

Land use and land cover changes in São Paulo Macro Metropolis and implications for water resilience under climate change

Variações no uso e na cobertura da terra na Macrometrópole Paulista e implicações para a resiliência hídrica sob mudanças climáticas

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ABSTRACT

The São Paulo Macro Metropolis (MMP) is a geographical arrangement that brings together the most significant Brazilian socioeconomic figures and faces numerous challenges, such as heavy pressure on natural resources. Through compilation, spatialization and cross-referencing of data, this work

assessed time series of land use and land cover of the last decades, the water supply status in an urban environment and climate data projection for MMP. Municipalities with different profiles were identified: those with positive final balances and those with negative final balances about the maintenance of their natural areas. Furthermore, more than half of the municipalities of the MMP have low water supply assurance, which can be aggravated due to climate change, as predicted in several climate models. The characterization of municipalities based on this information allowed identifying which of them are the most vulnerable, and these results indicate paths for coordinated actions at local and regional levels to increase water resilience in the macro-region.

Keywords: São Paulo Macro Metropolis. Land use and land cover changes. Ecosystem services. Water supply.

RESUMO

A Macrometrópole Paulista (MMP) é um arranjo geográfico que reúne os mais significativos números socioeconômicos brasileiros e enfrenta inúmeros desafios, como a grande pressão sobre os recursos naturais. Por meio da compilação, espacialização e do cruzamento de dados, este trabalho avaliou séries temporais de uso e ocupação da terra das últimas décadas, a situação do abastecimento de água no meio urbano e dados de projeção climática para a MMP. Foram identificados municípios com perfis distintos: os que apresentam saldos finais positivos e os que apresentam saldos finais negativos com relação à manutenção de suas áreas naturais. Além disso, mais da metade dos municípios da MMP possui baixa garantia hídrica, o que pode ser agravado devido às mudanças climáticas, como previsto em diversos modelos climáticos. A caracterização dos municípios a partir dessas informações permitiu identificar quais deles são os mais vulneráveis, e esses resultados indicam caminhos para ações coordenadas nos níveis locais e regionais para fins de ampliação da resiliência hídrica na macrorregião.

Palavras-chave: Macrometrópole Paulista. Mudanças de uso e ocupação da terra. Serviços ecossistêmicos. Abastecimento urbano.

1 INTRODUCTION

In 1950, there were only two “megacities” – urban agglomerations with 10 million inhabitants or more – on the planet: New York and Tokyo (UN, 2015). In 2014, 18 countries already had 28 megacities, with Rio de Janeiro and São Paulo as the two Brazilian megacities (UN, 2015). The discussion on megacities draws attention in the so-called “emerging” countries, such as China, India and Brazil (UN, 2015), because the populations concentrated in urban centres increasingly represent impacts on these centres and their surroundings.

While in megacities there is a growth guided by industries, commerce, ports and airports, knowledge centres and highly complex technological initiatives, there is, in addition, the growth of problems common to metropolises, such as poverty, violence, corruption, inequality, deterioration in buildings, insalubrity, water supply, pollution and traffic congestion (THE STATES OF THE WORLD’S CITIES, 2004, 2005). Furthermore, as already detected by Di Giulio *et al.* (2017) and Urbinatti and Ferreira (2019), there is great pressure on natural resources and major environmental challenges represented by the loss of ecosystem services, changes in the urban microclimate, inadequacies in the characteristics of land use, which are enhanced when megacities are conurbated with other large metropolises. To deal with these problems, as Graafland (2006) points out, it is necessary to understand cities beyond their political limits, with approaches that represent their spatial, social, environmental and economic realities.

In the Brazilian context, the São Paulo Macro metropolis (MMP) is considered one of these urban conurbations (Figure 1), in which are included, in addition to the megacity of São Paulo, composed of the municipalities of its Metropolitan Region, five other Metropolitan Regions, two Urban Agglomerations and a Regional Unit in the state of São Paulo, representing 21.5% of the state and 20% of the protected natural heritage of the state (EMPLASA, 2019).

1.1 LITERATURE REVIEW

The area of cities, compared to the limits of their municipalities, is generally small, but urbanization is still a human activity with the potential to provoke intense changes in land use, with strong impacts and consequences (ROCKWELL, 2009). Urbanization is one of the most impactful processes on the environment (CARVALHO; BRAGA, 2001), and the lifestyle practised in the major cities of the world generates high demand for energy, pollution, degradation of natural resources and greenhouse gases emission (FARIA, 2009; HOGAN *et al.*, 2001).

When associated with the impacts of climate change, urban problems intensify rising temperature, rising sea levels in coastal cities, heat islands, floods, water and food shortages, ocean acidification and impacts of extreme events (PBMC, 2016). These problems have created new challenges, such as water shortages caused by prolonged droughts, the proliferation of disease vectors such as dengue, zika, chikungunya and leptospirosis, and the increase in respiratory diseases related to climate and/or pollution.

The effects of urbanization have motivated studies currently called “water-food-energy nexus”, which analyze the interdependence between these sectors, necessary to ensure human well-being, poverty reduction and sustainability (FAO, 2014). Changes in one of these sectors may have impacts on the other two, considering the high demand for its products and the managerial challenge of properly balancing the use of water for human supply, irrigation, electricity production, among others (AHMADI *et al.*, 2020; FAO, 2014; SOUSA JÚNIOR, 2018). In the demographic transition and the transition of urban water consumption in Brazil, Carmo *et al.* (2014) point out the importance of the relationship between demographic dynamics and its consequences for water demand and use.

Water scarcity triggers conflict situations around complex water supply systems. Contrary to common sense, the metropolitan region of São Paulo is part of an area of insufficient availability of clean water, in a region of hydrological complexity (JACOBI; TORRES; GRESSE, 2019). This situation poses the challenge of improving equity in the distribution of water in the metropolis, strengthening access to the public water supply system, in addition to guaranteeing supply over time.

