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Temporal dynamics of land use, physical attributes, and hemeroby in the municipality of Sorocaba (SP): insights for planning in metropolitan municipalities

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ABSTRACT

Monitoring land use and land cover patterns, evaluating physical environmental attributes, and utilizing landscape indicators, such as hemeroby can significantly aid in the planning and preservation of ecosystem services. This study aimed to analyze the temporal dynamics of land use/land cover in the city of Sorocaba (SP) between 2007 and 2017, as well as the characteristics of the physical environment (i.e., slope and hypsometry) and hemeroby, aiming to provide elements for planning. The results showed the predominance of typologies: urbanized area; native vegetation; pasture; and temporary crops. The municipality's area is characterized by a low variation in hypsometric classes and a low slope, which favors territorial occupancy. The predominant levels of hemeroby are euhemerobiotic and metahemerobiotic, both reflecting significant anthropogenic interference, low self-regulation capacity, and an overriding need for human management and technological dependence. Therefore, urban expansion projects should consider the characteristics of the territory and adopt measures that minimize environmental impacts, facilitating the transition of landscape units with high hemeroby to levels with less anthropogenic interference and technological dependence.

KEY-WORDS: Landscape Ecology. Naturalness. Physical Environment.

1 INTRODUCTION

Humanity is living in the Anthropocene, a period marked by profound environmental and human consequences (CORLETT, 2015; ALBERTI, 2024). The expansion of urbanized areas presents challenges related to the depletion of natural resources, maintenance of ecosystem functionality, and human well-being.

The rapid growth in Brazilian municipalities has accelerated the conversion of natural landscapes into anthropogenic uses, directly affecting the provision of ecosystem services (e.g., water supply, air purification, recreation) to society, particularly in metropolitan regions (OLIVEIRA-ANDREOLI et al., 2019; OLIVEIRA et al., 2023). Human-dominated environments are characterized by high population density and altered areas, which contributes to ecological consequences and requires implementing sustainable strategies (WU, 2014; KONG, LIU, WU, 2020). The biophysical environment of cities is an important provider of ecosystem services (BOONE et al., 2012). Therefore, conducting integrated assessments of human impacts on the landscape is essential for ensuring adequate management.

Some environmental management issues only manifest at spatial scales, and regional research provides the elements for addressing these challenges (ERICKSEN, INGRAM, LIVERMAN, 2009). A better understanding of environmental problems is achievable by analyzing human actions across spatial and temporal scales, as well as the environmental and governance gradients that occur within landscapes (URIARTE et al., 2011). Therefore, approaches focused on metropolitan regions, which are characterized by high population density and highly urbanized landscapes, contribute to identifying environmental issues in these areas due to the loss of naturalness.

Monitoring landscape change patterns allows the indirect characterization of the ecological consequences resulting from anthropogenic activities. Land use/land cover represent the human component in a landscape, causing impact on ecological integrity and influencing the provision of ecosystem services both qualitatively and quantitatively (JACK, KOUSKY, SIMS, 2008; BURKHARD et al., 2012; LARONDELLE, HAASE, 2013).

Analyzing the landscape through environmental indicators can be highly valuable for assessing the dynamics of natural habitat loss and increasing artificialization caused by anthropogenic activities (FUSHITA et al., 2017). This approach enables a comprehensive description of the study area by encompassing both socioeconomic and environmental spheres at a given point in time, providing a scientific basis for socio-ecological system management and planning (BOTEQUILHA-LEITÃO; AHERN, 2002).

Identifying spatiotemporal patterns and the driving processes contributes to developing targeted intervention policies at the landscape level, facilitating planning, biodiversity conservation, water resource management, and providing ecosystem services (SILVA et al., 2022). Thus, monitoring landscape patterns is a highly valuable tool for decision-making and planning, particularly in highly urbanized areas.

This process can be enhanced by considering the structure and transformations of the landscape, as well as understanding the associated processes (BARBARA et al., 2014) and conducting environmental characterization (e.g., slope, hypsometry). The conservation of natural elements that support ecosystem services should be based on effective city environmental management and consider landscape modifications. In this context, hemeroby, an indicator proposed by Jalas in 1955, can be used to assess the proximity to natural conditions and the regulatory capacity of existing landscape elements (WALZ; STEIN, 2014). Applying an approach that considers the temporal dynamics of land use/land cover, the physical characteristics of the environment, and the degrees of hemeroby within the landscape can be highly valuable for planning efforts.

