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A 3-year study of water relations of urban street trees

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Summary

1. A 3-year field study of the water relations of street trees in New York City was undertaken with the following objectives: (i) to ascertain whether there was empirical evidence for water deficits; (ii) if water deficits occur, to correlate these events with prevailing weather conditions; (iii) to determine whether tree water relations varied systematically with street exposure; (iv) to compare street microclimate with that of a nearby park; (v) to compare water relations of two common street tree species; (vi) to evaluate the effectiveness of a minimum irrigation programme.

2. Water deficits in trees, as evidenced by midday stomatal closure, occurred but with lower frequency than is commonly expected. Average predicted frequency during the summer was 13% over a 21-year period. When deficits occurred, they were demand driven rather than supply limited. Deficit periods were characterized by maximum air temperatures on the street >41 °C and a maximum atmospheric vapour pressure deficit of 7·5 kPa. Official weather station data collected in a nearby park indicated far milder conditions, with a maximum air temperature and vapour pressure deficit of 32 °C and 2·5 kPa, respectively. Over the midday period, the mixing ratio, a conservative measure of atmospheric water content, was 8·4 g kg^{-1} lower on Columbus Avenue than in the park, indicating that the street microclimate was far drier.

3. The west side of the street received more solar radiation than the east and was usually slightly hotter than either the east or the park. Yet, trees on the west side of the street were not more water stressed. Though *Fraxinus pennsylvanica* transpired at higher rates and sustained more negative water potentials than *Tilia cordata* these differences were variable and could not be separated statistically. Similarly, *Fraxinus pennsylvanica* showed small but statistically non-significant responses to minimal weekly irrigation while *Tilia cordata* was unresponsive.

Key-words: arboriculture, microclimate, irrigation, *Fraxinus pennsylvanica*, *Tilia cordata*.

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Introduction

Water is widely recognized as the paramount factor limiting plant distribution and productivity on a global scale (Walter 1973; Boyer 1982; Kozlowski 1982). Even in regions of abundant natural precipitation, transient water deficits occur when atmospheric demand exceeds supply to plant roots. In natural communities, the frequency and severity of these deficits play a major role in determining the structure and species composition of the vegetation occupying a particular site. In managed landscapes, however, natural limitations to plant growth are frequently overcome by subsidies of limiting resources such as water. While a primary objective of horticulture is prescribing the nature and amount of such subsidies, plants in non-production landscapes often receive minimal subsidy despite having been deliberately planted in an artificial and potentially harsh environment. Nowhere is this situation more apparent than with urban street trees. Practical observations indicate that trees in urban environments have a drastically shortened life span in comparison with trees growing in natural stands. Life expectancies for new street tree plantings in the north-eastern United States are estimated to be 10 years, with up to 50% mortality occurring within a year of planting (Foster & Blaine 1977; Foster 1978a,b; Berrang &

Karnosky 1983). Given the pivotal role of water in natural plant communities and the altered hydrology of cities, it is frequently supposed that water deficits are in part responsible for this early mortality. There is a widespread belief among researchers and urban foresters alike that water deficits are especially common and severe in the environment of the street tree (Gerhold, Long & Dermitt 1975; Foster & Blaine 1977; Foster 1978a,b; Roberts 1977; Wilson 1977; Green 1980; Steiner 1980; Tattar 1980; Staby 1981; Genetics Working Group 1982; Berrang & Karnosky 1983; Spirn 1984). The hypothetical scenario for water stress in street trees holds that both curtailed water supply and excessive demand prevail in the urban environment. Water supply is decreased to roots because pavement and compacted soil prevent percolation into the root zone. At the same time, access to ground water and subsurface drainage is often eliminated. Atmospheric demand is increased because elevated temperatures and lower humidities accentuate the vapour pressure deficit. Despite this apparent concensus, observations of tree water status under actual street conditions are largely absent. Indeed, the few studies which have addressed urban tree water relations have involved simulated or simplified urban environments (parking lots on university campuses), have been relatively short term (several days to one growing season in duration), concentrate on a single species (*Gleditsia triacanthos* L. predominates), are at a scale not wholly appropriate to street trees (e.g. continuous canopies), or have used containerized trees (Miller 1977; Potts 1978; Christensen & Miller 1979; Potts & Herrington 1982; Vrecenak & Herrington 1984a). While these studies provide valuable insight into tree water status in specific cases, they provide a rather narrow foundation for generalities concerning water stress in street trees. Though no physiological measurements were made, the most comprehensive examination of urban tree populations to date reported that water and nutrient stress accounted for 56% of the tree mortality in 11 British cities while vandalism was a distant second, accounting for only 18% of the observed mortality (Gilbertson & Bradshaw 1985). Water stress is likely to be correlated temporally with seasonal precipitation and spatially with solar exposure and other features in the built environment. If such correlations exist, then there should be observable patterns of stress which could assist in selection and design of tree planting sites. The objective of this report is to document the frequency and severity of water deficits in street trees in a prototype urban site and to elucidate some of the correlated environmental variables. Such observations would provide strong validation for selection and improvement programmes which are frequently recommended (Gerhold & Steiner 1976; Santamour 1978; Genetics Working Group 1982), would aid in the development of operationally defined selection criteria and planting/maintenance specifications, and contribute to a general understanding of the urban environment.

This paper reports the results of a 3-year study of 20 recently planted street trees in Manhattan. The goal was to establish an empirical baseline for conditions potentially limiting the diurnal water balance of *in situ* street trees. There were six specific questions to be addressed.

1. Is there evidence for water deficits? In this study, four criteria were chosen as an operational definition of water deficit: (i) pre-dawn water potentials $<-0{\cdot}5$ MPa; (ii) failure to recover to the previous day's pre-dawn value; (iii) midday stomatal closure; and (iv) a decreasing seasonal trend in water potential.

