Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

Spatio-temporal evaluation of ecosystem services in the São Paulo Macrometropolis, Brazil

Avaliação espaço-temporal dos serviços ecossistêmicos na Macrometrópole Paulista, Brasil

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ABSTRACT

Urbanization is one of the key factors that drive changes in ecosystem services. Although various studies have analyzed relationships between land-cover change and ecosystem services degradation, few have explored the impacts in future scenarios in mega metropolitan areas. This work performed an individual and integrated spatio-temporal assessment of four ecosystem services in the São Paulo Macrometropolis, the largest urban agglomeration in Latin America, in different land-cover scenarios using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software. Correlation analysis and map algebra were used to identify trade-offs and synergies, as well as hotspots and coldspots of multiple ecosystem services. The results showed decreasing trends in the supply capacity of erosion control, carbon storage, and seasonal water yield in the entire São Paulo Macrometropolis and most of its Regional Units, as well as evidence of a worsening of trade-offs between the ecosystem services evaluated. Furthermore, areas with a high supply of three or more ecosystem services were coincident with Conservation Areas, emphasizing the importance of these protected areas. By revealing important relationships among four ecosystem services, the outputs suggest regions and combinations of services for which spatial planning and appropriate conservation mechanisms can be used to optimize synergies and mitigate trade-offs. The results can help land use planning practitioners and decision-makers to design management strategies and policies for conservation and restoration based on linkages between specific units and associated ecosystem services and their trade-offs in this strategic region of Brazil.

Keywords: land-cover change; territorial assessment; ecosystem services mapping, environmental planning, dynamic modeling.

RESUMO

A urbanização é um dos principais fatores que impulsionam as mudanças nos serviços ecossistêmicos. Embora vários estudos tenham analisado as relações entre a mudança da cobertura da terra e a degradação dos serviços ecossistêmicos, poucos exploraram os impactos em cenários futuros em grandes áreas metropolitanas. Este trabalho realizou uma avaliação espaçotemporal, individual e integrada, de quatro serviços ecossistêmicos (controle de erosão, armazenamento de carbono, qualidade do hábitat e regulação da água) na Macrometrópole de São Paulo, a maior aglomeração urbana da América Latina, em diferentes cenários de ocupação do solo usando o *software* Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). Análise de correlação e álgebra de mapas foram usadas para identificar *trade-offs* e sinergias, bem como *hotspots* e *coldspots* de múltiplos serviços ecossistêmicos. Os resultados mostraram tendências decrescentes na capacidade de oferta de controle de erosão, armazenamento de carbono e produção sazonal de água em toda a Macrometrópole Paulista e na maioria de suas Unidades Regionais, bem como evidências de piora dos *trade-offs* entre os serviços ecossistêmicos avaliados. Além disso, áreas com alta oferta de três ou mais serviços ecossistêmicos foram coincidentes com Unidades de Conservação, enfatizando a importância dessas áreas protegidas. Ao revelar relações importantes entre os quatro serviços ecossistêmicos, os mapas sugerem regiões e combinações de serviços para os quais o planejamento espacial e mecanismos de conservação apropriados podem ser usados para otimizar sinergias e mitigar *trade-offs*. Os resultados podem ajudar os profissionais de planejamento do uso da terra e os tomadores de decisão a projetar estratégias de gestão e políticas para conservação e restauração com base nas ligações entre unidades específicas e serviços ecossistêmicos associados e seus *trade-offs* nesta região estratégica do Brasil.

Palavras-chave: mudança na cobertura do solo; avaliação territorial; mapeamento de serviços ecossistêmicos, planejamento ambiental, modelagem dinâmica.

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Conflicts of interest: the authors declare no conflicts of interest.

Funding: São Paulo Research Foundation (FAPESP) for grant 2015/03804-9 (Thematic Project MacroAmb "Environmental Governance in São Paulo Macrometropolis in a climate variability context") and the National Research Council (CNPq) for scholarship 305188/2020-8.
Received on: 05/26/2023. Accepted on: 08/21/2023.
https://doi.org/10.5327/Z2176-94781638

Introduction

Brazil is a megadiverse country and is home to important world's biodiversity hotspots (Myers et al., 2000). Therefore, a total of 18.6% of the country's territory are protected areas (Marques et al., 2022), established and managed to ensure the conservation of biodiversity, which positively affect the supply of ecosystem services (Spanò et al., 2017). Nonetheless, these areas feature a high degree of endemism and extensive environmental disturbance due to the conversion of native vegetation for anthropogenic use and new deforestation fronts (Marques et al., 2022).

Moreover, rapid urbanization that occurs in large Brazilian metropolises has been generating various environmental and social problems and has resulted in severe ecosystem services degradation (Carbone et al., 2020), as well as threats to conservation areas. Examples of negative impacts related to increasing population density and demands of urban environments that emerge in mega cities are floods, insufficient water availability, the urban heat island effect, poor air quality, and noise pollution, all of which are expected to be further exacerbated by the vulnerability of each region to climate change impacts, affecting human health and the well-being of population and ecosystems (Lourdes et al., 2021).

Ecosystem services were defined by the Millennium Ecosystem Assessment (MEA, 2005) as the benefits that ecosystems provide to people and the contributions (direct and indirect) of ecosystems to human well-being (De Groot et al., 2010). Nevertheless, this concept is still evolving, and it also can be described as the actual processes, functions, and flows of services that benefit people (Costanza et al., 2017).

The pressures of human actions on natural resources, such as population growth, urbanization, industrialization, and agricultural activities, have impacted the provision of ecosystem services. As a result, there are negative effects on biodiversity, natural habitat, food production, quality and quantity of water, air quality, and levels of pollution, which also negatively affect human well-being (MEA, 2005; Hernandez et al., 2010).

Land use and land cover are one of the key factors that drive changes in ecosystem services and, therefore, this topic has been the subject of several publications, mainly after the MEA, which was carried out between 2001 and 2005 (Costanza et al., 2017). Studies cover different contexts, from the national one (Verde et al., 2020) to the regional one, such as watersheds (Li and Wang, 2020) and protected areas (Lecina-Diaz et al., 2019), as well as at the municipal (Moein et al., 2018) and local level (Liu et al., 2022).

Despite this large number of works that focuses on ecosystem services, few explored the analysis of spatial and temporal dynamics in the integrated assessment of different ecosystem services. Most of them have exclusively performed local cartographic analysis, without exploring both the spatial and temporal analysis of various ecosystem services (Aryal et al., 2022). Thus, the spatio-temporal analysis of the relationships between ecosystem services remains a major challenge in scientific research (Ndong et al., 2020), especially the quantitative mapping of the impacts arising from land use change on the provision of ecosystem services in future scenarios (Sun and Li, 2017).

