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Vegetation as a climatic component in the design of an urban street An empirical model for predicting the cooling effect of urban green areas with trees

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Abstract

The cooling effect of small urban green wooded sites of various geometric configurations in summer is the object of this study. It was studied experimentally at 11 different wooded sites in the Tel-Aviv urban complex during the period July–August 1996. An empirical model is developed in this study for predicting the cooling effect inside the wooded sites. The model is based on the statistical analysis carried out on 714 experimental observations gathered each hour from the 11 sites on calm days, when urban climate is expressed. Two factors were found to explain over 70% of the air temperature variance inside the studied green site, namely, the partial shaded area under the tree canopy and the air temperature of the non-wooded surroundings adjoining the site. The specific cooling effect of the site due to its geometry and tree characteristics, besides the shading, was found to be relatively small, about 0.5 K, out of an average cooling of about 3 K at noon. The cooling effect of the green wooded areas on their immediate surroundings at noon was also analyzed. The findings corroborate earlier studies that the range is noticeable. At small green sites, the cooling effect estimated in this study is perceivable up to about 100 m in the streets branching out from the site. The empirical findings in this study permit development of tools for incorporating the climatic effects of green areas in the urban design. Some policy measures are proposed accordingly, for alleviating the ‘‘heat island’’ effect in the urban environment. © 2000 Published by Elsevier Science S.A. All rights reserved.

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1. Introduction

As urbanization progresses, the ‘‘heat island’’ problem is aggravated mainly because of the reduced density of the green vegetation in the urban environment [1]. Additions to public green areas usually lag behind the urban development. Private green areas in the courtyards of apartment houses are also declining, due to conversion for parking purposes.

The reduction in the green area densities has an adverse effect on local air temperature. Rosenfeld et al. [2,3] illustrate the case for downtown Los Angeles over the period 1882–1984. With increasing irrigation and orchards, the city of Los Angeles cooled by 2 K until the 1930s. Since then, as asphalt replaced trees, the city warmed by 3 K. The phenomenon is universally typical. In macro, the control measures suggested are mainly vegetation and high-albedo roofs and streets. Rosenfeld et al. [2] study in alleviating the heat-island problem, believe in a three-pronged strategies beyond microclimate below trees: (a) cool roofs, (b) cool pavements, and (c) vegetation for evapotranspiration.

Vegetation surfaces show lower radiative temperatures than other inanimate ones of the same colour. The difference in maximum temperature may exceed 20 K [4]. In the case of large green areas such as parks, vegetation affects the air temperature above it and thus improves the thermal environment of the urban area. Jauregui [5] found that in Chapultepec Park (500 ha) in Mexico City, the effect of the park on air temperature is noticeable at a radius of 2 km, about the same as its width. In a new paper on Tama New Town’s Central Park in Japan by Ca et al. [6] found that the influence area of the park (about 35 ha) can extend

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to a distance of 1 km in the northwest direction when the wind is very strong.

In micro, the effect of vegetation on the thermal environment of its surroundings area is rather small but still significant. In Israel, Givoni [7] found that the cooling effect of Haifa's Biniamin Park (0.5 ha) is noticeable 20 to 150 m outside it. In Japan, Hunjo and Takakura [8], using a numerical model, showed a range of 200 m in the direction of the wind, the width of the green area being 300 to 700 m. The results of their simulations indicate that the range of the effect is a function of the green area scale and the intervals between the green areas. They suggest that smaller green areas with sufficient intervals are preferable for effective cooling of the surroundings to lumped larger green areas.

The cooling effect in small areas is obtained mainly through shading [9,10]. Other factors that inhibit penetration of solar radiation, besides shading, may also play a role in determining the cooling effect of a green site. The geometric configuration may also affect temperature variations, as was found to be the case in non-wooded building structures [11,12]. [1]

In the present project, to allow for geometric variations, the empirical study covered a set of urban green habitats of different sizes, shapes and built-up morphology. Measurements of air temperature, humidity, wind velocity, solar radiation penetration and surface radiant temperature [2] were carried out at the sites during the summer of 1996.

The object of this empirical study was to determine the factors affecting the microclimate inside the green site and its influence on the surrounding areas. On the basis of the statistical findings, an empirical model was developed for predicting the maximum cooling effect inside the site and its range outside the site. The model may be useful in cost–benefit analysis in designing a green area. [3]

2. Methodology

Statistical analysis of the collected experimental data on air temperature and humidity inside and outside the sites was carried out with the aid of linear regression models. The relationships to be explained are the cooling and humidity effects of the site on its own microclimate and on its immediate surroundings.

Comparison of these effects among different sites is problematic. From the publications cited above it is known that the air temperature inside the site depends on the shading intensity (partial shaded area), on the thermal properties of the soil, and on the air temperature of its immediate background. The latter varies among different urban sites due to factors affecting the air temperature such as vegetation, built-up geometry, topography, traffic density and other anthropogenic heat-release factors. [4] Comparison of the sites' air temperatures to that of a single outside reference point such as a nearby meteorological station would lead to wrong conclusions in our case, even when the comparison is done for days of measurements at a single site. To overcome this problem, the cooling effect was considered in this study as the difference between the air temperature measured at the site and that at the corresponding ''reference point'', chosen so as to comply with the following two criteria:

(a) The reference point is close to the site (50 to 100 m from it).

(b) The reference point is treeless and receives sunshine most of the day.

Thus for each site a ''reference point'' is selected. It represents the site background without vegetation effects.

The cooling effect so defined is still to some extent a function of the surrounding background temperature. This background factor will be estimated and incorporated in the empirical model. We note, parenthetically, that when the background air temperature variation among the sites is relatively small (say 1 K to 2 K), the suggested measure simplifies the comparison without further ado.

The humidity effect of the site is evaluated in the same way, as the difference between the humidity (absolute or relative) of the site and that of its reference.

3. Sites and observations

The present study was conducted during the summer (July–August) of 1996 on 11 urban green areas with trees, chosen so as to represent a variety of typical areas such as small gardens and courtyards, avenues with and without traffic and ''canyon'' streets with trees. The sites were located in the so-called Dan complex, consisting of Tel-Aviv proper and the adjoining cities of Givatayim and Ramat-Gan (Fig. 1). This region is characterized by an almost uniform topography and small climatic variations from day to day during the summer season. Consequently one would expect small variations in the climatic factors among the sites' backgrounds.

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[1] The geometric configuration of a ''canyon''-form street in Swaid and Hoffman's cluster thermal time constant (CTTC) model is represented by the height/width ratio and by the sky view factor.

[2] Measurements of solar radiation penetration and surface temperature at the studied sites are being considered for use in further development of an analytical urban climate CTTC model, previously developed in former works (see Refs. [8–10]).

[3] Following the empirical model, a more general analytical model is being developed based on the CTTC model (see Refs. [8–10]) and will be discussed in a separate paper.

[4] In a private letter, Rosenfeld mentions that in Los Angeles in summer anthropogenic heat-release factors are a few percent effect. This may also be the case in the Dan complex studied in this paper.

