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Despite Being Distinguished as the 2020 European Green Capital, Lisbon Has Lost Public Green Areas over the Previous Decade

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Abstract: With the objective of assessing Lisbon's environmental improvement and sustainable development, we measured the changes in Lisbon's vegetation cover over the 2010–2020 timeframe considering three categories: public green areas (PGA), street trees (ST), and urban green infrastructure (UGI). We calculated the vegetation cover (m^2), vegetation cover per resident (m^2 $person^{-1}$), and % of vegetation cover. PGA and ST covers were made available by the municipality, while UGI cover was estimated from the NDVI calculated from multispectral satellite images (Landsat 7–8). Since only the PGA cover decreased 2% (the ST and UGI covers increased 38% and 5%, respectively), Lisbon has lost PGA over the previous decade. The values of PGA per resident were below the minimum value of 12 m^2 $person^{-1}$ at the city scale and in most parishes (19 parishes out of 24 in 2020). While the values of % of UGI were above the desired value of 30% at the city scale, in 2020 there were three parishes with values below the minimum of 5%. This information is important to prioritize measures that promote sustainable urbanization in those parishes. Our study raised many questions, suggesting the need to standardize the methods for measuring the urban vegetation.

Keywords: multispectral satellite images; Normalized Difference Vegetation Index; public green areas; street trees; urban vegetation categories; urban green infrastructure

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1. Introduction

With more and more people living in urban areas (by 2050, around 70% of the human population will be living in cities [1]), the negative impacts of urbanization are building up and potentiating each other. The negative impacts of urbanization include ecological degradation [2,3], atmospheric pollution [4], noise [5,6], social inequalities [7–10], physical and mental health problems [11,12], and an overall reduction in human wellbeing [13,14]. If we add to the negative impacts of urbanization those of climate change (e.g., heat waves, extreme droughts, torrential floods), it becomes essential and urgent to develop measures that promote urban sustainability in its three dimensions (social, economic, and environmental) [15,16]. Urban sustainability has definitely entered the local, regional, national, and international political agendas (e.g., the United Nations' Sustainable Development Goal 11—Sustainable Cities and Communities). In agreement, the European Commission launched an initiative that recognizes and rewards local efforts to improve urban sustainability: the European Green Capital. Starting in 2010, this award is given each year to a city that (i) has a consistent record of achieving high environmental standards and provides them with public recognition; (ii) is committed to ongoing and ambitious goals for further environmental improvement and sustainable development; and (iii) can act as a role model to inspire other cities and promote best practices to all other European cities (https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award_en) (accessed on 6 June 2022). Distinguishing a city as the European Green Capital is based on the following 12 environmental indicators: air quality; noise; water; sustainable land use and soil; waste and circular economy; nature and biodiversity; green growth and eco-innovation; climate change mitigation; climate change adaptation; sustainable urban mobility; energy performance; and environmental governance (https://environment.ec.europa.eu/topics/urban-environment/european-green-capital-award/applying-eu-green-capital_en) (accessed on 6 June 2022).

In 2020, Lisbon was the first Southern European city to be distinguished as the European Green Capital. Therefore, our objective was to assess Lisbon's recent environmental improvement and sustainable development. For that, we measured the changes in Lisbon's vegetation cover over the 2010–2020 decade because (i) 2020 corresponds to the year in which Lisbon was distinguished as the European Green Capital and reflects the current situation; and (ii) 2010 corresponds to a period of serious economic crisis in the country (2008–2013) and precedes several territorial changes in local administrative policies (the new Municipal Master Plan was approved in 2012 [17]) and strategic measures targeting urban biodiversity, and climate change adaptation and mitigation. We focused on the changes in Lisbon's vegetation cover because urban vegetation is essential to guarantee the following: (i) environmental quality, as it creates ecological niches and therefore promotes nature and biodiversity, reduces pollutants, and noise [18], which are among the indicators for selecting the European Green Capitals; and (ii) human wellbeing, as it reduces psychological stress and human respiratory problems, induces positive emotions, and facilitates renovation of cognitive resources [19]. Furthermore, the urban vegetation can contribute to adapt and mitigate the negative impacts of climate change (also indicators for selecting the European Green Capitals) through (i) carbon sequestration in plant tissues and organs, (ii) reducing heat waves by reducing albedo and providing shade and evapotranspiration, and (iii) reducing torrential floods and extreme droughts by intercepting rainwater and promoting greater infiltration and retention of water in soils [20–22]. The benefits of Lisbon's vegetation in climate change mitigation and adaptation become even more relevant as Portugal is particularly vulnerable to climate change impacts that result mainly from a decreasing annual precipitation and more intense extreme weather and climate events, particularly heat waves, droughts, and floodings [23]. Finally, cities are composed of very diverse populations in cultural, socioeconomic, and generational terms, which often brings greater challenges to certain groups in terms of health, wellbeing, and social participation [8–10]. Specifically, the most vulnerable groups, such as ethnic minorities and the elderly, often lack green spaces close to their homes [24], and therefore cannot enjoy the benefits they provide. We anticipate social inequalities in the access to Lisbon's vegetation as Lisbon is one of the oldest European capitals (since 1256), was rebuilt following the 1755 earthquake [25], and therefore some areas of the city were urbanized many centuries ago, while other areas were recently urbanized, with expected consequences for vegetation cover. Altogether, the management and strategic expansion of Lisbon's vegetation can help address the triple challenge of climate change, environmental degradation, and social inequalities.

