Structure of the Microclimate at a Woodland/Parking-Lot Interface

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ABSTRACT.—Radiation balances and vertical and horizontal profiles of air temperature, vapor pressure and wind speed were measured across the interface of a large asphalt parking lot and an 18-m-tall *Quercus velutina* forest. The partitioning of available energy over the adjacent areas shows steep gradients between the parking lot and forest microclimates. Horizontal temperature and humidity gradients across the interface were on the same order of magnitude as the vertical gradients above the respective surfaces.

URBAN ENCROACHMENT into forested areas is one of the major land-use changes occurring in the eastern coastal region of the U.S. This transfer of forest land to urban uses takes place with little knowledge of or thought given to the maintenance of the forest as a naturally occurring environmental buffering system. It is possible, however, that methods can be devised to successfully mesh urban expansion into the forest environment while maintaining the ability of the forest to ameliorate the suburban climate.

This study was devised to quantify the physical exchanges of air-transported latent heat (water vapor) and sensible heat between and within forested areas and adjacent paved areas. Knowledge of the magnitude and variations of these exchanges can lead to the determination of the microclimatic impact of developments in wooded areas. It also may allow the size, orientation, and composition of proposed city plantings and greenbelts to be designed to maximize any ameliorating effect on the local city microclimates.

ENERGY BUDGETS

The radiant energy absorbed at the earth's surface (Rn) is dissipated by evaporating water (LE), heating the air (A), and heating materials on and below the surfaces (S).

$$Rn = LE + A + S \qquad [1]$$

There are other processes that may affect the surface energy balance, which are not included in equation 1, such as photosynthesis, respiration, and canopy storage of energy. These are very small consumers of energy and can be neglected in this case.

In a given localized urban environment with no vegetation, there is no large source of water for evaporation. Therefore, the available radiant energy is used primarily to heat the air and the various materials that make up the surfaces in the city.

$$Rn = A + S \qquad [2]$$

Buildings and paving, having large heat capacities, absorb large amounts of heat during the day, making S a much larger term than in a natural environment. Convection processes convert much of this to sensible heat immediately during the day and later into the night.

In adjacent vegetated areas the relative amounts of energy utilized in LE and A vary as a function of the type of vegetation, the soil moisture available for transpiration, and the potential evapotranspiration rate.

The ratio of the fluxes of sensible heat and latent heat (A/LE) or Bowen Ratio

$$\beta = A/LE \qquad [3]$$

can be estimated from the temperature and humidity gradients above the canopy:

$$\beta = \frac{Cp\,\rho\,Ka\,\frac{\partial T}{\partial z}}{\frac{Mw/Ma}{P}\,L\,Ke\,\frac{\partial e}{\partial z}} \qquad [4]$$

where:
- Cp = the specific heat of air
- ρ = the air density
- Ka = the turbulent exchange coefficient for sensible heat
- T = the air temperature
- Mw/Ma = the ratio of the molecular weights of water and air
- P = the atmospheric pressure
- L = the latent heat of vaporization
- e = the vapor pressure of water in air
- Ke = the turbulent exchange coefficient for water vapor
- z = height

If the ratio Ka/Ke is known, or the equality of Ka and Ke is assumed, then equation 4 can be solved with measurements of the gradients of temperature and air vapor pressure. The Bowen Ratio thus determined can then be used with the energy balance, equation 1, to determine the fluxes of LE and A:

$$LE = \frac{Rn - S}{1+\beta} \qquad [5]$$

$$A = \frac{Rn - S}{1+\frac{1}{\beta}} \qquad [6]$$

The usefulness of the one-dimensional Bowen Ratio model is in question near a surface discontinuity. It is valid only when the vertical fluxes of LE and A are independent of height (z) above the canopy. Therefore, it can be used only when measurements are made within the internal boundary layer, which forms at the windward (leading) edge of a stand and thickens with distance downwind.

