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WATER USE BY SHRUBS AS AFFECTED BY ENERGY EXCHANGE WITH BUILDING WALLS

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ABSTRACT

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Landscape plants in urban areas are routinely grown next to buildings which are sources of sensible heat and radiation. An experimental study was conducted to explore how building walls affect water use by adjacent landscape plants. Instantaneous rates of sap flow were measured using heat-balance, stem-flow gauges attached to wax leaf ligustrum shrubs growing adjacent to all four walls of a building shell. For comparison, sap flow was also measured on shrubs grown away from the influence of the building. Peak flow in plants adjacent to each wall occurred when direct beam irradiance on the wall and wall temperature were at their maxima. Peak flow was highest in plants adjacent to east and west walls, and lowest in plants adjacent to the north wall. Longwave radiation emitted by the walls appeared to be a major factor affecting flow while reflected radiation from walls was of secondary importance because of the low albedo of the walls. Cumulative flow was greatest in the shrubs grown away from the influence of the building, probably due to the absence of any shading by walls during the day, and to wind speeds that were higher than those adjacent to the building.

INTRODUCTION

Water use by vegetation is controlled by the physical environment in which the plants grow, and by the plant response to that environment. In cities, vegetation must contend with an environment that is significantly different from rural areas (Landsberg, 1981). These differences are caused by changes in the energy and water balances produced by buildings, roads, etc., by reductions in the amount of vegetation, and by combustion processes associated with automobiles and industry (Landsberg, 1979; Estournel et al., 1983; Cayan and

Douglas, 1984). Plants are routinely grown next to buildings, roads and fences that are sources of radiation and sensible heat.

Urban vegetation has a beneficial role in cities not only from an aesthetic standpoint, but also by modifying urban climate and affecting human comfort in indoor and outdoor spaces (Mayer and Höppe, 1987). Huang et al. (1987) concluded from a modeling analysis that shading and evaporative cooling by vegetation could significantly reduce the energy required to cool buildings. Latent heat lost through transpiration from vegetation is an important component of the urban energy balance. Ross and Oke (1988) found that urban energy balance models could accurately simulate net radiation but not sensible and latent heat fluxes because of the inability to deal with the impact of water availability on evapotranspiration (ET).

Urban vegetation may use more water per unit of vegetated area than in rural areas due to advected sensible heat from non-vegetated areas. Oke (1979) found that latent heat flux from an irrigated suburban lawn exceeded net radiation on both an hourly and a daily basis. Feldhake et al. (1983) found that advected energy accounted for 35% of the latent heat flux from turfgrass in cities. Kalanda et al. (1980) found that ET rates in suburban areas often approached or exceeded equilibrium values.

Because of the complex nature of the urban environment, only a limited amount of research has been done to quantify effects of the urban environment on water use by vegetation or to determine water requirements for maintaining urban landscapes. We conducted an experimental study using heat-balance, stem-flow gauges to explore how instantaneous and daily water use of shrubs may be affected by energy exchange with adjacent building walls.

MATERIALS AND METHODS

The study was conducted from mid-June to early July 1988, on a 1-ha plot of bermudagrass (*Cynodon dactylon* L.) at the Texas A&M University Turfgrass Field Laboratory in College Station, Texas (30.4°N, 96.2°W). The orientation of the bermudagrass plot was south-east to north-west, parallel to the prevailing summertime wind direction. The bermudagrass was maintained at a cutting height of 0.03 m and was irrigated by sprinklers. A cotton field maintained as a breeding nursery was upwind of the grass. Between the cotton and the grass was a slightly elevated dirt road. The distance between the cotton and the leading edge of the grass was 10 m.

A 4.9 m × 4.9 m building shell with 2.5-m-high rough-cut pine walls was constructed in the bermudagrass plot at a distance of 35 m from the leading edge of the grass (Fig. 1). The thickness of the walls was 19 mm, and the interior surfaces were insulated with R5 foam board insulation. The walls were painted (color No. 1D44C, Devoe and Raynolds, Inc., Louisville, KY) which produced

