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The role of local land-use on the urban heat island effect of Tel Aviv as assessed from satellite remote sensing

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ABSTRACT

Climate change in cities has received much focus in the past few decades. Heat stress in urban areas has an adverse effect on human health and is expected to worsen in the future due to the global warming. Vegetation has been shown to mitigate this effect, but introducing 'green' areas into the metropolitan space is a challenging task. We assessed the thermal load in terms of surface temperature in Tel Aviv, the biggest metropolitan area of Israel. The thermal effect of four different urban land uses was estimated. Specifically, we compared the cooling effect of residential areas with high vegetation cover (referred here as 'green' residential) to that of small to medium size (2–40 ha) public parks. To this end, we used satellite data of land surface temperature (LST) and the Normalized Difference Vegetation Index (NDVI), as a surrogate for vegetation cover. High-temporal data were combined with high spatial resolutions data to produce 10-year average LST and NDVI maps at high spatial resolution over Tel Aviv. As expected, industrial areas had the highest LST due to lowest ratio of vegetation to free space area (1%), while 'green' areas displayed the lowest LST. Green residential and small-medium public parks had comparable thermal loads, with green residential having slightly lower LST (by 0.5 °C). In general, small-medium public parks displayed higher LST than expected. Inefficient use of free spaces for vegetation, i.e., relatively low vegetation cover to free space ratio, was probably the main cause for this. Public parks had a higher local cooling effect, but a less continuous one on the proximate surrounding (30–90 m from the park), probably due to their relative location in the urban fabric. Our results suggest that 'greening' areas within the private urban space should be encouraged at the expense of building new small-medium parks in metropolitan areas that lack the sufficient free space for larger parks. The outcome of this study may have key implications for urban planners seeking to mitigate urban heat island effects under the limitation of existing dense urban layout.

Introduction

Climate change in cities has received much focus in the past few decades. Urban heat islands (UHI), in which urban areas are warmer than their surroundings, is caused by altered surface cover and anthropogenic activity (Kleerekoper, van Esch, & Salcedo, 2012; Oke, 1995). Heat stress in cities is expected to worsen in the future due to the adverse effect of increasing urbanization and global warming on human health (Johnson, Stanforth, Lulla, & Luber, 2012; Kovats & Hajat, 2008). Numerous studies have proposed strategies to mitigate this effect. Most studies suggest increasing the 'green' urban areas, since plants have a cooling effect through transpiration and shade (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Muller, Kuttler, & Barlag, 2013; Oke, Crowther, McNaughton, Monteith, & Gardiner, 1989; Potchter, Cohen, & Bitan, 2006; Rogan et al. 2013; Spronken-Smith & Oke, 1998). However, as metropolitan areas usually lack the required public spaces, greening of building façades and street tree planting in residential neighborhoods could be the most practicable solution (Gill, Handley, Ennos, & Pauleit, 2007).

Urban planners have understood that a knowledgeable design of the city is essential to reduce the burden of heat stress (Stone, Hess, & Frumkin, 2010). An increase of 2 °C to 5 °C is expected due to future expansion of urban areas (Lin, Liu, Ma, Li, & Shi, 2013). A built environment changes the absorption and reflection of solar radiation and the surface energy balance (Bowler et al. 2010). Anthropogenic factors that contribute to this effect are fossil fuel consumption (e.g., vehicles and air conditioning), construction

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materials (e.g., stones and concrete vs. wood), open spaces (paved roads and parking lots vs. green parks and trees), and city morphology (e.g., high buildings vs. private houses) (Mirzaei & Haghighat, 2010; Petralli, Massetti, Brandani, & Orlandini, 2014). All of these are referred to as urban design and are regarded as urban design indicators.

Although there are several strategies to mitigate the UHI effect, most studies focus on the cooling effect of urban parks and gardens (Bowler et al. 2010; Cohen, Potchter, & Matzarakis, 2012; Eliasson and Upmanis 2000; Feyisa, Dons, & Meilby, 2014; Kleerekoper et al. 2012; Shashua-Bar & Hoffman, 2000). For example, Shashua-Bar and Hoffman (2000) showed that urban parks may have a cooling effect of up to 1.5 °C–3 °C, depending on the time of day. Oliveira, Andrade, and Vaz (2011) concluded that even small parks of ~0.24 ha could mitigate the adverse effects of UHI and the potential additional effects of global warming in cities. Others showed that medium to large size parks (>150 ha) have an even greater thermal effect (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Andrade & Vieira, 2007; Eliasson and Upmanis 2000; Jauregui, 1990; Shashua-Bar & Hoffman, 2000). In Taipei and Manchester, large parks have important cooling effects, implying that vast green spaces constitute critical environmental capital to mitigate climate effects (Chang, Li, & Chang, 2007; Gill et al. 2007).