Considering this, the present study aimed to analyze the temporal dynamics of land use in the municipality of Sorocaba (SP) between 2007 and 2017, perform environmental characterization, and assess the level of landscape artificiality through the hemeroby, generating information that can support physical environmental planning in a metropolitan municipality.

2 OBJECTIVE

We aim to analyze the temporal dynamics of land use/land cover in the municipality of Sorocaba (SP) between 2007 - 2017 and conduct an environmental characterization and assessment of landscape artificiality (hemeroby).

3 METHODOLOGICAL PROCEDURES

3.1. Study Area

The municipality of Sorocaba (47° 34' 12.000'' W / 23° 21' 3.600'' S and 47° 18' 10.800'' W / 23° 35' 20.058'' S) is in the southwestern region of the São Paulo State (Figure 1). The total

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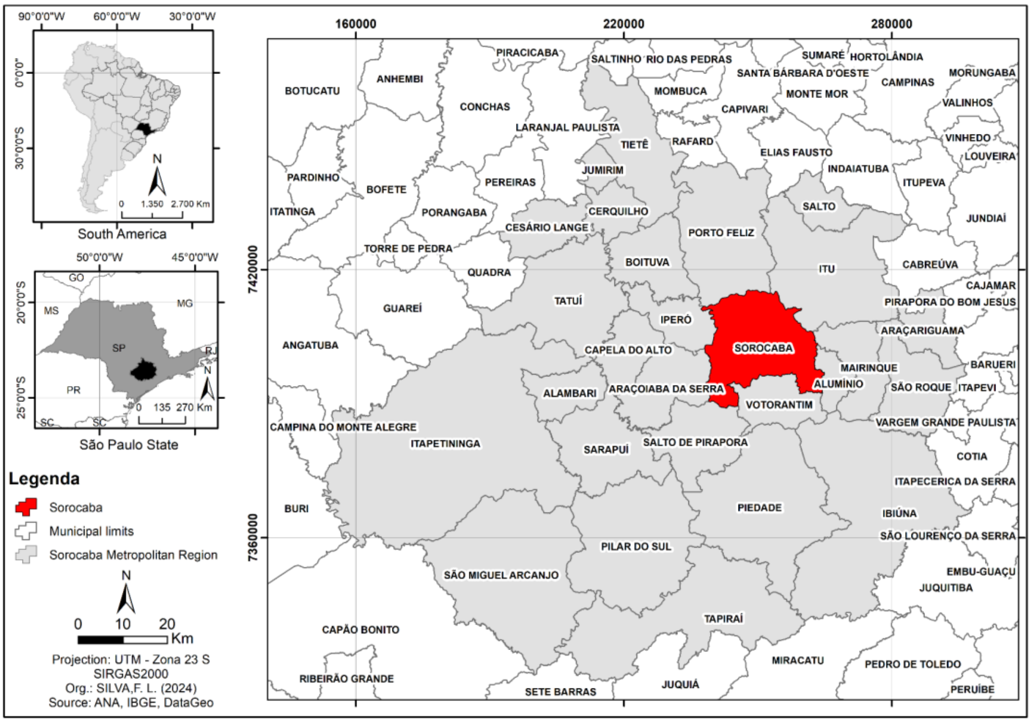
area of the municipality is 450,382 km², and according to the 2022 demographic census, there are 723,682 inhabitants (IBGE, 2024). Sorocaba is situated in an industrially oriented region (CETESB, 2023) drained by the Sorocaba River Basin, whose watershed is part of the Sorocaba-Médio Tietê Water Resources Management Unit (UGRHI 10).

It is important to note that Sorocaba is part of the Metropolitan Region of Sorocaba (MRS), established by Complementary Law nº 1,241/2014 (SÃO PAULO, 2014). The objectives include regional planning and the rational use of existing resources within the territory. The MRS comprises 27 municipalities grouped into three subregions (Subregion 1, Subregion 2, and Subregion 3), in which Sorocaba is part of Subregion 3 (SÃO PAULO, 2014), the most densely populated and industrialized. Over 1.7 million inhabitants reside in this area, and the MRS generates 45.4 billion reais (IPEA, 2017).