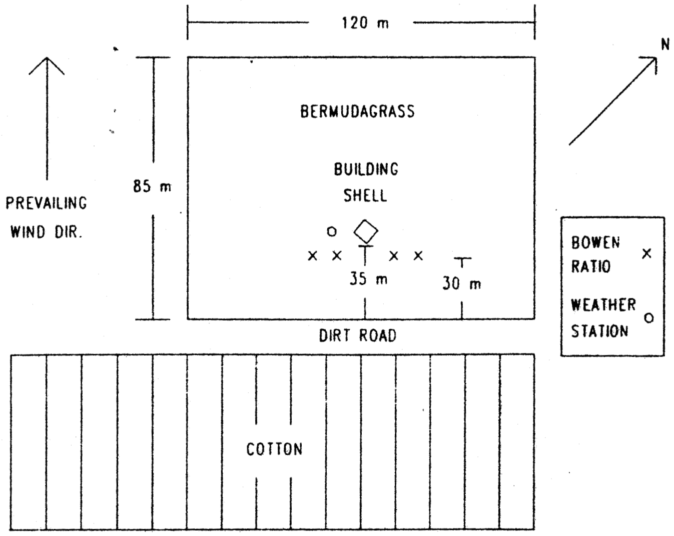

Fig. 1. Diagram of the plot layout showing the location of the building shell, weather station an Bowen ratio systems.

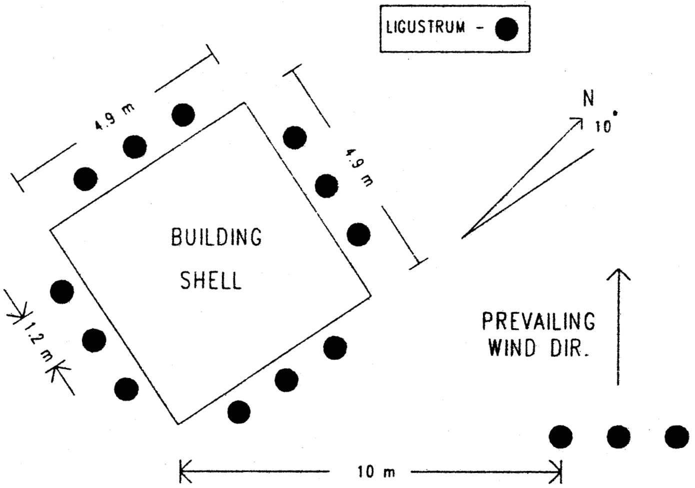

Fig. 2. Diagram showing dimensions of the building shell and location of the ligustrum.

an albedo of 0.17. No roof was constructed. Azimuths of the four walls were 10°, 100°, 190°, and 280° measured east of north.

Three wax leaf ligustrum (*Ligustrum japonicum*) in 11.3-l pots containing fritted clay were placed in front of each wall at a distance of 0.5 m from the wall as shown in Fig. 2. The distance between plants was 1.2 m. The pots were inserted into aluminum cylinders buried in the soil so that tops of the pots were flush with the soil surface. An additional three plants, 1.2 m apart, were inserted 10 m east of the building (Fig. 2). Plants were watered daily, usually at sunset, and the pots wrapped in plastic to prevent soil evaporation.

Leaf area was determined for each plant using measurements of leaf length and width. Stomatal resistance on upper leaves was measured at selected periods with a steady-state porometer (model LI-1600, LI-COR, Inc., Lincoln, NE).

Flow rate of water (sap) in the xylem was measured on the center plant at each wall, and on the center plant of the three positioned away from the building, using stem-flow gauges (model SG10, Dynamax, Inc., Houston, TX) of the Baker and Van Bavel (1987) design which employed the heat-balance method. With this method, a steady, known amount of heat is applied to the plant stem by a flexible heater which encircles the stem. The heater is enclosed in foam insulation which extends above and below it. Sap flow rate is determined as a residual in the heat balance using the equation

$$F=(P-q_u-q_d-q_r)/[C(T_u-T_d)] \tag{1}$$

where F (g s^{-1}) is the sap flow rate, P(W) is the power supplied to the stem, q_u and q_d (W) are the respective upward and downward fluxes of heat conducted in the stem tissue, q_r (W) is the radial, outward flow of heat, T_u and T_d (K) are stem surface temperatures above and below the heater, respectively, and C (J g^{-1} K^{-1}) is the heat capacity of the sap.

Upward and downward fluxes are determined using Fourier's law and measurements of stem surface temperatures above and below the heater. Radial flux is calculated by multiplying a gauge conductance by the output of a thermopile located on the inner and outer surface of a cork backing between the heater and the foam insulation. Gauge conductance can be determined using eq. 1 during periods of zero flow (Baker and Van Bavel, 1987). The gauge design assumes that the temperature of the xylem fluid can be estimated by temperature measurements on the stem surface. Thus, $FC(T_u-T_d)$ is an estimate of the heat carried by the sap. Detailed information regarding the heat-balance method can be found in Sakuratani (1981), Baker and Van Bavel (1987) and Ham and Heilman (1989).