An important aspect of the park cooling effects is their thermal influence on the immediate surrounding area. It was shown that temperatures gradually increased with increasing distance from the park, up to approximately 500 m–1000 m (Papangelis, Tombrou, Dandou, & Kontos, 2012; Ren et al. 2013; Upmanis, Eliasson, & Lindqvist, 1998; Yu & Hien, 2006). This spatial cooling effect was found to be related to the park size, with a greater effect for larger parks up to a certain threshold (Ren et al. 2013). Conversely, Feyisa et al. (2014) reported a maximum park cooling distance of only 240 m and a maximum park cooling intensity of 6.72 °C in Addis Ababa (Ethiopia) and concluded that the cooling effect of urban green space is mainly determined by species group, canopy cover, size and the spatial design of parks. Moreover, Ivajnšič, Kaligarič, and Žiberna (2014) concluded that the maximum cooling distance of urban green space is rather small and it is therefore even more important in small cities where dispersed green areas could neutralize elevated air temperatures caused by the UHI effect.

When public space is limited, other greening strategies are suggested. Covering roofs or façades with plants might reduce the thermal load resulting in cooling of the urban environment (Campiotti et al. 2011; Wong & Lau, 2013). Green roofs and façades represent a sustainable technology for improving both energy efficiency of buildings, and thermal insulation in winter. Though attractive, their cooling effects have not been extensively studied (Bowler et al. 2010). Street tree planting in residential areas might also help in reducing UHI effect. An aggregate number of trees have an important impact on the thermal balance through shading and plant-transpiration. In this case, it is suggested to prioritize trees over grasses because they provide shade and require relatively limited irrigation (House-Peters & Chang, 2011; Rosenzweig, Solecki, & Slosberg, 2006). In spite of the recent studies on the overall cooling effects of residential greening, its local effect compared to that of public parks has yet to be studied.

In this study, we investigated thermal patterns in Tel Aviv, Israel. Specifically, we compared the cooling effect of green residential areas (i.e., buildings with private gardens and street trees) with that of public parks within the neighborhood space. We used satellite data to investigate the UHI effect in Tel Aviv, Israel. Land surface temperature and vegetation cover at 20 sites representing four different urban land uses were compared. High-temporal low-spatial resolution data were combined with low-temporal high-spatial resolution using two different satellites to produce detailed time series maps of the study area. The aim was to estimate and compare the cooling effects of green residential areas and public parks, in the neighborhood space. This paper seeks to answer two questions: (a) what are the thermal effects of different land uses on their surrounding in the metropolitan city of Tel Aviv? And (b) how can the UHI effect be mitigated in a dense urban fabric? Answering these questions may help urban planners mitigate the UHI effect. By analyzing sites that display different types of land-uses we show that there is a quantitative relation between the surface temperature and physical features that can be modeled.

Data and methods

Study area

Tel Aviv, the core of Israel's major metropolitan area, is a dynamic urban area located in the most developed part of Israel. Although having an overall compact land-use structure, it includes areas with inefficient land use causing debate on its planning policy. Tel Aviv is the largest city in the metropolitan area (52 km^2) located along the east coast of the Mediterranean Sea. Its 414,600 inhabitants comprise almost 12% of the population in the entire metropolitan area of Israel (CBS Israel, 2013). The city serves as the cultural heart and financial center of the country. It was developed as a relatively compact city with mixed land use in which residential areas converge with commercial, office, as well as industrial areas.

The climate is Mediterranean, characterized by subtropical hot and dry summers with extreme humid conditions during the summer (30 °C and 83% relative humidity (Cohen, Potchter, & Matzarakis, 2013)). In the summer months (June–August), these temperature and humidity regimes are highly persistent (Saaroni & Ziv, 2000). Such conditions are commonly defined as discomfortable for humans (McGregor & Nieuwolt, 1998). Hot and humid conditions in summer result from the combined effects of the Mediterranean Sea and urbanization (Potchter et al. 2006; Saaroni & Ziv, 2003). In summer, Tel Aviv develops an UHI effect at both midday and at night (Bitan, Noy, & Turk, 1992).

We selected Tel Aviv for two main reasons: (1) the nature of the urban fabric in its diverse neighborhoods, which enabled a comparison between areas on a relatively small scale; and (2) its potential increase of thermal risk over the years due to a general policy of residing in high densities as a principle guideline for the city development (Tel Aviv Municipality, 2006).

Selected sites

In order to examine how UHI effect is expressed in different local urban design, 20 sites comprising four urban land uses were selected (Fig. 1):

(i) Green residential: Five sites of residential buildings with high vegetation of dense canopied trees and grasses, in streets and private gardens.
(ii) Residential: Five sites of residential buildings with little, usually low, vegetation. Vegetation consists mainly of shrubs or single trees.
(iii) Public parks: Five sites of small to medium sized green parks with trees with/without grasses, within the neighborhood space.
(iv) Industrial: Five sites of dense building for industrial purposes with no vegetation.