According to the Köppen classification, the climate is classified as Cwa, characterized by a dry season and a rainy season, with an average annual precipitation of 1,219 mm (CLIMATE-DATA, 2024). A forest survey conducted by the state in 2020 (SÃO PAULO, 2020) classified the remaining forests in the Sorocaba region as Semideciduous Seasonal Forest and Dense Ombrophilous Forest.

Figure 1 – Geographic localization of Sorocaba municipality



Source: Prepared by the authors, 2024.

3.2. Methodological Procedures

Land use/land cover data were obtained through manual digitization of polygons from two satellite images: one from Landsat 5 (TM sensor, orbit: 2020, point: 76, dated June 20, 2007, with a spatial resolution of 30 meters), provided by the National Institute for Space Research (*Instituto Nacional de Pesquisas Espaciais* – INPE, in Portuguese); and another from Landsat 8 (TM sensor, orbit: 2020, point: 76, dated June 15, 2017, with a spatial resolution of 30 meters), obtained from the United States Geological Survey. A false-color composite of the images (5R4G3B or 6R5G4B) was performed to assist in the visual interpretation and classification of land use types, which was based on the texture and tone of the images, following the multilevel classification from the Brazilian Technical Manual of Land Use (IBGE, 2013).

For environmental characterization, primary data on slope and hypsometry were obtained from topographic maps from the Brazilian Institute of Geography and Statistics (IBGE) for Boituva (SF-23-Y-C-I-4), Itu (SF-23-Y-C-II-3), Salto de Pirapora (23-F-Y-C-IV-2), and Sorocaba (SF-23-Y-C-V-1), at a scale of 1:50,000.

Aiming to describe the hemeroby level types in the municipality of Sorocaba (SP), a classification based on six categories (Table 1), often used in the literature, was used. Each land use and cover type identified was classified into one of the level types of hemeroby, considering its regulatory capacity, anthropogenic interference, artificialization, and technological dependence.

It is worth mentioning that all data were input or developed using ArcGIS 10.2 software, georeferenced to Zone 23 South, utilizing the Universal Transverse Mercator (UTM) projection system, datum SIRGAS2000.

Table 1- Degrees of hemeroby and their respective description.

LEVEL TYPES	DESCRIPTION
Ahemerobiotic	A natural landscape with high self-regulation potential, and with minimal to no anthropogenic interference or technological dependence.
Oligohemerobiotic	A natural landscape similar to the previous description but with a higher degree of anthropogenic interference.
Mesohemerobiotic	Semi-natural landscapes that experience moderate anthropogenic interference, characterized by partial artificialization, low technological dependence, and limited self-regulation capacity.
Euhemerobiotic	Artificial landscapes dominated by agribusiness activities, with a strong dependence on human management and technological inputs, with moderate to high anthropogenic interference and low self-regulation capacity.
Polihemerobiotic	Artificial landscapes that include peri-urban areas, transition zones between agricultural and urban environments, and mining sites, characterized by strong dependence on human management, high anthropogenic interference, and significant energy dependence.
Metahemerobiotic	An artificial landscape entirely created and dependent on human management, experiencing excessive anthropogenic interference. A defining characteristic is the complete destruction of biocenoses and a high level of technological dependence.

Source: Adapted from Blume & Sukopp (1976), Haber (1990) and Walz & Stein (2014).

4 RESULTS AND DISCUSSION

The municipality of Sorocaba was divided into eight hypsometric classes (Figure 2), each grouped into 62-meter intervals. The lowest observed value is in the central portion of the municipality, corresponding to an altitude of 595 meters. The highest recorded value was 1,032 meters, found in the southwestern region, where the greatest hypsometric values are also concentrated. It is important to note that the wetlands of the Sorocaba River are located in the