Furthermore, although urban sprawl has become one of the most important factors increasing people's demands for ecosystem services, intensifying the supply scarcity of them (Yuan et al., 2019), scarce studies have been carried out in intensely urbanized areas of large territorial extension (Wang et al., 2022), such as the São Paulo Macrometropolis (SPM).

The SPM is the largest urban agglomeration in Latin America (Tavares, 2018), and the dynamics and characteristics of this territory have been affecting the provision of relevant ecosystem services (Gonçalves et al., 2021). As described in Cruz et al. (2017), soil erosion is a serious problem in the SPM due to intensive anthropogenic influences and its inherent vulnerability. Carbon storage is also relevant in this territory considering the scenario of climate variability that can intensify the socio-environmental problems arising from the urbanization and deforestation that occur at different locations of the SPM (Araújo et al., 2020). The SPM also supports high levels of biodiversity and provide different habitat for species with diverse ecological functions in the nature, but predictive studies regarding the potential species redistribution within the SPM area under different climate change scenarios found forecasts of generalized species losses for the whole Atlantic Forest extension (Vasconcelos, 2020). Ultimately, it must be highlighted that one of the most important challenges to be faced in the SPM is water security, due to natural characteristics of its watersheds, impacts of intense urbanization and deforestation, high population contingent and economic activities that demand large amounts of water (Jacobi et al., 2015). Thus, it is necessary to evaluate the changes in land use and land cover associated with the metropolization process to balance the regional development of this area and its environmental protection.

This study evaluated the spatio-temporal variation between four ecosystem services in different scenarios to guide decision-makers in formulating future regional environmental public policies. The specific objectives were as follows: 1. to evaluate the supply potential of four ecosystem services in the SPM in different land-cover scenarios; 2. to identify trade-offs and synergies between individual and integrated ecosystem services in the macro-metropolitan context; and 3. to assess the connection between areas of high and low supply of ecosystem services and the Environmental Conservation Areas.

Materials and Methods

Study area

The SPM (Figure 1) is home to more than thirty-six million inhabitants (IBGE, 2022), which represents about 75% of the total population of the State of São Paulo. It is a region with a high population density and many economic activities that amounts to approximately 83% of São Paulo's Gross Domestic Product (GDP) and 27.3% of Brazilian GDP (IBGE, 2022).

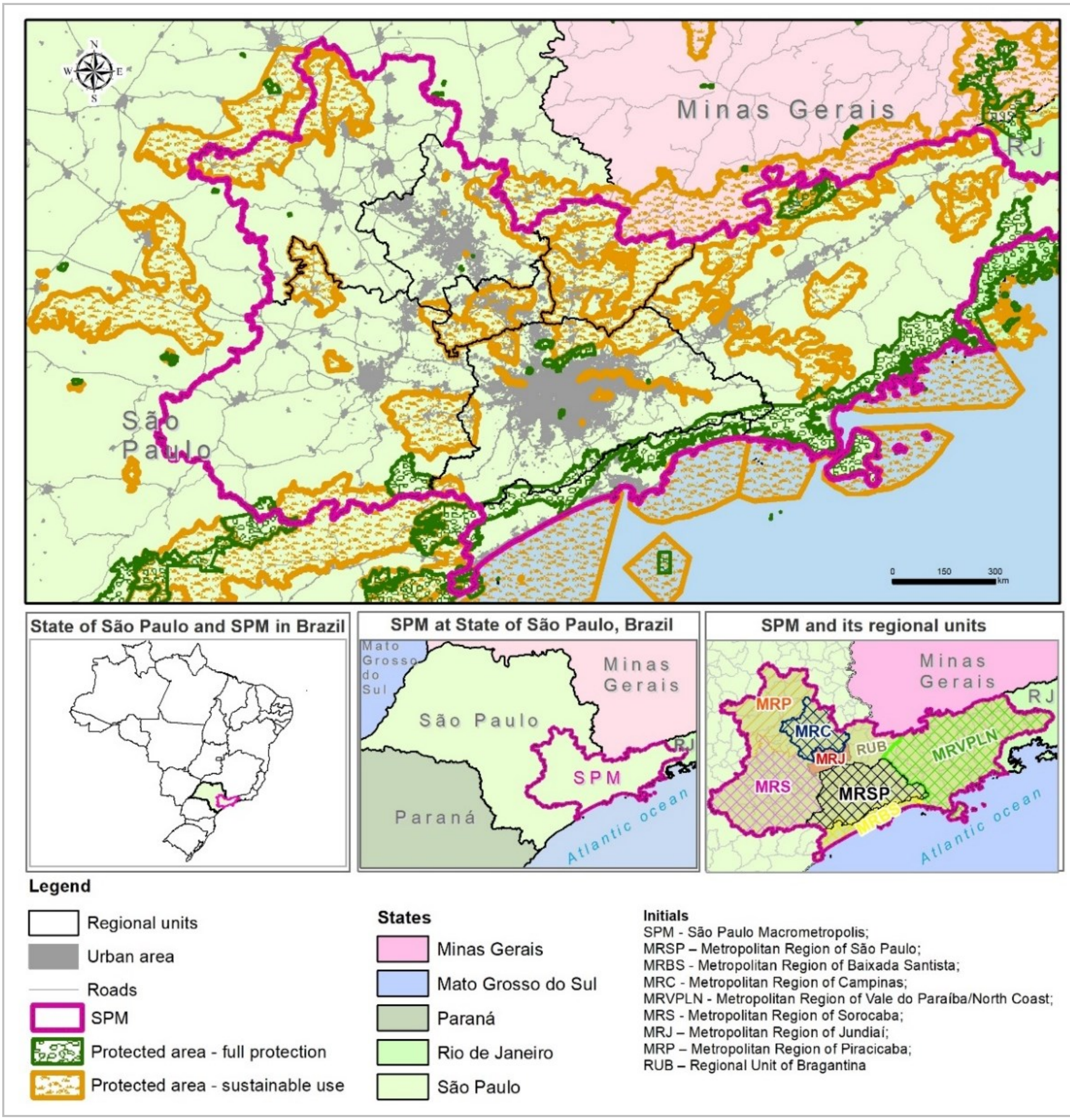

Figure 1 – São Paulo Macrometropolis location in Brazil and the State of São Paulo, with emphasis on its regional units and conservation areas.

It covers 53,000 square kilometers and encompasses 174 municipalities, belonging to eight Regional Units, named: MRSP — Metropolitan Region of São Paulo; MRBS — Metropolitan Region of Baixada Santista; MRC — Metropolitan Region of Campinas; MRVPLN — Metropolitan Region of Vale do Paraíba/North Coast; MRS — Metropolitan Region of Sorocaba; MRJ — Metropolitan Region of Jundiaí; MRP — Metropolitan Region of Piracicaba; and RUB — Regional Unit of Bragantina.