The year 2014 was the driest in the history of the State of São Paulo since data began to be recorded in the 1930s. Between 2013 and 2015, the water levels of the main reservoirs in the Metropolitan Region of São Paulo (RMSP) decreased drastically due to an extreme drought phenomenon, which affected more than 20 million people. The low levels of precipitation recorded in the summer of 2020, in front of reservoirs with very low volumes, foreshadow a new water crisis, which is already revealed in the restrictions of hydroelectric generation (JACOBI; TORRES; GRESSE, 2019).

Drought events have increased in frequency and their consequences for the supply of water and energy are reflections of climate change that require investment in adaptation policies for the RMSP, as pointed out by Sousa Júnior *et al.* (2016).

The basins of the Billings and Guarapiranga dams, in São Paulo, are important regions that provide ecosystem services, in particular, the production of water for public supply. Although protected by land use planning since the 1970s (watershed protection and recovery laws), these basins are strongly pressured by the use of the land around the dams, not directed to preservation (PMMA SÃO PAULO, 2017).

According to Kowarick (2002), the characteristics of land use and land cover are forcing factors that determine not only the growth and development of cities but also the consequences and impacts of the latter. As an example, the author points to housing issues as contributors to determine the urban

lifestyle. In the case of the city of São Paulo, as pointed out by Leonel *et al.* (2019) and Sampaio and Pereira (2003), a significant part of the population of São Paulo is still homeless or lives in precarious conditions, due to a lack of infrastructure services (sanitation, urban waste collection, among others) or because it is located in areas at risk of landslides, flooding and fire, due to poor electrical connections.

Sampaio and Pereira (2003) already identified elements in the National Policy on Protection and Civil Defense (PNPDEC) and in the Strategic Master Plan (PDE) of São Paulo to prevent new occupations in risk areas. These plans also provided for the urbanization of needy areas and actions for “Social and Territorial Equity and Inclusion” as a way to reduce the contrast between accumulation and poverty.

On the other hand, Amato-Lourenço *et al.* (2016) point out that the creation of green areas can minimize the effects of urban expansion, such as the suppression of vegetation cover, in addition to contributing to the improvement of the population’s quality of life. In São Paulo, projects such as the creation of 100 urban parks (SECRETARIA MUNICIPAL DO VERDE E MEIO AMBIENTE, 2012) and the São Paulo City Green Belt Biosphere Reserve (RBCV) seek to alleviate the pressure generated by urbanization on water springs and water sources, as noted by Rodrigues *et al.* (2006).

Environmental heritage, ecosystem services, protection of water resources through Payments for Environmental Services (PES) (PAVANI *et al.*, 2020), reforestation and erosion scenarios, pasture and forest areas estimates and changes between these categories, all these aspects are interconnected in the analysis of the MMP. The analysis of the land use and land cover dynamics is, therefore, fundamental for assessing uses, dependence and impacts on the provision of ecosystem services. Its use is ideal for the macro-regional context of insertion of the MMP. According to Verburg *et al.* (2009), the quantification of specific features and their relationship with ecosystem functions provide an important information base for policy development and territorial planning.

Adaptive governance focused on experimentation and learning, which brings together actors to collaborate in collective actions for conflict resolution (FOLKE *et al.*, 2005), has been suggested to face contexts such as the 2013-2015 water crisis. According to Torres and Jacobi (2020), such issues need to be dealt with at a macro-regional scale in the context of participatory management. However, there is a mismatch in the negotiation between civil society and government, as detected by Marques *et al.* (2020), who, on the other hand, identify opportunities for engagement between civil society and academia for water governance.

2 METHOD

The study area of this paper, the São Paulo Macro Metropolis (MMP), covers 53.4 thousand km², with 174 municipalities (50% of the urbanized area of the state of São Paulo), which represented 74.7% of the state population, in 2018, and 81.9% of the state GDP in 2016 (EMPLASA, 2019). Of this population, according to the 2010 Census (IBGE, 2010), 2.68 million people lived in subnormal agglomerates (EMPLASA, 2019). The MMP covers the following metropolitan regions: Urban Agglomeration of Jundiaí (AUJ), Piracicaba Urban Agglomeration (AUP), Metropolitan Region of Baixada Santista (RMBS), Campinas Metropolitan Region (RMC), Metropolitan Region of Sorocaba (RMS), Region Metropolitan Region of São Paulo (RMSP), Metropolitan Region of Paraíba Valley and North Coast of São Paulo (RMVPLN) and Regional Unit of Bragantina (URB).

To support the analysis, 3 data sets were used, which were processed and assigned in the mesh of municipalities of the MMP’s cutout and arranged by period, as shown in Figure 2.

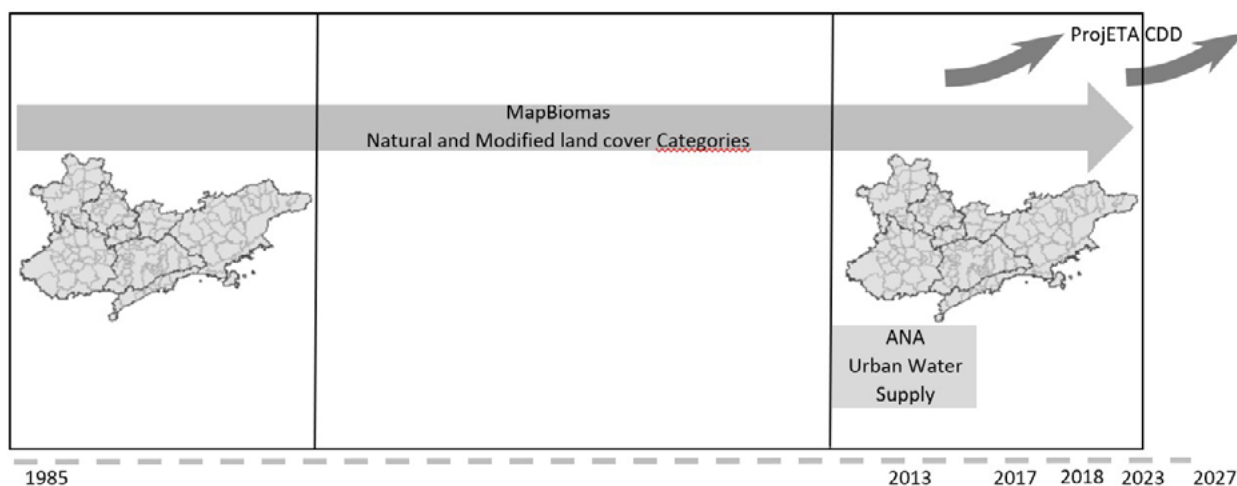


Figure 2 | Diagram with data considered as a support for work analysis: MapBiomias Transitions 1985-2018; Atlas ANA 2013 of Urban Water Supply; Projection of the Projeta’s CDD variable in the periods from 2013 to 2017 and 2023 to 2027.