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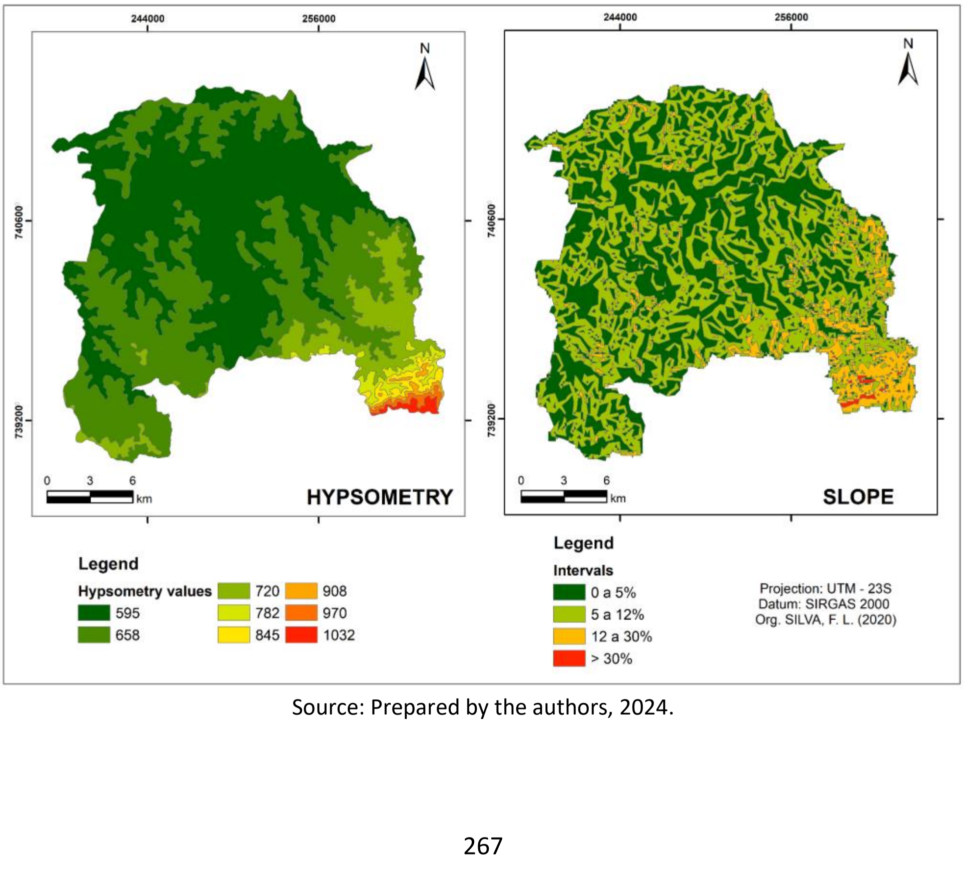
areas with the lowest hypsometric values (595 meters), through which the Sorocaba River flows across the municipality.

In terms of slope (Figure 2), the territory was found to be mostly flat. Low slope values (0 to 6%) generally indicate flat terrain (ARANTES, 2022), which is conducive to activities, such as urbanization and agribusiness. Approximately 43.5% of the area was classified as very flat (slope < 5%), 47.92% as gently to moderately undulating (5 to 12%), 8.27% as undulating to strongly undulating (12 to 30%), and only 0.31% of the area was considered strongly undulating (FLORENZANO, 2008). Biasi (1992) emphasizes that the maximum limit for urbanization is within the 12 to 30% range; areas with higher values should be preserved with native vegetation cover.

When evaluating the slope of the municipality of Sarandi (PR), Rigoldi, Paula Sousa, and Caraminan (2020) found that mechanization in the region faces challenges accessing steeper areas, leading to changes in land use and the introduction of activities such as forestry. While analyzing the slope of the municipality of Americana (SP), Trevisan and Moschini (2015) noted that this factor is one of the main determinants for the development of agribusiness and housing-related activities. The authors also linked the favorable topographic features to the historical context of the area's occupation. In another study conducted in the inland regions of São Paulo State, Silva et al. (2017) also observed that low variations in hypsometry and slope favor the development of anthropogenic activities, which were observed in the Monjolinho River Basin (SP). Therefore, it is likely that the economic activities developed in the municipality of Sorocaba (SP) are supported by the physical characteristics of the territory, leading to the establishment of industries, agricultural development, and livestock farming.

Figure 2 – Slope and Hypsometry of the municipality of Sorocaba.



Source: Prepared by the authors, 2024.

