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SATELLITE-BASED INVESTIGATION ON THE SURFACE COOLING EFFECTS OF URBAN PARKS AND THEIR RANGE – A CASE STUDY FOR NORTH RHINE-WESTPHALIA, GERMANY

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With 9 figures and 1 appendix
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Summary: Green infrastructure (GI) has a cooling effect owing to shading and evapotranspiration and therefore has a climate regulating function within metropolitan areas. Urban parks are a type of GI that act as park cool islands (PCIs) and play a major role in mitigating the surface urban heat island. This study aims to (1) investigate the status quo of the surface cooling effect intensity of selected urban parks in North Rhine-Westphalia (NRW), including their cooling range, and to (2) propose a methodological approach for investigating the PCI intensity using remote sensing data considering the occurrence of mixed pixels. To achieve these tasks, land surface temperature values based on Landsat 8 images from three different days in 2018 and 2019 were observed. In addition, a method for the reduction of mixed pixels was developed. The results confirm a surface cooling effect of 1–5 K and thus the existence of a PCI. The impact of the surface cooling effect was found within a minimum range of 150 m. However, the process of identifying the cooling area was complicated by the high proportion of GI in cities in NRW, compared to other study areas. Further research on the influencing parameters of the surface cooling effect is needed.

Zusammenfassung: Grüne Infrastruktur (GI) hat aufgrund von Beschattung und Evapotranspiration einen kühlenden Effekt, daher profitieren Metropolregionen von dessen klimaregulierender Funktion. Urbane Parks als eine Form von GI bilden eine park cool island (PCI) aus und spielen somit eine wichtige Rolle bei der Linderung der Auswirkungen der oberflächlichen städtischen Wärmeinsel. Die vorliegende Studie hat zum Ziel, (1) den Status quo der Intensität des Oberflächenkühlungseffekts innerhalb ausgewählter städtischer Parks in Nordrhein-Westfalen (NRW) unter Betrachtung der Kühlreichweite zu untersuchen und (2) schlägt einen methodischen Ansatz für eine Untersuchung der PCI Intensität mit Fernerkundungsdaten hinsichtlich des Vorkommens von Mischpixeln vor. Dazu wurden Landoberflächentemperaturwerte aus Landsat 8 Bildern an drei verschiedenen Tagen in den Jahren 2018 und 2019 generiert. Zusätzlich wurde eine Methode zur Reduktion von Mischpixeln entwickelt. Die Ergebnisse bestätigen den Kühlungseffekt von 1–5 K und damit die Existenz einer PCI bei einer minimalen Kühlreichweite von 150 m. Es wurde deutlich, dass der Prozess der Identifizierung der Kühlreichweite durch den hohen Anteil an GI in Städten in NRW im Vergleich zu anderen Untersuchungsgebieten erschwert wird. Weiterer Forschungsbedarf besteht im Hinblick auf die Einflussparametern der Oberflächenkühlung.

Keywords: green infrastructure, land surface temperature, park cool island, North Rhine-Westphalia, remote sensing, mixed pixels

1 Introduction

Nowadays, increasing urbanization and climate change are serious issues faced by cities and the urban population (IPCC 2015; United Nations 2019) because they encourage the formation of a specific phenomenon: the urban heat island (Oke 1982). Both the surface and air heat up more during the day and cool off less during the night in urban surroundings than in rural ones (Mohajerani et al. 2017). The temperature gradient results from the various structures in cities; buildings exhibit high levels of imperviousness and heat storage, in contrast to natural habitats (Oke 1982). When explicitly referring to the surface temperature gradient, the term surface urban heat island (SUHI) is the most accurate (Voogt and Oke 2003). The resulting warm temperatures in metropolitan areas affect human life because, for example, they lead to a decrease in welfare and an increase in mortality (Tan et al. 2007; WMO and WHO 2015). Therefore, it is relevant to mitigate heat island effects.

It is well known that green and blue spaces within urban areas can be beneficial because of their climate regulating functions (e.g., Chang et al. 2007; Chang and Li 2014; Feyisa et al. 2014; Gill et al. 2007; Gunawardena et al. 2017; Shashua-Bar et al. 2009; Tan et al. 2021). Evaporation, transpiration,

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and the shading of water and vegetation lead to lower temperature increases than open impervious surfaces. Hence, a cooling effect occurs and mitigates the high temperatures in urban areas (Gunawardena et al. 2017; Shashua-Bar et al. 2009; Vailshery et al. 2013). The term green infrastructure (GI) includes both green and blue spaces because it can be defined as a network of natural and semi-natural areas (Hansen et al. 2017; Mell 2008; Naumann et al. 2011). It covers several GI types, such as agricultural land, lakes, cemeteries, and urban parks. Urban parks also have a recreational function, which strengthens the importance of this GI type in addition to its climate regulating functions. Therefore, this study focused on urban parks. Because of their cooling abilities, they are referred to as park cool islands (PCIs); the park area has lower temperatures than surrounding areas (Spronken-Smith and Oke 1998). The term PCI intensity describes the temperature difference between urban parks and their surroundings. The cooling effect is not limited to the area within the park; it also affects the surroundings (Feyisa et al. 2014; Hamada and Ohta 2010). The effect reaches a certain distance, which is referred to as the cooling range.

