Science of the Total Environment 724 (2020) 138182

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Using green to cool the grey: Modelling the cooling effect of green spaces with a high spatial resolution

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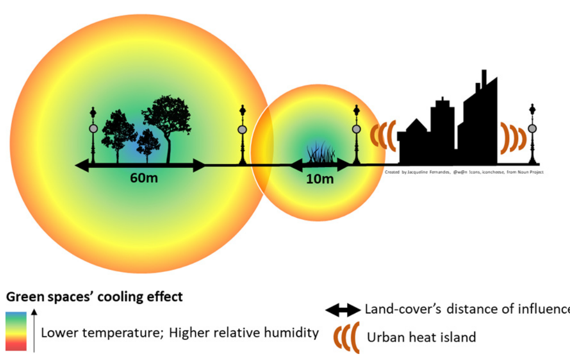
HIGHLIGHTS

- Urban planning needs high spatial resolution information to mitigate the urban heat island effect.
- Land-cover type (green and grey spaces) and urban morphology strongly influence the cooling island effect.
- Parks with high density of trees reduce temperature (1-3° C) and increase relative humidity (2-8%) mostly during summer.
- Tree canopy area influences temperature and relative humidity as far as 60 m.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 December 2019
Received in revised form 3 March 2020
Accepted 23 March 2020
Available online 25 March 2020

Editor: Elena Paoletti

Keywords:
Artificial areas
Urban green infrastructure
Land-cover
Nature-based solutions
Urban heat island
Urban microclimate

ABSTRACT

The urban heat island effect creates warmer and drier conditions in urban areas than in their surrounding rural areas. This effect is predicted to be exacerbated in the future, under a climate change scenario. One way to mitigate this effect is to use the urban green infrastructure as a way to promote the cooling island effect. In this study we aimed to model, with a high spatial resolution, how Mediterranean urban parks can be maximized to be used as cooling islands, by answering the following questions: i) which factors influence the cooling effect and when?; ii) what type of green spaces contributes the most to the cooling effect?; iii) what is the cooling distance of influence? To answer these questions we established a sampling design where temperature and relative humidity were measured in different seasons, in locations with contrasting characteristics of green and grey cover. We were able to model the effect of green and grey spaces in the cooling island effect and build high spatial resolution predicting maps for temperature and relative humidity. Our study showed that even green spaces with reduced areas can regulate microclimate, alleviating temperature by 1–3 °C and increasing moisture by 2–8%, on average. Green spaces with a higher density of trees were more efficient in delivering the cooling effect. The morphology, aspect and level of exposure of grey surfaces to the solar radiation were also important features included in the models. Green spaces influenced temperature and relative humidity up to 60 m away from the parks' limits,

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https://doi.org/10.1016/j.scitotenv.2020.138182

whereas grey areas influenced in a much lesser range, from 5 m up to 10 m. These models can now be used by citizens and stakeholders for green spaces management and human well-being impact assessment.

1. Introduction

The expansion of urban populations leads to the continued growth and development of urban areas (United Nations, 2018). This development is destroying and/or fragmenting natural and seminatural habitats with consequent loss of biodiversity and ecosystem services, which in turn affects human well-being (Alig et al., 2004; Grimm et al., 2008). These urban areas then become novel ecosystems, where impermeable surfaces and artificial barriers (e.g. roads and buildings), grey spaces, intersperse with small and isolated patches of green spaces (Voogt and Oke, 2003). Among other environmental problems that cities face, the urban heat island effect negatively interferes with both biodiversity and human well-being (Gill et al., 2007; Grimm et al., 2008).

The urban heat island effect is a climatic phenomenon characteristic of urban areas that creates warmer and drier conditions in cities than their surrounding rural areas (Oke, 1982). This effect is caused by the urban geometry and the nature of its materials. For example, asphalt and concrete absorb and store solar radiation during the day, which is slowly released at night (Ahmed Memon et al., 2008). Thus, the climatic urban heat island is usually more intense at night than during the day, being more pronounced during winter than summer, and more apparent in periods with little wind (Oke, 1982). However, the impacts of this effect in the socio-ecological system are stronger during summer (Ahmed Memon et al., 2008; Ward et al., 2016). This effect can be further exacerbated by climate change, which increases the magnitude and intensity of the heat island's adverse effects (Feyisa et al., 2014). In urban areas, these negative effects consist of consequences for biodiversity management, such as higher and more frequent demands for irrigation (Nouri et al., 2013) and the spread of some pests (Tubby and Webber, 2010). Other negative effects include consequences for citizens' thermal comfort and health, in particular children, elders, and citizens with health problems, leading to, for instance, respiratory and cardiovascular problems. Thus, the current and further exacerbated urban heat island effect is a major challenge that needs to be managed in urban areas (Hamstead et al., 2018; Madrigano et al., 2015; Salata et al., 2017; Yang et al., 2013).

One way to mitigate the impact of the urban heat island effect is to use the urban green infrastructure (Feyisa et al., 2014; Oliveira et al., 2011; Susca et al., 2011), defined as the multifunctional network of green spaces that provide multiple environmental, social and economic benefits to urban areas (Pauleit et al., 2017). This is seen as a key nature-based solution for the urban heat island effect, climate change mitigation and resilience in cities (Keeler et al., 2019). Natural-based solutions supported by vegetation avoid heat build-up by creating shadows and increasing relative humidity through evapotranspiration (Voogt and Oke, 2003). Other added values of urban green spaces are the reduction of air pollution and noise levels (Fang and Ling, 2005; Matos et al., 2019; Yin et al., 2011), carbon storage (Ren et al., 2011) and acting as habitat for biodiversity (Pinho et al., 2016), among other important ecosystem services (Gomez-Baggethun et al., 2013; Keniger et al., 2013; Munzi et al., 2014). However, different types of green spaces provide a different proportion of ecosystem services (Mexia et al., 2018; Vieira et al., 2018) and consequently not all green spaces are likely to provide the same level of mitigation to the urban heat island effect.

