Arch. Met. Geoph. Biokl., Ser. B, 29, 327–344 (1981)

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551.521.1:551.525.2:551.588.7

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Urban Parks, Energy Budgets, and Surface Temperatures

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With 12 Figures

Received April 6, 1981

Summary

This paper deals with the results of the combination of two deterministic models: a multi-layered canopy leaf energy budget model CANOPY and a complex street canyon energy budget model URBAN 3. Both models were validated previously. In comparing the effect of street parks and roof gardens in contrast to non-vegetated city blocks. four typical urban morphologies were created, ranging from high-rise structures to low buildings and combinations thereof. These building systems were exposed to typical summer and winter scenarios for three latitudes. The simulations indicated a variety of increases in absorbed shortwave radiation and net radiation, and decreases in sensible heat flux and system reradiation compared to non-vegetated environments. It is believed that the discussed features represent generalized limits of the possible effect of adding vegetatived surface covers to non-vegetated city blocks.

Zusammenfassung

Stadtparks, Energiebudgets und Oberflächentemperaturen

In dieser Arbeit werden die Ergebnisse der Kombination von zwei Modellen mitgeteilt: eines Energiebudgetmodells CANOPY für eine mehrschichtige Vegetationsdecke und eines Energiebudgetmodells URBAN 3 für einen komplexen Straßenzug. Für den Vergleich des Einflusses von bewachsenen Straßen und Dachgärten im Gegensatz zu nicht bewachsenen Häuserblocks werden vier typische Stadtformen, reichend von Hochhaus-Strukturen bis zu niedrigen Gebäuden und deren Kombination zugrunde gelegt. Diese Gebäudesysteme werden typischen Sommer- und Winterverhältnissen in drei geographischen Breiten ausgesetzt. Diese Simulationen zeigten im Vergleich mit unbewachsener Umgebung eine Verschiedenheit in der Zunahme von absorbierter kurzwelliger Strahlung und Strahlungsbilanz und in einer Abnahme des sensiblen Wärmeflusses und der Rückstrahlung. Es wird angenommen, daß die besprochenen Merkmale verallgemeinerte Grenzen für die mögliche Wirkung der Anlage von Vegetationsflächen zu nicht bewachsenen Häuserblocks anzeigen.

0066-6424/81/0029/0327/$ 03.60

1. Introduction

A review of the literature revealed that apparently only a few sporadic investigations have dealt with the question as to what degree will a city's energy budget and surface temperatures be changed by the addition of street parks and roof gardens. Most works examined were empirical and for unique situations – of limited value in deriving worldwide generalizations (see [1]). To our knowledge, no systematic modelling efforts have appeared which attempt to ascertain the cause and effect of city-vegetation interrelations on a detailed block-by-block basis. However, among the more analytical approaches was a paper by Hall [2].
Previously, a multi-layered stand leaf energy budget model CANOPY was developed for the purpose of systematically investigating vegetation influences on urban interfaces [3]. The magnitude of the output of this deterministic-parametric model compared favorably with the much more complex, expensive, and validated Soil-Plant-Atmosphere Model SPAM [4, 5].

2. Aspects of CANOPY

Because this model has been described in detail previously [6], only the salient features will be noted. The guiding principle used was the energy budget of a leaf. For unobstructed horizontal canopies, the shortwave term can be obtained in a variety of ways (e.g., [7]). Several approaches can be used for the equivalent longwave sky component (e.g., [8]). The sensible and latent heat fluxes were modelled with the methods of Gates and Papian [9]. Following Monteith [10], three components of shortwave absorption by leaves in the interior of the canopy were simulated: the direct radiation of sun flecks, the diffuse radiation created within the canopy as a result of transmission and scattering by sunlit foliage, and the diffuse radiation coming from the sky. The absorption of longwave radiation in the canopy included the averaged reradiation of leaves above and below each layer. Infinitely large exchange coefficients were assumed in regard to the profiles of stand air temperatures, air humidities, and wind speeds. The validity of such assumptions has been depicted previously [11].
Two boundary conditions need to be specified: top of canopy (solar radiation, atmospheric counterradiation, air vapor pressure, wind velocity, and air temperature) and bottom of the soil column (where the temperature time-derivative approaches zero at about 1 m). Leaf temperatures for each vegetation layer were computed by iterations of the leaves' energy budget.

3. The Combination of URBAN 3 and CANOPY

Previously, URBAN 3, a model which makes use of the microscopic perspective of the energy budgets of urban places, was introduced [3, 12, 13, 14]. By using such a model, a city or parts of cities can be subdivided into street canyon systems enabling a block-by-block analysis of energy fluxes into or out of buildings (e.g., [15]).

The physical nature of an urban landscape can be simulated in terms of its structure. In URBAN 3 the simulation of the exchanges of energy was modelled by the absorption of shortwave and longwave radiation and the dissipation of that energy which accurs among the many city surfaces. The resolution of the model is sufficiently detailed to examine cities even on a building-by-building basis. Each street canyon system represents a set of buildings or surface areas. Each surface is subdivided into sunlit and shaded portions. For every subdivision the amounts of shortwave and longwave reflections and reradiations, are computed. Obviously, beyond this system, other buildings can become potential obstructions. Thus the height of the skyline in all directions has to be obtained by projecting vectors from several points inside the system to the surrounding urban terrain [16]. In the model, the relationships of the sun's shading between blocks with different heights is determined as a function of the sun's azimuth and altitude. In the calculation of reflected shortwave radiation and emitted longwave radiation from the surroundings, view-factors have to be obtained. A view-factor is the ratio of emitted or reflected radiation by a surface that is intercepted by another surface to the total radiation emitted or reflected by the former surface. This proportion of energy is a function of distance between the points or areas and the angles between this line-of-sight and normals to the incremental areas. For finite areas, the applicable view-factor equations were integrated by analytical solutions [15]. The predictions of resultant surface temperature compared favorably with observations. URBAN 3 can be used best for sensitivity analyses of the responses to certain prescribed input scenarios. Fig. 1 shows a much simplified flow chart of URBAN 3 combined with CANOPY.