Sakuratani (1981) and Baker and Van Bavel (1987) demonstrated that sap flow rate in herbaceous plants could be estimated with the heat balance method to within 10% of transpiration. We obtained similar results when testing the gauges on ligustrum in a controlled environment chamber, and found no evidence of lags between transpiration and sap flow caused by plant capacitance.

Stem-flow gauges were attached to the stem between the soil surface and the lowest branch, and were covered with a polyethylene rain shield to prevent water from shorting out the gauge heaters. Additional foam insulation was attached above and below each gauge, and gauges, rain shield and insulation were wrapped in aluminum foil to minimize effects of radiation on the heat balance of the stems. As a further precaution against water damage, gauges were disconnected from the power supply during the night. The power applied to the stems was generally in the range of 0.2 W. A value of 0.42 W m^{-1} C^{-1} was used for the thermal conductivity of the stem (Steinberg et al., 1989). Gauges were interrogated every 15 s by a digital data system (model CR7, Campbell Scientific, Inc., Logan, UT), and the signals averaged over 30-min periods. Data were transferred to a microcomputer for processing.

Air temperature, humidity, wind speed and direction were measured at an elevation of 1.5 m above the surface at a portable weather station 10 m west of the building. Temperature and humidity were measured with a shielded, aspirated probe (model CSI207, Campbell Scientific) which used a resistance hygrometer, while wind speed and direction were measured with a Gill anemometer and wind vane (models 12102 and 12302, R.M. Young Co., Traverse City, MI). Air temperatures adjacent to each wall were measured with shaded, fine-wire (30 AWG) thermocouples at a distance of 0.5 m from the walls and an elevation of 1.5 m above the surface, while wind speeds at the same locations were measured with Gill anemometers. Global irradiance was measured at the weather station with a LI-COR model LI-200SCZ pyranometer, while diffuse irradiance was measured with a similar pyranometer shaded with an occulting ring. Direct beam irradiance was calculated as the difference between global and diffuse irradiance. Direct beam irradiance on the walls was calculated using the equation of Radke (1982)

$$E=(E_h/\sin a)(\cos a \cos \alpha_d \sin i+\sin a \cos i) \tag{2}$$

where E is the direct beam irradiance on the wall, E_h is direct beam irradiance on a horizontal surface, a is solar elevation angle, α_d is the difference between solar and wall azimuth angles, and i is wall inclination angle.

Meteorological sensors were interrogated every 10 s and outputs averaged over 30-min periods with a model CR21X data logger (Campbell Scientific). Wall, ligustrum and bermudagrass temperatures were measured at 30-min intervals during daylight hours with a hand-held infrared radiometer (model 110, Everest Interscience, Tustin, CA).

Latent and sensible heat flux densities from the grass upwind of the building were determined using the Bowen ratio method which is based on a rearrangement by Bowen (1926) of the energy balance to yield

$$LE=-(R_n+G)/(1+B) \tag{3}$$

where LE, R_n and G are flux densities of latent heat, net irradiance and soil heat, respectively, in units of W m^{-2}, and B is the Bowen ratio. The Bowen ratio is defined as

$$B=H/LE=\gamma(K_h/K_v)(\Delta T/\Delta e) \tag{4}$$

where H is sensible heat flux, γ is the psychrometric constant, K_h and K_v are respective eddy diffusivities for heat and water vapor transport, and ΔT and Δe are differences in potential temperature and vapor pressure, respectively, between two elevations in the boundary layer above the surface.

Four battery-powered Bowen ratio systems designed by Gay and Greenberg (1985) were placed upwind of the building at a distance of 30 m from the leading edge of the grass. Wet and dry bulb measurements at elevations of 0.3 and 1.3 m above the surface were made by psychrometers containing resistance thermometers and ceramic wicks mounted on an exchange mechanism. This configuration produced a fetch:height ratio of 23:1. Heilman et al. (1989) showed that the Bowen ratio method can be used successfully at fetch: height ratios as low as 20:1. Psychrometers were exchanged every 6 min to eliminate sensor bias. Net irradiance was measured with net radiometers (model Q3, Micromet Systems, Inc., Seattle, WA), mounted at an elevation of 1.5 m above the grass. Soil heat flux was determined using heat flux plates (model HFT-1, Micromet Systems) at 5 cm below the soil surface and calculations of the change in heat content in the 0–5-cm layer using soil temperature measurements at 2.5 cm. Three heat flux plates wired in series were used for each system, and three thermocouples wired in parallel were used for soil temperature measurements for each system.

