



RESEARCH ARTICLE

Neighbourhood character affects the spatial extent and magnitude of the functional footprint of urban green infrastructure

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Received: 9 October 2019 / Accepted: 26 May 2020
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Abstract

Context Urban densification has been argued to increase the contrast between built up and open green space. This contrast may offer a starting point for assessing the extent and magnitude of the positive influences urban green infrastructure is expected to have on its surroundings.

Objectives Drawing on insights from landscape ecology and urban geography, this exploratory study investigates how the combined properties of green and grey urban infrastructures determine the influence of

urban green infrastructure on the overall quality of the urban landscape.

Methods This article uses distance rise-or-decay functions to describe how receptive different land uses are to the influence of neighbouring green spaces, and does this based on integrated information on urban morphology, land surface temperature and habitat use by breeding birds.

Results Our results show how green space has a non-linear and declining cooling influence on adjacent urban land uses, extending up to 300–400 m in densely built up areas and up to 500 m in low density areas. Further, we found a statistically significant declining impact of green space on bird species richness up to 500 m outside its boundaries.

Conclusions Our focus on land use combinations and interrelations paves the way for a number of new joint landscape level assessments of direct and indirect accessibility to different ecosystem services. Our early results reinforce the challenging need to retain more green space in densely built up part of cities.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10980-020-01039-z>) contains supplementary material, which is available to authorized users.

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Keywords Urban green infrastructure (UGI) · Ecological flows · Rise-and-decay functions · Neighbouring effects · Breeding birds · Land surface temperature

Introduction

Maintaining or improving the quality of urban green infrastructure, UGI, (here understood as including ‘blue’, i.e. water elements but otherwise used in the more restrictive sense as *functionally connected larger green spaces* of different types) is a widely recognized strategy for making cities more liveable, attractive and, in certain ways, resilient (Pauleit et al. 2018; Andersson et al. 2019). Much of the value stems from the ability of UGI to lift the overall quality of the urban landscape and thus human wellbeing throughout cities (e.g. Cho et al. 2009; Selman 2009). Many ecosystem services need to be generated where people live, work and spend most of their time rather than at a distance, which make the spatial arrangement of different land uses and cross boundary interactions critically important (Colding 2007; Blitzer et al. 2012; Andersson et al. 2015). On these grounds, strategically integrating UGI into the urban fabric has been presented as a direct instrument for changing the overall functionality and liveability of cities (Kabisch et al. 2017).

The challenge we face is to develop scientifically based land use planning approaches and tools that help urban planners and architects make better use of ecological principles such as connectivity, distance and complementarity (Dunning et al. 1992; Dale et al. 2001; Nassauer and Opdam 2008). Whereas originally the urban landscape was depicted as green spaces embedded and often isolated in a matrix of built up and other sealed areas, more recent studies describe cities as small scale heterogeneous mosaics of different land uses or covers (e.g. Cadenasso et al. 2007). This has two implications for applied ecology and ecosystem service research: First, we need a better understanding of multiple types of edges and transition zones. Arguably, the often fine grained urban land use mosaics can be understood as dominated by different types of edges (Cadenasso et al. 2003, 2007), which ecologists have long recognised as leading to specific dynamics not that well captured by the individual land use classes (e.g. Wiens et al. 1985; Forman and Collinge 1997; With and King 1997; Miller and Hobbs 2002; Cadenasso et al. 2006). These edge effects have multiple roots, from different organisms seeking to exploit resources in atypical habitats to different spatial morphologies that lead to distinct local climates. Second, edge dynamics must be translated into benefits or other implications for people. Many recent

studies on ecosystem services have taken a spatially explicit approach where flow—the connection between the origin (place) of the service and the final human beneficiaries—is recognised as a central feature (e.g. Bagstad et al. 2013; Haase et al. 2014). However, flow is often described as a uniform, quasi-constant linkage between discrete units (of UGI in our case), even when the relationship is most likely changing with distance in a non-linear manner.

One approach to capture gradual, context-sensitive and most likely often non-linear edge or adjacency effects is to calculate distance *rise-or-decay functions* (Lausch et al. 2015; Fernández 2019) of functional ‘spill-over’ (cf. Fisher et al. 2009; Blitzer et al. 2012). Applying and developing this approach, this paper explores new ways of characterising UGI components as embedded in and influencing other land uses, e.g. residential areas (and thus the ‘living habitat’ of humans in cities). The hypothesis is that the size of the impact UGI has on its surroundings will depend on the character of said surroundings. In this pilot study we use rise-and-decay functions as a method for capturing and visualising this emergent functional landscape, and put the hypothesis to a first test by looking at two qualitatively different environmental/ecological functions: abiotic transition zones around UGI characterized by land surface temperature (*coolscape*), and the extension of ‘ecological quality’ (in terms of presence or richness of breeding birds, a *birdscape*). To be able to use our method to test our hypothesis we first developed spatially explicit data sets for UGI and built up density for two points in time (to match the temperature and bird data) for the city of Leipzig, Germany. Second, we identified service-providing units (SPU) of the UGI, defined as “the smallest distinct physical unit that generates a particular [ecosystem services] and is addressable by planning and management” (Andersson et al. 2015, p. 158), for temperature and birds, respectively. Third, we developed a contiguous land surface temperature data set where varying surface emissivity was accounted for.