It is important to consider climate adaptation when designing and implementing GI, especially urban parks, within cities. In recent years, the cooling effect and its interaction with certain parameters, such as size (Bao et al. 2016; Vaz Monteiro et al. 2016; Yang et al. 2017), landscape metrics (Cao et al. 2010; Chen et al. 2014; Dugord et al. 2014; Li et al. 2020; Yu et al. 2017), green space characteristics (Du et al. 2017; Jaganmohan et al. 2016) and the normalized difference vegetation index (NDVI) (Buyadi et al. 2013; Feyisa et al. 2014; Hellings and Rienow 2021; Yang et al. 2017; Zhang et al. 2017), have been studied. Most of these studies were conducted in Asia (e.g., Du et al. 2017; Li et al. 2020; Lin et al. 2015; Yu et al. 2017; Zhang et al. 2017) and only a few in Europe (e.g., Oliveira et al. 2011; Skelhorn et al. 2014; Skoulika et al. 2014). Even fewer studies have been conducted in Germany (e.g., Alavipanah et al. 2015; Dugord et al. 2014), especially in the Federal State of North Rhine-Westphalia (NRW). It is important for city planners to gain knowledge on the cooling effect with respect to local conditions, to obtain the most benefit for the urban population. As the literature mainly focuses on Asia, knowledge local to NRW is scarce. Therefore, this study focuses on NRW to enhance the level of local knowledge. German cities provide a high amount of GI, resulting in an average of 183 m distance to green spaces in residential areas (Wüstemann et al. 2017). NRW is of particular interest because it has the highest number of inhabitants and population density in Germany (Statistische Ämter des Bundes und der Länder 2020).

There are various approaches examining the temperature patterns of the park cooling effect (the PCI intensity). In terms of measurement, either in situ or remote sensing data can be used to measure air or land surface temperature (LST). In contrast to in situ data, a remote sensing approach benefits from free data availability and continuous spatial coverage over large areas, and is therefore often used (e.g., Li et al. 2020; Wang et al. 2019; Yang et al. 2017; Zhang et al. 2017). Although there is no strong linear relationship between surface and air temperatures, the surface temperature still approximates the overall thermal conditions because it influences the air temperature (Armson et al. 2012; Schwarz et al. 2012). In terms of remote sensing, a major challenge remains. Because of the relatively low spatial resolution of thermal satellite imagery (e.g., 100 m for Landsat 8) mixed pixels occur within the border zones of two different land use types or neighboring units that are considered separately from each other. These mixed pixels might lead to a distortion of the findings because they intermix the spectral information. Very few studies in the context of PCI intensity analysis have proposed methods to reduce this mixed pixel problem (e.g., Cao et al. 2010). Therefore, this study addressed this issue.

This study aims to investigate the status quo of the surface cooling effect intensity within selected urban parks in NRW, including the cooling range, and to propose a methodological approach for investigating the PCI intensity using remote sensing data, addressing the mixed pixels issue. The following research questions were formulated:

- How does the cooling effect of selected urban parks in NRW behave, especially with regard to the cooling distance?
- How can the spatial limitations of LST data retrieved by remote sensing be addressed?

2 Methods

2.1 Study site and park selection

The Federal State of NRW, which has both a high green rate and population density, was chosen as the study site for the investigation (Fig. 1). It is located in western Germany in Central Europe and