2. If water deficits occur, what are the prevailing meteorological conditions and how frequently do they occur?

3. Do street microclimate and plant response vary predictably with street exposure?

4. Does the street environment differ dramatically from a nearby urban open space?

5. Do different tree species with reported tolerance for urban conditions perform differently under similar conditions?

6. How do street trees respond to a minimum irrigation regime?

Materials and methods

Study site

The field site was selected to meet the following characteristics: an urban street setting; recently planted trees of uniform age, with canopies accessible from the ground; sufficient number of trees in a small enough area to meet the practicalities of replication and repeated sampling over a diurnal period; several species or cultivars represented; proximity to an urban open space with an independent record of weather conditions; contrasting exposures to maximize environmental gradients. These criteria were met on Columbus Avenue between 68th and 75th streets on the upper west side of Manhattan, New York City, USA (40°46′N, 73°58′30″W). Columbus Avenue is one of 15 major streets which run nearly the length of Manhattan. The bearing of all these streets is 30°E, creating exposures which are nominally east and west. Columbus Avenue is paved in black asphalt 18·3 m wide, bordered by concrete sidewalks 4·6 m wide. Store fronts predominate at street level, with residential apartments above. Building heights range from approximately 3·5 m (one storey) to 37 m (12 storeys) over the seven-block study area, with 88% of the total street frontage occupied by buildings 15–21 m (5–7 storeys) high, creating, in effect, a shallow canyon. Building facades are concrete, brick, glass and sandstone.

Sampling frequency

Continuous monitoring of street level conditions was not feasible. Instead, sequences of diurnal measurements at monthly intervals were made over three growing seasons. A study spanning the first years after planting was chosen to provide a profile of tree performance during the establishment period when water stress is supposedly most critical (Foster & Blaine 1977). Observations were made during the following periods:

July–September 1983,
May–September 1984,
June–August 1985.

Eleven visits were made over the 3-year period.

Trees

Twenty in-ground trees were observed, eight on the east side of the street and 12 on the west side. Trees were spread along the entire seven-block area at irregular intervals but never less than 10 m apart. Nine trees were green ash (*Fraxinus pennsylvanica* Marsh. 'Marshall's Seedless') and 11 were littleleaf linden (*Tilia cordata* Mill. 'Greenspire'). Green ash is native to the eastern USA and littleleaf linden is native to Europe (Bailey 1949). These cultivars are among the more frequently planted in urban areas in the north-eastern USA in recent years.

All trees were planted in March 1982, independent of this research, in accord with standard planting practices (City of New York Parks Recreation and Cultural Affairs Administration, Dept of Parks 1975). Trees were growing in square openings cut in the sidewalk 1·88 m^2 in surface area. Cast iron tree grates which lay at grade over a shallow sand layer reduced the exposed surface of the tree pit to 0·59 m^2. In the spring of 1983 the trees were approximately 4 m high and diameters 1·4 m above the ground ranged from 41·7 to 60·6 mm.

During the 1984 season observations focused on documenting absolute differences in evaporative demand between sides of the street, using small trees in containers. The use of small containerized trees eliminated the self-shading found in large canopies, and permitted maintenance of conditions where water supply was non-limiting. Fifteen second-year seedlings of each species were brought from the Cornell campus to observe under street conditions during each observation period. Trees were maintained well-watered in a 1 : 1 : 1 soil : peat : perlite mix (by volume) in No. 1 black plastic nursery containers. During street observations the pots were enclosed in white plastic bags to prevent evaporation and were supported on narrow boards 1·2 m above the sidewalk. Fresh trees were used for each observational period.

Environmental monitoring

Site microclimate was monitored continuously during the observation periods at stations located mid-block on block 4 on each side of the street with a battery powered portable data logger (CR-21, Campbell Scientific Inc., Pullman, Washington). Point sampling cannot adequately describe a complex three-dimensional street environment, yet is the only practical alternative for most micrometeorological field studies (e.g. Tuller 1973). In the present study single-site monitoring stations were used to provide an indication of the aboveground environmental dichotomy between different exposures. Air temperature at 10 cm, 2 m and 3 m above the pavement was measured by thermistors (model 101, Campbell Scientific Inc. Pullman, Washington) inside non-aspirated, open-ended shields (lengths of polyvinyl chloride pipe wrapped in reflective plastic film). Relative humidity was measured with similarly shielded probes (model 201, Campbell Scientific Inc. Pullman, Washington) at a height of 2 m. Solar radiation was measured at 2 m with silicon pyranometers (model LI 200-S, Li-Cor Inc., Lincoln, Nebraska). All sensors were mounted on lightweight metal masts.

Shadow casting

A shadow casting study was conducted to aid in placing the monitoring stations so as to avoid corner effects. This was done using a scale model of the street and a custom-built rotatable, tiltable platform with light source capable of simulating seasonal and diurnal patterns of solar declination and elevation. A quantitative analysis was conducted to determine the potential duration of exposure to direct sun during the growing season using the method outlined by Mazria (1979). Specifically, a south-facing 240° skyline was plotted from the vantage point of each pyranometer location using a map (scale 1 inch: 40 feet) and known building heights. This was overlain on plot of the solar path at 40°N for appropriate dates to determine when the sensor location, and hence the entire tree canopy, would receive direct solar radiation.

Plant water status

Beginning prior to dawn, leaf water potential of both in-ground and containerized trees was measured every 3–6 h using a pressure bomb (model 3005, Soilmoisture Equipment, Santa Barbara, California). Stomatal conductance, and leaf temperature were measured at the same intervals with a null-balance porometer (model 1600, Li-Cor Inc., Lincoln, Nebraska). Stomatal conductance and water potential were measured on three fully expanded sun leaves (or terminal leaflets in the case of ash) in the lower portion of each canopy of the in-ground trees. In 1984, these measurements were made on containerized trees also.