4. A Continuum of Urban Street Canyon Systems

Four characteristic urban building combinations were created in order to compare the resultant behavior of energy budgets of street parks and roof gardens with changing physical structures as represented by the four urban surroundings (Fig. 2). These neighborhoods were meant to represent a typical continuum between high-rise buildings and low structures, with combinations thereof. For all buildings, fifty percent of the walls were

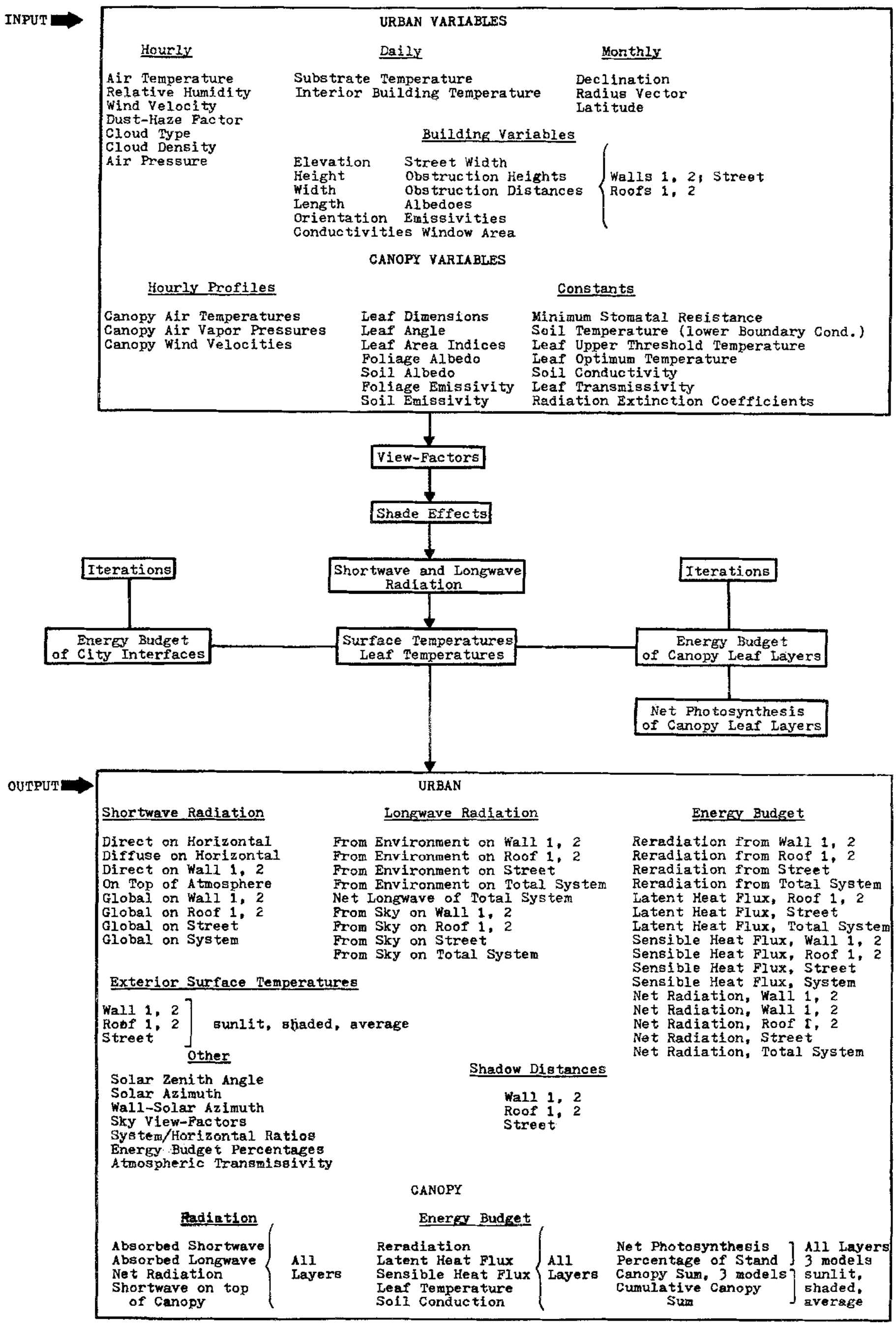

Fig. 1. Generalized flow chart of the combined urban (URBAN 3) and canopy (CANOPY) computer models

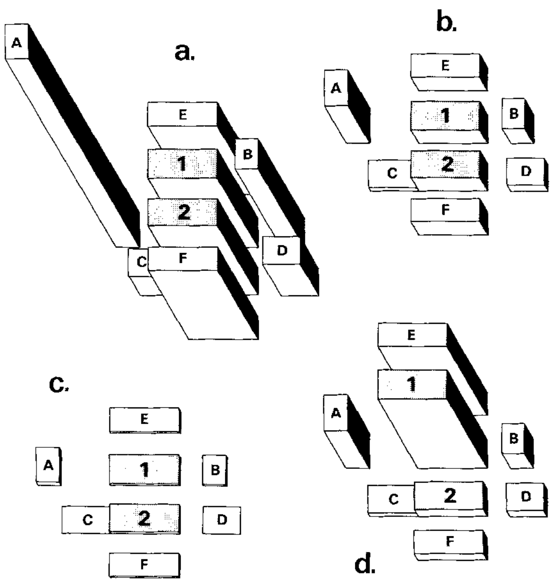

Fig. 2. Selected urban morphologies. System a – building heights: 1 = 2 = E = F = 168 m (550 ft), A = 457 m (1500 ft), B = 191 m (625 ft), C = 46 m (150 ft), D = 76 m (250 ft). System b – building heights: 1 = 2 = E = F = 34 m (110 ft), A = 91 m (300 ft), B = 38 m (125 ft), C = 9 m (30 ft), D = 15 m (50 ft). System c – building heights: 1 = 2 = E = F = 3 m (11 ft), A = 9 m (30 ft), B = 4 m (12.5 ft), C = 1 m (3 ft), D = 1.5 m (5 ft). System d – building heights: 1 = E = 168 m (550 ft), 2 = F = 17 m (55 ft), A = 91 m (300 ft), B = 38 m (125 ft), C = 9 m (30 ft), D = 15 m (50 ft)