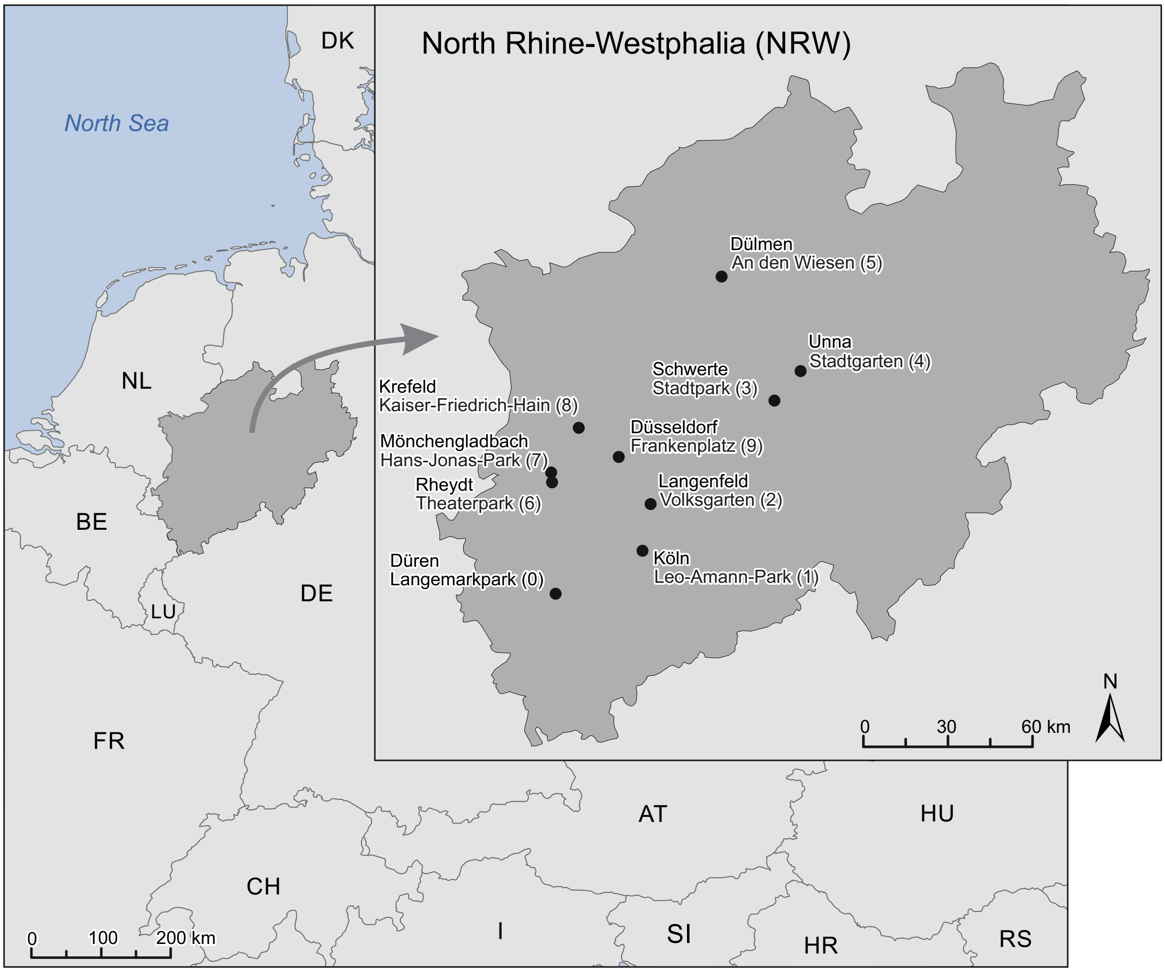

Fig. 1: Location of the study sites

has a warm-temperate oceanic climate, with an annual mean temperature of 11.1 °C and an area of 34,098 km². A total of 17.9 million inhabitants live in the state, distributed over 53 cities and urban districts. It is the most densely populated state in Germany (excluding federal city states), with 526 inhabitants per km².

Previous studies on the surface cooling effect in Germany have focused on one city (e.g., Alavipanah et al. 2015; Dugord et al. 2014), whereas this investigation examined single parks in several cities. To detect suitable parks within NRW, the official land use/land cover map provided by the geodata authority of NRW (ATKIS Basis-DLM by GeoBasis NRW) was used. The database is updated at least every 3 years and has a spatial accuracy of ±3 m (Bezirksregierung Köln 2020a). The classes 'park' and 'green space" are both referred to as 'park' in this study. All parks were inspected based on several parameters: (a) a minimum distance of 300 m from other GI elements, such as water bodies, cemeteries, bare land, agricultural land or green ways; (b) a minimum park size of 1 ha; and (c) homogenous surroundings with mainly impervious surfaces (see the archetypal model, Fig. 2). Ten parks distributed throughout the NRW (Fig. 1 and Appendix 1) were chosen based on these criteria. These parks consist mainly of trees, grass, and some non-vegetative materials, such as footpaths. Although some of the surroundings of the selected parks contained scattered tree cover, both the parks and their neighborhoods represent the archetypical model as far as possible.

2.2 Landsat 8 land surface temperature product

LST, generated from Landsat 8, was utilized owing to the high spatial resolution of its thermal bands and its feasibility for small-scale analysis (Ermida et al. 2020; Roy et al. 2014). Based on Ermida et

Fig. 2: Archetypal model with ideal conditions for the investigation of the surface cooling effect

al. (2020), the LST data were derived from Google Earth Engine by a statistical mono-window algorithm, using ASTER emissivity data and NDVI data to adjust the results. All cloud-free images were selected for the summer periods (June to August) of 2018, 2019, and 2020, resulting in three images: (a) 03.07.2018, (b) 29.06.2019, and (c) 23.08.2019. The Landsat images were taken at approximately 10 am and have a recording spatial resolution of 100 m. After post-processing, the U.S. Geological Survey provides images with a resolution of 30 m (Ermida et al. 2020).

All available LST images of the study period were combined for analysis, aiming to reduce the impact of specific temporal weather conditions and achieve a more general outcome (Fig. 3). Therefore, the pixel-wise mean of all three images was calculated. However, three of the 10 selected parks were only covered by two of the three Landsat images; thus, the means for parks 6, 7 and 8 were calculated based on only two images, (a) 03.07.2018 and (c) 23.08.2019.

A 300-m buffer zone around the parks was established to obtain information on the cooling distance. A distance of 300 m was chosen because of the high interference of other GIs at further distances (Wüstemann et al. 2017). The radius was further divided into six equal zones consisting of 50-m steps, as shown in Appendix 1. They will be referred to as zones 1-6 in the following sections. The values representing the mean LST of each zone and the park itself were calculated. To achieve this, a mixed pixel reduction process was developed (Section 2.3).

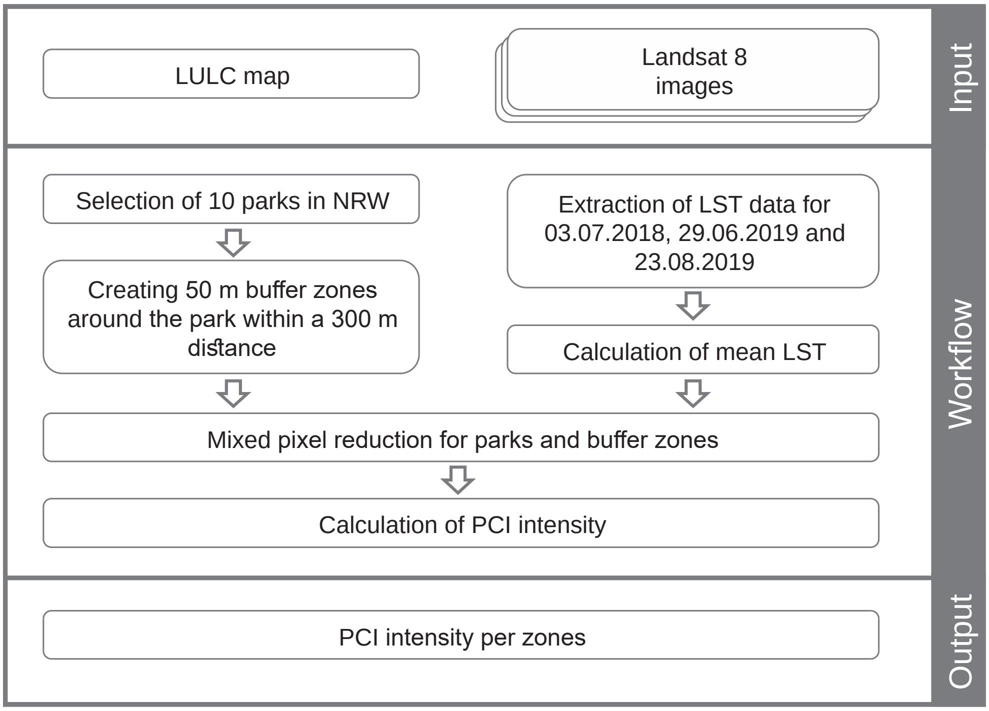

Fig. 3: Processing workflow for calculating mixed pixel reduced PCI intensities derived from Landsat 8 mean LST data