Study area

The Eastern German city of Leipzig is a dense city of about 600,000 inhabitants (Statistical agency of the free state of Saxony 2019) featuring an extensive but unevenly distributed UGI embedded in a radio-

symmetrically shaped compact urban landscape. One prominent feature are the artificial channels, floodplain wetlands, rivers as well former open pit mines that have now been flooded and transformed into large lakes. UGI is predominantly found along a north south gradient west of the centre where large remnants of the Leipzig well-known hardwood floodplain forests (Haase and Gläser 2009) provide the core and kind of north–south axis across the town. Other prominent UGI elements include larger and smaller urban parks—some of them placed on former brown-fields—allotment gardens and comparatively central tree-rich cemeteries. Large (old, mostly 19th and early twentieth century established) parks and green spaces are usually located in the dense built residential space (see classification below) whereas low-density residential spaces include less and smaller parks.

Leipzig's UGI is unevenly distributed across a 'green heart', two dense eastern and western built up 'blocks' and less dense or comparatively rural surroundings.

Mirroring the density of the built up areas, population density in Leipzig is highest in the housing estates located east and west from the central floodplains; the densest districts have > 12,000 inhabitants per km² whereas the lowest densities in the outer parts of the city report a less than 100 inhabitants per km².

Methods

Identification of service-providing units and density of built-up area

Information on the composition and extent of UGI for 2005 (temperature) and 1993 (breeding birds) was derived from local biotope datasets (Sächsisches Landesamt für Umwelt 1994; Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie 2010) including land use information on different types and sizes of UGI elements, as well as on built-up land uses. Both datasets were used to identify SPUs of the UGI, and the location and type of residential areas (Fig. 1). The availability of a consistently classified time series of biotope data ensured a good match and comparability between the two regarded time steps of the bird dataset and the land surface temperature image. Population data for the city of Leipzig was acquired

for the years 1993 and 2005 at district level (Amt für Statistik und Wahlen Stadt Leipzig 2019).

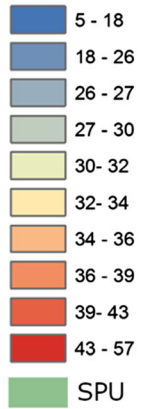
We derived potential SPUs, i.e. relevant functional elements of the UGI, for both the *coolscape* and the *birdscape* from the respective biotope map. Service-providing units include green areas, parks, allotments, cemeteries, grassland, forest, fallow land, excavation, landfill, rivers, and lakes. Arable land is considered as a service-providing unit only for the *coolscape* as the intensely used agricultural areas do not provide breeding grounds (Fig. 1).

Spatial disaggregation of population densities was carried out using an "intelligent dasymetric mapping" (IDM) approach described by Mennis and Hultgren (2006). In this case study, IDM is used to disaggregate the population of Leipzig onto relevant built-up land. Like dasymetric mapping, IDM is an area interpolation approach for small-area estimates, characterized by the use of an ancillary dataset to obtain higher resolutions in the spatial disaggregation process (Eicher and Brewer 2001; Mennis and Hultgren 2006). This is achieved by intersecting statistical data of "source zones"—here, the population count per district—with the ancillary dataset—here, categorical land-use data—to derive "target zones", i.e., spatially homogeneous mapping units, onto which data is redistributed as a combination of areal weighting and a relative density of the corresponding ancillary class (ibid., cf. Equation 2). This relative density is, here, a function of, e.g., built-up density and/or building structure type.

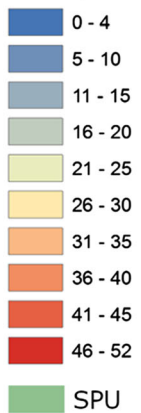
In this case study, population statistics on the level of urban districts for the city of Leipzig (Amt für Statistik und Wahlen Stadt Leipzig 2019) was disaggregated to built-up area as ancillary classes derived from the local biotope datasets 1992/93 as well as 2005 (Saxon biotope and land-use mapping, cf. Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie 1994, 2010). The local biotope datasets define a set of built-up land-use classes of varying relative densities, e.g. urban residential areas of different building structure types such perimeter block development, terraced houses, single houses and semi-detached houses, or clustered high-rise, residential areas of rural character, as well as mixed-use areas. Here, relative densities were derived with the centroid method described by Mennis and Hultgren (2006). This method obtains a sample of land-use types based on the spatial relationship of a district's centroid and