Source: Own elaboration.

Data related to land use and land cover are made available by MapBiomias; by CPTEC/Inpe, the data related to the projections of climate variables; and by the National Water Agency (ANA), data related to Urban Water Supply.

MapBiomias (MAPBIOMAS PROJECT, 2019) is a multi-institutional initiative that systematically produces and disseminates land use and land cover data for the entire Brazilian territory, detailing the transitions that have taken place annually in 27 categories since 1985. Coverage and transitions data are available in *raster* format, suitable for the production of maps and geoprocessing operations, and in electronic spreadsheet format, with the quantitative areas, grouped by biomes, states and municipalities.

For this work, the land cover *raster* data categories were grouped as shown in Table 1, showing the mapping with only two groups of categories: Natural and Modified. The Natural group includes the preserved natural environment categories, and the Modified group includes the categories in which there have been anthropogenic land cover changes. This grouping seeks to distinguish the categories with the greatest potential for providing ecosystem services from those with the lowest potential for conventional economic activities and other occupations. It is important to emphasize that the transitions between categories occurred from the Natural group to the Modified and vice versa, and, therefore, the increase of areas in the Natural group may refer not exactly to natural areas, but also to regions that, at some point, were intended for recovery and regeneration.

Table 1 | Grouping of land use and land cover categories in MapBiomias.

<i>Natural</i>	<i>Modified</i>
Rocky Outcrop	Agriculture
Salt Flat	Forest Plantation
Natural Forest	Urban Infrastructure
Grassland	Mining
Other Non-Forest Natural Formation	Mosaic of Agriculture and Pasture
Beach and Dune	Non Observed
River, Lake and Ocean	Other Non-Vegetated Area
	Pasture

Source: Own elaboration

Two groups were made considering absolute values regarding area and percentage of transitions so that it was possible to identify the municipalities with the greatest loss and those with the greatest gain of areas in the Natural group in the period analyzed. Thus, the municipalities with the highest transition rate and the current *status* of coverage are identified with the categories with the highest potential for offering ecosystem services.

Regarding climate data, CPTEC-Inpe used the ETA regional model and performed the downscaling of the global models BESM, HadGEM2-ES, MIROC5 and CanESM2, and obtained the climate variables projections with annual, monthly, daily and 3-hour frequency for South America for the period 2006 to 2099 in the RCPs (*Representative Concentration Pathway*) 4.5 and 8.5 scenarios (CHOU *et al.*, 2014a; CHOU *et al.*, 2014b; and LYRA *et al.*, 2018).

For this study, it was used the variable Annual Mean of Maximum Number of Consecutive Dry Days (CDD) of the annual climate projections of the ETA HadGEM RCP 4.5 model, which is available with a spatial resolution of 5 kilometres for the states of the southeastern region of Brazil on the Projeta platform (CPTEC/Inpe, 2020). This index was selected for being able to indicate periods of low rainfall and conditions that favour drought. These data are temporally divided from 1961 to 2005, the period in which they represent the results of the model using observed data, and from 2006 to 2099, the projection period for climate scenarios.

Data on the water supply to the population are found in the Atlas Brazil – Urban Water Supply by the National Water Agency (ANA, 2020) and are also part of this work. In it, each Brazilian municipality is classified as follows: “satisfactory supply”, in which the municipality does not present criticality in terms of water source or water supply infrastructure; “expansion of the production system”, in which the municipality does not present water supply problems, but there is a need to expand the units of the production system; “low water assurance”, in which the water supply system of the municipality needs a new water body or is in a condition of rationing, collapse or alert (in 2013); and “no information”.

3 RESULT

3.1 LAND USE AND LAND COVER CHANGES

Considering the use and coverage transitions identified in the MapBiomas data for the MMP cutout, there was a reduction of 0.26% in the Natural group categories in the MMP throughout the period from 1985 to 2018. Although the percentage is practically nil, this does not mean the absence of transitions in the period, because the transitions of the categories occurred in both directions: from the Natural group to the Modified group and vice versa, oscillating over the years.

Land use and land cover transitions history culminates in the most recent data from 2018, which show the current panorama of the landscape, and, through them, it is possible to identify regions with different characteristics regarding the maintenance of areas in the Natural category, as seen in Figure 3, with the representation of the percentage of area in the Natural category of each municipality.