Given urban vegetation's multiple socioenvironmental benefits, some indicators and respective minimum reference values have been proposed, such as the minimum value of green areas per resident (proposed by Matias and Caporusso [26] and adapted by Lucon et al. [27]), which was set at 12 m^2 per person. Furthermore, when the urban vegetation covers (i) 30% of a city, it has been considered adequate; and (ii) less than 5% of a city, it creates characteristics similar to those of a desert [28]. These indicators were based on specific types of urban vegetation. Indeed, in a city, we can find vegetation with regular maintenance in public or private green areas (e.g., gardens, parks, streets, avenues), and natural and semi-natural vegetation without maintenance. Therefore, three urban vegetation categories can be considered [26]: (i) public green areas (PGA), which includes squares, parks, and institutional areas for environmental protection that can be for collective or restricted use, and for which the green areas per resident indicator are defined; (ii) street trees (ST), which includes the streets, avenues, and roundabouts with vegetation; and (iii) urban green infrastructure (UGI), which includes the previous categories (PGA and ST), and the natural and semi-natural vegetation in the urban area, for which the urban vegetation indicator senso lato is defined. The different urban vegetation categories are associated with different main functions (Figure 1). Despite the unquestionable role of urban vegetation, and some researchers' contributions (e.g., [26–29]), there are still no recommendations from international organizations (e.g., World Health Organization, United Nations) on which urban vegetation category to consider, nor the range of these values that ensure life quality of the urban population.

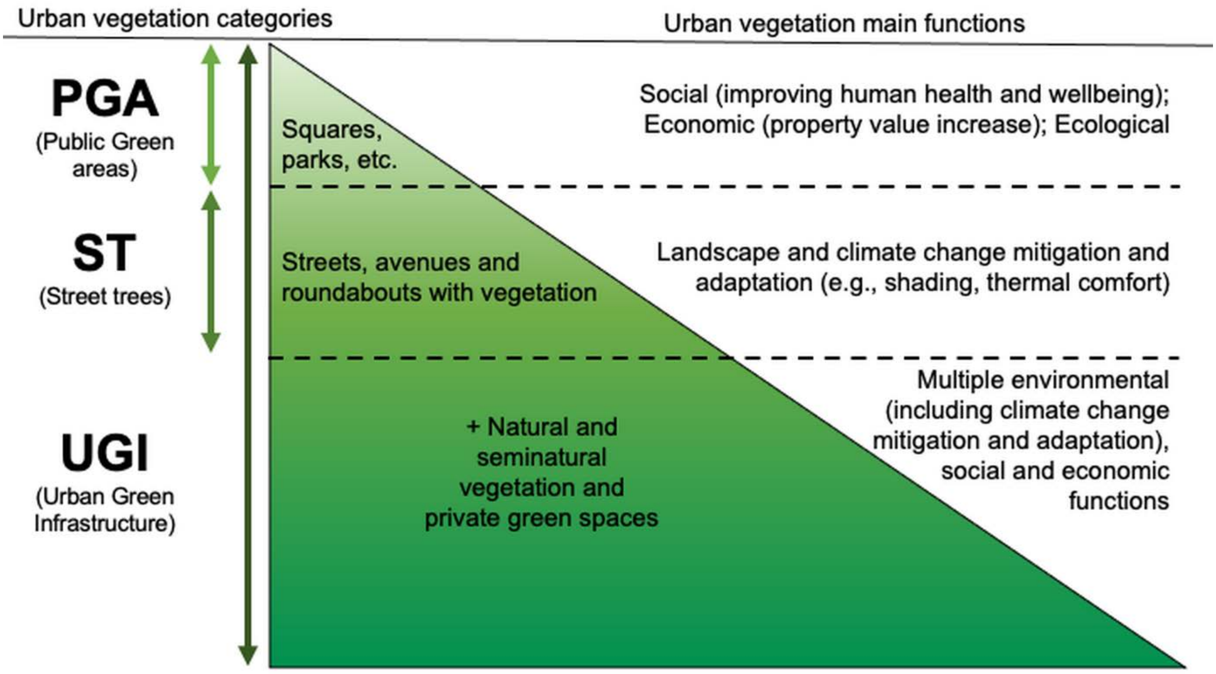

Figure 1. Urban vegetation categories and their main functions. Functions are listed based on their descendent importance for each urban vegetation category.

Therefore, we measured the changes in Lisbon's vegetation cover using the three urban vegetation categories (PGA, ST, and UGI). In the case of PGA and ST, the municipality (Câmara Municipal de Lisboa) made the data available. Since geoprocessing tools have been used successfully to assess urban vegetation [30,31], we used them to estimate the UGI. The UGI cover was estimated from the Normalized Difference Vegetation Index (NDVI) obtained from multispectral satellite images (Landsat 7–8). NDVI allows to detect the vegetation state (vigor vs. stress) and its cover in parks, squares, green corridors, stadiums, forests, etc. [30]. Then, by crossing this information with field data and information generated by GIS, it was possible to obtain adequate, reliable, and fast estimates for the UGI cover. To assess the changes in Lisbon's vegetation, we calculated, for each urban vegetation category, the indicators that relate the vegetation per resident, and the % of vegetation in 2010 and 2020. Finally, and considering the coexistence of areas in Lisbon that were urbanized many centuries ago, and others, in the last decades, we also studied the PGA per resident and the % of UGI for each parish (we focused on these two indicators because minimum values have been proposed). We hypothesize that the oldest parishes will have lower values for the indicators and that, although the city of Lisbon has environmental sustainability as a goal, the economic development of the last decade must have compromised the expansion of the urban vegetation. The information obtained through this study can contribute to prioritize measures in parishes with a greater lack of vegetation, and facilitate the sustainable planning of the urban territory, reconciling environmental quality with social and economic objectives.