At an urban level, the effects of temperature reduction and relative humidity increase provided by the urban green infrastructure are often referred to as the urban cool island effect (Shashua-bar et al., 2009), with authors suggesting that the urban heat island effect can be mitigated by effective landscape planning and management (e.g. Du et al., 2017; Norton et al., 2015). Furthermore, this cooling effect can also be observed at a local scale, with studies showing that a single park can reduce temperature from 1 °C to 7 °C, depending often on its physiognomies (Georgakis and Santamouris, 2017; Lu et al., 2017; Oliveira et al., 2011). Although this cooling effect has been previously mechanistically modelled (e.g. Oliveira et al., 2011), empirical models are also necessary, since they provide not only the ground truth for such mechanistic models, but also the way to understand which factors influence the magnitude of the cooling effect. These models are related not only to green space characteristics, such as park's area and vegetation structure, but also to season period, time of the day and amount of solar radiation under specific types of macroclimate (Aram et al., 2019; Fan et al., 2019; Oliveira et al., 2011; Yu et al., 2018). Besides the parks' cooling capacity within their boundaries, urban green spaces are also able to influence their surrounding areas (Aram et al., 2019). All previous factors might interact with each other giving eventually contrasting outcomes in terms of the cooling effect. Thus, it is necessary to have empirical models in order to understand, in a detailed way, the amount of green area and the type of vegetation structure that maximizes the cooling effect under certain background macroclimates.

In terms of studying vegetation as a cooling tool, most works have only valued changes in temperature, measured either in situ or by remote sensing (Aram et al., 2019) and only few studies have measured relative humidity, a variable with large implications in not only the performance of biodiversity, but also on human thermal comfort. For instance, Hamada and Ohta (2010), despite showing the results of daily specific humidity measured in 24 sensors in Nagoya, Japan, failed to discuss their relevance for the urban heat island effect. In Mediterranean urban areas, summer months are particularly important to measure both temperature and humidity (Cohen et al., 2012). In fact, some studies developed in Mediterranean climate areas, such as Cohen et al., 2012 and Skoulika et al., 2014, addressed both parameters. However, in the first work, several parks were studied using just one measurement site for each park, whereas in the second work, the authors did not value the area's relative humidity, since it presented almost uniform results in the studied park, with differences rarely exceeding 5–10% between the measuring points.

Most studies on the impact of urban green spaces in the cooling island effect have been carried out in Eastern Asia and their results cannot be generalized to other regions (Aram et al., 2019). Also, most of these studies are focused either on large and central parks or medium-sized parks, and smaller and local green spaces have been largely overlooked (Aram et al., 2019). Another important issue for the management of the urban green infrastructure is the effect that green spaces have beyond their borders on microclimate, with previous works showing either no effects or effects up until 330 m (Aram et al., 2019). Although it is known through several works that larger parks provide cooling effects, the few existing works on small parks have already demonstrated the noticeable cooling effect within these parks and their surroundings (Park et al., 2017), which indicates the necessity of further research into this matter (Aram et al., 2019). Therefore, modelling green spaces' effect on temperature and relative humidity with a high spatial resolution, either within parks' boundaries and their surroundings, is still lacking in Mediterranean urban areas.

Recent papers highlighted the importance of different qualitative and quantitative green spaces' components (e.g. trees, shrubs, herbs) for the delivery of ecosystem services (Mexia et al., 2018; Vieira et al., 2018), such as climatic regulation (Xu et al., 2017). However, there is still a gap in research literature in order to understand the cool island effect produced by different types of green spaces, in different seasons and beyond their borders. For that, high spatial resolution studies are needed especially in understudied Mediterranean urban areas. This information is key to municipalities and stakeholders to improve management strategies and guide the implementation of nature-based solutions to mitigate the urban heat island effect and to adapt to climate change (Wang et al., 2018).

This study aimed to model, with a high spatial resolution, the cooling island effect of green spaces in Mediterranean urban areas. More specifically, this study asked: which factors influence temperature and relative humidity of green and grey areas? What type of vegetation contributes the most to the cooling effect? What is the distance of influence of green and grey areas? To answer these questions, a sampling design was established, where temperature and relative humidity were measured in different seasons, in locations with contrasting characteristics of green and grey cover (urban matrix) to test the influence of different variables on microclimate.

2. Methods

2.1. Study area

This work was performed in the Almada municipality (38°9.771′N, 9°9.828′W), an urban area of south-west Europe located within the metropolitan area of Lisbon, on the western coast of Portugal (Fig. 1). This city is characterized by a Mediterranean climate, with north and north-western prevailing winds, being bordered by the Atlantic Ocean to west, and by the Tagus river to east and north. It has an area of approximately 70 km^2, being one of the most populated municipalities of Portugal, with about 174,000 habitants (INE, 2012).

To conduct this study, two pairs of green (parks) and grey (squares) areas were selected in Almada's urban core: park "Comandante Júlio Ferraz" (hereby named park A), adjacent to "S. João Batista" square (square A), and park "Municipal da Juventude" (park B), adjacent to square "Largo do Tribunal" (square B) (Figs. 1 and S1). Park A has 2.04 ha and is covered by lawn and scattered trees with large canopies, mainly *Populus nigra* and *Platanus* sp., while park B is smaller (0.49 ha) with a higher density of trees, mainly *Pinus* sp. with large canopies. Square A has 1.11 ha and is covered by concrete and limestone surfaces, with three water features and few aligned trees, while Square B has 0.44 ha with no vegetation and impervious surfaces similar to that of square A (Figs. 1 and S1). Both parks are surrounded by a dense urban matrix of high to low rise buildings. In those buildings and surrounding area (radius of 250 m) reside approximately 10,500 citizens, of which 34% are older than 65 years (INE, 2012).

2.2. Environmental variables

Temperature (in °C) and relative humidity (in %) were measured in the considered parks and squares using 19 microclimate sensors