Fig. 1 and Table 1 present the location, view and description of the sites. On average there are three floors per building in the built

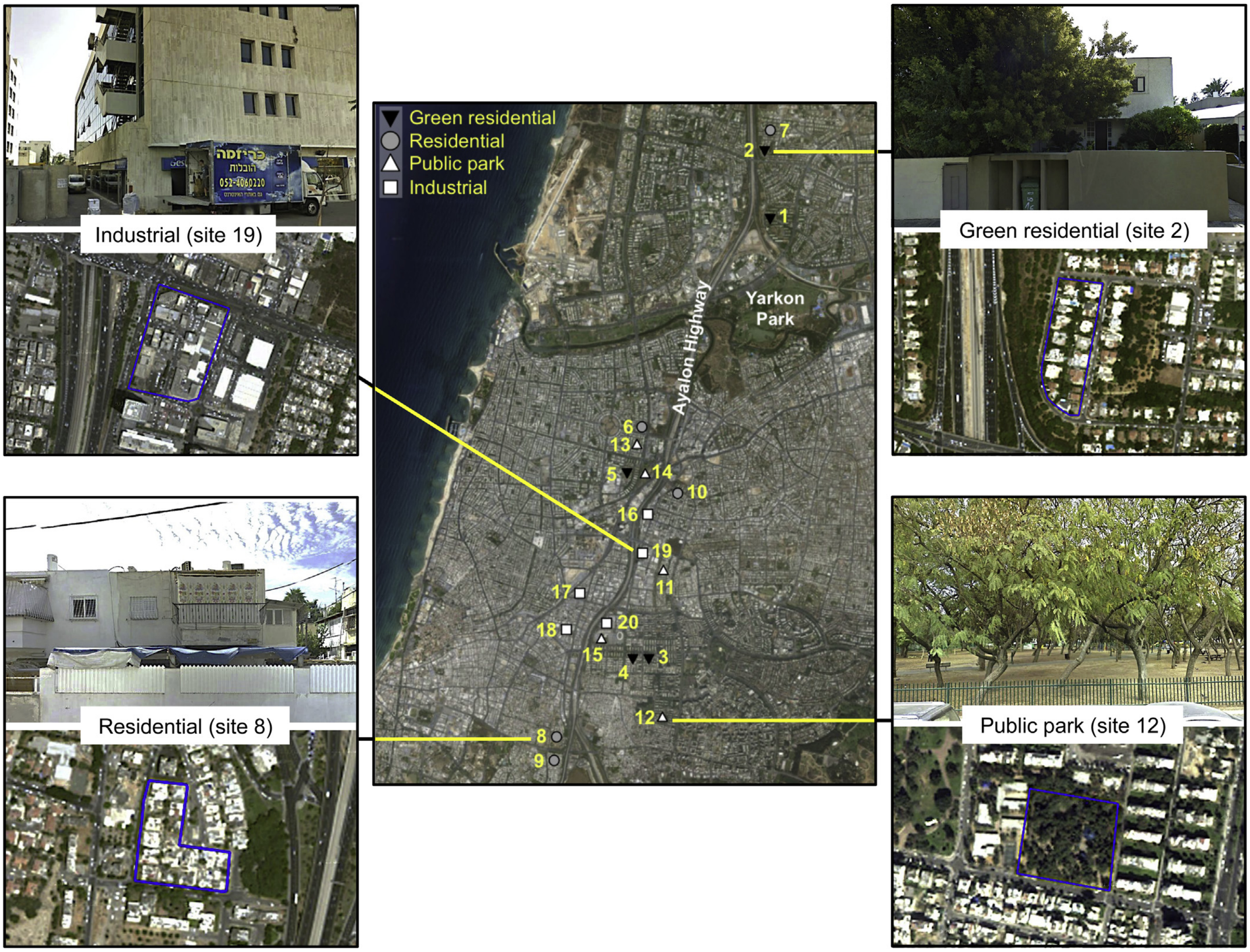

Fig. 1. Tel Aviv, the major metropolitan city of Israel. The 20 sites of this study that comprised four different urban land uses are presented in the map (see details in Table 1). Street and closer aerial view of selected sites are also shown.

sites (excluding public park sites). All potential sites were mapped first according to their size for each type of land-use. All sites were selected far from the sea (~3 km), as a conditional criteria using GIS software. This was conducted to diminish the effect of sea breeze on surface temperature (Lensky & Dayan, 2012), as sea breeze reduces thermal effect, decreasing its effect with increasing distance (Muller et al. 2013). The final sites were selected with expert knowledge to determine how well the sites fit the land-uses definitions.

To further understand the thermal pattern over the entire city, we divided it into five main urban land use types according to information from the Tel Aviv municipality (Fig. 2a). As discussed earlier, Tel Aviv is a relatively compact city with mixed land-uses; however, in general it can be segmented into five main areas as illustrated in Fig. 2a. The metropolitan CBD and employment areas are located along the historical industrial belt and Ayalon highway, as well as a relatively new employment area located on the eastern edge of Yarkon Park – a 3.5 square kilometer area comprising the main green urban area of Tel Aviv. The park is well connected to Tel Aviv's northern residential neighborhoods. These neighborhoods are considered suburban residential neighborhoods with relatively low connectivity to the Tel Aviv's central urban fabric. Commercial land use is somewhat dispersed in the city, including two main shopping malls, while main shopping streets are located in 'central' Tel Aviv. A main residential area in Tel Aviv is the 'central' Tel Aviv complex refers to the enclosed area between the Mediterranean Sea to the west, and the Ayalon Highway to the east. It includes historic residential areas, which were originally planned by Patrick Geddes as a modern Jewish garden city. The idea was to create green public spaces within residential blocks in the form of parks and squares. However, due to the growing needs and constraints of time, the planned area development never fully materialized (Hysler Rubin, 2013).

