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Environmental injustices on green and blue infrastructure: Urban nexus in a macrometropolitan territory

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ABSTRACT

Green-blue infrastructure in urban regions guarantees the provision of resources such as water, energy, and food, which are interdependent and fundamental in ensuring human development. In this study, we analyzed the environmental injustice issue relationships of the supply and production of water, energy, and food in the São Paulo Macrometropolis, Brazil. Its 180 municipalities were compared and categorized into 'losers' and 'winners' based on the urban nexus approach, the proportion of green infrastructure, and human development. We applied a neural network self-organizing map to official publicly available data to obtain clusters of municipalities featuring combinations of 19 indicators. The results showed four clusters with three containing characteristics of receivers (Capital, Hinterland, and Developed Receivers) and one of providers, the latter aggregating municipalities with a strong role in providing water, food, and subsidies for energy generation. However, the providers also included the municipalities that had the greatest inequities in terms of human development and social inclusion. The importance of evaluating the co-benefits of green-blue infrastructure in urban spaces can serve as an adaptation strategy to both improve natural resource management and offer support to different processes and ecosystem functions. Our study provides a comprehensive understanding of complex urban systems by considering environmental justice and nexus synergies.

1. Introduction

Achieving sustainability of urban systems is highly challenging because of the depletion of local natural resources and respective ecosystem services (ES), the role of urbanization, and global environmental changes (Filho et al., 2020; Langemeyer and Connolly, 2020; Seto et al., 2017). One of the consequences of urbanization, as described by Seto et al. (2017), is that ecosystem functions could be affected, such as food production, carbon sequestration, and losses of agricultural land. Furthermore, urbanization may affect the use of energy in buildings and technological improvements in energy efficiency.

A paradigm shift towards interdisciplinary knowledge about urban systems to increase resource efficiency and sustainability has occurred, encompassing concepts like ES (Escobedo et al., 2019; Langemeyer and Connolly, 2020; Romero-Duque et al., 2020), green-blue infrastructure (GBI) (Kati and Jari, 2016; Zhu et al., 2019), and the urban water-energy-food (WEF nexus hereafter) (Artioli et al., 2017; Gondhalekar and Ramsauer, 2017). Moreover, associated with issues of natural resource/ES provisioning, environmental justice-related problems have become especially acute in dense and complex urban areas (Andersson et al., 2019; Ernstson, 2013).

Conflicts and trade-offs related to the conservation of natural areas and alternatives for economic development have been well explored (Agrawal and Redford, 2009; Hansen et al., 2015), but a substantial knowledge gap still exists regarding wide, diverse, and demanding metropolitan areas. For those, the threat of unsustainable living is represented by significant asymmetries and a lack of

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integrated analysis of socio-environmental vulnerability and injustices among territories (Ajibade, 2019; Favaro et al., 2016; Mapar et al., 2017). In addition, studies on urban sustainability mainly center on the Global North, focusing on complex challenges of food systems and related constraints such as water and energy (Blay-Palmer et al., 2018; Keivani, 2010), however, in the very rapidly and unplanned urbanizing Global South such studies are even more essential to tackle global sustainability challenges (Yücel and Barlas, 2010).

In this study, we focus on the São Paulo Macrometropolis (SPM) and consider the different roles of its 180 municipalities in providing or receiving benefits of ES and human development. Since the 1950s, São Paulo state has been rapidly urbanizing with people migrating from all over the country to the richest and most developed urbanized region, resulting in peripheralization of poverty among the pertaining municipalities and resource constraints related to a lack of developed alternatives (Ferreira, 2011), the need to conserve GBI assets, and the demands and threats to the provision of ES (Favaro et al., 2016). Considering that there must be "losers" and "winners" (Middleton et al., 2015), we shed light on the constraints related to intermunicipal inequities, as they can easily be obfuscated in urban resilience and sustainability studies (Meerow and Newell, 2019; Zhang et al., 2019). Our hypothesis is that the macrometropolitan municipalities that have the highest proportions of GBI and ES provisioning in relation to their populations are also likely to register the lowest indicators of welfare and human development. Thus, in this article, we analyze environmental injustices related to the supply and production of water, energy, and food in the SPM, Brazil, and compare and categorize the different municipalities as 'losers' or 'winners' from the perspective of the urban nexus, GBI, and levels of human development.

2. Conceptual framework

2.1. Green-blue infrastructure and ecosystem services

The GBI has been defined as a combination of vegetation (green) and water bodies (blue) belonging to networks that associate natural and designed landscape components, such as forest reserves, urban parks, water bodies, green roofs, settlements, and canals (Ghofrani et al., 2017; Lamond and Everett, 2019; Well and Ludwig, 2019). This term emerged from a growing awareness of the need for a more integrated and systematic approach to managing urban GBI (Lamond and Everett, 2019). In turn, ES was defined by the Millennium Ecosystem Assessment as the benefits that people obtain from ecosystems, which include i) provisioning services such as food, water, timber, and fiber, ii) regulating services that affect climate, floods, disease, wastes, and water quality, iii) cultural services that provide recreational, aesthetic, and spiritual benefits, and iv) supporting services, including soil formation, photosynthesis, and nutrient cycling (MEA, 2005, p. 39).

The GBI's functional connections and interrelations within and adjacent to cities have the potential to provide a broad range of ES to urban residents (Andersson et al., 2019). This infrastructure also has the potential to subsidize different ecosystem functions that ensure the provision of resources (e.g., water, food, and energy) and environmental regulation services (e.g., microclimate regulation and carbon sequestration) that are indispensable for human development and the prosperity of cities (MEA, 2005; Well and Ludwig, 2019). Thus, GBI offers a holistic perspective of increasing resilience towards addressing complex urban challenges, as natural and social environments interact with limited resources and space constraints (Alves et al., 2019; Escobedo et al., 2019; European Commision, 2012).

However, despite the relevance of natural ecosystems, there are documented problems with the distribution and accessibility of both GBI and its benefits (Andersson et al., 2019). The inequities in the distribution of resource provisioning and benefits have implications for 'when and for whom' GBI offers an opportunity to meet different ES needs (Andersson et al., 2019; Ernstson, 2013). Historically, policy, planning, and management have treated gray and green infrastructure networks as separate (Andersson et al., 2019), leading to challenges for the development of policy integration for using GBI as an alternative to induce sustainability, urban resilience, and intersectoriality in the complex management of natural resources (Sirakaya et al., 2018).

The intense conurbation and systematic waterproofing of urban areas associated with population growth and increased water demands impose a constant increase in water scarcity and related risk situations. This is clearly observed in the SPM, where the constant search for water from distant sources delineates a territory where water is a matter of dispute, thus demanding energy expenses for its supply and generating pressure between public supply and the need for water for food or energy production, as in the case of ethanol production from sugarcane (Benites-Lazaro et al., 2020; Giatti et al., 2016; Jacobi et al., 2015).

2.2. Urban environmental justice

The urban environmental justice perspective that addresses human-ecosystem interactions has started from an explicit focus on detrimental effects and socio-environmental inequities (Ernstson, 2013; Langemeyer and Connolly, 2020). The perspective of inequities among ES provisioning and social benefits in an urbanized territory requires an exploration of the issue of environmental justice, a concept that was conceived in the United States in the early 1980s in the context of the struggle for racial equity (Beretta, 2012). Environmental justice was defined by the US Environmental Protection Agency as "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (EPA, 1998, p. 7).