Little information on the boundary-layer thickness above very rough surfaces such as forests is available. Shinn *(1971)* calculated, from wind-tunnel shear-stress measurements above a simulated forest canopy (see *Sadeh 1974* for measurement details), that the thickness of this boundary layer (α) grew linearly with horizontal distance (x) for at least 25 canopy heights (H) from the leading edge.

$$\Delta\alpha = 0.08x, \qquad x \leqq 25H \qquad [7]$$

METHODS

Three towers were installed across the interface of a 1.8-ha asphalt parking lot and an adjacent black oak *(Quercus velutina)* forest in Storrs, Connecticut, Lat. 41°47′30″N, Long. 72°14′30″W. Wind speeds, air temperature, and humidity were measured with sensitive cup anemometers and aspirated thermocouple psychrometers at four heights on each tower, extending above the canopy of the forest.

The forest was 20 m tall. One tower was located at the edge, one approximately 2H (H = tree height) within the forest, and one approximately 2H out into the parking lot (fig. 1).

Net radiation (Rn), ground heat flux (S), and ground surface temperatures were measured in both the parking lot and the forest with miniature net radiometers, heat flux disks, and thermocouples respectively. The instrumentation and data recording system used are described in Miller et al. *(1975)*. Data were collected during the summers of 1973 and 1974 under a number of different synoptic weather conditions.

Smoke tracers were utilized to observe the three-dimensional patterns of air movements under various synoptic conditions. Smoke was released at several

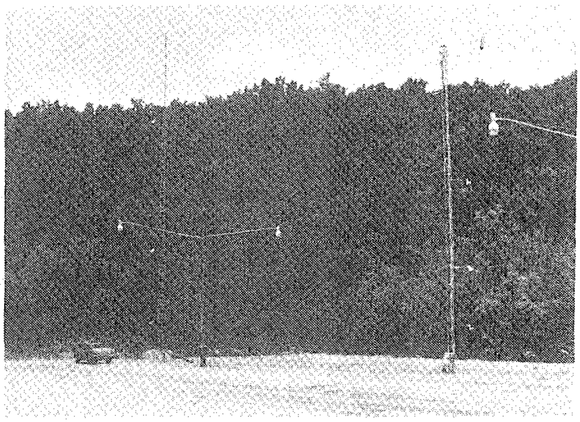


Figure 1.—Parking lot and edge towers and the experimental site forest vegetation of predominately black oak (*Quercus velutina*).

heights at the edge and at varying distances from the edge.

RESULTS

The Energy Balances

Figures 2 and 3 show the partitioning of the energy balances over the two areas on a sample day, 4 July 1974. Flux of sensible heat (A) in the parking lot was calculated from equation 2. A and LE over the forest were calculated from equations 5 and 6 from gradients measured within the boundary layer as defined by equation 7.

The net radiant energy available (Rn) over the parking lot and forest were within 2 percent of each other. The soil heat flux (S) was approximately 20 percent of Rn in the parking lot and 2 percent of Rn in the forest.

Most of the available energy above the forest (f) was used to evaporate water ($LE_f \approx .8$ Rn), while in the parking lot ($_P$) most of the available energy was sed to heat the air ($A_P \approx .8$ Rn).

Air Temperatures and Humidities

The air temperature over the parking lot warmed faster after sunrise and cooled faster after sunset than in or over the forest. After sundown the parking-lot air was cooler through much of the

Figure 2.—The parking lot energy budget, air temperature, surface temperature, and air vapor pressure, July 4, 1974.