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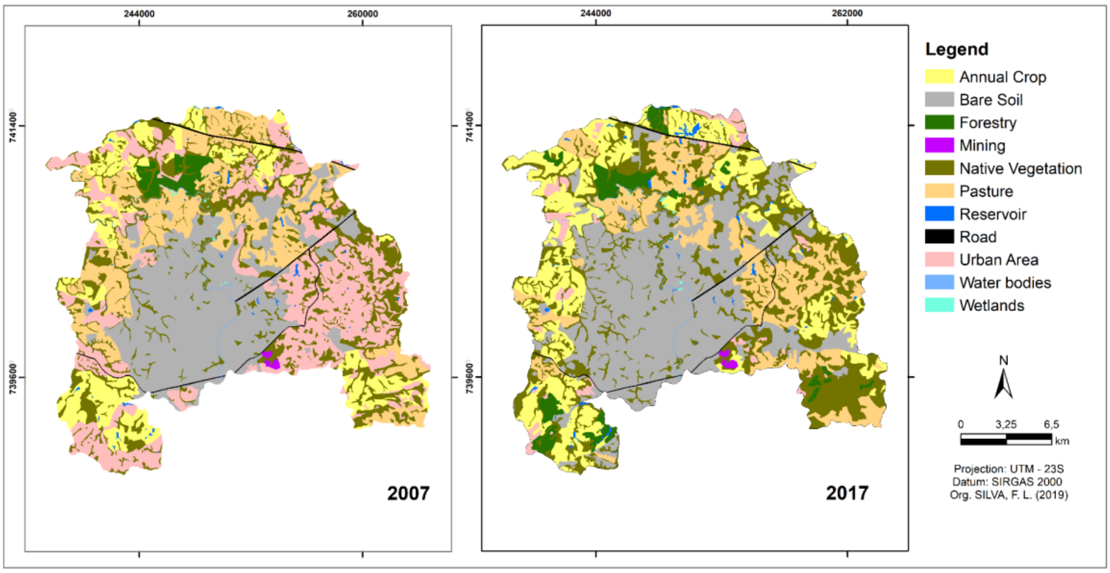
It is noteworthy that the Environmental Master Plan of Sorocaba, currently under revision, regulates land use/land cover, particularly concerning the quality of urbanization, aiming to discipline this process (SOROCABA, 2014). This regulatory instrument also encompasses conservation units and environmentally protected areas, given the abundance of springs in the region due to the low hypsometric elevations and flat regions. Furthermore, as part of the MRS and subject to specific regulations (SÃO PAULO, 2014; BRASIL, 2015), the municipality must promote sustainable development, contribute to integrated urban development, utilize the territory rationally, and protect the environment. However, the planning of the physical environment in Sorocaba (SP) is still in its early stages, and anthropogenic actions have contributed to the degradation of natural ecosystems (SILVA et al., 2020).

During the period from 2007 to 2017, eleven (11) land use/land cover typologies were identified (Figure 3, Table 2). Over these ten years, there was an increase in urbanized areas and a slight reduction in areas designated for agribusiness, as well as a decrease in uncovered areas, typically used for agricultural practices. The predominant classes, in terms of area, were 'Non-Agricultural Anthropogenic Area' and 'Agricultural Anthropogenic Area,' which together occupy more than 70% of the territory, reflecting a highly anthropized landscape.

Figure 3 – Patterns of land use/land cover in the municipality of Sorocaba.



Source: Prepared by the authors, 2024.

In 2007, approximately one-quarter of the territory was occupied by urbanized areas, while a considerable portion of the territory consisted of uncovered areas, which may be related to agribusiness (Table 2). Temporary crops (e.g., sugarcane) occupied less than one-sixth of the total area, while pastureland accounted for nearly 17% of the territory. It was found that less than 19% of the municipality is covered by native vegetation; however, the landscape is fragmented, particularly in urbanized and agricultural regions. A large portion of the remaining vegetation is associated with water bodies (such as Permanent Preservation Areas), Legal

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Reserves, or areas specifically protected by the municipal government, including Municipal Conservation Units and Urban Parks.

Table 2 - Patterns of land use/land cover in the municipality of Sorocaba.

Class	Typologies	2007		2017		Variation
		Area (ha)	(%)	Area (ha)	(%)	(%)
Non-Agricultural Anthropogenic Area	Urban area	11,493.71	25.50	15,062.21	33.42	31.05
	Road	382	0.85	382	0.85	0
	Mining	81.13	0.18	86.16	0.19	6.20
Agricultural Anthropogenic Area	Bare soil	10,805.62	23.97	1,164.94	2.58	-89.22
	Annual crop	5,225.68	11.59	8,394.99	18.63	60.65
	Pasture	7,392.75	16.40	7,169.19	15.91	-3.02
	Forestry	813.07	1.80	1,723.92	3.82	112.03
Natural	Native vegetation	8,513.34	18.89	10,592.70	23.50	24.02
Aquatic	Wetlands	32.07	0.07	39.95	0.09	24.57
	Water bodies	145.48	0.32	145.41	0.32	-0.05
	Reservoir	186.85	0.41	310.25	0.69	66.04
	TOTAL	45,071.71	100	45,071.71	100	-

Source: Prepared by the authors, 2024.