2. Materials and Methods

2.1. Study Area

The study area is the city of Lisbon, which is in Southwest Europe, on the north bank of the Tagus River (38°43′00″ N; 9°07′59″ W). Lisbon is the largest city in Portugal (ca. 84 km^2 in 2020 and 100 km^2 in 2020) and the most populated one (547,733 residents in 2020 and 552,704 residents in 2020—Statistics Portugal, 2010, 2020—https://censos.ine.pt) (accessed on 28 January 2022). The climate is Mediterranean, characterized by hot and dry summers, which contrast with cold and rainy winters. Most precipitation occurs between October and April. According to the climatological normal (1971–2000), the average annual temperature is 18 °C, the average minimum temperature is 9 °C, the average maximum temperature is 27 °C, and the average annual precipitation is 726 mm (https://www.ipma.pt/pt/oclima/normais.clima/1971-2000/012/) (accessed on 13 June 2021).

Lisbon's vegetation includes trees, shrubs, and herbaceous plant species which occur in several environments such as avenues, public gardens, botanical gardens, olive groves, vegetable gardens, orchards, and recreational farms. Altogether, there are more than 400 thousand trees belonging to more than 100 different species, and hundreds of species of shrubs and herbaceous plants that make up Lisbon's vegetation [32].

2.2. Data Collection (Urban Vegetation Cover and Population)

Currently, Lisbon is composed of 24 parishes, but in 2010, it was composed of 53 parishes (Table S1). Most of the changes that occurred in the parishes correspond to merging two or more smaller parishes to form a larger one. Only one large parish (Santa Maria dos Olivais) was divided into two smaller ones (Olivais and Parque das Nações). In this period there was also urban expansion (+35.5 ha) in Parque das Nações. Therefore, to facilitate the comparison between the two years, we used the geographic limits of the current parishes, and calculated the 2010 indicators assuming the merging parishes.

Lisbon's population (total and per parish) in 2010 and 2020 was obtained through national census recorded by the Instituto Nacional de Estatística (Statistics Portugal, 2010, 2020—https://censos.ine.pt (accessed on 28 January 2022)—Table S2). The PGA and the ST covers were made available, free of charge, by the Urban Information Center of the Lisbon City Council (https://geodados-cml.hub.arcgis.com/datasets/CML::espa%C3%A7os-verdes/explore?location=38.744107%2C-9.159734%2C13.00) (accessed on 5 November 2021). Lisbon's Municipality database on PGA and ST includes a list of the sites that correspond to PGA and ST, and their respective areas, which were determined based on field observations. Using the list of the sites that correspond to PGA, it was possible to attribute each PGA site to its respective parish and calculate the PGA per person at the parish scale. The UGI cover was estimated based on the Normalized Difference Vegetation Index (NDVI) calculated from multispectral satellite images at the city and parish scales.

Satellite Image Analysis and Mapping

To calculate the NDVI, we used satellite images made freely available by the United States Geological Survey—USGS (https://www.usgs.gov/) (accessed on 9 September 2020). The satellite images were selected through the Earth Explorer Imaging Division catalogue, using the spatial reference Datun: WGS 84/EPSG: 4326. Since the peak of biological activity in Mediterranean climate regions occurs during spring, we selected satellite images taken during this season. Furthermore, as photosynthetically active vegetation absorbs a large fraction of radiation in the red region (630–690 nm) due to the chlorophyll, and reflects a large fraction in the near-infrared region (760–900 nm) due to the cellular structure of the leaves, using satellite bands 3 and 4 allows an estimate of the active vegetation. The criteria for selecting the satellite images were low cloud cover, taken during springtime in the Northern Hemisphere, with spatial resolution (PAN) of 15 m to Landsat 7–8, and using the spectral bands 3 (near-infrared—NIR) and 4 (red—RED). Although the original Landsat 7–8 satellite images had a 30 m resolution, using the panchromatic band increased their resolution to 15 m. Therefore, we reassembled the image pixels for 15 m resolution and corrected the images geometrically. Applying the abovementioned criteria, the satellite image used to calculate the NDVI in 2010 was taken on 25 April 2010, and the one for 2020 was taken on 22 May 2020.

After the necessary atmospheric corrections the Geography Information System (GIS) converted digital image levels (ND) to radiance [33,34], after which the images were submitted to atmospheric correction using the DOS (dark object subtraction) method [34,35]) and the clipping of the area of interest (using the vector boundaries provided by Lisbon Municipality), we calculated the NDVI using bands 3 and 4 from Landsat 7–8 combined with the Geographic Information System (GIS) to estimate the area occupied by Lisbon's vegetation according to Moreno et al. [30]. NDVI was calculated as follows [36–38]:

$$NDVI = (NIR - RED)/(NIR + RED)$$

NIR is the reflectance at the wavelength corresponding to near-infrared (band 4), and RED is the reflectance at the wavelength corresponding to red (band 3).

The NDVI values vary between −1.0 and +1.0, with healthy, active, and dense vegetation presenting NDVI values above 0.5, while NDVI values within the range of 0.2–0.5 indicate scarce vegetation and/or associated with a low-activity plant phenophase [39]. Therefore, and considering that the satellite images were taken in spring and based on the analysis of the histogram distribution of the NDVI values, we used 0.44 as the NDVI cut-off value.

The raw NDVI values (obtained from the satellite images) were further calibrated with field validation by using 98 sample points spread across the city of Lisbon to confirm that it was vegetation (we used Garmin eTrex® 30× GPS and Canon SX540 HS digital camera—20.3 megapixels). The selected satellite images were reclassified using the ArcGIS 10.2 program. After the calibration, the pixels considered for estimating the UGI cover comprised fragments of native and exotic vegetation in built or unbuilt areas, formed by the afforestation of streets and squares, parks, gardens, vacant lots, and backyards, and even isolated tree canopies big enough for classifier recognition according to the spatial resolutions of the images. After the NDVI requalification, the UGI cover was estimated for the city and for each parish.