According to Silva and Fonseca (2013), the SPM is considered a 'city-region' because its productivity growth is based on the dissemination of flexible, logistical, and high-tech production arrangements. Its territorial expansion occurs on a regional scale and the dynamic development of this territory includes strategic transport and communication networks, as well as the social life linked to important economic activities that take place there.

Torres et al. (2019) mention that the SPM is an area that integrates goods, people, real estate speculation, agribusiness, ecosystem services, slums, dormitory cities, and vulnerabilities, with the city of São Paulo as a polarizing center. Momm-Schult et al. (2015) point out that this 'global city' encompasses an urban network with diversified functions that establish economic relationships with several other urban agglomerations, and is considered a possible platform for policy integration.

About 21% of the natural heritage of the State of São Paulo, protected through Conservation Units, is within the limits of the SPM (EMPLASA, 2014), showing a high potential for the performance of ecosystem services, such as the provision of wood, leaves, fruit, seeds, and food; carbon storage and sequestration; regulation of water flows, maintenance of water quality; and areas of outstanding natural beauty (MEA, 2005; Haines-Young and Potschin, 2018). Population growth, together with the industrial and irrigated agriculture activities, tends to threaten the supply of ecosystem services, indicating the importance of identifying in which areas the processes of loss of these services occur.

Data sources and processing

Data from multiple sources were adopted to support the analysis, as shown in Table 1. All data were standardized to a resolution of 30×30 m, and projected to the SIRGAS 2000 reference system and the UTM projection system zone 23 S, which were used as input data in the Integrated Evaluation of Ecosystem Services and Tradeoffs — InVEST software (SHARP et al., 2018). Four InVEST models were adopted: sediment delivery ratio (SDR), carbon, habitat quality (HQ), and seasonal water yield (SWY).

Analysis of land use and land-cover change

Land-cover data for 1985 and 2015 were obtained from the Mapbiomas Project (Souza et al., 2020), whose maps have been widely used in environmental studies in Brazil (Fiorini et al., 2020; Petroni et al., 2022; Silva Cruz et al., 2022). The data were generated for all of Brazil in the period from 1985 to 2020, with a spatial resolution of 30 m each year.

The trend scenarios for 2030 and 2050 in the SPM were obtained from Machado and Freitas (2021), who used the Dinamica EGO software for future land-cover simulations. This software is based on a transition matrix from the observed change pattern in the period from 1985 to 2015 to simulate scenarios according to specific conversion rules and pre-established parameters (Soares-Filho et al., 2002). Machado and Freitas (2021) adopted six land-cover classes, which were used to modeling trend scenarios: 1. Natural Forest, 2. Planted Forest, 3. Pasture, 4. Agriculture, 5. Urbanized area, and 6. Water bodies. Proximity to roads, water bodies, urban sectors, protected areas, and mountainous areas, as well as the type of soil and elevation of the terrain, were considered static and dynamic variables by the authors. The results were used as input data for mapping ecosystem services in the SPM.

Mapping of ecosystem services

Four relevant ecosystem services in the macro-metropolitan context were evaluated, namely: "erosion control" (ERO), "carbon storage" (CARB), "habitat provision" (HAB), and "water regulation" (WAT). They are services of great importance to local and global interests, in line with the Sustainable Development Goals (SDGs) defined in the 2030 Agenda of the United Nations (mainly SDG 6 – Clean water and sanitation; SDG 11 – Sustainable cities and communities; SDG 13 – Climate action; and SDG 15 – Life on land), and represent important challenges to be faced in the study area.

Table 1 – Spatial data sources for InVEST models.

Data	Type	Resolution	Data sources	InVEST model
Digital Elevation Model (DEM)	Raster	30 m	NASADEM (JPL, 2020)	SDR, SWY
Sub-basins/ watersheds	Vector (polygon)	---	Own elaboration using NASADEM and ArcGIS Hydrology tools 10.7.1	SDR, SWY
Land use and land cover map (1985 and 2015)	Raster	30 m	Mapbiomas Coleção 5.0 www.mapbiomas.org	SDR, SWY, HQ, Carbon
Land use and land cover map (projected to 2030 and 2050)	Raster	30 m	Machado and Freitas (2021).	SDR, SWY, HQ, Carbon
Soil map	Vector (polygon)	1:250.000 and 1:100.000	Rossi (2017)	SDR, SWY
Erosivity of the rains	Raster	1 km	Teixeira et al. (2022)	SDR
Average annual evapotranspiration	Raster	1 km	WorldClim 2.1 (Fick and Hijmans, 2017),	SWY
Average annual rainfall	Raster	1 km	WorldClim 2.1 (Fick and Hijmans, 2017),	SWY
Highways	Vector (line)	---	Openstreetmaps	HQ

Erosion control

The SDR model was used to assess the ES “erosion control potential.” The annual soil loss was calculated using the revised universal soil loss equation (USLE) (Wischmeier and Smith, 1978). Digital Elevation Model (JPL, 2020), watersheds, rainfall erosivity (K) (Teixeira et al., 2022), soil erodibility (K) (Mannigel et al., 2002; Rossi, 2017), cover-management factor (C) and conservation practices factor (P) were input data. C and P values were obtained from Silva (2003) and Pavani et al. (2020), as described in the Supplementary Material.

Carbon storage

The Carbon InVEST model was used to assess the “carbon storage” ecosystem service. This model simplifies the carbon cycle and assumes a linear change in carbon sequestration over time, which is intrinsically related to changes in land use and land cover. The overall carbon sequestration is the sum of indicative values of aboveground biomass, belowground biomass, soil organic matter, and dead organic matter, which are associated with land use and land cover classes. The carbon pools data were taken from Pavani et al. (2018), as shown in the Supplementary material.

Habitat quality

The HQ model assumes that biodiversity patterns can be estimated by analyzing land use and land cover maps together with the threat raster. In this model, habitat quality is only a proxy for biodiversity, estimating the extent of habitat and its degradation in landscapes. We defined three sources of threat to represent the man and nature-dependent influences on the habitat: agriculture, urbanized area, and roads (paved and unpaved). The data required for the model included land use maps, threat data, and threat sources, presented in the Supplementary material. The half-saturation constant was set at 0.05, following the guidance by Sharp et al. (2018).

Seasonal water yield

The SWY model quantifies the relative contribution of a portion of the landscape to seasonal baseflow (BF) and quick flow (QF) based on the topographic position of a pixel (Sharp et al., 2018). The input parameters were the monthly average precipitation and the reference monthly evapotranspiration (Fick and Hijmans, 2017), digital elevation model (JPL, 2020), land use and cover, hydrological group of soils (Rossi, 2017), and watersheds. The values of the biophysical table relating the use and land cover, the type of soil and the curve number, and monthly values of the evapotranspiration coefficient (Kc) were obtained from Sartori et al. (2005) and Marques (2018). The table of rainfall events was calculated from the database provided by the Department of Water and Electricity of the State of São Paulo. The model was then run using the input parameters and the standard function of rainfall seasonality (α=1/12), the function of the local topography and soils (βi=1), and the parameters of the pixel recharge fraction (γ=1) of the model. The supplementary material shows the details of the data sources.

