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Urban growth and loss of green spaces in the metropolitan areas of São Paulo and Mexico City: effects of land-cover changes on climate and water flow regulation

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Abstract

Urban green spaces provide ecosystem services that directly or indirectly benefit people, however, urban growth (especially in developing countries) generates the loss of these green areas and consequently of their ecosystem services. This paper aims to present the effects of land use and land cover changes in the last 30 years on two basic urban ecosystem services, water flow regulation and local and regional climate in two of main Latin American megacities (São Paulo and Mexico City). The study focuses on urban green spaces because they reduce the urban heat island effects, improve air quality, create habitats for biodiversity conservation, provide cultural services, and contribute to flooding prevention and groundwater conservation. A spatial analysis with the aid of geographic information systems was performed to assess (i) the urbanization process of the Metropolitan Areas of both cities over time; (ii) how this process generated changes in the land cover in both metropolises, and (iii) how these changes caused environmental negative impacts on ecosystem services. The loss of green areas as a consequence of urban expansion in the Metropolitan Areas of São Paulo and Mexico City changed the spatial distribution of urban heat island and increased the surface runoff, generating floods during the rainy periods. Our results suggest the urgent need for implementation of ecosystem-based spatial planning and ecological restoration of urban green areas in both studied cities to prevent further losses in ecosystem services and to improve the quality of life of urban inhabitants.

Keywords Ecosystem services · Landcover changes · Megacities · Urbanization

Introduction

Currently 56% of the world population lives in urban areas—particularly in megacities -, and it is expected that by 2050, 7 of 10 people in the world will live in cities. (World Bank 2022). In Mexico, nearly 80% of population live in cities: the country has 14 cities with 1 to 5 million people and 1 with more than 10 million, Mexico City, whose population by 2030 is expected to increase to more than 24 million. Also, Brazil has 19 cities with a population between 1 and 5 million, as well as 2 cities with more than 10 million – Sao Paulo and Rio de Janeiro. Moreover, Sao Paulo is expected to have more than 24 million inhabitants by 2030 (Urbanet 2022).

The scale and speed of urbanization and peri urbanization make cities critical spaces for sustainability, accentuated by the socio-environmental crisis. Urbanization is one of the main drivers of land-cover changes that has characterized the Anthropocene (Elmqvist et al. 2013; Haase et al. 2018; Stoett and Dalby 2022), mainly in developing countries due

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to the growth of the urban population (Parris 2016). The increasing population and urbanization cause pressure on natural resources and high demand for Ecosystem Services (ES), which can lead to environmental degradation such as water degradation and climate alteration (Seto et al. 2011; Sirakaya et al. 2018). Loss of ES due to the human-driven conversion of native vegetated areas into urban land has been widely reported in developing countries (Mendoza-González et al. 2012; Estoque and Murayama 2013; Crespin and Simonetti 2016).

In this context, Urban Green Spaces (UGS) generate several environmental and social benefits providing important ES to the population. Among these benefits, UGS decrease air temperatures (Oliveira et al. 2011), and urban heat island (UHI) (Solecki et al. 2005; McPherson and Simpson 2003). Furthermore, UGS reduce the superficial flow of water aiding in the maintenance of the better moisture in soils, the impact of the winds, the solar incidence (O'Dell et al. 1977; Nowak and Dwyer 2007; Fang and Ling 2005; McPherson and Muchnick 2005) and contribute to the mitigation of climate change by increasing carbon sequestration capacity (Davies et al. 2011; Murata and Kawai 2018). Many middle and low-income countries are working on a series of policies to conserve these UGS, although they are depleting in cities all over the world (Okech and Nyadera 2021; Shuvo et al. 2020).

A study conducted in high-income countries (25 European cities) identified that between 7.3% and 41% of lands reserved for UGS had been changed to different land uses (Kompil et al. 2015); in megacities from Asia, for example in Beijing, UGS had decreased by 199 km^2 between 2000 and 2010 and the remaining green areas had become increasingly isolated. The volume of water runoff controlled by UGS first increased and then decreased with the increment in summer rainfall. The runoff reduction rate continuously decreased from 23% in 2000 to 17% in 2010, which is mainly attributed to the composition changes in UGS in Beijing (Zhang et al. 2015).

It is estimated that between 2000 and 2030 urban areas will expand by around two times and approximately 5 billion people will be living in cities at the end of this period (Fragkias et al. 2013). Currently half of humanity live in towns or cities and it is expected that within eight years this will increase to 60% (Shaw et al. 2020). In this context, there is an urgent need to face the problems of climate change and water flow regulation in urban areas. This need is directly related to the Sustainable Development Goals of the United Nations Development Program (United Nations 2015), especially regarding the objective 11 "Sustainable cities and communities". Thus, this work aims to explore the impacts of land use and land cover changes (LULC) in the last 30 years, caused by the rapid growth of the urban areas of the Metropolitan Areas of Sao Paulo (MASP) and Mexico City (MAMC), on the UGS and, consequently, on two crucial ES: climate and water flow regulation.

This article summarizes the key characteristics of the two largest Metropolitan Areas in Latin America and their urbanization processes over time. Then geoprocessing techniques were used to evaluate LULC that occurred in each metropolitan area. Finally, the quantification of LULC in urban areas and the impacts on the ES climate and water flows regulation are presented and discussed.

Methods and analytical framework

The urban growth process in the MASP and the MAMC

The evolution of the two most populated urban areas in Latin America, the MASP and the MAMC, occurred mainly in the last four decades (Secretaría de Desarrollo Social 2012; Lima et al. 2018). The growth of both populations is defined by the aggregation of extended urban complexes formed by several municipalities (Secretaría de Desarrollo Social 2012; Lima et al. 2018). Today, the MASP and the MAMC are among the ten most populated cities of the world, occupying the places 4° and 5º, respectively (United Nations 2018). As a main consequence, the distribution of vegetated areas is non-uniform in the two metropolises. Only the wealthiest neighborhoods are characterized by a large amount of vegetation and tree-aligned streets, while downtown and peripheral areas are almost devoid of vegetation.

Native vegetated areas in the MASP and the MAMC are mainly located on the outskirts of urban areas, characterized to be zones of environmental protection and preservation of water sources. Some important urban parks of both megacities provide ES that help to mitigate the effects of urban climate and improve the amount and quality of water in addition to reducing floods in urban areas (Coutts and Hahn 2015; Almeida et al. 2018; Secretaría del Medio Ambiente 2018).

Data analysis and mapping

To analyze the process of urban growth in the MASP and in the MAMC and its impact on the UGS, which generates the loss of important ES, an extensive bibliographical review was conducted added to digital processing of satellite images (Landsat 5, 7 and 8) as well as of the database available on the Protect Planet page (Protected Planet 2014), from which the data for the elaboration of the maps of the protected natural areas in the MASP and the MACM were obtained (Fig. 1).