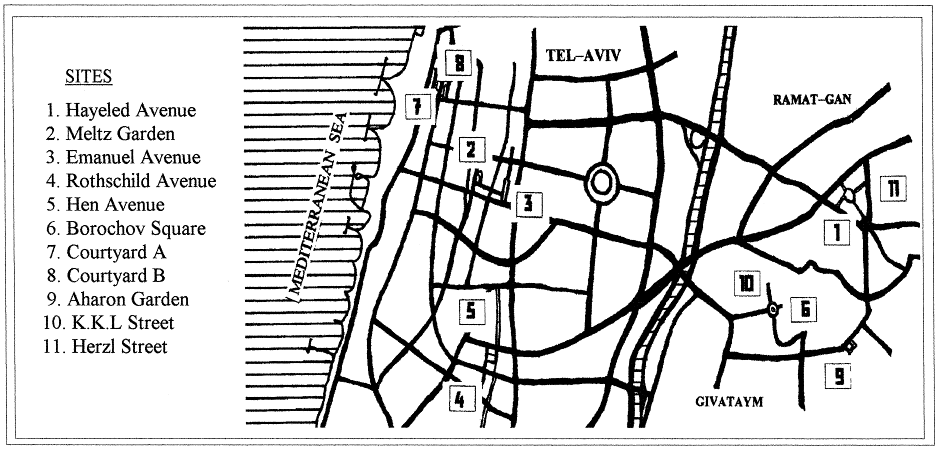


Fig. 1. The observation sites.

At each site, several observation points, spaced at about 20 m, were chosen inside it over its length and several points outside. Temperature measurements were taken with wind velocity not exceeding 0.5 m/s in the sites. On the days of measurement, the Standard Meteorological wind velocity was between 1 and 2 m/s during the day and calm, less than 0.5 m/s, during the evenings and nights. No measurements were taken on windy days.

Dry and wet bulb temperatures (DBT and WBT), were measured at 0600, 0900, 1500, 1800 and 2400 h, approximately at the height of 1.80 m. Emphasis was on the 1500 h (1410 solar time) data, representing the maximum daily temperature. Besides the climatic variables, the partial shaded area around each observation point in the site was also determined at 1500 h.

Temperatures were measured with a DB–WB Sling hygrometer. Parallel readings were taken for comparison with the aid of a digital thermometer (DT) with its sensor shielded in an aluminum foil cylinder 3 cm in diameter 5 cm in length, open on both sides and painted white on the outside. Measurements with the DBT and DT devices showed almost insignificant differences throughout. Temperature and humidity were measured in the shade. Wind direction and velocity were measured in parallel with the aid of a cup anemometer. Solar radiation intensity (direct and transmitted through the tree canopy) was measured with a Kipp and Zonen solar pyranometer. Surface temperatures (ground, tree trunks, leaves above and below the canopy) were measured with an infrared (IR) thermometer calibrated against the DBT thermometer bulb. The IR thermopile detector spectral response in the range of 7–18 μm.[2]

Table 1 lists the number of observation points inside each site (100 points altogether) and the corresponding

Table 1
Site data and measurement plan

Site	Width of site (m)	Length of site (m)[a]	Number of observation points[b]	Number of observations[c]	Dates of measurements (1996)
(1) Hayeled Avenue	22	200	14	140	July 2, 5, 10, 12, August 18
(2) Meltz Garden	35	112	10	80	August 2, 4, 6, 8
(3) Emanuel Avenue	30	115	9	72	August 2, 4, 6, 8
(4) Rothschild Avenue	45	245	18	108	July 25, 28, 29
(5) Hen Avenue	35	250	17	102	July 25, 28, 29
(6) Borochov Square	60	60	4	24	July 22, 23, 31
(7) Courtyard A	15	30	4	16	August 11, 13
(8) Courtyard B	20	25	4	16	August 11, 13
(9) Aharon Garden	40	25	4	16	August 26, 27
(10) K.K.L. Street	30	90	5	30	July 22, 23, 31
(11) Herzl Street	20	220	11	110	July 2, 5, 10, 12, August 18
Total	–	–	100	714	–

[a] Where readings were taken.
[b] Spacing 20 m.
[c] Not included — observation points outside the sites.

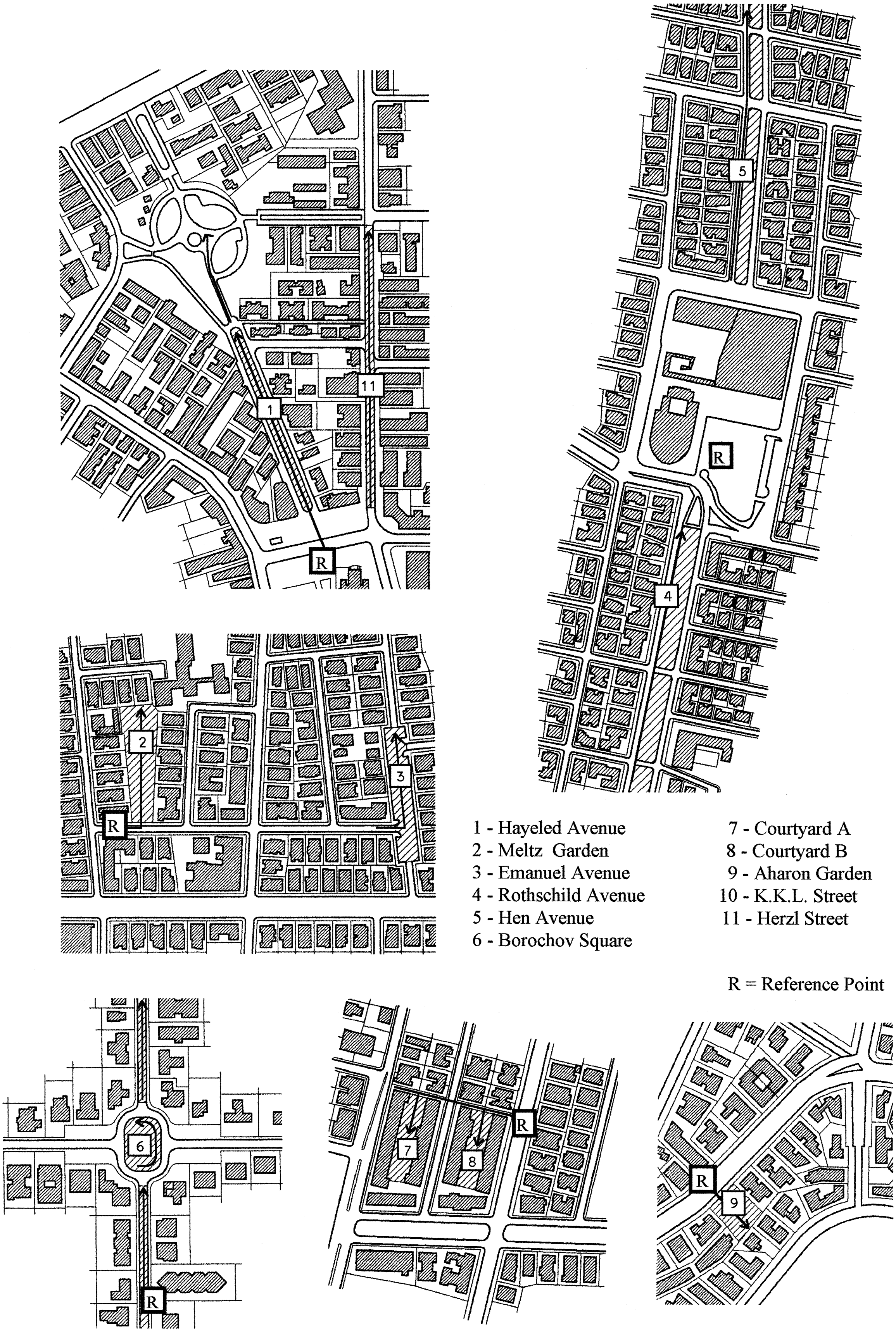


Fig. 2. Site maps.

total number of observations over the period of analysis (714 each hour). Not listed in the table are about 45 points outside the sites (see further discussion in Section 4). Site width ranged between 15 m (courtyards A) and 60 m at Borochov Square, the intersection of four streets. The buildings bordering the sites are 12 to 15 m high.

