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Mapping heat and traffic stress of urban park vegetation based on satellite imagery - A comparison of Bucharest, Romania and Leipzig, Germany

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Abstract

Large and comparatively compact European cities such as Bucharest and Leipzig struggle with considerable urban heat island (UHI) effects characterized by heat and drought together with high concentrations of air pollutants (NO_2, SO_2, O_3, CO_2). However, a healthy urban green infrastructure is necessary to reduce the impacts of UHI on human health. Therefore, continuous monitoring schemes are required for green infrastructure in order to improve human life in such cities. Satellite remote sensing can provide the means for monitoring urban vegetation status. In this study, vegetation indices, mostly based on the spectral bands located in the red-edge region, were computed from Sentinel-2 imagery, and land surface temperature (hereafter LST) was estimated from Landsat 8 data. The aim was to assess the individual and cumulative effects of both *vicinity to roads* and *estimated LST* on tree vegetation health in urban parks using analysis of variance. Vegetation indices indicated stressed vegetation. However, tracking urban tree health required a combination of indices, and therefore of spectral ranges, rather than one specific index alone, as the effect sizes varied between parks, cities and along the centre-periphery gradient. Therefore, spaceborne data can provide spatially-explicit indicators for stressed urban vegetation and, thus, decreasing ecosystem services delivery. Future studies are encouraged to decipher further the relation the spatial configuration of urban systems and remote sensing based stress indicators of urban trees using publicly available datasets to enable comparative studies.

Keywords Land surface temperature · Air pollution · Green infrastructure · Stressed vegetation · Landsat 8 · Sentinel-2

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Introduction

Among the most pressing environmental features that European cities face nowadays are air pollution and the urban heat island effect (Weber et al. 2014b). These stressors have an effect on urban vegetation status (WHO 2000b; Mills 2017; Smithers et al. 2018) and, ultimately, on the human health (Currie and Bass 2008; Baró et al. 2014). The pollutants responsible for deteriorating urban air quality and affecting human health directly are oxides of nitrogen (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO) and particulate matter (PM) (Gulia et al. 2015). The main urban sources of air pollution are traffic and industrial activities, as well domestic fuel burning for heating facilities (Karagulian et al. 2015). ***Traffic*** is increasing in many European cities, mainly due to the extended car use (Weber et al. 2014a). The ***urban heat island effect*** describes the phenomenon of increased temperatures in urban areas when compared to their rural surroundings (Nastran et al. 2019). Assuming that only little pervious surface exists within a city, meaning that less energy is used in evaporating water, then less solar energy is reflected and more heat is stored by buildings and the ground in urban compared to rural areas (Schwarz et al. 2011; Nastran et al. 2019).

Urban vegetation can deliver a full range of ecosystem services and counteract both heat and air pollution stress (Baró et al. 2014; Livesley et al. 2016; Vieira et al. 2018). Previous studies showed vegetation's role in mitigating the effects of urban heat island (Georgi and Zafiriadis 2006 ; Weber et al. 2014b; Smithers et al. 2018) and in decreasing air pollution (Nowak et al. 2018). Both ecosystem services result in an improvement of the citizen's life. Vegetation performs better when it is in a good physiological state and thus being able to collect particles on the leaves and capture NO_2, SO_2 and O_3 by stomata processes (Lausch et al. 2016; Vieira et al. 2018). Therefore, it is necessary to assess vegetation's health in order to determine whether or not and how well urban vegetation can provide urban ecosystem services related to the Sustainable Development Goal (SDG) of human well-being (UN General Assembly, 2015).

Vegetation health can be studied using non-invasive reliable tools, which assess spectral traits. State-of-the-art Earth Observation technology acquires important information over large areas, which can be both basis and support for decision-making processes in urban planning (Lausch et al. 2016). In particular, vegetation indices based on two or more spectral bands are promising means to extract physical, biochemical, and ecophysiological characteristics of vegetation. The spectral and spatial characteristics of publicly available remote sensing data acquired by Landsat 8 (Zhao et al. 2017) and Sentinel-2 (Drusch et al. 2012) have high potential for urban applications (Frampton et al. 2013; Addabbo et al. 2016; Pesaresi et al. 2016). Sentinel-2 acquires multispectral data in narrowband, valuable for assessing vegetation state (Frampton et al. 2013). Previous studies clearly show a relationship between environmental factors and vegetation state. The impact of air pollutants is explored by research such as of Tomašević et al. (2005), Säumel et al. (2012), Van Wittenberghe et al. (2013), while the urban heat island effect characterized by heat and drought is investigated by Nouri et al. (2013), Paunescu et al. (2013) and Kunz et al. (2016). Moreover, Landsat-8 delivers images with thermal infra-red (TIR) bands which allow the estimation of LST over large areas and also canopy temperature, a key monitor of photosynthesis, respiration and transpiration (Roberts et al. 2015). Previous studies focus on very high resolution, commercial data (Nouri et al. 2013).

Thus, we identified a research gap for combining high spatial resolution open access data from multiple platforms sensors to assess urban vegetation health, especially in compacted densely populated areas. Since most studies analyze urban vegetation stress as a response to only one parameter (Säumel et al. 2012; Kunz et al. 2016), we will address the combined effect of multiple environmental factors on urban vegetation status.

Two cities with similar urban structure were chosen for this study: Bucharest, Romania, and Leipzig, Germany. Both cities are very well comparable in terms of their size, the distribution of land cover classes within the city, the existing tree species and environmental changes and pressures that both cities underwent in the past and recent years. This is due to the cities' post-socialist past including suburban sprawl, increasing car numbers and increasing built-up densities (Chiriac et al. 2009; Weber et al. 2014a), housing vacancies in the inner city and large industrial brownfields and unused places across the cities' area (Haase et al. 2017). Both cities record an exceedance of NO_2 and SO_2 critical values for vegetation in and around the city center (WHO 2000a; Leeuw and Ruyssenaars, 2011; Mills 2017). Air pollution increases during the winter because of heating based on fossil fuels like coal and natural gas, which affects vegetation on long-term (Ioja 2009).

Urban environments represent complex ecosystems where numerous elements mutually interact and where the relationship of causality is very dynamic (McPhearson et al. 2016). The difficulty for an accurate statistical modelling of causal relationships or chains initiated e.g. by urban heat in urban environments comes from the multiple elements and their connecting variables that form each feature. Everything adds up to the complex aggregate that is the urban environment (Breuste et al. 2013). Thus, urban ecosystems are heterogeneous, and the impact on urban vegetation health is context-dependent, so the results from single sites might not be transferable. As a consequence, we propose an approach to identify the most affected parks across two cities using freely available remote sensing data.

The specific objectives of this study are 1) to compare public parks' vegetation status in Bucharest and Leipzig along an urban-to-rural gradient, and 2) to assess the impact of the vicinity to roads and LST on vegetation vitality and their joined impact on each park based on open access remote sensing data.

Material and methods

Study areas

Bucharest and Leipzig are characterized by an intensive urbanization after the communist fall in 1989 (Mihai et al. 2016) and the German reunification in 1990 (Weber et al. 2014b). This process is represented mainly by land cover conversion (e.g. pervious surfaces transformed into residential facilities or large commercial areas), which lead to an overall increase of built-up areas.

Bucharest is located at 44°25′ North latitude and 26°06′ East longitude and it covers 230 km^2, with a population of approximately 2 million inhabitants. Leipzig is located at

51°20′ North latitude and 12°23′ East longitude and it covers 300 km^2, with approximately 600.000 inhabitants. Annual mean temperatures of both cities are similar. Bucharest records 10 °C (Ioja 2009) and Leipzig 9 °C (Weber et al. 2014b), with tendency to increase in the future years. (Ioja 2009; Weber et al. 2014b).

In order to provide a standardized comparison method from the center to periphery, the two cities were split into five multi-rings that cover their entire administrative areas. The radius of each ring is 2-km, based on the urban development phases observed during field campaigns. These multi-buffers deliver a straightforward understanding of the land cover variation from the city center to periphery (Fig. 1). What is more, it provides the context for visualizing the variation of LST and air pollutants across the five circular sections.