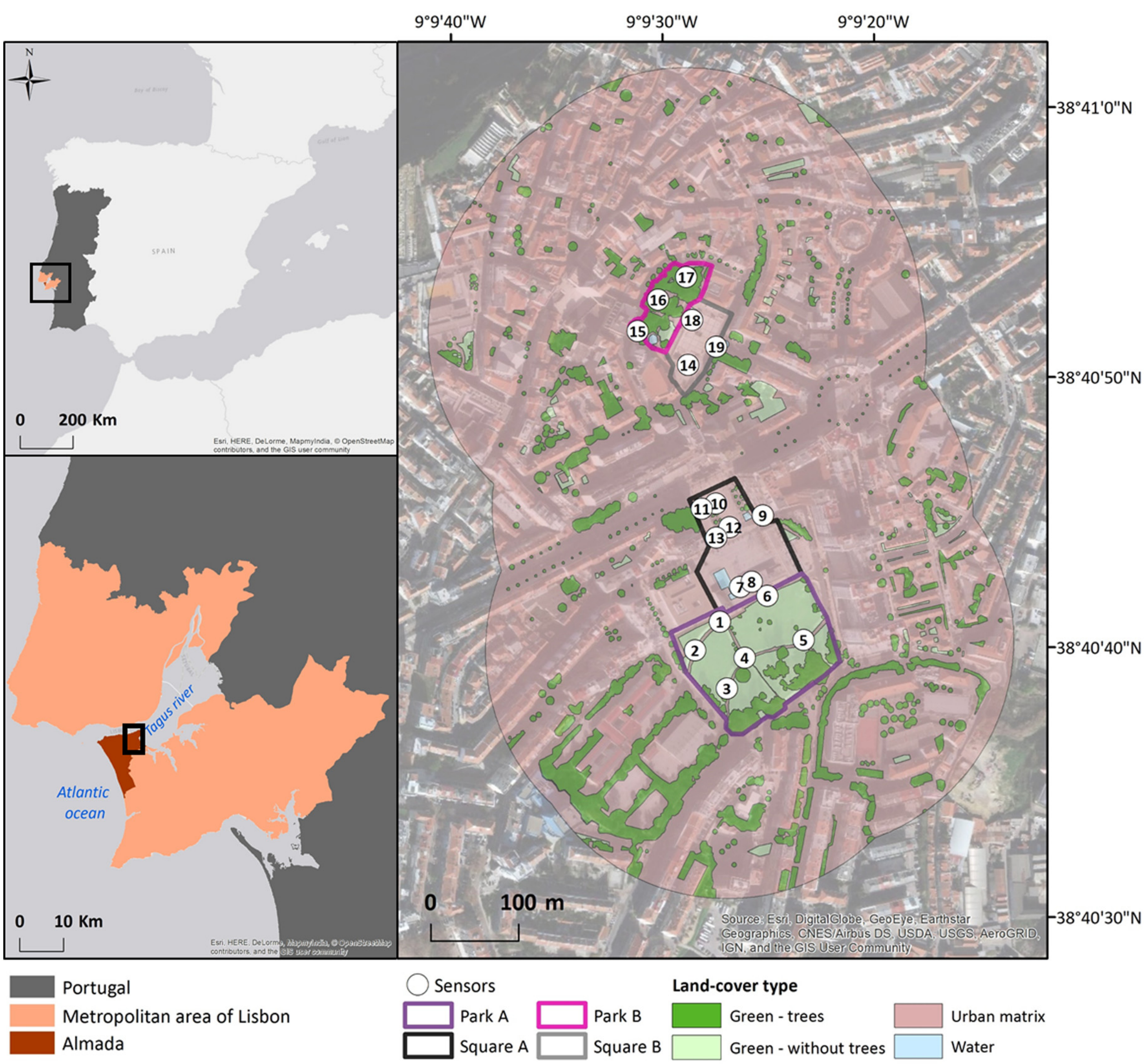

Fig. 1. Location of the study area (Almada municipality, within Lisbon's metropolitan area) showing land-cover type and sensors location. Sensors are numbered from 1 to 19.

coupled with data-loggers (iButtons™), with a stratified distribution per land-use (park/square): 9 in green spaces (6 in park A, 3 in park B) and 10 in grey areas (7 in square A, 3 in square B). These sensors were placed in streetlamps at 3 m height, facing north, being protected with custom-made white vented shields as in Hubbart (2011). These sensors were programmed to collect data every 10 min and reported hourly averages. The sensors were deployed during summer (from August to October 2017) and winter (from December 2017 to March 2018).

Land-use and land-cover types were characterized to understand the influence on microclimatic variables. To do so, a circular area with a 240 m radius centered at each sensor was manually photo-interpreted and classified, using satellite imagery (WorldView-2, available in ArcMap v.10.7.1) with a very high spatial resolution (0.5 m), which has a positional accuracy of 3.5 m (Barazzetti et al., 2016). To detect the influence of land-cover types in climate regulation, a distance of 240 m was considered (Pinho et al., 2008a). Land-cover types were then classified, in circular areas (i.e., buffers) around the sensors, in terms of their potential influence in the microclimate variables: green - trees (tree canopy); green - without trees (shrubs and herbaceous vegetation); water (water features); urban matrix (buildings, roads, sidewalks) (Fig. 1).

The potential solar radiation, a measure of the amount of solar radiation potentially reaching a surface (Kumar et al., 1997), was calculated for the four locations and surrounding areas, in watt-hour/m^2 (WH m^{-2}). This variable is often used as a surrogate of local microclimate (Pinho et al., 2016), and it represents the urban morphology of a given area, with higher values associated with drier and warmer environments. Potential solar radiation was calculated based on a digital surface model with a spatial resolution of 2 m, through the "area solar radiation" tool in ArcMap v.10.7.1 (ESRI), using values of 2018 and monthly intervals. This digital surface model was obtained from elevation contours provided by the Municipality of Almada, and from the cartography of buildings (with heights information) and tree canopy (with an assumption of a mean tree canopy of 6 m height). Once calculated, the potential solar radiation was extracted to each sensor point through the ArcMap software "extract values to points" tool.

The normalized difference vegetation-index (NDVI), often used as a surrogate of vegetation density and cover, was calculated for the entire satellite image, from Sentinel-2A Level-1C multispectral imagery (10 m spatial resolution) from the European Space Agency (downloaded from the USGS website: http://earthexplorer.usgs.gov/) acquired on 14 July 2017. This Sentinel-2A image was atmospherically corrected from Top-Of-Atmosphere (TOA) Level-1C to generate Bottom-Of-Atmosphere (BOA) Level-2A with Sen2Cor plugin (v2.1.2) on the Sentinel Application Platform (SNAP, v5.0.7). In the SNAP software, NDVI was calculated using the following equation:

$$NDVI = \frac{\rho\mathrm{NIR} - \rho\mathrm{Red}}{\rho\mathrm{NIR} + \rho\mathrm{Red}}$$

where ρNIR and ρRed correspond to the reflectances on the near-infrared and red bands, respectively. Once calculated, the NDVI was extracted to each sensor point.