Satellite data

Estimating UHI effect requires high spatial and temporal resolution data due to its high variability in time and space. Satellite orbits and instrumentation yield a trade-off between their spatial and temporal resolutions, i.e., high spatial resolution at low temporal resolution and vice versa. Two of the main satellites in NASA's earth observing system are Landsat and Terra satellites. Landsat satellites have been operating since the 1970s with high spatial resolution of 30-m in the spectral, and 60-m in the thermal bands, with a low repetition time of 16 days. Terra is a sun synchronous satellite that was launched in 2000. It passes over any given point of Earth's surface at around 10:30 a.m. and 10:30 p.m. local mean solar time, providing products such as land surface temperature (LST)

Table 1
General description of the selected sites for this study comprising four urban land uses in Tel Aviv metropolitan (Green residential, residential, public park and industrial). Veg. is the total evergreen vegetation cover during the summer (June–August), and was calculated from the mean NDVI using Eq. (1) (see in Section 2.5).

Site	Land use	Description	Total area (ha)	Built area (ha)	Built area (%)	Veg. (%)
1	Green residential	Apartment buildings	17.2	3.6	21	46
2		1–2 floors buildings	14.5	5.1	35	35
3		Apartment buildings	16.3	4.5	28	35
4		Apartment buildings	12.1	3.8	26	30
5		Apartment buildings	27.2	7.2	39	38
6	Residential	Apartment buildings	7.9	3.3	45	13
7		Apartment buildings	21.3	6.2	39	8
8		Apartment buildings	9.5	3.2	45	13
9		Apartment buildings	3.3	1.4	42	11
10		Apartment buildings	11.9	4.5	38	14
11	Public park	Park (near industrial)	2.6	0.1	4	26
12		Park (near paved road)	12.8	0	0	40
13		Park (near paved road)	9.8	0	0	41
14		Park (near paved road)	42.4	0	0	44
15		Park (near paved road)	13.6	0	0	21
16	Industrial	Industrial area	19.4	9.4	49	5
17		Commercial area	19.6	11.3	58	0
18		Commercial and offices	14.6	7.9	54	0
19		Commercial and offices	30.7	20.4	66	1
20		Industrial and offices	10.2	6.3	61	2

and Normalized Difference Vegetation Index (NDVI), which is a spectral measure of vegetation. We used the LST and NDVI products of these satellites, because they are freely available online with relatively high temporal and spatial quality, which makes them very reliable for such analysis.

The 1-km night LST (MOD11A2) and 250-m NDVI (MOD13Q1) products of the MODerate resolution Imaging Spectrometer (MODIS) onboard Terra (https://lpdaac.usgs.gov/products/modis_products_table/) were used to generate a 10-year time series over Tel Aviv. Temporal Fourier analysis was applied to get the long-term mean LST and NDVI during the summer (June–August) on a pixel basis, as described in Lensky and Dayan (2011). Landsat thermal and spectral data (http://earthexplorer.usgs.gov/) were calibrated according to the USGS guide, and corrected for atmospheric absorption.

Downscaling procedure and LST spatial profiles

To downscale MODIS spatial resolution to a 30 m Landsat resolution, we applied the pixel block intensity modulation technique proposed by Guo and Moore (1998):

$$LST_{30}^{MODIS} = \frac{LST_{930}^{MODIS} \cdot LST_{30}^{Landsat}}{LST_{930}^{Landsat}}$$

where LST_{30}^{MODIS} is the 1-km MODIS LST downscaled to the 30-m Landsat resolution; LST_{930}^{MODIS} is the 1-km MODIS LST data in its