Surface temperature

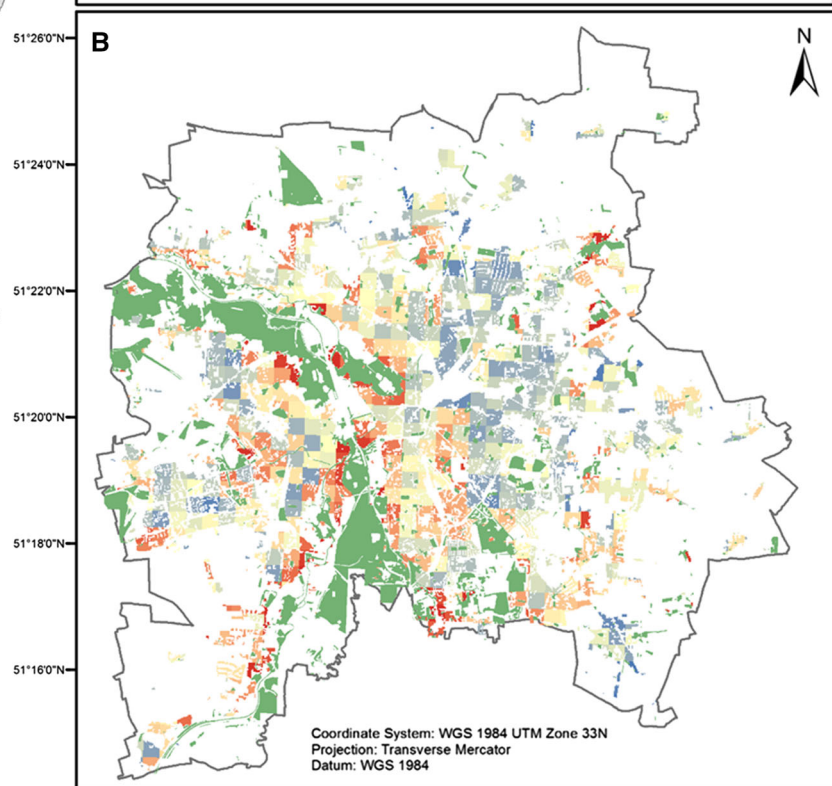
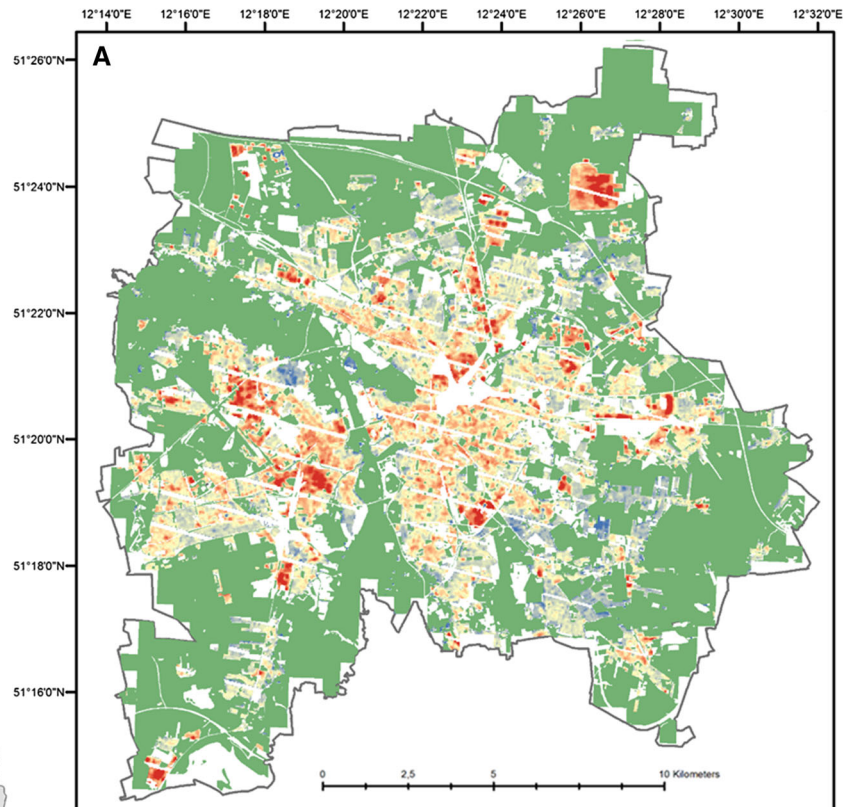
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Bird species richness



Cartography: Thilo Wellmann



◀ **Fig. 1** Map of Leipzig’s service providing units (SPU) as derived from two biotope maps (the discrepancy in SPU area between **a** and **b** is due to the fact that intensive agriculture is not considered a SPU regarding bird habitat) with the regarded response variables for the robust regression analysis for all considered built-up surfaces, **a** Land surface temperature derived from Landsat 7, **b** breeding bird species richness as surveyed in the years 1991 to 1993 and **c** the location of the city of Leipzig in Germany

the underlying ancillary class. From this sample, relative densities for each built-up (ancillary) class was estimated. Furthermore, for some ancillary classes, relative densities were pre-set to contain no population. Population was subsequently disaggregated using the following equation (Mennis and Hultgren, 2006):

$$\hat{y}_t = y_s \left(\frac{A_t \hat{D}_c}{\sum_{t \in s} (A_t \hat{D}_c)} \right) \quad (1)$$

where \hat{y}_t is equal to the population estimate of each target zone t , i.e. homogeneous spatial mapping unit, y_s is equal to the population count given for the source zone, i.e. the statistical unit such as the urban district,

A_t is equal to the area of the target zone t , and where \hat{D}_c is equal to the estimated or pre-set relative density of the corresponding ancillary class c .

For density classification, we calculated the NDVI from Landsat 5 TM (Thematic Mapper) for both target years 1993 (1993-07-02, congruent to the breeding bird dataset) and 2005 (here actually 2004-08-08 since there were no clear sky summer observations available from 2005), since in 1993 Landsat 7 was not yet launched. Using the population disaggregation and NDVI data, the built-up land uses are then categorized into density classes (Fig. 2). We split both indicators around their median value to generate four equally large classes based on the parameters in Table 1.

Determination of land surface temperature

Earth observation data were retrieved from Landsat 7 ETM + (Enhanced Thematic Mapper) for 2004-08-09 at 11:51:05 local time. Of the available bands we used the Near Infrared band and the red band featuring a 30 m ground resolution from both Landsat 5 and 7 as well as the thermal infrared band (around 11.50 μm) from the Landsat 7 ETM + sensor. The latter features a 60 m ground resolution (in comparison to 120 m in