Demands for environmental justice highlight the fact that the right to balanced and responsible uses of land and natural resources is within the interest of achieving a sustainable planet for humans and other living beings (Ramirez-Andreotta, 2019). Otherwise, an unfair lack of access to natural resources due to development projects, especially for socioeconomically and politically marginalized groups, can be considered a matter of environmental injustice (Anguelovski and Martínez Alier, 2014; Middleton et al., 2015). Thus, environmental (in)justice denotes an important issue of how powerful groups may dominate environmental decisions to the exclusion of others (Benites-Lazaro and Mello-Théry, 2019; Walker, 2012).

Increasingly, the consensus on natural resource shortages and access shows that environmental justice is an important value that must be pursued in GBI availability and ES provisioning, although there is a limited understanding of the precise ways used to measure and respond to environmental justice needs (Alves et al., 2019; Zhu et al., 2019). It is important to highlight that environmental justice literature mainly focuses on three modes of (in)justice: (a) distributive justice, which refers to who "wins" and "loses" in suffering environmental burdens and benefits with respect to environmental interventions, (b) procedural justice, which identifies who is involved, and who has influence in terms of decision-making, and (c) recognition justice, which describes who is given respect or not, and whose interests, values, and views are recognized and taken into account (Middleton et al., 2015; Schlosberg, 2007; Svarstad and Benjaminsen, 2020). In this study we focus

our analysis on distributive justice.

2.3. Urban water-energy-food nexus approach

The World Economic Forum (2011) presented the nexus framework from a WEF security perspective; however, subsequent versions have considered various facets with alternative components, such as water resources or food as the central component and land use–water–energy (Biggs et al., 2015). The nexus approach takes the interactions, interdependencies, and dynamics between resource systems into account to harmonize their perspective and the management of sectors that were addressed separately in the past (Benites-Lazaro et al., 2020).

From this perspective, there are convergences with the urban nexus approach, which has gained global notoriety based on the understanding of the interdependent relationships, as marked by trade-offs and synergies (Artioli et al., 2017; Hoff, 2011). Thus, an urban nexus can be defined as: "*an approach to the design of sustainable urban development solutions. The approach guides stakeholders to identify and pursue possible synergies between sectors, jurisdictions, and technical domains, so as to increase institutional performance, optimize resource management, and service quality*" (GIZ and ICLEI, 2014).

Growing urbanization has been viewed as a key factor of WEF nexus problems, as it shifts land use patterns, the spatial distribution of populations, and concomitant infrastructures and resource flows (Artioli et al., 2017; Heard et al., 2017). To be sustainable, cities depend on policies and integrative governance that connect them with broad territories of influence and with global environmental issues (Castán Broto, 2017; Seto et al., 2017). The existing urban nexus literature shows that, considering the interdependence of the production chains and supply of water, energy, and food, the development and management of sustainable and resilient cities is crucial for social inclusion and improving the quality of life of its population (Artioli et al., 2017; Covarrubias, 2019; Heard et al., 2017).

Fig. 1 shows the structure of our conceptual framework in which GBI represents the natural assets needed to guarantee ES, i.e., those that provide support to the provision of water, energy, and food. The nexus framework consists of arrangements improved based on the interdependence of scarcities, and is thus related to the search for synergies to mitigate trade-offs among supply chains. However, this flow, in the sense of our analysis, cannot be addressed in a large and complex urban system without considering who provides GBI and ES and who receives support for improving human development (Andersson et al., 2019; Zhu et al., 2019). Based on this interpretation, the nexus can be conceived as an opportunity to increase the potential to share the benefits of GBI and ES, while considering that there is a need to focus on reducing inequities. Within this intent, how to identify the nexus through available secondary data related to an agglomerate of municipalities that constitute an urban complex system remains a challenge (Albrecht et al., 2018; Arthur et al., 2019).

3. Methodology

3.1. Study area

With nearly 34 million inhabitants distributed across 180 municipalities that occupy an area of 52,000 km^2 and account for approximately 28% of Brazil's gross domestic product (GDP), the SPM was established based on the developmental flows and pressures of the extended metropolitan regions of São Paulo, Campinas, and Baixada Santista. The SPM features eight water resource management units (managed according to river basin boundaries), nearly 20,000 km^2 of vegetation cover, and a large network of enterprises that are dedicated to industrial, agricultural, and service activities (DAEE, 2013).

Apart from the absence of governance and institutionalization, the SPM is recognized as a city-region and has been analyzed in several recent studies with regard to the process of regional urbanization in which very different municipalities interact through their socio-occupational dynamics and functionalities in the metropolitan system (Blay-Palmer et al., 2018; Torres et al., 2019; Travassos et al., 2020). It is important to note that although there are significant agricultural areas and industries in the SPM, data from the two latest demographic census indicated that in 2000 only 1.70% of the workforce was farmers and this proportion fell to 1.59% in 2010, demonstrating a pattern of occupation and work strongly connected to urban dynamics (Pasternak; Bógus, 2019). The SPM is the object of a number of São Paulo state government planning initiatives, including the Macrometropolis Action Plan, which

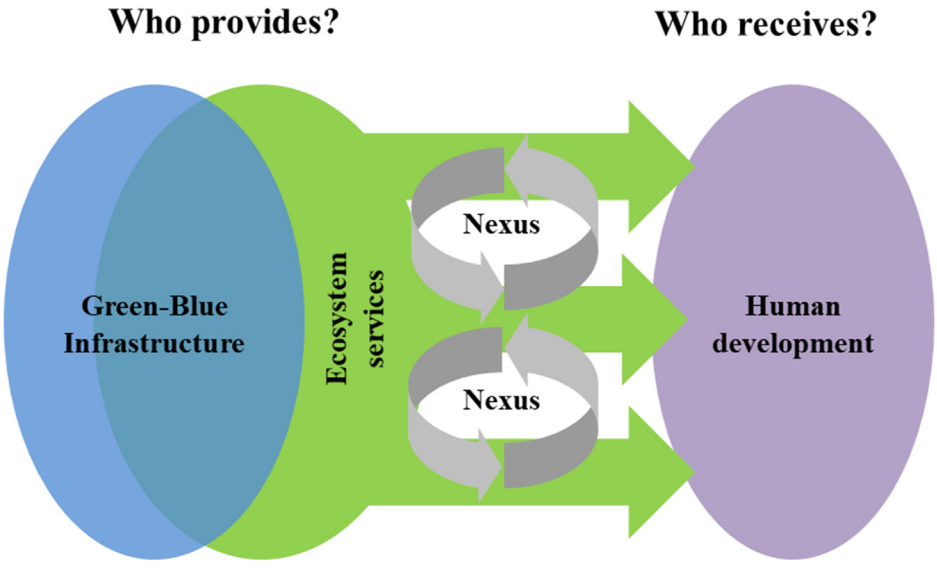

Fig. 1. Conceptual framework involving GBI, ES, and the nexus approach in environmental justice concerns.

Table 1
Description of the indicators used in this study, as well as their measures and sources.

