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The Effect of Increasing Vegetation Cover on Energy Demand for Heating and Cooling Buildings in a Dense Mediterranean City

Methodology and Case Study

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ABSTRACT: The study examines the effects of adding vegetation to a Tel Aviv neighbourhood on the microclimate, and subsequently on electricity consumption for heating and cooling. Computer simulation was employed to generate modified weather files that account for urban effects in different building configurations. These files were then used as inputs for detailed computer simulation of building energy performance. Elevated night-time temperatures in the urban location increase summer cooling relative to the reference rural site, but reduce winter heating, resulting in a net decrease of 2-7% in overall electricity use for heating and cooling (depending on building characteristics). The reduction in the potential for cooling by night ventilation will increase the prevalence of air conditioning use and make buildings more vulnerable to potential loss of electric power during episodes of extreme heat. Implementing a strategy of extensive planting, so that a green surface fraction of 0.5 is obtained, results in a mean annual temperature reduction of about 0.3 °C and an energy saving relative to the current condition of about 2-3%.

KEYWORDS: building energy simulation; climate cooling potential; microclimate modelling; vegetation; urban heat island mitigation

1. INTRODUCTION

Increasing vegetation cover is one of the main strategies for mitigating urban heat islands and reducing energy consumption in buildings [1]. Computer simulation of air temperature, usually on a typical hot day, has been employed to assess the energy saving potential of vegetation on hot summer days [2] using software such as ENVI-met [3], which includes detailed procedures for describing plants. Most studies have been performed for low-rise buildings in low-density neighbourhoods, and results invariably demonstrate a cooling effect. The studies then estimate the reduction in air conditioning loads, rarely carrying out a detailed building energy simulation. With the exception of studies on green roofs, e.g. Moody & Sailor [4], few modelling studies have demonstrated a systematic methodology for assessing the site-specific effect of vegetation in dense urban neighbourhoods on **annual** energy consumption. Fewer still have attempted to account for the full effects of shading by adjacent structures, lower wind speed and increased humidity – in addition to modification of air temperature.

The present study has the following objectives: To describe a methodology designed to carry out an assessment of the effect of vegetation on annual building energy consumption, which may be applied in any location; and to illustrate it by means of a case study for several (residential) building types in a warm climate. The case study focuses on a dense, medium rise neighbourhood, a typology that is found all around the Mediterranean and is becoming increasingly common in new construction in developing world cities.

2. METHODOLOGY

Urban microclimate was simulated using the Canyon Air Temperature (CAT model) [5]. Using measured data from a rural reference weather station as input, CAT generates modified TMY files for urban street canyons of varying geometry and different vegetation cover, which incorporate urbanized values for dry bulb temperature of the air, relative humidity and wind speed. These data are used to modify .epw files used as inputs for the EnergyPlus building thermal simulation software (US DOE, 2008).

Energy consumption was simulated for 5 scenarios: 1) a stand-alone building at the rural reference weather station; 2) the same building, but shaded by similar adjacent structures, to account for the effects of shading in a typical city street, but with no modification of the weather file; 3) conditions in

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typical streets in Tel Aviv, to illustrate all urban effects, including shading by adjacent structures and a modified weather file; 4) same as scenario (3), but with additional plant cover in the urban neighbourhood (50% of non-built area); 5) same as scenario 3, but with all existing vegetation removed.

2.1 Study area

Tel Aviv comprises the core of Israel's largest metropolitan area and is located on the eastern coast of the Mediterranean Sea. Its climate is classified as Mediterranean (Köppen Csa), with mild, rainy winters and warm, humid summers. It has 530 heating degree-days (to 18.3 °C) and 3,810 cooling-degree-days (to 10 °C). The study area comprises the Ramat Aviv neighbourhood, about 1.5 km inland from the Mediterranean Sea (32°11'N, 34°79'E). Streets are 15-25 m wide and flanked by buildings of varying height, from two or three storeys to as many as 16 storeys.

2.2 Simulating the urban microclimate

The CAT simulation requires descriptions of the sites of both the weather station providing the boundary conditions and of the urban street canyon that is the object of the exercise. The details required for both locations include the geometry of the site, represented by building height, street width and street orientation; thermal properties of the wall materials and the ground surface; and land cover within a radius of 1,000 meters, specifically the proportion of the surface covered by vegetation and bodies of water, for each of 32 sectors arranged in a radial pattern surrounding the site [6]. In addition, data for the reference weather site (only) include aerodynamic parameters describing the surface roughness, required to generate the logarithmic profile of the wind speed above the ground, and annual temperature data used to model the subsurface temperature.