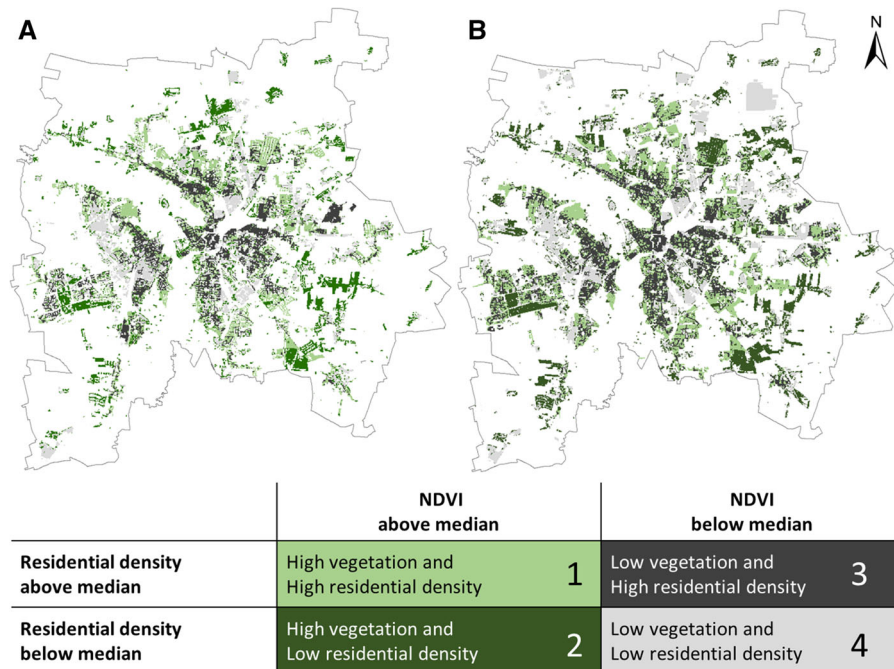


Fig. 2 Classification of residential density and the normalized difference vegetation index (NDVI) into four density classes for the city of Leipzig in **a** 1993 and **b** 2005

Table 1 Parameters for density classification, which are based on the normalized difference vegetation index (NDVI) and residential density

		NDVI (dimensionless)		Residential density (inhabitants/km ²)	
		1993	2005	1993	2005
1	High vegetation and high residential density	0.4–1	0.4–1	3700–54,300	3700–36,200
2	High vegetation and low residential density	0.4–1	0.4–1	0–3700	0–3700
3	Low vegetation and high residential density	0–0.4	0–0.4	3700–54,300	3700–36,200
4	Low vegetation and low residential density	0–0.4	0–0.4	0–3,700	0–3700

the case of the Landsat 5 thermal band). For this study, we used the high gain mode band.

Land surface temperature was determined using Landsat 7 data (acquired on 2004-08-09 local time) since it features superior spatial resolution compared to its predecessor Landsat 5 and its successor Landsat 8. For the recalculation of sensor radiance to surface temperature the NDVI (Normalized Difference Vegetation Index, Eq. 1) is needed to account for varying surface emissivity. The NDVI is an indicator for the greenness of plants (Gitelson and Merzlyak 1997) and is describing the relation between absorbed light in NIR and the red part of the electromagnetic spectrum.

The transformation of the at-sensor radiances acquired by the Landsat 7 ETM + spectroscope to land surface temperature involves correction for both the atmosphere and the surface emissivity (Coll et al. 2010). For the atmospheric correction, we used a web-based tool provided by NASA (<https://atmcorr.gsfc.nasa.gov>; (cf. Barsi et al. 2003). This tool computes three atmospheric parameters τ , $L\uparrow$, and $L\downarrow$ (Band average atmospheric transmission: 0.76, effective bandpass upwelling radiance: 1.83 W/m²/sr/um and Effective bandpass downwelling: 2.99 W/m²/sr/um) based on reference atmospheres that are interpolated with the MODTRAN tool (Berk et al. 1987). To account for varying surface emissivity, the NDVI threshold method was deployed (Sobrino et al. 2004). This is a commonly applied procedure making use of the fact that vegetation and built-up structures feature different degrees of surface emissivity. In our study, we used an ArcGIS implementation of this procedure by Walawender et al. (2012).

Breeding bird species count data

The breeding bird dataset used in this study contains presence/absence information for 120 bird species in

1132 cells (500 by 500 m each). The primary data were collected over the three breeding periods in the years 1991 to 1993 for the whole city area by ornithologists surveying each cell at least 5 times per breeding season. This scheme leads to comparably reliable species absence information (StUfa 1995).

Statistical modelling

For the modelling of the ‘scapes’ surrounding the SPUs, i.e. rise-and-decay functions for the chosen indicators, we used robust linear regression based on the MM estimator by Yohai (1987), provided in the R package *robustbase* (Maechler et al. 2019). The Yohai MM estimate is a popular, commonly used, highly efficient type of maximum-likelihood estimation with a high breakdown value, i.e., robustness of the estimate even in the presence of a substantial number of outliers or noise in the dataset (Yohai 1987; Rousseeuw and Leroy 2005; Alma 2011; Yu et al. 2014). The MM estimation method uses a redescending score function, i.e. more extreme outliers are given lower importance in the computation of the regression estimate.

In this case study, land surface temperature and breeding bird species count correspond to the dependent response variables, which are modelled as a function of the predictor variable distance to SPU across the whole city (Fig. 1). Both bird and temperature data were also collected from all SPU values within the area of study. The functional relationship between distance and the response variables was derived for each density class of built-up area. Hereby, per density class, a set of robust linear regression models was fitted to distinct value ranges of the distance predictor, i.e., a model has been fitted per categorical 100 m distance interval up to a total distance of 600 m. This has been done to account for

possible non-linear interactions between the variables along the whole distance plotted. Additionally we also calculated a regression model over the whole range (continuous) of 600 m (Table 3).