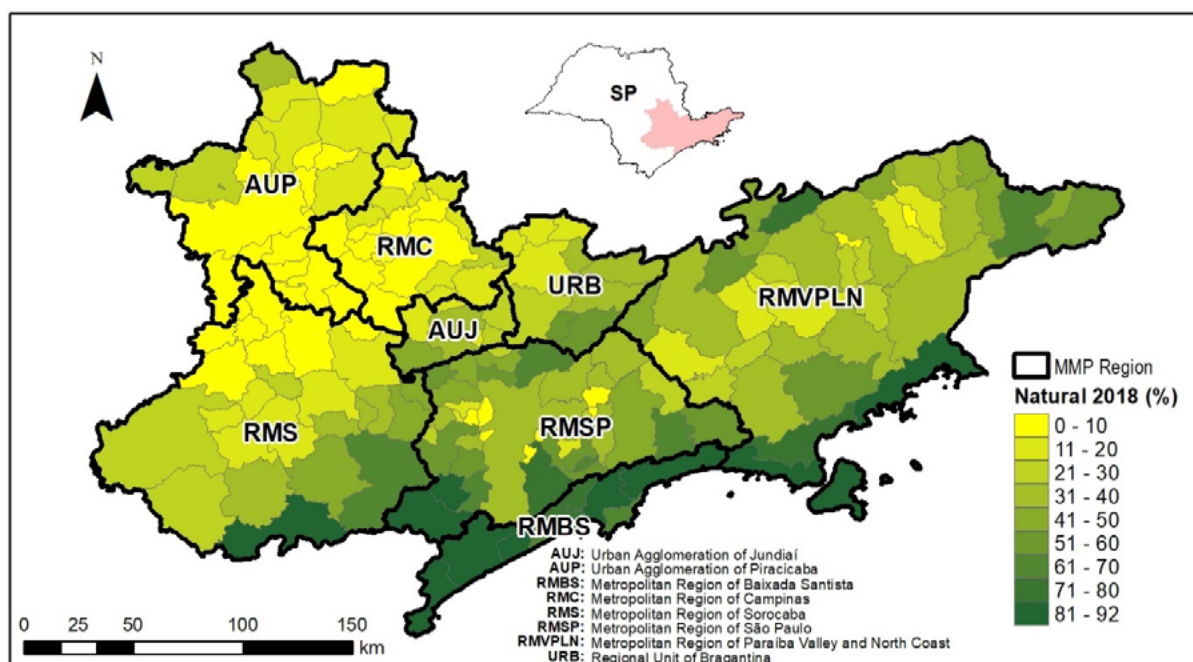


Figure 3 | Municipalities of the MMP and respective percentages of Natural coverage in 2018.

Source: Elaborated by the authors from MapBiomas data (MAPBIOMAS PROJECT, 2019).

Most municipalities in the Metropolitan Regions of Campinas and Sorocaba and the Urban Agglomeration of Piracicaba have less than 20% of their coverage among those categorized as Natural. These municipalities form a continuous block that expands to the Urban Agglomeration of Jundiaí and the Regional Unit of Bragantina. On the other hand, there are municipalities with more than 80% of coverage categorized as Natural, which are concentrated in the coastal strip of the state, with emphasis on the Metropolitan Region of Baixada Santista, with most of its municipalities with this characteristic.

When analyzing other municipalities, it is possible to observe that the percentage of the Natural group of São Caetano do Sul is 0.1%, and, on the other hand, 92% of the territory of Ubatuba belongs to the Natural group, and even so, there was a transition of 0.8% from the Modified group to the Natural group. This fact partially reflects the results found by Farinaci (2012) in research about the intention of rural producers to expand forest areas on their properties. According to the author, in municipalities such as Ubatuba, Monteiro Lobato and São Luiz do Paraitinga, the answer was affirmative, while in municipalities such as Campinas, Jundiaí and São José dos Campos, most producers do not intend to increase forests.

Figure 4 shows the history of the municipalities of the MMP regions according to the percentage of the accumulated final balance of the transition period from the Natural group to the Modified group. That is, in 33 years, the final balance indicates that there were municipalities that eliminated up to 18.5% of their area with transitions from the Natural to the Modified group and municipalities that increased by up to 9.6% of their area with transitions from the Modified to the Natural group. In terms of absolute values, some municipalities suppressed up to 55 km² of the categories of the Natural group and, as well, municipalities that increased up to 41 km² of these categories.

The numbers of transitions in the municipalities were grouped considering the final balance of the Natural group with the absolute values of the area and, also, the final balance of the Natural group as a percentage of the municipality's area. For both area and percentage, the 5 municipalities in the MMP with the highest and lowest balance at the end of the period were identified.

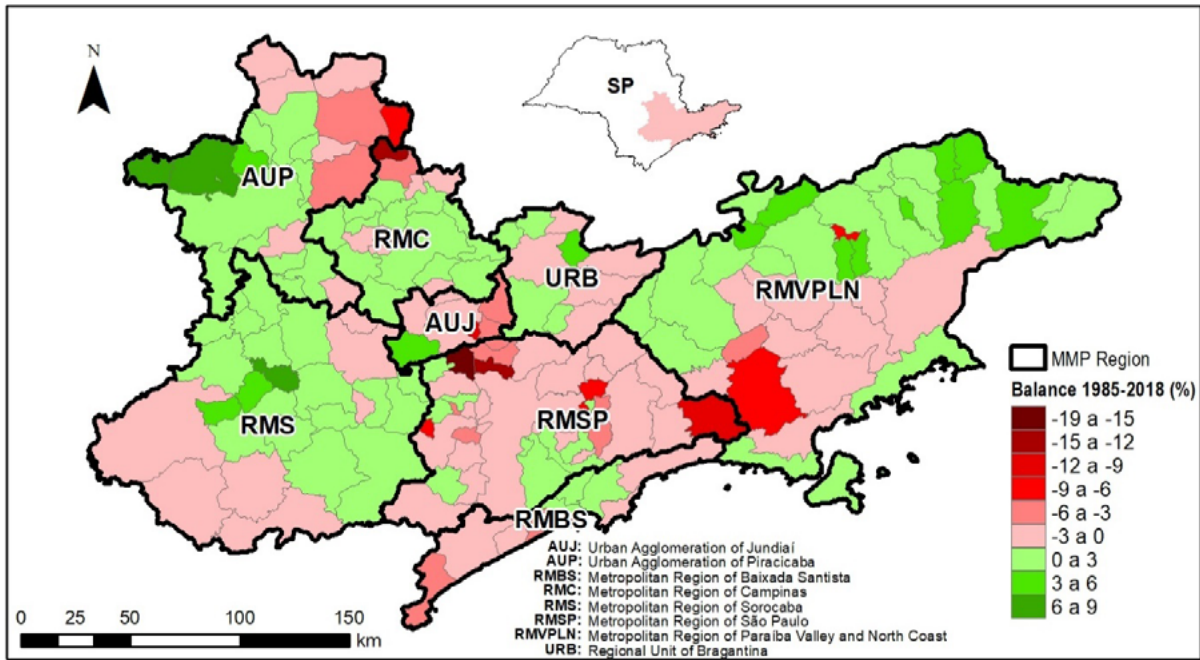


Figure 4 | Map with the percentage of land cover transitions between 1985 and 2018 in the MMP. Shades of red indicate loss of natural areas, and shades of green indicate gain.