All Bowen ratio sensors were interrogated several times per min and data were transmitted to a microcomputer for processing and analysis. Energy balance components were calculated as 12-min averages, assuming equality of eddy diffusivities for heat and vapor transport.

RESULTS AND DISCUSSION

Before the impact of the building walls on water use of the shrubs could be assessed, it was necessary to determine whether inherent differences in sap flow existed among the five plants to which stem gauges were attached. On 20 June these plants were placed side by side at a location away from the influence of the building, and sap flow was measured in each plant under the same environmental conditions. As shown in Fig. 3, sap flow rates per unit leaf area were similar for the five plants. Cumulative sap flow for Plants 1–5 were 1.75, 1.87, 1.87, 1.73, and 1.85 kg m^{-2}, respectively. Selected morphological data on the five plants are listed in Table 1.

Weather conditions during the study were characterized by partly cloudy skies, high temperatures, and moderate wind speeds. Results from 1 July, which are representative of those obtained during the entire study, will be discussed. Global irradiance, air temperature and relative humidity on 1 July are shown in Figs. 4 and 5.

Sap flow rates on 1 July for the plants adjacent to the walls, and for the plant away from the building, are shown in Fig. 6. Highest flow rates occurred in plants adjacent to east and west walls, with peak flow occurring at mid-morning for the plant at the east wall, and in late afternoon for the plant at the west wall. Flow rates in the plant next to the south wall were lower than in the plants next to east and west walls, and away from the building. Flow was lowest in the plant adjacent to the north wall. Cumulative flow was greatest for the plant away from the building (Table 2). Stomatal resistances ranged from 200 to

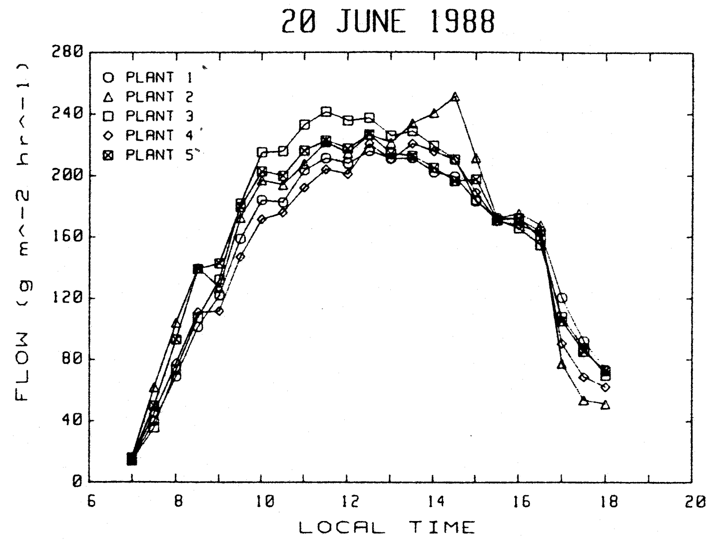

Fig. 3. Sap flow per unit leaf area, measured on 20 June 1988, in the five ligustrum placed side by side away from the influence of the building.

TABLE 1

Selected morphological data on wax leaf ligustrum to which stem flow gauges were attached

Plant	Leaf area (m^2)	Height (m)	Width (m)	Stem diameter (mm)
1	0.2815	0.79	0.58	11.0
2	0.2956	0.74	0.56	10.2
3	0.2750	0.71	0.55	10.7
4	0.3234	0.74	0.59	11.0
5	0.2311	0.67	0.48	10.0

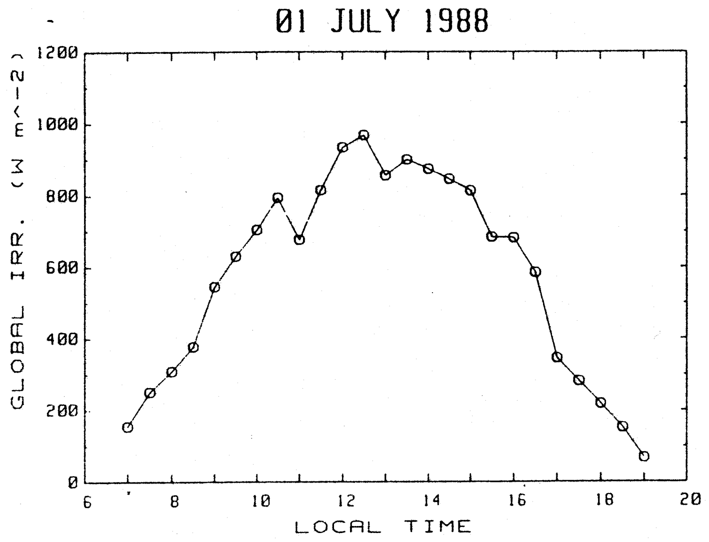

Fig. 4. Global irradiance on 1 July 1988.