The programs used to elaborate the maps were *IDRISI Selva* 17.2 (from Clark Labs) and the *Quantum GIS* 2.10.1

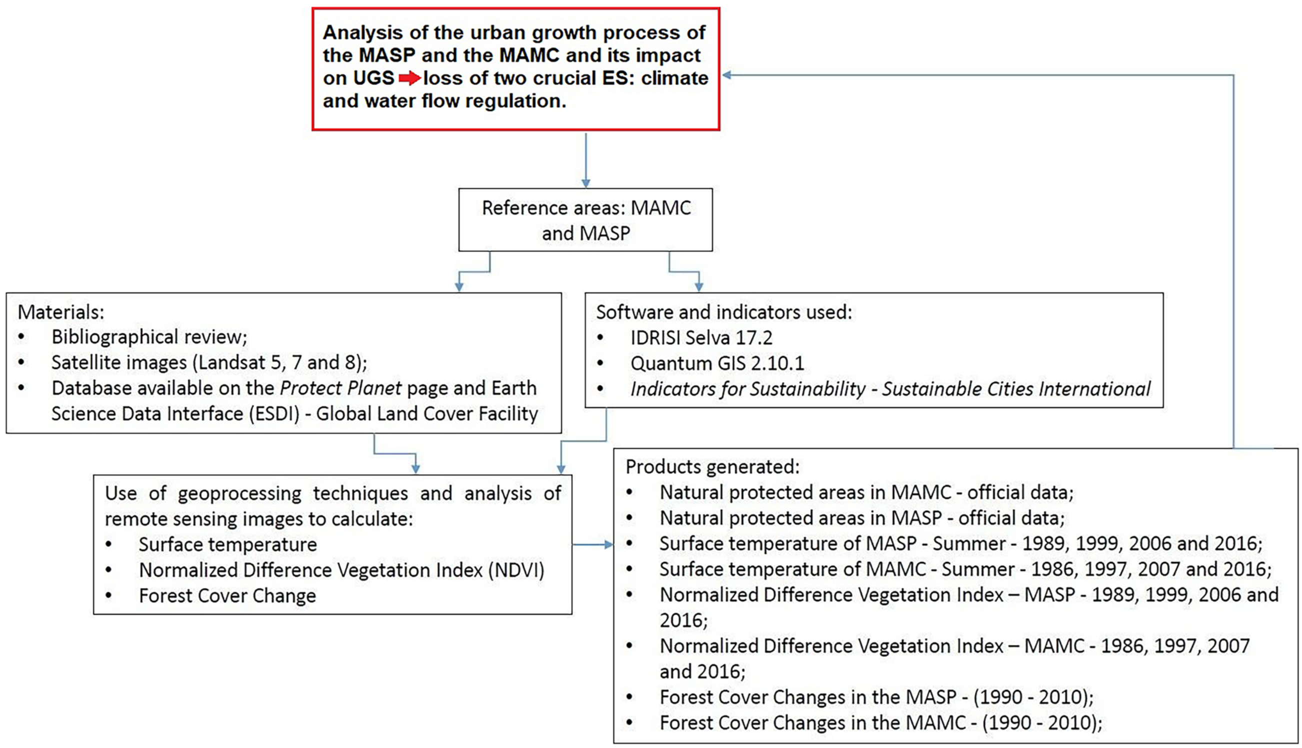

Fig. 1 Research development diagram

(open access). The percentage of preserved green areas in comparison to the population in both metropolises was based on the Indicators for Sustainability (Sector: Environment / Indicator: Green spaces) from the Sustainable Cities International. The calculation consisted of the division of the total green areas (persistent vegetation and forest gain)—obtained from the area statistics report generated during the image classification process carried out for the elaboration of the maps "Forest Cover Change—MAMC (1990–2016)" and "Forest Cover Change—MASP (1990–2016)"—by the total population of the two metropolises in 2018 (United Nations 2018). The resultant values should be considered as an approximation of reality, since the classified images may contain small errors from both the satellite images with which they were produced and the classification process itself.

The satellite images used to generate these maps come from the Global Land Cover Facility—Earth Science Data Interface (ESDI) (2023). This information was later updated until the year 2016 through the data provided by Global Forest Change of the Department of Geographical Sciences of the University of Maryland (Hansen/UMD/Google/USGS/NASA (2013)—http://earthenginepartners.appspot.com/science-2013-global-forest) (Hansen et al. 2013).

To understand how the loss of urban green spaces can change the local climate, the steps described below were followed:

(a) Initially, surface temperatures were calculated by processing the images from the Landsat 5, 7, and 8 satellites. The results were presented in maps that show the radiance per unit of source area in each study region from 1989 to 2016 for MASP, and from 1986 to 2016 for MAMC.
(b) The surface temperature images were classified and normalized and a chromatic pseudo-color scale was applied to better identify the temperature behavior of the targets in the images that compose the final maps' composition.
(c) After generating the surface temperature maps, the next step consisted of a thermal classification. This thermal classification, adapted from Barros and Lombardo (2016), has three subdivisions (Table 1), and its central idea is to identify the formation of the UHI phenomenon in the two metropolises and measure the thermal

Table 1 Thermal classification of urban heat island (UHI) by the thermal differences in land surface temperature (ΔT)

UHI level	Division standard ΔT (ºC)
Strong	> 8
Moderate	4 – 8
Freshness Island	< 4

Adapted from Barros and Lombardo (2016)

differences in land surface temperature (ΔT) generated by urban centers concerning the UGS.

(d) In the case of MASP, the municipality of Cotia was chosen as the reference region for calculating the ΔT, since a large part of its territory is covered by areas of preservation of native vegetation and water resources.

(e) In the case of the MAMC, the municipality of Milpa Alta was defined as the reference zone because it is poorly urbanized and has a convenient difference in altitude of less than 100 m concerning the more urbanized area of the metropolis, which avoids possible comparison problems generated by large differences in altitude.

The basis of the methodology used here is the transformation of the matrix surface data measured by satellite into vector layers, according to a simple classification of the values, so then they can be compared to other layers of information, such as the Normalized Difference Vegetation Index (NDVI), which denotes the growth state and spatial distribution density of vegetation, calculating according to the reflectivity of the near infrared band (NIR) and red band (RED) in the Landsat satellite images (Jones and Vaughan 2010). NDVI is dimensionless and ranges from −1.0 to 1.0, with higher values being associated with denser vegetation and lower values associated with sparser vegetation. The lowest values represent bare ground.

The images used to calculate the NDVI were the same as those used to calculate the surface temperature and refer to the paths 260 (rows 46/47) and 219 (rows 76/77) for MASP and MACM, respectively. The results of the NDVI calculations for the two study areas -i.e., MASP and MAMC- were compiled into a map composition with normalized values from 1986 to 2016 for MAMC, and from 1989 to 2016 for MASP.

Finally, to show how vegetation removal and replacement by urban materials generates an increase in surface runoff and consequently flooding, data from the databases of the Secretaría de Gestión Integral de Riesgos y Protección Civil (2019) and the Companhia de Engenharia de Tráfego de São Paulo (2019) were used to define the areas that are most susceptible to flooding within each metropolitan area and assist in identifying its relationship with the absence of UGS.

Results and discussion

Climate regulation

Metropolitan area of Sao Paulo (MASP)

Urban areas create their own climates due to the impact of urban development on the energy and humidity balance (Oke et al. 2017), thus contributing to the formation of the UHI phenomenon. However, assessing climate change generated by urban growth and the benefits offered by green areas in cities is extremely difficult, as weather stations are often not enough to meet the heterogeneity of the urban grid; therefore, the surface temperature measured by satellite is a viable and efficient alternative for spatial studies of the phenomena related to the air temperature in the low atmosphere, since this has a close relationship with the longwave radiation emitted by the surface.