When the CAT model is run for a single urban location, the required inputs may be entered manually into the text files read by the software. However, the derivation of the inputs for an urban area comprising thousands of grid elements at a resolution of 100 x 100 meters requires an automated procedure to process data from several sources. These sources include a spatially explicit GIS database describing building footprints; and satellite images that are analysed to provide estimates of the surface cover fractions [7]. The values for each grid cell were estimated using an automated procedure developed using the R software [8] and ArcGIS 10.6 [9].

CAT is a 'canyon' model, in which the entire urban area is described by means of simplified urban elements referred to as street canyons [10], for which a detailed surface energy balance may be calculated. Zhou et al [11] described an automated procedure for identifying such street canyons and assigning a street orientation even if building footprints are irregular and there are no discernible paved roads between adjacent building blocks, based solely on the plan form view of the buildings and the distances among them.

Anthropogenic heat, which may have a substantial impact on air temperature in dense urban locations, is estimated using a procedure that accounts for heat given off from buildings and automobiles [11]. Heat transfer from buildings includes steady-state conduction through facades, which is calculated using typical thermal properties of walls and windows and the difference in air temperature between the building interior (according to season) and exterior at hourly time steps. Heat loss by convection is estimated assuming a fixed number of air changes per hour between the interior and the exterior, based on the construction quality and airtightness of fenestration. In summer, heat ejected by air conditioners is assumed to be proportional to the difference in air temperature between the interior and exterior. Heat emitted by automobiles is estimated as the product of the heat emitted by a typical car (3,795 J/m [12]) and the number of vehicles travelling down the street, assigned according to street width (broad streets have more traffic) and a diurnal traffic profile.

2.3 Effects of vegetation

The vegetated CAT model uses parameterizations to estimate evapotranspiration and surface temperature, and accounts for changes in soil moisture and the canopy resistance of different types of vegetation as well as the green surface fraction [13]. This fraction was estimated for the current (baseline) conditions using NDVI values obtained from remote sensing images [11].

2.4 Building characteristics

Energy simulations were carried out for three building variants having the same floor plan but representing different standards of construction: a pre-1980 'standard' building complying with Israel standards for thermal insulation (SI 1045); a 'green' building with the same floor plan but complying with the energy requirements of the Israel green building standard (SI 581); and a building with a 'curtain wall' design similar to some of the new residential construction in Tel Aviv.

The building has an H-shaped floor plan that is very common in Israel. It comprises four apartments per floor, each of about 84 m^2 in floor area. The window to wall ratios for all facades of the building are 0.11 - 0.12, except for the curtain wall variant, which has a window to wall ratio of 0.3 on the north and south facades.

The building is a concrete frame construction with infill walls of hollow concrete blocks. Thermal insulation values of envelope elements are shown in Table 1:

Table 1: Building thermal properties

	wall	roof	windows		
	U-value (W/m²K)	U-value (W/m²K)	U-value (W/m²K)	SHGC	shading
'standard'	2.10	2.60	5.9	0.85	external
'green'	0.83	0.69	3.1	0.52	external
'curtain wall'	0.66	0.69	1.8	0.35	none

3. RESULTS

3.1 Model validation

The microclimate model was validated using the 'Tel Aviv coast' weather station data as the objective of the simulation and the rural 'Bet Dagan' station of the Israel Meteorological Service, about 7 km inland, to force the model. Fig. 1 illustrates model performance for a typical week in summer.

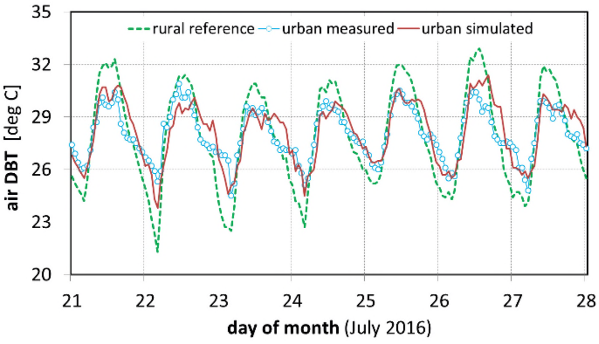

Figure 1: Model performance in summer.