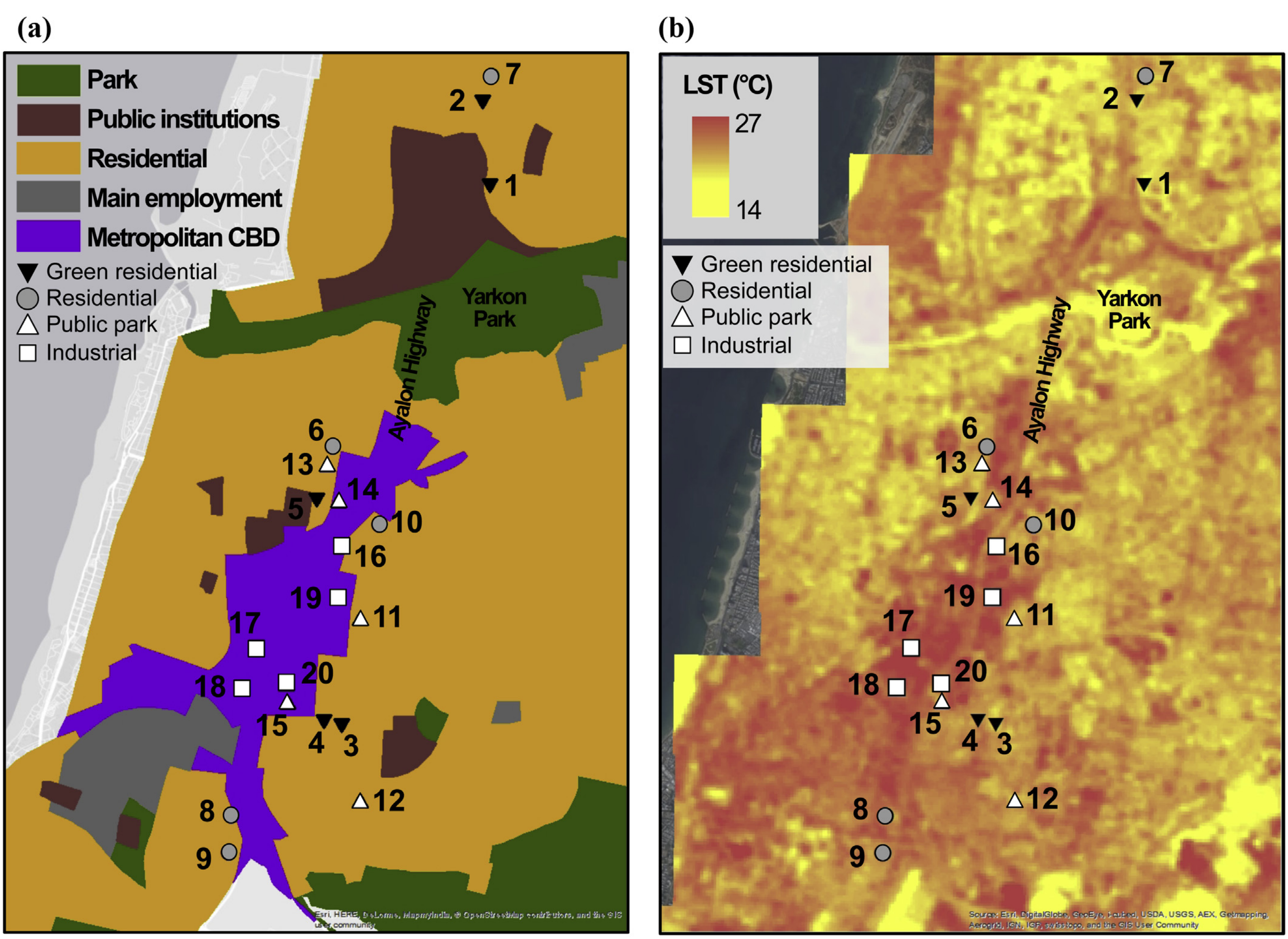

Fig. 2. Maps of Tel Aviv's (a) main urban land uses, and (b) mean surface temperature (LST, °C) in night summer months (June–August). The 20 selected sites for this study (Table 1), the Ayalon Highway (the main highway that crosses the city), and the Yarkon Park (the largest park in Tel Aviv), are indicated in both maps.

original resolution (925 m) resampled to 930 m; $LST_{30}^{Landsat}$ is the LST from Landsat channel 6 (60 m) resampled to 30 m; and $LST_{930}^{Landsat}$ is the mean Landsat LST over the MODIS LST pixel resolution (930 m).

The same procedure was used to downscale the 250-m MODIS NDVI data to 30-m:

$$NDVI_{30}^{MODIS} = \frac{NDVI_{270}^{MODIS} \cdot NDVI_{30}^{Landsat}}{NDVI_{270}^{Landsat}}$$

where $NDVI_{30}^{MODIS}$ is the 250-m MODIS NDVI downscaled to the 30 m Landsat resolution; $NDVI_{270}^{MODIS}$ is the 250-m MODIS NDVI data in its original resolution (231 m) resampled to 270 m; $NDVI_{30}^{Landsat}$ is the NDVI from the 30 m Landsat channels; and $NDVI_{270}^{Landsat}$ is the mean Landsat NDVI over the MODIS NDVI pixel resolution (270 m).

Then, LST_{30}^{MODIS} and $NDVI_{30}^{MODIS}$ were used to calculate night LST and the mean NDVI during the summer (June–August). We used night summer temperatures because radiative cooling during this time was seen to accentuate the spatial variability in LST (Lensky & Dayan, 2011).

To estimate the spatial thermal effect of green residential and small-medium public park sites we measured LST at 30 m intervals (Landsat pixel size) in three directions. We excluded the coastline direction from the analysis due to the sea breeze cooling effect (Muller et al. 2013). Directions were selected using Google earth map (Google earth©) to assess that there was no significant land use change between the site and the surrounding area. After 90 m there was a significant change in land use at several sites; thus we did not measure LST after that distance. ArcGIS (ESRI) was used to calculate the spatial thermal profile and to produce contour maps of LST.

Estimation of vegetation cover from NDVI

The Normalized Difference Vegetation Index (NDVI) is a good surrogate for vegetation cover (Huete et al. 2002) and biomass production (Helman, Lensky, Mussery, & Leu, 2014; Helman, Mussery, Lensky, & Leu, 2014). It is defined as (Rouse, Haas, Deering, Schell, & Harlan, 1974):

$$NDVI = \frac{R_{0.8} - R_{0.6}}{R_{0.8} + R_{0.6}}$$

where $R_{0.6}$ and $R_{0.8}$ are the reflectance at the red (0.6 μm) and near infra-red (0.8 μm) bands, respectively. It is a unitless index, normalized to get values between −1 and 1, with a full vegetation cover approaching 1.