occupied by windows with drawn shades, and all buildings were constructed of concrete. The walls, roofs and windows had different albedos and emissivities. The zone between building 1 and 2 was occupied by an eight-layered canopy (leaf area index LAI = 4), simulating a street park. The roof gardens of building 1 and 2 were treated similarly. It was hypothesized that the plant canopies were supplied with optimum soil moisture and fertilizer, being free of detrimental diseases.

Several climatic scenarios were considered. First, a typical clear summer day in August was simulated with shelter-height air temperatures varying from 20°C to 33.5°C and wind speeds from 3.6 to 5.4 m/s (both peaked at 1300 hrs). The air temperatures at shelter height were decreased vertically according to the dry adiabatic lapse rate. The interior air temperature of the buildings was set constant to a comfort standard of 23.9°C (75 F). The same summer scenario was used for latitudes 10°N, 34°N, and 50°N. Second, a typical winter day was simulated for latitudes 10°N and 34°N, omitting latitude 50°N because of lack of photosynthesis during this season.

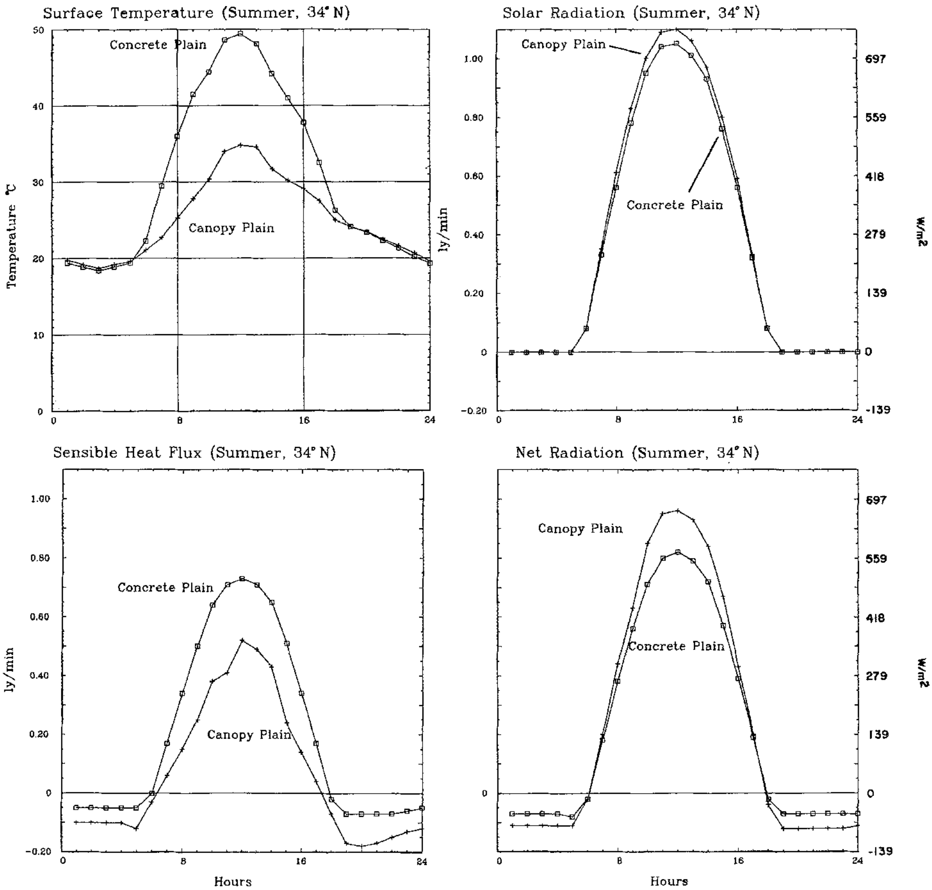

Fig. 3. Contrasts of energy budget components and surface temperatures of a concrete plain and a canopy plain (summer, 34°N)

For latitude 10°N the air temperature was varied from 12.5°C to 24.4°C; and for 34°N it was varied from 6.7°C to 18.9°C. The wind speeds and humidities used were those of the summer day.

5. Concrete Plain Versus Canopy Plain

Before beginning a systematic analysis of the effect of vegetation on urban energy budgets, influenced by a variety of different street canyon systems, it appears adviseable first to compare two unobstructed, non-urban plains: concrete and canopy. Fig. 3 serves as an example of the resultant, contrasting energy budgets (latitude 34°N), using the above described summer climatic scenario. The most noticeable contrasts were in sensible heat flux H which declined 29 percent at noon from that of the concrete plain. The latent heat flux LE of the canopy plain was of a magnitude similar to H. In the latter case, conduction G had become trivial below the canopy. The surface temperature dropped 15°C near noon, whereas the canopy surface temperature was slightly higher than that of the concrete during the night. This was a result of the "insulating" effect of the canopy. Because of the lower albedo (a function of the changing solar elevation) of the canopy plain, absorbed solar radiation Q increased 5 percent. Net radiation R increased 9 percent partially because of the lowered surface temperature of the canopy plain. The above findings are believed to delimit the maximum possible contrasts permitted between the two media under unobstructed circumstances.