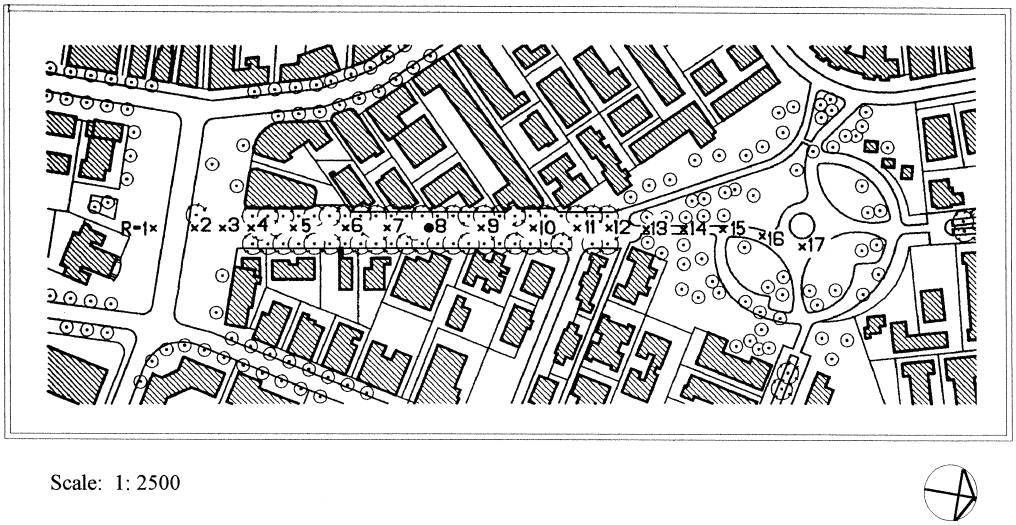
The sites include two ''canyon'' streets with trees along the sidewalks (Herzl and K.K.L.). The two avenues (Rothschild and Hen) also have trees along a 12-meter median strip. These avenues and Herzl Street carry heavy traffic. The other sites are gardens and avenues closed to vehicle traffic.

The site maps are given in Fig. 2, with reference points denoted by R. All site axes are oriented close to North–South. All sites are planted with Ficus trees about 50 to 70 years of age, except for Meltz Garden and Herzl Street, which are planted with a variety of trees with Poinciana predominating.

Some preliminary results of the thermal and humidity effects inside the sites are summarized in Figs. 3 and 4 and in Tables 2 and 3.

The pattern of the cooling effect along Hayeled Avenue site is shown in Fig. 3, where point 1 is the reference point, and point 2 is about 40 m outside the entrance to the site, bordering the street, under a large Ficus tree. Saito et al. [1] and Rosenfeld et al. [2] found that even a single tree can affect the air temperature of the immediate surrounding area. In Fig. 3, the cooling effect at point 2 is about 1 K at 1500 h, compared to the maximum cooling effect of 2.5 K at point 8 inside the site.

Similar cooling effect patterns were found in all other 10 sites (Fig. 5). The weakest cooling effect is found near



HAYELED AVENUE

* The X's denote the observation points (spaced at about 20 m)
x R = Reference point
● 8 = The point of maximum cooling effect at noon

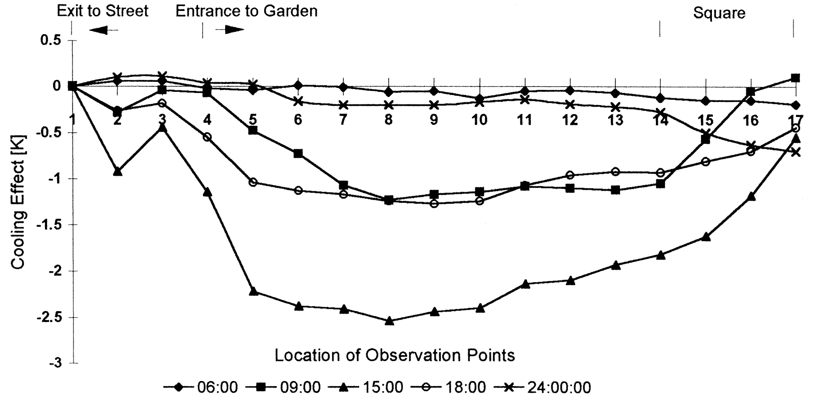


Fig. 3. The daily cooling effects along the Hayeled avenue site [K] (averages for the days of measurement).

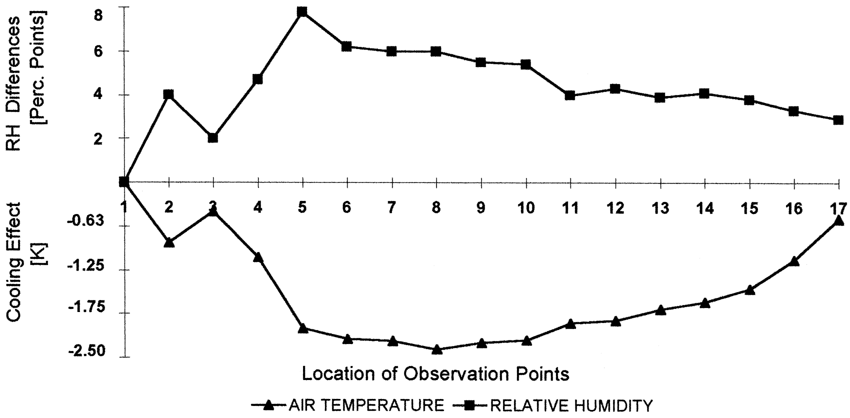


Fig. 4. Comparison between cooling effects [K] and relative humidity differences [percentage points] measured along the Hayeled avenue; time 1500 h.

the entrance, and the strongest one inside the site around the midsection.

Further statistical analysis of the factors determining these effects is given in Section 3.

The maximum cooling effects obtained inside the 11 sites are summarized in Table 2. Each figure is the average for the days of measurement at the coolest point inside each site, usually at its midsection. The average effect at 1500 h is about 3 K, ranging from 1.3 K for Herzl Street, to about 4 K for the small Aharon garden (0.15 ha). No significant cooling is found before sunrise (0600 h), or at midnight (2400 h). The average levels outside the sites for the whole surveyed season were between 24.5°C at sunrise and 32.7°C at noon.

The partial water vapour pressure for all observations was calculated from the DB and WB temperatures, with no consistent significant differences found between the sites and their respective reference points. This may be due to the fact that except for the Melts garden and the two courtyards, these sites are not irrigated. The absence of evapotranspiration change within the site does not mean no evapotranspiration. It indicates a low rate of evapotranspiration which as Oke [10] observed ''probably occurs from the top of the trees and does not mix throughout the volume'' under the tree canopy. The effect of evapotranspiration, in our case, was expressed in cooling the canopy leaves. The leaves surface temperature, at noon, relative to the reference air temperature (At Hayeled Avenue) was −3.1 K under the canopy and −1.1 K above the canopy. Without wind and without the evapotranspiration effect say in dead leaves the surface irradiant temperature of the leaves above the canopy would have been much higher than the air temperature, probably exceeding 20 K [4].

With regards to relative humidity, significant differences were found: the air temperature inside the site is lower than at the reference point, the saturation vapour pressure is also low and the corresponding relative humidity inside the site is consequently high. As the vapour pressure almost generally does not vary, the relative humidity differences along the length of the site follow a pattern similar to the cooling effect, with the reverse sign as expected. The pattern of the maximum humidity differences and the maximum cooling effect at noon for the Hayeled site are presented in Fig. 4. The maximum humidity difference at noon, at observation point 8, is about 6 percentage points. Similar relative humidity patterns as in Fig. 3 were obtained at all the other sites.