Integrated analysis of ecosystem services

The analysis of trade-offs and synergies was made from the evaluation of numerical and spatial correlation. Data from the four ecosystem services, in the four years analyzed, were normalized on a scale from 0 to 1 so that the highest values correspond to a greater supply of each service. For carbon storage, habitat quality, and water regulation, a positive indicator was used (the higher the value, the better the service); and for erosion control, the soil loss values were transformed into logs because the amplitude of the values was very high (Duarte et al., 2016) and then normalization was performed in a descending order (that is, the lower the value, the better the service).

The correlation between the four ecosystem services across the study area and in the different regional units was calculated using “Band Collection Statistics” of the “Spatial Analyst Tools/Multivariate” of ArcGIS 10.7.1, which calculates the correlation matrix between normalized raster files. There is synergy if the correlation coefficient is positive and negative values indicate a trade-off between ecosystem services. The absolute value of the correlation coefficient also indicates the intensity of the relationship between ecosystem services. The higher the value, the stronger the trade-off/synergy (Li et al., 2020; Yang et al., 2021).

To spatially assess the relationships between the four ecosystem services, we used the conceptual basis of the method proposed by Cademus et al. (2014), based on Carr and Zwick (2007), adapting for the identification of hotspots/coldspots of ecosystem services (Egoh et al., 2008; Schröter and Remme, 2016). Using ArcGIS 10.7, normalized values were grouped into three provision-level classes for each of the four ecosystem services, whose values were defined by calculating descriptive statistics and evaluating their cumulative frequency distributions. Then the values were coded to 1, 2, and 3, representing low, medium, and high provisioning levels, respectively, using ArcGIS 10.7.1’s Reclassify tool. To represent these areas spatially and quantitatively, interaction codes (ICs) were defined from the combination of the individual ecosystem service level in a bundle of ecosystem services, according to Equation 1:

$$IC=(ERO\times1000)+(CARB\times100)+(HAB\times10)+WAT \quad (1)$$

Where: IC is the four-digit IC, a number between 1111 (all four services have the lowest supply values) and 3333 (all four services have the maximum supply values); ERO is the erosion control service value erosion control; CARB is the value of the carbon storage service; HAB is the value of the habitat provision service; and WAT is the value of the water regulation service.

Those areas with at least three services at the lowest level of supply were classified as coldspots, and the areas with 2 services at the highest level of supply at least represented hotspots (the strongest synergies between the services). Finally, the correlation between ecosystem service hotspots and coldspots and natural protected areas in the SPM was analyzed.

Results and Discussion

Spatio-temporal assessment of ecosystem services in different scenarios

Figure 2 and Table 2 present the results obtained through the mapping of ecosystem services in the SPM during the four years analyzed, as well as the main driver of change: land use and land cover. The results reveal that changes in land use and land cover between 1985 and 2050 are dominated by transitions from natural systems to agricultural or urban environments, with a decrease in Natural Forest and Pasture, and an increase in planted forests and urbanized areas. The spatial pattern of built-up area growth is consistent with the shrinkage of cultivated land, and is closer to roads and main urban centers. The data corroborate the analysis performed by Gonçalves et al. (2021) and Machado and Freitas (2021), who identified significant transitions from natural systems to agricultural or urban environments. Although, overall, there has not been a substantial variation in the percentages of native vegetation in the SPM and its regional units, it should be noted that there is a loss of biodiversity and ecosystem services associated with the loss of mature forests and the degradation of more preserved areas (Calaboni et al., 2020).

The results obtained with InVEST indicated that the supply of ecosystem services analyzed has been negatively affected by changes in land use and cover, and that these changes were different depending on the ecosystem service and the Regional Unit evaluated. Individually, the SPM showed a decrease in the ability to control erosion, carbon storage and water regulation, and low values and variables of habitat provision in the four years evaluated.

According to Figure 2 and Table 2, the MRBS, the Southern MRSP, and the North Coast of MRVPLN presented relatively higher values for the four ecosystem services indicators evaluated, while the MRC, the MRP, the MRJ, and the RUB had the lowest scores in the overall result.