Irrigation

During the 1983 growing season an irrigation treatment was imposed on five in-ground green ash and five linden. A team from the Central Park Conservancy injected 0·02 m^3 (5 gal) of water into each tree pit every week from June to August. Timed injections at a constant low pressure at four locations in each pit achieved equal application at each point and avoided surface run-off.

Central Park climate

Hourly data from the observation station 1·4 km north-east of the study area in Central Park were obtained from the National Weather Service in New York for each day during which street conditions were monitored. Atmospheric water vapour pressure deficit (VPD) and specific humidity were calculated from temperature, relative humidity and barometric pressure and used as a basis for comparing the evaporative demand of the park with that of Columbus Avenue.

Data analysis

Analysis of variance was performed on plant response variables for specific periods of interest using General Linear Models (GLM) procedures contained in the Statistical Analysis System software package (SAS Institute, Inc., Cary, North Carolina) on the mainframe computer at Cornell University. To test for seasonal declines in predawn and midday water potentials, analysis of variance was performed on the slopes of seasonal trends for the four combinations of species and exposure.

To address the issue of return frequency of apparently stressful conditions on Columbus Avenue (evidenced by midday stomatal closure), an empirical *water stress type day profile* was developed from the recent history of meteorological conditions prevailing in Central Park immediately preceeding the stress period. Assuming that the occurrence of type day conditions in Central Park would be one of the indicators of water stress on the street, weather records for a 21-year period from Central Park were analysed to determine the return frequency of type day conditions. Weather data for Central Park for the period 1961–82 were obtained from standard archival sources (Northeast Regional Climate Program 1983; National Oceanic and Atmospheric Administration 1961–1982).

Results

SITE MICROCLIMATE

On a given day, the microclimates for the two street exposures and Central Park were defined by inputs of solar radiation, with modifications imposed by building height, street width, and street orientation. The buildings on Columbus Avenue effectively raised the horizon, truncating the diurnal pattern of exposure to direct sun (Fig. 1). Throughout the growing season, tree canopies at mid block were shaded until 12.30–13.00 h Eastern Daylight Time (EDT) on the east side of the street. At midday, incident radiation rose abruptly to full sun levels as the sun emerged from behind the roofline. On the west side of the street, trees received morning sun beginning *c.* 08.00 h EDT and were cast in shade in the late afternoon as the sun disappeared behind the roofline.

While building height affected duration of exposure to direct sun, shadow casting analysis clearly shows how street orientation was primarily responsible for the differences between the east and west sides of the street (Table 1). Assuming a uniform five-storey (18·29 m) building height on both sides of the street, a point at the bottom of the canopy on the west (east-facing) side of Columbus Avenus (bearing 30° east at 40° north latitude) would receive 1:20–1:30 h more direct sun per day between March and September than would a parallel point on the east. Using actual building heights and a reference point corresponding to the mast locations indicated differences between exposures (Table 1) which were closer to values obtained in the field (Fig. 1).

Over the course of a sunny day, peak temperature and atmospheric VPD lagged several hours behind peak inputs of solar radiation (Fig. 2). The west side of the street always peaked earlier in the day than the east. Contrary to expectation, VPD was frequently lower on the street for part of the day than in Central Park, as on the morning and early afternoon of May 1984 (Fig. 2b). Again, in August 1984 Central Park VPD exceeded both sides of Columbus Avenus prior to 09.30 h and continued to exceed the east side of the street until 13.30 h (Fig. 2e). This occurred when the street was shaded and is in part due to the fact that saturation vapour pressure is temperature-dependent. Whenever temperature is higher, VPD might also be expected to be higher. It is also likely that absolute differences in vapour concentration, expressed as vapour pressure (VP), between the park and the street would contribute to differences in VPD. During the May 1984 observation, the VP in Central Park was essentially equal to the street before noon, intermediate between the east and west sides of the street between 12.30 h and 17.30 h, and lower than the street for the rest of the