Both city centers are mostly covered by built-up area, almost 90%, followed by urban green area, varying from 9 to 10%. Comparing the rest of the circular sections, built-up coverage decreases in favor of pervious land cover classes such as agricultural land or forest (Table 1). Leipzig records a larger percentage of green urban areas because its parks are larger than the ones in Bucharest thanks to the floodplain forests in the heart of the town (Haase 2003). Also, agricultural area is present in the outskirts of Leipzig due to intensive land use for farming and fertile loess soils, a tradition that was never abandoned around German cities (Haase et al. 2017). In Romania, newly built residential neighborhoods replaced abandoned areas or agricultural land in the city's outskirts after 1990 (Mihai et al. 2016).

Temperature values in Bucharest are overall higher than the ones recorded in Leipzig due to its more southern location. However, some distribution patterns can be observed according to which average temperature values computed for each ring decrease from city center to suburbia. The fifth ring of Leipzig is covered mainly by agricultural land. Critical thresholds for NO_2 are exceeded in and around the city centers, while closer to suburban areas SO_2 critical thresholds are exceeded. Exceeded values are indicated with red borderline for each air pollutant (WHO 2000a; Leeuw and Ruyssenaars, 2011; Mills 2017).

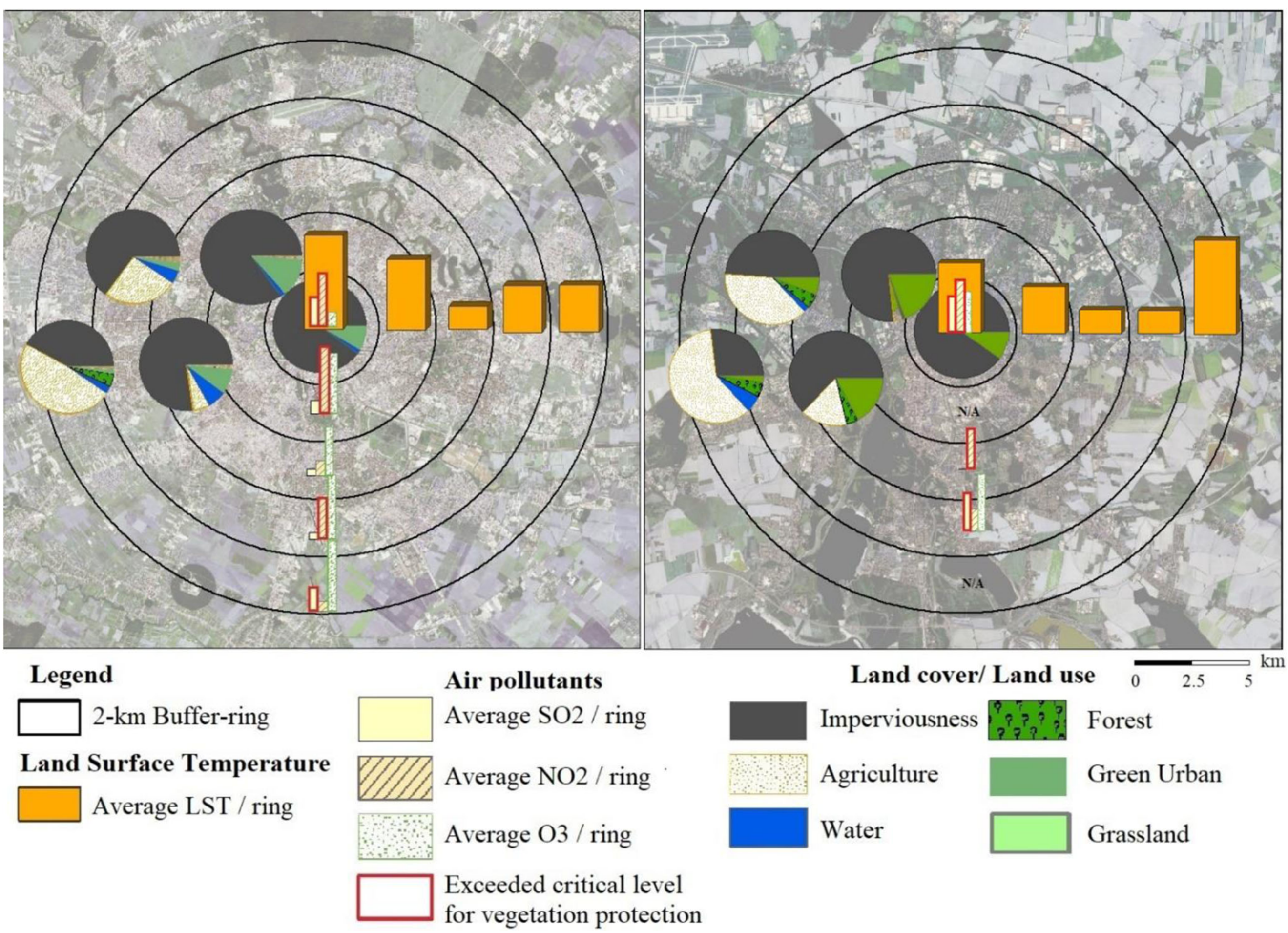


Fig. 1 Multi-ring buffer around city center. Images show percentages of LCLU classes for each ring, average values of LST for each buffer ring and the annual means of air pollutants for each buffer ring. Source: Processed Air pollution data from National Agencies (No data available for Leipzig for all rings); Land cover/ Land use data from Urban Atlas 2012 (Meirich 2008); Processed LST data from Landsat 8 imagery; Basemap from Sentinel-2 imagery.

Table 1 Land cover and land use class percentages for each city and mean LST values per each buffer-ring (with B = Bucharest, L = Leipzig)

	Multi-Ring Buffer	Built-Up	Green Urban Areas	Agriculture	Forest	Grassland	Water	LST (°C)
B	1	89.8	8.6	–	–	0.2	1.4	33.5
	2	84.6	12.1	0.8	–	1.0	1.5	32.9
	3	76.9	8.9	5.9	0.3	1.4	6.5	32
	4	64.1	2.7	25.9	0.8	1.9	4.6	32.3
	5	41.8	1.3	48.7	4.5	1.0	2.6	32.3
L	1	89.0	9.8	–	–	1.2	–	25
	2	75.8	18.7	3.0	0.1	1.2	1.2	24.6
	3	61.9	17.2	15.7	3.7	0.8	0.8	23.7
	4	49.0	5.8	37.5	5.4	0.8	1.5	23.8
	5	27.1	1.8	60.1	5.1	0.4	5.6	25.5

Source: Land cover/ Land use data from Urban Atlas 2012 (Meirich 2008); Processed LST data from Landsat 8 imagery

Both countries have similar proportion of passenger cars in terms of used engine fuel. However, alternative energy is preferred by 1.58% of all cars in Germany, whilst in Romania the market for environment-friendly fuel is expanding slowly; only 0.14 of all cars use alternative energy (European Commission 2017). On the other hand, both countries are above the average values in the European Union in terms of emissions of CO_2 per km (Fig. 2). Thus, traffic is still a major contributor to air pollution throughout old cars which run on diesel or petrol.

For the vegetation vitality comparison, ten parks within each city were selected (Fig. 3). The parks have different characteristics: their sizes range from 3.5 ha to 110 ha for Bucharest and from 1 to 109 ha for Leipzig; they are located across all five urban circular sections; they have different irrigation systems; their micro-climates are characterized by different temperature values (Table 2).

Field observations revealed that parks in Leipzig are only irrigated by sprinkler systems, whilst for Bucharest the management system requires complex preservation with complementary solutions: sprinkler systems and, for some parks, additional solutions such as water transported by cars or by garden hoses from the nearby lakes (Table 2). Parks are popular among citizens as they deliver a good environment for spending time, no matter their location inside the city or their size. Generally, parks with a small area are cleaner than the ones with a large area, possibly because they are easily maintained.