From 2007 to 2017, there was an increase in urbanized areas in the Sorocaba municipality. Additionally, a reduction in the 'Agricultural Anthropogenic Area,' particularly in the 'bare soil' typology, was observed. On the other hand, there were increases in annual crops, pasture, and forestry, indicating shifts in land use/land cover patterns over these ten years. Throughout the evaluated period (2007–2017), no reduction in wetlands or reservoirs was observed in the municipality of Sorocaba (SP). Furthermore, there was a slight increase in native vegetation, particularly in urbanized areas, possibly due to greater connectivity between vegetation fragments.

In the evaluated interval, both positive and negative variations in land use/land cover were observed, as well as instances of no variation (Table 2). Negative variation was noted in bare soil, which may be related to urban expansion and possibly the sugarcane harvest, where previously uncovered areas were converted to other uses, such as urbanization. This type of change reflects a transformation process in the landscape of Sorocaba (SP) over the years. There were small variations in the mining and pasture typologies, as well as on the roads and the Sorocaba River, which showed no variation during the analyzed period. However, changes were observed in urban areas, reservoirs, forestry, and native vegetation. These shifts may indicate different land-use dynamics and interventions over the years, reflecting both urban growth and environmental management concerning natural areas and infrastructure.

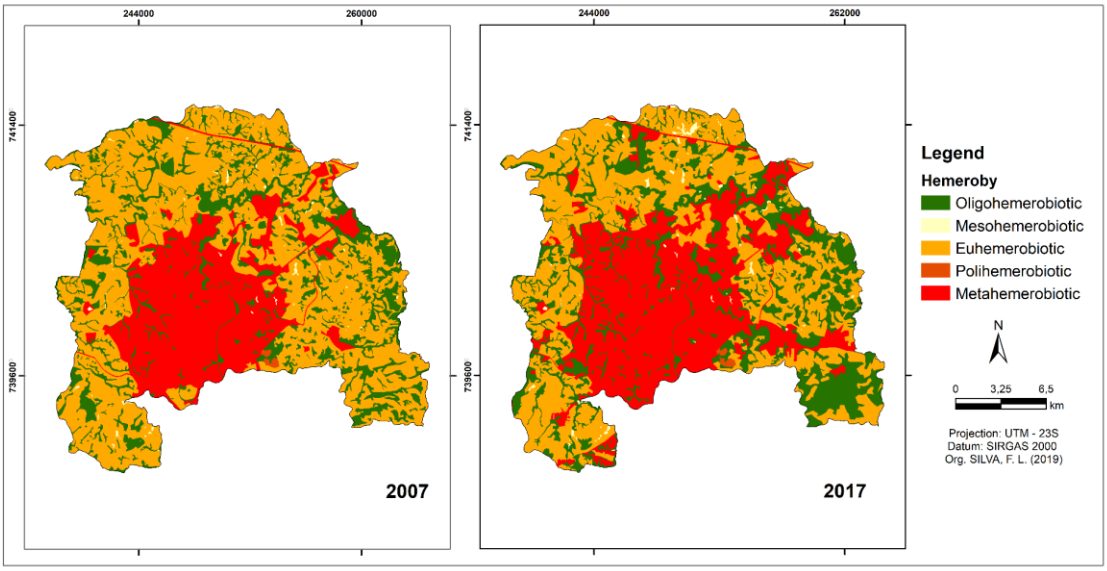
The concept of forest transition, as discussed by Farinaci and Batistella (2012), refers to a phenomenon where the rate of increase in vegetation cover surpasses the losses resulting from deforestation in an area. This concept indicates a positive shift in forest dynamics, suggesting a potential recovery or expansion of vegetated areas, even within contexts of intense urbanization and economic development. This finding aligns with the present study, as an increase in native vegetation was observed in the municipality of Sorocaba (SP). This situation is likely a result of public management efforts to restore green areas and the formulation of environmental public policies (SMITH et al., 2018).