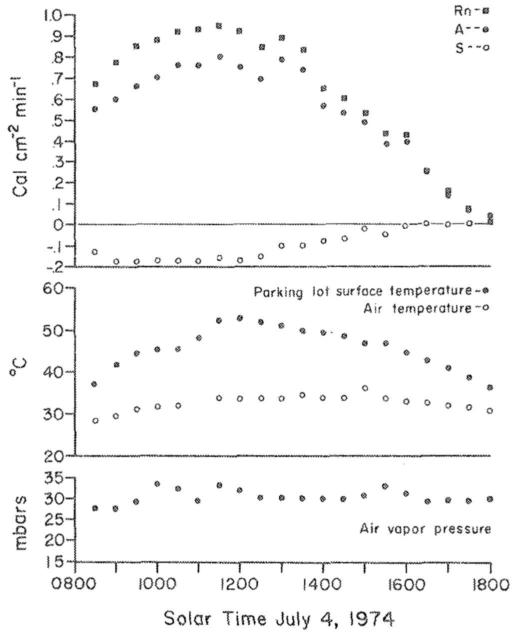
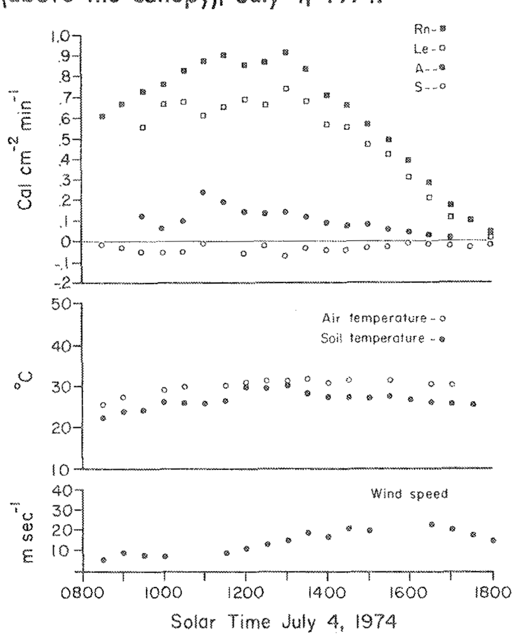


Figure 3.—The forest energy budget, air temperature, soil temperature, and windspeed (above the canopy), July 4, 1974.



night than the air under the forest canopy. This differential cooling and warming was in response to parking-lot surface temperatures, which ranged up to 55°C on some clear days. The daytime horizontal air temperature differences between the parking lot and forest were on the order of 3°C on warm days.

Air above the top of the canopy was heated most rapidly during the day and cooled at night similar to, although slower than air above the parking-lot surface. Therefore the profiles above the canopy were similar to but less steep than those above the parking lot.

The edge temperatures were similar in magnitude to those in the parking lot during the day, with slightly delayed heating and cooling responses. At night the edge temperatures were closer to those in the forest.

Vapor pressure data showed the forest to be consistently more humid than the parking lot. Near the ground the horizontal differences between the forest and open were generally on the order of 2 to 3 millibars both day and night.

Figure 4 demonstrates midday temperature and vapor pressure gradients across the edge on a clear day with the wind blowing into the stand *(Miller 1975)*.

Effects of Wind Direction

The data shown in figures 2, 3, and 4 are from periods when the wind was blowing into the stand.

Figure 4 shows steep horizontal gradients of VP just outside the forest edge and temperature gradients well into the forest. When the wind was from the forest, the horizontal temperature difference was smaller. The water vapor was apparently transported well out into the parking lot.

Figure 5 shows the forest energy balance on 6 July, a day with the wind from the forest. The ratio of A to LE above the forest on 4 July (wind into the stand) was slightly smaller than 6 July (wind from the stand). But no consistent trend in this effect could be correlated. Therefore the differences in ratio on these two days were ascribed to the higher potential evapotranspiration rates on 4 July.

Figure 4.—Air temperature isotherms (solid lines) and air vapor pressure isobars (dotted lines) across the parking lot forest edge with the wind blowing into the forest (after *Miller 1975*).