Results

Built-up density

Figure 2 lists the elicited median NDVI values and the total building for each built-up land use class. Generally, higher residential density and lower NDVI values translate into denser urban settings, whereas lower values for population density and higher values for NDVI indicate built-up areas of lesser density. We categorized population density and NDVI values into four density classes as follows: (1) High vegetation and high population density, e.g. green old and new built estates, that we consider as medium dense; (2) High vegetation and low population density, e.g. single houses and village-type settlements in the periphery considered as low density development; (3) Low vegetation and high population density, e.g. dense old built estates including downtown that we consider as highest built-up density class; and (4) Low vegetation and low population density, e.g., industrial and commercial land, again considered as low density class (Fig. 2). Using Student's *t* test we determined that the means of the elicited classes are significantly different from each other for both the *birdscape* and the *coolscape* (Table 2). For a comparison of Student's

t test across the distinct distance value ranges, please see Table A1 in Appendix A1.

Rise-and-decay functions for the elicitation of 'scapes'

The applied robust regression analysis elicited statistically significant decay functions, thereby revealing extended distal influences of service-providing units on both abiotic, physical properties (land surface temperature) as well as biotic, ecological patterns (breeding bird species richness) (Table 3). For both land surface temperature and bird species richness it is shown that the highest changes occur in rather close proximity to service-providing units (Figs. 3, 4 and Table A2).

Land surface temperature—the 'coolscape'

In the analysis, it is found that the mean land surface temperature for areas of different vegetation and population densities differ significantly (Table 2). Moreover, a statistically significant relationship between the distance to service-providing units and land surface temperature, characterized by a set of rise-functions, can be found for every density class. Consequently, with increasing distance to service-providing units, land surface temperature tends to increase.

Looking at Fig. 3 and Table A3, it is clear that for all density classes, increases in land surface temperature are highest in the immediate vicinity of service-providing units, i.e. distances of up to 100 m distance.

Table 2 Cross tables showing the differences in the mean values, between the row (reference value) and the column variable with the significance level of a Student's *t* test with **a** representing surface temperature and **b** bird species richness

Density class				1	2	3	4
Name	Mean	± SD	Number				
High vegetation and high residential density	(A) 33.05	(A) 1.62	1	(A) 0.26 ***	(A) -2.03 ***	(A) -3.49 ***	
	(B) 21.96	(B) 9.43		(B) -1.23 ***	(B) 2.38 ***	(B) 1.66 ***	
High vegetation and low residential density	(A) 32.79	(A) 1.94	2			(A) -2.30 ***	(A) -3.76 ***
	(B) 23.21	(B) 9.10				(B) 3.62 ***	(B) 2.90 ***
Low vegetation and high residential density	(A) 35.09	(A) 1.46	3				(A) -1.46 ***
	(B) 19.58	(B) 9.01					(B) -0.72 ***
Low vegetation and low residential density	(A) 36.56	(A) 2.91	4				
	(B) 20.30	(B) 9.35					

Signif. codes: ***($p < 0.0001$).

Table 3 Model coefficients and their significance level derived from a robust linear regression for the different density classes with **a** representing surface temperature and **b** bird species richness over a 600 m distance range

		(A) Surface temperature		(B) Birds species richness	
		Intercept	Slope	Intercept	Slope
1	High vegetation and high population density	32.64***	0.00396***	25.04***	-0.01452***
2	High vegetation and low population density	32.39***	0.00496***	25.22***	-0.00926***
3	Low vegetation and high population density	34.57***	0.00352***	22.02***	-0.01196***
4	Low vegetation and low population density	35.17***	0.01003***	25.60***	-0.02123***

***Significant parameter ($p < 0.001$)

It is also clear that the land surface temperature increase is more pronounced in denser urban settings compared to lower density, more 'open' built-up areas (Fig. 3 and Table A3 in Appendix A3). For example, in case of the first density class, the findings suggest that over a distance of up to 100 m from a service-providing unit, land surface temperature increases by approximately 0.025 °C per metre, or about 2.5 °C in total. This is a twofold increase compared to low density settings represented by the second density class, where land surface temperature increases by 0.008 °C per metre, i.e. about 0.8 °C in total.

At distances greater than 100 m, the observed slopes are decreasing substantially; for class 1, no significant change in land surface temperature is observed for distances greater than 200 m, whilst for the density classes 3 and 4 the *coolscape* extends up to 300 m. Only in the case of class 2 the *coolscape* extends beyond that to 400 m (Fig. 3 and Table A3 in Appendix A3).

Consequently, the SPU-induced *coolscape* has an effective area that is substantially larger than the SPUs themselves and that is characterized as a non-linear relationship between the distance to SPUs and land surface temperature. Thus, residents benefit from SPUs directly, i.e. on-site, as well as near SPUs, due to the distal cooling effect. The coefficients derived by the fitting of robust linear regression models to the distinct distance value ranges indicate an influence *scape* extending up to 500 m from a SPU (Table A2).

Breeding bird species richness—the ecological 'birdscape'

In contrast to the rise-functions derived for land surface temperature, the ecological *birdscape* is

characterized by a set of decay-functions. Consequently, with increasing distance to service-providing units, the number of breeding bird species tends to decline. Contrary to the *coolscape*, the steepest drop in bird species richness occurs within distances of up to 100 m–300 m from the SPUs. In the first 100 m there is a slight although non-significant increase in bird species richness in two of the four density classes (significance level see Table A2 in the appendix). The elicited negative trends are statistically significant afterwards for distances of up to 500 m ($p < 0.001$) for all density classes (Fig. 4). Looking at the slope coefficients listed in Table 3, a similar pattern, as in the temperature *scape* unfolds, where the fourth density class—i.e., low density setting—is strongest influenced by an SPU.