2.3. Data analysis

2.3.1. Distance of influence

To visually interpret the obtained climatic data, an interpolation of the mean temperature and relative humidity was performed using the inverse distance weighted (IDW) interpolation. This interpolator assumes that the weight of each measured point (i.e., local influence) decreases with the distance to the sampling points, being therefore suitable for distance sensitive phenomena, such as studying the cooling capacity of green spaces.

To characterize the relation between microclimate data and land-use type and cover, the area of each land-cover type in the sensors' vicinity was included, using buffers with different radius (5, 10, 15, 30, 60, 120, 150, 200, 240 m). Since the land-cover type "water" showed a similar area for all distances, it was not considered for further data analysis.

The influence of land-cover type in mean temperature and relative humidity of summer, winter, and the average of both seasons, was assessed using Spearman correlation coefficients, relating the area of each land-cover type with microclimate values (Pinho et al., 2008b). The distance (circular area radius) that showed the highest correlation coefficient was considered as the distance of influence of the land-cover in the tested microclimate variable, being used in further analysis. It was assumed that, if the coefficient increases with distance, the newly added areas affect microclimate regulation; if the coefficient decreases or stagnates, these newly added areas are not contributing to microclimate regulation (Pinho et al., 2008a; Pinho et al., 2008b). Correlations were considered significant for p-values < 0.05.

2.3.2. Other data analysis & software used

To model the average temperature and relative humidity in the study area, the explanatory variables were considered as follows: area of each land-cover at the distance of highest correlation; potential solar radiation of extreme month values (summer and winter solstices) of each sensor; NDVI values at the location (pixel) of each sensor. These variables were submitted to a generalized linear model (GLM) with identity link (and normal distribution). All models with any combination of up to two independent variables were considered. The maximum number of independent variables was chosen to take into account the number of independent samples available ($n = 19$), in order to retain a reasonable number of degrees of freedom. The link and distribution were chosen after checking that the shape of the relationship between variables was approximately linear and the residuals followed a normal distribution. From all possible models for each microclimate variable, the best performing model (highest R), for which all participating independent variables presented a significant contribution, was retained. Cross-validation was performed for each of the considered models by removing 10 times five random sensors (approximately 25% of the total number of sensors) and running each model with information for 14 sensors and then applying the model to the five sensors removed. Then, correlations were performed between the observed and predicted microclimatic data for the five sensors removed, and the mean of the ten R^2 was considered as the R^2 of the validation.

Data acquisition, analytical operations, and output maps were performed in ArcMap v.10.7.1 (ESRI). Databases were managed using Excel 356 and statistical analysis was performed in Stata 11.1.

3. Results

Considering both green and grey areas analysed, the highest differences of temperature and relative humidity were found between park and square B (Tables 1 and S1; Figs. 2 and 3). These differences were higher during summer, when park B was, on average, 0.9 °C cooler than the nearby square.

The area covered by trees was significantly correlated with the microclimatic variables for almost all distances, being negatively correlated with the mean summer temperature and positively correlated with summer and winter mean relative humidity (Table 2). Thus, with an increase in tree canopy area, there was a decrease in temperature and an increase in relative humidity. Inversely, an increase in grey areas was related to an increase in temperature and a decrease in relative humidity. The area of green - without trees showed mostly non-significant correlations, and some significant correlations for the largest distances (Table 2). We interpreted these significant correlations as a random event since there is no ecological rationale for explaining a significant influence of small shrubs and grasses at such high distances

Table 1
Mean (and standard deviation) of summer and winter temperature (T) and relative humidity (RH) in the parks and squares analysed (n = number of sensors placed).

Microclimate variables		Park A	Square A	Park B	Square B
		n = 6	*n* = 7	*n* = 3	n = 3
T (°C)	Summer	23.2 (5.1)	23.4 (4.9)	22.3 (4.1)	23.2 (5.2)
	Winter	12.9 (3.0)	13.1 (2.8)	12.5 (2.5)	12.7 (3.0)
RH (%)	Summer	59.7 (19.7)	57.7 (19.2)	61.3 (17.9)	58.9 (19.7)
	Winter	78.9 (15.9)	78.2 (15.8)	81.2 (15.3)	79.3 (16.1)

(150 m and 240 m). Averaging both seasons (summer and winter) showed that, for mean temperature and relative humidity, the correlation pattern was similar to the previous results, although with less significant results than summer and winter separated (Table S2).

The distance from the sensors for which the highest correlation was found between tree canopy area and summer mean temperature and relative humidity was 60 m, suggesting this value as the distance of influence of trees on the mean summer temperature and relative humidity. For shrubs and herbaceous vegetation, the influence distance was 10 m for the summer relative humidity (Table 2).

During the month with the lowest potential solar radiation (December), the two squares received a higher radiation than adjacent parks, due to buildings' shadowing. In the month with the highest potential solar radiation (June), all analysed locations displayed very high values, which were particularly high on the roof of buildings (Table S1; Fig. S2). However, it is important to highlight that this variable calculates the amount of energy reaching materials, just considering the area's morphology (e.g. surface's aspect and inclination, and influence of surrounding buildings) and not the materials' type.

The potential solar radiation of June and December did not show significant correlations with the microclimate variables. The NDVI showed significant negative correlations with the mean summer temperature and significant positive correlations with winter relative humidity (Table 3).

Within the models tested to explain microclimate (Tables S3 and S4), the best models were represented by two variables and season period separated. The microclimate variables for which models showed a significant contribution of both tested environmental variables were: mean summer temperature, mean summer relative humidity and mean winter relative humidity (Table 4). The final models obtained were characterized as follows: i) mean summer temperature included the tree canopy area in a distance of 60 m and the potential solar radiation of June, explaining 64% of the variance; ii) mean summer relative humidity also included tree canopy area in a distance of 60 m radius, and the area of urban matrix in a distance of 10 m, explaining 78% of the variance; iii) mean winter relative humidity included the area of urban matrix in a 5 m distance radius and the potential solar radiation of December, explaining 67% of the variance (Table 4; Fig. 4). The final models were cross-validated, with an R^2 of 0.64 for mean summer temperature, 0.67 for mean summer relative humidity, and 0.65 for mean winter relative humidity.

With these models, it was possible to estimate the mean summer temperature (in °C), and the mean relative humidity (in %) of summer and winter, for the entire study area (Fig. 5).