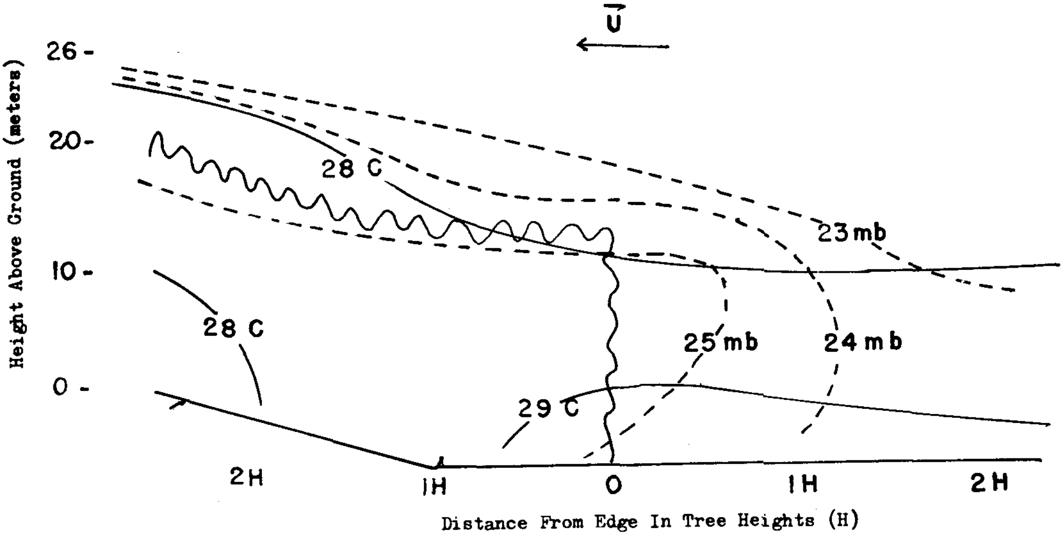
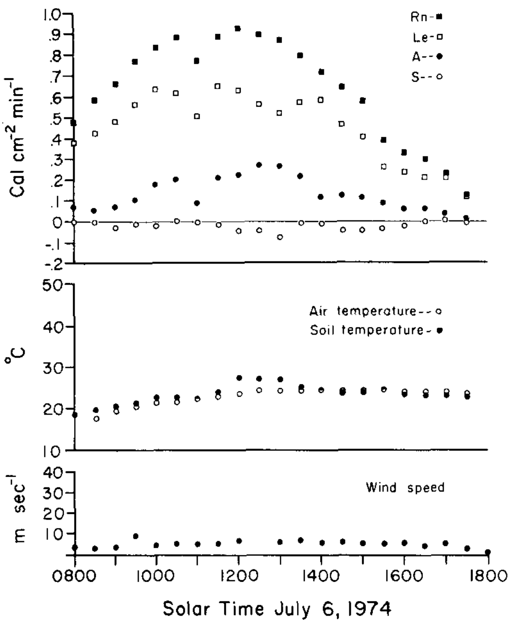


Figure 5.—The forest energy budget, air temperature, soil temperature, and windspeed (above the canopy), July 6, 1974.



Advection Across the Interface

The term advection is used here to mean horizontal transport of an air property such as sensible or latent heat.

Smoke releases showed that the air from the parking lot penetrated the forest edge easily and steadily when the wind direction was from the open to the forest. An occasional weak vortex appeared at the edge during periods of very low wind speeds. Once the smoke penetrated the stand edge it drifted and dissipated below the temperature inversion at the top of the canopy.

Calculations of the amount of sensible heat transported across the interface were presented by Miller *(1975)*. From the horizontal temperature and wind speed gradients it was estimated that between 10 and 20 percent of the sensible heat produced on the parking lot was advected into the adjacent tree stand.

DISCUSSION

The profile data suggest that the region of the interface can be broken into three distinct microclimates. One is formed over the forest, and its characteristics are determined primarily by the energy exchanges at the top of the canopy. The second is formed beneath the canopy. The third is formed over the parking lot and is characteristic of the exchanges at that surface.

The characteristics of the interfaces or mixing boundary layers between the three air masses change both spatially and over time as each of the microclimates responds to changing conditions. Apparently the interface between the parking lot air and that beneath the canopy moved horizontally and was within the forest edge during the day and outside it at night. This indicates that when sensible heat moved horizontally, from the forest at night and to the forest during the day, the major portion of the air mixing takes place some distance beyond the edge in the direction of movement.

These findings combined with those of Bergen *(1975)* indicate that the edge effects extend about 2 to 3 tree heights into the forest. Here the horizontal temperature gradients and wind velocities decreased rapidly inside the forest. At the tower site approximately 2H into the forest, the temperature gradients and wind speeds were very weak, indicating little if any advection that far into the forest. The effects of the edge on the air turbulance were indicated by Bergen *(1975)*, who calculated increased drag on the air mass some 30 meters (approximately 3H) downwind of a clearing in the forest.

The extent of the edge effects into the parking lot are a little less clear. The smoke tracers showed that with wind from the lot, air from greater than 2H penetrated the edge when the windspeed was greater than 4 mph. When less than 4 mph only the smoke released near the edge penetrated. When the wind was from the forest there were changes in the temperature and vapor pressure gradients well beyond the location of the tower located 2H into the parking lot *(Miller 1975)*.

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