It has been shown that the ratio between solar radiation absorbed by three-dimensional building systems and two-dimensional horizontal surfaces under cloudless conditions varies considerably with latitude and season [17]. Fig. 4 shows such a comparison in summer and winter (34°N) for absorbed solar radiation and reradiation in the various street canyon systems outlined above. Considering absorbed solar radiation, the high-low system d showed greatest variation: its summer ratio of about 1.3 near noon changed in winter to a range of 2.0–2.8. The other systems remained near, or slightly below, a ratio of 1 because of mutual shading. For different latitudes and seasons, such ratios of Q can become larger (e.g., system d reached a ratio of > 5 at 50°N, winter). For the case of reradiation I, all systems exceeded that of a horizontal plain. This was very much a function of surface area: the larger the surface area, the greater was the ratio.

6. The Impact of Vegetation on the Energy Budget of Urban Structures

The following discussions concern street canyon systems all containing street parks and roof gardens. Summarized by Fig. 5 are the percentages of the energy budget components for a concrete plain, canopy plain, non-vegetated building systems, and vegetated building systems (summer, 34°N noon and midnight). The lower portion of the graph gives an indication of the great variability to be expected in the apportionment of energy budget components upon the introduction of the different building systems. In contrast to the plains' section of the figure, environmental infrared radiation E from the urban environment itself became an important portion of the input, reaching seventy percent for system a. Obviously, for the low-structure system c this portion was small. The introduction of vegetation

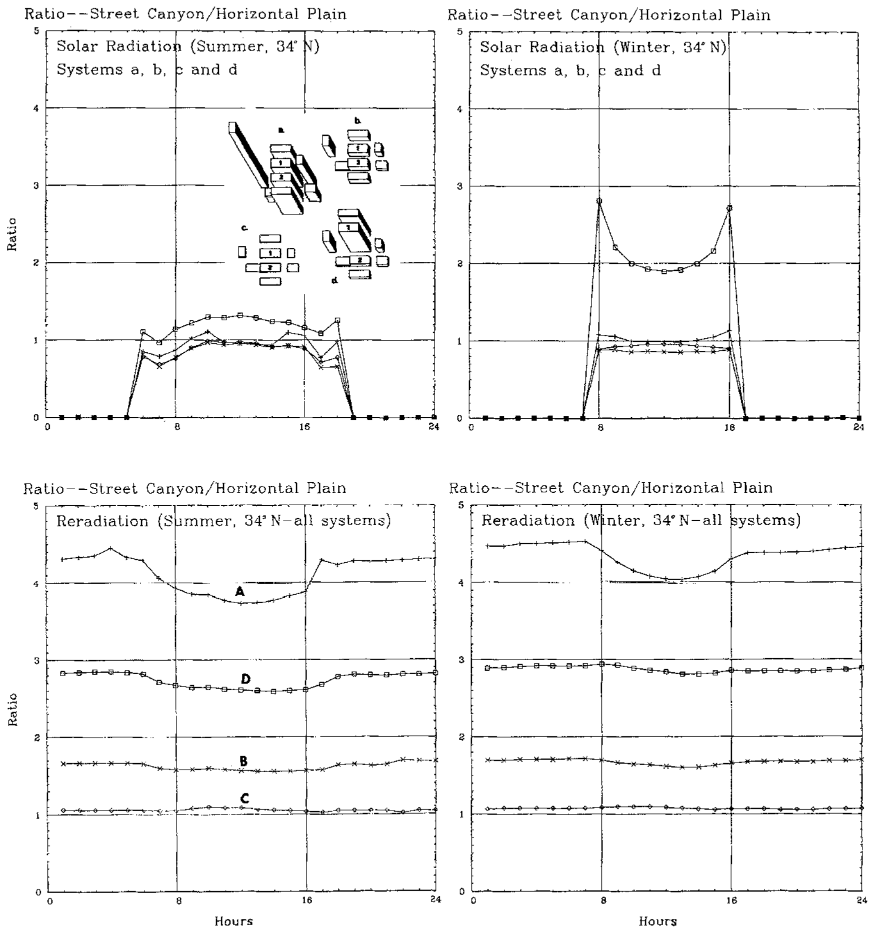

Fig. 4. Ratio-concrete-macadam street canyon systems versus an unobstructed plain of identical cover. Plus = system a, x = system b, diamond = system c, square = system d

resulted in almost equal amounts (output) for sensible heat flux H and latent heat flux LE.

6.1 Comparison with Non-Vegetated Plains

The concrete plain (comparable to non-vegetated roof tops) reached a noon-time temperature of 49°C, whereas the macadam plain (comparable to the street) boasted 51°C [18]. Temperature decreases for the vegetated surfaces were considerable. The street park temperatures of systems a and c were

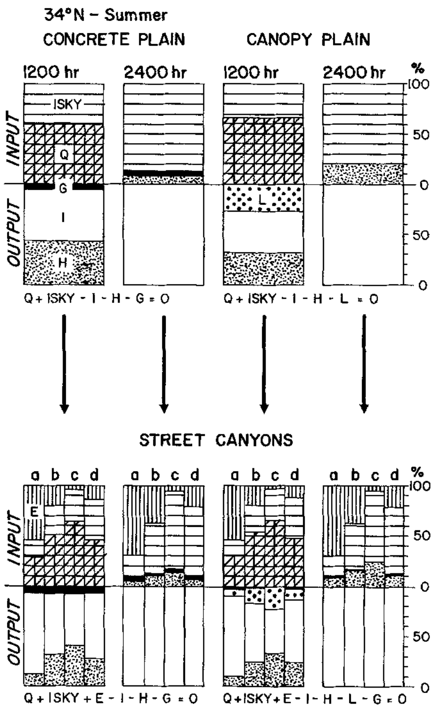

Fig. 5. Percentages of energy budget components of the concrete plain, canopy plain, non-vegetated building systems, and vegetated building systems (summer, 34°N noon and midnight). Q = absorbed solar radiation, $ISKY$ = infrared sky radiation, E = infrared environmental radiation (from neighbouring buildings), I = reradiation, H = sensible heat flux, L = latent heat flux, G = conduction

about 33°C and 35°C, respectively. For the roof these temperatures were 31.5°C (system a) and 34°C (system c). Fig. 6 shows similar comparisons. This time the contrasts were between a non-vegetated plain and system sensible heat flux, net radiation, reradiation, and net longwave.