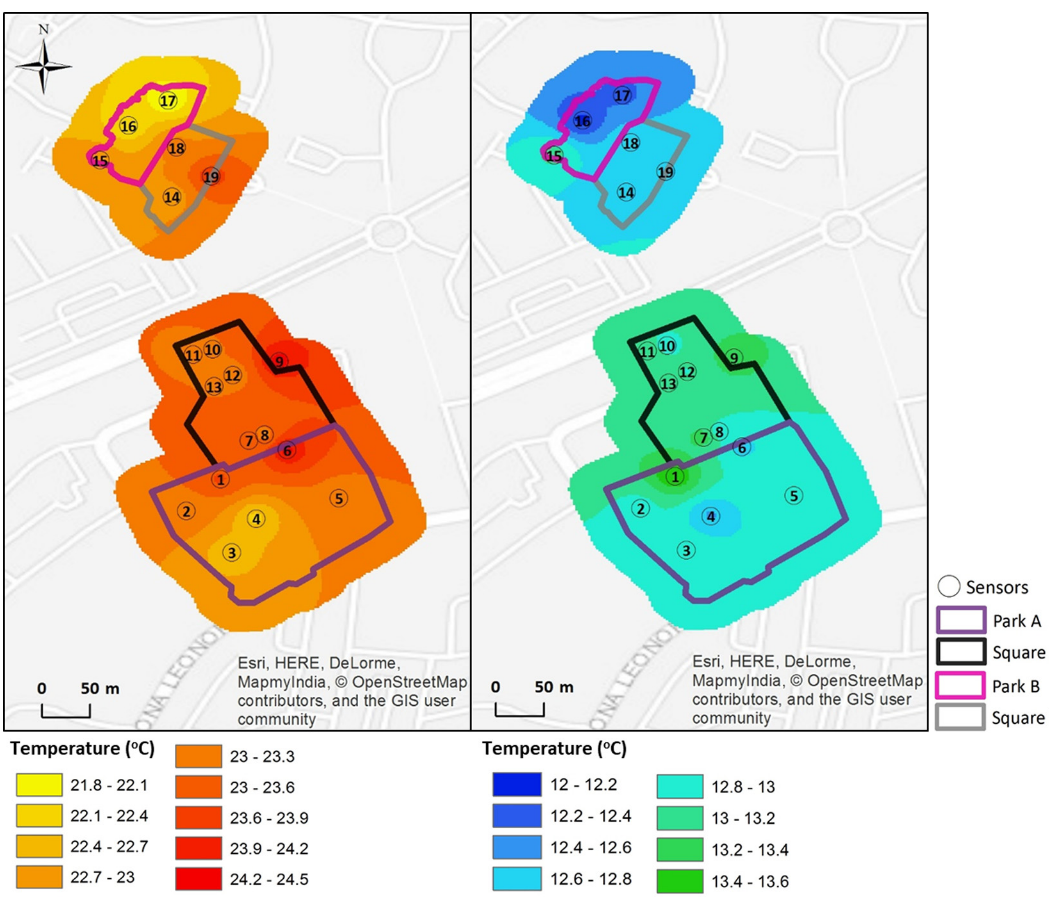

Fig. 2. Maps of the mean temperature (°C) during the analysed periods of summer (left) and winter (right), considering the data collected by microclimatic sensors. Maps are represented in different scales of analysis for a better visual interpretation of the results found.

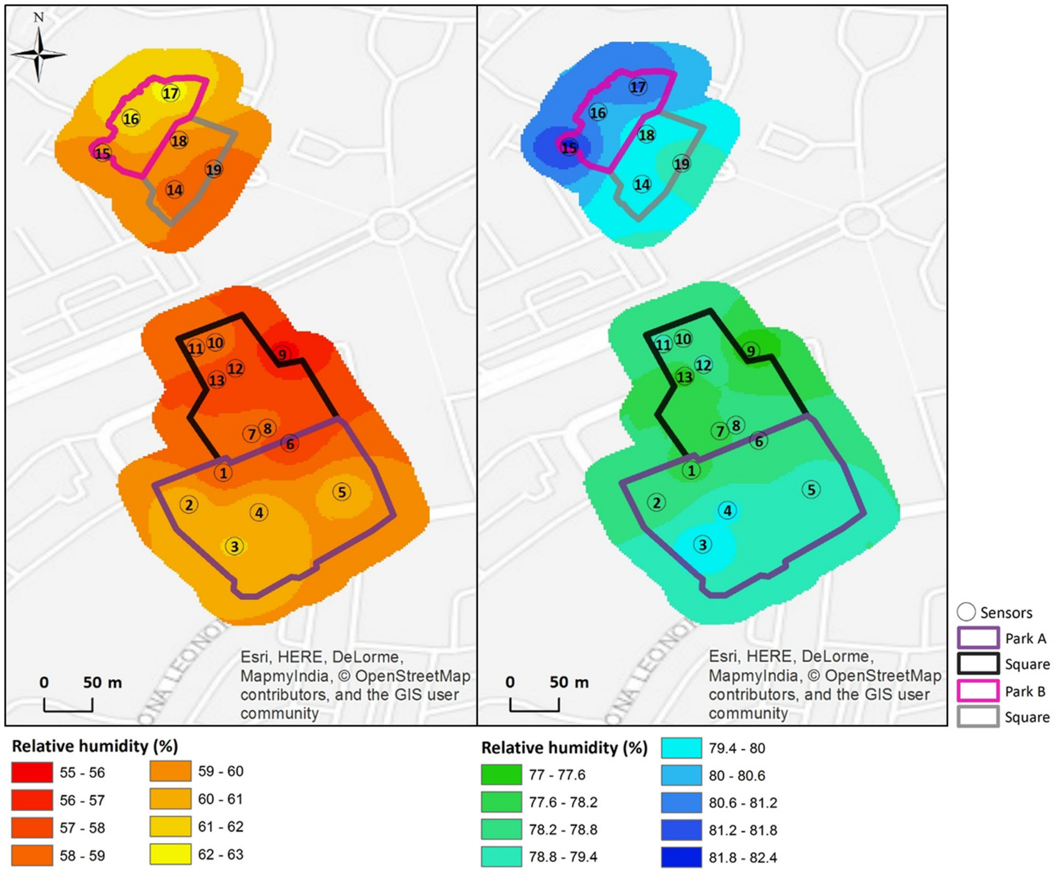

Fig. 3. Maps of the mean relative humidity (%) during the analysed periods of summer (left) and winter (right), considering the data collected by microclimatic sensors. Maps are represented in different scales of analysis for a better visual interpretation of the results found.