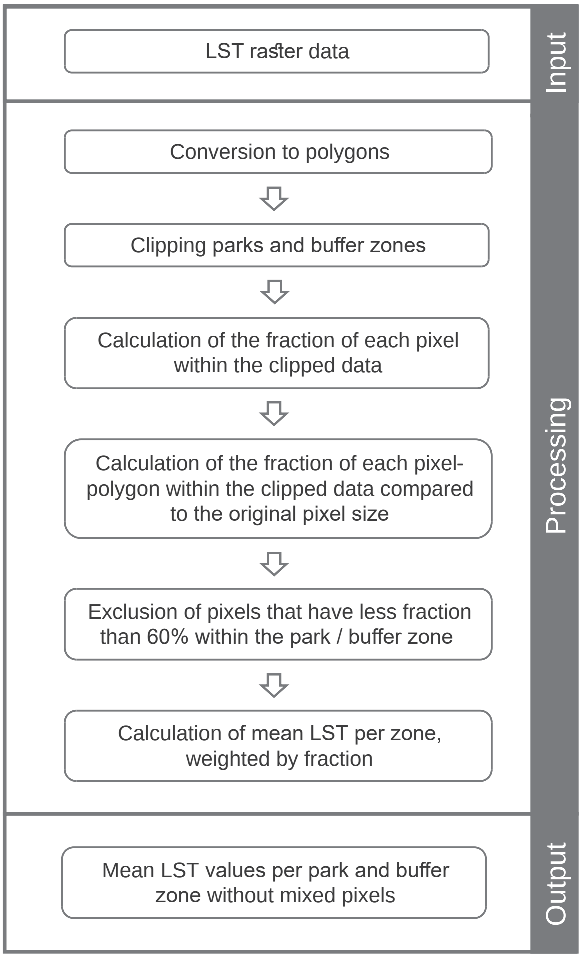

Fig. 4: Mixed pixel reduction

2.3 Mixed pixel reduction

When calculating the mean LST values of the parks and buffer zones, a problem with mixed pixels in the border regions occurred. Including a pixel representing a mix of parks and surroundings when calculating the mean LST of the parks, for example, would falsify the results. Therefore, it is crucial to exclude mixed pixels from further analysis (see also Cao et al. 2010). The LST images were processed in ArcGIS Pro 2.7 (Fig. 4). An automated process was built using the ArcGIS ModelBuilder. Only pixels with a minimum fraction of 60 % located within either the park or buffer zone polygons were included in further analysis. The mean value for each park and buffer zone was calculated with respect to the relevant pixel fractions.

The mixed pixel reduction process excluded pixels near the park and buffer borders. An example from park 1 is shown in Figure 5. The pixels removed from the investigation are shown in white. Consequently, the overall areas of the park and buffer zones were reduced.

2.4 Analysis and statistics

The LST values were further analyzed by calculating the PCI intensity (ΔT) using the following equation:

$$\Delta T = T_u - T_p, \qquad (1)$$

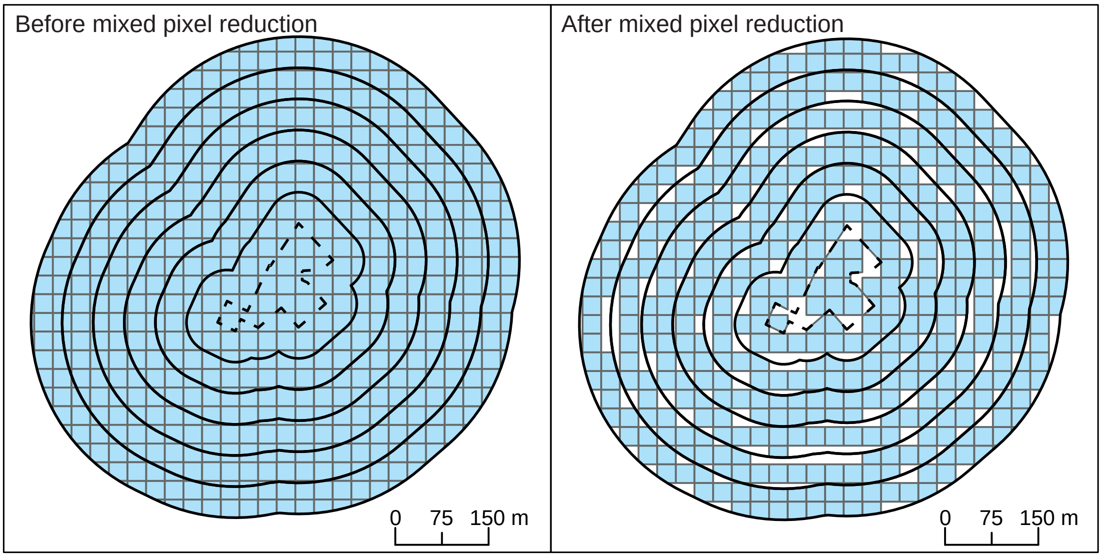

Fig. 5: Impact of the mixed pixel reduction process for park

where T_u represents the urban LST (the buffer zones) and T_p represents the LST of the park. The PCI intensity was calculated for each buffer zone, resulting in six PCI intensity values for each park, to obtain a gradient and thus information on the cooling range. A logarithmic regression was conducted for PCI intensity with respect to distance. Based on the assumption that the cooling effect can only be detected until the PCI intensity stagnates or starts to decline, the regression only considered the buffer zones before a potential stagnation point (Yu et al. 2018).