6.2 Comparison between Non-Vegetated and Vegetated Plains

Surface Temperatures and Reradiation: Results indicated that at noon the macadam street temperature reached about 47°C (system c). The analogous temperature for the same system, after the introduction of a street park, was about 34°C, a reduction of 13°C. Opposite trends were found in the tall-structure system. The temperature of the completely shaded street of this system slightly exceeded the macadam surface temperature (about

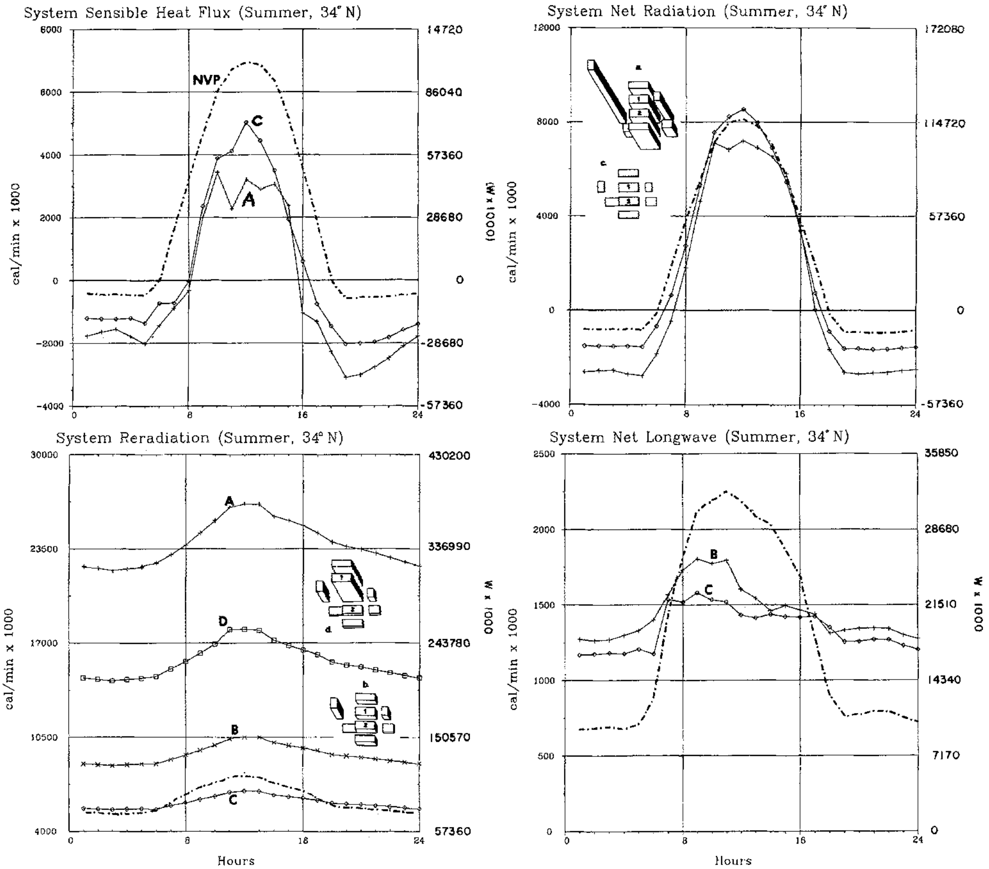

Fig. 6. Contrasts of vegetated system energy budget components of systems a and c with a non-vegetated plain (summer, 34°N). *NVP* = non-vegetated plain

0.5°C). For both systems, vegetated surface temperatures exceeded non-vegetated during the night because of the previously mentioned insulating effect of canopies. Considering the reradiation of entire systems (street, roof tops 1 and 2, walls 1 and 2), street canyon a declined by 4 percent (midday) because of the introduction of vegetation. This decline became trivial at night. For system c the midday decline reached 16 percent. Night-time reradiation was virtually identical between the two types of surface covers [18].

In winter these trends continued (Fig. 7). During the middle of the day the street park temperature of system a (completely shaded) was about

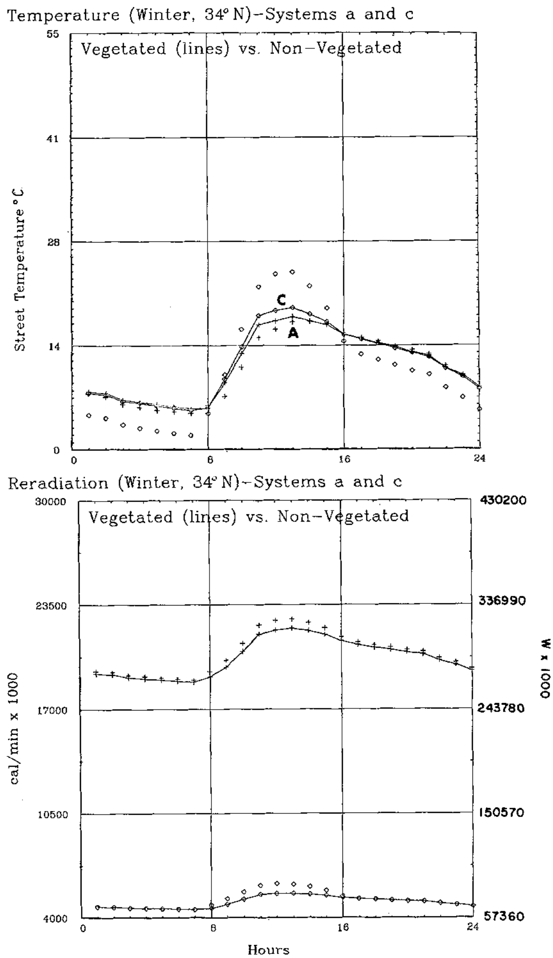

Fig. 7. Surface temperatures and reradiations I of the streets and entire building systems a and c – vegetated versus non-vegetated (winter, 34°N). Symbols connected by solid lines refer to vegetated surfaces

1°C higher than that of a macadam surface. On the other hand, for the partially sunlit street park of system c, a reduction of about 5°C ensued. Midday reductions of 3 and 10 percent (summer: –4 and –6 percent) in system reradiation resultet for canyons a and c.