CIS is a famous park in Bucharest which is visited by many citizens and tourists because it delivers great vegetative landscape with many species and because it is the biggest park located in the city center. It was built on top of a swamp and nowadays it contains a lake. KIS is a well-maintained park, one of the cleanest parks in Bucharest, also centrally located, but the number of visitors is reduced because the average time for visitors is limited to a couple of minutes.

In Leipzig, the sample includes two different types of parks: old, 19th and early twentieth century founded, public parks that are mostly in the style of former English landscape gardens such as MAR, VOL or ABT. Other parks are considerably younger created after 1990 in line with a larger-scale revitalization of industrial and railway brownfields in the inner parts of the city such as LEN or HEN. The latter park type is different concerning its biophysical conditions as brownfield soils are often less deep, less humid and more porous than the natural loamy soils the old parks and their trees stock on. Moreover, the water holding capacity of the brownfield-

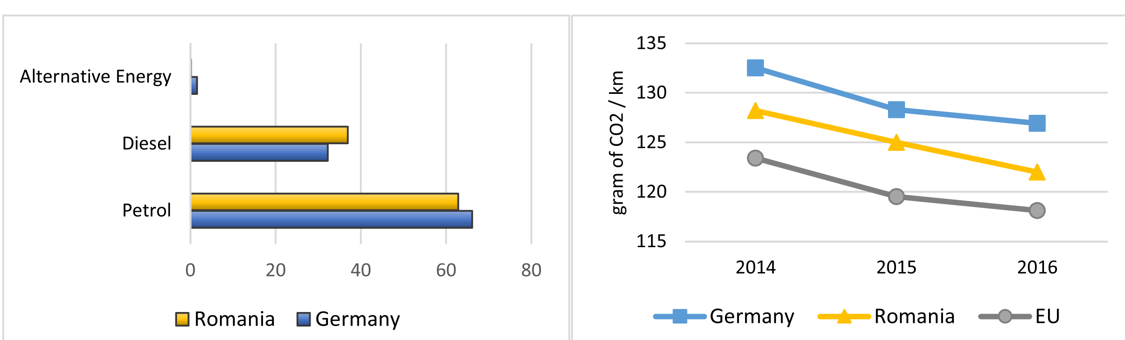


Fig. 2 Proportion of passenger cars by combustion (left) and Average CO_2 emissions per km from new passenger cars (right). Source: Eurostat, Passenger cars in the EU, European Commission, 2017

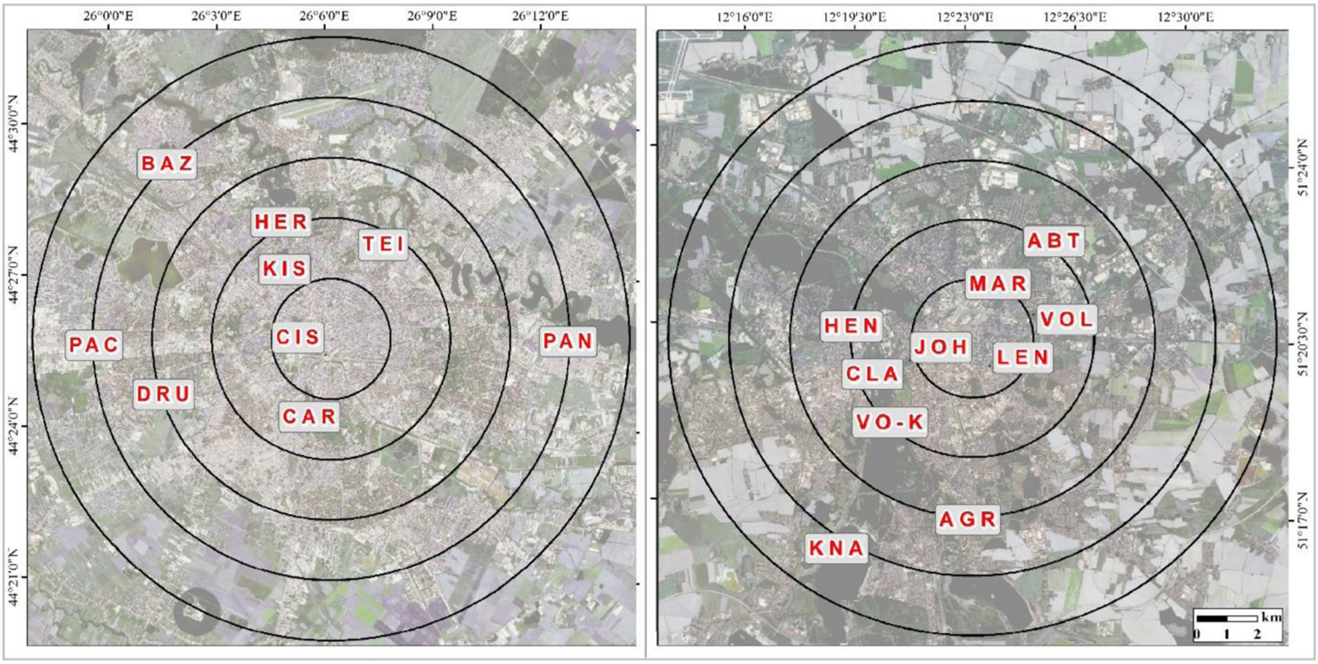


Fig. 3 Spatial distribution of selected parks for Bucharest (left) and Leipzig (right). Source: Basemap from Sentinel-2 imagery.

Table 2 Park characteristics and information

City	Park Name (acronym)	Park Name (long name)	Area (ha)	In-ground irrigation	Other solutions for irrigation	Visitors	Cleanliness
B	CIS	Cismigiu Gardens	16	X	X	👤👤👤	👍
	UNI	Union Park	3.5		X	👤👤	👍👍👍
	KIS	Kiseleff Park	31	X		👤	👍👍
	CAR	Carol Park	41		X	👤👤👤	👍👍
	HER	Herastrau Park	110	X	X	👤👤👤	👍👍
	TEI	Tei Park	9	X		👤👤	👍
	DRU	Drumul Taberei Park	30	X		👤👤👤	👍👍
	PAN	Pantelimon Park	52	X		👤👤	👍
	PAC	Peace Park	2.5	X		👤	👍👍👍
	BAZ	Bazilescu Park	14	X		👤👤👤	👍👍
L	LEN	Lene-Voigt-Park	5			👤👤👤	👍👍👍
	MAR	Mariannenpark	19			👤👤	👍👍
	VOL	Volksgarten	4			👤👤	👍👍
	ABT	Abtnaundorfer Park	19			👤	👍
	CLA	Clara-Zetkin-Park	109	X		👤👤👤	👍👍
	JOH	Johannapark	11			👤👤👤	👍👍
	HEN	Henriettenpark	1			👤👤	👍👍
	VO-K	Volkspark Kleinzschocher	45			👤👤	👍👍
	AGR	Agra-Park	13	X		👤👤	👍👍
	KNA	Knauthainer Park	10	X		👤👤	👍👍

parks is considerably lower than that of the old parks. Last but not least, the age of the trees in both revitalized areas, LEN and HEN, is less than in all other parks although we also find there some old trees being remnants of the former (railway side green) land use (Haase 2001).

Datasets and methods

In Earth Observation, there is usually a compromise between spatial and spectral resolution because of the mixed spectral response within a pixel and the free availability of data (Thenkabail et al. 2012). Here, multispectral satellite imagery (Landsat 8 and Sentinel-2) that matched vegetation peak season (August) was combined with additional spatial information such as air pollution data from National Environmental Agencies, road network from Open Street Map and datasets distributed within the framework of Land Copernicus Program (Table 3).

Remote sensing based spectral indices offer information related to plant traits such as leaf biochemistry, photosynthetic processes and canopy structure (Homolová et al. 2013). However, vegetation indices based on spectral bands located in the red-edge region have lower background effect and are known to be positively correlated to pigments and nutrients, especially chlorophyll (Ramoelo et al. 2015; Gholizadeh et al. 2016). Satellite images were used to extract information for each park.