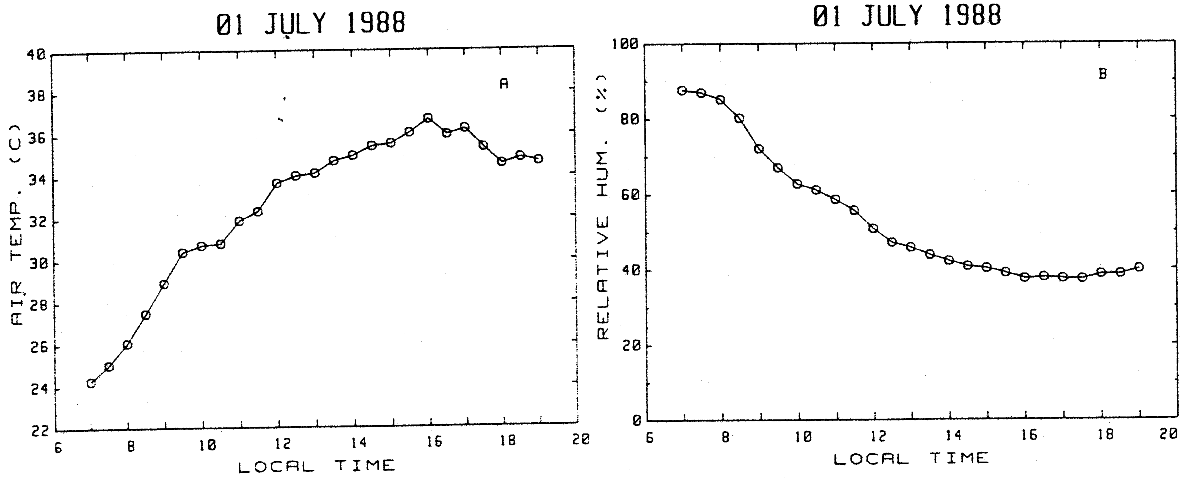

Fig. 5. Air temperature (a) and relative humidity (b) measured at the weather station on 1 July 1988.

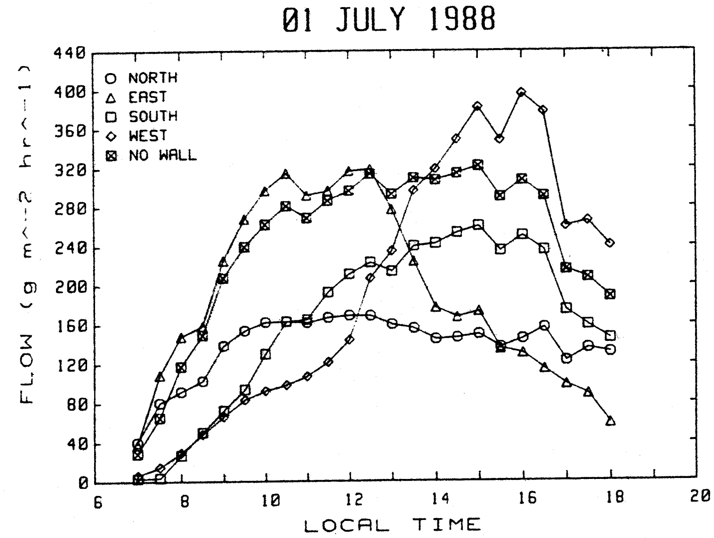

Fig. 6. Sap flow in ligustrum adjacent to north, east, south and west walls, compared with flow in ligustrum away from the building (no wall) on 1 July 1988.

400 s m^{-1} with no differences found among the five plants. Also shown in Table 2 are cumulative flows on 29 June, 30 June, and 2 July 1988.