The climatic characteristics of the MASP (high temperatures for most of the year and a mean annual precipitation of 1,400 mm) favor the existence of dense zones of tropical forest (Atlantic Forest Biome) over the region, with a predominance of open fields, typical of the high parts of southeastern Brazil, and dense ombrophilous forests, typical of the humid zones (Lima and Rueda 2018; Zanetti et al. 2017; Painel Brasileiro de Mudanças Climáticas 2016). Originally this biome covered the entire area now belonging to the MASP, but due to the high rates of deforestation, a large part of the forest has disappeared, as well as certain environmentally protected areas. What remains of this biome today is situated mainly in conservation units which form part of the region known as the São Paulo Green Belt Biosphere Reserve, and in some urban parks such as the State Park of *Fontes do Ipiranga*, *Ibirapuera* Park and *Olavo Egydio Setúbal* Park (*Carmo* Park) (Fig. 2).

The surface temperature gradients for the MASP (from 1989 to 2016), measured by the thermal band of the satellites, had the lowest spatial values from 16 °C to 18 °C (Fig. 3) and were mainly concentrated in the south and southeast limits of the metropolitan area, in a section of the São Paulo Green Belt Biosphere Reserve.

The highest surface temperatures (above 30 °C) were concentrated mainly in the north, central and east parts of the urban area, regions without vegetation or with low vegetation cover (Fig. 4).

Taking as reference the municipality of *Cotia*, it is possible to notice that the Strong UHIs present themselves mainly in the north, central and east zones of the city of São Paulo, corresponding generally to the neighborhoods of *Mooca*, *Tatuapé*, *Itaquera*, *Lapa* and *Vila Pirituba*, as well as parts of the municipalities of *Guarulhos* and *São Caetano do Sul*.

Moderate UHIs occur in some areas within the main urban zone, especially in the so-called "Gardens neighborhoods", urbanized areas with high rates of urban afforestation in the municipality of São Paulo, and in the peripheral areas of other municipalities of the MASP, especially in zones of recent occupation, where the land cover is being gradually replaced by urban materials (Fig. 3).

In the peripheral areas of such cities, it is very common for native vegetation to be withdrawn at large scales for future housing construction, consequently leaving exposed soils that generate strong changes in surface temperatures in short periods. It is important to note that the moderate

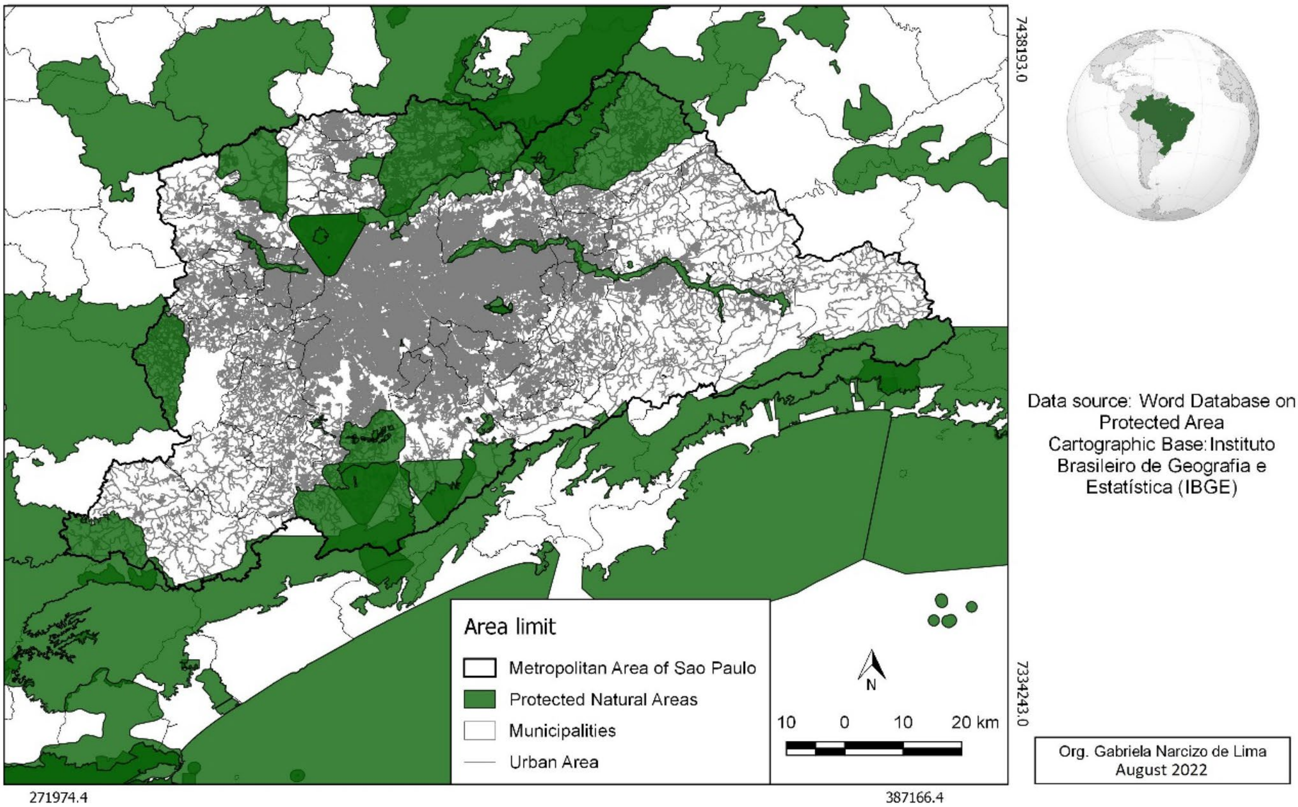

Fig. 2 Natural protected areas in the Metropolitan Area of São Paulo. **Data Source:** Elaborated by the authors based on data from Protect Planet—https://www.protectedplanet.net

UHIs covering the peripheral areas of recent occupation in the MASP have expanded over the years, experiencing an almost exponential increase between 2006 and 2016.

The Freshness Islands (i.e., ΔT < 3 °C concerning the reference point) occur mainly on the outskirts of MASP, mostly coinciding with the "São Paulo Green Belt Biosphere Reserve", a large area formed by different conservation units surrounding the urban spot of the MASP, which has NDVI values ranging from 0.3 to 0.9 (Fig. 4) and presents extensive green areas.