In addition, a thematic map published by the State Agency for Nature, Environment and Consumer Protection of the State of NRW (INKAS map; LANUV 2020) was examined to support the final discussion. It presents the characteristics of the park surroundings, including construction types and levels of imperviousness.

3 Results

3.1 Land surface temperature patterns

Different LST patterns were observed for parks and their surroundings, as shown in Figure 6. The parks generally exhibited lower temperatures than the buffer zones. For some parks, relatively low LST values were observed within the 300 m surroundings (parks 4, 5, 7, and 8), whereas others showed higher values (parks 2, 6, and 9). Parks 0, 1, and 3 were characterized by the highest LST values. Altogether, a heterogeneous LST distribution was detected within the park surroundings.

The mean LST values per park and buffer zone are shown in Figure 7-A. The LST of all the parks increased significantly within the first two buffer zones. The LST values of parks 0, 1, 3, and 8 increased constantly across all buffer zones, while park 1 had the highest values. The lowest values from the park area to buffer zone 4 were represented by parks 5, 7, and 8. Parks 4, 6, and 9 demonstrated a decrease in LST starting from buffer zone 3-4, while park 4 had the smallest values overall in zones 5 and 6.

3.2 Park cool island intensities and cooling range

Based on the LST values, the gradient of the PCI intensity (ΔT) of each park was calculated and is shown in Figure 7-B. All parks showed a PCI increase at least until buffer zone 3 (150 m). Most parks presented similar PCI intensity gradients, indicating a flattening gradient in zones 3-6 (parks 1, 2, 3, 5, 7, and 8). Different trends were observed for the remaining parks (parks 0, 4, 6, and 9). Park 0 showed the strongest and most significant increase. Parks 1, 3, and 8 were also characterized by a constant and slight increase but approximately 2 K less intense than park 0. The remaining parks showed a decrease starting at a certain buffer zone and lasting for one or more buffer zones (parks 4, 6, and 9).

The mean PCI intensity values and variations of all the parks and buffer zones are shown in Figure 8. The mean values show that the PCI intensity increases within 150 m, with low variation between the parks. Starting from 150 m, the intensity flattened, with increasing variation between the parks. Furthermore, the regression model presented in Figure 9 shows a logarithmic correlation between the buffer zones and the PCI values for the first 150 m, with $R^2 = 0.67$ (adjusted $R^2 = 0.66$). The parameter distance was able to significantly predict the PCI intensity ($F_{(1, 28)} = 57.345$, $p < 0.001$).

The parks were clustered into groups based on the INKAS map (Fig. 6). Most park surroundings were characterized by a high level of imperviousness. Some of these contained large stretches of industrial areas and high-density development (parks 0, 1, and 6), while others contained densely built residential areas without industry (parks 7, 8, and 9). The remaining parks were surrounded by less impervious surfaces, characterized by less dense residential areas and a low level of industry and showing a more heterogeneous structure (parks 2, 3, 4, and 5).

4 Discussion

4.1 The cooling effect and its range in NRW

In accordance with the results, the surface cooling effect of parks was detected in the NRW. The investigated parks showed 1-5 K lower LST values than their surroundings within 300 m; thus, the parks function as PCIs. This also affected the thermal conditions of neighboring surfaces. Regardless of building type, the surrounding surfaces showed lower LST values: both industrial and residential surfaces near the parks were cooler than comparable surfaces in at further distances. In theory, in accordance with the archetypal model representing a homogenous structure, the PCI intensity is expected to increase strongly, followed by stagna-