Source: Elaborated by the authors from MapBiomas data (MAPBIOMAS PROJECT, 2019).

According to the final balance, as shown in Table 2, the AUP, RMC and RMS regions, located in the western MMP, presented a positive percentage concerning the Natural vegetation classes. In the other regions, the percentage was negative, including in the RMVPLN, where the predominance of municipalities with a positive balance in Serra da Mantiqueira and the North Coast was not enough to compensate for the decrease in the other municipalities.

Table 2 | Classification of regions according to the balance of area of the Natural vegetation class from the transitions of categories in the period from 1985 to 2018.

Region	Population (2019)	Area (km ²)	Natural Balance (km ²)	Natural Balance (%)
Metropolitan region of Sao Paulo (RMSP)	21.734.682	7.947	-146	-1,84
Metropolitan region of Baixada Santista (RMBS)	1.865.397	2.429	-49	-2,04
Urban Agglomeration of Jundiaí (AUJ)	815.338	1.269	-10	-0,80
Regional Unit of Bragantina (URB)	434.655	2.768	-8	-0,29
Metropolitan Region of Paraíba Valley and North Coast (RMVPLN)	2.552.610	16.178	-6	-0,04
Metropolitan region of Campinas (RMC)	3.264.915	3.792	17	0,45
Urban Agglomeration of Piracicaba (AUP)	1.495.220	7.368	23	0,32
Metropolitan region of Sorocaba (RMS)	2.143.786	11.611	43	0,37
São Paulo Macro Metropolis (total)	34.306.603	53.362	-137	-0,26

Source: Own elaboration

Regarding the percentage of areas that underwent a transition from Natural to Modified, the municipalities of Cajamar, Caieiras, Engenheiro Coelho, Várzea Paulista and Salesópolis have the highest values (18.5%, 12.6%, 12.2%, 11.4% and 9.6%, respectively). On the other hand, the highest final balances in the percentage of transition from Modified to Natural were in the municipalities of Iperó, Santa Maria da Serra, São Pedro, Águas de São Pedro and Cabreúva (8.5%, 7.9%, 6.8%, 5.2% and 4.8%, respectively).

As for the final balance, in absolute values of areas that underwent a transition from Natural to Modified throughout the period, the municipalities of Paraibuna, Salesópolis, Cunha, Cajamar and Limeira had the highest values (55 km², 41 km², 25 km², 24 km² and 23 km², respectively).

The municipalities of São Pedro, Piracicaba, Santa Maria da Serra, São José do Barreiro and Iperó, on the other hand, had the highest balances in absolute values of transitions from the Modified to Natural categories (41 km², 21 km², 20 km², 17 km² and 14 km², respectively). Thus, the municipalities of Cajamar and Salesópolis stand out with the highest percentages and absolute values of areas transitioning from Natural to Modified categories, and the municipalities Iperó, Santa Maria da Serra and São Pedro stand out with the highest percentages and absolute values of areas in transitions from Modified to Natural categories.

There is, furthermore, a group of municipalities with the lowest percentages of their areas in the Natural categories in 2018. They are the municipalities of São Caetano do Sul, Hortolândia, Sumaré, Cerquilha and Santa Bárbara d'Oeste, with a maximum of 3% of their territory in the Natural categories. On the other hand, the municipalities of Ubatuba, Ilhabela, Tapiraí, Juquitiba and Bertioga present, in 2018, percentages of the area in the Natural categories in approximately 90% of their territory.

The municipality of Cajamar, due to its proximity to the metropolitan region of São Paulo, has several logistic and distribution centres and concentrates its economic activities on the extraction of wood and stone; food, cosmetics, metallurgy and chemical industry; limestone mining, in addition to general product logistics (MDIC, 2018). The economic activities and geographic location of the municipality of Cajamar help to explain the decrease in natural areas verified in the data.

Iperó, representing the opposite, is the municipality with the greatest increase in natural areas and is located in the metropolitan region of Sorocaba. In this municipality, it is inserted part of the Flona de Ipanema, where environmental education activities and awareness of the population have been implemented in the surroundings over time.

At the municipal level, there are still problems in maintaining vegetation areas when new master plans and zoning laws are discussed, especially in areas of environmental protection in the Cerrado. In São José dos Campos, the Cerrado, which covered 30% of the municipal territory, currently represents only 1% of this native coverage (CODAZZI, 2019).

3.2 CLIMATE PROJECTIONS

The annual data of the CDD variable of the climate projection generated by CPTEC/Inpe and made available in the Project Platform were processed for the cut-off of the MMP considering the regional model ETA-HadGEM-ES. These data comprise the historical period from 1961 to 2005, constituted from observed data, and those that comprise the projection period under the RCP 4.5 scenario, from 2006 to 2099.

The CDD climate index is obtained from the Precipitation variable (PREC) data and indicates the number of consecutive days with precipitation less than 1 millimetre in the period in which the highest values may characterize conditions favourable to drought. The historical annual average of the CDD in the MMP was 20.6 (1961 to 2005), the average for the period 2038 to 2042 was 22.7, and the average for the last five years of the projection was 28.1 (end of the 21st century). It can be noted that this is a growing index according to the observation of these 3 averages and is an important reference in urban supply issues, among others.

A great amplitude was observed in this index in the periods from 2013 to 2017 and 2023 to 2027, and the difference in the average for each period is shown in Figure 5. According to the projection, except for some points in the North Coast of São Paulo, the entire MMP will have a longer sequence of dry days in the period from 2023 to 2027 (around 2025), considering the period from 2013 to 2017 (around

2015) as a reference due to the water crisis. In addition to the index not being favourable for the entire MMP in the 10-year projection, there is a range that includes the URB, AUJ, RMC and AUP, in which there is an even greater criticality, with an extension of dry days by approximately another month.