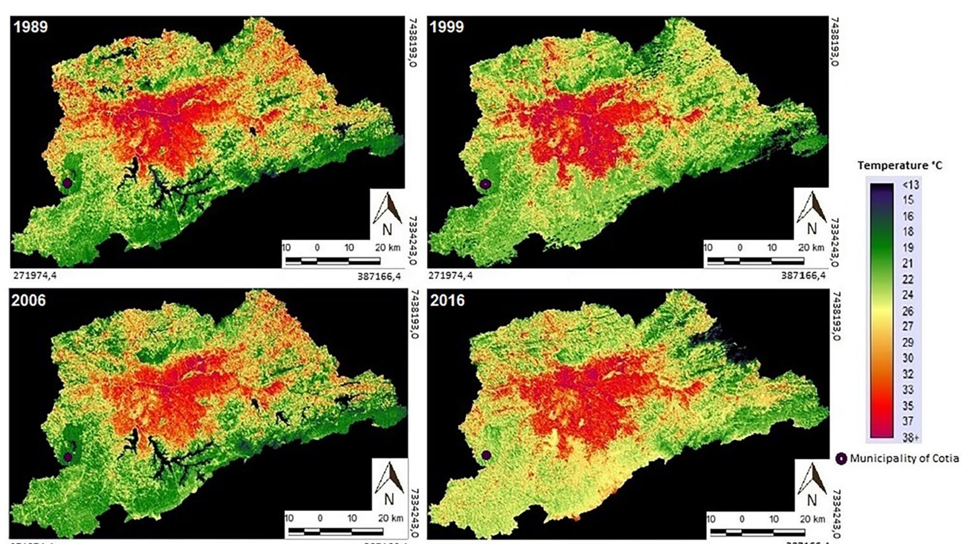

Fig. 3 Surface temperature in summer in the Metropolitan Area of São Paulo during the period 1989–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

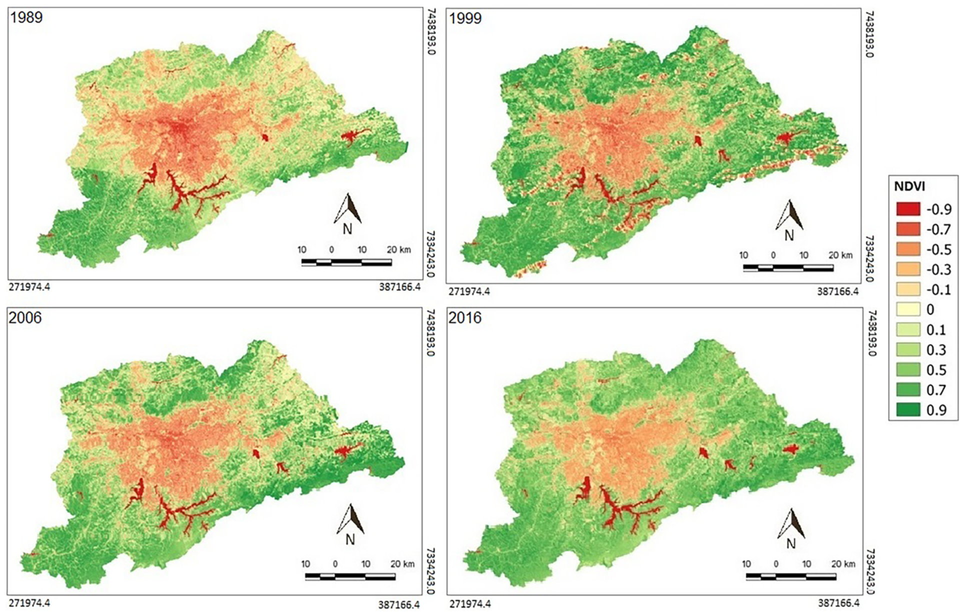

Fig. 4 Normalized Difference Vegetation Index in the Metropolitan Area of São Paulo during the period 1989–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

Metropolitan Area of Mexico City (MAMC)

Green areas in the MAMC do not have a heterogeneous distribution, they are, however, more notorious in the southwest part of the city where mountains are located, which is also the region where the main part of the ES related to water provision and climate regulation are present. The south part is where the largest natural reserves and wetlands are located. Food production in Mexico City is concentrated mainly in the delegations located in the south and southeast due to the expansion of the urban area towards the North and East (Fig. 5) (Procuraduría Ambiental y del Ordenamiento Territorial 2010, 2019).

In contrast to the MASP, where the mean annual precipitation is ~ 1,400 mm, and the native vegetation is characteristic of more humid zones, the main ecosystems in MAMC (temperate forests, shrublands, and grasslands) are characterized by the fact that they endure long periods of drought during a dry season from December to May and are less vigorous, even during the rainy season when more than 80% of the total precipitation amount fall (García 2004). These ecosystems are present mainly in the lower parts of the valley, around the main urban spot and to the north of the territory, and, since they do not present dense vegetal biomass, the spectral response registered in the satellite images often resembles bare soils (Fig. 6).

The most representative NDVI values (between 0.3 and 0.9) are found in areas dominated by temperate forests, also known in Mexico as pine-oak forests. This forest ecosystem grows at altitudes ranging from 2,200 and 3,000 m and they are mixed forests that change from broadleaf trees (mainly oaks, genus *Quercus* of the beech family *Fagaceae*) to conifers (*Pinaceae* trees of genus *Pinus*, and genus *Abies*, and *Cupressaceae* species) when in higher areas. On the MAMC these are present in the highlands, skirting the more densely urbanized area to the east, south, and west, forming, at the same time, part of the vegetation found within the reference zone (Municipality of *Milpa Alta*) chosen for the calculation of ΔT (Fig. 7).

The strong UHIs in the MAMC show a dynamic behavior over the years that have intensified in the last two decades. The northern part of the metropolitan territory repeatedly showed high surface temperatures concerning the most forested areas. Still, the most intense UHIs were located mainly in the central part of the urban zone (Fig. 6), where, as early as 1973, Jáuregui (1973) had found heat islands of up to 10 °C in the urban canopy layer on clear winter nights.

The moderate UHIs appear mainly between the warmer zones and the Freshness Islands. It is interesting to note that over the years the moderate UHIs gave way to the strong UHIs, which increased in size but not in intensity (Fig. 7). The Freshness Islands are formed mainly on the more vegetated zones and protected areas located in the less urbanized municipalities forming part of the metropolitan zone -i.e., *Tepetlaoxtoc, Texcoco, Ixtapaluca, Tlalmanalco, Amecameca, Atlautla, Huixquilucan, Jilotzingo, Isidro Fabela, Nicolás Romero, Villa del Carbón*, and *Cuajimalpa*- as well as in the higher areas of difficult urbanization.