In Mediterranean-climate regions the NDVI during the summer comes mainly from the evergreen woody vegetation. The evergreen vegetation cover can be estimated from NDVI if assuming homogenous distribution of the vegetation species (Glenn, Huete, Nagler, & Nelson, 2008). Because this assumption is valid for our study sites, the percentage of vegetation cover (VC) could be calculated:

$$VC = 100\% \cdot \frac{NDVI_{Full} - NDVI}{NDVI_{Full} - NDVI_{Ground}} \quad [1]$$

where $NDVI$ is the value to be converted to vegetation cover (%), $NDVI_{Full}$ and $NDVI_{Ground}$ are NDVI values of full vegetative cover (for evergreen vegetation: NDVI = 0.65) and bare ground (NDVI = 0.04, which was the lowest value in industrial sites), respectively.

Statistical analyses

We used linear regression to assess relationships between mean NDVI and LST, and between built areas and LST for the 20 sites. Good correlation is considered when Pearson's (R) coefficient approaches 1. To estimate the significance of the correlation, the two-tailed probability of a Pearson correlation coefficient was calculated (Cohen et al. 2013). The two-tailed student t-test was applied to test if the mean values of green residential and public park sites were significant. The one-way Anova was used to test significant difference between the four land uses with a Bonferroni correction for multiple comparisons analysis. Data analysis was carried out using statistical software: Microsoft Office Excel 2011.

Results

Thermal patterns of Tel Aviv major urban land uses

Fig. 2b shows the thermal patterns of the major urban land uses in Tel Aviv during the summer as the mean night LST over ten years (2000–2010). Two areas with opposite thermal load can be noticed.

First, the metropolitan central business district (CBD) with the highest LST: The CBD is a historic industrial strip located in the central area of Tel Aviv. Formerly, the industrial sector was concentrated in the southern and eastern part of Tel Aviv extending north through the years toward the Ayalon Highway (the main highway that crosses the city). Presently, the CBD is located along the Ayalon Highway and is characterized by a dense built up area including residential and nonresidential land uses. The thermal stress in this industrial strip is relatively high in comparison to other locations in Tel Aviv (Fig. 2b).

The second, with the lowest LST, is the Yarkon Park. Between these two thermal extremes is the so-called 'central' Tel Aviv complex.

Surface temperatures and NDVI in selected sites

Fig. 3a shows the cooling effect of vegetation in the sites from Fig. 1, in terms of mean summer NDVI and night LST. The relationship observed in Fig. 3a is exponential, thus beyond a certain LST threshold, the cooling effect of vegetation is attenuated.

Green residential sites had a lower mean LST than public parks by 0.5 °C ($p < 0.05$, using two-tailed student t-test), with an average of 21.7 °C compared to 22.3 °C. This was in spite of a comparable vegetation cover with mean NDVI of 0.25 and 0.26 ($p > 0.5$) in green residential and public park sites, respectively. Public parks had large spatial variability in vegetation cover expressed in large standard deviations from the average NDVI (horizontal error bars in Fig. 3a). This was also displayed in LST variability (vertical error bars in Fig. 3a).

Residential sites with low vegetation cover had relatively high LST (mean = 22.8 °C), while industrial sites had the highest LST (mean = 24.4 °C). Fig. 3b shows that LST was also highly, but positively related (Pearson's (R) = 0.89, $p < 0.01$) to built areas (% from total site area). The only exception was the public park sites that had higher LST than expected (indicated in Fig. 3b). There was no correlation between the area and LST ($p > 0.5$).

The vegetation (% cover) to free space (% from total site area) cover ratio is shown in Fig. 4. Green residential sites had a significantly higher vegetation to free space ratio, with more than half of the free space covered by vegetation. Public parks had less than 35% of their free space covered with vegetation, which was also nearly their total area (see Table 1). Residential and industrial sites had the lowest vegetation to free space ratio, with 20% and <1% from their free space covered by vegetation, respectively.

Spatial thermal profiles around 'green' sites

LST generally decreased with distance when moving from the site toward the surrounding areas, in all green residential and

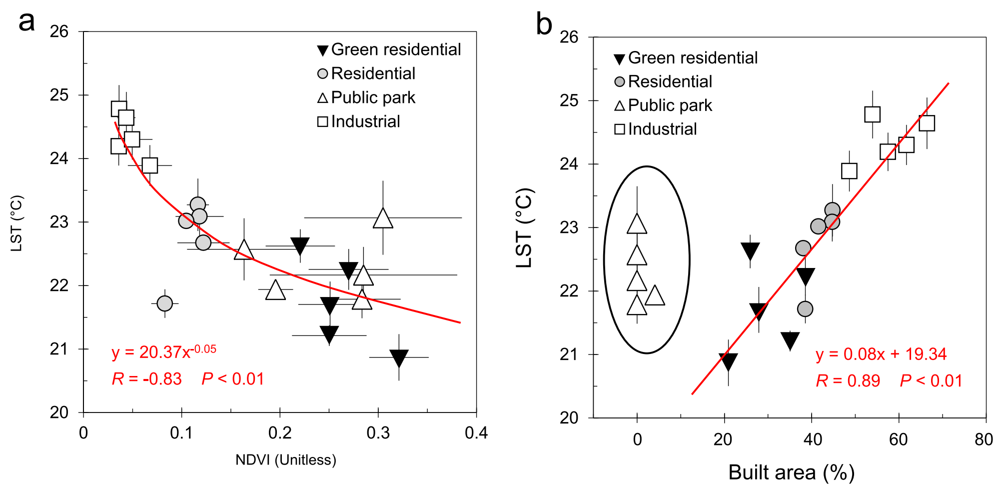

Fig. 3. The relationship between surface temperature (LST, °C) and (a) NDVI, a surrogate for vegetation cover, and (b) built area, in the 20 sites comprising different urban land uses (Table 1). The thermal effects of vegetation and built area are significant ($P < 0.01$). Error bars denote spatial variability within the site area as $\pm 1\sigma$.