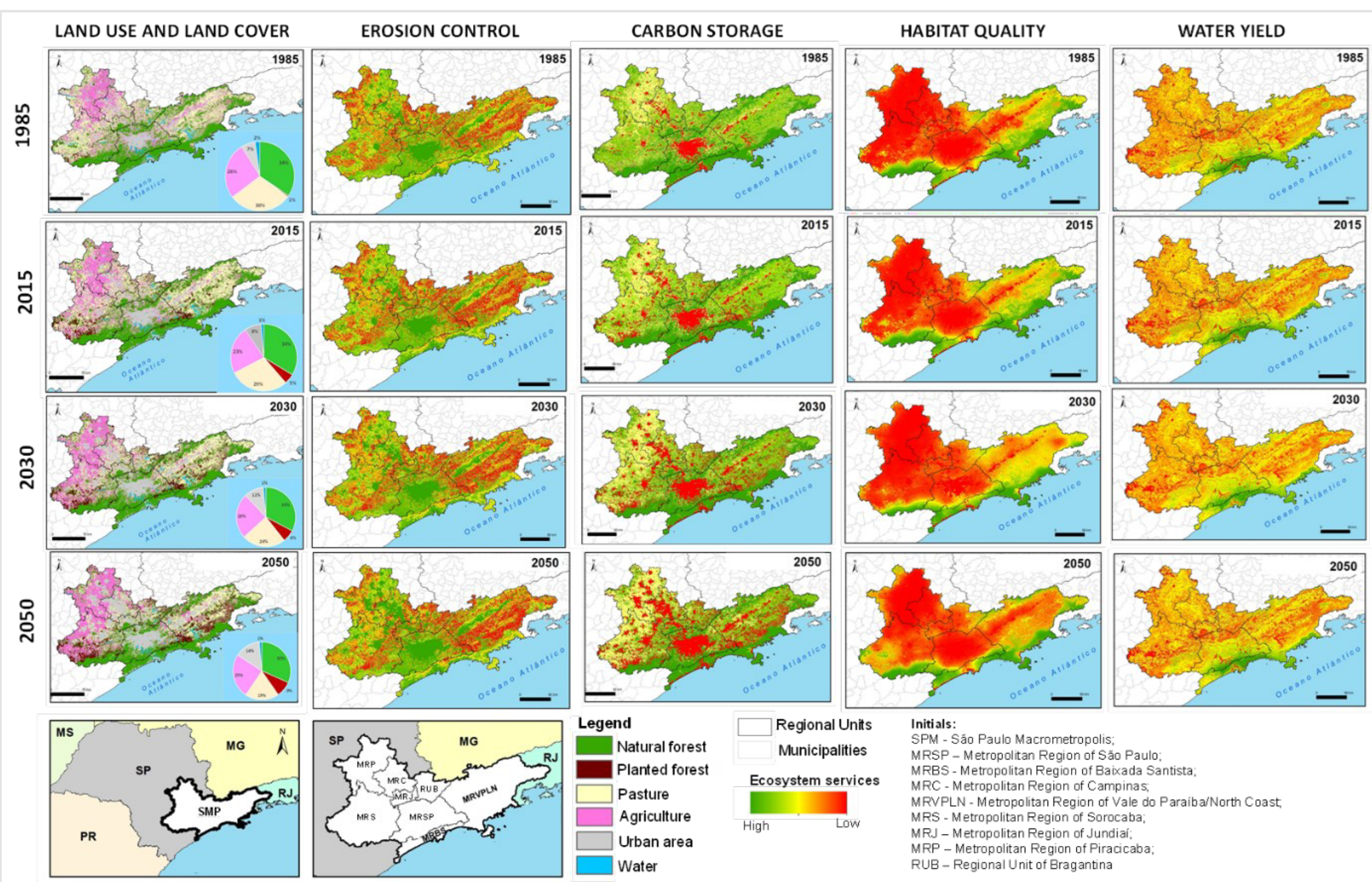

Figure 2 – Indicators of ecosystem services in different land-use and land-cover scenarios (1985, 2015, 2030, and 2050). The red color indicates a low supply of ecosystem services, and the green color shows a high supply of ecosystem services.

Table 2 – Average values of ecosystem service indicators in the São Paulo Macrometropolis and its Regional Units from 1985 to 2050, indicating increase and decrease trends in the provision of services.

Ecosystem services	Regional Unit	YEAR 1985	2015	2030	2050	Trend	Ecosystem services	Regional Unit	YEAR 1985	2015	2030	2050	Trend
Soil loss (ton)	MRJ	64,35	73,35	71,58	68,14		Habitat quality	MRJ	0,18	0,15	0,13	0,13	
	MRP	67,57	73,49	80,22	80,30			MRP	0,13	0,06	0,09	0,07	
	MRBS	58,49	55,45	60,88	63,03			MRBS	0,67	0,68	0,60	0,58	
	MRC	22,02	81,74	103,45	132,60			MRC	0,10	0,09	0,08	0,07	
	MRS	51,28	66,13	69,79	75,71			MRS	0,34	0,27	0,20	0,24	
	MRSO	27,27	59,60	62,61	65,20			MRSO	0,22	0,22	0,22	0,20	
	MRVPLN	115,41	145,58	174,60	214,80			MRVPLN	0,45	0,46	0,57	0,55	
	RUB	125,04	208,36	228,07	242,62			RUB	0,29	0,26	0,37	0,33	
	SPM	74,27	98,94	109,74	124,23			SPM	0,33	0,31	0,32	0,28	
Carbon storage (Mg)	MRJ	133,78	126,34	125,01	123,45		Water yield (mm)	MRJ	430,93	422,93	419,19	411,13	
	MRP	48,55	53,49	51,24	48,18			MRP	464,29	463,75	451,88	443,95	
	MRBS	298,86	297,25	295,48	293,23			MRBS	1.005,75	1.003,48	1.001,83	1.001,21	
	MRC	34,67	42,58	40,86	38,65			MRC	499,33	494,63	489,34	483,43	
	MRS	116,37	115,52	111,58	106,33			MRS	455,75	449,24	445,55	443,83	
	MRSO	180,26	168,18	165,81	162,52			MRSO	686,56	678,25	674,21	671,94	
	MRVPLN	154,13	153,96	151,18	147,92			MRVPLN	586,96	567,77	558,11	552,89	
	RUB	124,03	117,69	115,66	113,57			RUB	510,56	504,86	482,76	483,50	
	SPM	131,21	129,83	127,09	123,64			SPM	555,91	552,81	543,57	545,27	

Low supply of ecosystem services — High supply of ecosystem services.

The data presented in Table 2 indicate a general downward trend in the supply of services in the SPM if the conversion rates from 1985 to 2015 remain in 2030 and 2050. There is a trend to decrease the erosion control capacity in the SPM and in most regional units in the analyzed period, evidenced by the increase in the rate of soil loss, apart from the MRJ and the MRBS, which showed slight oscillation, but with a rate of change predominantly below 10%. Concerning the carbon service, the results indicate that all regional units showed decreasing values, as well as the SPM itself. Regarding the habitat provision service, the MRBS and the MRSP showed a slight downward trend from 1985 to 2050 due to threat factors of anthropogenic origin. On the other hand, the MRVPLN showed an improvement trend in this indicator compared to 1985 values. In the water regulation service, all regional units showed a downward trend, according to the data in Table 2, but with a little variation rate, of 1 to 2%. As precipitation and evapotranspiration were considered constant, and are variables that, according to other studies that applied the SWY, widely affect the base flow values and the spatial distribution of the results (Wu et al., 2022), only the change in land use and cover did not significantly influence the results.

Forested ecosystems provide diverse services and values to human society (Jenkins and Schaap, 2018), and the results of our modeling have indeed shown a positive effect on the four ecosystem services, increasing the benefits at the regional level. The MRVPLN and the MRBS have a coastline highly preserved due to many protected areas, notably in the Serra do Mar Biodiversity Corridor and the Mantiqueira Ecological Corridor, and the wide diversity of ecosystems in the Atlantic Forest Biome (Gonçalves et al., 2021). Natural forest also represents a natural protection against erosion by minimizing the direct impact of rain on the soil and increasing the infiltration capacity and water retention, through the incorporation of organic matter (Silva et al., 2003). Trends modeled for 2030 and 2050 indicate that this high percentage of vegetation will remain.

On the other hand, deforestation reduces the benefits generated by the ecosystem and may intensify the negative effects of climate change, for example (Jenkins and Schaap, 2018). The MRP, the MRJ, and the MRC are areas of low supply, where anthropogenic uses, notably urban areas, are relatively more relevant and should increase in 2030 and 2050, accounting for a vast share of impacts on ecosystem services supply (Gómez-Baggethun et al., 2013). As highlighted by Calaboni et al. (2020), the replacement of older forests by younger ones and, concomitantly, varied processes of loss and gain of native vegetation in the different regional units of the SPM can lead to a reduction in the supply of ecosystem services, such as soil erosion, carbon sequestration and fixation, biodiversity protection and provision of water ecosystem services.

Trade-offs and synergies between ecosystem services

The average values of the spatial correlation coefficients between the four ecosystem services evaluated are presented in Figure 3 and show a positive correlation (synergy) between carbon storage and habitat provision in all Regional Units and the SPM as well, although values below 0.39 were obtained in the MRJ, the MRC, the MRP, and the RUB. This mutual gain relationship was also found by Duarte et al. (2016), in a study carried out in the Quadrilátero Ferrífero region, in the State of Minas Gerais, Brazil.

