al.* (2009) considered the 10: 1 and 15: 1 range to be ideal.

The physicochemical parameters analyzed in the compost were subjected to variance analysis and the means were compared by the Tukey's test at a 5% probability level. The results are shown in Table 8.

Performance analysis of the different prototype models pointed out significant statistical differences between them regarding the parameters of conductivity, organic carbon, total nitrogen, fixed and volatile solids, and C:N ratio.

Table 6 – Common geometric models identified by the type of search source and frequency.

Type of search source	Common geometric models identified
Bibliographic search	1st: Cylindrical 2nd: Rectangular 3rd: Trapezoidal 4th: Others*
Marketing research	1st: Rectangular 2nd: Cylindrical 3rd: Hexagonal 4th: Trapezoidal 5th: Spherical

*Bags, baskets, plastic, 20-liter bottle or small windrows.

Table 7 – Organic mass variation in bench test stage according to prototype.

Prototype	Initial mass (g)	Average final mass (g)	Mass reduction (%)
P_1	300.00	61.13	79.26
P_2		53.14	82.28
P_3		46.36	84.54
P_4		63.85	78.71
P_5		64.26	78.58

Figure 5 – (A) Composting kit delivered to volunteers and (B) preparatory workshop.

The sanitary parameters and the ease of turning the compost were also analyzed, and the results are shown in Table 9.

Turning the compost was considered difficult in the prototypes which parts of organic waste fall out during the process, and easy when performed without difficulty and loss of compost. Prototype P3 (triangular prism) was considered difficult for turning the compost due to the geometry of its base, which has reduced space available for the movement.

Sanitary aspects registered with "*yes*" indicate the frequent and uncomfortable presence of leachate, vectors, and foul odor, whereas aspects marked with "*no*" correspond to the sporadic presence or absence of them. The P1 and P3 geometric models were not approved in relation to the sanitary aspects evaluated, as they resulted in the occurrence of leachate, presence of vectors, and foul smell during the operation period.

Selection of geometric models for testing with volunteers

The process of selecting the models for users' evaluation on usability has also considered the performed marketing research (S1). Although the most common geometries found in the market were rectangular, cylindrical, and hexagonal, it was decided to replace the cylindrical model with the cube, since the cylindrical prototype presented great difficulty to be handled with and negative occurrences regarding the sanitary aspects during the monitoring process. Thus, the prototype models P2 (hexagonal prism), P4 (cube), and P5 (parallelepiped) were chosen. They have also obtained the best results in sanitary aspects, turning process, and agronomic characteristics. The models statistically differ from each other concerning parameters of conductivity, organic carbon, and total nitrogen (Table 8).

Usability test with volunteers (S3)

According to Catecati *et al.* (2018), the best way to test the functionality and usability of a product, prototype, or system is by subjecting it to user testing, in which daily practice brings results to identify possible difficulties in use and operational behavior. The authors also recommend that volunteers be encouraged to propose improvements to the tested equipment.

The volunteers' perceptions regarding the tested prototypes were collected through a structured questionnaire, applied at the end of the test (after 50 days). The questions were based on studies conducted by Faverial and Sierra (2014) and Bringhenti *et al.* (2015). The aspects evaluated on the practice of composting and user testing with prototype models are shown in Table 10.

Two volunteers with previous experience (V3 and V4) required less time for assembling and monitoring the composters. They also registered fewer negative occurrences during the experiment. However, regardless of previous experience, all five volunteers had difficulties in adjusting the moisture level of the waste mixture.

Table 8 – Results of statistical analysis for the averages of the analyzed parameters, according to prototype model[1].

Prototype Model	Parameters					
	Electrical conductivity	Organic Carbon	Total Nitrogen	C:N ratio	Fixed Solids	Volatile Solids
P_1	0.5526 a	39.4260 a	2.6020 a	15/1 ab	21.1272 ab	78.8728 ab
P_2	0.6178 ab	39.0560 a	2.6640 a	14/1 bc	18.6634 b	81.3366 a
P_3	0.6256 ab	38.2360 a	2.4460 b	15/1 a	23.1784 a	76.8216 b
P_4	0.4536 c	32.2000 b	2.2634 c	14/1 c	19.0610 b	80.9390 a
P_5	0.6564 a	32.0020 b	2.2200 c	14/1 c	19.9572 ab	80.0428 ab
Reference values Normative Instruction SDA/MAPA 25/2009	*	min. 0.50	*	max. 20/1	*	*

[1]The averages followed by distinct letters statistically differ according to the Tukey's test at a 5% probability level; P1: cylinder; P2: hexagonal prism; P3: triangular prism; P4: cube; P5: parallelepiped; *there are no reference values for these parameters in the Normative Instruction SDA/MAPA 25/2009 (BRASIL, 2009).