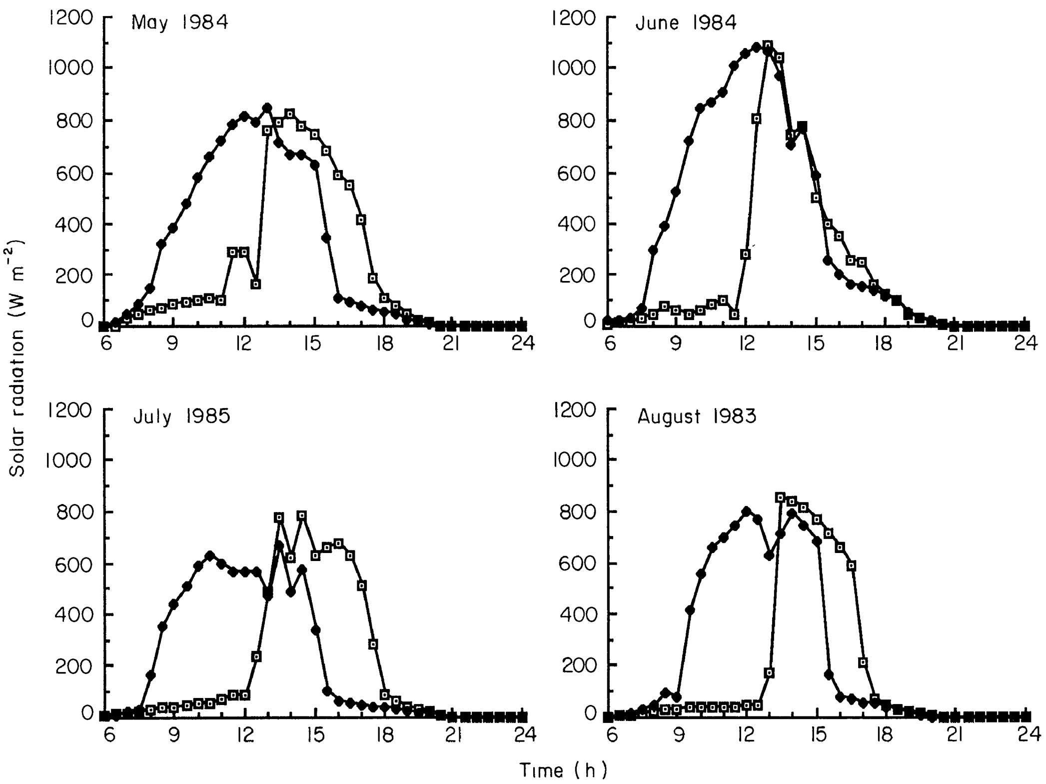

Fig. 1. Diurnal pattern of solar radiation over the growing season in the wavelengths 400–1100 nm for the east (——□——) and west (——◆——) exposures on Columbus Avenue. Days were chosen to show clear, sunny conditions.

Table 1. Exposure to direct solar radiation (in hours and min) calculated from a shadow casting analysis for mid-block locations 2 m above the pavement on the east and west sides of Columbus Avenue Real building heights are referenced to the locations of the monitoring stations between 71st and 72nd streets

	Actual building heights			Idealized five-storey buildings		
Month	East	West	Difference	East	West	Difference
Mar	2:35	4:10	1:35	3:30	4:50	1:20
Apr	4:05	5:35	1:30	4:05	5:25	1:20
May	4:40	6:45	2:05	4:40	6:00	1:20
Jun	4:45	7:10	2:20	4:55	6:25	1:30
Jul	4:40	6:45	2:05	4:40	6:00	1:20
Aug	4:05	5:35	1:30	4:05	5:25	1:20
Sep	2:35	4:10	1:35	3:30	4:50	1:20

day (Fig. 2c). In August 1984, the VP in Central Park was lower than both sides of the street except between 11.00 h and 13.00 h when it was similar to values on the east side (Fig. 2f).

In contrast to the 1984 season, which provided what could be considered a 'typical' range of conditions, the 15–17 August 1983 sampling showed extremes for both temperature and atmospheric moisture (Fig. 3). On 16 August, midday air temperatures at the lower canopy level reached 41 °C (Fig. 3d) while on both 15 and 16 August VPDs reached maximums of 3·9 and 7·4 kPa, respectively (Fig. 3b,e). Over the same period in Central Park, the maximum temperature was 32 °C and the maximum VPD was 2·3 kPa (Fig. 3a,b,d,e). During this period VP was relatively constant between 1·5 and 2·0 kPa in Central Park. Both sides of the street had lower VPs than Central Park and decreased during the middle of the day.

Vapour pressure varies with total atmospheric pressure, but is insensitive to temperature in an open system (Amdur 1965). It is therefore unlikely that the apparent dryness of the street atmosphere was an artefact of higher temperatures. To confirm this observation, a completely conservative expression of atmospheric humidity was calculated. The mixing ratio, the ratio of the weight of water vapour in a gaseous sample to the dry weight of the sample, was calculated as:

$w = 0{\cdot}622e/(p-e)$,

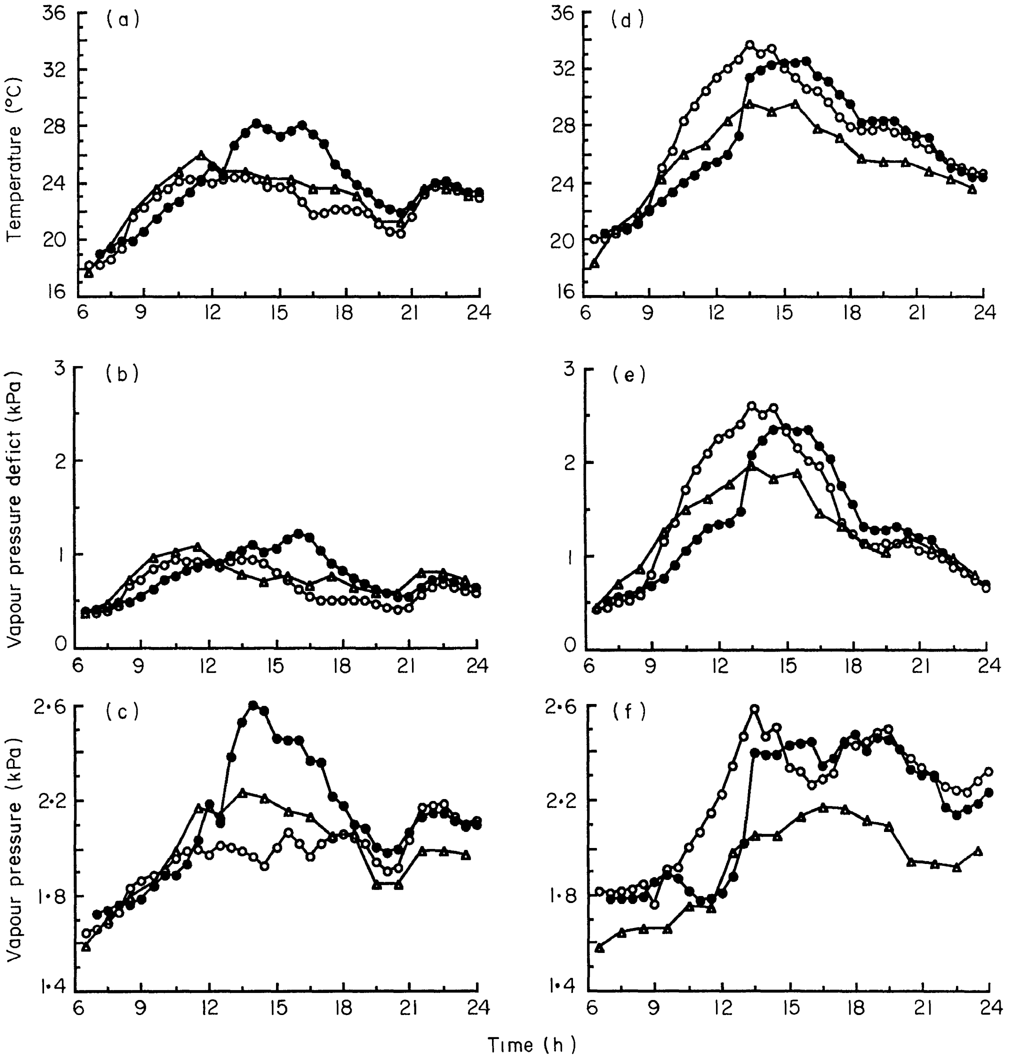

Fig. 2. Diurnal patterns for temperature, vapour pressure deficit and vapour pressure for the east (——•——) and west (——○——) sides of Columbus Avenue and for Central Park (——△——). (a)–(c) spring, 22 May 1984; (d)–(f) late summer, 22 August 1984.

where *w* is the mixing ratio; *e* is the partial pressure of water vapour; and *p* is the total barometric pressure (Gates 1980).

The mixing ratios closely paralleled the patterns indicated by vapour pressure and therefore are not presented. It is interesting to note, however, that on 15 August 1983, mixing ratios in Central Park varied only slightly, from 8·9 to 10·8 g kg^{-1} while on the east side of Columbus Avenue the range was from 3·2 to 8·2 g kg^{-1}. On 16 August, the mixing ratio in Central Park varied from 11·6 to 12·5 g kg^{-1}, while on the west side of Columbus Avenue it varied between 3·2 and 10·9 g kg^{-1}. According to the representative values cited by Gates (1980), the water content of the street atmosphere was similar to that of a cold, dry air mass.

Transpiration is tightly coupled to atmospheric VPD only when the canopy is well ventilated. As the following evidence shows, trees on Columbus Avenue were probably sufficiently ventilated under daytime conditions to justify the use of VPD as an indicator of the transpirational demand experienced by the trees. The lowest windspeeds encountered in this study occurred on 19 July 1984. Under these 'worst case' conditions, average windspeed between 06.00 and 20.00 h was 1·4 m s^{-1} and never fell below 1·0 m s^{-1}. (At night, average windspeed dropped to 0·67 m s^{-1}. The combination of low windspeed and nocturnal stomatal closure would be expected to decouple transpiration from atmospheric VPD.) For *Fagus sylvatica* (which has leaves with a characteristic dimension similar to the species on Columbus Avenue) Dixon & Grace (1984) reported aerodynamic resistances of *c.* 0·2 s mm^{-1} and stomatal resistances of *c.* 1·0 s mm^{-1} at windspeeds exceeding 1 m s^{-1}, indicating that stomatal resistence was the factor limiting transpiration. Observations on Columbus Avenue indicated that wind velocity of 1 m s^{-1} was sufficient to cause gentle movement in leaves in the outer canopy so that actual boundary layer conductance for individual leaves on the street would have been even higher than if the leaves had been immobilized as in Dixon and Gates'