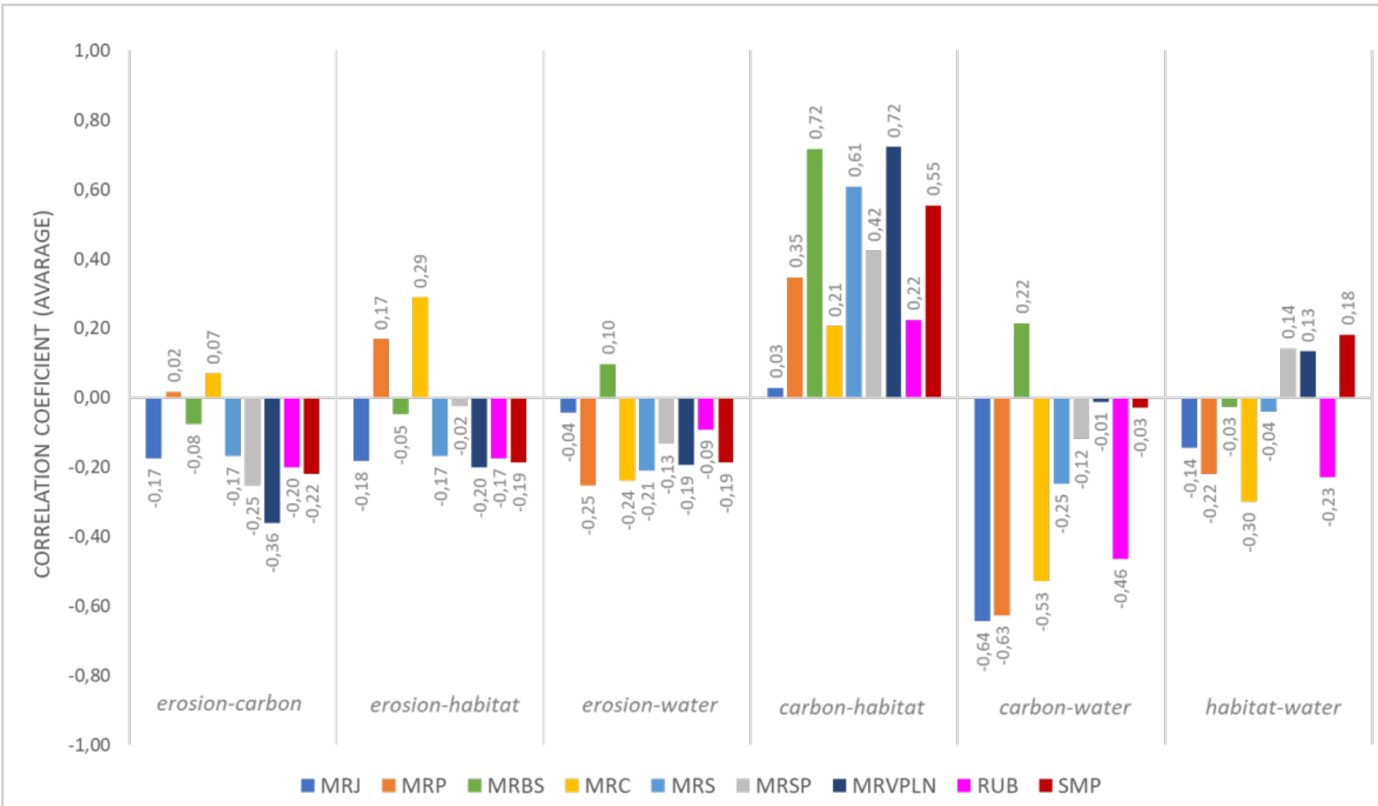

Figure 3 – Averages of spatial correlation coefficients between pairs of ecosystem services across the São Paulo Macrometropolis and its different Regional Units.

The relationship between carbon storage and habitat was also described as synergistic on a global scale by Larsen et al. (2011). Gutsch et al. (2018) also found strong synergies between carbon and habitat services in different management strategies, partially driven by the positive relationship of the proportion of broadleaf trees to net ecosystem production and total biomass.

The greatest synergies between carbon and habitat were found in the MRBS (0.72) and the MRVPLN (0.72). In fact, carbon pools and intact habitats are provided by continuous and extensive forest landscapes in those metropolitan regions, as also discussed by Xu et al. (2023).

On the other hand, there was a predominantly negative correlation between carbon storage and water regulation (trade-off) in all Regional Units, except for the MRBS, where high values of carbon storage were positively related to high values of baseflow. In the trade-off between carbon and water, the highest values were found in the MRJ (-0.64), the MRP (-0.63), and the MRC (-0.53). In the MRSP and the MRVPLN, as in the SPM itself, the values were close to zero. Bennet (2009) uses the relationship between these services to exemplify a unidirectional negative interaction, because even if afforestation increases carbon sequestration, the process of tree growth increases evapotranspiration, reducing the capacity to use water.

For other pairs, the correlation coefficient found was predominantly lower than 0.39, with the majority being low negative values obtained between erosion control and carbon storage (except in the MRP and the MRC, with positive coefficients, but below 0.1, indicating little or no correlation), erosion control and water regulation (except in the MRBS, with a positive coefficient, but less than 0.10), erosion and habitat control (only in the MRP and the MRC, with a synergistic relationship, but coefficients under 0.39), and habitat provision and water regulation (excluding the MRBS, the MRSP, and the MRVPLN, which presented positive coefficients and also below 0.39).

A low spatial congruence between the service modeled by the SDR (erosion control) with other services was also verified by Duarte et al. (2016), who found few areas providing very high retention rates and many areas providing medium to low rates, a fact that influenced the low correlation between services even after converting the values into a logarithmic scale.

In cases of trade-offs (i.e., negative correlation coefficients), if water regulation is selected as the target ecosystem service for conservation, for example, carbon storage may not be efficiently protected in most Regional Units and in the SPM. Likewise, if we only select carbon storage as the targeted ecosystem service for conservation, water regulation will not have the best results.

Further evidence that changes in land cover have been impacting the supply of ecosystem services is the tendency toward a decrease in positive correlations (a reduction in synergies) and an increase in negative values (a greater intensity of trade-offs) between services, if the scenarios modeled take effect in 2030 and 2050 (Figure 4).

The results are especially important when considering adaptation to climate change and city resilience. The strong trade-off areas among the ecosystem services represent potential ecological risk areas (Xu et al., 2023). The evidence of a worsening of trade-offs between the ecosystem services evaluated indicates that it may become an important problem in future scenarios under climate change. However, as land cover was the main driver of ecosystem services change, further research that incorporates multiple drivers of change is needed to understand how climate factors, for example, interact with and drive changes in ecosystem services and trade-offs at a macrometropolitan scale.