Firstly, images from spaceborne sensors were atmospherically corrected and spectrally calibrated using the appropriate bands for aerosol retrieval and cloud detection (Louis et al. 2016).

Secondly, narrowband and broadband vegetation indices as proxies for biophysical and biochemical plant parameters such as chlorophyll content, moisture and foliar structure were extracted from Sentinel-2 images using ENVI software (Exelis Visual Information Solutions, v5.3) and SNAP Toolbox (SNAP - ESA Sentinel Application Platform, v5.0) (Table 4).

LST was estimated based on a single-channel algorithm as developed by (Sobrino et al. 2004) using ENVI software. This method was successfully used for LST retrieval from Landsat 8's TIR band 10. Previous studies show that band 10 shows better results than band 11 (Jiménez-Muñoz et al. 2014; Yu et al. 2014).

Analysis

Due to a given normal distribution of the data values of all samples, correlations were reported using the Pearson coefficient which is frequently used in many environmental studies (Govindaraju et al. 2012; Tote et al. 2014). Here, the Pearson coefficient was used to test the strength of the association between (a) LST and imperviousness degree and (b) LST and park's area. Moreover, the relationship between vegetation indices and average LST estimated inside a buffer zone around parks was tested. This analysis provides the context for assessing the strength of vegetation for decreasing temperatures around it, within a buffer of 150 m (Du et al. 2017). The number of random points distributed across each city is $n = 375$.

Analysis of variance (ANOVA) was applied to investigate the individual impact of traffic, temperatures and their joined interaction on vegetation status. Values of the vegetation indices were taken as the response variable and parameters, which characterize the local settings were integrated as explanatory variables. Vegetation indices were considered significant at the $p < 0.10$ level (Dahiru 2011). In addition, the effect size η was calculated for each ANOVA test in order to identify how important the difference between the groups is. The values of η were reported from 0 to 1 (Richardson 2011).

Table 3 Datasets used in analysis and sensor characteristics

Dataset	Sensor/ Source	Provider	Acquisition date Bucharest	Acquisition date Leipzig	Resolution/ MMU	Spectral Bands
Land Surface Temperature	Landsat 8 imagery	USGS	August 5, 2016 (DOY 218)	August 18, 2016 (DOY 231)	30 m (15 m panchromatic)	11 Spectral Bands
Vegetation indices	Sentinel-2 imagery	ESA	August 8, 2016 (DOY 221)	August 27, 2016 (DOY 240)	10, 20, 60 m	13 Spectral Bands
Land Cover/ Land Use	Urban Atlas	ESA – Copernicus Land Program	2012	2012	1 ha	–
Degree of imperviousness	Imperviousness Layer	ESA – Copernicus Land Program	2012	2012	20 m	–
Monthly mean values of air pollution	Air pollution data	National Agencies http://www.anpm.ro http://statistik.leipzig.de/statcity/index.aspx	2012	2012 (No data available for Leipzig for all stations)	–	–

Table 4 Vegetation indices used in urban vegetation stress/state analysis

Indicated parameter	Index name	Index abbreviation	Formula	Reference
Chlorophyll	Chlorophyll Red-Edge	Chl Red-edge	$\frac{B7}{B5}^{-1}$	(Gitelson et al. 2006)
Chlorophyll	Red Edge Normalized Difference Vegetation Index	RENDVI	$\frac{B6-B5}{B6+B5}$	(Sims and Gamon 2002)
Chlorophyll	Plant Senescence Reflectance Index	PSRI	$\frac{B4-B2}{B6}$	(Sims and Gamon 2002)
Chlorophyll; LAI	Simple ratio	SR	$\frac{B8}{B4}$	(Blackburn 1998)
Water	Moisture Stress Index	MSI	$\frac{B11}{B8}$	(Ceccato et al. 2001)

Results were reported using three classes of effect size magnitude: small, medium, large (Richardson 2011).

All statistical analyses were done using SPSS Statistics 13.0 (IBM Corp 2013). Three *NULL* hypotheses were tested for each park:

(1) H_0: Distance to roads has no significant effect on vegetation indices.
(2) H_0: Land surface temperature recorded within park has no significant effect on vegetation indices.
(3) H_0: Joined interaction of distance to roads and land surface temperature has no significant effect on vegetation indices.

The threshold of $p < 0.10$ was used to reject the NULL hypotheses and to accept the alternative hypotheses:

(1) H_1: Distance to roads has significant effect on vegetation indices.
(2) H_1: Land surface temperature recorded within park has significant effect on vegetation indices.
(3) H_1: Joined interaction of distance to roads and land surface temperature has significant effect on vegetation indices.

Results

One major result of our study is the finding for the correlation between high LST and high degree of imperviousness. Leipzig records a higher value of positive correlation $r = .710$ at p *value* $= 0.01$ than Bucharest. Leipzig reports an overall larger variance of LST across the entire city compared to Bucharest. Bucharest records a $r = .666$ at a p *value* $= 0.01$. In the case of testing the linear association between the average LST within the 150-m buffer around the parks' areas ($n = 10$), r reveals a negative correlation.

The context of vegetation indices was studied using boxplots representing average values of vegetation indices for each analyzed park (Fig. 4). The processed data was cleaned and the outliers were removed.

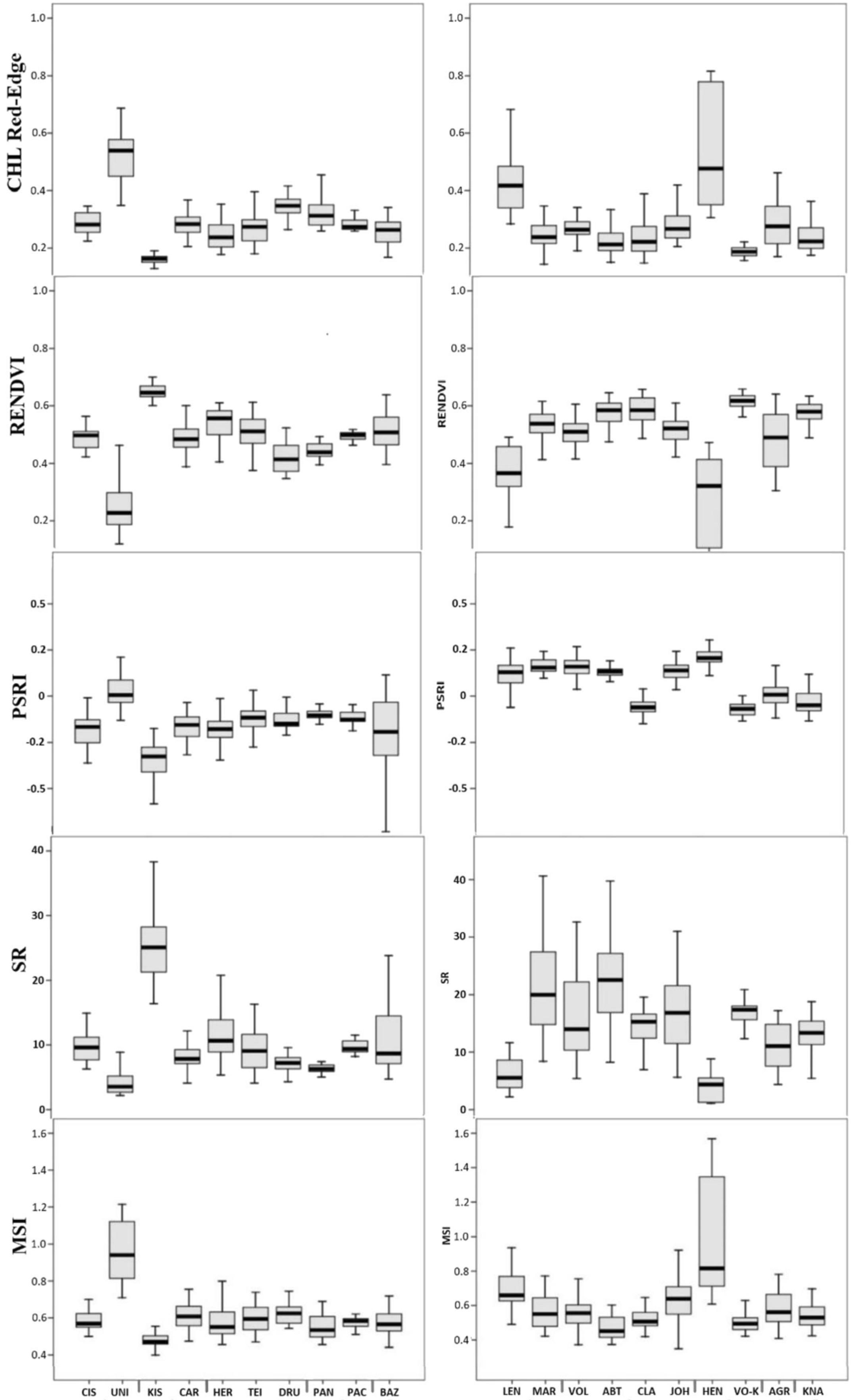
Average LST values calculated around the parks in Leipzig reveal a strong positive correlation with Chl Red-Edge, PSRI, RENDVI (chlorophyll content indicators) and MSI (moisture stress indicator) (Table 6). On the opposite pole, the correlations between the average values of vegetation indices and average LST around the parks in Bucharest are not similarly strong. Some indices get close to a good positive correlation ($r \sim 0.5$).