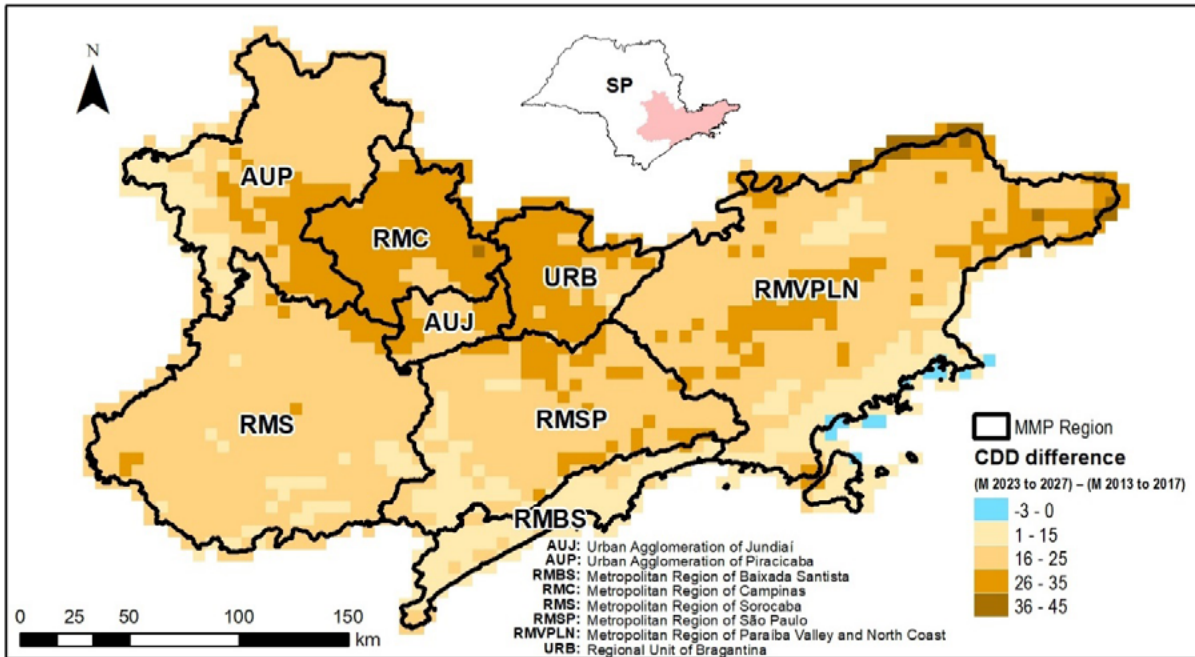


Figure 5 | Map of the MMP representing the difference of the CDD index averages from 2023 to 2027 and 2013 to 2017. The positive values, which occupy almost fully the map, indicate that there was an increase in the index during the two periods.

Source: Elaborated by the authors from Projeta data (CPTEC/Inpe, 2020).

3.3 URBAN SUPPLY

Seeking alternatives to ensure water security is a management challenge, especially when considering the direct effects of climate change on the volume of precipitation, the increasing demand for water supply, industrial use and irrigation in the MMP. It is worth mentioning that some municipalities, such as São Paulo, depend on springs that are beyond their territory.

According to the Master Plan for Utilization of Water Resources to Macrometropolis Paulista, eight Water Resources Management Units are comprised by the MMP: Paraíba do Sul, North Coast, Piracicaba/Capivari/Jundiaí, Alto Tietê, Baixada Santista, Mogi Guaçu, Tietê/Sorocaba and Ribeira de Iguape and South Coast.

The data on the water supply situation of the municipalities of the Urban Water Supply Atlas for the territorial cutout of the MMP are shown in Figure 6, which shows that 58% of the municipalities in the MMP need investment in this area and are in a situation of low water assurance or require expansion of the production system.

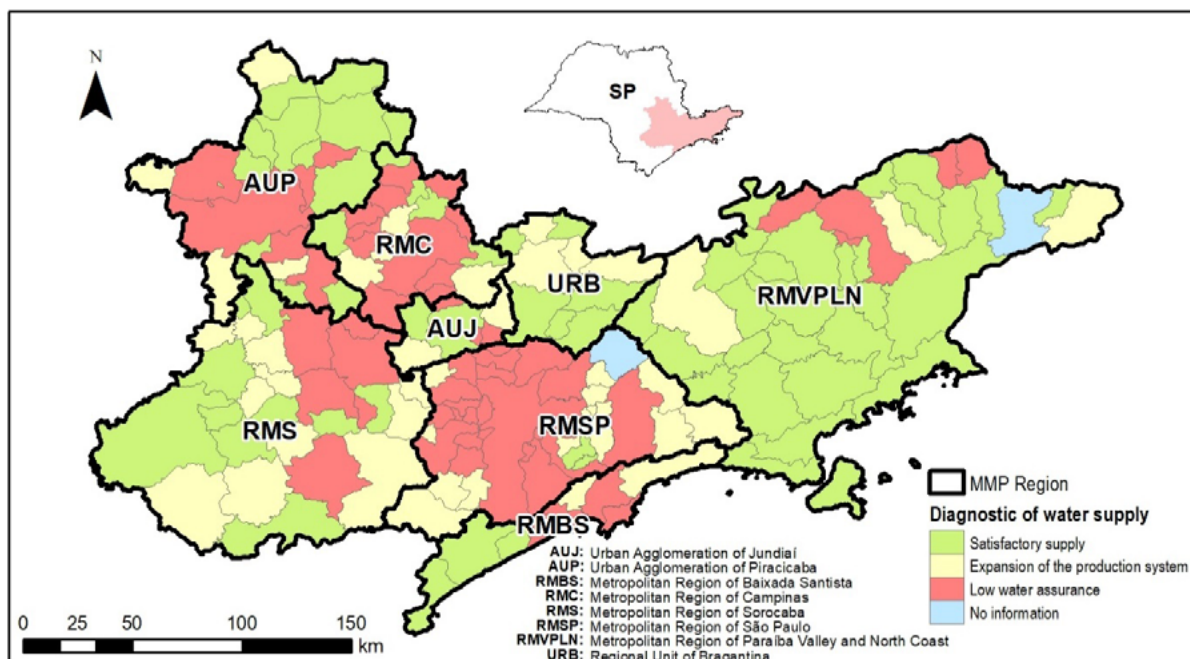


Figure 6 | Map with the qualification of water supply in the MMP, according to the Urban Supply Atlas.