We could detect the *birdscape* effect, i.e., higher species richness, of SPUs up to 400 m for the density classes 1, 2 and 3. For the fourth class, the *birdscape* could be detected up to 600 m from the SPU (Fig. 4). In the high residential density classes 1 and 3, bird species richness outside the SPU showed the overall least influence of SPUs. Furthermore, compared to the less dense populated classes, they exhibit the overall lowest number of bird species adjacent to SPUs. The fourth density class shows a bird richness distribution strongly influenced by the presence and adjacency of SPU. When averaging over all four density classes the *scape* extends to 500 m (Table A2).

Discussion

Using one environmental and one ecological variable (treated as and assumed to be independent), both relevant for capturing different aspects of urban

environmental quality, we have showed how urban morphology and density patterns can be described in terms of function rather than structure, shifting or redefining the boundaries normally used to define and classify urban land use (Haase et al. 2014). This will help the identification of areas undersupplied not only in terms of direct access to or allocation of UGI and thus SPUs (Schetke et al. 2012; Kabisch et al. 2016; Wolff and Haase 2019)—which primary serve as

assessment units in prevailing ecosystem services assessments (Maes et al. 2013; Haase et al. 2014; Pauleit et al. 2018)—but outside the functional influence of the of SPUs.

For land surface temperature, the density classes 1 and 3—high and low NDVI/high Pop—appear to be the coolest areas in the entire city (Median of 33 °C). For class 3, the existence of neighbouring SPUs clearly has a cooling effect, which is in agreement with

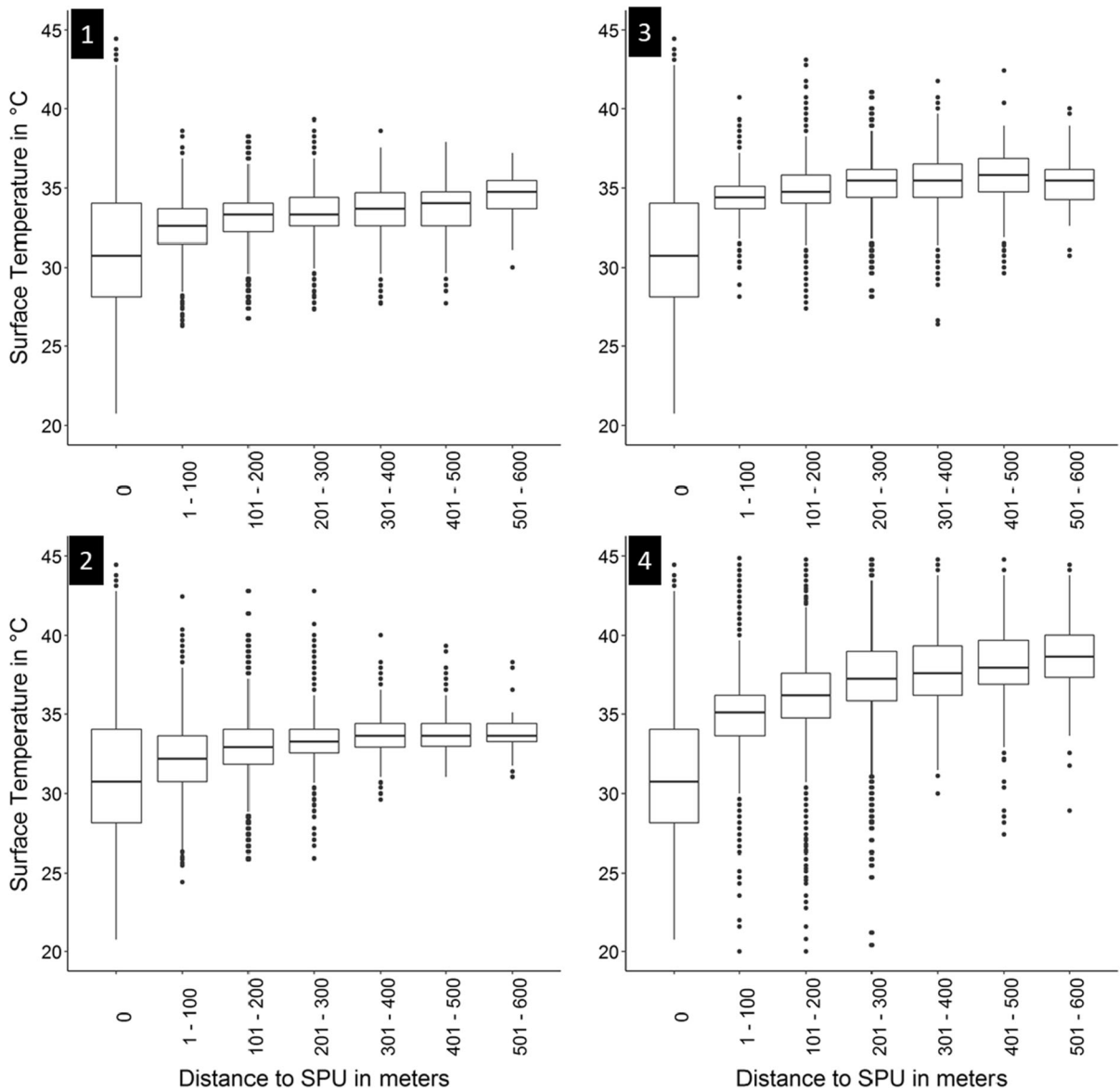


Fig. 3 Relationship between distance to service providing unit (SPU) (0 representing the SPU itself) and surface temperature for the four density classes. The robust linear regression model

coefficients derived for each distance range are presented in Table A3 in the Appendix