4. Discussion

In this work we were able to model, with a high spatial resolution, the effect of green and grey areas in the heat and cool island of urban areas with a Mediterranean climate. The impact of the green (vegetation) in the cooling island effect was disentangled in the models that described the reduction in temperature – "the true cooling effect", and the increase in relative humidity – "the humidification effect". With these models, we were able to build predicting maps for temperature and relative humidity, which can be used by citizens and stakeholders for urban green spaces management and human well-being impact assessment.

Vegetation structure, composition and management are important to optimize the capacity of the green to produce the cooling island effect (Bowler et al., 2010; Oke et al., 1989; Zhou et al., 2017). More specifically, in this work, we found that the land-cover predictors of both temperature and relative humidity models, whether for winter or summer, were associated with: i) the area occupied by the green specific land-use type, namely trees (and not vegetation without trees such as shrubs and herbs); and/or ii) the area occupied by the grey land-use type, which accounts for buildings, roads, impermeable areas, etc. These results suggest that in urban areas with a Mediterranean climate, trees are more efficient in performing the cooling island effect and mitigating human heat stress during the day, than grasslands, which is in

Table 2
Correlations coefficients (Spearman ρ) between the summer and winter mean temperature (T), relative humidity (RH) and the area of three classes of land-cover analysed in different sized buffers (between 5 and 240 m): green - trees = area of tree canopy; green - without trees = area of shrubs and herbaceous vegetation; urban matrix = area of roads, sidewalks and buildings. Significant correlations are marked: * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$.

Microclimate variables		Land-cover	5 m	10 m	15 m	30 m	60 m	120 m	150 m	200 m	240 m
T (°C)	Summer	Green - trees	−0.59**	−0.63**	−0.60**	−0.65**	−0.77***	−0.60**	−0.44	−0.16	0.22
		Green - without trees	−0.1	−0.18	−0.16	−0.2	−0.13	0.26	0.46*	0.26	0.48*
		Urban matrix	0.59**	0.57*	0.50*	0.41	0.34	0.1	−0.02	−0.14	−0.21
	Winter	Green - trees	−0.22	−0.26	−0.22	−0.37	−0.64**	−0.55*	−0.38	−0.23	0.26
		Green - without trees	−0.32	−0.3	−0.27	−0.25	−0.33	0.06	0.35	0.35	0.54*
		Urban matrix	0.44	0.44	0.42	0.38	0.43	0.24	−0.02	−0.23	−0.28
RH (%)	Summer	Green - trees	0.47*	0.47*	0.51*	0.72***	0.82***	0.71***	0.68**	0.36	−0.1
		Green - without trees	0.36	0.45	0.44	0.42	0.35	−0.2	−0.34	−0.44	−0.55*
		Urban matrix	−0.71***	−0.76***	−0.71***	−0.68**	−0.57*	−0.29	−0.04	0.03	0.09
	Winter	Green - trees	0.64**	0.64**	0.66**	0.72***	0.80***	0.74***	0.51*	0.16	−0.34
		Green - without trees	0.11	0.15	0.13	0.16	0.15	−0.32	−0.56*	−0.46*	−0.61**
		Urban matrix	−0.64**	−0.58**	−0.52*	−0.44	−0.31	−0.12	0.11	0.31	0.32

Table 3
Correlations coefficients (Spearman ρ) between summer and winter mean temperature (T), relative humidity (RH) and normalized-difference vegetation index (NDVI) and the potential solar radiation (PSR) of the month with the highest - June (jun) and lowest – December (dec) PSR. Significant correlations are marked: * - p < 0.05; ** - p < 0.01; *** - p < 0.001.

Microclimate variables		NDVI	PSR jun	PSR dec
T (°C)	Summer	−0.60*	0.28	0.33
	Winter	−0.43	0.09	0.23
RH (%)	Summer	0.71***	−0.09	−0.3
	Winter	0.53*	−0.12	−0.41

accordance with other studies (Lee et al., 2016). In the same line, Potchter et al. (2006) compared parks in Tel Aviv and showed that those with a higher amount of tree canopy tended to be cooler than parks with fewer trees and larger lawns. Vieira et al. (2018) also found that a vegetation type characterized by a more complex structure had a higher capacity to provide ecosystems services such as climate regulation, whereas lawns, which have a less complex structure, were associated to a lower capacity to provide this service. Other authors found that multilayer plant communities were the most effective in terms of their cooling and humidifying effect, which was associated with factors such as canopy density and area, tree height and solar radiation (Zhang et al., 2013). These results suggest that the type of green is very relevant when aiming at optimizing the cooling island effect in urban areas, with trees being extremely important, most probably due to higher evapotranspiration capacity and higher shading effect, which blocks a significant portion of solar radiation (Grimmond and Oke, 1991; Oke et al., 1989; Teuling, 2018).

We also found that the summer and winter relative humidity models had as predictor the area occupied by grey, i.e. the urban artificial land-use. Although the green component was associated with the reduction of temperature and increase of relative humidity in the summer, the area occupied by grey areas, presented the opposite behaviour. These artificial areas contribute to the increase of temperature and decrease of relative humidity due to the lack of vegetation and the presence of paved and impermeable surfaces, such as roads and parking lots, that can absorb solar radiation as heat (Oliveira et al., 2011). These impermeable surfaces promote water runoff into the stormwater system, instead of being absorbed by plants or water bodies, which cool the area through evapotranspiration and evaporation (Berland et al., 2017). Another reason is the presence of dark surfaces, such as roads, that absorb more energy, which get hotter than lighter-coloured surfaces. Buildings and other artificial infrastructures also contain high levels of thermal mass, that store heat during the day and slowly release it overnight (Radhi et al., 2014). Additional contributions to drier conditions might be caused by the change in wind speed due to denser urban matrix (Wang et al., 2019). Mechanical air conditioning, which exhausts heat into the environment, especially in the summer (de Munck et al., 2013), is another factor. The urban heat island is also exacerbated by the changes in climate, especially during heatwaves. We found that the capacity of green areas to regulate microclimatic, or produce the cooling island effect was dependent on the type of surrounding grey areas. However, not only the type of artificial surfaces or the area that they occupy were found to be important to understand the cooling island effect. The morphology, aspect and level of exposure of the artificial surfaces to the solar radiation are also important features to be considered. In fact, both the summer average temperature and the winter average relative humidity models, included as predictors, the potential solar radiation measured in June and in December, summer and winter solstices, respectively. This variable represents a measure of the urban morphology (e.g. orography, density of the urban fabric, buildings' location) that contributes to the existence of different microclimates shown by differences in temperature, relative humidity, wind frequency and speed, and radiation at short distances. Thus, the urban heat island effect and the green cool island effect are bidirectional phenomena that, to be modelled, need to have the green and grey components of the urban system. Therefore, the next question is what amount of those elements is needed to regulate the urban microclimate.