Table 9 – Sanitary aspects and ease of turning according to each prototype.

Stage	Prototype Model	Turning compost	Presence of leachate?	Presence of vectors?	Presence of foul odor?
Stage 2	P_1	Easy	Yes	Yes	Yes
	P_2	Easy	Yes	No	No
	P_3	Difficult	Yes	Yes	Yes
	P_4	Easy	No	No	No
	P_5	Easy	No	No	No

P1: cylinder; P2: hexagonal prism; P3: triangular prism; P4: cube; P5: parallelepiped.

Due to difficulties in adapting the use of prototypes in daily routines, it was observed that the employed volunteers decided to operate the composters at the weekends, which indicates an adaptive practice.

Results with volunteers in a research conducted by Faverial and Sierra (2014) indicated that 68% of the participants did not report any difficulties in the practice of composter operation in a domestic environment and that the main difficulties encountered were: presence of vectors, odor, and leachate; and difficulty in finding an adequate and safe place to implant (or store) the composter. Such findings are similar to those found in the present study.

Concerning the usability aspect, the hexagonal prism and cube models were preferred. The preference for the models was attributed to the ease of adding residues and turning the compost, in addition to the more ergonomic design presented by both of them.

Although the rectangular-based model (parallelepiped) promoted greater reduction in volume and degradability of organics, the usability was not approved by four (80%) of the five volunteers, due to the difficulty in use. Although this geometry was more frequent in the marketing research and the second most common in the bibliographic search, it was not approved by the users, which reinforces the importance of considering the human factor in the design of composting equipment.

The results concerning the users' evaluation of the prototype models were compared with the literature, as demonstrated in Table 11.

It is worth mentioning the lack of studies on usability for these kinds of equipment to provide a broader comparison with the obtained results, especially concerning the approaches to make the equipment used in decentralized composting more efficient and effective.

Projects adapted from domestic composters

With the aid of the SolidWorks 2016 software version 9000, and by adding the improvements proposed by the volunteers to the best rated models of composters in the research (hexagonal prism and cube), two conceptual models of composters were projected for better usability. The projected designs are shown in Figure 6.

Conclusions

It was statistically found that the geometry of the composter influenced the characteristics of the compost in terms of organic carbon parameters, total nitrogen, C:N ratio, fixed and volatile solids and, consequently, its agronomic quality.

Table 10 – Aspects evaluated by volunteers in the test with composter prototypes.

Evaluated aspect	Volunteers				
	Volunteer 1 (V1)	Volunteer 2 (V2)	Volunteer 3 (V3)	Volunteer 4 (V4)	Volunteer 5 (V5)
Motivation	Proper waste disposal	Learn how to compost	Proper waste disposal	Proper waste disposal	Learn how to compost
Pros	No leachate, family participation and operational simplicity	No leachate and operational simplicity	No leachate and operational simplicity	No mold, no leachate, no foul smell and family participation	Operational simplicity
Cons	Low moisture level, presence of vectors and time spent in operation	Low moisture level, presence of vectors, space taken and lack of family participation	Low moisture level, presence of vectors and mold, and difficulties in turning the compost.	Low moisture level, presence of vectors	Low moisture level, presence of vectors, mold and foul smell, and lack of family participation
Average operating time (minutes)	21	20	10	7	27
Operating frequency	Weekly (fixed day)	Weekly (according to users' availability)	Weekly (fixed day)	Weekly (according to users' availability)	Weekly (fixed day)
Intention to continue using it?	No	No	Yes	Yes	Yes
Geometric model with less approval	Parallelepiped	Parallelepiped	Parallelepiped	Cube	Parallelepiped
Preferred geometric model	Hexagonal prism and cube	Cube	Cube	Hexagonal prism	Cube and hexagonal prism

Table 11 – Factors related to the use of composters in domestic environments, according to the literature and the test performed with users.