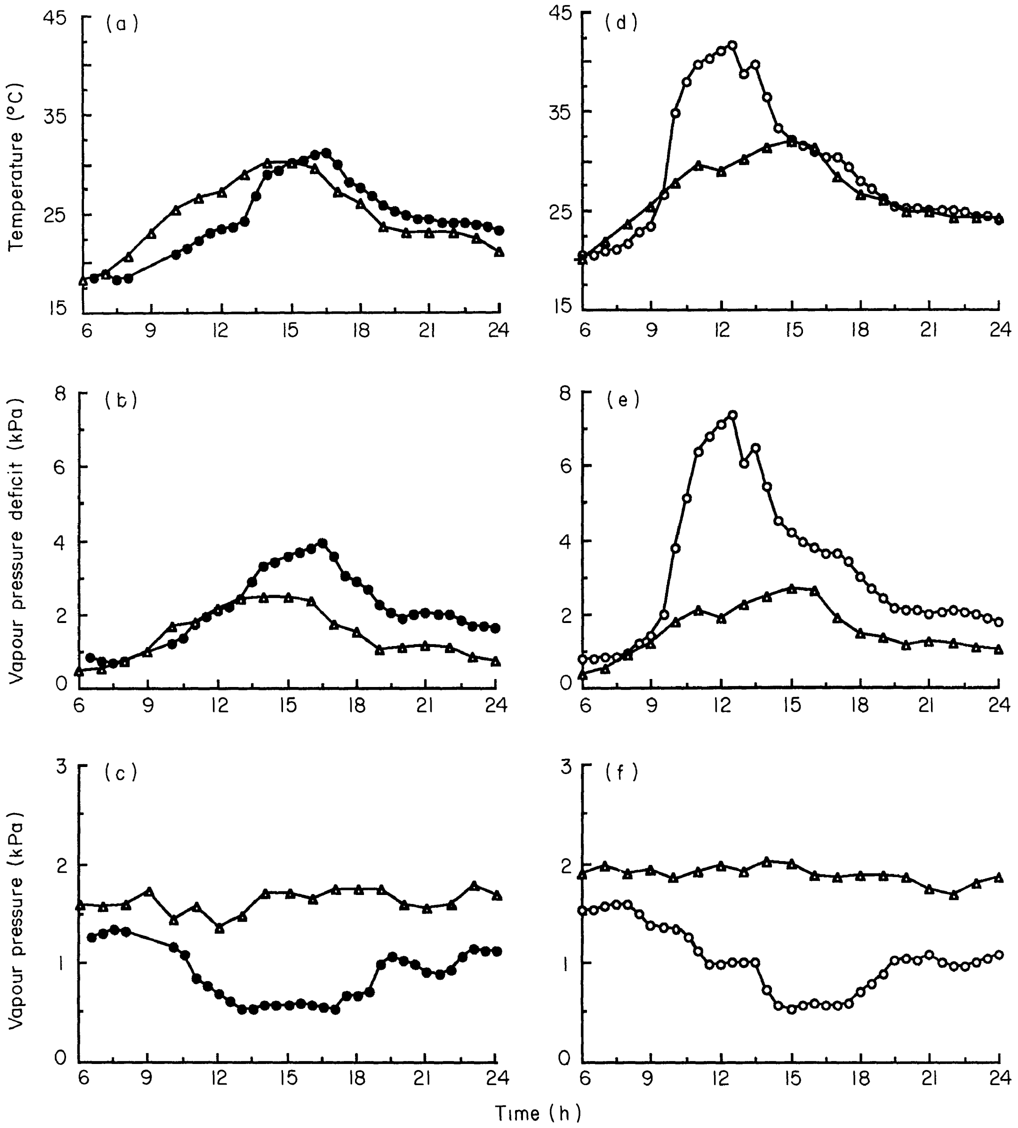

Fig. 3. Diurnal time courses for temperature, vapour pressure deficit and vapour pressure for the east (——●——) and west (——○——) sides of Columbus Avenue and Central Park (——△——) during a period of exceptionally high atmospheric demand: (a)–(c) east vs. Central Park for 15 August 1983; (d)–(f) west vs. Central Park, 16 August 1983.

report. Therefore, under the conditions prevailing on Columbus Avenue, it is likely the VPD is a meaningful indicator of evaporative demand. Cumulative evaporative demand (expressed as the area under the diurnal VPD curves between 6.00 and 20.00 h) is a convenient index for comparing the relative evaporative demand (Fig. 4). For the nine dates when complete data sets were available, diurnal evaporative demand (averaged for both sides of the street) was higher on Columbus Avenue than in Central Park except for 19 July and 19 September 1984. The August 1983 observation was extreme, with the western exposure developing a very high demand (51·6 kPa day^{-1}), approximately twice the demand in Central Park. On six occasions atmospheric demand was lowest in Central Park, yet on six occasions there were negligible differences among the three sites. Excluding the August 1983 measurements which occurred on two consecutive days, differences between exposures were negligible on six occasions and higher on the east than west on two occasions. Diurnal atmospheric demand was less variable in Central Park than either the east or the west street exposures, with standard deviations of 4·13, 7·43, and 11·47, respectively.

TREE WATER STATUS

The effect of season-long irrigation on trees subjected to a period of high atmospheric demand in August 1983 is of special interest. Though irrigated ash trees had somewhat higher stomatal conductances and lower water potentials, analysis of variance showed no significant differences between irrigated and non-irrigated trees at any time of day. Irrigation treatment was therefore ignored in subsequent analyses of species and exposure effects.

Minimum (midday) and maximum (predawn) daily leaf water potentials, averaged by species and exposure, failed to show a consistent pattern of tree

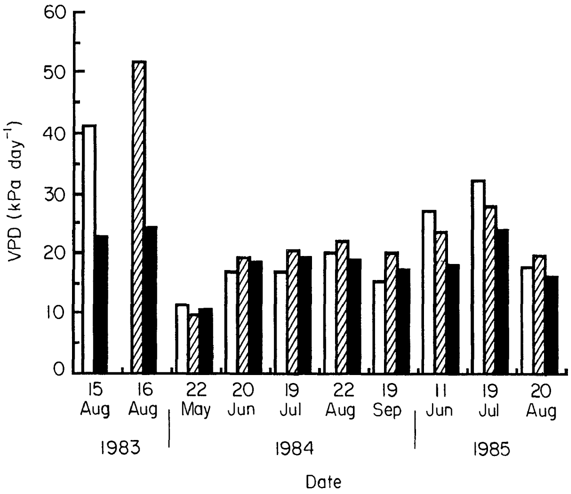

Fig. 4. Cumulative vapour pressure deficits for Central Park (■) and the east (□) and west (▨) exposures on Columbus Avenue for days during which tree water relations were monitored. Cumulative vapour pressure deficit is expressed as the area under the curve for hourly averages between 06.00 and 20.00 h. In August 1983, the east and west sides of the street were monitored on successive days and are shown with the respective data from Central Park.

water status over the study period (Table 2). It should be noted that maximum water potentials always coincided with predawn observations while minimum potentials frequently did not coincide with midday. Maximum leaf water potential was unaffected by any of the anticipated sources of variation (Table 2). Minimum water potential showed significant variation, but showed an exposure × year interaction. Seasonal trends in maximum and minimum water potential proved more useful than individual observations in addressing differences between exposures and species (Table 3, Fig. 5). Each tree was treated as a replicate observation and the slopes of the seasonal water potential curves were treated as response variables in an analysis of variance. Direct measurement of soil water was not feasible, yet it is generally accepted that pre-dawn plant water potential is largely controlled by soil water potential (Hinckley, Lassoie & Running 1978; Kozlowski 1982). Thus, seasonal decrease in pre-dawn water potential would indicate depletion of soil water, while seasonal decrease in minimum (midday) water potential would include the effect of increasing atmospheric demand during the hotter summer months.