Regulation of water flow

Climate change exacerbates environmental variability, adding a degree of unpredictability to weather and climate conditions -i.e., more intense rainfall events and more frequent storms- causing human and material losses. Floods and landslides

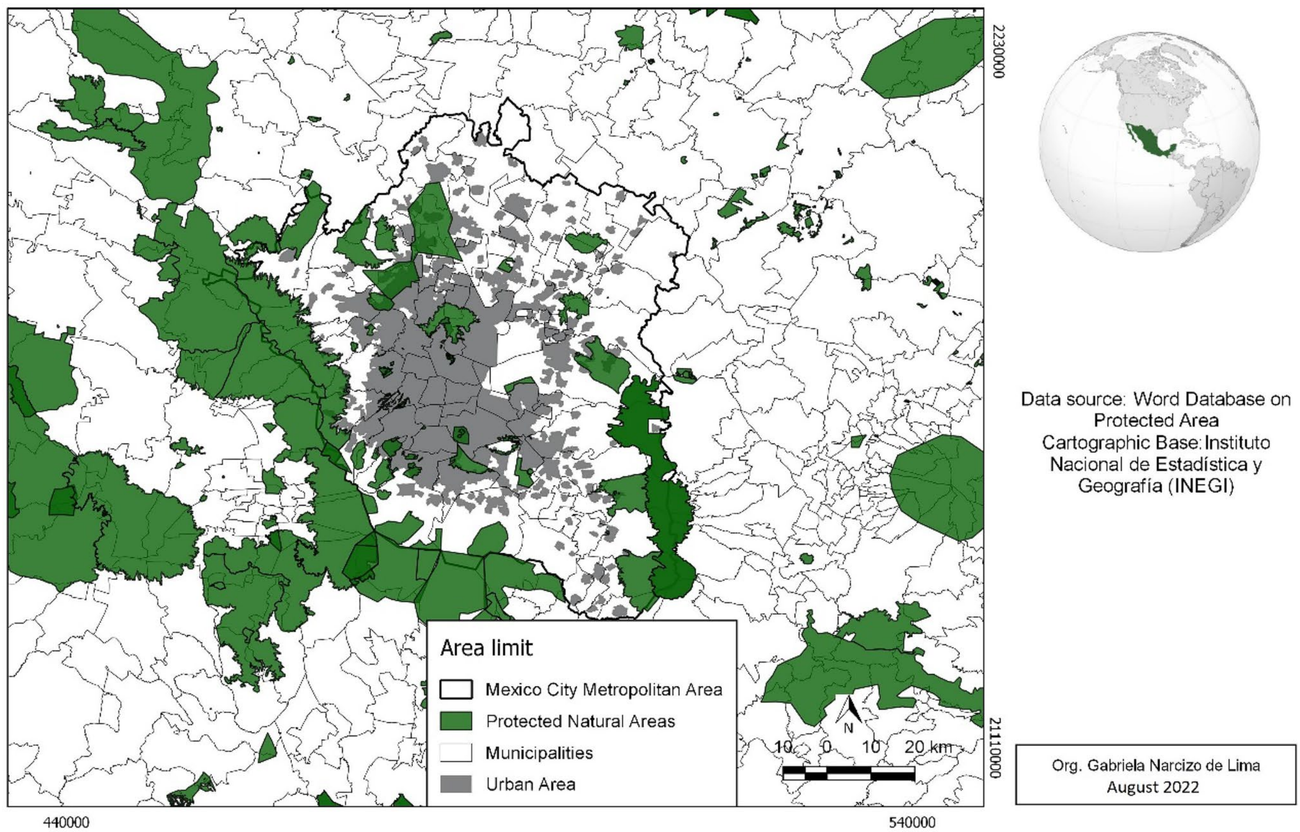

Fig. 5 Native protected areas in the Metropolitan Area of Mexico City. **Data Source:** Elaborated by the authors based on data from Protect Planet—https://www.protectedplanet.net

become more common, and the presence of large urban areas with vulnerable occupations intensify their effects (Lopez-Cruz et al. 2021; Abeldaño-Zuñiga et al. 2021).

Locally, this climatic intensification occurs due to the replacement of vegetation by concrete and asphalt infrastructures, and implies greater retention of heat on surfaces, increasing the temperature of certain zones of both metropolitan areas (i.e., the MASP and the MAMC) (Oke et al. 2017). The ensuing floods in both cities affect the population, industry, and commerce, causing damages from an economic and social point of view.

The urbanization process in both metropolitan areas (i.e., MASP and MAMC) has led to the long-lasting or irreversible environmental impacts such as the suppression of native vegetation; soil sealing; contamination, rectification, channeling and grounding of rivers and lakes; intensive occupation of floodplains; pollution of watercourses and air and the formation of the UHI phenomenon, that consist of a profound change of the whole natural system.

The practice of channeling rivers, streams, and lakes changes the behavior and the regime of the rivers and intensifies the water amount and energy of surface runoff. In some cases, these pipes temporarily solved the problem; however, the MASP and the MAMC continued their unplanned growth, requiring more and more measures to control both urban drainage and floods. The damage caused by floods -mainly in the rainy season (which in both areas occurs in the summer)—is enormous when all the affected areas are considered.

The hydrographic complex of the MASP corresponds to the Alto Tietê Hydrographic Basin, which is located entirely in the state of São Paulo. About 70% of the metropolitan region is in this basin, and the relationship between the two approaches is narrow. In the Alto Tietê Hydrographic Basin, large dams can be found, built for different purposes, as well as important rivers that cut the metropolis, such as Tietê, Pinheiros, and Tamanduateí. On the other hand, the MAMC was built on the Mexico Hydrographic Basin, which is characterized by the meeting of four valleys located in central Mexico. This basin originally covered a system of lakes, that were desiccated, and on these areas rests most of the urban zone that forms the metropolis.

Although in the peripheries of the two metropolitan areas it is possible to observe soil uses related to agriculture (temporal and irrigated crops) and logging, the main alteration

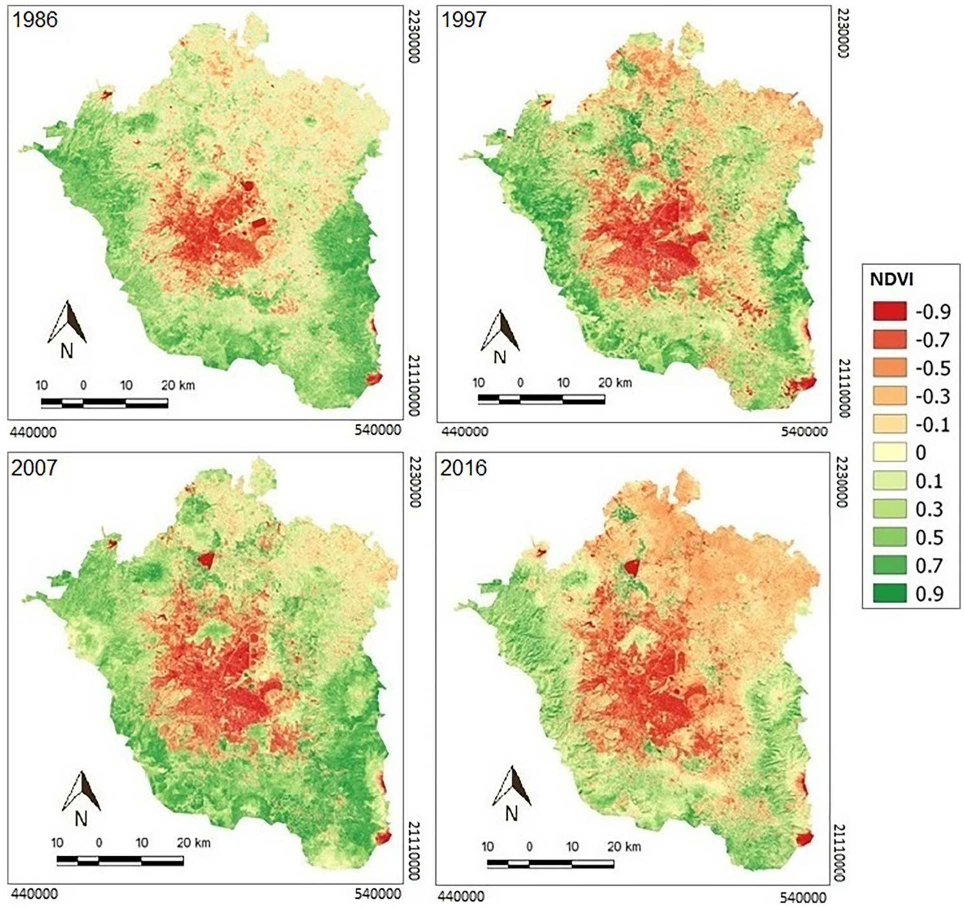

Fig. 6 Normalized Difference Vegetation Index in the Metropolitan Area of Mexico City during the period 1986–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

of the native vegetation of the basins areas was carried out to expand the urban centers, which currently occupy almost the entirety of the territory. The alteration of the surface of both hydrographic basins (i.e., Alto Tietê and Mexico) has significant impacts on the outflow. These impacts are usually characterized in terms of their effect on flood frequency and intensity.