Energy Budget Components: According to Fig. 8, the street park of the low-structure system c depicted a noontime decline of 6 percent in net radiation R. This decline (instead of the increase common for concrete

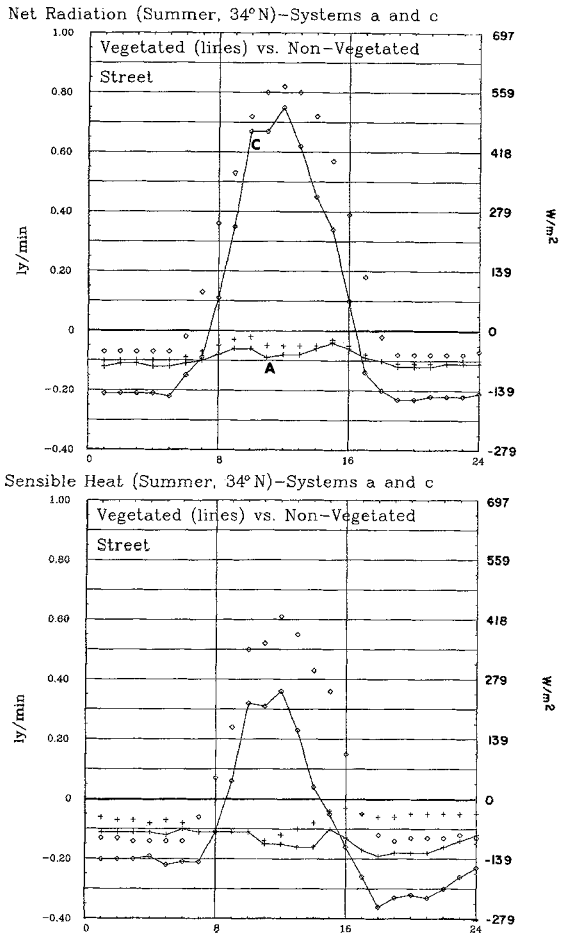

Fig. 8. Net radiation R and sensible heat flux H of the streets of systems a and c – vegetated versus non-vegetated (summer, 34°N). Symbols connected by solid lines refer to vegetated surfaces

surfaces) was caused mainly by the lower albedo of a macadam surface compared with that of a canopy. For the tall system a the same trend was exhibited, except that R remained below zero during the entire 24-hour period. At least for system c, the reduction of sensible heat flux H was more massive: a reduction of 41 percent near noon. Again, the convection values for the tall system a remained below zero. The analogous reductions for winter were 15 percent for R and 50 percent for H (not shown).

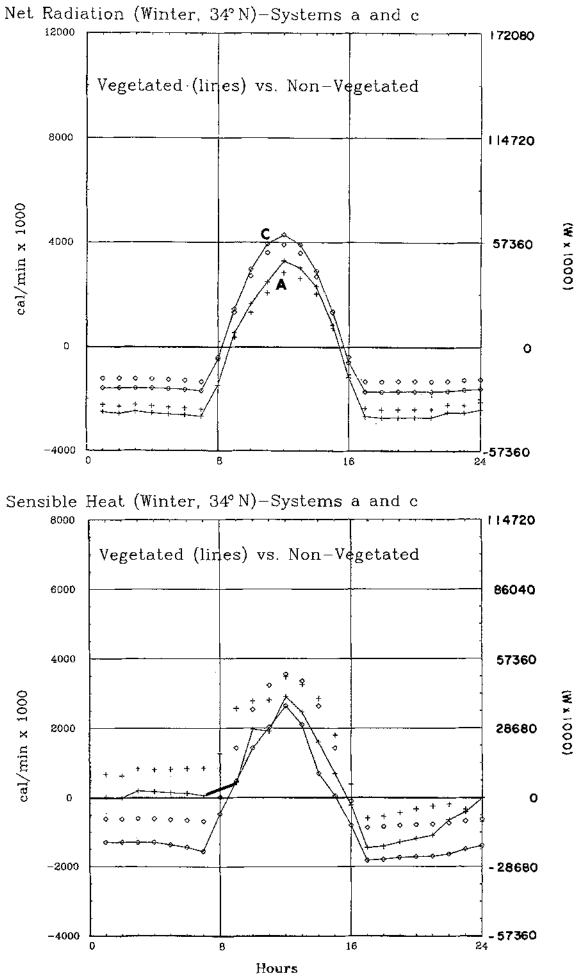

Fig. 9. Net radiation R and sensible heat flux H of the entire systems a and c – vegetated versus non-vegetated (winter, 34°N). Symbols connected by solid lines refer to vegetated surfaces

Moving from the individual urban facets (e.g., streets) to the entire system produced reversals in the above discussed trend of R. Increases of R, compared to non-vegetated surfaces, of 15 and 11 percent resulted for systems a and c during the summer midday hours. This was because the entire system contained two roofs, two walls, and only one street, overwhelming the opposing macadam effect of the street (Fig. 8). Noon latent