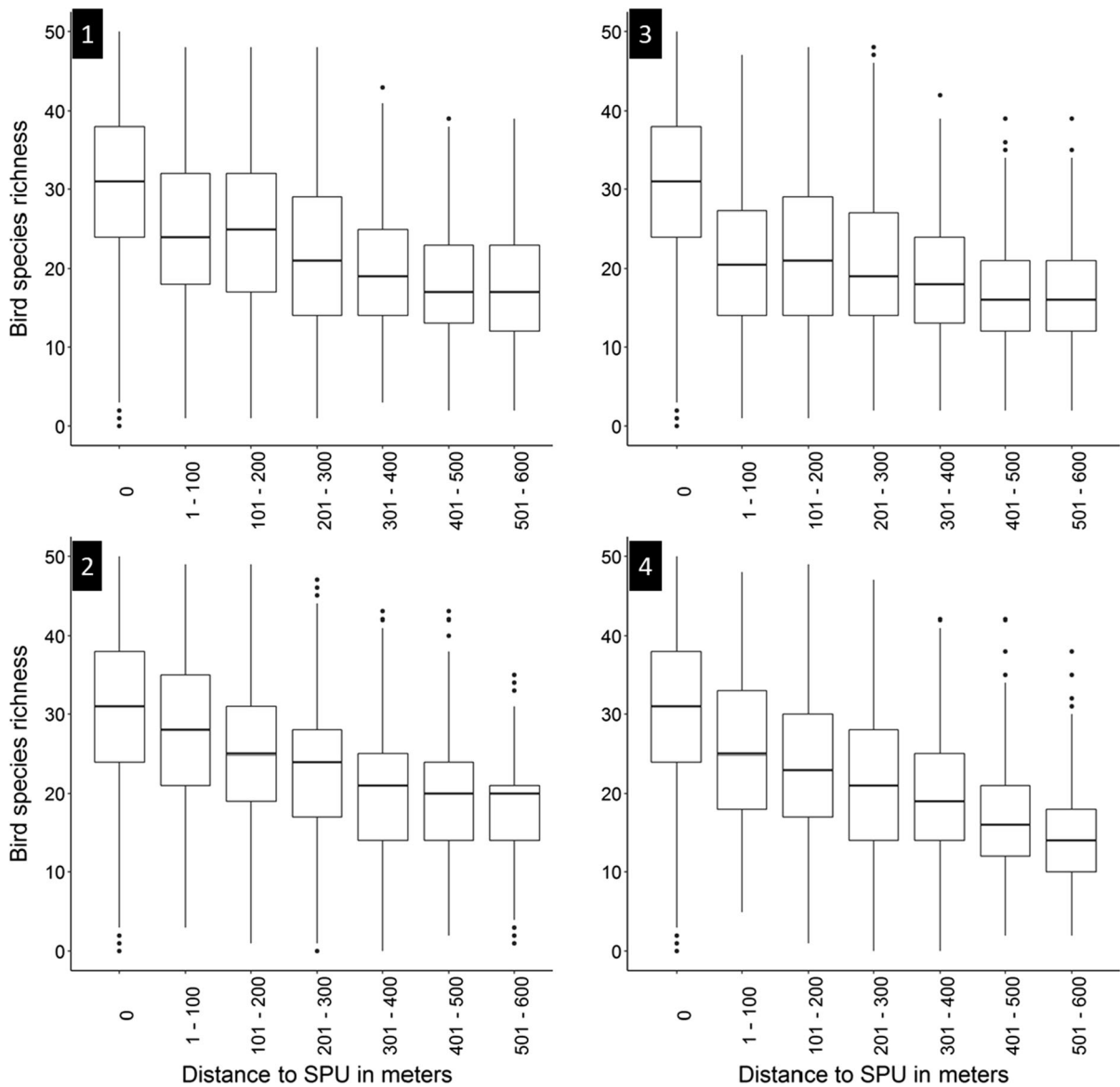


Fig. 4 Relationship between distance to service providing unit (SPU) (0 representing the SPU itself) and bird species richness for the four density classes. The robust linear regression model

coefficients derived for each distance range are presented in Table A2 in the Appendix A2

the findings of Cheng et al. (2014) and Fernández (2019). For class 1, we find comparatively low ('cool') surface temperatures despite a high population density. Thus, the need for SPUs providing cool air is low. In other words, we find two working options for green cooling, SPUs or 'built in' green. Class 2 is less dependent on SPU adjacency since temperatures are lower on average than those of class 4, which has been

attributed to its high sealing rates (Median of 35.1 and 36.1; Haase and Glaser 2009).

For breeding bird species richness, it has been shown that species richness is typically the highest in the immediate vicinity of SPU, irrespective of density class. However, built-up density has a significant impact on the influence of SPUs as distances increase. In this regard, our findings indicate that low-density urban settings with more built in green spaces, e.g.,

(village-type or peripheral) single house developments, appear to themselves better support breeding bird species richness when compared to low-density land with less green, i.e., industrial and commercial land, which seems to be the most environmentally 'hostile' towards breeding birds. Relative to density class 4, the decline in species richness appears to be less pronounced in density class 3, i.e., high-density residential estates, although the overall species count in close proximity to SPU is lower in comparison. Apparently, also a dense city can provide suitable habitat for specific breeding birds given a good 'quality' of the urban matrix, although remaining reliant on a nearby SPU (cf. Strohbach et al. 2009, for the same study area). This is in line with findings by Prevedello and Vieira (2010) who indirectly point to this by concluding that said quality of the urban matrix generally increases with increasing structural similarity with habitat patches, supporting biodiversity both in UGI and, presumably, its surroundings.