Table 3 shows the averages of the maximum relative humidity effects at the various sites, calculated as percentage points (the difference between the relative humidity percentage inside the site and at its reference). The maximum effect at 1500 h was about 10 percentage points at Rothschild Avenue, Aharon garden and courtyard B. Tables 2 and 3 indicate that the average cooling at 1500 h inside the sites is about 2.8 K and the humidity effect 7.7 percentage points. These effects are to be related to the average levels at the reference points. The average air temperature at 1500 h outside the sites was 32.7°C (31.8°C to 33.7°C) and the average relative humidity 66.4% (63% to 69.1%) for the whole surveyed period.

The relationship between the cooling and the higher relative humidity effects at 1500 h, as shown in Fig. 4, was

Table 2
Daily maximum cooling effects, [K] (averages for the days of measurement inside the sites)

Site	0600 h	0900 h	1500 h	1800 h	2400 h
(1) Hayeled Avenue	−0.10	−1.30	−2.50	−1.20	−0.20
(2) Meltz Garden	−0.70	−2.30	−2.90	−2.40	−1.20
(3) Emanuel Avenue	−0.40	−2.10	−3.30	−2.20	−0.70
(4) Rothschild Avenue	–	−1.40	−3.20	−1.80	–
(5) Hen Avenue	–	−1.40	−2.80	−1.70	–
(6) Borochov Square	–	−1.30	−2.90	−1.20	–
(7) Courtyard A	–	−1.50	−2.50	−2.30	–
(8) Courtyard B	–	−1.80	−3.40	−2.60	–
(9) Aharon Garden	–	−2.30	−4.00	−1.60	–
(10) K.K.L. Street	–	−1.00	−2.30	−1.10	–
(11) Herzl Street	0.30	0.20	−1.30	−0.50	0.20
Average	−0.20	−1.50	−2.80	−1.70	−0.50

–: Not measured.

Table 3
Daily relative humidity effect [percentage points] (averages for the days of measurement inside the site)

Site	0600 h	0900 h	1500 h	1800 h	2400 h
(1) Hayeled Avenue	1.0	5.9	6.0	2.8	1.1
(2) Meltz Garden	4.7	10.0	9.4	9.8	7.2
(3) Emanuel Avenue	1.2	8.6	9.9	7.0	4.2
(4) Rothschild Avenue	–	3.8	10.4	6.4	–
(5) Hen Avenue	–	3.3	9.4	5.2	–
(6) Borochov Square	–	6.6	8.9	5.6	–
(7) Courtyard A	–	6.1	5.2	10.8	–
(8) Courtyard B	–	8.6	10.9	12.7	–
(9) Aharon Garden	–	7.4	10.2	6.2	–
(10) K.K.L. Street	–	4.9	3.4	3.6	–
(11) Herzl Street	0.9	−0.4	1.2	0.2	−1.3
Average	1.9	5.9	7.7	6.4	2.8

approximated by a linear regression. The slope parameter for all sites was found to be −3.2 percentage points for each degree centigrade of cooling, as expected from psychometric equations. The average correlation coefficient was −0.860 — highly significant, as expected.

4. Analysis of the cooling effect

The multiple linear regression method was applied in estimating the cooling effect inside the sites. The explanatory variables considered are shading coverage, background (reference) air temperature, and the site specific effect.

The shading coverage plays an important role in predicting the air temperature inside a site in analytical models (e.g., Refs. [7,10]). In a green area with trees, the cooling effect is determined by the amount of canopy shading. Different levels of shading will produce different levels of the cooling effect: for example (Fig. 3) the fluctuations of the cooling effect along Hayeled Avenue are due to non-uniform shading.

The shading coverage effect expresses the effect of the factors governing the penetration of solar radiation (permeability). The canopy shading is determined inter alia by canopy shape and depth and leaf area distribution, spacing of the trees, and growth factors such as cultivation and irrigation regime.

The second explanatory variable considered is the background air temperature. The contribution of this variable is very important for comparison of the measurements taken on different days at a particular site, as well as among sites.

The third variable in the regression model represents the cooling effect, here the so-called ‘‘site specific effect’’. It encompasses the effect of all unspecified variables governing the site microclimate such as geometric configuration, tree characteristics and growth factors. The effect of the unspecified variables is represented by the constant term which is the intercept of the regression line.

The three explanatory variables were found to be independent. The correlation between shading coverage and background air temperature is zero. Consequently, the regression coefficients of the multiple linear model can be estimated separately by simple regressions. This procedure has the advantage of simplicity but more important, it allows to judge whether the estimated coefficients differ among the sites.

4.1. The tree canopy shading effect

The shading effect at noon was estimated for each site separately from measurements along it, using linear regressions:

$$\Delta T_{(v-r),j,v} = a_v + b_2 \mathrm{PSA}_{j,v} \tag{1}$$

where j,v is the observation point j at site v, r is the measurement at the reference, $\Delta T_{(v-r),j,v} = T_{j,v} - T_{r,v}$ is the average cooling effect at point j of site v, and $\mathrm{PSA}_{j,v}$ is the partial shaded area around the jth observation point of site v. The method of estimating PSA is described in Fig. 6. In this work, at each site the observation points were chosen spaced at about 20 meters inside it over its length. The area around the observation point (X) was divided into n usually 5 to 10 rectangular strips of equal widths.

The shading coefficients b_2 for the various investigated sites are shown in Table 4. The observations used in these regressions were the averages for the measurement days at the n observation points along each site. $\mathrm{PSA}_{j,v}$ has the same value for all measurement days and the same number of days for all observation points. Thus, the coefficient estimated from the averages of the cooling effect yields exactly the same value as that derived from the daily observations.

All correlations are statistically highly significant. On the average, this factor accounts for about 70% ($r^2 = 0.83^2 \times 100$) of the cooling effect variance for the studied sites. The shading coefficient b_2 was found to have about the same magnitude (−3.23) at all sites, except at the Hayeled Avenue (−2.15). Thus complete shading coverage from the canopy is expected to have an average cooling effect of 3.23 K at all the sites and of about 2.15 K at Hayeled Avenue (probably because this site was not irrigated).

Saito et al. [1] found a similar effect between daytime air temperature and green coverage ratio at the city of Kumamoto, Japan. The average effect of the green areas found there was $b_2 = -1.7$ as against to −3.2 found here.

The constant term a_v calculated by the regression in Eq. (1) is the estimate of the ‘‘site specific effect’’ (see Section 4.4). With b_2 known, a_v can be obtained from:

$$a_v = \Delta \overline{T}_{(v-r)} - b_2 \overline{\mathrm{PSA}}_v \tag{2}$$

where $\Delta \overline{T}_{(v-r)}$ and $\overline{\mathrm{PSA}}_v$ are the averages over all observation points of site v, at 1500 h, for all the measurement days.