2.3. Urban Vegetation Indicators and Calculations

As previously mentioned, Lisbon's Municipality database on PGA and ST included a list of the sites that correspond to PGA and ST, and their respective covers. Therefore, we simply calculated the cover occupied by the different components of PGA and ST for the city and of PGA for each parish. The sum of the PGA components for each parish, and consequently for Lisbon, are presented in Table S2, which also includes the sum of the ST components for the city. The UGI cover was estimated based on the Normalized Difference Vegetation Index (NDVI) calculated from satellite images and validated with field data. PGA, ST, and UGI covers were calculated for 2010 and 2020 (Table 1).

Table 1. Changes over 2010 and 2020 in the indicators for the urban vegetation categories at the city scale. The right-most column shows the variation between 2010 and 2020 for each parameter; grey shading in this column shows the decreases in the vegetation indicators (please see Section 2). Shading colors in the 2010 and 2020 columns reflect whether the value is above or below the respective minimum recommended value (please see Section 2).

Indicator		2010	2020	Δ (2020–2010)
Urban vegetation	Based on PGA	5,802,308 m²	5,712,700 m²	↓ 2%
	Based on ST	414,247 m²	570,658 m²	↑ 38%
	Based on UGI	32,235,682 m²	33,818,324 m²	↑ 5%
Urban vegetation per resident	Based on PGA *	10.6 m² pers⁻¹	10.3 m² pers⁻¹	↓ 3%
	Based on ST	0.8 m² pers⁻¹	1.0 m² pers⁻¹	↑ 37%
	Based on UGI	58.9 m² pers⁻¹	61.5 m² pers⁻¹	↑ 4%
% of Urban vegetation	Based on PGA	6.9%	5.7%	↓ 17%
	Based on ST	0.5%	0.6%	↑ 16%
	Based on UGI *	38.2%	33.8%	↓ 12%

* Identifies the urban vegetation category for which the indicator was developed and for which minimum values have been suggested.

Based on the urban vegetation covers, we calculated the following indicators, for the years 2010 and 2020, for the city derived from PGA, ST, and UGI as follows:

$$\text{Urban vegetation per resident } (m^2\,person^{-1}) = \text{urban vegetation cover } (m^2)/\text{number of residents}$$

$$\text{Urban vegetation } (\%) = \text{urban vegetation cover } (m^2)/\text{total area } (m^2) \times 100$$

Based on the values of the vegetation cover per person for 2010 and 2020, these were categorized (Table 1 and Figure 3) as:

(i) Low when the values were <12 m² person⁻¹ (shaded in red in Table 1 and shaded in red and yellow in Figure 2);
(ii) Adequate when the values were >12 m² person⁻¹ (shaded in green in Table 1 and shaded in different green intensities in Figure 3; the more intense the green, the higher the PGA per person value).

Based on the values of the % of vegetation for 2010 and 2020, these were categorized (Table 1 and Figure 3) as:

(i) Low when the values were <5% (shaded in red in Table 1 and Figure 3);
(ii) Intermediate when the values were >5% but <30% (shaded in orange in Table 1 and shaded in yellow and light green in Figure 3);
(iii) Adequate when the values were >30% (shaded in green in Table 1 and shaded in two more intense greens in Figure 3; the more intense the green, the higher the % of UGI).