Factor	Literature review*	Users' feedback
Waste management	- Layout interference in the composter filling and compost removal.	- Removable bottom to remove compost.
Installation requirements	- Simple and flexible installation - Mobility (portable).	- Handles and wheels for management and mobility.
Operational capacity	- Appropriate dimensions to existing space. - Adequate capacity to local organic waste production and frequency of use (daily, weekly, etc.).	- Insufficient capacity to the organic waste generated
Aesthetics and ergonomics	- Be visually attractive and encourage use. - Contain visual instructions on how to use.	- Round edges for better accommodation and turning of waste.
Operational requirements	- To provide simplified usage procedures and be accessible to different kinds of users.	- Flexibility in operation frequency.
Environmental and sanitary aspects	- The design must allow internal aeration and minimize the release of odors into the environment. - The design should facilitate cleaning and hygiene. - It should contain vector protection barriers. - Low noise emission (equipment with an electronic system).	- Removable tray for cleaning and collecting leachate. - Cover with screen for air circulation.
Cost	- Compatible with used material and technology.	- Use of resistant and sustainable material (recycled).

*Based on Jayaprakash, Lohit and Abhilash (2018) and Metcalfe *et al.* (2012).

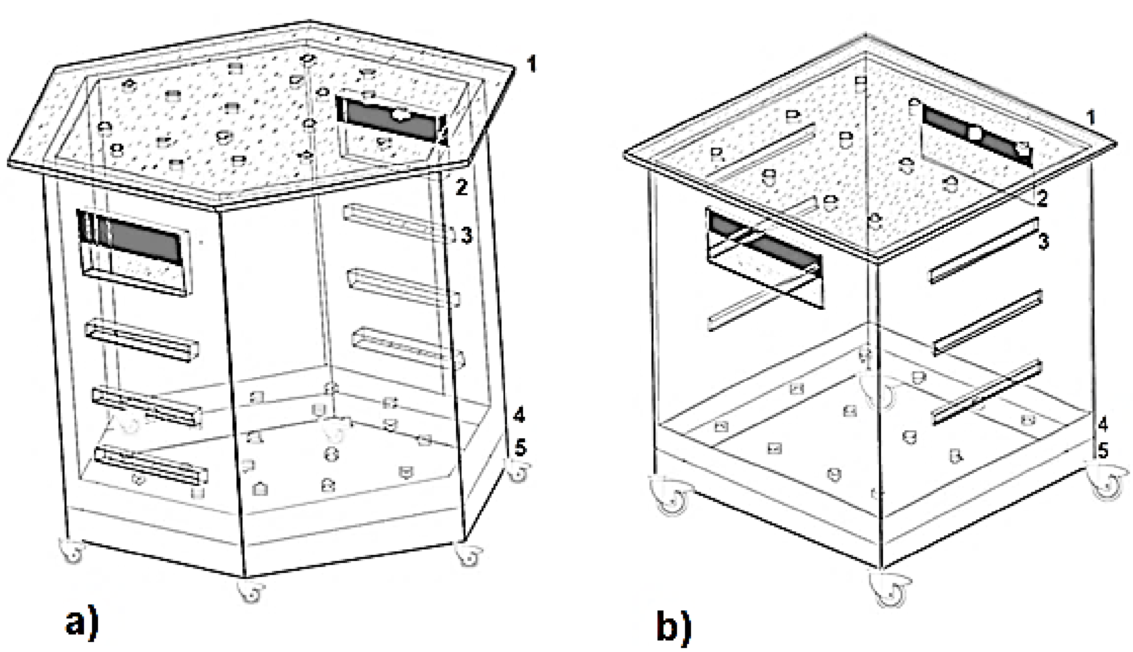

Figure 6 – Illustrative scheme of small-scale composter prototypes. (A) hexagonal prism; (B) cube; dimensions of 0.25 m x 0.25 m x 0.25 m, approximately totaling 15 L.
1: Perforated and screened removable cover; 2: handles; 3: screened ventilation opening; 4: removable bottom for collecting leachate; 5: removable bottom for final compost removal.

The practice of composting and the daily operation by volunteers led to a preference for two geometric composter models: hexagonal prism and cube. Ergonomics, ease of use, and facility for turning composting were decisive factors in this choice. It can be seen, therefore, that geometry influenced the usability of the tested prototypes.

The improvements proposed by users contributed to the design of easier-to-use models, which may contribute to the dissemination of the small-scale composting technique and the continuity of household practice or in similar environments, which are aspects of waste minimization and sustainability.

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