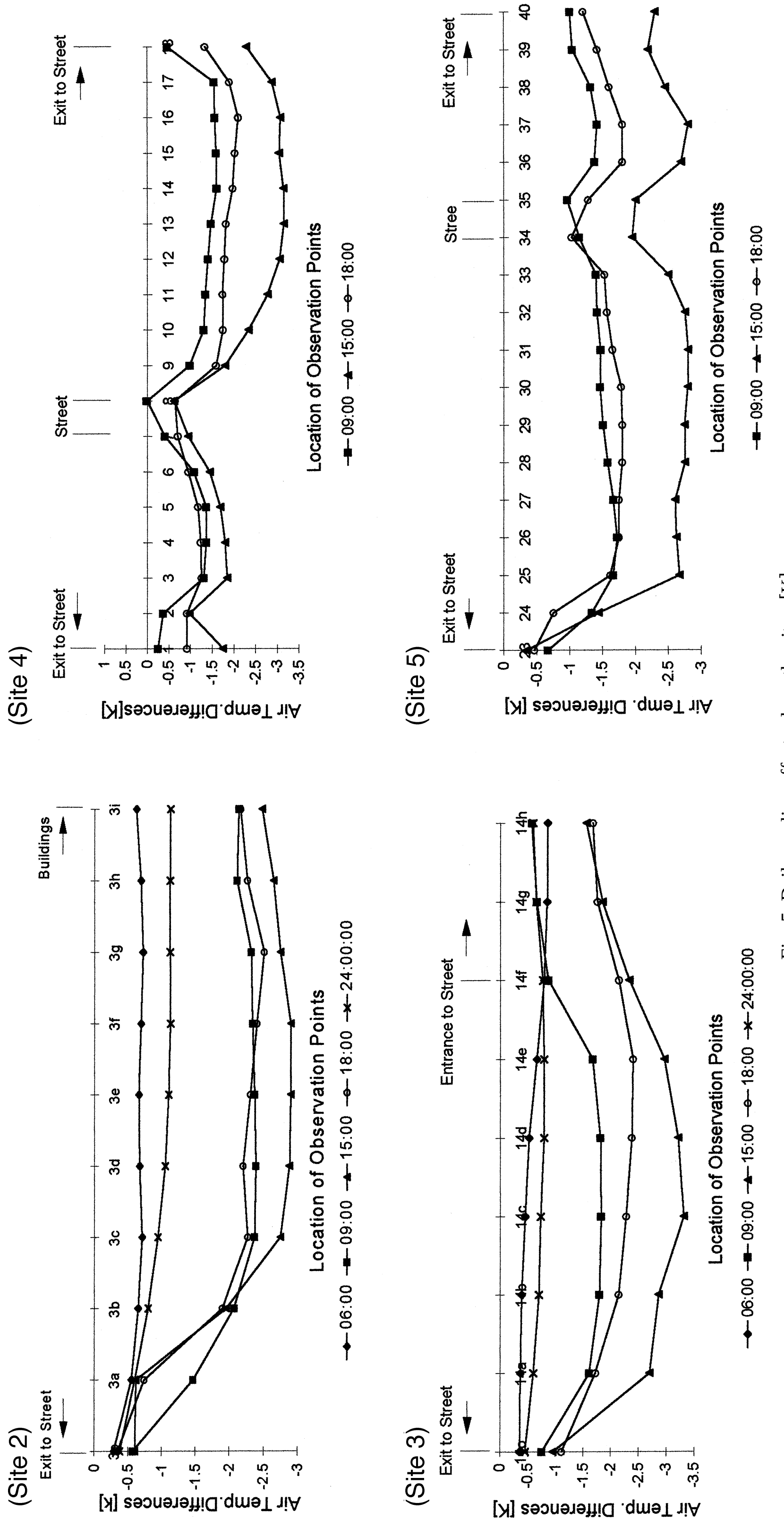


Fig. 5. Daily cooling effects along the sites: [K].

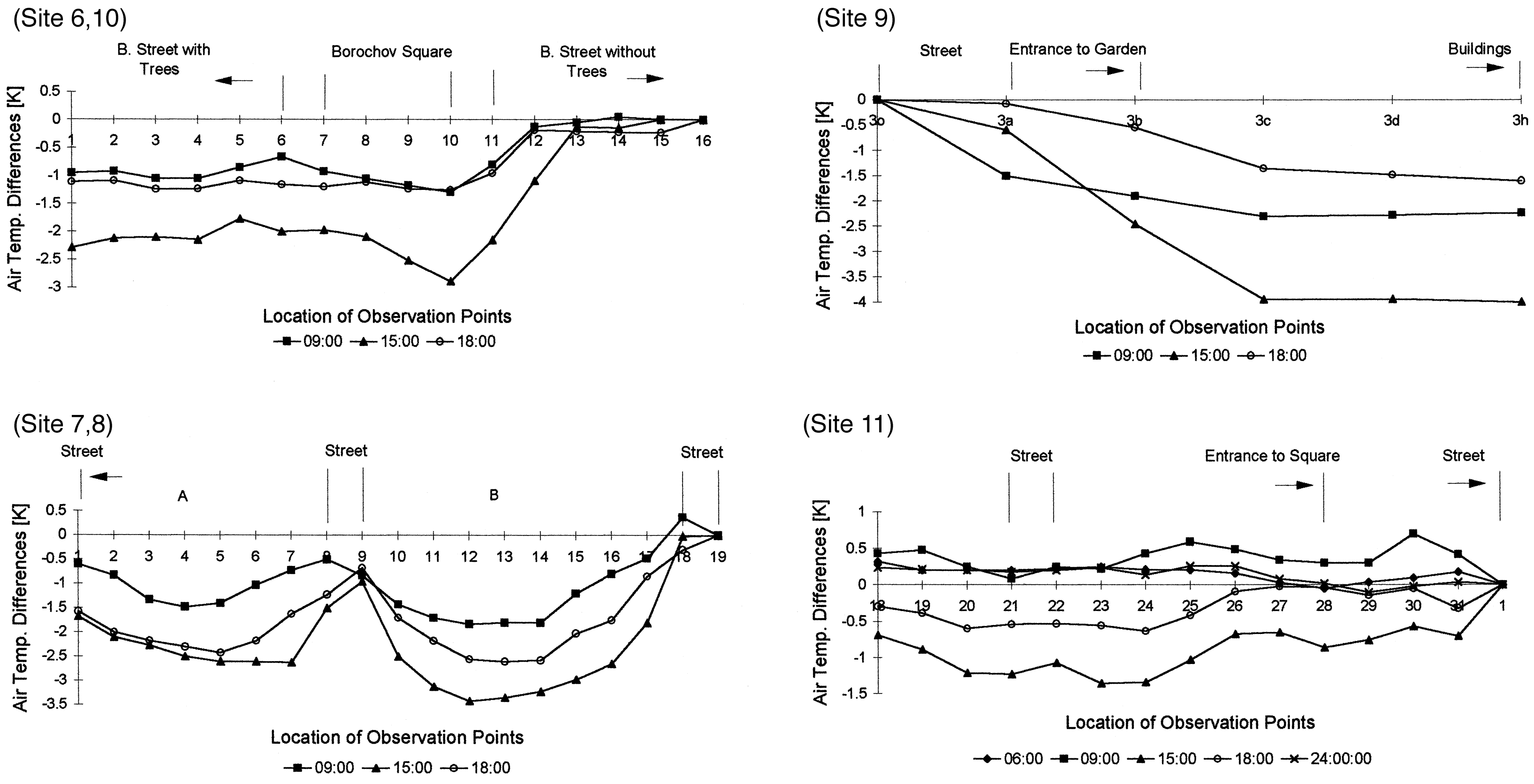


Fig. 5 (continued).

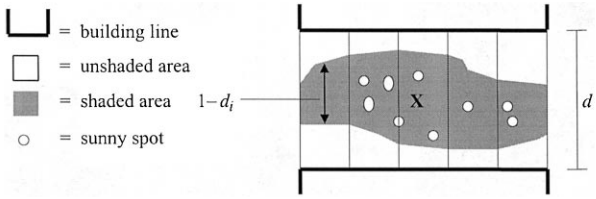


Fig. 6. Estimation of Partial Shaded Area (PSA). Denoting by: d = average length of each strip, equal to the site width, around the observation point (X). d_i = average unshaded length of the *ith* strip. The partial unshaded area (PUSA) around the observation point (X) is: $PUSA = \Sigma\ d_i / nd$. The partial shaded area PSA is: $PSA = 1 - PUSA$. Judgement was allowed in estimating the equivalent average length of sunny spots along a strip.

According to the results in the last column in Table 4, the average partial shaded area at 1500 h at all sites was about 61% (PSA = 0.609) and contributed to about 80% of the total cooling effect of the sites.