Table 2. Analysis of variance for maximum and minimum leaf water potentials for all years. Maximum leaf water potentials are predawn values. Minimum water potentials occurred at various times during the middle of the day

Source	df	Mean square	*F*-value
Maximum water potentials			
Mean	1	0·080237	
Model	11	0·022954	1·23
Exposure	1	0·013682	0·73
Species	1	0·047906	2·56
Year	2	0·039078	2·09
Exp × Species	1	0·016520	0·88
Exp × Year	2	0·015473	0·83
Species × Year	2	0·036008	1·92
Exp × Species × Year	2	0·000845	0·05
Error	41	0·018733	
Corrected Total	53		
Minimum water potentials			
Mean	1	0·221209	
Model	11	0·117546	4·04*
Exposure	1	0·142859	4·91*
Species	1	0·011492	0·40
Year	2	0·245157	8·43*
Exp × Species	1	0·090366	3·11
Exp × Year	2	0·148494	5·11*
Species × Year	2	0·051347	1·77
Exp × Species × Year	2	0·061091	1·05
Error	41	0·029072	
Corrected Total	53		

* Significant at $P = 0{\cdot}05$.

Although there were again two-way interactions, the patterns were fairly clear. In six of the 12 cases, predawn water potential declined over the season, suggesting seasonal depletion of soil water (Fig. 5). There appeared to be seasonal declines in midday water potential in eight of the 12 cases but only five trends were significant (Fig. 5). Note that four of the significant declines occurred in 1984. Ash on the west side of the street actually showed an increase during the summer of 1984.

The performance of containerized trees during the 1984 growing season provides a means of comparing midday water status of in-ground trees with that of plants with adequate soil moisture (Fig. 6). During the 1984 growing season, water potentials were highest and conductances lowest in May. Over the remainder of the summer, conductances varied widely at a given water potential within an observation period, probably due to small-scale variation in both time and space which could not be resolved by the sampling regime. Ash had higher maximum stomatal conductances (9–10 mmol m^{-2} s^{-1}) than linden (7 and 8 mmol m^{-2} s^{-1}). Water potentials fell below −2·0 MPa in June, July and September in both ash and linden. Water potentials were generally lower in in-ground trees yet, except in September, street trees maintained conductances essentially equalling containerized trees. Therefore, despite apparently greater water stress in the street trees, they were able to maintain high stomatal conductances. There are two possible reasons for this. First, the appearance of less water stress in the containerized trees could be an artefact unrelated to water supply. In addition to being well-watered, the containerized trees were much smaller than the street trees and would have had lower axial resistance to water flow. At a given driving force, the smaller trees would be expected to have higher conductances. Second, the street trees had probably

Table 3. Analysis of variance for seasonal trends in predawn and midday leaf water potentials

	df	Sum of squares	*F*-ratio	$P > F$
Predawn water potentials				
Year 1				
Model	3	0·1342	4·3	0·0210
Species	1	0·0126	1·23	0·2843
Exposure	1	0·1175	11·47	0·0041
Species × exposure	1	0·0041	0·40	0·5378
Error	12	0·1537		
Year 2				
Model	3	0·0240	7·5	0·003
Species	1	0·0071	6·74	0·0211
Exposure	1	0·0047	4·49	0·0525
Species × exposure	1	0·0122	11·50	0·0044
Error	12	0·0148		
Year 3				
Model	3	0·0219	0·4	0·710
Species	1	0·0171	1·09	0·3162
Exposure	1	0·0024	0·16	0·7003
Species × exposure	1	0·0024	0·15	0·7149
Error	12	0·1879		
Midday water potentials				
Year 1				
Model	3	0·3924	4·9	0·013
Species	1	0·0415	1·57	0·2287
Exposure	1	0·3435	13·02	0·0026
Species × exposure	1	0·0073	0·28	0·6056
Error	12	0·3957		
Year 2				
Model	3	0·0514	0·9	0·457
Species	1	0·0041	0·22	0·6482
Exposure	1	0·0077	0·41	0·5314
Species × exposure	1	0·0396	2·12	0·1671
Error	12	0·2614		
Year 3				
Model	3	0·1656	1·6	0·223
Species	1	0·0570	1·74	0·2120
Exposure	1	0·0122	0·37	0·5541
Species × exposure	1	0·0965	2·94	0·1120
Error	12	0·3936		

been subjected to temporary water deficits which could result in osmotic adjustment, permitting water uptake from the soil at relatively high rates despite reduced supply.

While there was frequently a 0·5–1·0 MPa difference between the predawn maximum and the midday minimum water potential (Fig. 5), trees recovered rapidly to predawn water potential values by early morning even under the extreme conditions of August 1983 (Fig. 7). Though not statistically different, it is interesting that irrigated ash trees on the east side of the street had more negative water potentials than unirrigated controls.

Stomatal conductance varied widely from tree to tree at a given time of day (Fig. 8). It is likely that even on the same side of the street at the same instant, individual trees experienced different solar exposure owing to variation in building height and spacing. Though midday stomatal closure was observed in individual trees on several occasions during the study, the typical pattern was an early morning increase in conductance in response to increasing light and VPD followed by a midday plateau (Fig. 8c,d,f) or a gradual increase over the day (Fig. 8e). The clearest case of midday stomatal closure (Fig. 8a) or a morning peak in conductance (Fig. 8b) occurred during the August 1983 sampling. Though maximum conductances were lower during this observation period than in 1984 (Fig. 6), ash again showed a pattern of higher conductances than linden.