Source: Elaborated by the authors based on data from the Urban Supply Atlas (ANA, 2020).

The map indicates that in all regions of the MMP there are municipalities with low water assurance, except the Bragantina Regional Unit, and that in the two most populous regions, the Metropolitan Regions of São Paulo and Campinas, most of their municipalities are in this situation. It is important to point out that the areas of contribution of water supply systems are beyond the municipal limits, the metropolitan regions and even the MMP, as is the case of the Cantareira Water Supply System, with upstream areas in the state of Minas Gerais. Thus, the supply of water to the population, coming from ecosystem services, originates in other adjacent municipalities.

3.4 CRITICAL MUNICIPALITIES

From the combination of the 3 information compiled and processed, considering the different profiles of the municipalities in the MMP concerning the history of land use and land cover changes, their current natural areas with potential for the production of ecosystem services and the urban supply situation, 20 municipalities whose contexts are more unfavourable were identified (Table 3).

These are municipalities that have less than 20% of their territory with natural coverage, have a negative balance of the maintenance of natural areas and have a diagnosis that indicates a low water assurance or need to expand the water production system.

Table 3 | MMP municipalities with unfavourable characteristics regarding the provisioning of ecosystem services for water production and the need for investment in supply systems (in descending order by the Non-natural Area percentage in 2018).

Region	Municipality	Converted Natural Area (%)	Non-natural Area in 2018 (%)	Diagnostic of Water Supply
RMSP	São Caetano do Sul	-0.3	99.9	Low water assurance
RMC	Hortolândia	-0.7	98.6	Expansion of the production system
RMC	Sumaré	-0.2	97.3	Low water assurance
RMVPLN	Potim	-8.3	96.4	Low water assurance
AUP	Rio das Pedras	-0.1	95.6	Low water assurance
AUP	Cordeirópolis	-0.5	94.2	Low water assurance
RMSP	Osasco	-1	93.8	Low water assurance
RMS	Salto	-0.1	93.7	Low water assurance
RMSP	Carapicuíba	-1.5	93.6	Low water assurance
RMSP	Itaquaquecetuba	-6.4	92.8	Expansion of the production system
RMSP	Taboão da Serra	-0.7	92.0	Low water assurance
RMC	Artur Nogueira	-3.1	91.7	Low water assurance
RMSP	Jandira	-4.8	89.1	Low water assurance
RMC	Santo Antônio de Posse	-1.9	88.4	Low water assurance
RMC	Vinhedo	-0.7	82.4	Low water assurance
AUJ	Várzea Paulista	-11.4	81.9	Low water assurance
URB	Bragança Paulista	-1.2	81.8	Expansion of the production system
AUJ	Louveira	-0.5	81.6	Low water assurance
RMS	Itu	-0.7	80.5	Low water assurance
RMSP	Mauá	-2.4	80.1	Expansion of the production system

Source: Own elaboration

There are municipalities in unfavourable conditions in all regions, except for the RMBS. However, it is worth noting that the RMSP and the RMC together hold the majority of the municipalities (60%). The situation is made worse by climate change projections, which point to longer periods of consecutive dry days throughout the MMP, with more intensity in the MRC and its surroundings.

4 DISCUSSION

The use of land use and land cover data to analyze the history of occupation and identify patterns is an important tool for land management. Lira *et al.* (2012) used it in 3 areas in the state of São Paulo to study the structure of the landscape over time (1960 to 2000) and the implications of changes in biodiversity. On the other hand, this work sought to extract from the coverage use data the indicators of production of ecosystem services on a municipal scale for the MMP.

Water production by the environment is sensitive to different types of land use and cover, and one of the main threats to the RMSP's water sources is the uncontrolled urban occupation in its protected areas (COSTA, 2015; FRACALANZA FREIRE, 2015). According to Carmo *et al.* (2014b), this occupation causes domestic sewage, garbage and the diffuse load of pollution generated in urbanized areas to compromise the quality of raw water and make the water source unfeasible, given the increased cost

of treatment and the threat of reducing the quality of water to be distributed to the population. The impairment of surface-water resources in the Alto Tietê Basin, for example, occurs from the peripheral occupation of the metropolitan area of the RMS, which occurs not only, but mainly, by low-income settlements (CARMO *et al.*, 2014b).

In rural areas, conventional agriculture maximizes food supply, fibre and raw materials, but entails environmental disadvantages such as loss of biodiversity, superficial runoff of water and nutrients, silting of watercourses, emission of greenhouse gases, aquifer contamination, among other problems (POWER, 2010).

In MMP, suppressing natural vegetation due to the expansion of urban occupation and other uses in rural areas reduces the number of ecosystem services offered, such as water production. In addition, the low water assurance and the deficiency in the supply infrastructure registered by the National Water Agency indicate the urgent need for investment in public policies to change the situation.

As seen before, there is an aggravating factor in the identified trend of increasing CDD index values over a 10-year horizon for the entire MMP, whose trend corroborates Chou *et al.* (2014a), which show temperature increase projections all over South America, with different intensities, and the decrease in the volume of precipitation in an intensified way, and, consequently, increase in CDD values for the Southeast region of Brazil.