public park sites (Table 2). Fig. 5 shows the increase in LST from the border of these two types of land use, at intervals of 30 m. The *y*-axis in Fig. 5 is the difference between the LST at distance x and at distance x-30 m (ΔLST), while the x-axis is the distance x of the LST measurement. Public parks have a strong cooling effect in the park area, but a much smaller effect on their proximate surrounding area (i.e., high ΔLST after 30 m). Green residential areas (in the web version), on the other hand, had a much smaller effect than that of the public park, but a more continuous one with a moderate increase in ΔLST with distance. The spatial patterns of LST are shown in Fig. 6 as LST contours with the mean NDVI also presented in the background.

Discussion

Efficient 'green' use of private gardens in residential area mitigate thermal load better than public gardens

Urban land uses with low vegetative cover were more affected by the UHI effect in Tel Aviv. Differences in LST were up to 13 °C within the city area (Fig. 2b). The role of vegetation in diminishing UHI was obvious in the case of Tel Aviv, where the Yarkon Park, the largest in the city, had the lowest LST (average of 18.5 °C). This reinforces the literature indicating that large parks have a more prominent cooling effect. On a local scale, vegetation (NDVI) attenuated LST in four different urban land uses, bolstering the role of vegetation in mitigating UHI effect (Fig. 3a). A significant negative correlation between NDVI and LST was demonstrated, as previously reported also by Mackey, Lee, and Smith (2012). This research also demonstrated that a built area affects the thermal load, with highest LST measured in industrial sites where the built area was higher than 49% (Fig 3b). This emphasizes the contribution of surface cover, characterized by high albedo, to the high LST.

A thought-provoking result revealed that public parks (small-medium sized), which do not contain built areas, displayed higher LST than expected (Fig. 3b). Apparently, it could be expected that such public parks would have a lower LST compared to green residential areas. However, a closer look into the related literature shows that research on public parks often concentrates on medium and large parks (100–500 ha), while small–medium parks (3–50 ha) have been less studied. Indeed, studies point to the relationship between the park's size and its cooling effect in medium to large parks (Alcoforado et al. 2009; Andrade & Vieira, 2007; Eliasson and Upmanis 2000; Jauregui, 1990; Shashua-Bar & Hoffman, 2000), but the effect of smaller scale parks is not as obvious (Andrade & Vieira, 2007). Therefore, it is possible that in small-medium public parks, inhibiting factors may exist that reduce their cooling effect.

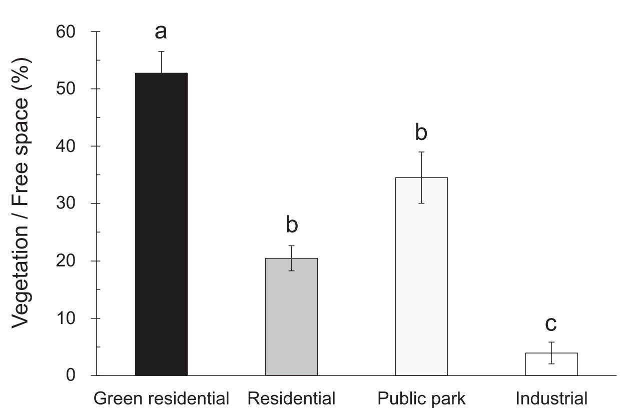

Fig. 4. The mean ratio between vegetation cover and free space (in %) in the four land use types (Table 1). Error bars denote standard error, with different letters indicating significant difference between land use using one-way Anova test with $\alpha = 0.1$ after Bonferroni correction for multiple comparisons.

Table 2
The LST measured at 30 m intervals from the site in counter direction to the coastline, in 'green residential' and 'public parks' land uses (See Section 2.4 for explanation).

Land use	Site	LST (°C)			
		0 m	30 m	60 m	90 m
Green residential	1	20.9	21.2	21.4	21.6
	2	21.2	21.5	21.6	21.9
	3	21.7	22.0	22.2	22.5
	4	22.6	22.7	22.8	23.0
	5	22.3	21.9	22.2	22.8
Public park	11	21.9	21.9	22.5	22.6
	12	21.8	22.1	22.4	22.6
	13	22.2	22.4	23.1	23.7
	14	23.1	24.0	23.9	24.0
	15	22.6	23.9	24.7	24.6