In the MASP the amount of green areas per inhabitant is higher than in the MAMC (Table 2), and the total of green areas lost in the MASP is lower than that of reforested areas between 1990 and 2016 (Table 3), meanwhile, in the MAMC the opposite phenomenon occurs.

The area statistics report generated during the image classification process carried out for the elaboration of the maps "Forest Cover Change—MAMC (1990–2016)" and "Forest Cover Change—MASP (1990–2016)" showed that 63.7 km^2 of green areas in MAMC have been lost, which represents a 21% greater area than that reforested in the same period (Table 3), but these values are not recognized officially by the government.

It is also important to note that, although there is a high vegetation surface in the outskirts of the MASP urban area, mainly belonging to the protected areas of the "São Paulo Green Belt Biosphere Reserve", there are very few green areas inside the cities that would be essential to ensure greater regions of infiltration and to reduce floods during rainy periods (Fig. 8).

At the MAMC the situation is even more critical than in the Sao Paulo counterpart. The way the basin was urbanized generated horizontally extended cities with few green areas and a large part of its buildings on the dissected lakes. The north of the MAMC is the region most deprived of vegetation as being extremely urbanized; there are no urban parks with large extensions (Fig. 9). The zones where most native vegetation was lost in the MAMC between 1990 and 2016 are defined as urban expansion fringes to the northwest and east of the main urban area, while the reforested areas mainly refer to high altitude temperate forests, possibly destined for logging.

The reduction of the forest surface changes the hydrological cycle and causes a clear difference in infiltrated and surface water flows between the waterproofed areas and those with preserved vegetation, to such an extent that more than 84% of the areas susceptible to flooding in MASP and MAMC are located in urban areas with little or no vegetation. The areas most susceptible to flooding within the two metropolises were determined from previous records that show points where floods occurred between 2016 and 2017 (Table 4).

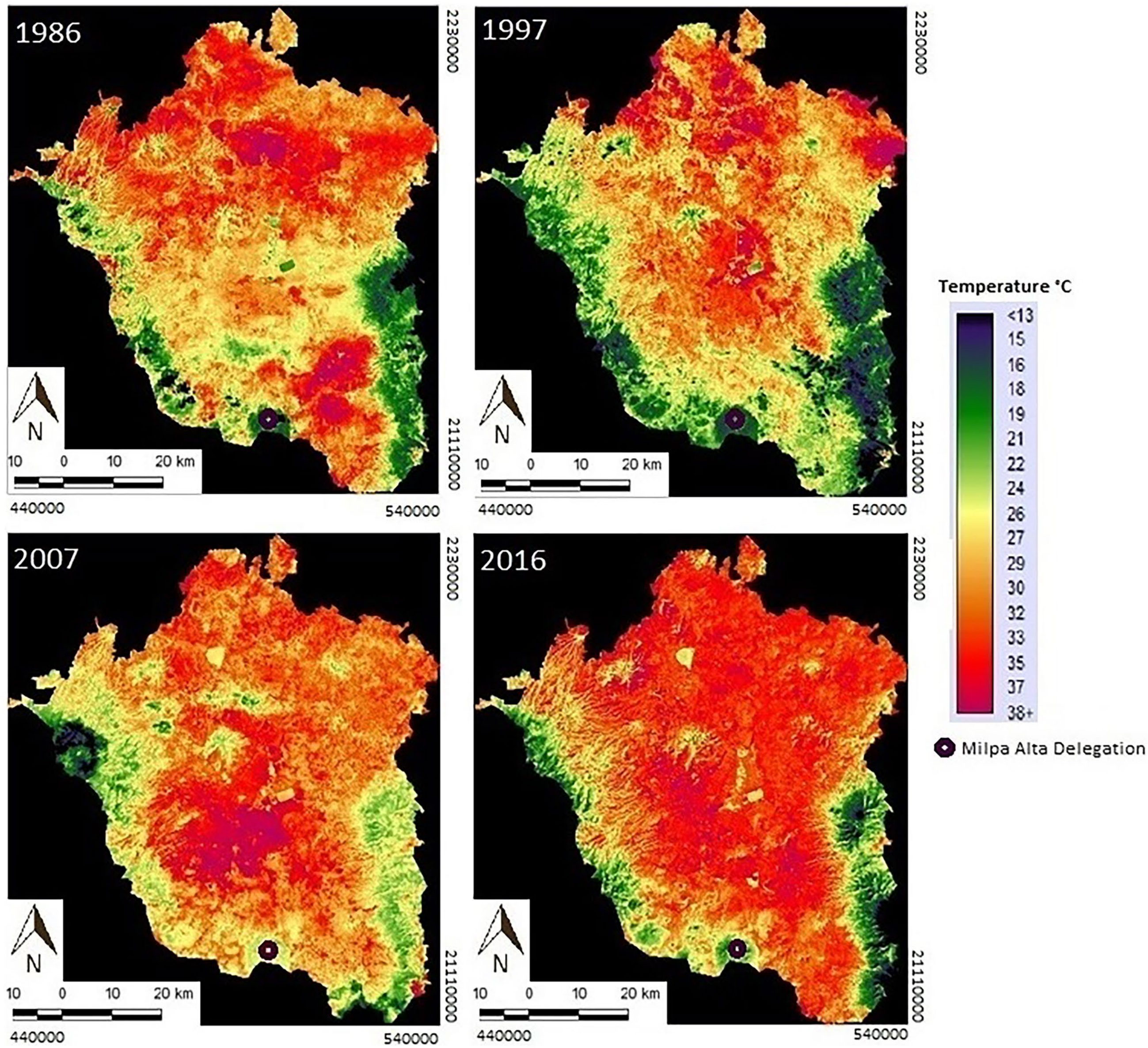

Fig. 7 Surface temperature in summer in the Metropolitan Area of Mexico City during the period 1986–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

Table 2 Total green area, total population, and green area per inhabitant in the Metropolitan Area of São Paulo (MASP) and the Metropolitan Area of Mexico City (MAMC) in the year 2016

Metropolitan area	Total green area (km^2)	Total population ($\times 10^3$)	Green area per inhabitants (m^2)
MASP	4,093	21,297	192
MAMC	1,569	21,157	74