To a large extent, differences in flow among plants adjacent to the walls were due to differences in radiation balances of the plants caused by shading, and by reflected shortwave and emitted longwave radiation from the walls. The impact of each of these factors varied with the direct beam irradiance on the walls (Fig. 7(a)). Maximum irradiance on the east wall occurred 3 h before solar noon and was lower than the maximum irradiance on the west wall which occurred 4 h after solar noon. The lack of symmetry about solar noon was due to the 10° offset of wall azimuths from true north, south, east and west. Solar elevation angle was 17° higher when the sun was at the same azimuth as the east wall than when at the azimuth of the west wall. Direct irradiance on the

TABLE 2

Cumulative sap flow per unit leaf area during daylight hours on 29 June to 1 July 1988, for ligustrum adjacent to and away from building walls

Day	Cumulative flow (kg m^{-2})				
	North wall	East wall	South wall	West wall	No wall
29 June	1.65	1.64	1.36	1.66	1.90
30 June	1.29	1.76	1.67	1.93	2.53
01 July	1.59	2.21	1.87	2.23	2.78
02 July	1.91	2.42	1.81	2.31	3.05

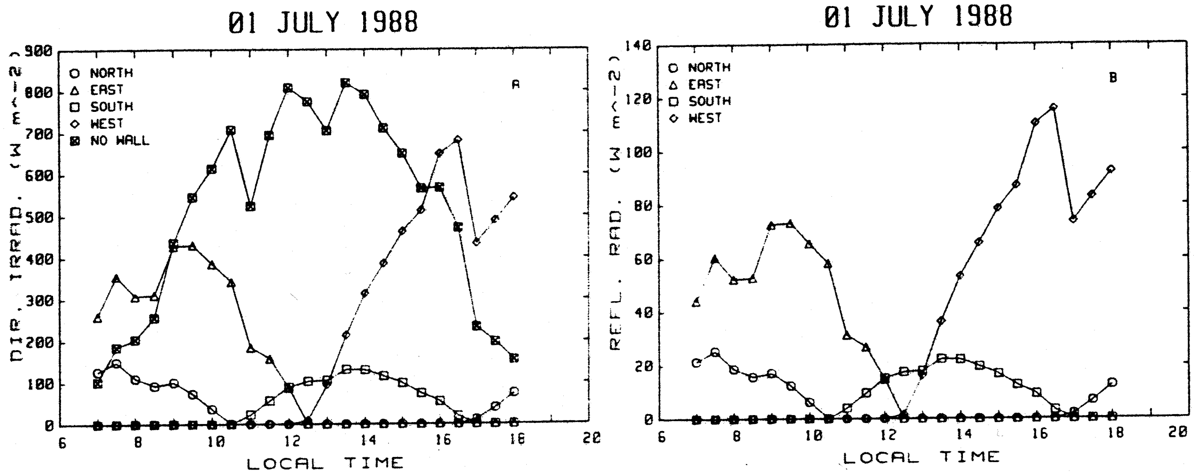

Fig. 7. Direct beam irradiance on the building walls, and on a horizontal surface (no wall) on 1 July 1988 (a), and direct beam irradiance reflected from building walls (b).

south wall was low due to the high solar elevation angles (82° at solar noon) during the middle of the day.

Periods when plants adjacent to any particular wall were shaded corresponded, though not exactly, to the periods in Fig. 7(a) when direct beam irradiance on the wall was zero. Plants were shaded over a slightly shorter period of time than indicated by a zero direct beam irradiance because they were located a short distance (0.5 m) from the wall. Maximum amounts of direct beam irradiance reflected from the walls ranged from 21 W m^{-2} from the south wall to 119 W m^{-2} from the west wall (Fig. 7(b)).

Longwave radiation emitted by the walls was a major component of the radiation balance. Diurnal variations in wall temperature coincided with changes in direct beam irradiance on the walls. As shown in Fig. 8(a), large changes occurred in temperatures of the east and west walls during the day, with the east wall reaching 59°C in mid-morning and the west wall 67°C in late afternoon. These temperatures produced maximum exitances of 690 and 759 W