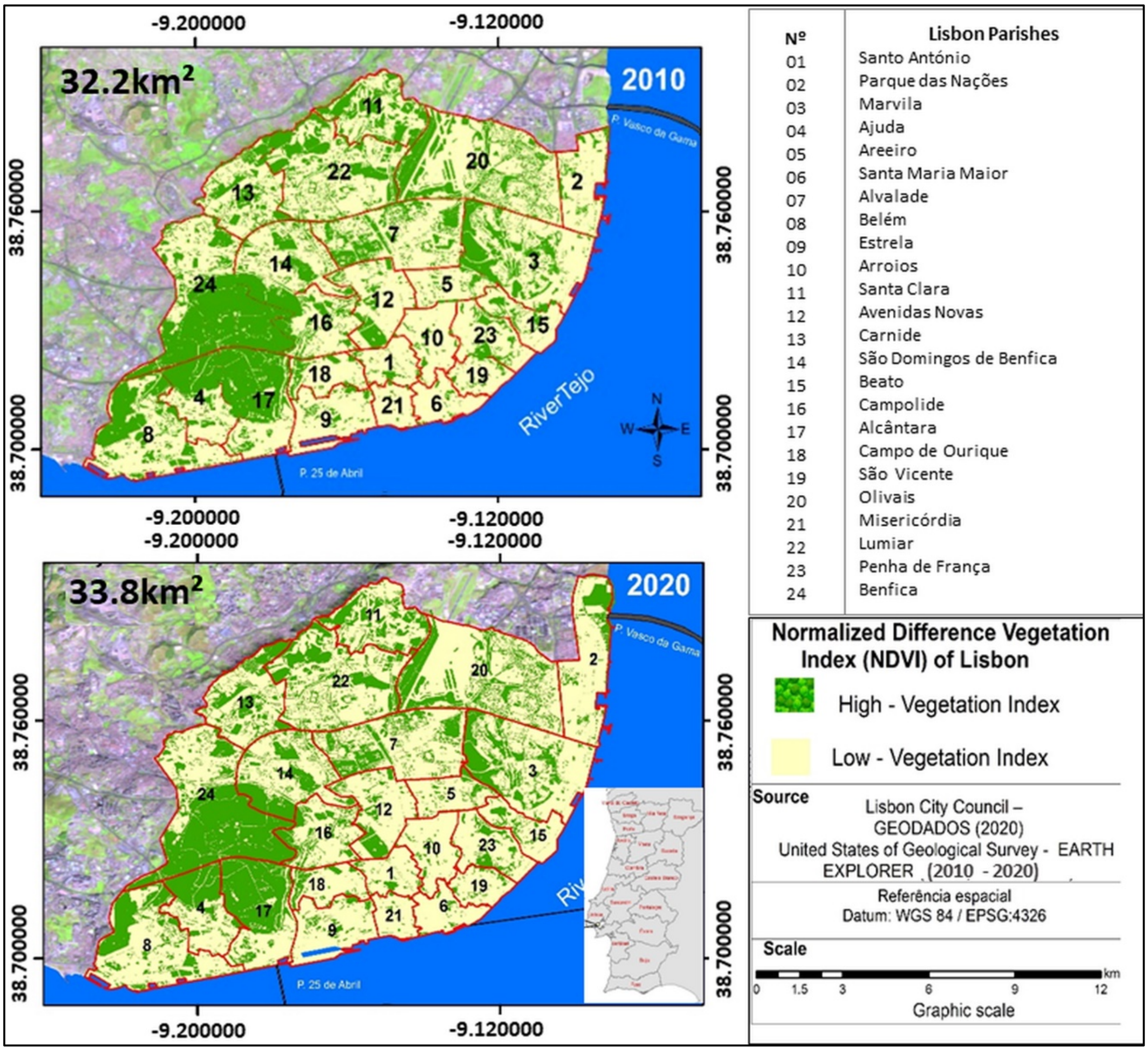

Figure 2. Lisbon's UGI cover (km²) for 2010 and 2020. Lisbon's UGI cover was estimated from the NDVI obtained from Landsat 7–8 images, using the spectral bands 3 (near-infrared) and 4 (red), with a spatial resolution (PAN) of 15 m.

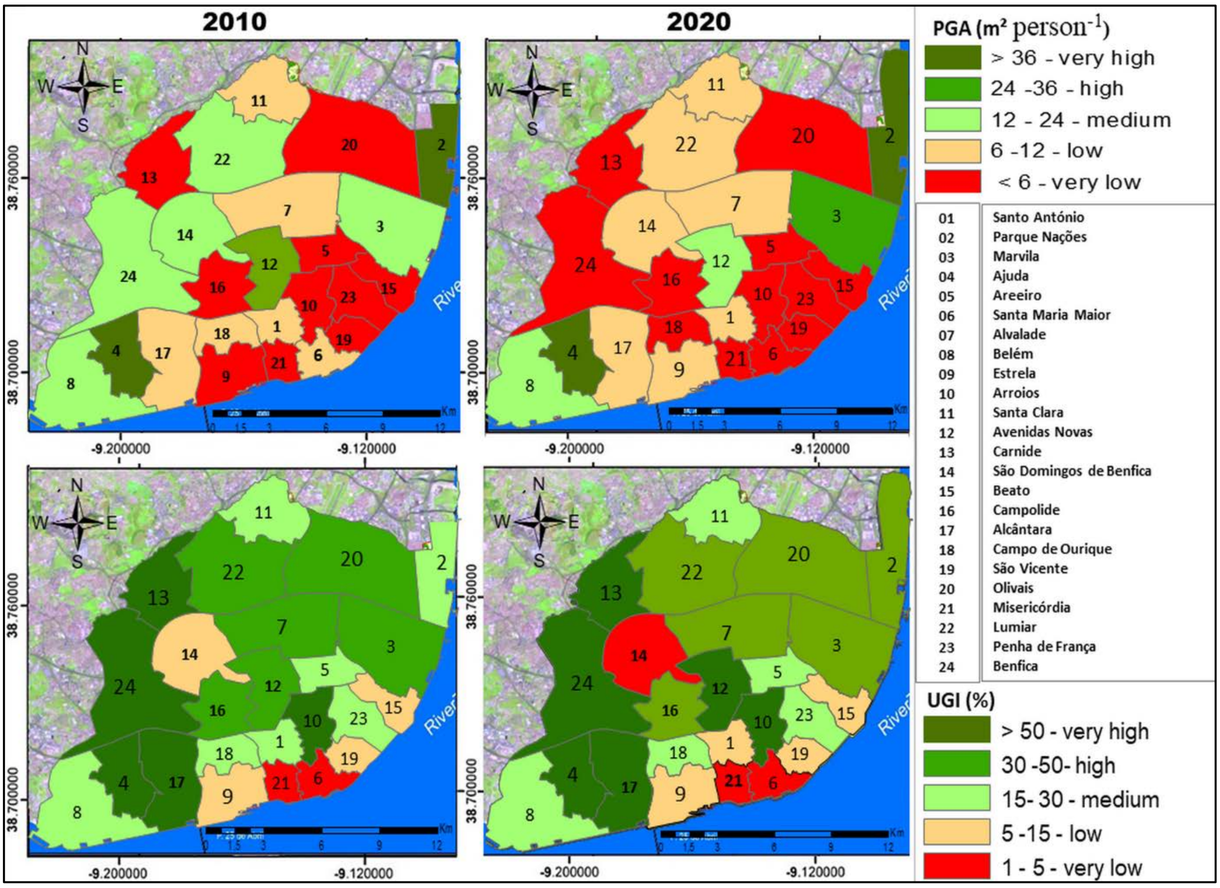

Figure 3. Lisbon's vegetation indicators at the parish scale for 2010 and 2020: PGA per resident (maps in the upper line) and % of UGI (maps in the lower line).

To assess the indicators' temporal changes between 2010 and 2020, we made the following calculation:

$$\Delta_{2020\text{–}2010}\ (\%) = (\text{parameter}_{2020} - \text{parameter}_{2010})/\text{parameter}_{2010} \times 100$$

To test our hypothesis that the older and more central parishes will have lower values for the indicators, and given that the urban vegetation indicators were developed for specific urban vegetation categories (the green areas per resident focused on PGA [26] while the urban vegetation senso lato focused on UGI [28]), we further calculated the PGA per person and the % of UGI at the parish scale, and their changes over time.