Silva (2010) identified an intense dynamic of land use/land cover changes in the Sorocaba municipality from 1988–1995 and 1995–2003, highlighting the predominance of urbanized areas and pastures. These historical shifts provide context for the observed trend of increasing urbanization and land use/land cover transformation in Sorocaba (SP) over time. Bortoleto et al. (2016) and Silva et al. (2020) also conducted land use/land cover analyses in Sorocaba, confirming the dominance of agricultural areas and large urbanized zones. The authors further associated the remaining vegetation with aquatic environments and rural properties.

The level types of hemeroby identified for the municipality of Sorocaba (SP) are shown in Figure 4. As shown, five-level types of hemeroby were identified. The landscape is characterized by high anthropogenic interference, reliance on human management, low self-regulation capacity, and high technological dependence.

The oligohemerobiotic level is represented by the remaining native vegetation fragments in the municipality. The mesohemerobiotic level refers to the existing aquatic environments, which are impacted by human activities but show a low level of modification. Areas designated for agriculture and livestock are classified as euhemerobiotic. Polihemerobiotic units correspond to mining sites. Finally, the metahemerobiotic level encompasses areas with high levels of impermeabilization, high technological dependence, and human interference, such as urbanized areas and road networks.

Figure 4 – Patterns of the hemeroby level types in the Sorocaba municipality



Source: Prepared by the authors, 2024.

During the evaluated period (Table 3), the hemeroby of the municipality of Sorocaba was primarily represented by the euhemerobiotic and metahemerobiotic level types, which together accounted for over 80% of the territory in 2007. Landscape units classified as oligohemerobiotic occupied less than 20% of the landscape, while the mesohemerobiotic and polihemerobiotic level types represented less than 0.6% of the landscape.

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Table 3 – Level types of hemeroby in the Sorocaba municipality

Level types	2007		2017		Variation
	Area (ha)	(%)	Area (ha)	(%)	(%)
Oligohemerobiotic	8,690.90	19.28	10,778.06	23.91	24.02
Mesohemerobiotic	186.85	0.41	310.25	0.69	66.04
Euhemerobiotic	24,237.12	53.77	18,453.04	40.94	-23.86
Polihemerobiotic	81.13	0.18	86.16	0.19	6.20
Metahemerobiotic	11,875.71	26.35	15,444.21	34.27	30.05
Total	45,071.71	100	45,071.71	100	-

Source: Prepared by the authors, 2024.

Regarding the hemeroby level types in 2017, the patterns found were similar to those of 2007 (Table 3). Once more, the euhemerobiotic and metahemerobiotic level types predominated. However, the area classified as euhemerobiotic decreased, accounting for less than 76% of the territory. Oligohemerobiotic units expanded to occupy nearly 24% of the landscape. An increase was also observed in the polihemerobiotic and mesohemerobiotic level types, representing about 1% of the total area.

Positive variations were observed for all hemeroby level types, except for the polihemerobiotic units, which are directly associated with agriculture. Despite the increase in the oligohemerobiotic units, there was also a rise in units characterized by a complete loss of biocenosis and substantial anthropogenic interference (i.e., metahemerobiotic).

The Sorocaba municipality (SP) underwent an intense urbanization process between 1985 and 2020, in which rural areas were converted into urban spaces (RIBEIRO et al., 2024). This process negatively impacts natural systems and affects their stability due to the high degree of landscape modification, particularly in densely populated regions. Therefore, it is essential to restore the municipality's natural areas and mitigate diffuse pollution and pollutant loads to aquatic environments. Municipal planning and creating mechanisms to prevent the conversion of wetland ecosystems within the municipality are crucial. By understanding the implications of urbanization on ecosystem resilience and functioning, strategies can be implemented that promote sustainable development in urban centers across Latin America (ALBERTI, 2024; RIBEIRO et al., 2024), given the similar challenges faced.

The predominance of hemeroby level types indicating anthropogenic interference and high technological dependence can be considered a reflection of the anthropization of the landscape and the construction of artificial structures (FUSHITA et al., 2017). Furthermore, it is important to note that hemeroby is an indicator that helps assess the naturalness and regulatory capacity of the elements that constitute the landscape. This facilitates the understanding of processes associated with landscape transformations and the monitoring of its dynamics, making it useful for planning and decision-making (BÁRBARA et al., 2014; WALZ; STEIN, 2014; NUCCI et al., 2016).