Another important result of our study shows the impact of traffic-related pollution and heat, taken as two individual factors, on vegetation health. Moreover, their combined impact is tested for being a cumulative stress for vegetation. Values of effect sizes were used for mapping the individual and the cumulative stress of the two analyzed factors on urban trees. All the charts corresponding to each park were mapped for Bucharest and Leipzig, showing the differences between the groups.

Comparing the summary results of the Two-way ANOVA between the external factors and vegetation status and tree vegetation, we can observe that some parks report a higher number of vegetation indices with statistical significance: CAR, HER, PAC, BAZ in Bucharest and CLA, AGR in Leipzig (Table 7).

Some parks in Bucharest (CIS, KIS, DRU) and Leipzig (LEN, MAR, ABT, JOH, VO-K) are reported to have only one parameter affected by either traffic or high temperatures. CIS reports a combined influence of the two factors $\eta = 0.304^{**}$ for MSI (Fig. 9) and for the rest of the vegetation indicators there is a statistical significance with LST. LEN reports a combined influence for SR with $\eta = 0.358^{**}$ (Table 7).

Effect sizes of ANOVA are used for mapping the impact's level of the two analyzed factors on tree vegetation. Vegetation in Bucharest is affected no matter the location in the buffer-rings. However, to be noted that the less affected parks are the ones located to the north of the city, in areas with a low degree of imperviousness (Figs. 5, 6, 7, 8, 9). Leipzig reveals a concentric layout of the effect size bars, as they decrease from the city center towards the periphery. One park (HEN) stands out as it reports the highest values of effect size for all analyzed indices (Figs. 5, 6, 7, 8, 9).


CHL Red-Edge
RENDVI
PSRI
SR
MSI
CIS UNI KIS CAR HER TEI DRU PAN PAC BAZ
1 2 3 4 5
LEN MAR VOL ABT CLA JOH HEN VO-K AGR KNA
1 2 3 4 5

◀ **Fig. 4** Boxplots showing the average values for each vegetation index in relation to each park, categorized by the five buffer rings. Left column: Bucharest; Right column: Leipzig. Source: Processed data from Sentinel-2 images.

Discussion

The main finding of our study is that Bucharest is more affected by the urban heat island effect than Leipzig is. Bucharest records overall higher temperatures and longer intervals of heat waves than the German city (Rusanescu et al. 2011; Cheval and Dumitrescu 2014), but also Leipzig is becoming more and more affected (Weber et al. 2014b).

Similar to other studies, it is demonstrated that the higher the surface sealing is, the higher the LST is (Gusso et al. 2014) (Table 5). This correlation can be seen along the buffer rings: the imperviousness coverage decreases in relation to LST, from the center to periphery. However, the values for Bucharest indicate that the UHI effect is strong even in areas facing a rather low degree of surface sealing. The analysis includes sample points with no soil sealing but with extreme high LST because of agricultural land, which stores heat, particularly in dry periods (Sun et al. 2011; Omran 2012). This applies mainly for the fifth multi-ring buffer in Leipzig, which records the highest values of LST due to the lack of vegetation on agricultural land in that timeframe. Soil properties play an important role here but also the state of the soil after longer drought periods, especially in peripheral agricultural lands (Haase 2009).

Moreover, our analysis shows that not all vegetation in Bucharest is able to mitigate the temperatures as indicated by LST during summertime. Based on the results of the negative correlation between the average LST within 150-m buffer around the park and its area, it can be interpreted that the lower the park's area is, the higher the LST is. In Leipzig, the conditions are different: in and around parks, the temperatures are lower than the ones corresponding to impervious surfaces. Large parks perform better for mitigating the temperatures around them, compared to small parks. This result is supported by the findings of Vieira et al. (2018).

In order to analyze if vegetation contributes differently to decreasing temperatures around parks based on its health, we tested the correlation between vegetation indices and LST within a buffer of 150 m around the parks (Du et al. 2017).

For Leipzig, the positive correlations between indicators and estimated LST around the parks show that the better the vegetation health in the German city is, the lower the LST recorded around it. Vegetation successfully delivers air temperature cooling and thus effectively mitigates the impact of the urban heat island (Maes et al. 2016). For Bucharest, the correlation coefficients are not as strong as for Leipzig. This can be explained by the fact that the Romanian city experiences an overall stronger heat island effect over the entire city area (Cheval and Dumitrescu 2014). Thus, its LST variance is not large from one buffer ring to another. The urban vegetation in a limited number of parks in Bucharest deliver cooling ecosystem services by mitigating high temperatures.

Based on these correlations, we conclude that even though the UHI effect is more intense in Bucharest compared to