The four sites: Borochov Square, Aharon Garden, K.K.L. and Herzl Streets, were excluded from the analysis because of the minor variation found in the PSA among the observation points along each of them.[5] In calculating a_v for these four sites, b_2 was taken equal to the average for the sites in Table 4 (-3.23). a_v for the four sites was calculated according to Eq. (2) and was found to be:

- Borochov Square: $a_v = -0.57$
- Aharon Garden: $a_v = -0.56$
- K.K.L. Street: $a_v = -0.02$
- Herzl Street: $a_v = +1.03$

The first three values of a_v are of the same order of magnitude as those for the other sites in Table 4 and have the same sign. This fact confirms our assumption that b_2 has about the same value for all studied sites. The a_v for Herzl Street is different, and probably reflects the heavy traffic in daytime.

4.2. The background effect

The background effect was assumed to have the same value for all sites. It was estimated by regressing the cooling effect at the site's coolest spot as the dependent variable with respect to the air temperature at the reference as the explanatory variable:

$$\Delta T_{(v-r),i,j,v} = \text{constant} + b_1 T_{i,r,v} \tag{3}$$

where point j is the coolest spot of site v in the ith day of measurement, usually found around the middle of the site. This place was chosen for the analysis to emphasize the background effect.

The background effect was estimated separately at 0900, 1500 and 1800 h. The results are given in Table 5. The number of observations was 44 for each hour. All correlations are statistically highly significant.

The background coefficient b_1 is seen to vary over the day. It is small at noon ($b_1 = -0.315$) and is about the same at 0900 h ($b_1 = -0.515$) and at 1800 h ($b_1 = -0.636$). These findings clearly indicate that the background air temperature affects the level of cooling inside the site. The higher the background air temperature, the stronger the cooling effect. For example, when the background temperature rises by say 10 K, the cooling effect at noon is enhanced by about 3.15 K. The difference in the cooling effect between any two sites v_1 and v_2, due to the difference in their background air temperatures, equals $b_1(T_{r,v_1} - T_{r,v_2})$.

4.3. The site specific effect

The site specific effect a_v, as estimated by Eq. (1), is affected by the site's average background air temperature $\bar{T}_{r,v}$ in the same way as the cooling effect ΔT (Eq. (3)). To compare the a_vs among the various sites, they are rescaled to relate to a single reference air temperature ($\bar{T}_{v,r}$) which is the average of all sites' reference air temperatures, as follows:

$$A_v = a_v - b_1\left(\bar{T}_{r,v} - \bar{T}_r\right) \tag{4}$$

where A_v is the rescaled specific effect.

The rescaled site specific effect A_v[6] relative to the average background air temperature at 1500 h during the surveyed season ($\bar{T}_r = 32.7°\text{C}$) is given in Table 6 and is on the average about -0.5 K (except for the streets). The site specific effects are relatively small and all have the correct negative sign (except for courtyard A). On the average, the site specific effect, apart from shading, contributes about 18% of the total cooling effect (see last column in the table). In contrast, the site specific effect of Herzl Street is positive about 0.75 K (see Section 4.1 above). Accepting the assumption that the shading effect of trees (coefficient b_2) at this site is the same as for the others (-3.23), the positive effect of 0.75 K may reflect the heavy traffic. Relative to the average site specific effect value of about -0.5 K, the effect of the traffic in Herzl Street is about 1.2 K. This traffic effect is not noticeable in the two avenues — Rothschild and Hen, nor at Borochov Square. These three sites are much wider than Herzl Street and their tree canopies are higher, so that the superior cooling effect may be due to the stronger ventila-

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[5] In Herzl Street, the PSA level was 0.65 at nine observation points and 0.55 at other two points. In Aharon Garden, the PSA was 0.90 at three observation points and 0.75 at a fourth. Such slight variation in the explanatory variable is not sufficient for significant results in the regression analysis.

[6] In calculating a_v (relation 2) the shading coefficient used is $b_2 = -2.15$ for the Hayeled Avenue and $b_2 = -3.23$ for all the other sites.

Table 4
Results of regression analysis between cooling effect ($\Delta T_{(v-r)}$) and partial shaded area (PSA) for the different sites; time: 1500 h

Site	$\Delta\bar{T}_{(v-r)}$ (K)	$\overline{\mathrm{PSA}}_v$	n	a_v	b_2	r	$[(b_2\overline{\mathrm{PSA}}_v)100]/(\Delta\bar{T}_{(v-r)})$
(1) Hayeled Avenue	−1.919	0.650	14	−0.5260	−2.15	0.865	72.8
(2) Meltz Garden	−2.248	0.460	10	−0.8181	−3.11	0.760	63.6
(3) Emanuel Avenue	−2.470	0.633	9	−0.5230	−3.07	0.901	78.7
(4) Rothschild Avenue	−2.143	0.622	18	−0.0696	−3.33	0.937	96.6
(5) Hen Avenue	−2.375	0.635	17	−0.3078	−3.25	0.786	86.9
(7 + 8) Courtyard A + B	−2.476	0.656	8	−0.2680	−3.37	0.830	89.3
Average	−2.272	0.609	76	–	–	0.830	81.3

tion. In K.K.L. Street, the traffic is minimal and consequently the effect is negligible.

4.4. The cooling effect model

Combining the shading and background effects of Eqs. (1) and (3), we have:

$$\Delta T_{(v-r),i,j,v} = a_v + b_1\left(T_{i,r,v} - \bar{T}_{r,v}\right) + b_2\mathrm{PSA}_{j,v} \tag{5}$$

where the subscript i denotes the measurement day.

In Eq. (5), the term $b_1(T_{i,r,v} - \bar{T}_{r,v})$ represented the effect of the site's background air temperature deviation on day i on the cooling effect. Thus, the day-to-day cooling effect variations, at a certain hour, are due merely to changes in the background air temperatures. As this effect is measured relative to the site's average reference ($\bar{T}_{r,v}$), the term ($T_{i,r,v} - \bar{T}_{r,v}$) cancels out on the average.

The estimating model where the background effects are related to a single background air temperature $\bar{T}_r$, is given in Eq. (6):

$$\Delta T_{(v-r),i,j,v} = A_v + b_1\left(T_{i,r,v} - \bar{T}_r\right) + b_2\mathrm{PSA}_{j,v} \tag{6}$$

Note that in Eq. (5) the average temperature at the site reference $\bar{T}_{r,v}$ is used for estimating the cooling effect while in Eq. (6) the average background air temperature $\bar{T}_r$ is used, hence, the use of A_v instead of a_v.

Both Eqs. (5) and (6) yield the same estimate for the cooling effect. However, as the site's average background air temperature $\bar{T}_{r,v}$ is usually not known in advance whereas $\bar{T}_r$ (which is characteristic of the region) is known, the rescaled model in Eq. (6) is preferable, apart from the fact that A_v is meaningful for comparison purposes among the studied sites while a_v is not.

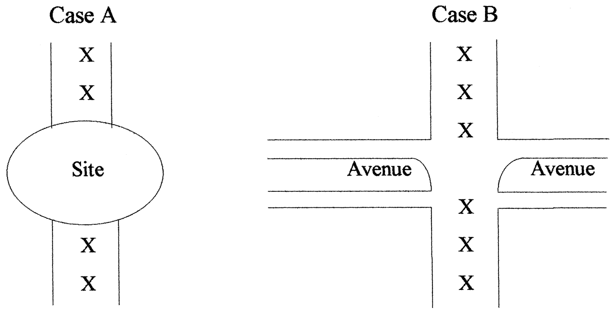
Substituting the estimated parameter values for 1500 h according to Eq. (6), the empirical cooling effect model for the studied sites, related to a single background air temperature $\bar{T}_r = 32.7°\mathrm{C}$ is given below in Eq. (7):

$$\Delta T_{(v-r),i,j,v} = 10.3 + A_v - 0.315T_{i,r,v} + b_2\mathrm{PSA}_{j,v} \tag{7}$$

where $10.3 = -b_1\bar{T}_r = -0.315 * 32.7°\mathrm{C}$, $b_2 = -2.15$ for the Hayeled Avenue; $b_2 = -3.23$ for the other sites.