Data Source: Area statistics report for raster images -Forest Cover Change—MAMC (1990–2016) and Forest Cover Change—MASP (1990–2016) maps and United Nations 2016

Table 3 Changes in forest cover in the Metropolitan Area of São Paulo (MASP) and the Metropolitan Area of Mexico City (MAMC) during the period 1990–2016

Metropolitan area	Forest loss (km^2)	Forest gain (km^2)	Persistent forest (km^2)
MASP	125.9	590.6	3,502.0
MAMC	63.7	50.5	1,518.6

Data Source: Area statistics report for raster images—Forest Cover Change—MASP (1990–2016) and Forest Cover Change—MAMC (1990–2016) maps

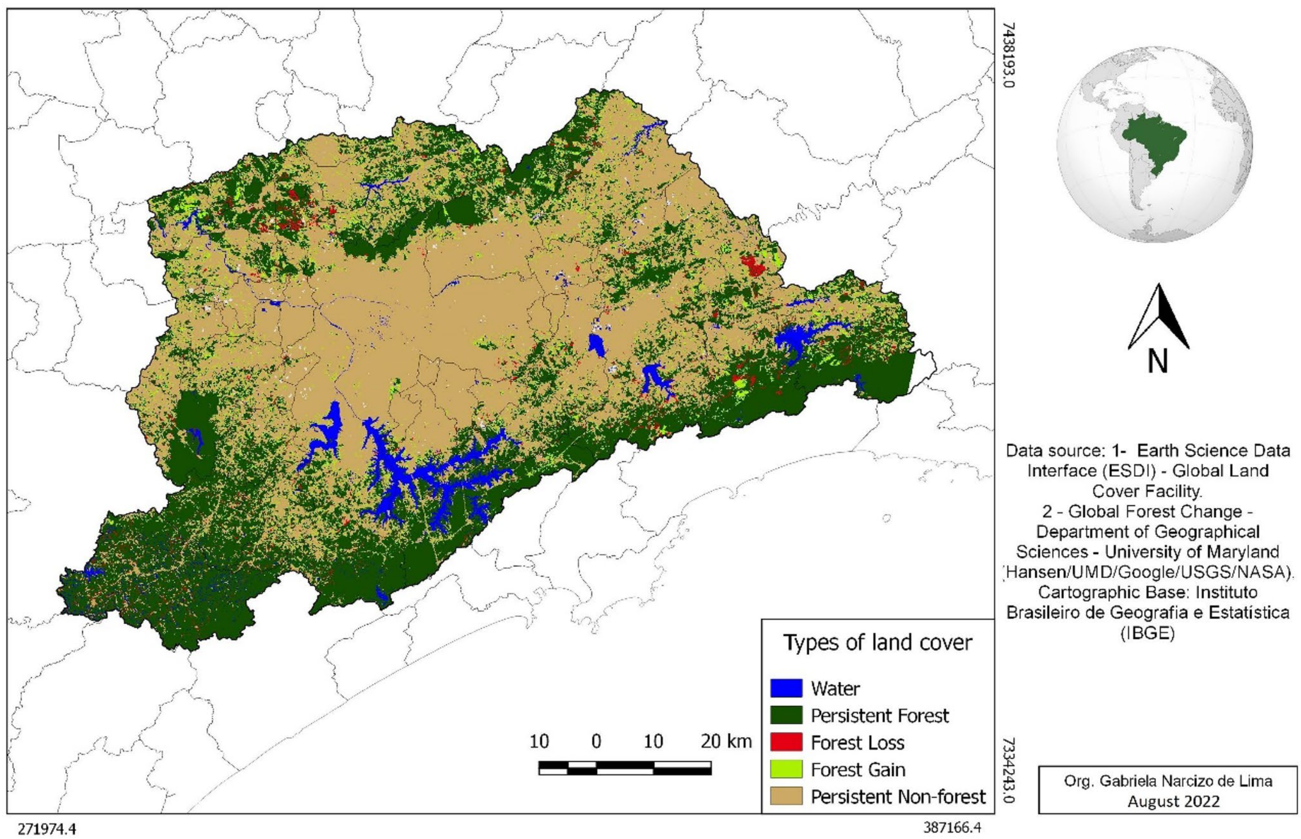

Fig. 8 Forest cover changes in the Metropolitan Area of São Paulo during the period 1990–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

In the case of the MASP, of the 103 areas where floods were reported in 2018, 87 were located within the most densely urbanized area. It is important to mention that the Companhia de Engenharia de Tráfego de São Paulo (2019) draws attention to the high number of cases registered near the confluence of the two main rivers that divide the metropolis (*Tietê* and *Pinheiros*). This region of the metropolis is characterized by dense urbanization in the vicinity of the rivers' flood gutters, as well as a precarious system of drainage with old and inefficient pipes.

At the MAMC, a total of 178 flood records were observed in 2018, around 85% of these (150) occurred in densely urbanized areas. According to the Secretaría de Gestión Integral de Riesgos y Protección Civil (2019), the cases were distributed throughout the metropolitan area, but there is a greater concentration within the main valley, more specifically in the areas where the lakes that were drained for the construction of the city were originally located. As in the MASP, in the MAMC the drainage system is precarious and does not efficiently serve the entire metropolis, considering the proportions of the cities that compose it.

The presence of more UGS within the cities would be of great aid towards the water infiltration and reduction of floods, especially in periods of extreme climate events (for example during La Niña years). Several authors have already warned about the importance of the presence of UGS (Xiao and McPherson 2002; Xiao et al. 1998; Lin et al. 2011; Oliveira et al. 2011; Kaczorowska et al. 2016; Baró 2016; Almeida et al. 2018; Rocha 2021), and the data presented in our research indicates that the implementation of UGS at different points within urban areas reduced surface runoff and flooding compared to the deployment of a few larger green area units, which is the urban planning standard used both the MASP and the MAMC.

A good example of this is the so-called Sustainable Urban Drainage Systems (Zhou 2014) which consist of UGS designed to maintain hydrological characteristics as close as possible to pre-occupancy conditions. The main objectives of this system are to reduce flows and rates of outflow and the additional volumes resulting from urbanization, to promote the natural recharge of aquifers, to minimize the concentration of pollutants and act as a buffer zone in case