The measured temperature at the urban station (light blue circles) is generally warmer at night and cooler in daytime than at the rural reference station (dashed green line). This is due to the combined effect of its proximity to the sea and its urban characteristics. The simulated temperature (solid red line) demonstrates the ability of the model to pick up both effects. Statistical analysis shows a root mean square error (RMSE) for the entire year (8760 hours) of 2.02 °C, with a mean absolute error (MAE) of 1.11 °C.

3.2 Urban effect on air temperature

Figure 2 shows the spatial pattern of the simulated UHI of Ramat Aviv for a typical summer night (July 30, 2016). Temperature differences are displayed relative to the reference weather station at Bet Dagan.

The urban heat island has a clear diurnal pattern, simulated for the hot spot indicated in Figure 3: it is small or even slightly negative during daytime throughout the entire year. At night, the UHI intensity reaches a mean maximum of nearly 3 °C, observed shortly before sunrise, but the variance is quite large, as indicated by the values for the 10th percentile and 90th percentile of hours, at under 2 °C and nearly 5 °C, respectively.

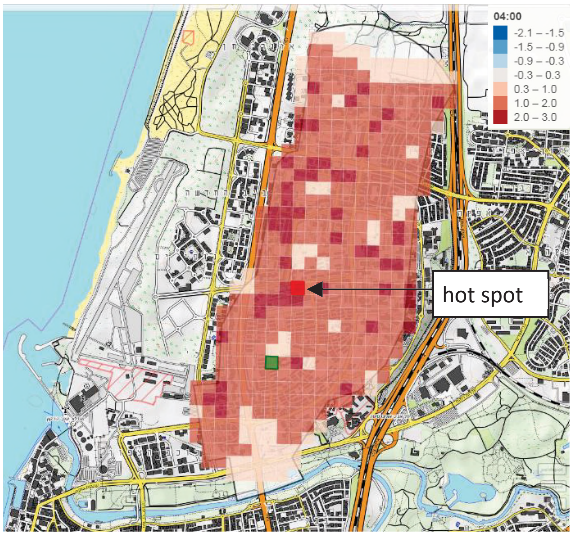

Figure 2. Ramat *Aviv UHI simulated by CAT for 04:00 on July 30, 2016*

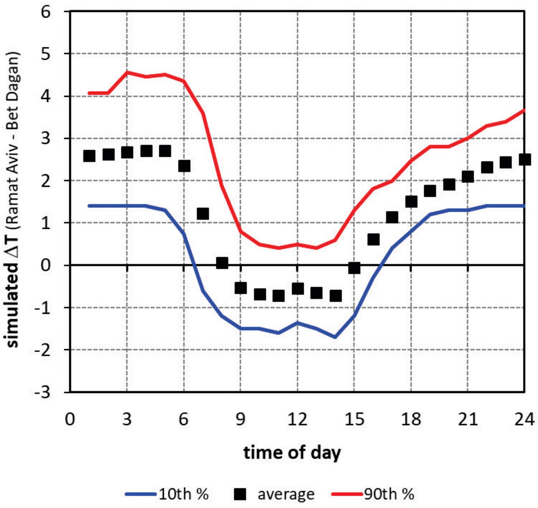

Figure 3: The simulated diurnal pattern of the UHI in Ramat Aviv, drawn from the mean hourly differences between the urbanized weather file and the reference weather file for an entire year.

3.3 Effect of vegetation on air temperature

Increasing vegetation cover to 50% of the non-built area in the suburban neighbourhood is expected to reduce air temperature. Fig. 4 shows the simulated magnitude of this effect over the entire year.

As the figure shows, the effect of adding surface cover vegetation on air temperature is in fact quite modest, for two reasons:

- First, the spatial extent of additional plant cover that may be added to an existing urban fabric is limited. The green fraction of Ramat Aviv, measured within a 1,000 meter radius of the site being modelled, is currently 0.29, and the built fraction of the developed area is 0.22 (some of the periphery is still undergoing development). The scenario evaluated, whereby the green fraction is increased to 0.5, is probably the maximum possible practical

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intervention, and would entail a substantial reduction in the areas currently devoted to roads and vehicle parking lots.