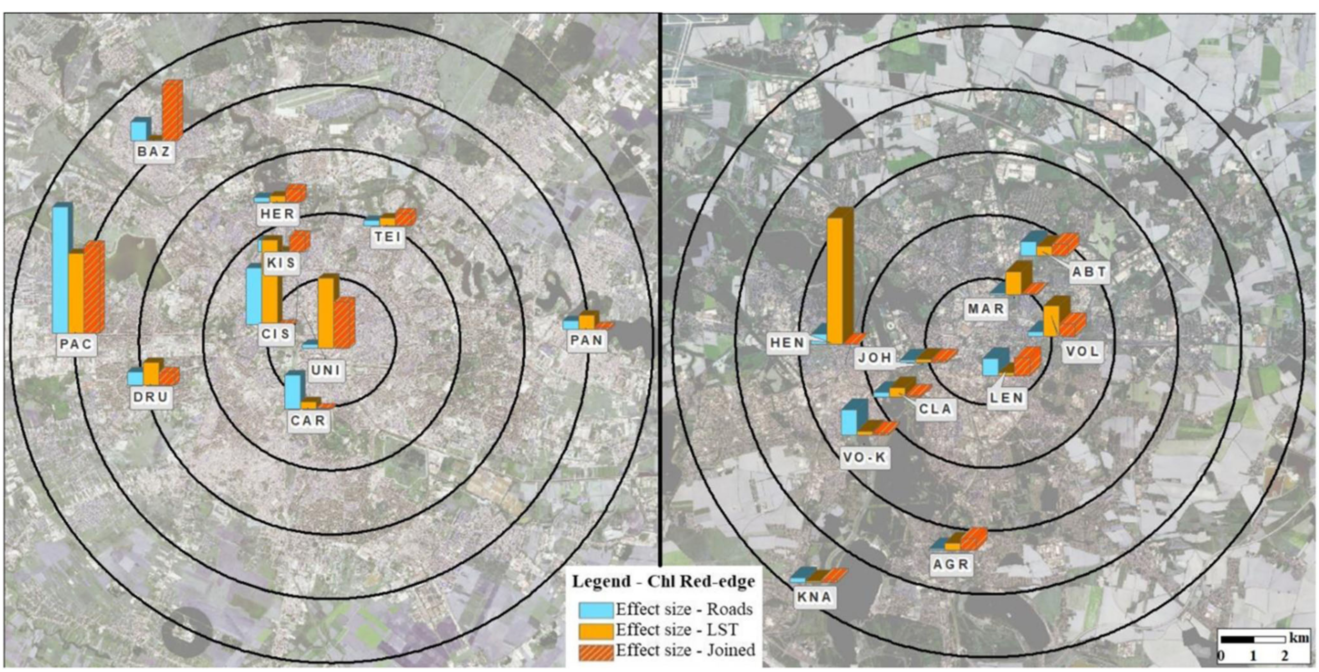


Fig. 5 Map of effect size in ANOVA for the impact of traffic and LST on vegetation, taken individually and joined, related to Chl Red-edge in Bucharest (left) and Leipzig (right)

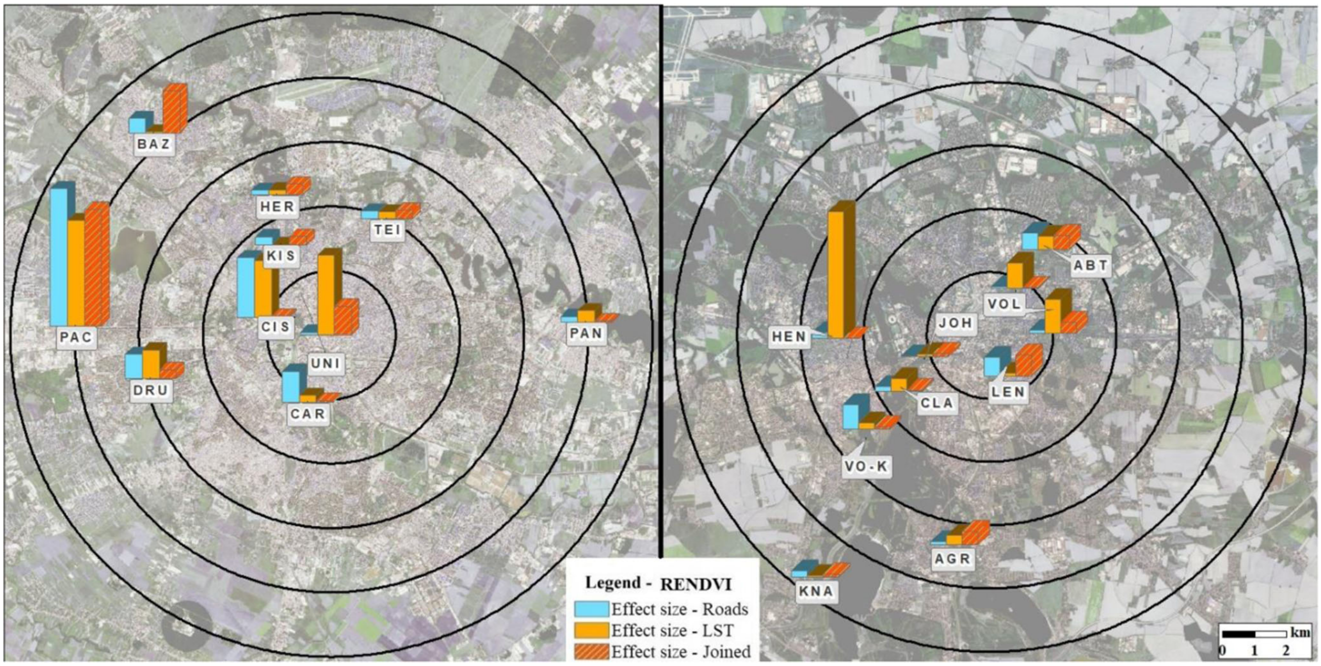


Fig. 6 Map of effect size in ANOVA for the impact of traffic and LST on vegetation, taken individually and joined, related to RENDVI in Bucharest (left) and Leipzig (right)

Leipzig, the parks in both cities have an overall positive impact for mitigating the heat island effect measured by the proxy of LST.

Park vegetation must be in a healthy state to provide their claimed services properly and to mitigate the external pressures such as heat and air pollution. We shall further discuss our findings in terms of vegetation health conditioned by two environmental factors, which was our second objective in this study.

Here, we map the impact of traffic and heat-stress on urban park vegetation, similar to previous studies (Malthus and Younger 2000; Xiao and McPherson 2005; Asmaryan et al. 2013), but we answer directly the question: Which parks are most affected by traffic and LST? Whereas earlier studies

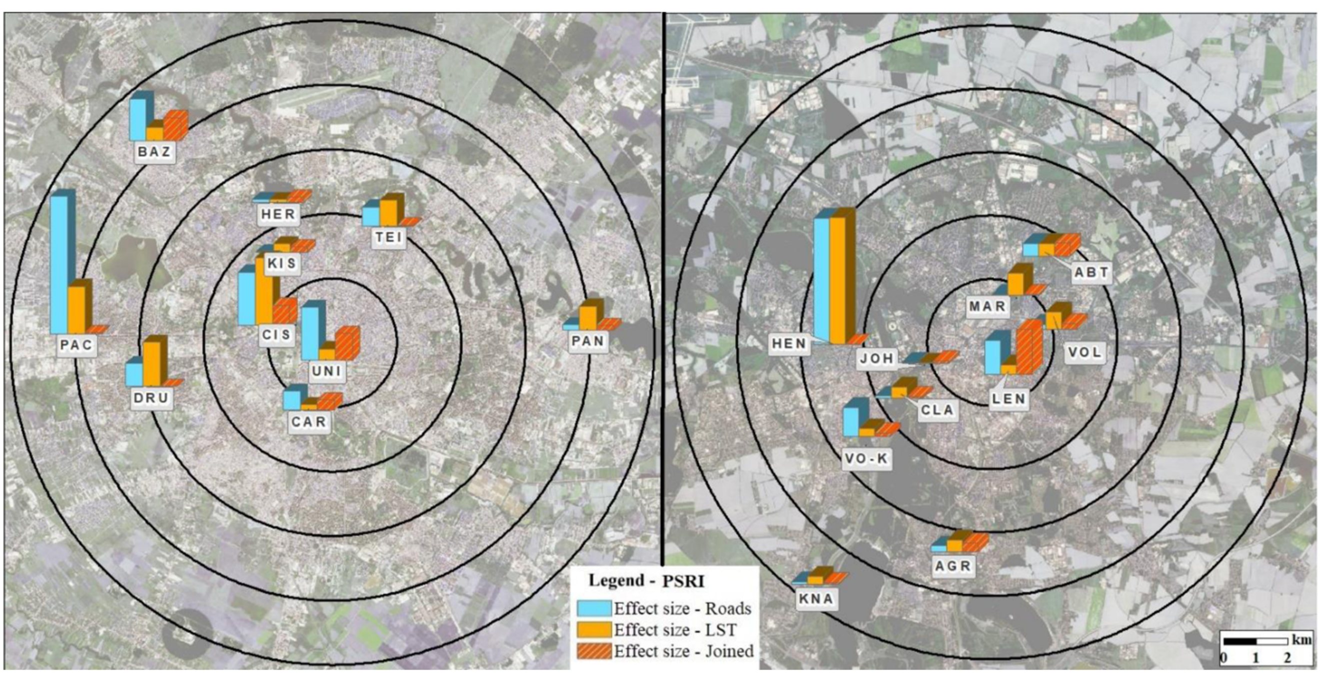


Fig. 7 Map of effect size in ANOVA for the impact of traffic and LST on vegetation, taken individually and joined, related to PSRI in Bucharest (left) and Leipzig (right)