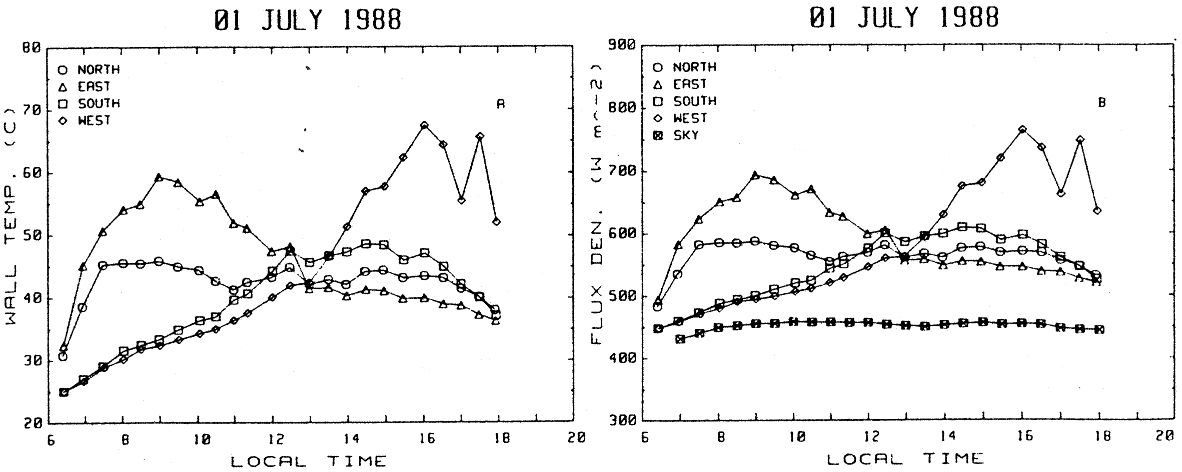

Fig. 8. Surface temperatures of the building walls on 1 July 1988 (a), and flux densities of wall exitance and longwave sky irradiance (b).

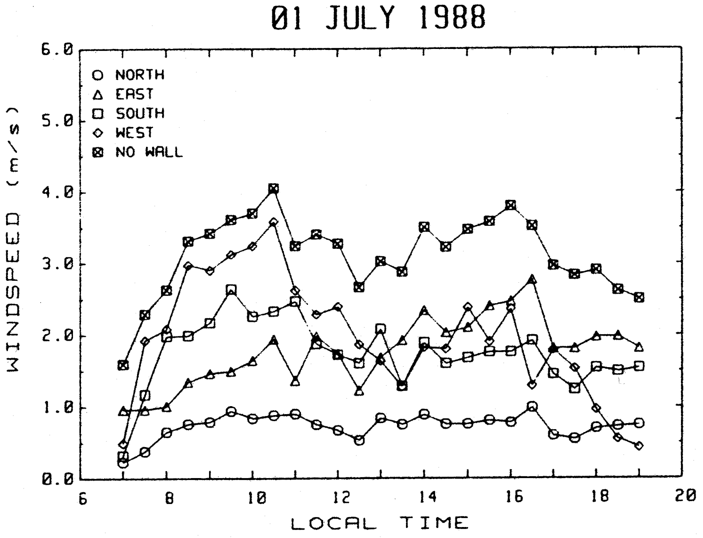

Fig. 9. Wind speeds adjacent to the building walls compared with the wind speed at the weather station (no wall) on 1 July 1988.

m^{-2} (Fig. 8(b)), which were higher than global irradiance at mid-morning and late afternoon. Temperature changes of north and south walls were less dramatic. Maximum exitances from north and south walls were 587 and 604 W m^{-2}. Exitances from all four walls were substantially higher than the longwave sky irradiance, as estimated by the method of Idso (1981), during most of the day (Fig. 8(b)). Longwave sky irradiance ranged from 420 to 446 W m^{-2}.

Cumulative sap flow in the plant away from the building was higher than in plants adjacent to the walls. No shading of that plant occurred, and sky irradiance was not blocked by walls. In addition, wind speed away from the building was as much as 30% greater than the highest wind speeds measured adjacent to the walls (Fig. 9). Wind direction ranged from 137 to 215°. Because of wind speed differences and similar plant geometries (Table 1), aerodynamic resistances for heat and vapor flux away from the wall were lower than resistances adjacent to walls.

Plants adjacent to the buildings were generally 2–4 °C warmer than the air throughout the day (Table 3). Smaller plant/air temperature differences were found away from the building. In the morning, plants adjacent to north and east walls had the higher temperatures, while in the afternoon, plants adjacent to south and west walls were warmer. Similarly, the air temperature adjacent to the east wall was higher than at the other walls in the morning, while the air adjacent to the west wall was warmer in the afternoon.