Indicator	Description	Measure	Sources
Human development			
fimd	Firjan Index of Municipal Development (consolidated)	0 to 1	Firjan System
fimd_edu	Firjan Index of Municipal Development (education)	0 to 1	Firjan System
fimd_empl_income	Firjan Index of Municipal Development (employmentand income)	0 to 1	Firjan System
fimd_health	Firjan Index of Municipal Development (health)	0 to 1	Firjan System
hdim	Municipal HumanDevelopment Index	0 to 1	IBGE
hr_nutri	Hospitalization rate bymalnutrition	Per 100,000 inhab	Datasus
hr_add	Hospitalization rate byacutediarrhealdiseases	Per 100,000 inhab	Datasus
gdp_per_capita	GDP per capita	In thousandsof reais	IBGE
total_pop	Total population		IBGE
GBI infrastructure and WEF nexus			
ha_forest	Hectares ofvegetation cover	ha	MapBiomas
ha_forest_inhab	Hectares ofvegetation cover byinhabitant	ha/inhab	IBGE; MapBiomas
ha_pasture	Hectares oflivestockandagriculturalland	ha	MapBiomas
ha_pasture_inhab	Hectares oflivestockandagriculturallandbyinhabitant	ha/inhab	IBGE; MapBiomas
elect_cons	Amountof total electricityconsumption	kWh	São Paulo StateSecretariatof Energy and Mining
elect_cons_inhab	Amountof total electricityconsumptionbyinhabitant	kWh/inhab	IBGE; São Paulo StateSecretariatof Energy and Mining
water_cons_an_l_s	Flowofwaterconsumptionbylivestockproduction in liters per second	l/s	NationalWaterAgency
water_cons_an_l_s_inhab	Flowofwaterconsumptionbylivestockproduction per inhabitant in liters per second	l/s/inhab	IBGE; NationalWaterAgency
water_cons_ir_l_s	Flowofwaterconsumptionbyirrigatedagriculture in liters per second	l/s	NationalWaterAgency
water_cons_ir_l_s_inhab	Flowofwaterconsumptionbyirrigatedagriculture per inhabitant in liters per second	l/s/inhab	IBGE; NationalWaterAgency

[1] Data referring to vegetation coverage as aggregated from natural forests and forests planted for commercial purposes.

regards regional development through infrastructure and logistics actions and projects with guidelines extending to 2040 (Emplasa, 2014), and the São Paulo Macrometropolis Water Resources Master Plan (DAEE, 2013) dedicated to multiple water uses and scenarios up to 2035. These plans are relevant because they address population growth, environmental impacts, and perspectives on climate-related crises like the unprecedented drought from 2013 to 2015 (DAEE, 2013). The SPM can be understood as a complex and interdependent territory with large and historically relevant pressures, including economic development, heterogeneity and spatial fragmentation, severe trade-offs among scarce water resources and energy, and an intrinsic need for food production and provision (Giatti et al., 2016; Sinisgalli et al., 2018; Travassos et al., 2020).

3.2. Data sources

At the time of this study, 2016 was the most recent year with the highest availability of information on the 180 municipalities of the SPM, and several Brazilian public information systems could provide sources of indicators capable of measuring the (1) aspects related to human development of each of the municipalities, (2) the amount of land destined for livestock and food production, and (3) the green infrastructure that contributes to well-being and human development through the provision of ES (Millennium Ecosystem Assessment, 2005), represented here by the amount of hectares of vegetation coverage.

However, to allow comparisons between municipalities of considerably different magnitudes and characteristics, we chose to work with coefficients obtained by relativizing the provision of ES by normalizing to the municipal population, as described in Table 1. This was the basis for comparing municipalities regarding the proportional provision of benefits associated with GBI and ES and the access to human development.

Our understanding of human development was oriented on the United Nations Development Programme (UNDP, 1990), and the main quality of life and inequities indicator of this study is the Firjan Index of Municipal Development (FIMD), which is a composite indicator calculated annually by the Firjan System[1] for Brazilian municipalities based on an equal weighting of official public statistical variables for three dimensions of human development: employment/income, health, and education.

Overall, the FIMD's main objective is to monitor the achievements and socioeconomic challenges of municipalities through 15 variables that quantify the local generation of employment and income, education quality, and primary health care coverage. The FIMD is similar to the Municipal Human Development Index (HDI-M) that has been released by the Brazilian Institute of Geography and Statistics (IBGE), however, the former includes the most recent data available from the 2010 national census.

3.3. Statistical analysis

Based on the dataset described in Table 1, the SPM municipalities were clustered using the self-organizing map technique or Kohonen networks, which represents a class of neural-network algorithms in the unsupervised-learning category (Kohonen, 2001). This technique permits a nonlinear projection of a large dimensional data manifold on a low (two)-dimensional grid, which can visualize common dependencies between variables, similarity relationships, and cluster structures within larger data sets (Benites-Lazaro and Andrade, 2019). The algorithm of the self-organizing map technique identifies the data structure within the multidimensional space and projects it to a flat mesh, creating a knowledge map that can observe similarity relationships in the multidimensional space (Villasenor et al., 2017).

[1] Firjan (Federation of Industries of the state of Rio de Janeiro) is a private and non-profit organization, which is composed of five Brazilian institutions that work in an integrated manner to guide actions at the economic, political, and social levels to promote development of Brazilian municipalities.

In this study, we used LabSOM, an open-source software system, to investigate the self-organization characteristics of the artificial neural networks of Kohonen. The self-organizing map technique is modeled as a two-dimensional hexagonal grid, where each hexagon represents both an artificial neuron and a location for data point mapping (Villasenor et al., 2017). In this study, we first normalized the data, and then we trained the model through neural networks with 64 neurons from 19 variables for the 180 municipalities of the SPM. Ward's clustering algorithm was used to generate a self-organizing map and clustering results (Ward, 1963). The final self-organized map was the outcome of the neural network iterative training process, by which the network learned to project similar patterns into close-location hexagons in the map (Benites-Lazaro and Andrade, 2019). Based on the results of LabSOM that clustered the SPM municipalities, a descriptive variable analysis that included information related to human development, green infrastructure, and the amount of land and water destined for livestock and food production was performed through tables and boxplot graphics created in R software.

4. Results

4.1. Cluster identification

Figs. 2 and 3 shows the clustering and the spatial configuration of the 180 SPM municipalities, respectively, within four clusters that are named below according to some of their remarkable characteristics (considering the aims of the study):

- Capital Receivers (influenced by São Paulo, capital city) - 16 (8.9%) municipalities with a total amount of 14.6 million inhabitants (43.3% of the SPM's population). This cluster demonstrates a strong influence of the municipality of São Paulo (with the largest population in the SPM of 12 million); besides being highly urbanized, this cluster also contains considerable amounts of vegetation coverage, including natural forests. The dimension of human development evaluated as the best by a Firjan index of 0.9833 (Caraguatatuba) for this cluster was education, followed by health (0,9429 [São Bernardo do Campo]), and employment and income (0,7260 [Caraguatatuba]). The average of the consolidated Firjan index was 0.7838 ± 0.06;

- Hinterland Receivers - 23 (12.8%) municipalities and 4.8 million inhabitants (14.0%). This cluster includes the highest number of hectares of land dedicated to livestock production and agriculture. The education dimension recorded the highest Firjan index value, for Atibaia (0.9913), followed by health (0.9464 [Botucatu]) and employment and income (0.7548 [Porto Feliz]). For this cluster, the average of the consolidated Firjan index was 0.8165 ± 0.06;
- Developed Receivers - 93 (51.7%) municipalities and 13.8 million inhabitants (41.1%). This cluster aggregates the municipalities with the highest GDP per capita, including the municipalities with thermoelectric generation[2] and most of those with the highest values of the human development indicators. The highest recorded Firjan indices for health, education, and employment and income were 0.9618 (Jundiaí), 0.9988 (Águas de São Pedro), and 0.7667 (Nova Odessa), respectively, while the average for the consolidated value was 0.7941 ± 0.06;
- Providers - 48 (26.7%) municipalities and the lowest population at 527.600 inhabitants (1.6%). This cluster characterizes the highest amount of assets in terms of GB I and ES provisioning and the lowest values for the indicators of human development. Laranjal Paulista showed the highest value for the employment and income dimension in this cluster, which at 0.6391 is the lowest value in the macrometropolitan region. In terms of health and education, Saltinho presented the highest values of 0.9399 and 0.9813, respectively. Although these observed values are relatively high, when compared to the other three clusters the set of municipalities in this cluster has most of the lowest values for all human development dimensions. The average of the consolidated Firjan index for this cluster was only 0.7222 ± 0.06.