3. Results

3.1. Changes in Lisbon's Vegetation Cover: City Scale

Between 2010 and 2020, the only urban vegetation category that decreased its cover (i.e., area in m^2) was the PGA (2% decrease in relation to 2010—Table 1). The UGI cover showed a slight increase (+5%), while the ST cover showed a big increment (+38%). These changes in the covers of the urban vegetation categories occurred concurrently with Lisbon's expansion (+ 35.5 ha).

When considering the vegetation cover per person for the three urban vegetation categories, we observed that between 2010 and 2020 (Table 1), (i) the values of PGA per resident decreased slightly (−3%) with an overall value below the minimum one (<12 m^2 person^{-1}), (ii) despite the largest increase within the urban vegetation categories (+37%), the values of street trees (ST) per resident were well below the minimum value ($\leq$1 m^2 person^{-1}), and (iii) the values of the UGI per resident increased slightly (+4%) with overall values well above the minimum value, and above 50 m^2 per resident in both years.

Finally, when considering the % cover for the three urban vegetation categories, we observed that between 2010 and 2020 (Table 1), (i) the values of % of PGA decreased 17%, with values below 10% and close to the minimum value (5% of PGA) in both years, (ii) despite the 16% increase, the values of % of ST were well below the minimum (values < 1%) in both years, and (iii) despite the 12% reduction, the % of the UGI showed values above the adequate value (>30%).

3.2. Changes in Lisbon's Vegetation Cover: Parish Scale

In 2010, only eight parishes showed values of PGA per resident above the minimum value (>12 m^2 $person^{-1}$), while 16 parishes showed values of PGA per resident below the minimum value (from those, 10 parishes showed very low values of PGA per resident—<6 m^2 $person^{-1}$) (Figure 3). In 2020, even fewer parishes showed values of this indicator above the minimum value (only 5 parishes), and 19 parishes showed values of PGA per resident below the minimum value (from those, 12 showed very low PGA per resident—<6 m^2 $person^{-1}$). Considering the changes between 2010 and 2020 in the PGA per person (Table 2), we observed (i) a decrease in 14 and (ii) an increase in 10 parishes. Campo de Ourique and Santa Maria Maior were the parishes that showed the largest reductions in the PGA per person (−94% and −80%, respectively), while Parque das Nações was the parish that showed the largest increase in the PGA per person (+1600%). Therefore, the urban vegetation available for residents' use decreased at the parish scale (Table 2 and Figure 3), while at the city scale it decreased or increased according to the urban vegetation category being considered (Table 1).

Table 2. Variation between 2010 and 2020 in parishes' PGA per person and % of UGI (please see Section 2). The variation values were calculated based on Table S2 for PGA per person, and Table S3 for % of UGI. Grey shading shows the parishes where we observed a decrease in the vegetation indicators.

Parish	Changes in PGA $Person^{-1}$ (Δ (2020–2010)/2010)	Changes in the % of UGI (Δ (2020–2010)/2010)
Ajuda	↓ 26%	0%
Alcântara	↓ 39%	↑ 7%
Alvalade	↓ 22%	↓ 4%
Areeiro	↑ 68%	0%
Arroios	↑ 140%	0%
Avenidas Novas	↓ 32%	↑ 9%
Beato	↑ 11%	0%
Belém	↑ 18%	↓ 10%
Benfica	↓ 65%	↑ 2%
Campo de Ourique	↓ 94%	0%
Campolide	↓ 4%	↑ 10%
Carnide	↑ 30%	↓ 2%
Estrela	↑ 170%	↑ 20%
Lumiar	↓ 58%	↓ 2%
Marvila	↑ 59%	↓ 3%
Misericórdia	↓ 51%	0%
Olivais	↑ 46%	↓ 7%
Parque das Nações	↑ 1607%	↑ 170%
Penha de França	↓ 36%	↑ 14%
Santa Clara	↑ 7%	↓ 4%
Santa Maria Maior	↓ 80%	0%
Santo António	↓ 22%	↓ 25%
S. Domingos de Benfica	↓ 40%	↓ 15%
São Vicente	↓ 6%	0%

From the 24 parishes that constitute the city of Lisbon, almost half presented values of % of UGI > 30% in both years (i.e., 11 parishes in 2010 and 12 in 2020 presented adequate values of % of UGI—Figure 3). Only two parishes (Misericórdia and Santa Maria Maior) showed values of % of UGI below the minimum value (<5%) in 2010. In 2020, there was an additional parish (São Domingos de Benfica) showing a % of UGI below the minimum value. In both years there were four parishes with low values of % of UGI (between 5% and 10%). The parish with higher values of % of UGI was Benfica (>70% in both years—Table S3).

Considering the changes between 2010 and 2020 in the % of UGI (Table 2), we observed (i) a decrease in nine parishes; (ii) no change in eight parishes; and (iii) an increase in seven parishes. Santo António was the parish that showed the biggest reduction in the % of the UGI (−25%), while Parque das Nações was the parish that showed the biggest increase in the % of the UGI (+170%). Altogether, the values of the % of urban vegetation decreased in most parishes and in the city (Figures 2 and 3 and Table 2) for all urban vegetation categories (Table 1).

4. Discussion

By measuring the changes in Lisbon's vegetation cover between 2010 and 2020, our study clearly shows that Lisbon lost public green areas (PGA) over that timeframe. Furthermore, and despite the gain in urban green infrastructure (UGI) cover, the concomitant territorial expansion resulted in a reduction in the % of UGI. Finally, ST cover expanded considerably, but this urban vegetation category occupies a small area compared to PGA and UGI.