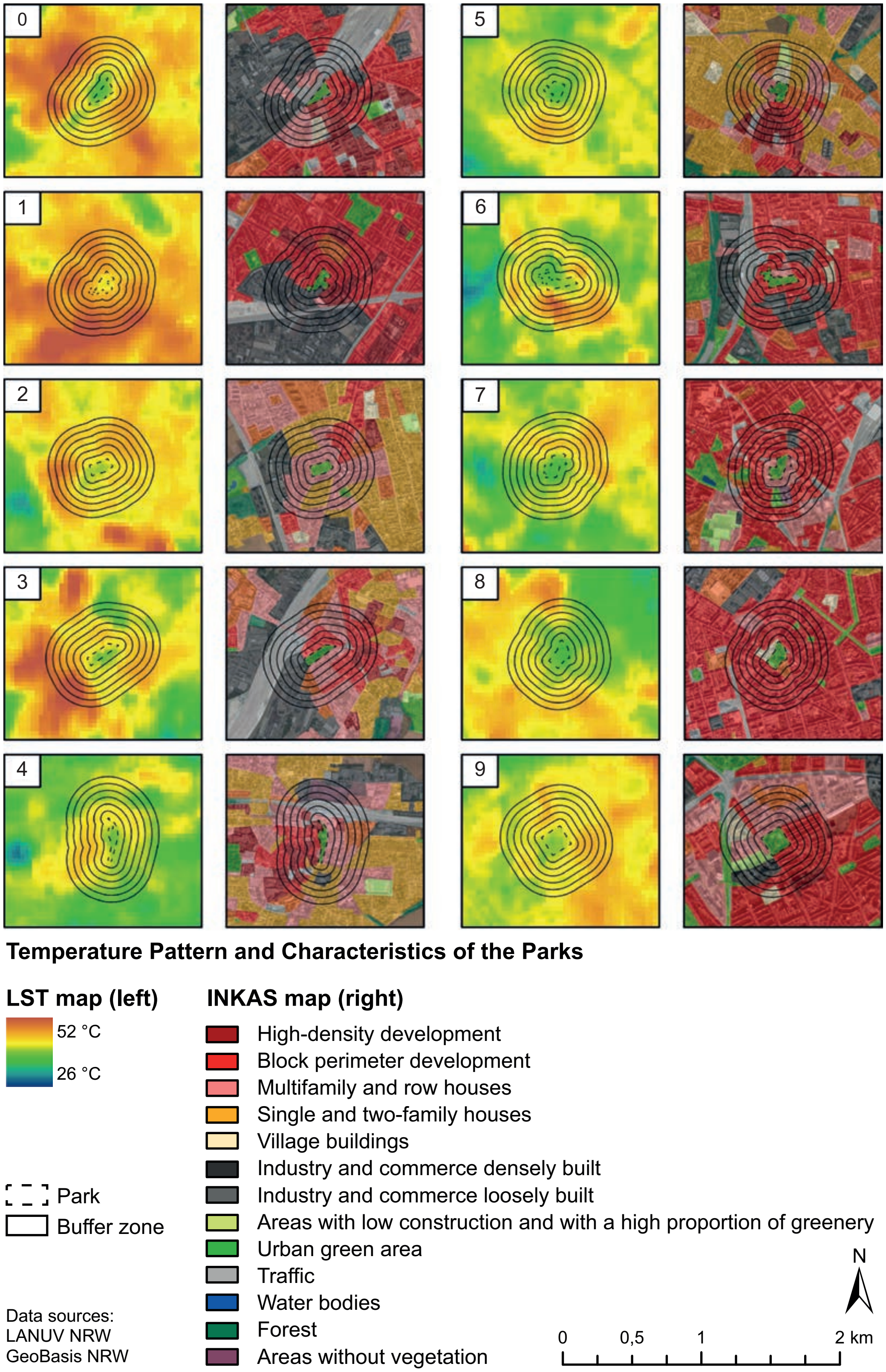

Fig. 6: Temperature patterns and characteristics of the parks

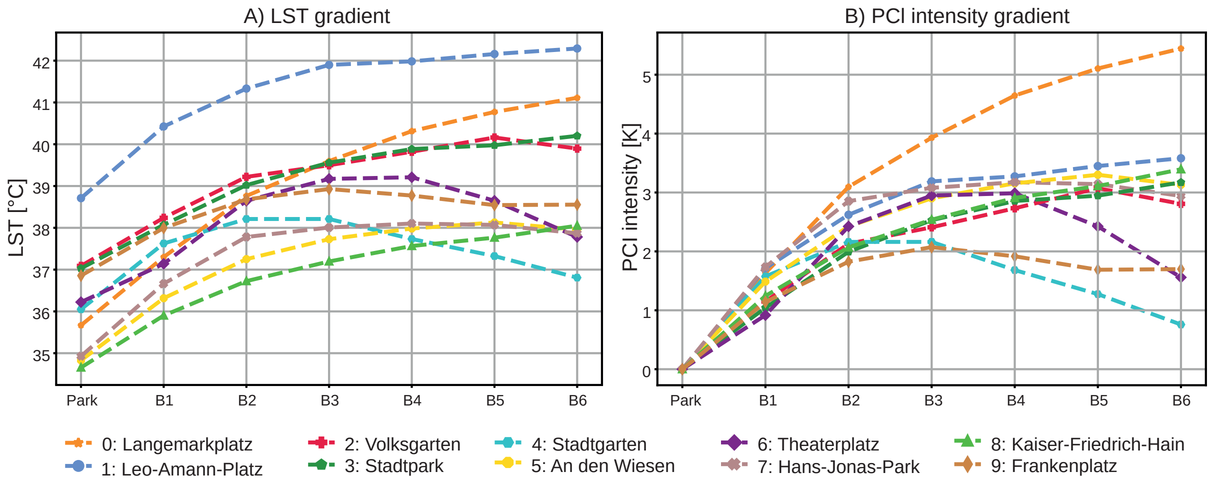

Fig. 7: LST and PCI intensity gradients for all parks

tion. Hence, the further the distance to the park, the larger is the difference between the LST of the impervious areas and the park. However, after a certain distance, the PCI intensity remains stable. This is considered the spatial limit of the cooling impact (Du et al. 2017; Yu et al. 2018). In the present study, a strong increase in PCI intensity was observed for all parks within the first 150 m. In line with the logarithmic regression model, the distance factor explained 66 % of the variation in PCI intensity (Fig. 9). The ideal PCI intensity pattern corresponding to the archetypical model was approximated because the logarithmic function best characterized the relationship between PCI intensity and distance. This was substantiated by the trend of the mean PCI intensity values (Fig. 8); a stagnation was clearly visible starting at 150 m. However, the more distant zones (150-300 m) showed high variability in LST values between the investigated parks and were thus more difficult to generalize. For some parks, the PCI intensity increased beyond 150 m (parks 0, 3, and 8). This might indicate