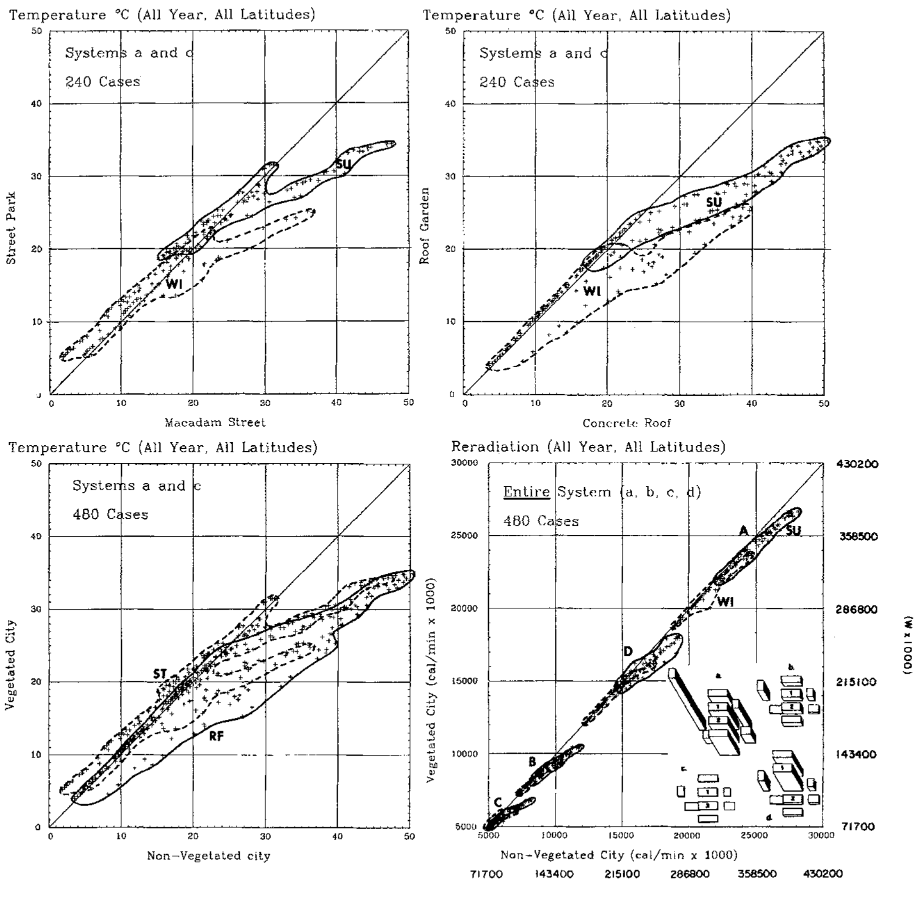

Fig. 10. Bounded scatter plots of non-vegetated versus vegetated surface temperatures for summer and winter (10°N, 34°N, 50°N). Latitude 50°N was omitted for winter. *SU* = summer, *WI* = winter, *ST* = street, *RF* = roof. Letters *A, B, C, D* designate street canyon systems

heat flux *LE* declined 35 percent (system a), 21 percent (system b), 14 percent (system c), and 18 percent (system d) compared to a non-urban, unobstructed canopy.

Fig. 9 indicates noontime increases of 16 and 10 percent of *R* for systems a and c and decreases of 16 and 26 percent for *H*. In the latter case one can observe a potential night heat island reduction of about 76 percent compared to a non-vegetated surface (*H* remained above zero during the night, beginning at about 2400 hrs).

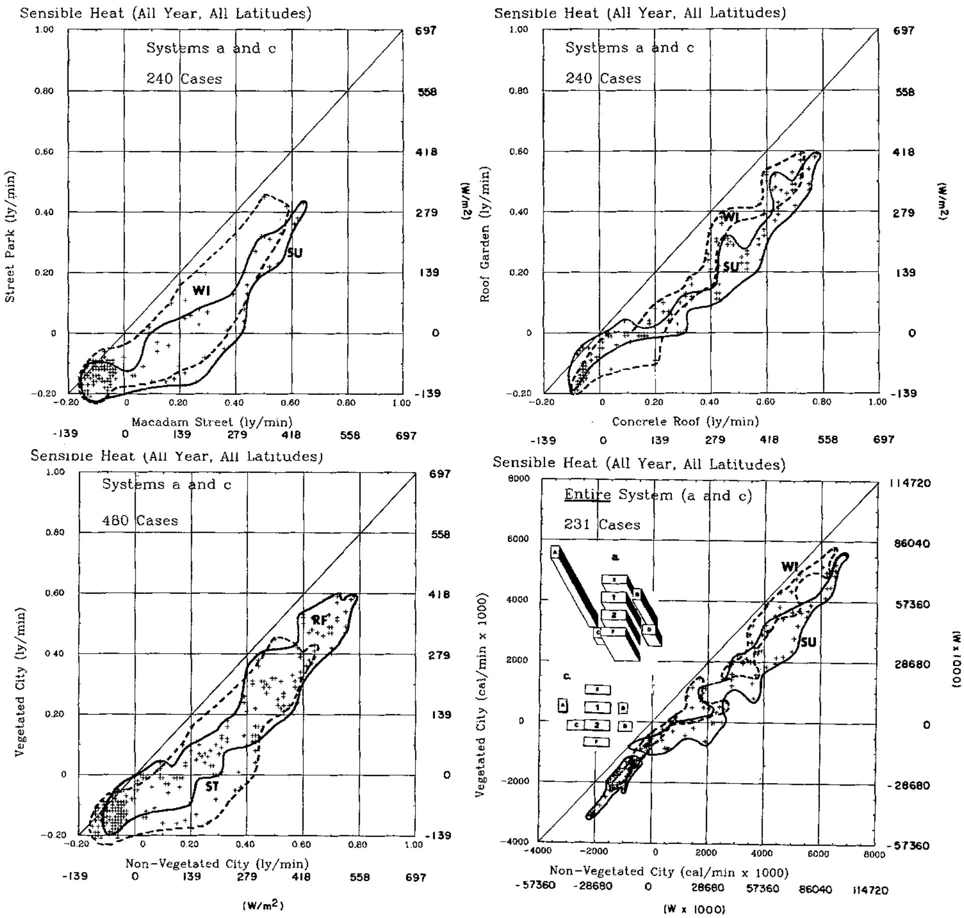

Fig. 11. Bounded scatter plots of non-vegetated sensible heat flux H for summer and winter (10°N, 34°N, 50°N). Latitude 50°N was omitted for winter. *SU* = summer, *WI* = winter, *ST* = street, *RF* = roof, Letters *A, B, C, D* designate street canyon systems

7. Summary of Results

The above examinations were carried out for summer and winter and latitudes 10°N, 34°N, and 50°N. Because of the resultant massive output, only the salient features will be discussed. As an example, Fig. 10 shows the results when the data for summer and winter and the three latitudes were combined. The upper portion of the graph compares street parks and roof gardens versus their non-vegetative analogue (240 cases), whereas the bottom portion combined the above into the entire system (480 cases).