Unlike typical urban landscapes, our building was surrounded by an extensive area of actively transpiring vegetation which generated only low to moderate amounts of sensible heat (Fig. 10). Nevertheless, the building itself had a significant impact on the water use of the adjacent shrubs. Our study was

TABLE 3

Plant and air temperatures adjacent to north (N), east (E), south (S), and west (W) walls, and away from the building (NW) on 1 July 1988. A broken thermocouple prevented measurement of air temperature at the north wall

Time	Plant temp. (°C)					Air temp. (°C)			
	N	E	S	W	NW	E	S	W	NW
0700	29.4	27.7	24.8	24.7	25.7	26.1	24.6	24.7	25.4
0730	29.6	28.8	25.8	26.2	27.9	27.6	25.6	25.5	26.5
0800	31.0	32.1	27.8	27.2	28.4	28.4	26.4	26.2	28.0
0830	30.2	32.4	28.2	27.9	31.2	29.0	27.2	27.1	29.1
0900	32.4	33.0	28.8	27.9	30.7	30.0	28.4	28.2	30.2
0930	32.9	34.1	31.2	29.7	31.5	30.8	29.4	29.0	31.3
1000	33.0	35.5	33.4	30.9	33.0	31.9	30.4	30.1	32.4
1030	33.4	35.6	32.6	31.3	33.3	32.5	30.9	30.9	33.2
1100	34.4	36.2	34.0	31.8	32.3	32.4	31.1	31.1	33.5
1130	35.6	35.8	34.9	31.6	33.8	32.8	31.5	32.4	33.9
1200	35.5	36.7	36.0	33.9	32.6	33.7	32.3	33.1	34.9
1230	35.7	36.9	37.7	34.6	35.9	34.4	32.8	33.4	35.4
1300	35.4	34.7	35.8	35.5	34.9	34.2	32.7	34.3	35.8
1330	38.3	34.1	36.8	37.4	35.6	34.8	33.2	35.8	36.1
1400	35.4	33.1	36.6	39.3	35.7	35.2	33.6	36.1	36.7
1430	36.0	33.8	36.5	37.1	35.2	35.5	33.9	36.7	37.1
1500	36.2	34.7	36.8	37.3	34.5	35.6	34.2	36.5	37.6
1530	35.8	34.3	36.4	38.1	35.7	35.3	34.1	36.9	37.2
1600	33.3	33.8	37.0	37.9	36.3	35.5	34.3	36.9	37.4
1630	35.9	34.4	36.6	39.3	35.1	35.3	34.1	37.7	37.4
1700	34.6	34.0	36.6	35.6	33.8	35.1	34.4	36.1	36.1
1730	34.2	33.9	36.6	38.8	35.2	34.8	34.1	36.3	36.4
1800	33.6	33.3	33.3	34.4	34.1	34.4	33.4	34.2	34.9

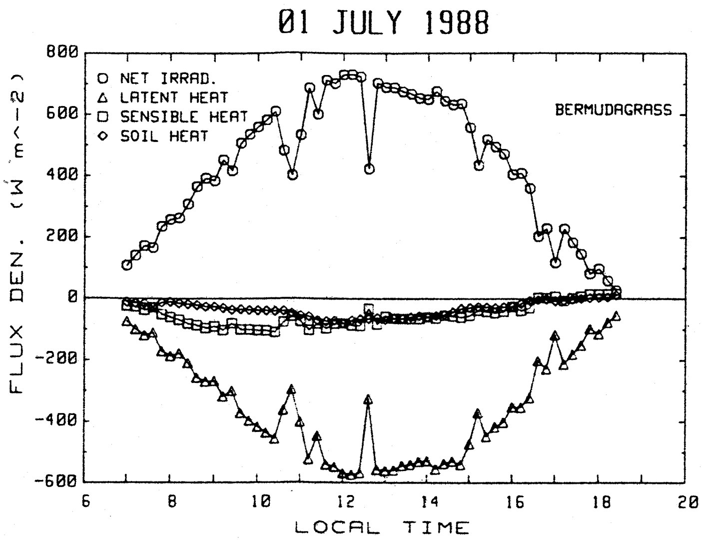

Fig. 10. Energy balance of the bermudagrass upwind of the building on 1 July 1988. Values are averages from the four Bowen ratio systems.

conducted during a period when the solar declination was at a maximum, which at our latitude, resulted in high solar elevation angles at midday. As a result, the contribution of the south-facing wall to the radiation balance of adjacent shrubs was relatively low compared to what would occur earlier and later in the season, and at higher latitudes. In a landscape, the magnitude of the radiation exchange will vary not only with illumination geometry, but also with thermal and optical properties of the construction materials.

Although we did not attempt to quantify convective transport, we did observe that the building reduced substantially the wind speeds adjacent to it. We conclude that, for a given temperature and humidity gradient, convective transport of heat and water vapor in plants adjacent to buildings will be reduced by the walls. Further research is necessary to quantify the aerodynamic behavior of landscape plants.

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