Hotspots and coldspots between ecosystem services

The relationships between ecosystem services were also visualized from the areas that have the highest (hotspots) and lowest values (coldspots) of multiple ecosystem services in the four years analyzed (1985, 2015, 2030, and 2050), together with the Conservation Areas taking place in the SPM (Figure 5). The hotspots, that is, areas containing at least two services with the highest scores, occupied approximately 26 and 27% of the entire study area in 1985 and 2015, respectively, and were concentrated in the MRBS; south and north of the MRVPLN; and south of the MRSP and the MRS. The trends for 2030 and 2050 indicate a reduction in the areas with the highest values of the four ecosystem services, reducing to about 18% in the last year, which is another indicator of the decrease in the offer of integrated ecosystem services due to changes in the use and coverage of the land in the SPM. This fact indicates the importance of public policies aimed at the conservation and recovery of areas that provide multiple ecosystem services. On the other hand, coldspots, that is, areas containing at least three or more ecosystem services with the lowest scores, occupied approximately 17% of the entire study area in 1985 and 2015, and were concentrated in the MRS and the MRP, occurring sparsely in the study area, and generally coincided with pasture and watercourse areas. The trends for 2030 and 2050 indicate an increase in the areas with the lowest values of the four ecosystem services, rising to around 18 and 23% in the scenarios projected for 2030 and 2050, respectively.

Both individual and grouped ecosystem service hotspot areas, as well as areas that are not providing multiple services in their fullness (coldspots), also indicate areas that should be prioritized to reduce the negative impact of human activities on the ecosystem and favor protection and regional ecological conservation. According to Spanò et al. (2017), despite several studies showing a positive correlation between hotspots and protected areas, many places with a high supply of ecosystem services are situated outside regulated and managed areas, remaining vulnerable to human pressures, as is the case in the SPM. These areas are also important for financing projects aimed at enhancing the provision of ecosystem services, such as payment for ecosystem services, REDD+, and other carbon pricing schemes.

The identification of these ecosystem service hotspots helps to give the real dimension of the importance of these natural environments through a systemic and holistic view. The knowledge of this potential to offer ecosystem services constitutes, therefore, an important tool for environmental management and provides more arguments in favor of conservation, or even for the creation of new protected areas.

UR	SE	1985	2015	2030	2050	Trend
MRJ	ero-carb	-0,15	-0,15	-0,19	-0,20	
	ero-hab	-0,23	-0,21	-0,18	-0,11	
	ero-wat	-0,02	-0,02	-0,05	-0,09	
	carb-hab	0,03	0,03	0,03	0,02	
	carb-wat	-0,62	-0,64	-0,65	-0,65	
	hab-wat	-0,14	-0,14	-0,15	-0,15	
MRP	ero-carb	0,03	0,02	0,02	0,01	
	ero-hab	0,19	0,19	0,16	0,15	
	ero-wat	-0,24	-0,25	-0,25	-0,26	
	carb-hab	0,36	0,35	0,35	0,34	
	carb-wat	-0,58	-0,62	-0,65	-0,66	
	hab-wat	-0,19	-0,20	-0,24	-0,24	
MRBS	ero-carb	-0,06	-0,09	-0,07	-0,09	
	ero-hab	-0,02	-0,04	-0,08	-0,06	
	ero-wat	0,11	0,10	0,09	0,08	
	carb-hab	0,76	0,71	0,70	0,69	
	carb-wat	0,24	0,21	0,20	0,21	
	hab-wat	-0,01	-0,05	-0,02	-0,03	
MRC	ero-carb	0,08	0,07	0,07	0,07	
	ero-hab	0,30	0,30	0,29	0,28	
	ero-wat	-0,21	-0,25	-0,25	-0,26	
	carb-hab	0,23	0,21	0,21	0,18	
	carb-wat	-0,45	-0,54	-0,56	-0,56	
	hab-wat	-0,28	-0,29	-0,30	-0,32	
MRS	ero-carb	-0,23	-0,18	-0,15	-0,12	
	ero-hab	-0,23	-0,17	-0,15	-0,12	
	ero-wat	-0,20	-0,20	-0,21	-0,22	
	carb-hab	0,65	0,65	0,59	0,55	
	carb-wat	-0,23	-0,22	-0,27	-0,27	
	hab-wat	-0,06	-0,05	-0,04	-0,03	
MRSP	ero-carb	-0,27	-0,29	-0,24	-0,22	
	ero-hab	-0,01	-0,01	-0,02	-0,05	
	ero-wat	-0,14	-0,14	-0,13	-0,13	
	carb-hab	0,50	0,43	0,39	0,37	
	carb-wat	-0,14	-0,11	-0,27	-0,11	
	hab-wat	0,15	0,15	0,13	0,14	
MRVPLN	ero-carb	-0,39	-0,36	-0,35	-0,34	
	ero-hab	-0,21	-0,21	-0,19	-0,19	
	ero-wat	-0,12	-0,19	-0,22	-0,25	
	carb-hab	0,78	0,75	0,73	0,63	
	carb-wat	-0,01	-0,01	-0,01	-0,01	
	hab-wat	0,14	0,14	0,13	0,13	
RUB	ero-carb	-0,23	-0,22	-0,20	-0,17	
	ero-hab	-0,15	-0,15	-0,18	-0,21	
	ero-wat	-0,08	-0,09	-0,09	-0,11	
	carb-hab	0,23	0,23	0,22	0,21	
	carb-wat	-0,52	-0,46	-0,44	-0,43	
	hab-wat	-0,24	-0,23	-0,23	-0,22	
SMP	ero-carb	-0,25	-0,23	-0,21	-0,18	
	ero-hab	-0,15	-0,17	-0,21	-0,22	
	ero-wat	-0,14	-0,20	-0,20	-0,21	
	carb-hab	0,65	0,56	0,52	0,48	
	carb-wat	-0,05	0,00	-0,03	-0,03	
	hab-wat	0,24	0,19	0,19	0,11	

Figure 4 – Evolution of the values of the spatial correlation coefficients between the pairs of ecosystem services across the São Paulo Macrometropolis and its different Regional Units in the four years evaluated.