There are possible actions within the scope of performance of the cities to improve this scenario since the municipalities are responsible for the use and occupation policies in their territories. Regarding land use and land cover, actions to recover degraded areas and restore natural vegetation in areas of permanent preservation can be implanted to increase the regularity of water flows, especially in times of greater criticality. The identification of springs with environmental liabilities, for example, can be provided through data from the Rural Environmental Registry, as proposed by Coutinho *et al.* (2018).

Regarding climate improvement, the 10 steps of the UNISDR campaign to build a resilient city (UNDRR, 2021) can be implemented, focusing on water scarcity as a natural disaster, and the implementation of a municipal climate change adaptation plan under the framework of the Global Covenant of Mayors for Climate & Energy (GCOM, 2021).

On the other hand, one must also emphasize that the mitigation of supply problems in the most critical municipalities and regions of the MMP takes place through the management of the MMP as a whole, especially because the production of water occurs at the scale of hydrographic basins, considering that these extrapolate the limits of the metropolitan regions of the MMP and even the state of SP. Thus, even if the most critical municipalities are more likely to be prioritized, as evidenced in this study, analyses are necessary for planning in the macro-region scale, as indicated by Torres and Jacobi (2020), especially in participatory management arrangements.

Such perspective, concerning participatory management, is corroborated by Folke *et al.* (2005), who suggest adaptive governance, focused on experimentation and learning, which brings together actors to collaborate in collective actions for conflict resolution, as an approach to face crises with these characteristics. In this context, Marques *et al.* (2020) identified discrepancies in the negotiation between civil society and government, in water management, while indicating opportunities for engagement between civil society and academia for effective governance – the study was carried out in some of the MMP municipalities, the metropolitan region of Vale do Paraíba, but the conclusions reflect the conditions found throughout the macro-metropolis.

About water supply, in addition to investing in infrastructure works, policies can be adopted to stimulate the reduction of water demand with the implementation of governance to promote consumer co-responsibility and fiscal incentives.

Given the different land use and land cover profiles of the municipalities in the MMP, the implementation of PES programs is a policy strategy to seek a form of compensation for those with greater capacity to produce ecosystem services compared to those with high demand and production limitations due to their consolidated area predominantly destined for other purposes. The sanctioning of Law 14.119, of 2021, which institutes the National Policy of Payments for Environmental Services (BRASIL, 2021), encourages and supports this type of strategy.

The deployment of water PES associated with the demands of vegetation cover is a potential instrument to assist in the conservation of water resources regarding quality and quantity (LIMA *et al.*, 2013). However, it is essential to strengthening the management bodies of the PES, including the training of its members, to ensure the maintenance of conserved areas, regardless of the political changes that may occur in the municipality or state (JARDIM, 2010).

The actions previously listed, as an example at the municipal level, become more efficient as they are transposed to the MMP scale, as they seek to identify common objectives, sharing experiences and results, making municipal decision-makers the key players in adaptive governance.

5 CONCLUSION

The history of land use and land cover transition, the urban supply situational framework and the projections of climate variables and indexes for MMP municipalities have generated public management challenges. These challenges, especially water supply, where there is a growing demand and limited supply of ecosystem services, require actors attentive to the impacts of climate change predicted by different models. The models show an upward trend in temperature, rainfall reduction and greater frequency of consecutive dry day periods. In addition, land use and land cover changes directly affect water production, and despite the MMP having a balanced number of natural areas after three decades, there were significant transitions over the period and municipalities with different profiles regarding the maintenance of areas with greater capacity to produce ecosystem services.

In this context, even municipalities that dominate urban areas, and, consequently, with a smaller rural area for investment in ecological restoration, should guide their policies to the expansion of climate resilience, and actions such as the revitalization of the urban fabric, through the deployment and the restoration of parks and green areas, which contribute to cooling temperature and dampening floods. Investment in nature-based solutions (NbS) and ecosystem-based adaptation (EbA) has advanced in this regard and contributes to the generation of numerous other co-benefits.

The amount of natural area in the municipalities of the MMP is quite variable, both in percentage and in absolute values, and these dynamics affect the provision of ecosystem services. Land use and land cover transitions in the last 30 years culminated in a practically neutral balance in the MMP, however, the transitions occurred, as 53% of the municipalities increased their natural areas, and 47% reduced them.

Concerning urban supply, 58% of the municipalities in the MMP need investment to continue supplying the growing demand. The Metropolitan Regions of São Paulo and Campinas stand out, with most of their municipalities in such conditions. The outcome of transitions to natural coverage areas was positive for the RMC and negative for the RMS. However, the availability of natural areas for the RMC, in 2018, is lower, with most of its municipalities maintaining less than 20% of their territory with natural coverage, and this characteristic has been observed in a continuous block of municipalities on the Metropolitan Region of Sorocaba and the Urban Agglomeration of Piracicaba.

In addition, the provision of ecosystem services can suffer negative impacts caused by changes in the average temperature, volume and intensity of rainfall and longer dry periods as an effect of climate

change, even given the projection of an intermediate scenario, in which mitigation policies and actions are considered to reduce greenhouse gas emissions.

The provision areas of ecosystem services go beyond the political limits of the municipalities, and, in the case of water production for the MMP, they go beyond their limits, such as the basins that contribute to the Cantareira Supply System. Therefore, there is a need to identify and map the producers and consumers of ecosystem services at the river basins scale, to evidence existing flows.

The mosaic of different profiles of the municipalities of the MMP, built along decades and facing great challenges, especially with water supply, requires actions to identify and recover springs and degraded areas, construction of resilient cities, water supply infrastructure investment, demand management incentives, adaptive governance and implementation of payment programs for environmental services.

The adoption of municipal climate adaptation planning and policies that integrate these issues is urgent, especially for the 20 municipalities in the MMP listed with a natural coverage percentage of less than 20%, with a history of diminishing natural coverage area during the analysis period and with a diagnostic of unfavourable water supply.

Finally, there is a need for discussion on integrated MMP management to equalize municipal differences to improve the capacity of managers to understand the territory, to identify their role in the MMP, its deficiencies and its potential in this new geographic arrangement, which needs policies aimed at sustainable actions.

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