Fig. 4 compares the data dispersion among the clusters related to human development. In this figure, it is possible to observe intersections and outliers for the indicators. As can be seen, the Providers cluster presents a high concentration of municipalities with low human development, as demonstrated by the FIMD indicator and its components.

Fig. 5 presents the data dispersion for the environmental conditions favorable to the provision of ES and shows that municipalities categorized as Providers have the highest values for the number of hectares of land (proportional to the population) dedicated to vegetation coverage, livestock, and food production, whereas the three receiver clusters have lower values and are more variable. Thus, considering the heterogeneity between the clusters in Figs. 2–5, two main classes were assigned to the municipalities from the perspective of ES provisioning capacity and living conditions: (1) ES receivers with higher human development levels (Capital, Hinterland, and Developed Receivers); and (2) ES providers with lower human development levels (Providers).

Finally, to highlight the largest disparities of ES provisioning versus receiving, we ranked the five highest- and lowest-ranked municipalities according to the variables of food production area, vegetation cover, and livestock land per inhabitant (ha_ food_inhab, ha_pasture_inhab and ha_forest_inhab) with their human development index (FIMD) (Tables 2 and 3). The Providers cluster contains all municipalities with the highest ranks of the three variables.

The Natividade da Serra, Anhembi, Redenção da Serra, and Areias municipalities have the highest proportions of vegetation coverage, amount of land dedicated to livestock and food production, and the lowest FIMD (Tables 2 and 3). The smallest areas of forests and livestock/food production were found in São Caetano do Sul; this is unsurprising as this area has the highest FIMD of the entire SPM and does not produce food nor has it a forest area, as it is completely urbanized.

4.2. Nexus indicators in the SPM

In Fig. 6, the data dispersion among the clusters for water flow used in irrigated agriculture (Fig. 6a) and livestock needs (Fig. 6b) is shown (both proportional to the population). The municipalities in the Providers cluster showed the largest data range for irrigated agriculture and livestock needs. According to the data collected for the 180 municipalities, the average water flow consumption of animals was 3.69×10^{-4} l/s/inhab. ± 6.12×10^{-4} l/s/inhab., whereas the average water consumption of irrigation was 1.09×10^{-3} l/s/inhab. ± 2.64×10^{-3} l/s/inhab. Fig. 6 confirms that the providers of ES are the same municipalities that register inequities, demonstrating low human development. Fig. 6c shows the consumption of energy per inhabitant among the municipalities, with an average of 790.2 ± 217.6 kWh/inhab.; this also represents a demand or a possible trade-off within the nexus.

[2] The main source of electricity in the SPM is obtained from hydroelectric plants. Thermoelectric energy, in this case, is activated in situations of water scarcity.

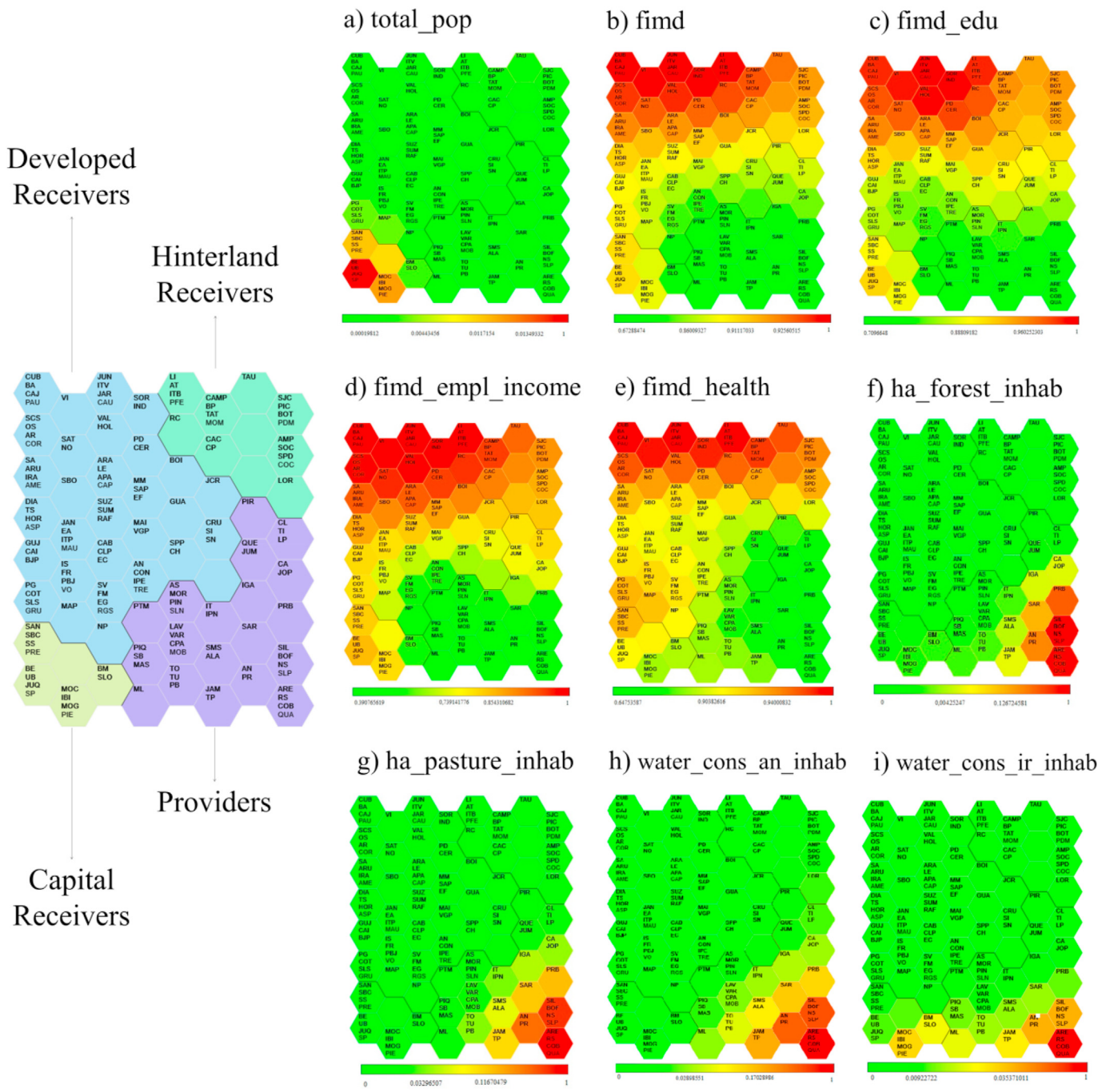

Fig. 2. Clustering of the municipalities of the SPM through the studied variables.

5. Discussion

5.1. SPM environmental injustice and GBI

The results of the clustering of all SPM municipalities using the self-organizing map technique verified that the observed data and the heterogeneity of the Providers cluster compared to the other clusters (Fig. 2; Tables 2 and 3) reveal environmental injustices based on the relationships established between the municipalities regarding the provisioning, flow, and access to water, energy, food, and human development. This finding supports our hypothesis that a high support of ES and green infrastructure is associated with low human development indicators. Although the existing literature presents GBI as having a positive association with social justice (Wolch et al., 2014; Zhu et al., 2019), our analysis indicates that in complex urban systems such as the SPM inequities appear to be interrelated with municipal singularities and disconnected from the regional level. It corroborates the need to understand different functionalities among municipalities in urban regions because they can encompass iniquities in relation to certain green policies and thus have consequences for the poorest social groups. Therefore, the concept of justice applied to sustainable development must become central (Krueger and Savage, 2007; Pasternak; Bógus, 2019).