Our findings also point at redevelopment options for 'hostile' urban environments to support breeding bird species richness. For example, density class 4 may be redeveloped and densified, thereby turning it either into medium-density (density class 1) or high-density (density class 3) urban built-up land. As indicated by the elicited *birdscape*, in the former case, greening of backyards could directly provide suitable habitats (see the findings by Wellmann et al., 2018 for greenness and spatial-temporal vegetation trait variations in Leipzig), whereas in the latter case, it is emphasized that a strong dependency on SPU remains, calling for adequate improvement and maintenance of UGI.

Overall, our study shows that distance to SPUs is clearly a relevant factor also for bird species richness, although there are other decisive factors that need to be accounted for in a more fine-tuned model. For example, the pattern of inner-city perimeter development areas featuring higher bird species richness despite the—partial but not overall—lower extent of vegetation and higher sealing rates compared to low density built-up areas at the peri-urban fringes point to other factors influencing bird communities. Species response to landscape structure varies with species traits (e.g. dietary preferences, mobility, sensitivity to different disturbances) (e.g., Blair 1996; Wellmann et al. 2020) and a more detailed analysis of the potential ecosystem services provide and how far into

the denser built up parts of the city these extends will require a more nuanced measure than the species richness we used as a proxy.

Our results indicate that physical distance (scaled to match different functions) to UGI together with density might offer a reasonable and reliable low-investment proxy, especially for temperature. The method helps to highlight the influence green SPUs may have outside their physical/morphological boundaries, not least in terms of how they influence the distribution of potential ecosystem services, and provides urban planners with another tool for balancing urban development needs and assess indirect impacts. The presented rise and decay functions show how the density and morphological properties of SPU surrounding areas/neighbourhoods affects both cool air flowing from the SPUs into the residential space and limit use or visitation by birds. It could be shown that benefits are particularly strong in close proximity (100 m) but extends up to distances up to 500 m from SPUs. In this context, the derived rise-functions could provide a useful tool for urban planning and the implementation of greening measures (Pauleit et al. 2018). Furthermore, our results point to likely synergies between the elicited '*scapes*'—or a multifunctional influence of SPUs—as hypothesized by Haase et al. (2012).

However, what we present are the first estimates, and to better guide planning and design of urban landscapes many functions will require or at least benefit from more detailed models. Multiple studies have demonstrated the importance of urban high-grain morphology and landscape composition including height data, and taking these factors would likely provide additional insights for how to plan, design and manage the areas next to SPUs. For example, Hamstead et al. (2016) show how an urban land use classification based on the combination of green and grey infrastructure can better predict temperature differences. This can be traced back to factors like higher surface sealing rates and denser building structures that do not permit the circulation of near-ground cool air (Ziter et al. 2019), thereby amplifying the need for a regular pattern of green spaces in denser areas of cities. Our models—in strong agreement with Ziter's study—showed first evidence of the strong impact of soil sealing also for decay of cooling effects into the urban space. Similarly, studies of urban ecology have highlighted the importance of access to

different resources, of various barriers and, more generally, landscape configuration (e.g. Clergeau et al. 2001; Melles et al. 2003; Andersson and Bodin 2009) in addition to the composition effects we could show.

Conclusions

This study shows how modelled rise and decay functions can be used to extrapolate and visualise functional transitions and more gradual transitions between UGI and other types of urban (primarily built, sealed) land uses (Cadenasso et al. 2003). Multiple different decay (or increase, depending on the function and indicator) functions provide a framework for comparing continuous mathematical expressions—as proxies for different functions—across cities and UGI constellations, or over time in the same landscape. Our results are quite clear, despite simplifications like the straightforward definition of SPUs, surrounding land use density and a distance measure based only on physical, perpendicular distance.

Comparing cities or urban districts in terms of the share of population with limited or no access to UGI benefits offer a novel and more spatially continuous way of looking at urban human-environmental systems. This pilot study, looking only at two different functions, still point to a promising new avenue for assessing multifunctionality and UGI contributions to urban quality: We found significant nonlinear rise- and decay functions for land surface temperature and breeding bird richness in dependence to their distance from a green space. Cooling effects as well as bird species richness depends on how away the nearest SPU is located, especially for sealed, built and inhabited space. Less dense areas do have clear advantages over dense ones in the efficiency of cooling the surrounding environment but not in terms of hosting more birds. Green ‘cool’ growth is possible but larger low dense areas offer important buffer spaces for keeping cities cool and diverse in bird species. The focus on functional connections and influence of UGI paves the way for a number of new joint assessments of direct and indirect accessibility of different biophysical functions and their related ecosystem services. It also provides a new concept (tool) for investigating the role of urban morphology, land use and population density combinations/patterns at neighbourhood to district (at least) scales.

As such, knowledge about the functional connections and influence of UGI, operationalised as SPUs, can both provide valuable general recommendations for planners and developers and be developed into a tool for directly assessing landscape impacts—across multiple functions—of changes in UGI. While highly promising, as the presented results show, the approach still needs further development and a critical reflection grounded in urban landscape and ecosystem services research.

Acknowledgements Open access funding provided by Stockholm University. This research was carried out as part of the project ENABLE, funded through the 2015–2016 BiodivERSA COFUND call for research proposals, with the national funders The Swedish Research Council for Environment, Agricultural Sciences, and Spatial Planning, Swedish Environmental Protection Agency, German aeronautics and space research centre, National Science Centre (Poland), The Research Council of Norway and the Spanish Ministry of Economy and Competitiveness. Thilo Wellmann receives a scholarship by the Deutsche Bundesstiftung Umwelt DBU (German Federal Environmental Foundation).

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