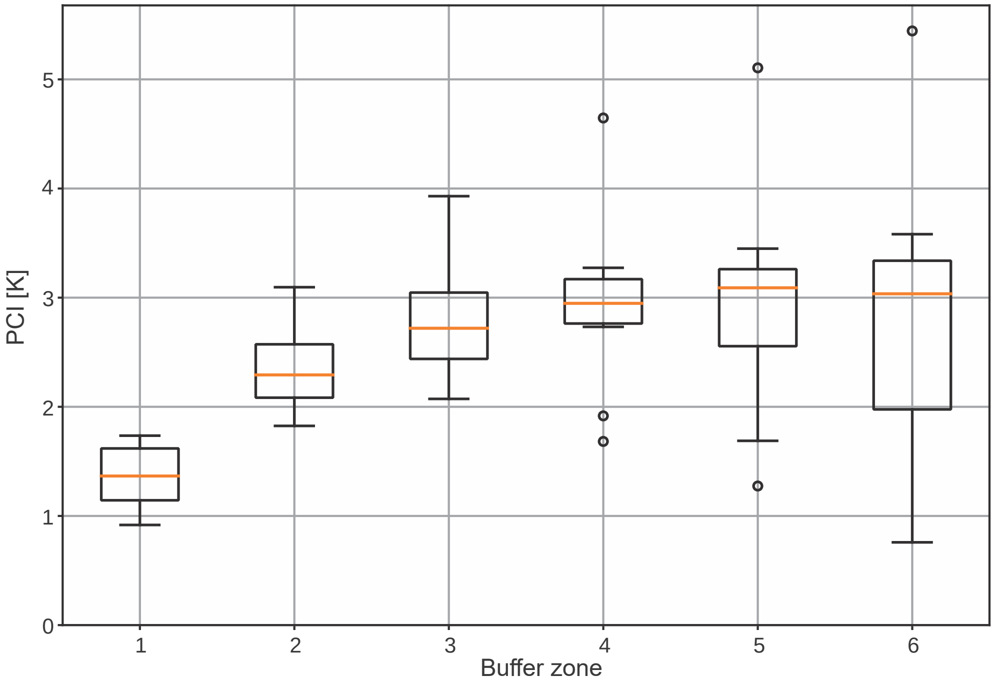

Fig. 8: Boxplots for all parks

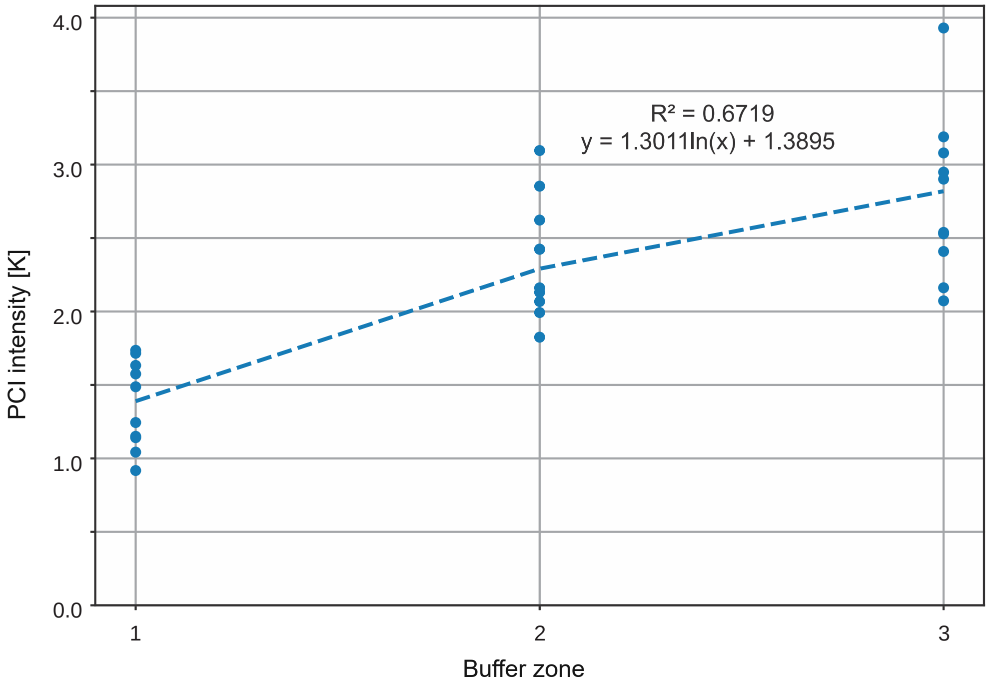

Fig. 9: Logarithmic regression model for buffer zone 1-3 with respect to the PCI intensity

that the cooling range reached further than 150 m. Other parks revealed stagnation at 150 m (parks 1, 5, and 7). The remaining parks indicated a strong PCI intensity decrease after a minimum distance of 150 m from the park (parks 2, 4, 6, and 9). A reason might be the heterogeneous structure of their outer zones, with additional GI elements and a less dense building structure, which would also impact the thermal conditions. It is assumed that the PCI intensity is independent of the absolute temperature of the park and its surroundings. Park 2 indicated relatively high temperatures and a strong cooling effect, while park 5 showed relatively low LST values with a similar cooling intensity.

The findings of this study match those of recent publications, which have also found a surface cooling effect. PCI intensities of 1.3-6.7 K (Du et al. 2017; Feyisa et al. 2014; Yu et al. 2017) have been observed. A large mean cooling range has been reported in some studies, ranging from 240-570 m (Du et al. 2017; Feyisa et al. 2014). In contrast, Yu et al. (2017) found a cooling distance of 104 m. However, most of these studies were conducted in different climate zones with differing city structures, which impedes direct comparison. Owing to low feasibility, recommendations for city planners based on the findings of highly divergent study sites should be followed with care. This highlights the importance of local research.