5. Thermal effects of green sites on their surrounding areas

The ‘‘surrounding area’’ of a site is defined in this study as the area just outside the entrance to the site (case A) or a street crossing the site (case B). These areas have no green vegetation.



For each site, several outside points of measurement were chosen at 20 m intervals. The air temperature measurements at these points were taken at the same hour between 1430 and 1530 h as at the other sites. The cooling effect was calculated as the difference between the air temperature at each observation point and that at the reference.

Table 5
Regression results of the background effect

	0900 h	1500 h	1800 h
Constant, a	13.19	7.32	17.57
Slope, b	−0.515	−0.315	−0.636
Correlation, r	−0.835	−0.547	−0.800

Table 6
The specific cooling effects of the sites; time: 1500 h

Site	n	$\Delta\overline{T}_{(v-r)}$ (K)	$\overline{T}_{r,v}$ (°C)	$\overline{\mathrm{PSA}}_v$	A_v (K)	$(A_v \times 100)/(\Delta\overline{T}_{(v-r)})$
(1) Hayeled Avenue	14	−1.92	31.8	0.65	−0.81	42.2
(2) Meltz Garden	10	−2.25	33.2	0.46	−0.61	27.5
(3) Emanuel Avenue	9	−2.47	33.2	0.63	−0.28	11.3
(4) Rothschild Avenue	18	−2.14	32.3	0.62	−0.26	12.1
(5) Hen Avenue	17	−2.38	32.3	0.64	−0.44	18.5
(6) Borochov Square	4	−2.37	32.3	0.56	−0.68	25.3
(7) Courtyard A	4	−2.49	33.7	0.75	+0.25	−10.0
(8) Courtyard B	4	−3.28	33.7	0.70	−0.70	21.3
(9) Aharon Garden	4	−3.59	33.2	0.87	−0.62	17.3
(10) K.K.L. Street	5	−2.09	32.3	0.64	−0.15	7.2
(11) Herzl Street	11	−1.00	31.8	0.63	+0.75	−75.0
Average (without streets)	100	−2.74	32.7	0.653	−0.46	18.4

Table 7
Cooling effect outside the site boundary (°C); time: 1500 h (averages for the days of measurement)

Site	Outside observation point	Orientation	T_r (°C)	Cooling effects (K)				
				Distances from site boundary				
				Border	20 m	40 m	60 m	80 m
(1) Hayeled Avenue	Hashtil St.	E–W	31.8	2.3	2.0	1.3	0.8	0.2
(1) Hayeled Avenue	Square	S–N	31.8	1.9	1.8	1.6	1.2	0.5
(2) Meltz Garden	Amsterdam St.	E–W	33.2	0.6	0.6	0.6	0.5	0.4
(3) Emanuel Avenue	Amsterdam St.	E–W	33.2	2.7	0.9	0.5	0.3	0.3
(3) Emanuel Avenue	Emanuel St.	S–N	33.2	2.9	2.3	1.8	1.5	–
(4) Rothschild Avenue	Bar Ilan St.	E–W	32.3	1.9	1.8	1.0	0.7	–
(4) Rothschild Avenue	Bar Ilan St.	W–E	32.3	1.9	1.8	1.4	1.1	–
(5) Hen Avenue	Hashoftim St.	E–W	32.3	2.2	2.2	0.4	0.1	–
(5) Hen Avenue	Hashoftim St.	W–E	32.3	2.2	2.2	0.7	0.4	–
(6) Borochov Square	K.K.L. st.	S–N	32.3	2.9	2.1	1.1	0.1	0.1
Average	–	–	32.5	2.15	1.77	1.04	0.67	0.30

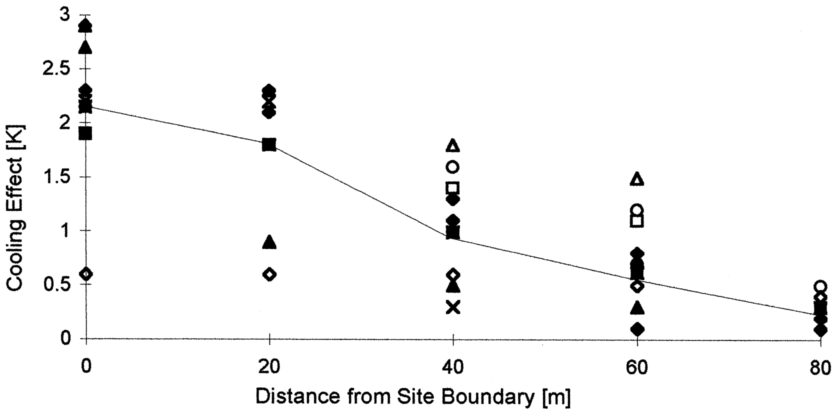


Fig. 7. Cooling effects outside the site versus distance from the site boundary [K]; time: 1500 h.

Table 8
Results of regression analysis of cooling effect outside the sites; time: 1500 h

Site	Orientation	n				Buffer zone (m)
(1) Hayeled Avenue	E–W	30	−0.822	0.275	0.270	10.2
(1) Hayeled Avenue	S–N	40	−0.681	0.179	0.172	10.4
(2) Meltz Garden	E–W	42	−0.750	−0.015	0.073	−2.1
(3) Emanuel Avenue	E–W	20	−0.902	−0.013	0.280	−0.5
(3) Emanuel Avenue	S–N	32	−0.769	0	0.121	0
(4) Rothschild Avenue	E–W	24	−0.786	0.113	0.188	6.0
(4) Rothschild Avenue	W–E	20	−0.900	0.055	0.121	4.1
(5) Hen Avenue	E–W	20	−0.906	0.384	0.524	7.3
(5) Hen Avenue	W–E	20	−0.783	0.255	0.380	6.7
(6) Borochov Square	S–N	30	−0.886	0.176	0.392	4.5
Total		278				

The average cooling effect at 1500 h outside the site boundary is shown for each site in Table 7. Here the cooling effect at each observation point is the average for all days of measurement and is listed without the minus sign. On the average, the cooling effect is 2.15 K at the boundary and drops to less than 0.5 K at a distance of 80 m.

Fig. 7 shows in a graphic way the relationship between the wooded site cooling effect on the surrounding area vs. the distance from the site boundary. The graph is drawn so as to pass through the averages at the bottom of Table 7 and thus shows a general decay trend.

A decay function of the exponential type was proposed to fit the data in the following form:

$$\frac{\Delta T_{(s-r),v}}{\Delta T_{(o-r),v}} = \exp(a_d - b_d s) \qquad (8)$$

where v is the site, subscripts o, s, r denote respectively the boundary point, the point at distance s (in 10 m, units) from it, and the reference point, T is the air temperature (°C), $\Delta T_{(s-r)v} = T_{s,v} - T_{r,v}$, a_d is the constant term, and b_d is the decay rate.

The linearized form of Eq. (8) was estimated separately for each site by the regression method. The regression coefficients are given in Table 8. All coefficients and correlations are statistically highly significant. The observations used in these regressions are the daily cooling measurements at 1500 h.

The estimated decay rate b for the various sites is not uniform. This is as expected since the attenuation effect depends on the size of the site, its orientation and its geometric configuration. The important fact, however, is that for all these sites the cooling effect vanishes at about 100 m from the boundary. Such being the case, the average b in these studied sites, is meaningful.