While the values of the PGA per person were below the recommended minimum value, Lisbon performed well in terms of % of UGI. Finally, as hypothesized, some of the older and central parishes showed a deterioration of the indicators' PGA per person and the % of UGI.

4.1. Changes in Lisbon's Vegetation between 2010 and 2020

Both the overall gain in ST and UGI covers, and the overall loss in PGA cover (Table 1), in Lisbon reflect the balance between losses and gains (Figure 2). Several factors contributed to the vegetation losses, namely:

(i) The reduction of urban vegetation due to land use changes: 13% less naturalized areas due to abandonment, 14% less natural vegetation due to the recovery of the Portuguese Navy in Parque das Nações, 1% less due to the reduction of vegetable gardens and undifferentiated agriculture and some illegal gardens, and the deforestation of eucalyptus trees in the airport region [40]. Furthermore, there was an increase in the built-up area. Although in 2010 Portugal was experiencing a serious economic crisis, in the 2010–2020 decade there was an economic recovery and consequent stimulus of the real estate market in Lisbon. Proof of this is the fact that in 2020 there was a 154% growth in the number of completed buildings in the Lisbon Metropolitan Area compared to 2015 [41]. This increase in completed buildings will have forced, in many cases, the conversion of green spaces (e.g., natural and semi-natural areas) into urbanized areas.

(ii) The precipitation reduction which, in a Mediterranean climate city such as Lisbon, greatly affects plant growth and survival. While 2010 was the wettest year in Lisbon since records began [42], the decade 2011–2020 was the second-driest in mainland Portugal since 1931. Although the rainfall in 2020 reached 85% of the normal value [43], it is likely that the low precipitation between 2010 and 2020 affected plant growth and survival, which may have contributed to a reduction in urban vegetation, and to lower estimates of the UGI area.

ST was the urban vegetation category that showed the largest gain in its cover (Table 1), reflecting many municipal actions targeting biodiversity and climate change adaptation and mitigation. As an example, Lisbon has been requalifying public spaces with trees [44], and the city is implementing an international project that will result in planting 4000 trees in the streets of Lisbon and another 240,000 in green areas (https://life-lungs.lisboa.pt/en/actions/planting-trees-and-shrubs) (accessed on 13 September 2022). Indeed, contributing to the vegetation gains, during this period there was a 13% increase in areas with semi-natural vegetation, and a 4% increase in areas that were naturalized by municipal management [40]. This vegetation gain occurred in some parishes, with particular emphasis on Parque das Nações, which had a 170% increase in its UGI cover compared to 2010 (Table 2 and Figure 3). This vegetation expansion resulted from the urban expansion of this parish of 35.5 ha (Table S2), and from several revegetation measures, including new central green spaces (21.4 ha), road framing (7.3 ha), and new local green spaces (5.2 ha) [40]. Part of these new green spaces are due to the implementation of the Ribeirinho urban green corridor [45]. Lisbon's landscape experienced several changes in this 10-year period to promote urban sustainability, in particular the implementation of the nine urban green corridors network (accounts for a total of 1942 ha [20]), which resulted in i) the implementation of 33 new areas of green spaces (+139.3 ha) and ii) the restructuring of 97.7 ha of existing green spaces [45]. Although in spring 2020 most of the urban green corridors network was completed, or only some fragments were still being completed, the majority of its implementation was carried out in recent years [20]. Therefore, it is expected that as the planted shrubs and trees grow, the urban green corridors network will contribute even more to the UGI cover estimated from the NDVI. Lisbon's urban green corridors were designed to improve urban mobility, and to promote environmental quality and people's wellbeing [45,46]. Recently, it was shown that the most frequented green corridors are the "greener" ones (i.e., those with more abundant trees and shrubs). The Ribeirinho urban green corridor, which contributed to increase of the % of the UGI in Parque das Nações, is also the most used by residents and tourists [20].

As hypothesized, the older and central parishes showed very low values of urban vegetation, especially of PGA (e.g., % of PGA < 1%—Campo de Ourique, Carnide, Misericórdia, Penha de França, and São Vicente) (Table S2) and, as they are quite populous, they also showed very low values of urban vegetation per resident (e.g., <1 m^2 of PGA $person^{-1}$). Although these parishes lack vegetation, the prospects of implementing new green spaces are reduced due to lack of space. Even the implementation of street trees is not likely an option because the streets and sidewalks are very narrow in these areas of the city [40,45]. However, there are alternatives that could contribute to bring nature (and all its benefits) back to these areas of the city. Indeed, public spaces' requalification can be a good approach, as shown by the example of urban requalification of Praça Duque de Saldanha and Avenida da República in Lisbon, where the partial replacement of traffic roads by new pedestrian zones and green areas had a positive impact on the thermal comfort [44]. In addition, green roofs have been shown to restore ecosystem services [47], and vertical gardens also promote psychological wellbeing [48] and can reduce cities' ecological footprint when integrated into urban agriculture systems [49]. Despite the enormous advantages that these green alternatives provide, there are still significant inconsistencies between political ambition and their in situ implementation [47].

While Lisbon performed well in terms of % of UGI (Table 1 and Figure 2), the values of PGA per resident in 2010 and in 2020 were below the minimum recommended value (12 m^2 $person^{-1}$—proposed by Matias and Caporusso [26] and adapted by Lucon et al. [27]) at the city scale (Table 1) and in most parishes (Figure 3). Despite the relative loss of vegetation in Lisbon, we did not observe a greater deterioration of this PGA per resident (Table 1) because Lisbon's population only increased ~1% between 2010 and 2020 (547,733 residents in 2010 and 552,704 residents in 2020—Table S2). For the indicator PGA per resident to improve, or to reach at least the minimum value, the PGA cover would have to increase and/or the population decrease. As previously mentioned, the increase in the built-up area [41] driven by the slight population growth, and especially the tourists' growth and the economic recovery, are not likely to favor an increase in the PGA cover.