- Second, because the effect of evaporation on air temperature in a street canyon is related to not only to the horizontal area but also to the ‘complete’ three-dimensional urban surface [14], the impact of such an intervention is comparatively lower in medium or high-rise neighborhoods than in neighborhoods where the majority of buildings are only one or two stories high.

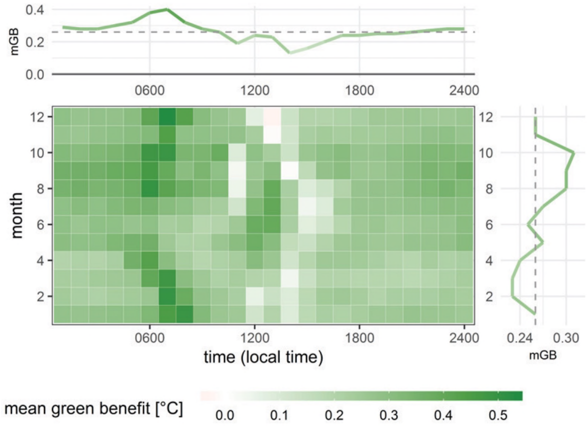

Figure 4: Effect of adding vegetation on air temperature in the urban site.

3.3 Building energy consumption

Table 2 shows the annual electricity demand for heating and cooling the standard case study 8-story building for each of the five scenarios.

Table 2: Simulated annual electricity consumption for heating and cooling the 8-story building selected for analysis.

	building electricity demand (kWh/a)		
	heat	cool	total
1 rural unshaded	16,575	40,734	57,309
2 rural shaded	20,053	34,636	54,689
3 existing canyon	10,587	40,503	51,090
4 ‘green' canyon	11,681	38,048	49,729
5 ‘no green’ canyon	9,935	41,930	51,865

The net effect of including shading by similar adjacent structures in the simulation (scenario 2, using the same .epw weather file as scenario 1) is to increase heating demand in winter but reduce cooling demand in summer. Scenario 3 demonstrates the urban effect: the city is warmer, so the building requires less heating but more cooling. Scenario 4, by lowering air temperature, reduces cooling demand but also increases heating requirements. Finally, in Scenario 5, removing all current vegetation increases air temperature, thus lowering winter heat demand but increasing summer cooling relative to the existing situation.

4. DISCUSSION

The objective of this study was to assess the outcome of interventions in the urban fabric to mitigate the effect of the urban heat island, and hence on building energy consumption. The methodology demonstrated here accounts, by means of appropriate software tools, for both urban effects and building effects, at high spatial and temporal resolution on an annual basis.

4.1 Assessing the impact

The urban effect on annual energy consumption depends on the balance between demand for summer cooling, which is aggravated due to the nocturnal heat island, and moderated by reduced winter demand for heating. In the case of Tel Aviv, which has a warm humid Mediterranean climate, the net urban effect was - counter-intuitively - a small **decrease** in annual energy demand. It is worth noting, however, that while the simulated reduction in winter heating (the difference between scenario 2 and scenario 3 in Table 2) is equal to nearly half of the total demand for the season, the increase in summer cooling demand, which was twice as large in the first instance, is only 17%. Simulation for future climate conditions in the Eastern Mediterranean in the period 2041-2070 project a general increase in seasonal mean temperatures of up to ~2.5 ^{0}C [15], so this balance could change as winter heating demand in the urban areas is eliminated entirely. Summer heat will be exacerbated, particularly during strong nocturnal heat island episodes.

Increasing the green fraction yielded a mean annual temperature reduction of about 0.25^{o}C relative to the existing condition, and a small reduction in building energy consumption equivalent to about 2.6% of the total annual demand for heating and cooling.

The electricity consumption of a conventional compression cooling system, such as the split air conditioners commonly used in Israel, depends not just on the sensible heat load, due to the dry bulb temperature of the air, but also on the latent load, due to its humidity. Vegetation can maintain a lower temperature than an adjacent paved surface, despite having a similar albedo (0.2-0.25) because of evapotranspiration, which releases moisture to the air and increases humidity. Thus, although near-surface air temperature in the presence of vegetation may be a little lower, the enthalpy of the air, and thus the total thermal load on the air conditioning system, is nearly the same.