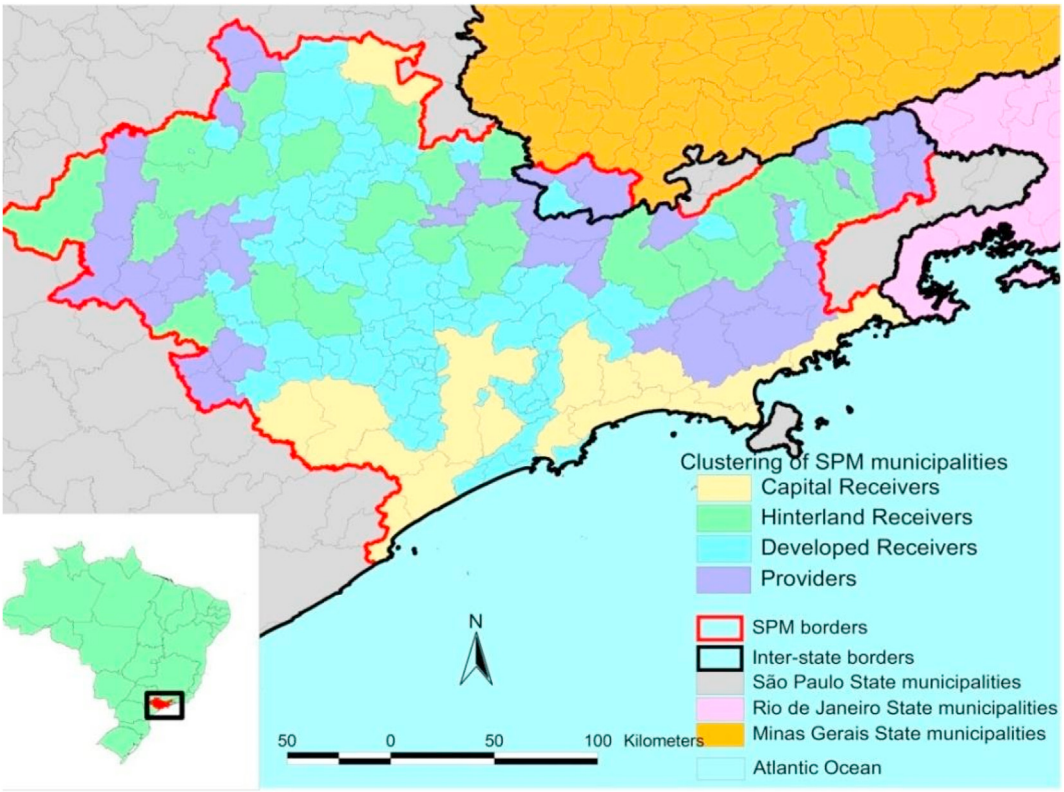

Fig. 3. Thematic map of the municipalities of the SPM based on the clustering results.

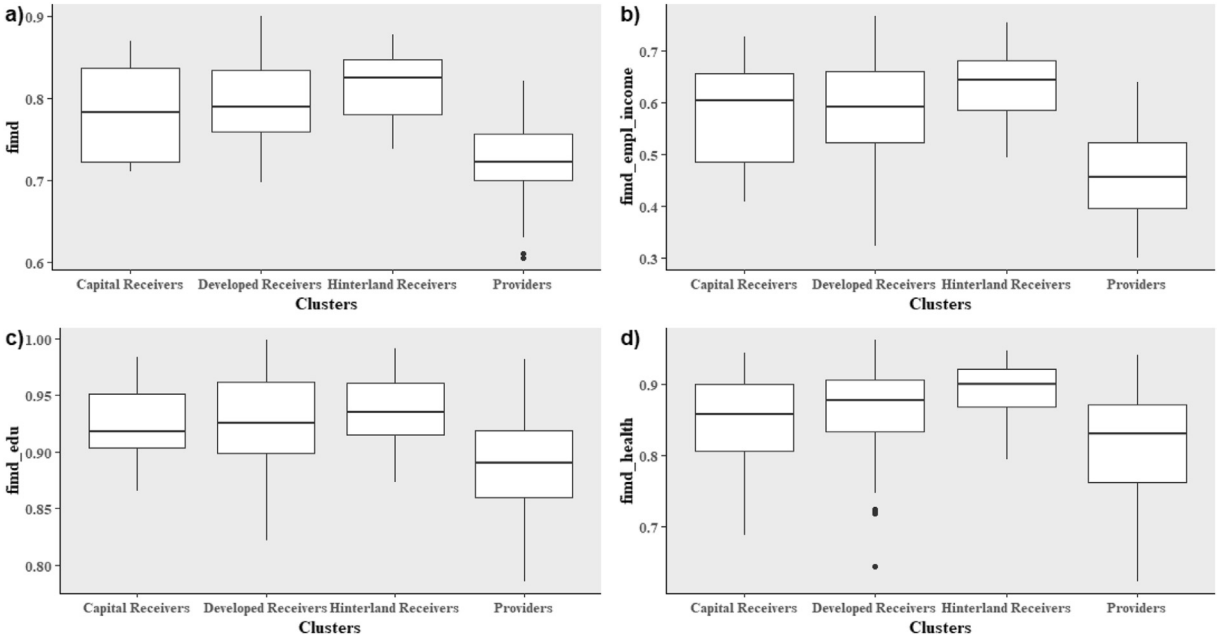

Fig. 4. Data dispersion of variables related to the human development conditions in the SPM.

Stating that inequities appear to be interrelated with municipal singularities is justified to the extent that the municipalities of the Providers cluster (water-food providers) support regional development by contributing to the provision of ES, which are fundamental for maintaining human life and supporting economic activities of the whole macrometropolis. However, these same municipalities have the poorest indicators of employment/income, health, and education, as well as trade-offs caused by the provision of these services. This type of trade-off occurs when the provision of an ES is hampered by the prioritization of another (Langemeyer and Connolly, 2020; Rodríguez et al., 2006).