Therefore, it would be important to understand to which extent the other urban vegetation categories (ST and UGI) could meet the recreational functions associated with the PGA and contribute to improve Lisbon's social equity in the access to green spaces.

To understand whether Lisbon's recent changes in vegetation cover follow a generalized European trend, we compared the changes in the natural and semi-natural vegetation in Lisbon's metropolitan area between 2012 and 2018 with those of other European cities (Berlin, Madrid, Milan, and Paris). For that, we consulted the Copernicus Urban Atlas (https://land.copernicus.eu/local/urban-atlas) (accessed on 20 December 2021). The changes in the natural and semi-natural vegetation in the five European metropolitan areas between 2012 and 2018 were very similar and very small (<1%), which suggest that Lisbon's recent vegetation changes follow a generalized European trend to preserve urban vegetation. However, given Lisbon's efforts and ambition to be distinguished as the 2020 European Green Capital, it is important that these "greening" measures and policies are sustained in the future. On the other hand, it is important to keep in mind that these five metropolitan areas differ significantly in the areas with natural and semi-natural vegetation: almost 40% of the land in Berlin's metropolitan area corresponds to natural and semi-natural vegetation, followed by approximately 36% in Lisbon's and Madrid's metropolitan areas, then 21% in Paris' metropolitan area, and, finally, less than 7% in Milan's metropolitan area, with important consequences for the environmental quality and wellbeing of their respective populations. Indeed, despite the lack of vegetation (as shown by less than 7% of areas with natural and semi-natural vegetation), Milan is gaining the reputation of a sustainable city (e.g., [50]), which shows how marketing and publicity can shade the discrepancy between the reality and the perceived reality.

4.2. How Can We Measure Changes in Urban Vegetation Cover?

Although this question (how can we measure changes in urban vegetation cover?) may seem trivial, answering it brought about numerous questions, namely, what type of urban vegetation to consider:

(i) Only public areas to which all citizens have access: This would exclude private zones that could provide numerous environmental and human wellbeing benefits [51,52]. However, only the status of public green space (i.e., PGA and ST) guarantees access for the entire population, and in accordance, the PGA category was used to define the green areas per resident indicator [26].

(ii) Only vegetation with maintenance: This would exclude the natural and semi-natural vegetation which strongly contributes to the UGI, and plays important ecosystem benefits and services, namely, in climate change adaptation and mitigation [53–55], and in accordance, this category was used to define the % of urban vegetation [28]. However, people prefer green spaces that are not too "wild" and with spaced trees [56] so that the areas with natural and semi-natural vegetation may not meet the necessary conditions of perceived safety and comfort necessary for recreational use and for some social groups (e.g., children, elderly, or people with reduced mobility).

As the different urban vegetation categories have different main functions (e.g., the PGA stands out in the recreational function while the UGI stands out in ecological functions—Figure 1), we consider that to measure the changes in urban vegetation we must consider more than one urban vegetation category. Additionally, as observed in Lisbon between 2010 and 2020, the covers of the different urban vegetation categories may follow different trends (Tables 1 and 2 and Figures 2 and 3).

On the other hand, it is necessary to establish, for each urban vegetation category, a qualitative scale that relates intervals of values with categories (i.e., low, medium, high). The definition of the minimum value of PGA per resident is an example of this effort: in Brazil it started with 15 m^2 $person^{-1}$ [57] and was later adapted to 12 m^2 $person^{-1}$ (proposed by Matias and Caporusso [26]). Although we made a suggestion in our study (Table

1 and Figure 3), the intervals that establish medium and high quality for this indicator are not defined, and other categories of urban vegetation, such as the UGI, are not considered.

To establish environmental quality indicators based on urban vegetation, it is also necessary that the values are proportional to the spatial scale of each urban vegetation category. For example, 30% can be considered adequate [28] for the UGI, but not for PGA, since no city would be able to have 30% of its area occupied by public green areas (parks, squares, gardens). Finally, given the role of urban vegetation in environmental quality and human wellbeing, we consider that for these recommended values (e.g., PGA per person and % of UGI) to ever be given a legal status, international organizations (e.g., the World Health Organization and the United Nations) should be involved in the urban vegetation measurement standardization and categorization.

5. Conclusions

Despite the measures to promote urban sustainability (as evidenced by the distinction of the 2020 European Green Capital, and the observed gain in the ST and UGI covers), over the last decade Lisbon has lost urban vegetation in terms of PGA. Furthermore, the urban vegetation indicators (area of urban vegetation per resident and % of urban vegetation) showed an overall reduction within the studied timeframe. Even the indicators derived from the UGI deteriorated due to the concomitant urban expansion, which diluted the gain in this urban vegetation category. Most of Lisbon's parishes (especially the older ones located in the city center) showed values of PGA per resident below the minimum recommended value of 12m^2 PGA person^{-1}, and some parishes showed values of % of UGI below the minimum recommended value of 5%. This information is important to prioritize measures that promote environmental quality, human wellbeing, and social equity to the population of those parishes. Our study raised many open questions, which led us to suggest the need to standardize the methods for measuring the urban vegetation changes. This standardization effort should be carried out under the "umbrella" of international organizations (e.g., World Health Organization, United Nations).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912112/s1, Table S1—List of the 24 parishes that currently comprise the city of Lisbon, and the changes that occurred in relation to 2010. Table S2—Characterization of the parishes that comprise the city of Lisbon in 2010 and 2020. Table S3—Changes over 2010 and 2020 in parishes' % of UGI.

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