Germany, and thus NRW, is characterized by a high level of greenery within urban regions (Wüstemann et al. 2017). Therefore, an approximation of the archetypal model is difficult to achieve. The high green rate leads to interference from other GI types within the 300-m buffer zone, impeding the investigation of the PCI intensity. It is therefore difficult to interpret whether the cooling distance exceeds 150 m. Either the values are distorted by other GI elements with cooling abilities or the effect stagnates at 150 m. However, it is of strong benefit for NRW and its inhabitants to maintain high coverage of green areas.

In addition, the results clearly show that industrial areas represent local LST maxima, followed by very dense built-up areas. Parks surrounded by these highly impervious and heated surfaces were characterized by higher LST values, as observed for park 1. In addition to the high heat storage capacity, the heat discharge of industrial areas might influence surrounding surfaces, such as neighboring parks, weakening their cooling effects (Li et al. 2011).

4.2 Addressing the remote sensing methodological approach

One specific objective of this study was to propose an adjusted methodological approach for the analysis of the surface cooling effect using LST data, to address the limitations of remote sensing. First, unlike other studies (e.g., Du et al. 2017; Feyisa et al. 2014; Li et al. 2020), the mean of three satellite images was considered (instead of using only a single). The mean value of more than one image represents more general conditions and flattens variability, since a single image is only a static snapshot of a specific weather situation. Thus, a single image may not accurately represent the average conditions. A maximum of three feasible images were obtained during the investigation period. However, if possible, it might be appropriate to include more than three images with the same conditions (season, flyover time, and sensor), to obtain the most representative result. The same principle was applied to the number of parks studied. Regarding the high variance of city structures in NRW, it is important to include more than one park, as shown in this study. Compared to an analysis with fewer parks, this allows for a more generalized investigation.

Second, a workflow to exclude mixed pixels was established to avoid effects on the results. Mixed pixels occur at the border of two land use types, for example, parks and their direct surroundings. The proposed workflow was based on the fraction of pixels within this border zone, which also prevented the inclusion of pixels from the border region into the LST calculation twice (i.e., for both zones). The applied method counted all the pixels that were not fully included in one zone weighted by the specific area. This further reduced the importance of the remaining mixed pixels. The adjustments thus led to more feasible Landsat 8 LST products for small-scale investigations. Although the reduction of mixed pixels means that smaller parks are represented by only a few remaining pixels (Fig. 5), the adjustment is still a more accurate projection of the real conditions.

4.3 Limitations

With respect to research methods, some limitations must be acknowledged. This study was limited by the high heterogeneity of the urban areas in the NRW. Ideally, the analysis of surface cooling effects requires homogenous surroundings. Large urban parks with homogenous surroundings and without interfering GI elements within a 300-m buffer zone (Fig. 1) do not exist in the NRW. Hence, parks that match the ideal conditions as far as possible were chosen. Additionally, small GI types, such as street trees or backyards, were not included, as these were not included in the land use/land cover input data.

Remote sensing is one of the key data sources in this study. Although the limitations of remote sensing approaches were addressed and the disadvantages minimized, it is still not possible to obtain a spatial resolution higher than 100 m for LST using Landsat 8. Furthermore, a 60 % pixel size threshold was estimated as an appropriate value to distinguish between the included and excluded pixels. It must be considered that another threshold might lead to different results. Owing to the flyover time of Landsat 8 at approximately 10 am, the SUHI was not captured at its maximum (Voogt and Oke 2003). Finally, it should be remembered that the data for parks 6, 7, and 8 were generated from two LST images instead of three.

5 Conclusion and outlook

The aim of the present research was to examine the current situation regarding the cooling effect and its range for urban parks in NRW, and to propose a methodological approach addressing the limitations of satellite-based analysis, in particular, mixed pixels. A surface cooling effect of 1-5 K was detected within a 150 m distance from the parks. The investigation was impeded for distances beyond 150 m owing to the high green rate of the study region, NRW. Because of the high variability of the city structure, it was difficult to isolate the impact of the park from other GI elements. However, a clear trend was identified for the first 150 m. The proposed approach for dealing with the mixed pixels was efficiently applied. Using this method, the results represent reality more precisely. This study contributes to the investigation of the surface cooling effect in NRW, contributing to filling the current knowledge gap. City planners benefit from local knowledge when integrating the cooling effect into climate adaptation concepts.

Since the status quo is generally covered by this study, the next step will be to examine influencing parameters on the cooling range for NRW. It is of interest to investigate the local impact of the park vegetative characteristics (such as trees, grass, and shrubs), the shape and size of the parks and the connectivity of multiple GI elements. Additionally, an investigation at the SUHI maximum might provide further insights. In addition to satellite images, unmanned aerial vehicles and in situ measurements can be utilized in the future to obtain an even higher spatial resolution.

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Appendix

ID	Park name, city	Park size [ha]
0	Langemarkpark, Düren	1.11

1	Leo-Amann-Park, Köln	1.3

2	Volksgarten, Langenfeld (Rheinland)	1.18

ID	Park name, city	Park size [ha]
3	Stadtpark, Schwerte (Ruhr)	1.29

4	Stadtgarten, Unna	1.15

5	An den Wiesen, Dülmen	1.3

ID	Park name, city	Park size [ha]	ID	Park name, city	Park size [ha]
6	Theaterpark, Rheydt	1.69	8	Kaiser-Friedrich-Hain, Krefeld	1.57
					
7	Hans-Jonas-Park, Mönchengladbach	1.65	9	Frankenplatz, Düsseldorf	2.48
					

Appendix 1: List of studied parks containing the parks' ID, name, city and size. An orthophoto is presented to give an overall impression of conditions of the surroundings. Orthophotos of the years 2017 to 2020 with different recording seasons were considered for this purpose (Bezirksregierung Köln 2020b). The applied buffer zones and the park shape are indicated by white lines.