Regarding the main objective of this study, that is, to identify the

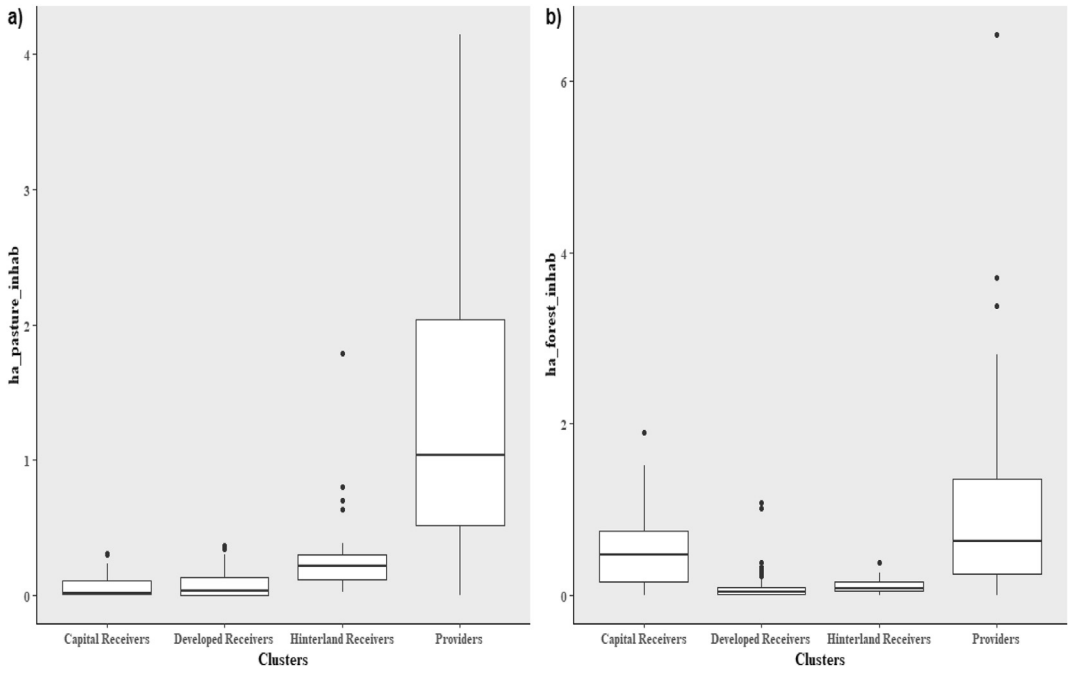

Fig. 5. Dispersion of data (per inhabitant) regarding (a) the total amount of areas for livestock and food production and (b) forests in the SPM.

Table 2
Ranking of municipalities with largest and smallest vegetation coverage area in proportion to their population and human development (FIMD).

Ranking	Municipality	Cluster	Forest (ha/inhab.)	FIMD
Highest values				
1°	Natividade da Serra	Providers	6.54	0.6728
2°	Anhembi	Providers	3.70	0.7217
3°	Redenção da Serra	Providers	3.37	0.7403
4°	Areias	Providers	2.81	0.6328
5°	Bofete	Providers	2.71	0.7233
Lowest values				
1°	São Caetano do Sul	DevelopedReceivers	0.00	0.8773
2°	Hortolândia	DevelopedReceivers	3.33×10^{-4}	0.8150
3°	Osasco	DevelopedReceivers	5.20×10^{-4}	0.8183
4°	Diadema	DevelopedReceivers	5.21×10^{-4}	0.8004
5°	Carapicuíba	DevelopedReceivers	5.23×10^{-4}	0.7510

Table 3
Ranking of municipalities with largest and smallest areas of livestock and food production in proportion to their population and human development (FIMD).

Ranking	Municipality	Cluster	Farming (ha/inhab.)	FIMD
Highestvalues				
1°	Anhembi	Providers	4.15	0.7217
2°	Natividade da Serra	Providers	3.69	0.6728
3°	Redenção da Serra	Providers	3.52	0.7403
4°	Areias	Providers	3.32	0.6328
5°	Lagoinha	Providers	3.14	0.6999
Lowestvalues				
1°	São Caetano do Sul	DevelopedReceivers	0.00	0.8773
2°	Diadema	DevelopedReceivers	2.29×10^{-5}	0.8004
3°	Santos	Capital Receivers	4.19×10^{-5}	0.8702
4°	Cubatão	DevelopedReceivers	7.37×10^{-5}	0.7852
5°	Taboão da Serra	DevelopedReceivers	7.56×10^{-5}	0.8018

losing and winning municipalities of the SPM, we performed an in-depth identification of the least favored municipalities and ranked them as shown in Tables 2 and 3. Given the importance of ES and nexus trade-offs we infer that the municipalities Anhembi, Natividade da Serra, Redenção da Serra, Areias, and Lagoinha (all in the Providers cluster), which contain the largest amount of land dedicated to animal grazing and agriculture production, may not be fully benefiting from the cultural and regulatory ES compared to

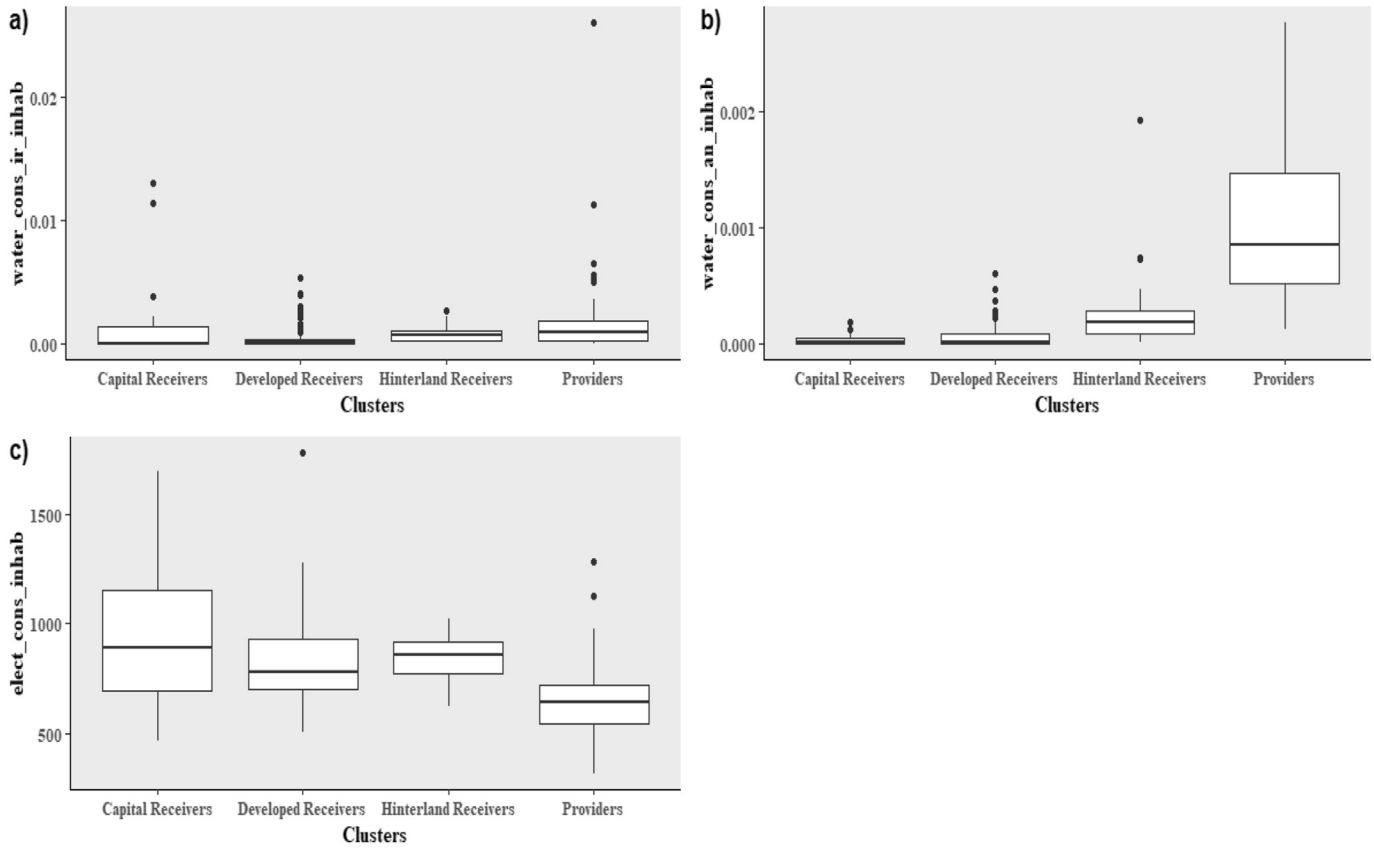

Fig. 6. Dispersion of data (per inhabitant) regarding total electricity and water for irrigation and animal production consumed in the SPM.

the other municipalities in the region. This is because animal production and agriculture have the potential to compromise the landscape and local biodiversity (Leip et al., 2015), which are essential elements for providing these two services to facilitate prosperity and welfare.