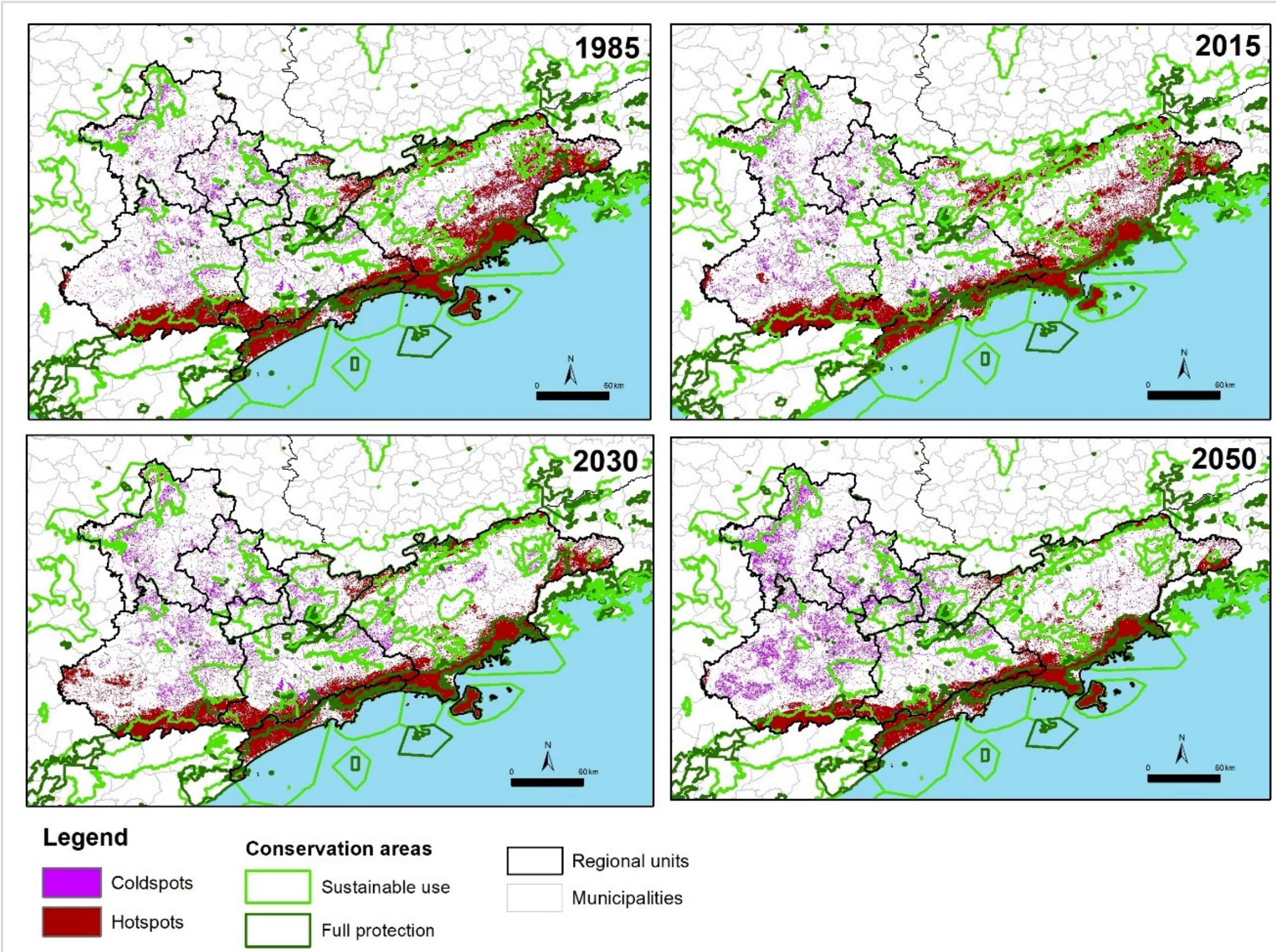

Figure 5 – Hostpots and coldspots of ecosystem services in the São Paulo Macrometropolis and its Regional Units in 1985, 2015, 2030 and 2050.

Hotspot areas and those adjacent to them may represent conservation priorities, as the loss or degradation of these sites can cause services to decline. In areas where only one service is dominant, restoration interventions can increase the supply of multiple ecosystem services. A though it is not possible to achieve high values for all ecosystem services, sustainable management solutions can increase the supply of ecosystem services and improve their overall performance (Spanò et al., 2017).

Proper implementation of environmental public policies can play an important role in the regulation of direct and indirect factors of change and help to conserve the system, through its influence on the maintenance of native vegetation cover and, consequently, on the provision of associated ecosystem services (Dib et al., 2020). The data are also relevant to encourage a more active participation of society in debating the problems, objectives, and solutions that influence their destinies, as well as investing in educational and communication processes of the ecosystem services for leaders and society in general, as they illustrate the importance of this theme for the well-being of humans and ecosystems.

It should be mentioned that there are some challenges for implementing this approach in territorial planning associated with the environmental modeling of ecosystem services, such as data pre-processing, quality, and scale of input data, the dynamics between ecosystem services driven by biophysical factors and management decisions, the uncertainties associated with environmental modeling, as well as the impossibility of considering all dimensions, interactions, and factors involved in the different regional units over time and space in the simulations (Cavender-Bares et al., 2015; Deng et al., 2016). Future studies must consider other drivers of ecosystem change, such as climate change and water regulation, as well as a broader range of ecosystem services aiming to deepen the understanding of service bundles at multiple scales and different scenarios.

Conclusions

This study revealed the spatio-temporal variation of four ecosystem services and the places with the highest and lowest potential for providing these services in the SPM and its regional units. The mapping of ecosystem services in two historical years (1985 and 2015) and two trend scenarios (2030 and 2050) showed that the SPM has its ecosystem services threatened, and needs attention to avoid a greater commitment to this provision, which can generate negative impacts not only on the environment but also on the economy, health and human well-being.

This approach allowed for the visualization of the change in individual ecosystem services and the integration of the results to provide an overall assessment of ecosystem services in the SPM and its different Regional Units. With this, it illustrated how the change in land use and cover can affect the provision of ecosystem services and generate subsidies for the definition of management strategies focused on just one service or multiple ecosystem services, and for the planning and monitoring of natural capital in the macro-metropolitan context.

Although additional drivers of change in ecosystem services were not considered in this study, such as climate change and water regulation, this study provided important data based on land-cover change to guide the planning of actions in conservation and environmental recovery with a view to maximizing the environmental benefits related to the ecosystem services evaluated in this strategic region of Brazil.

The methodological framework for analyzing individual services and their interactions in the SPM landscape proved to be useful to achieve the proposed objectives, and can help answer questions about the potential impacts of policy decisions on the future of biodiversity and ecosystem services, as well as support the formulation and implementation of restoration, conservation and sustainable use actions based on scientific foundations. Therefore, this approach can guide decision-makers to identify additional areas that require protection and improvement in order to achieve the sustainable management of natural resources.

Acknowledgments

We thank São Paulo Research Foundation (FAPESP) for grant 2015/03804-9 (Thematic Project MacroAmb "Environmental Governance in São Paulo Macro Metropolis in a climate variability context") and the National Research Council (CNPq) for scholarship 305188/2020-8.

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IKEMATSU, P.: conceptualization; data curation; formal analysis; investigation; methodology; writing — original draft. QUINTANILHA, J. A.: supervision; validation; writing — review & editing.

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