The linearized form of Eq. (8), estimated by the regression method, for *all* the sites together is:

$$\ln\left(\frac{\Delta T_{(s-r),j}}{\Delta T_{(o-r),j}}\right) = 0.1305 - 0.2313s \qquad (9a)$$

or, equivalently:

$$\Delta T_{(s-r),j} = 1.140\Delta T_{(o-r),j}(0.794^{s}) \qquad (9b)$$

where $\exp(0.1305) = 1.140$ and $\exp(-0.2313) = 0.794$. The correlation coefficient $r = -0.814$ is highly significant for the 278 observations.

The decay rate is on the average 0.231 (Eq. (9a)), for a unit of 10 m, or $b_\mathrm{d} = 0.0231$ when the distance is expressed in meters. Equivalently, the cooling effect drops successively by a multiplier factor of 0.794 for every 10 m (Eq. (9b)). In other words, the cooling effect drops by 20.6% [100(1 − 0.794)] every 10 m. The actual average cooling effect is compared with that estimated by the decay function (Eq. (9b)) in Table 9. The effect is perceivable up to about 100 m from the edge of the site.

The last column in Table 8, the ''buffer zone'', shows the distance from the site boundary at which the decay process of the cooling effect starts. This distance is $(a_\mathrm{d}/b_\mathrm{d}) \times 10$ m, and is arrived at by equating the right-hand side of relation 8 to zero and solving for s (in units of 10 m). On the average, the buffer distance is about 5.6 m from the site border, with little variation among the sites. The largest buffer distance is found in the Hayeled Avenue and is 10 m.

Table 9
Measured vs. estimated cooling effect with respect to distance from site boundary (K); time: 1500 h

	Site boundary	20 m	40 m	60 m	80 m	100 m
Average measured values	2.15	1.77	1.04	0.67	0.30	–
Estimated values (by decay function Eq. (9a))	2.15	1.54	0.97	0.62	0.38	0.24

The influence of a large wooded site on the surrounding air temperature was found to depend on its size [4,6]. For small green sites like those studied here (width 20 to 60 m, see Table 1), the perceivable influenced distance is small, about two to four times the width of the site. In large wooded sites, such as Chapultepec Park (500 ha) in Mexico City, Jauregui [5] found that the influence of this park reaches a distance of about 2 km, about the same as the park's width. Assuming that the cooling influence of the park follows a decay function as per Eq. (8), the cooling effect will drop by a factor of 0.986 (about 1.4%) every 10 m (equivalent to a factor of 0.75 every 200 m). Thus, if the cooling effect inside the park is say -3 K, then the effect at a distance of 1 km is small, about -0.7 K, but at a distance of 0.5 km it is about 1.5 K, which is quite significant. [7]

6. Summary and conclusions

In this study, we investigated the cooling effect at 11 small urban green sites with trees. The sites studied here have various geometric configurations: two gardens, four avenues, one green square, two courtyards and two streets. The analysis was carried out on measured air temperature data at noon gathered during July–August 1996, in the Tel-Aviv urban complex.

The average air temperature at the surrounding areas outside near the sites was 32.7°C, at 1500 h, with relatively small deviation from site to site during the period of measurement. The average cooling effect in all sites was about 2.8 K, ranging from as low as 1 K in a street with heavy traffic to as high as 4 K in the smallest garden (0.15 ha). The width of the sites ranges from 20 to 60 m.

An empirical model was developed for prediction of the cooling effect inside the sites, based on the statistical analysis carried out on the 714 experimental observations gathered each hour from the sites.

The following effects were found to be statistically significant. They are of special interest for the design of small urban green habitats.

- *The background effect*. The cooling effect in a wooded site was found to depend, among other factors, on the air temperature of its background outside the site. The higher this temperature, the stronger the cooling effect. Thus, we would expect a much stronger cooling effect of about 6 K in a typical garden in the southern part of Israel (say at Eilat), as against 2.8 K in the Tel-Aviv region. [8]

The estimated relationship between the cooling effect of a site and the background temperature, as proposed in this work, provides the means for proper comparison of sites with different background temperatures. To our knowledge, the proposed technique is novel.

- *The tree shading coverage*. As expected from previous studies in non-wooded urban spaces, the statistical analysis of our data indicates also that the shade factor plays a major role in determining the cooling effect of the site. Its effect is more or less the same for all 11 sites. In the studied sites, shading in summer is provided by the trees: on the average, about 80% of the cooling effect was contributed by tree shading.

The shading coverage factor, besides its uncontested role in the cooling process, is also a control variable. It can be regulated by the cultivation regime and by pruning, and in new sites by proper choice and placement of the shade trees.

Following the empirical model, a more general analytical model is being developed based on the cluster thermal time constant (CTTC) model. This model will consider the theory leading to the above two effects.

- *The site specific effect*. The site specific effect stands for the effects of many unaccounted variables such as tree characteristics, the site's geometric configuration, the water regime, etc. A priori, we would have expected a major role for this factor. However, apart from the trees' shading effect, what remains to be explained is minor. On the average, the specific effect contributes about 0.5 K of cooling in addition to the shading effect. The variation of the specific effects among the sites is small.
- *The effect of trees in the street*. The shading effect of trees in the streets was found to have the same magnitude of cooling effect as in the other sites. However, heavy traffic has an opposite effect of about 2 K [13]. This can explain the fact that the specific effect of Herzl Street is 0.75 K compared to -0.5 K, the average of the sites. The two sites Rothschild and Hen Avenues are also streets with heavy traffic, but with no noticeable heating effect. This may be due to the fact that these two avenues are wide (about 40 m) and their tree canopies relatively high (10 to 15 m high). The absence of heating effects in these two sites suggests that ventilation can be an important factor and should be taken into consideration in the design of trees in a street. In any case, it is important to stress the fact, as found in this study, that even a moderate tree shading coverage (say 60% as in the Herzl Street) more than offsets the heating effect of heavy traffic.
- *The cooling effect on the site surroundings*. The range of the cooling effect was found to be rather narrow and is perceivable up to 100 m from the site boundary. This fact corroborates earlier studies, although in our case we are dealing, by design, with much smaller green areas not wider than 60 m. The cooling values were found to follow an exponential decay function.

The cooling effects of small green areas as found in this study are significant. The effects are, however, local, and as such can be used to suggest some policy measures for

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[7] In relation 8, we assume $\exp(a_d)=1$, $\Delta T_o=-3$ K, $\Delta T_s=-0.2$ K, then $-0.2=-3(R)^{200}$ and solve for $R=0.986$.

[8] Eilat is about 10°C hotter in summer than Tel-Aviv, and the relative humidity about 20% at noon.

alleviating the so-called urban ‘‘heat island’’ effect in the urban environment.

(a) The range of the cooling effect being perceivable up to 100 m suggests small gardens, 200 m apart. These gardens can be designed to accommodate the recreational needs of young children and senior citizens. The proposed size of such gardens is 0.1 ha, equal to the area of the apartment building commonly found in the urban Tel-Aviv complex.

(b) The cooling effect of trees in streets was found to be significant. In a street with trees, with heavy traffic such as in Herzl Street, the cooling effect reaches about 1 K. Streets make up more than 25% of the urban city area. This policy measure, properly designed, is most effective in reducing the traffic heating effects. The cost is minimal.

(c) This study endorses Rosenfeld et al.’s suggestion [9] for at least one shade tree per eligible house to offset some of the cars’ parking effect in the courtyard.

(d) No consistent significant differences were found between the sites vapour pressure and their respective reference points. However, the fact that the leaves surface temperature, at noon, below and above the canopy was lower than the site reference point is due probably to wind over the canopies and to evapotranspiration.

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[9] Rosenfeld et al. [2] suggest three trees per eligible house.