4.2 Limitations of the study

The vegetation modelled in this study consisted of surface cover plants, such as grass or small bushes.

Their effect on building energy consumption was expressed through their impact on air temperature and relative humidity, by means of the modified weather file. Other plant types, such as trees, may have different effects: For example, they may induce a greater temperature reduction during the warmest daytime hours, but a smaller reduction at night, when trees may even lead to warmer air temperature because of reduced radiant cooling; and they reduce wind speed and thus the potential for cooling by ventilation. Vegetation also affects building energy consumption through radiant exchange: Because planted surfaces are typically cooler than pavement, the radiant fluxes incident upon building walls in the vicinity of planted surfaces are usually smaller [16]. This may be expected to lower cooling demand in summer, but increase heating demand in winter.

The cooling effect of vegetation depends to some extent on evapotranspiration. The vegetation model incorporated in CAT [13] simulates changes in soil moisture, which increases in response to precipitation, then decreases gradually in the absence of rain as water slowly evaporates. However, if the surface is planted, the model allows soil moisture values to decrease to a minimum value and, if there is still no rain, are then increased to the field capacity for the soil in question, to represent the effect of irrigation. In reality, irrigation may not be provided at the appropriate interval to compensate for the absence of rain, or it might not be supplied at all.

The buildings modelled in this study are medium rise: 8 storeys high. The impact upon them of vegetation at ground level may thus be expected to be lower than in the case of detached low-rise buildings. Additionally, apartments in the upper storeys of tall buildings do not benefit from the shading effects of vegetation.

Modelling tall buildings creates unique challenges, because the environmental conditions, especially wind speed, change with height above the ground. EnergyPlus has built-in procedures for treating tall buildings that account for the temperature gradient and in particular the effect of wind on the transfer coefficient for convection at wall surfaces. However, it does not simulate the effects of the urban environment on local wind patterns and air temperatures directly [17]. CAT accounts for some of the urban effects, in particular a transformation of wind speed from a measured value at the rural reference weather station to a more realistic urban wind. However, although CAT simulates an urban logarithmic profile for wind, based on estimated roughness length and displacement height as well as a lee vortex in the street canyon, the EnergyPlus input uses just one wind speed value that cannot account for local effects at different building facades.

Finally, the modelled energy consumption is an indication of the relative energy performance of buildings, subject to the precise values assigned to represent occupant behaviour, such as set point temperature or occupancy patterns. While this is true for all building energy simulation, it is important to remember that occupant behaviour may have a great impact on real-world energy consumption: Field studies have demonstrated large variations in actual electricity consumption for heating and cooling even among identical apartments in the same building [18].

CONCLUSIONS

The study described a methodology designed to carry out an assessment of the effect of vegetation on building energy consumption. Application of this process allows us to propose the following conclusions:

- Studies focused on energy saving should employ detailed building energy simulation software that is capable of performing dynamic calculations at appropriate time intervals for an entire year.
- Urban effects must be accounted for in the weather files used in any simulation of the energy performance of buildings. The magnitude of these effects is often greater than the impact of the mitigation measures proposed.
- It is essential to model the effect of shading by adjacent buildings or any other sizeable object, including trees (despite that this is still not always required for building certification).
- Generating reliable, appropriate, site-specific, urbanized data for building energy simulation remains a challenge: meso-scale simulations such as WRF are not capable of resolving the urban features at the required spatial resolution, while micro-scale tools such ENVI-met are limited to one or two days at most.
- Any estimate of the potential energy savings from implementation of vegetation is necessarily limited to the precise circumstances for which they were assessed, because it is affected by numerous unique factors such as the spatial extent of the application, the type of vegetation, the amount of irrigation, the geometry of the street canyon, the local climate and the detailed thermal design of the building. Although it may be possible to generalize, it should be accepted that the magnitude of the outcome of any intervention may be within the margin of error of the building energy simulation tool, and is certainly smaller than the actual variations among similar apartments exposed to the same conditions.

The methodology demonstrated here requires advanced computer skills, but the computer resources are modest, especially if the analysis is performed on a limited spatial scale. It may thus be applied nearly anywhere: the basic inputs are the measured climate data at a nearby weather station and a GIS database of building footprints and heights. Additional features of land cover are generated from satellite images that are publicly available.

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