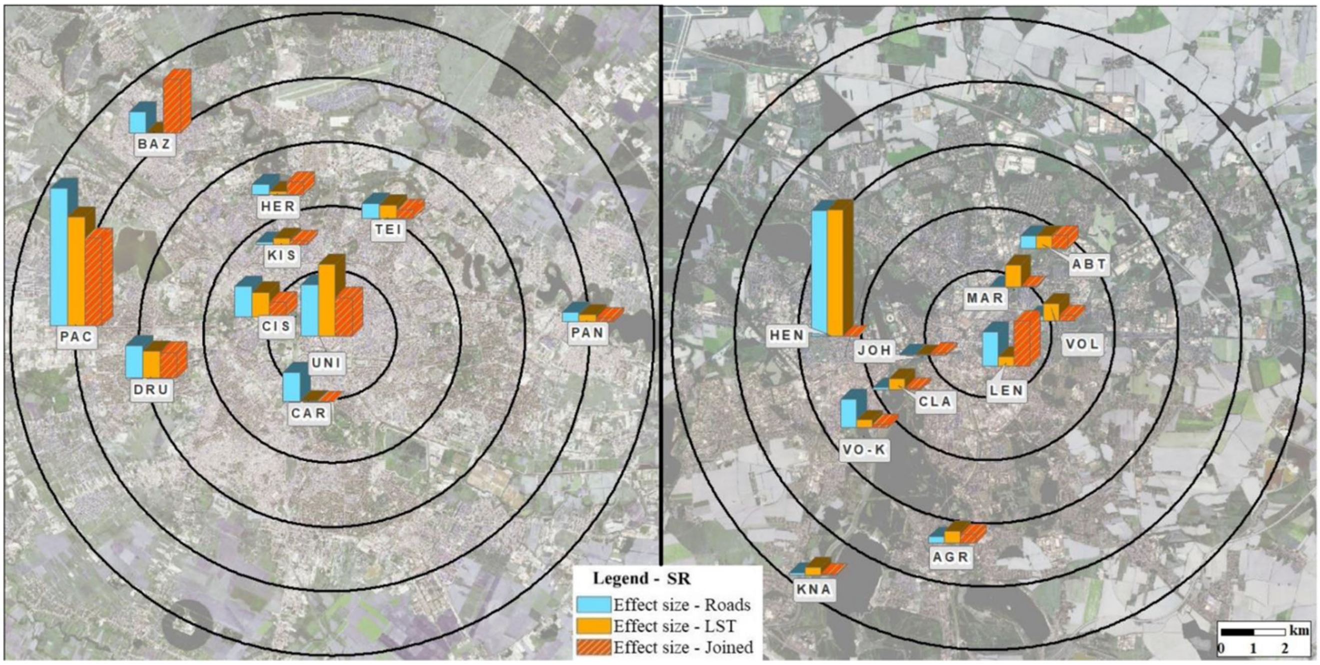


Fig. 8 Map of effect size in ANOVA for the impact of traffic and LST on vegetation, taken individually and joined, related to SR in Bucharest (left) and Leipzig (right)

focused on the health of urban forests or street trees (Malthus and Younger 2000; Oswalt and Clatterbuck 2004; Gusso et al. 2014; Livesley et al. 2016) or contamination of urban horticulture (Säumel et al. 2012), we focused our study on trees within parks. The majority of these studies succeed in classifying the vegetation in *healthy* or *unhealthy* as a response to one decisive parameter: either pollution (Vacek et al. 1999) or drought (Bhuiyan et al. 2017). To our knowledge, this study may be the starting point for mapping the joined influence of traffic-related pollutants and heat stress on selected parks from two big European cities.

The results of the study clearly show which parks are affected by traffic and high temperatures as indicated by spectral indices sensitive to biochemical and biophysical parameters.

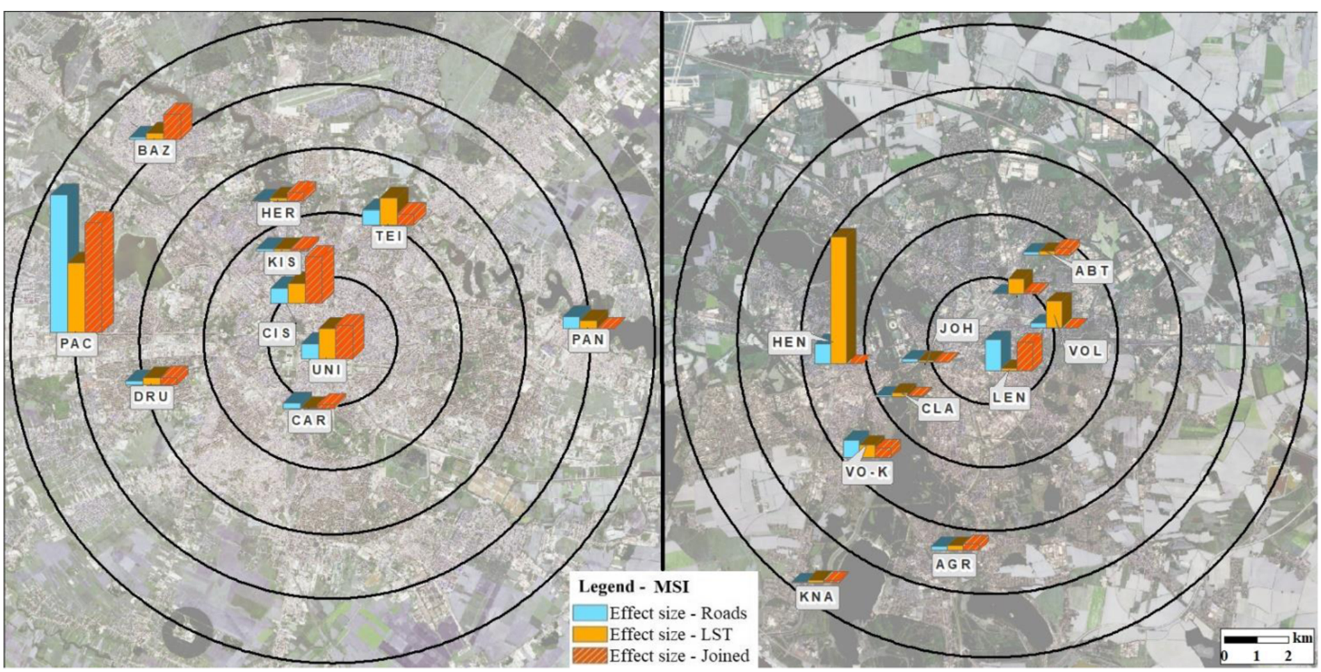


Fig. 9 Map of effect size in ANOVA for the impact of traffic and LST on vegetation, taken individually and joined, related to MSI in Bucharest (left) and Leipzig (right)

Table 5 Pearson correlation between LST and surface imperviousness and LST and park's area

	Bucharest	Leipzig
LST - Imperviousness	.666**	.710**
LST - Park area	−.645*	−.617**

*Correlation is significant at the 0.05 level

**Correlation is significant at the 0.01 level

The results are mapped using an urban-rural gradient in order to understand the local context of each park. Using remote sensing images, we can inspect for each park which parameters were affected by these external factors.

Some parks in Bucharest (CAR, HER, PAC, BAZ) and Leipzig (CLA, AGR) report a high number of vegetation indices with statistical significant effect size. This can be explained by the fact that more parks in Bucharest are sensitive to external factors compared to Leipzig, meaning that the closer to the road a tree is situated and stressed by high temperatures, the poorer is the vegetation state. The individual impact of LST shows an intense influence on the tree's fitness. In Bucharest, effect sizes are large across all buffer-rings, mainly within UNI, CIS, DRU, PAC. In Leipzig, effect sizes decrease from city to periphery, as described by LEN, HEN, VOL, VO-K (Figs. 5, 6, and 7). AGR and KNA, located in the fourth and fifth buffer rings, show the lowest influence from roads and LST on vegetation status.