These same municipalities, with the exception of Lagoinha, also have the highest amount of native forest coverage per inhabitant (Table 2), which indicates that they may represent the polar opposite of municipalities such as São Caetano do Sul (Developed Receivers), which is entirely urban and has high human development indicators. The water-food providers that have native forest coverage are limited by law from intensifying economic activities to ensure environmental preservation; therefore, they should receive other kinds of incentives to ensure economic and human development. In addition, the amount of water that has been designated for activities such as irrigation and watering animals (Fig. 6a and b) corresponds to assets that are provided by ES and contributes to demands from other municipalities and from the macrometropolis itself.

However, other benefits, such as agricultural inputs, markets, and job opportunities that may be provided by municipalities categorized as water-food receivers, should not be underestimated during policy making processes that consider the supply and consumption of natural resources in extensively urbanized territories such as the SPM. Similarly, considering the intertwined challenges of sustainable development goals (United Nations, 2015), the human development of these municipalities should not compromise the provision of cultural and regulatory ES and the quality of life of the population living in the municipalities categorized as water-food providers (Gebre and Gebremedhin, 2019).

It is important to note that 73% of the population of the municipalities of the Providers cluster resides in urban areas (IBGE, 2019), and the percentage of rural workers in the macrometropolis is very small (1.59% in 2010) (Pasternak, Suzana; Bógus, 2019). Thus, it should be recognized that the conservation of natural resources is not related to the significant impact of suppression of extractive activities, which would indicate that those municipalities are 'sacrifice zones' (Campos Tisovec-Dufner et al., 2019; Hansen et al., 2015; Katin, 2020) in favor of ensuring the necessary GBI. In fact, these municipalities are related to the urban dynamics of the macrometropolis, and are often housing alternatives for poorer people, since the cost of housing in more developed areas is very high. Thus, it can be reductionist to consider that conservation areas are impediments for development, and the question of justice must be addressed through better integration and opportunities for the populations of the Providers cluster, while considering the dynamics of trade, industry, and services to which they are already inserted.

Considering the study area's current urban planning, previous studies have argued, based on the differences in financial investments allocated to infrastructure projects for the metropolitan regions, that the current scenario of inequality may not change in the future; in other words, the metropolitan region of São Paulo will remain the owner of the largest amount of capital (Torres et al., 2019; Travassos et al., 2020). Our findings corroborate this assertion; for example, the Capital and Developed Receiving clusters comprise the metropolitan region of São Paulo and São Paulo city proper, with a group of ES receivers that includes 28, 431, 730 members of the population (84.4%) in the territory with respective demands for resources.

In relation to the guarantees of green infrastructure protection, ES provisioning, and generation of employment and income, the

Macrometropolis Action Plan suggests a series of alternatives; a prominent example includes the execution of actions directed towards sustainable tourism and payments for ES from the implementation of the 2009 Forest Remnants Program of the São Paulo State's Climate Change Policy (PEMC). However, such policies do not necessarily identify the specific relationships by which municipalities can be considered through their role in terms of environmental justice. Our criticism of these policies is that they should consider the environmental injustices within the macrometropolitan territory (Figs. 2–6, Tables 2 and 3). A useful alternative may be to promote sustainable development for municipalities in the Providers cluster through financial remuneration for environmental conservation, even if this type of policy would not exclude ES trade-offs (Jacka et al., 2008; Matthies et al., 2016; Pattanayak et al., 2010).

Sustainable tourism is also quoted as an alternative to development by the Macrometropolis Action Plan, which suggests that certain SPM natural conservation units can be explored through partnerships with the private sector. However, although the idea of exploring the multifunctionality of ecosystems in a sustainable manner is a positive one, this would introduce new stakeholders from the private sector that may compromise the policy's effectiveness (Leach et al., 2019; Mitchell et al., 2013).

Given this information, there is a concern that the distribution of benefits may not be homogeneous and fair among local residents and public and private organizations (Suwarno et al., 2016; Torres et al., 2019). The inclusion of third parties may represent a marginal policy, with the possibility of ensuring a lack of more robust policies dedicated to macrometropolitan development and protecting the region's green infrastructure; for example, municipalities such as Natividade da Serra, Bofete, and Redenção da Serra (Providers cluster) that could benefit from ecological tourism activities, given their low human development indicators presented in this study (Table 2) and the potential of their GBI, may encroach upon environmental protections.

Therefore, it is necessary for a management scheme dedicated to macrometropolitan challenges to engage in a responsible analysis of the benefits obtained by GBI in the territory to ensure that they will be distributed among all stakeholders involved. Moreover, the association between human development and ecological limits continues to demand new interpretations, as HDI-M does not contemplate ecological dimensions (we applied FIMD, which is analogous to this index) (Bravo, 2014; Maccari, 2014). Similarly, for nexus indicators, we believe that the analysis undertaken here for the macrometropolis allows us to jointly analyze the deficits between human development, environmental justice issues, and possibilities to search for synergies between the flows of providing water, energy, and food.

Despite nexus trade-offs presenting themselves as major challenges for decision makers, addressing these trade-offs is not necessarily a panacea; rather, these challenges should be viewed as alternatives capable of guiding public policy committed to efficiency, greater equity, and environmental justice (Schreckenberg et al., 2018; Vira et al., 2012). However, decision makers do not act on these complex problems holistically, instead pinning their hopes on 'magic bullets' (Bass, 2018) such as payments for ecosystem services without good evidence of their broader impacts. These impacts could include new negative externalities and trade-offs, misplacement of rights and responsibilities, economic efficiency-equity trade-offs, and top-down prescription as a part of broader structures of power where different groups influence the design and implementation of payment services schemes, thus influencing their effectiveness and distributional outcomes (Goh and Yanosky, 2016; Muradian et al., 2013; Pascual et al., 2014).

5.2. GBI analysis from the perspective of WEF nexus trade-offs

In exploring the interactions among nexus sectors, the receiver clusters are prominent in that they are important energy demanders per capita. Both the Capital and Developed Receivers, owing to their enormous populations, are also representative of the total demand of the macrometropolis. Although the electrical energy that supplies the SPM comes mostly from other regions, e.g., from the Itaipu power plant at the border with Paraguay, its supply and scarcity are in an elementary relationship with the formation of the macrometropolis in the analytical sense of the nexus. For example, this energy demand can be related to the contamination of the Billings dam, which is an enormous reservoir close to the São Paulo municipality. This contamination occurred because of a lack of planning in the face of strong pressures caused by the population and industrial growth of the 20th century (Giatti et al., 2016). The Billings Dam was prioritized for power generation and flood control, and thus received high loads of polluted water into its outflow (Hortellani et al., 2013; Rocha et al., 1985). The trade-off of this environmental liability occurred as a response to meeting developmental pressures, thus compromising the possibility of multiple uses and synergies among the dimensions of the WEF nexus. Currently, the ongoing search for water in distant locations of the territory causes disputes and additional energy expenses; in part this search occurs as a result of the impossibility of using water from the Billings dam itself (Giatti et al., 2016).