Thus, the strong degree of alteration in the studied landscape units is evident. The observed scenario has implications, including the compromise of the self-regulatory capacity of these units, the occurrence of strong anthropogenic interference, a high dependence on human management, and the need to use technologies. Oligohemerobic and mesohemerobic units (i.e., green and blue structures) are fundamentally responsible for providing ecosystem services, such as air purification and sediment control for water bodies (ARTMANN et al., 2017). Despite the existence of a master plan that provides guidelines for land use/land cover focusing on environmental preservation, there are deficiencies in the conservation of natural elements and maintenance of biodiversity (SILVA et al., 2019). The results indicate that the landscape is marked by hemeroby level types reflecting anthropogenic interference and a low capacity for natural regulation. Although there has been an increase in oligohemerobic areas, highly anthropized areas still predominate. This suggests that the urbanization process and agribusiness practices do not fully align with the provisions outlined in the master plan, highlighting the need for more stringent measures to ensure environmental preservation and vegetation recovery.

Level types of hemeroby reflecting high human interference and technological dependence were also observed by Pereira, Silva, and Veiga (2011) in a study of the landscape units in the Centro Cívico neighborhood of Curitiba (PR). At that time, five-level types of hemeroby were identified, and the high artificiality of the units was associated with the development of commercial activities and urban densification. When evaluating the hemeroby of the Pici neighborhood in Fortaleza (CE), Belem and Nucci (2011) found that more than 50% of the landscape exhibited low self-regulatory capacity and high technological dependence. In their assessment of a landscape in the inland region of São Paulo State, Ferreira et al. (2018) found a predominance of level types indicating high hemeroby (i.e., euhemerobic and metahemerobic). The authors associated this situation with the predominance of urban and agricultural areas, which play an important role in the introduction of pollutants and contaminants into the waters of the Monjolinho River.

Landscapes with high hemeroby level types depend on energy sources that generate detrimental effects on ecosystems, resulting in pollution, contamination, and environmental degradation (NUCCI; BELEM; KRÖKER, 2016). Human actions induce changes in natural systems; therefore, landscape recovery can be facilitated through the gradual restoration of landscape units, employing actions that induce changes in the hemeroby (KIEDRZYŃSKI et al., 2014). It is important to emphasize that increasing natural areas in anthropized regions is essential for the continued provision of ecosystem services and the maintenance of biodiversity (SILVA et al., 2022). In metropolitan municipalities, this measure is indispensable for ensuring an adequate quality of life for the population and for preserving natural resources.

5 CONCLUSION

The analysis used, considering land use/land cover patterns, physical attributes, and the level types of hemeroby of landscape elements, provides a basis for establishing intervention measures useful for planning and management in administrative units such as metropolitan municipalities. Sorocaba (SP) is characterized by a predominance of anthropogenic land use/land cover typologies. However, between 2007 and 2017, a reduction in areas for agribusiness and an increase in urbanized areas and native vegetation were observed. The anthropization of the landscape is facilitated by the low variation in hypsometric classes and the predominantly flat terrain. Regarding hemeroby, the euhemerobiotic and metahemerobiotic degrees predominate, reflecting significant human control and intervention in the landscape, which may compromise the self-regulation of elements and result in a loss of naturalness. This situation directly affects the provision of ecosystem services. The territory of Sorocaba (SP) is marked by the dominance of anthropogenic land use, yet during the study period, agribusiness areas decreased while urbanized areas and native vegetation increased. The results can serve as a foundation for establishing guidelines that help maintain natural elements and promote economic development, considering the restrictions imposed by natural ecosystems and the need to safeguard the benefits provided to the population in metropolitan regions. It is crucial to enhance connectivity between the remaining vegetation fragments and curb the expansion of urban areas and other impactful activities in ecologically sensitive or fragile areas. Urban expansion projects, such as master plans and regional development plans, must consider local characteristics and adopt measures to minimize environmental impacts. The following measures are recommended: controlling urban expansion around fragile ecosystems, implementing ecological corridors and integrating green spaces, restoring degraded areas, incentivizing agribusiness through environmental sustainability, and monitoring and enforcement.

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