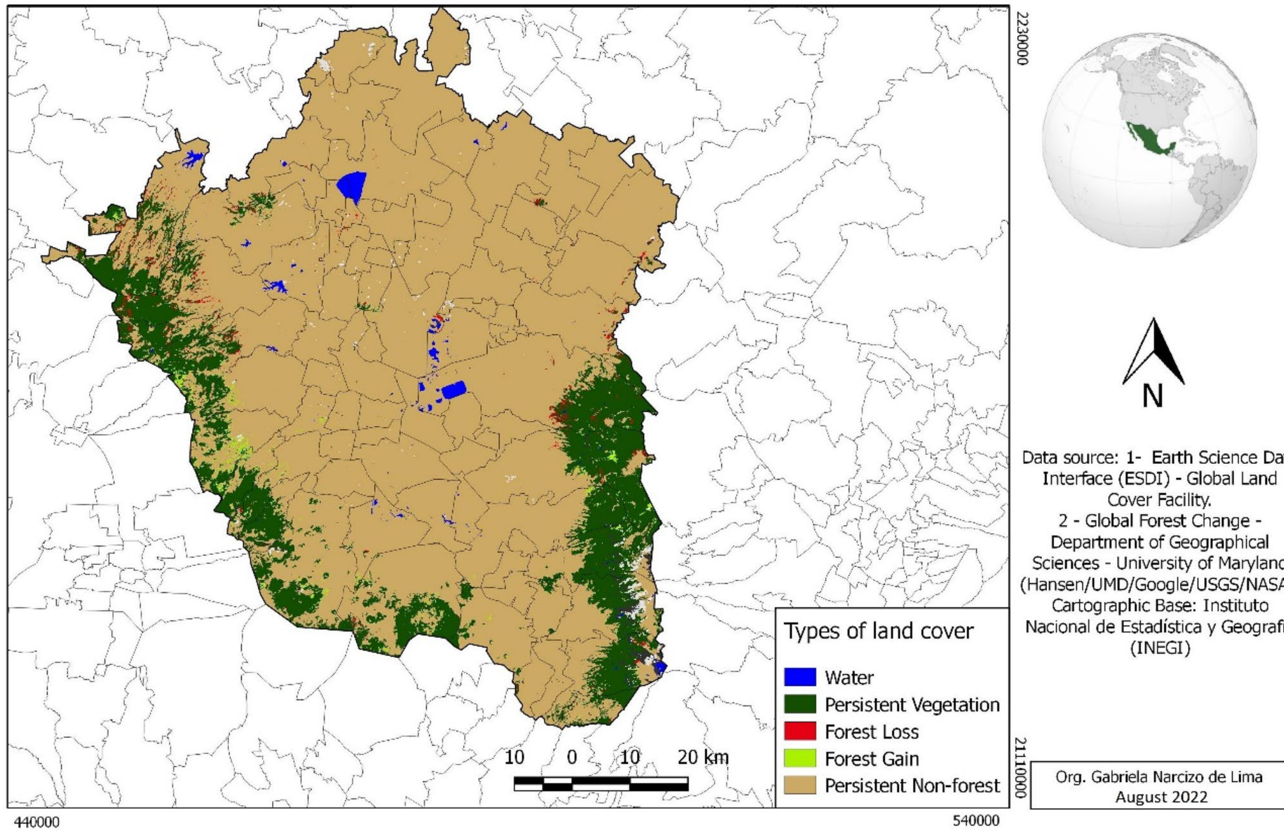

Fig. 9 Forest cover changes in the Metropolitan Area of Mexico City during the period 1990–2016. **Data Source:** Elaborated by the authors based on the digital processing of the images of Landsat 5, 7 and 8 satellites

of accidents with contaminant spills, and to provide habitats for animals, as well as to add aesthetic value to urban areas. The Sustainable Urban Drainage Systems were developed in the United Kingdom and resemble the Best Management Practices developed in the United States (Zhou 2014). Countries such as Australia, Sweden, and England have made use of this type of approach since the 1980s (Zhou 2014), but urban planning in the metropolitan areas analyzed here is still scarce and aimed at solving immediate, rather than long-term problems.

Table 4 Areas with high susceptibility to flooding in the Metropolitan Area of São Paulo (MASP) and the Metropolitan Area of Mexico City (MAMC) in 2018

Type of land cover	MASP	MAMC
Dense Urban	87	150
Wooded Urban	13	26
Protected Natural Areas	3	2
Total	103	178

Data Sources: Companhia de Engenharia de Tráfego de São Paulo (2019), Secretaría de Gestión Integral de Riesgos y Protección Civil (2019)

Conclusions

Sustainable development, which combines human well-being with the conservation and sustainable use of ES, is a global goal of the UN agreements (United Nations 2015) included in the Conventions on Climate Change, Biological Diversity and Combating Desertification. In this sense, the MASP and the MAMC can consolidate themselves as models of sustainable development considering the richness of their resources, having, at the same time, the possibility of promoting their primary production in an environment of high natural diversity, the available technical capacity and generally favorable legal instruments to the model. However, the ES are still treated as peripheral to the development of the two studied metropolitan areas.

It is known that the vast majority of ES-related research focuses on the more developed areas of the planet; nonetheless, the problems generated by rapid urbanization are mainly located in developing countries in tropical regions, with great biological diversity that is threatened by the LULC for unplanned growth of megacities. In this context, the MASP and the MAMC have a worldwide relevance; however, they do not develop themselves according to the standards of sustainable cities, even though they already possess legal instruments favorable to the sustainable development and protection of the green spaces and ES.

During the 20th century, protected areas within megacities have become an essential part of conservation strategies (Zambrano et al. 2019), minimizing the negative impacts of urban growth around the world (Pyke 2007). The benefits of their application, ranging from the simple effect of a shadow produced by vegetation as reducing the temperature of built and paved surfaces to the reduction of heat islands that are intensified with city growth are showed in this research, both for MASP and for MAMC.

The main green spaces in the MAMC and the MASP are located in the urban peripheries and that even these suffer the pressure of the continuous growth of the cities. In a calculation of the total of green areas per inhabitant in the two metropolises, considering the areas covered by the official delimitation of the two entities, a very encouraging result was obtained, mainly in the MASP, but the low presence or absence of native vegetation inside the urban areas were the main cause of the spatial distribution and the intensity of the UHIs in the MASP and the MAMC, as well as contributing strongly to the increase in surface runoff of rainfall. Thus, the results obtained in this research indicate the urgent need for the implementation of ecosystem-based spatial planning in both metropolitan areas, focusing on new UGS and the restoration of native habitats and their connectivity to prevent further ES losses and achieve the AICHI targets in both megadiversity countries (Tobón et al. 2017).

It was also observed in this study that UGS with irregular shapes have a better performance in ES provision, especially in climate regulation, since they are similar to natural areas. In addition to its shape, the size of the UGS is also relevant, since it is known that large green spaces have a significant influence on bioclimatic parameters in urban areas, while the effects of small UGS, while still important, are often less obvious. These observations coincide with previous works (Rosenfeld et al. 1995; Akbari et al. 2001; Lin et al. 2011; Millward and Sabir 2011; Baró 2016; He et al. 2018) and confirm the importance of UGS in providing wellbeing for urban dwellers.

The influence of UGS on the thermal environment has been previously demonstrated (Akbari et al. 2001; Lin et al. 2011; Millward and Sabir 2011; Baró 2016; He et al. 2018), however, despite these positive impacts, the use of UGS as an approach to heat mitigation and regulation of water flows may need additional measures to obtain the expected benefits, depending on the characteristics of each urban area, its UHI and the type of green spaces they have. Finally, the positive influence of UGS depends on the size and structure of the green space vegetation, the season and time of day, the obstruction of the sky generated by the buildings above the green areas, the prevailing climatic conditions in the area and the climatic zone where the green space is integrated (Spronken-Smith and Oke 1998; Upmanis and Chen 1999; Mirzaei and Haghighat 2010; Oliveira et al. 2011; Baró 2016; Oke et al. 2017; Lima and Magaña Rueda 2018; Rocha 2021).

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Data Availability All data used for this article are form free database.

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