Other parks in Bucharest (CIS, KIS, DRU) and Leipzig (LEN, MAR, ABT, JOH, VO-K) indicate vegetation stress for one parameter, mostly because they are medium-sized and thus easier to be maintained as they are located in a central area of the city. This is explained by the fact that the local authorities treat them with priority thanks to the recreational values they bring to citizens and tourists and thus indirectly contribute to cash flows from tourism.

For CIS in the first ring in Bucharest, only temperature acts as a decisive parameter on decreasing the vegetation status revealed by chlorophyll-related indices and moisture indicator. Also for CIS, both combined factors have an impact on the moisture indicator. For HEN in the third ring in Leipzig, SR indicates that vegetation is affected by both external factors. However, HEN in Leipzig records the highest values for effect sizes for each analyzed index, meaning that in this small park, the response of the trees locates closest to the roads are very different from the ones furthest of the roads.

Table 6 Pearson correlation coefficient between vegetation indices and estimated LST around the parks (150 m)

		LST around parks	
		Bucharest	Leipzig
Chl red-edge	Chl red-edge	.493	.875**
	RENDVI	−.441	−.888**
	PSRI	.498	.744*
	SR	−.142	−.613
MSI	MSI	.471	.885**

**Correlation is significant at the 0.01 level

*Correlation is significant at the 0.05 level

The parks that did not reveal any statistical significance for the interaction of the two factors on vegetation state are UNI, TEI, PAN and VOL, KNA. We can observe that UNI and TEI reveal a strong statistical significance for the individual impact of LST on vegetation status and PAN for both factors, but taken individually. UNI is a small park located in an ultra-central area in Bucharest, with high soil sealing which leads to the highest temperatures inside the city: average LST around this park is 33.33 °C. Therefore, temperature has an overwhelming impact on vegetation over traffic. VOL from Leipzig is similar to UNI from Bucharest because it is located close to the city center and the average LST around it is the second one among the analyzed parks: 24.58 °C.

In conclusion, integrating freely available remote sensing data from different sensors enables investigating the vegetation state in Bucharest and Leipzig and, more specifically, the factors which have an impact on trees: heat or traffic-related pollutants. Moreover, our study emphasizes the role of healthy vegetation in delivering ecosystem services, especially cooling services.

Conclusions

The results of this study show that Bucharest records a stronger urban heat island effect than Leipzig; therefore, the role of vegetation in delivering ecosystem services is limited. Here, analysis of public remote sensing data reveals that urban vegetation status can be affected by air pollutants due to high traffic and by high temperatures due to surface imperviousness. However, the impact of these factors is context dependent and it is related to the parks' location, area and management. The vegetation in Leipzig records lower influence of these factors in suburban areas than the central one, whilst vegetation in Bucharest is affected by traffic and heat stress throughout all five circular secitons, except for the few parks with efficient management. The two analyzed external factors influence vegetation at different levels from physical parameters and moisture content to photosynthesis processes based on chlorophyll. Hence, there is great potential to combine complementary public remote sensing data with high acquisition rates and spatial coverage such as Landsat 8 and Sentinel 2 imagery for monitoring urban vegetation's health related to current issues: traffic and high temperatures. Therefore, we

Table 7 Effect size of ANOVA for assessing the impact of external factors on vegetation

	Chl R-e	RENDVI	PSRI	SR	MSI	Chl R-e	RENDVI	PSRI	SR	MSI
			B: CIS					L: LEN		
Roads	0.231*	0.321**	0.269*	0.190	0.099	0.130	0.134	0.038	0.273*	0.233*
LST	0.343**	0.306**	0.338**	0.154	0.130	0.020	0.022	0.228*	0.075	0.014
Roads x LST	0.001	0.009	0.102	0.092	0.304**	0.136	0.151	0.055	0.358**	0.215
			B: UNI					L: MAR		
Roads	0.015	0.015	0.262	0.314	0.096	0.011	0.011	0.048	0.008	0.004
LST	0.282	0.423*	0.056	0.440*	0.192	0.174***	0.184***	0.113***	0.174***	0.115***
Roads x LST	0.188	0.154	0.132	0.236	0.216	0.005	0.006	0.016	0.007	0.015
			B: KIS					L: VOL		
Roads	0.047**	0.043**	0.004	0.013	0.013	0.038	0.022	0.151	0.036	0.037
LST	0.004	0.001	0.043**	0.038*	0.016	0.230	0.243	0.255	0.135	0.208
Roads x LST	0.066**	0.046*	0.027	0.024	0.018	0.096	0.078	0.051	0.042	0.005
			B: CAR					L: ABT		
Roads	0.139***	0.167***	0.095***	0.181***	0.037**	0.107***	0.117	0.021	0.098**	0.021
LST	0.031**	0.038**	0.028*	0.008	0.008	0.071**	0.097**	0.009	0.099**	0.029
Roads x LST	0.005	0.011	0.051***	0.002	0.028*	0.091**	0.103**	0.039	0.104**	0.053
			B: HER					L: CLA		
Roads	0.021***	0.026***	0.015**	0.063***	0.006	0.038***	0.038***	0.032***	0.019***	0.015**
LST	0.025***	0.027***	0.015**	0.019**	0.023***	0.075***	0.092***	0.037***	0.092***	0.036***
Roads x LST	0.056***	0.060***	0.028***	0.078***	0.057***	0.013**	0.011**	0.025***	0.015**	0.010**
			B: TEI					L: JOH		
Roads	0.023	0.041	0.096	0.093	0.100	0.020	0.006	0.001	0.009	0.027
LST	0.032	0.038	0.130**	0.081	0.176**	0.027	0.022	0.035	0.007	0.016
Roads x LST	0.051	0.047	0.006	0.054	0.072	0.021	0.027	0.015	0.023	0.005
			B: DRU					L: HEN		
Roads	0.054	0.130*	0.116	0.198**	0.026**	0.077	0.039	0.688	0.995***	0.156
LST	0.093	0.154*	0.221**	0.163**	0.048	0.957	0.913	0.697	1.000**	0.964
Roads x LST	0.054	0.049	0.001	0.157**	0.050	0.001	0.001	0.001	0.001***	0.001
			B: PAN					L: VO-K		
Roads	0.036	0.031	0.026	0.056**	0.077**	0.196***	0.180***	0.062***	0.227***	0.135***
LST	0.057**	0.063	0.119**	0.043	0.049	0.031**	0.047***	0.004	0.062***	0.099***
Roads x LST	0.009	0.007	0.022	0.022	0.001	0.018	0.021	0.004	0.029	0.074***
			B: PAC					L: AGR		
Roads	0.509	0.727**	0.686**	0.836***	0.893***	0.013	0.022	0.041	0.047	0.031
LST	0.321	0.559*	0.237	0.662**	0.451	0.052	0.067	0.103	0.096	0.034
Roads x LST	0.351*	0.618**	0.006	0.533**	0.715***	0.090*	0.096*	0.010	0.068	0.046
			B: BAZ					L: KNA		
Roads	0.075*	0.078*	0.209***	0.127**	0.015	0.033	0.043	0.026	0.016	0.002
LST	0.003	0.006	0.067	0.001	0.040	0.012	0.011	0.001	0.061	0.019
Roads x LST	0.226***	0.224***	0.114**	0.325***	0.161***	0.023	0.020	0.018	0.013	0.016

**Significant level 0.1 **Significant level 0.05 ***Significant level 0.01*

Small effect: <0.01Medium effect: 0.01–0.06Large effect: > 0.06

Parks are listed from city center to periphery. Cells are categorized based on result's magnitude (Richardson 2011)

Source: Processed data from Sentinel-2 and Landsat 8 imagery and OSM dataset

point out that free earth observation data can contribute to reach the Sustainable Development Goal of human wellbeing in urban areas.

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