The other side of the water-energy trade-off is the case of the Cantareira water supply system, which supplies the São Paulo municipality and its surroundings; this system's water is imported from the four municipalities in Minas Gerais state: Camanducaia, Extrema, Itapeva, and Toledo, all of which are in the Providers cluster. Similarly, to supply the same highly urbanized area, in 2018 the São Lourenço water supply system was inaugurated by siphoning water from 70 km away in the Ibiúna and Juquitiba municipalities (Capital Receiver cluster). Thus, water from a distant source was used to replace historically degraded water resources in densely urbanized areas, which required more energy for transportation and restricted the ability of the provider municipalities to use the water for their own development. According to some authors (Castán Broto, 2017; Rodríguez et al., 2006) this trade-off category refers to decision making focused on the immediate provision of an ES, thereby compromising said service or other services in the future. Such a tendency relates to a sanitary engineering predominant paradigm and respective centralized decision making (Jacobi et al., 2015; Poupeau et al., 2018). Therefore, in our study, we note that the nexus trade-offs in the SPM are entangled through space-time horizons.

Concerning the Macrometropolis Water Resources Master Plan (DAEE, 2013), the territory's capacity to mitigate the central problem of scarce water resources is referred to as a perspective of reversibility (Rodríguez et al., 2006). This perspective supposes new alternatives through reducing trade-offs. Thus, analytically, the centrality of water issues aligns with the applicability of the nexus proposal, as well as with the recognition of the importance of the GBI within the context of ES provisioning (Barbosa et al., 2019; Kati and Jari, 2016; Well and Ludwig, 2019).

By 2035, DAEE (2013) estimated the total water flow into the SPM to reach 283.07 m^3/s, of which 134.41 m^3/s would be for urban areas, 61.80 m^3/s for irrigation, and 86.86 m^3/s for industries. If these demands are compared with the consumption measured in 2008, irrigated agriculture would require an additional volume of 17.80 m^3/s to match that of the future, which represents an increase of 40.5% for the sector. The current water structures of the macrometropolis are not able to guarantee this flow. This suggests that, besides "a new large scale system to significantly increase the

availability of raw water" (DAEE, 2013, p. 4), operational control actions that could reduce the flow from almost 300 m^3/s to 251.44 m^3/s are required. The delicate framework in terms of water scarcity and its centrality within the nexus framework also present additional challenges in the face of the extreme possibilities posed by climate change. For that matter, the emergent and severe water crisis of 2014–2016 demonstrated the vulnerabilities of the São Paulo Metropolitan Region as well as the entire SPM, which was clearly interconnected by water scarcity. This crisis was understood within the framework of climate change determinant factors and circumstances, through the appearance of a new pattern of drought, insufficient information for management, an incapacity of previously delimited responses, and a lack of appropriate governance and preparedness (Castán Broto and Bulkeley, 2013; Sinisgalli et al., 2018; Torres et al., 2019).

In our analysis, we consider that the municipalities in the Providers cluster, as well as the existence of GBI in other clusters, must become targets for planning, but not merely in the sense of water scarcity. Moreover, optimizing the conservation of local resources, such as the preservation of water in the vicinity of large urban centers, may reduce the pressure of long distance water imports, and reduce electricity trade-offs and maintain water availability for food production (Perrone et al., 2011) in municipalities that have this territorial vocation. The nexus approach in this context can build synergies within increasingly sophisticated governance structures that may become increasingly adaptable to climate change (Pahl-Wostl, 2019; Urbinatti et al., 2020).

In encompassing the scope of the WEF nexus, it is conventionally challenging to explore indicators for the respective interactions and trade-offs among involved sectors. Moreover, some studies have developed intervention strategies based on the correspondence of flux, efficiency, and environmental impact; these are also related to the demands for water, energy, and food (Albrecht et al., 2018; Arthur et al., 2019). Hence, in our study, we explored the relationship with energy using two different approaches. First, there is a pertinent condition of injustice, as the Provider cluster also shows the lowest levels of energy consumption per inhabitant (Fig. 6c). Second, energy is intrinsic in the historical issue of water management for the entire territory.

In this study, the nexus becomes an element of considerable interest, as it corresponds to a possibility of optimizing flows between the availability of natural resources (GBI) and the provision of ES. Thus, when understanding the nexus as a possibility of actions directed towards flows, efficiencies, and impacts, there can be a correspondent search for synergies. However, these alternatives should also be aimed at mitigating environmental injustices that constitute an element of unsustainability in the dynamics of the territory (Figs. 2–6, Tables 2 and 3).

Regarding the replicability of this study and its propositions, the selected indicators allowed us to identify sustainability issues (i.e., environmental injustices) beyond the efficiencies and flows of the nexus production chains. In this sense, the consideration of flux indicators contributes to our understanding of similar contexts. Complementary to that we identified the issue of human development and categorized it as an impact indicator (Arthur et al., 2019). Moreover, the water and energy nexus associated with the food system approach has been a key concern to improve urban perspectives of sustainability (Blay-Palmer et al., 2018; Dubbeling et al., 2017; Sellberg et al., 2020). Thus, a similar analysis may be suitable for other urban systems, both in the Global South and Global North.

6. Conclusions

Analyzing the presence of GBI and the provision of ES relative to the populations of the study area's municipalities denotes environmental injustices in the studied urban system, thereby emphasizing intrinsic elements to consider in ensuring sustainable development. In principle, people in different municipalities have equivalent rights, but those who live in the providing municipalities supply the needs of their peers in the macrometropolitan system without being able to count on the same opportunities for human development. In this sense, given the interdependence and scarcity of resources in macrometropolitan territories, redressing these injustices can be an important component to ensure and optimize the supply of ES.

Macrometropolitan territories, having highly distinct but interconnected and dependent municipalities, constitute a challenge in terms of their analytical complexity and demands for planning and assertive, intersectoral actions. The self-organizing map technique categorized clusters that showed losers and winners in terms of GBI and the provision of basic ES to the sustainability of the SPM; additionally, it highlighted the inequities of opportunities for social inclusion and human development.

The approach of the WEF nexus remains a challenge, yet it may contribute towards interpreting relevant trade-offs in an urban system or a macrometropolitan territory. Concurrently, this study is limited to clippings that comprise elements of the nexus and their interactions. The issue inherent to energy, for example, was minimally contemplated owing to the unavailability of data (for all municipalities); otherwise we assumed data related to the energy demand per capita associated with territorial inequities. Additionally, we analyzed energy as intrinsic through space-time interactions within the nexus, as related to the historic tendency of bringing water from distant places to supply higher population concentrations. In addition to these constraints, water-food provisioning data in the nexus approach can be used to analyze trade-offs with energy demands for supplying the population and the systemic territorial problem of water scarcity. Furthermore, we stress the pertinence of relativized human development within ecological constraints and justice.

Large urban agglomerations are biased by their centralities associated with population agglomeration and by their economic activities. We believe that another type of centrality was evident in this study, as constituted from the ES guaranteed by the existence of GBI that were subject to trade-offs associated with scarcity. We argue that the SPM municipalities identified as Providers with the lowest human development indicators demonstrate the externalities and contradictions inherent in the currently unsustainable developmental logic. These water-food providers are, therefore, central to life support systems and economic prosperity in the macrometropolis. The primary contradiction, in that sense, is that human development in a vast urban agglomeration must be understood through territorial interdependencies. Thus, some areas with an elemental role in ES provisioning can have a low human development rate in addition to being a hot spot in terms of ecological support. Therefore, these supplying regions require alternatives to guarantee ES provisioning associated with environmental injustice mitigation.

CRediT authorship contribution statement

Mateus Henrique Amaral: Conceptualization, Methodology, Data curation, Writing - original draft, preparation. **Lira Luz Benites-Lazaro:** Conceptualization, Methodology, Data curation, Writing - original draft, preparation. **Paulo Antonio de Almeida Sinisgalli:** Writing - review & editing. **Humberto Prates da Fonseca Alves:** Data curation, Writing - review & editing. **Leandro Luiz Giatti:** Conceptualization, Methodology, Writing - original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. .Supplementary data

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