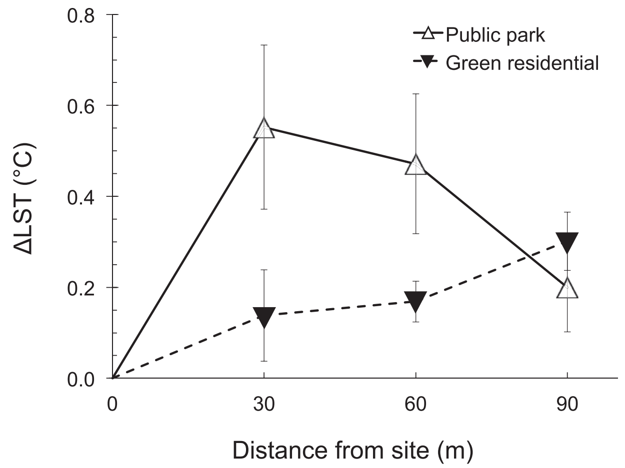

Fig. 5. Change in surface temperature (LST, °C) versus the distance from the sites' border for residential with vegetation and public park sites. Y-axis is the difference between the temperature measured at distance x and the measured at distance x-30 m. The distance 0 m is the LST measured at the site. Error bars denote $\pm 1\sigma$.

For example, Fig. 4 indicates that a factor that could explain this is the low vegetative cover in small public parks. The 'green' residential neighborhoods used their free space more efficiently for vegetation cover, with dense tree and shrub plantings in private gardens and facades. The status of the vegetation (i.e., water availability), could also contribute to the low NDVI in public parks, diminishing their cooling effect. More intensive irrigation in private gardens, relative to public parks, could result in higher NDVI, without necessarily indicating higher vegetation cover. In such cases, irrigated vegetation would mitigate thermal load through transpiration. Also, unlike previously reports (Alcoforado et al. 2009; Eliasson and Upmanis 2000), the size of the park did not contribute to the parks' cooling effect in small-medium size parks.

Location of public parks affects their spatial thermal load

Residential areas with vegetation also differed from neighborhood public parks in their spatial thermal effect. The change in temperature from small gardens integrated in residential land use toward the surrounding areas was moderate compared to that of public gardens (Figs. 5 and 6). This could result from the location of the public urban parks. Public parks are usually located near paved roads with high thermal load (see Table 1 and Fig. 6). Occasionally, public parks are also excluded from a continuous green surrounding. The outcome may be a significant increase in temperature when moving away from the public park area towards the surroundings. For example, major roads surround site 14, while site 15 is located next to a concrete parking lot. In both sites, the surrounding land-cover causes a relatively high thermal load.

Fig. 6. Spatial pattern of surface temperature presented as LST contours (°C) around two residential with vegetation and two public park sites. The mean NDVI is also shown in the background.

On the other hand, we find that generally, private gardens are located within continuously similar land use coverage. Because green residential areas usually indicate higher socio-economic status, this is most likely to affect the surrounding area in terms of vegetation cover (Kamphuis et al. 2010). Consequently, the temperature is also expected to be relatively low in such areas and the spatial effect of green residential areas, more continuous. An aggregate effect of green residential areas may result in an extended cooling effect on a wider surrounding area. Eventually, it could be compared to a park cooling island formation and may be considered as green residential cooling island (GRCI).

Nevertheless, it is important to stress that it is not accurate to conclude that small-medium public parks are not essential to mitigate thermal load. On the contrary, they have an important role especially on areas with high albedo. In addition, keeping urban open space is an important means that positively influences the physical health of the population (Zhou & Rana, 2012).

Finally, in Tel Aviv, one may notice the high NDVI to the north of the Yarkon Park and in the central (historic) area of Tel Aviv, while the southern area of Tel Aviv demonstrates lower NDVI (as well as higher LST (Fig. 2a, b)). Hence, it is central to highlight this disparity, not only from socio-economic aspect, but also from the physical aspect of land use coverage. Such disparity is displayed in terms of lower thermal load, affecting physical aspects of the quality of life.

Summary and implications for urban planning

This research analyses the effect of different land uses on surface temperature in the Tel Aviv metropolitan area. Four urban land use types including: residential area with vegetation, residential without vegetation (or low vegetation cover), public parks and industrial areas were analyzed. The selected public parks were small to medium size neighborhood parks (from ~ 3 to ~ 40 ha) and not large metropolitan parks, such as the Yarkon Park that has a greater cooling effect.

There was a similarity, in terms of vegetation cover and temperature, between 'green' residential sites and neighborhood public parks. However, public park space was less efficiently used for vegetation cover than private gardens in residential sites. As shown earlier, vegetation was denser in private gardens (vegetation cover/free space). A possible explanation is that irrigation in private gardens was better than in public parks, affecting plant transpiration and reducing thermal load more efficiently. Also, the location of the public parks, which is usually near roads and parking lots reduce their cooling effect.

Where vegetation coverage for mitigating UHI is the target, planners should characterize the particular purposes, i.e., creating 'green islets' to lower local thermal load. In a dense urban fabric this could be done not only by adding small to medium public parks, which are important for leisure activities, human interaction, as well as for physical health, but also by creating continuous green residential land use. By forming green residential neighborhoods, green residential cooling islands (GRCI) are created while maximizing the use of free spaces and maintaining a high quality of life. Hence, the aspects discussed in this study may have key implications for urban planners seeking to mitigate the UHI effect under the limitation of existing dense urban layout.

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