Our study showed that even green spaces with reduced areas (in our case 2.04 ha and 0.49 ha) can regulate microclimate, alleviating temperature by 1–3 °C and increasing moisture by 2–8%, on average. Despite being smaller green spaces, they regulated the area's microclimate beyond their borders. Green spaces with trees influenced winter and summer's temperature and relative humidity up until 60 m away from the parks' limits, while grey areas influenced the surrounding environment in a much lesser range, from 5 m up to 10 m. The found green spaces' cooling effect is in accordance with several studies which have shown that green areas can have positive effects on urban microclimate (e.g. Doick et al., 2014; Georgi and Zafiriadis, 2006; Wang et al., 2019). The magnitude of the cooling island effect found in this work is in the same range with the results of Bowler et al. (2010), a worldwide review paper. In relation to the minimum size required for a green space to produce a cooling effect, there are contrasting results. Monteiro et al. (2016) showed that, in London, parks smaller than 0.5 ha do not affect the microclimate of their surroundings and that the required size of a green space to achieve a mean nocturnal cooling of 1 °C on calm warm nights is around 33 ha. In a recent review, it was concluded that large parks (>10 ha) reduce temperature by 1–2 °C, which extends over a 350 m distance from the parks' boundary (Aram et al., 2019). However, different authors state that small green spaces can also produce a cooling island effect: in Lisbon, a park with 0.24 ha showed a temperature difference of 6.9 °C between shaded and sunny sites (Oliveira et al., 2011) and parks with 0.005 ha achieved a mean cooling effect of 1 °C during the day (Reis and Lopes, 2019); in Hong Kong, with a tree cover increase of 25% to 40%, parks with 0.001 ha reduced the daytime urban heat island effect by 0.5 °C (Giridharan et al., 2008). Thus, this effect seems to be an interaction between different factors and not only size dependent. In fact, other authors have stated that the features of green spaces such as area, shape, background climate, type of

Table 4
Explanatory variables of the generalized linear models (GLMs) for the mean summer temperature (T), mean summer relative humidity (RH) and mean winter RH: green - trees 60 m = area of tree canopy within a distance of 60 m from the sensors; urban matrix 5/10 m = area of roads, sidewalks and buildings within a distance of 5/10 m from the sensors; potential solar radiation (PSR) of the most extreme months - June (jun) highest mean, and December (dec) lowest mean. All variables selected are significant for $p < 0.05$.

Microclimate variables		Selected variables								
			Coefficient	Standard error	Z	P > |z|	95% confidence interval		AIC	R^2
T (°C)	Summer	Green - trees 60 m	−3.47E−04	8.26E−05	−4.20	0.00	−5.09E−04	−1.86E−04	1.13	0.64
		PSR jun	6.27E−06	2.79E−06	2.25	0.03	7.99E−07	1.17E−05		
		Constant	22.75	0.46	49.19	0.00	21.85	23.66		
RH (%)	Summer	Green - trees 60 m	7.66E−04	2.44E−04	3.14	0.00	2.88E−04	1.24E−03	2.79	0.78
		Urban matrix 10 m	−8.38E−03	2.67E−03	−3.13	0.00	−1.36E−02	−3.14E−03		
		Constant	59.56	0.84	71.01	0.00	57.91	61.20		
	Winter	Urban matrix 5 m	−6.32E−05	2.14E−05	−2.95	0.00	−1.05E−04	−2.12E−05	2.45	0.67
		PSR dec	−3.15E−02	6.62E−03	−4.77	0.00	−4.45E−02	−1.86E−02		
		Constant	81.91	0.55	148.5	0.00	80.83	82.99		

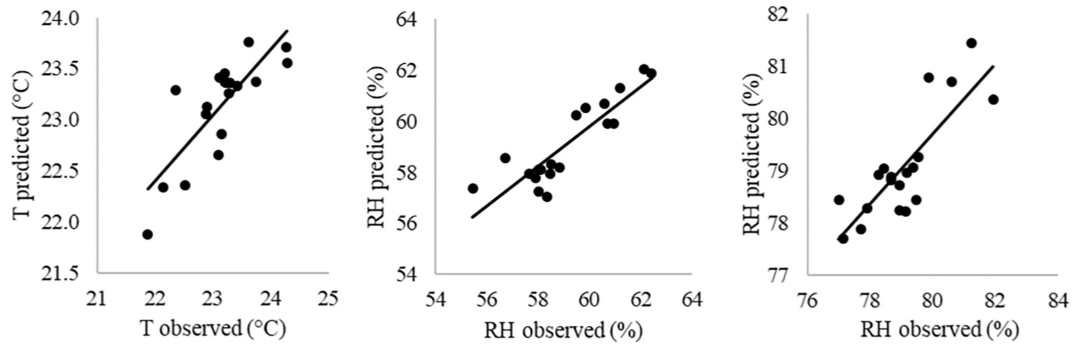

Fig. 4. Observed and predicted values for mean summer temperature (T) (left), mean summer relative humidity (RH) (center) and mean winter RH (right).

vegetation and structure, influence the parks' cooling effect distance and intensity (Chang et al., 2007; Feyisa et al., 2014; Upmanis et al., 1998). In this line, more studies in different background climates with different levels of interaction between factors, such as park size or vegetation type, should be performed in order to understand such complex interactions.

Temperature reduction and relative humidity increase were larger during summer than during winter, which further supported the conclusion that the higher the temperature, the stronger the potential for cooling (Shashua-Bar and Hoffman, 2002; Lin and Lin, 2010). Thus, the seasonal variations of temperature reduction and relative humidity increase were apparently related to air temperature change along the year, being higher in summer, which is in line with the conclusion of Hamada and Ohta (2010). This finding is in accordance with other studies either in the same climatic conditions (e.g. Oliveira et al., 2011; Reis and Lopes, 2019) or in temperate areas, where most studies have been conducted (Bowler et al., 2010). This climatic regulation was not as impactful during winter, with parks showing a reduction of 1.5 °C and 5% increased moisture, on average.