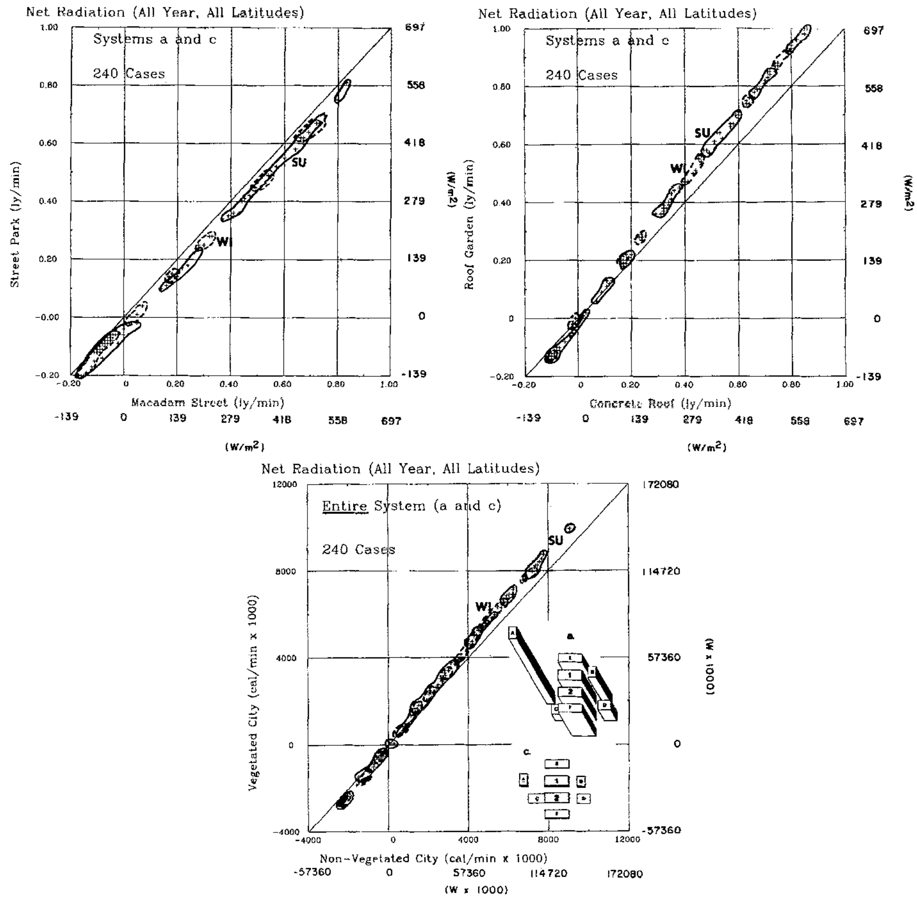

Fig. 12. Bounded scatter plots of non-vegetated net radiation R for summer and winter (10°N, 34°N, 50°N). Latitude 50°N was omitted for winter. *SU* = summer, *WI* = winter, *ST* = street, *RF* = roof. Letters *A, B, C, D* designate street canyon systems

For the street and roof sections of the figure, distinct summer and winter portions became apparent. For the street, lower night values (stratified according to season) exceeded the 45-degree slope by about 2–3°C. This was a result of the above mentioned insulating effect of the canopy "blanket". The higher daytime values showed the opposite regime: reductions up to 15°C from macadam street surface temperatures. For daytime values, the roof exhibited a reduction similar in trend, but there were only trivial increases above concrete roof surface temperatures during the night (about 0.5°C). The lower left portion of Fig. 10 portrays the combination two graphs of street and roof, whereas the lower right side of the figure compared all four entire street canyon systems in terms of reradiation I. In the latter case, it became clear that the nighttime blanket effect was largely lost or was insignificant, though the daytime decline in I remained, albeit of lesser magnitude compared with the individual building facets.

Fig. 11 shows the same worldwide, seasonal considerations for sensible heat flux H. Here, except for below-zero values, vegetated H never exceeded the convection caused by macadam, concrete, or combined non-vegetated surfaces. The depressions were most conspicuous for summer. Because of a less active latent heat flux, winter values showed slightly smaller declines. The lower right portion of the figure indicated, when the entire system was considered, that the above pattern persisted, except for the below-zero over-crossings of the 45-degree slope.

Fig. 12 treated net radiation R on a similar basis. For the street portion of the graph, vegetated surface R remained below that of the net radiation of a macadam street, whereas the opposite was true for the concrete roof-roof garden comparison. As mentioned above, this was largely caused by the albedo contrast between two types of surfaces. When viewing the entire system (the lower portion of Fig. 12), it became apparent that the combined surface areas of the entire system (two roofs, two walls, one street) largely cancelled the street effect, resulting in vegetated net radiation exceeding non-vegetated R during most of the daylight hours for all latitudes and seasons. It is believed that the discussed feature represents generalized upper and lower limits of the possible effect of vegetation on previously non-vegetated city blocks.

Acknowledgements

This research was funded partially by a grant from the University of California. Use of the computer facilities of the UCLA Office of Academic Computing is appreciated.

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