5. Conclusions

The empirical models developed within this study were able to deliver results predicting the effect of green spaces on microclimate within and beyond the parks themselves, through the analysis of the distance of influence of different land-use types with very high spatial resolution. The cooling effect model was not only based on temperature but also on relative humidity, which is an important factor in ecosystem functioning and human thermal comfort, often undervalued by most studies that focus on urban microclimate. These cooling and humidifying island effect models were the result of the balance between the green, areas with more dense trees, and the grey, which represents the area, morphology and exposure of artificial constructions.

The high spatial resolution was an important outcome in this work, since it can provide accurate and local information to citizens, stakeholders, policymakers and municipalities, for planning the most cost-effective vegetation type to increase the cooling effect, while considering the season period and the surrounding grey matrix. This information is extremely relevant for urban ecosystems management and for the

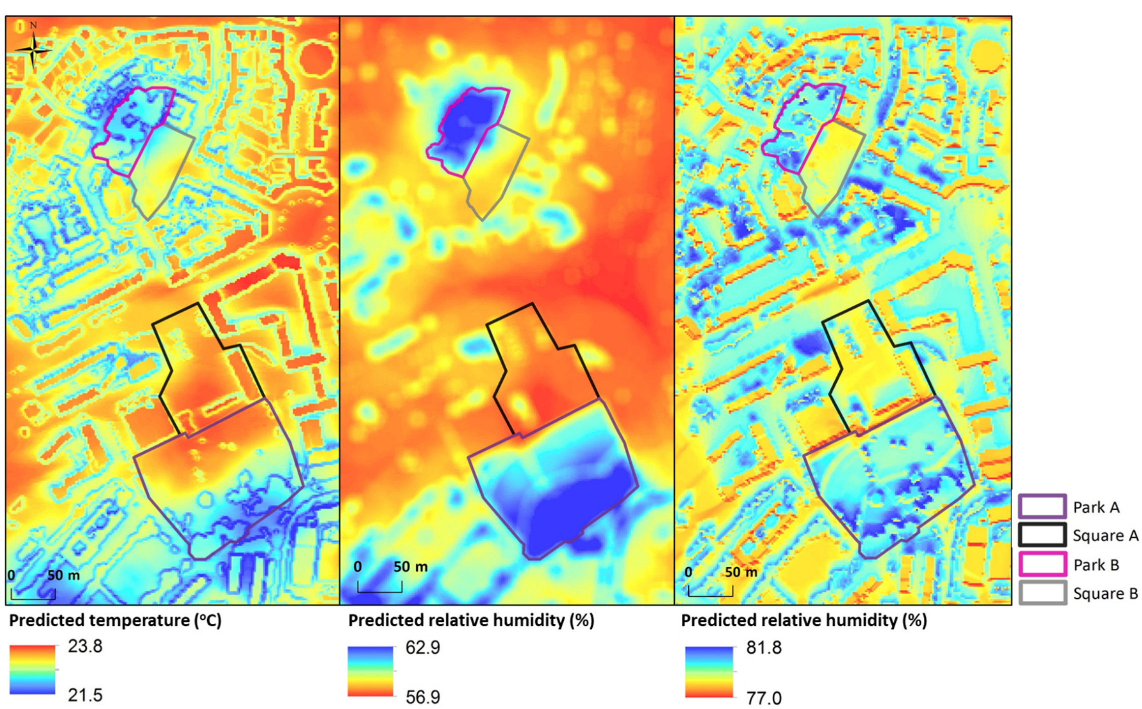

Fig. 5. Prediction maps made using the final models of the mean summer temperature (left) and mean relative humidity of summer (center) and winter (right). Relative humidity prediction maps are represented in different scales of analysis for a better visual interpretation of the results found. Note that the edge effect on temperature is a bias produced by PSR and should be disregarded, as this occurs due to a higher PSR in flat surfaces (tree top) than in vertical surfaces (tree edges).

general population, particularly those susceptible to the increase of temperature in urban areas.

Green spaces, even those with reduced areas, should be seen as a solution to the mitigation of the urban heat island effect and as an adaptation measure to climate change, at least under a Mediterranean climate, since they influenced the microclimate beyond their borders (up until 60 m). Green spaces dominated by trees should be a priority since they are more effective in the cooling island effect, in both intensity and distance of influence. In a Mediterranean climate-type region, characterized by warm to hot and dry summers and mild wet winters, the climatic regulation promoted by green spaces seems to occur mainly during summer, which is when this alleviating effect is most needed for urban dwellers and ecosystems.

Green spaces besides having a cooling and humidifying island effect are also a win-win solution for increasing biodiversity, saving energy, and improving air quality as well as mental and physical health.

CRediT authorship contribution statement

Filipa Grilo: Conceptualization, Data curation, Methodology, Writing - original draft, Writing - review & editing. **Pedro Pinho:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing. **Cristiana Aleixo:** Methodology, Writing - review & editing. **Cristina Catita:** Methodology, Writing - review & editing. **Patrícia Silva:** Writing - review & editing. **Nuno Lopes:** Writing - review & editing. **Catarina Freitas:** Writing - review & editing. **Margarida Santos-Reis:** Writing - review & editing. **Timon McPhearson:** Writing - review & editing. **Cristina Branquinho:** Conceptualization, Funding acquisition, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by a project promoted by the Department for Environment, Climate, Energy and Mobility of the City Council of Almada. FG and CA were funded by Fundação para a Ciência e a Tecnologia (FCT), with PhD scholarships (BIODIV PD/BD/140824/2018 and SFRH/BD/141822/2018, respectively), and FCT, through national funds, also funded PP, MSR and CB (project UID/BIA/00329/2019 – cE3c) and CC (project UID/GEO/50019/2019 - IDL). PP was also funded by the project BioVeins (H2020 BiodivERsA32015104). TM's participation was supported by the US National Science Foundation through (NSF) the Urban Resilience to Extreme Weather-Related Events Sustainability Research Network (NSF grant no. SES 1444755) and the US NSF Accel-Net Program NATURA project (NSF grant no. IOES 1927167).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.138182.

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