RETURN FREQUENCY

In this study, water deficits severe enough to induce stomatal closure were not commonly observed. The period between 15 and 16 August 1983 was the only observation where midday depression in stomatal conductance was common among the trees in the study (individual trees showed midday depression in July and August 1985). How uncommon are such events over the long term? The 3-month summer

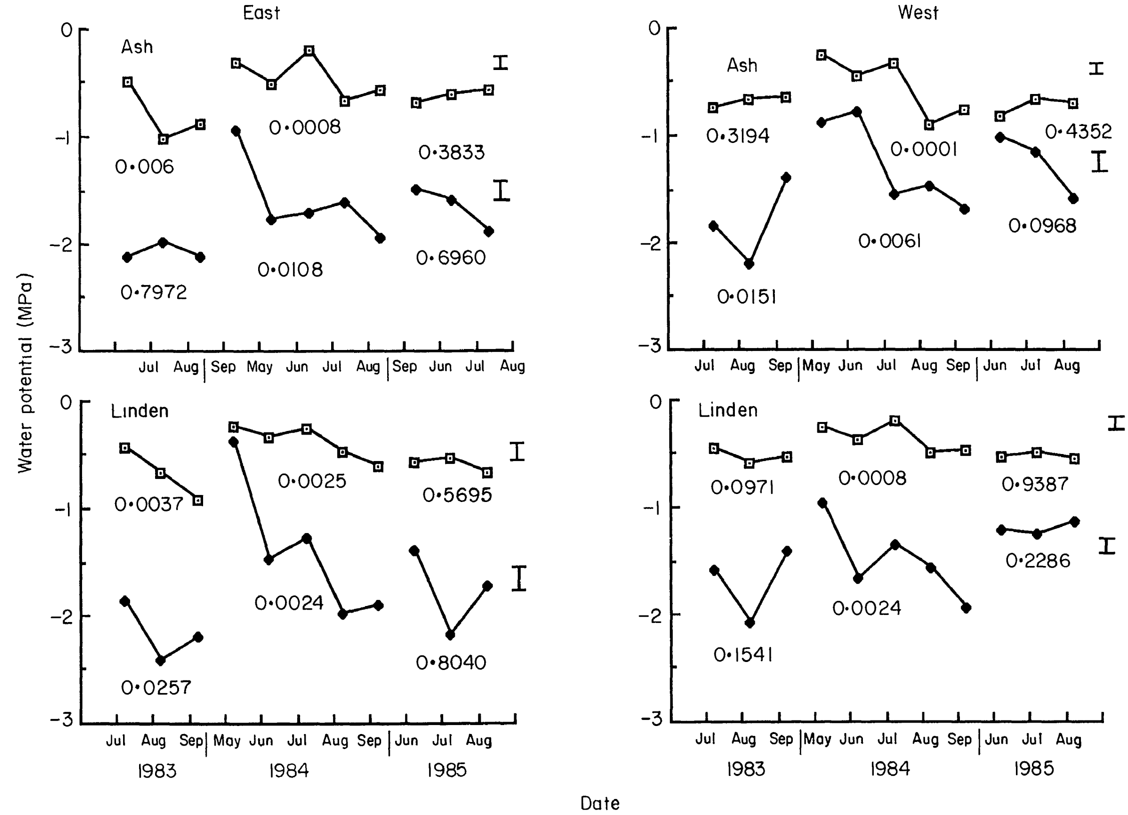

Fig. 5. Maximum and minimum leaf water potentials, averaged by species and side of the street, for all three years; ——◆——, minimum (midday) water potentials; ——□——, maximum (predawn) water potentials. Error bars denote the average standard error across all years for each combination of species and exposure. Significance levels are shown for each seasonal trend.

season of 1983 was the hottest since 1949, with 29 days when the maximum temperature reached 32·5 °C (Northeast Regional Climate Program 1983). Based on Central Park weather conditions, 16 August 1983 had maximum temperature of 31·3 °C, maximum temperature for the previous 2 days equal to or greater than 28·3 °C, and minimum relative humidities of less than 45%. Yet records indicate that the 1983 growing season was relatively wet in comparison with the 30-year normal. Furthermore, 6·07 cm of rain had fallen on 11 August and 0·89 cm on 12 August, making the occurrence of water stress all the more remarkable and suggesting a likely dependency on high atmospheric demand rather than limited supply. To address the issue of return frequency of apparently stressful conditions, an empirical type day profile was developed from these meteorological conditions in Central Park corresponding to the period of water deficit (16 August 1983). The type day provides a means for estimating the frequency of water-deficit periods from Central Park weather observations (Fig. 9). For 21 years for which complete records are available, this profile occurred on an average of 16·3 days per season or 13·4% of the time for the June–September period (122 days per season). Though type days occurred every year, their frequency in any given year is quite variable. The range of type day occurrences was 5 (in 1961) to 45 (in 1966) days per season and they were most frequent in July and least frequent in September.

Discussion

EVIDENCE OF WATER DEFICITS

Four indicators were used in this study as an operational definition of tree water deficits: predawn water potentials $< -0{\cdot}5$ MPa, failure to achieve nocturnal recovery to the previous predawn potential, seasonal decrease in predawn potential, and midday stomatal closure.

The criteria of low predawn potentials and absence of nocturnal recovery present inconsistent evidence for the development of water stess between precipitation events. Over a 3-year period, the lowest average predawn leaf water potential was −0·9 MPa, with −0·5 MPa more typical. Because there is little available water below −0·5 MPa and using predawn leaf water potential as an estimate of soil water status, this suggests that soil water could become limiting with droughts only slightly longer in duration. Yet nocturnal recovery to the previous day's predawn water potential was always observed.

Cumulative water deficits (where evapotranspiration exceeds precipitation) normally develop by midsummer even in the north-eastern US where

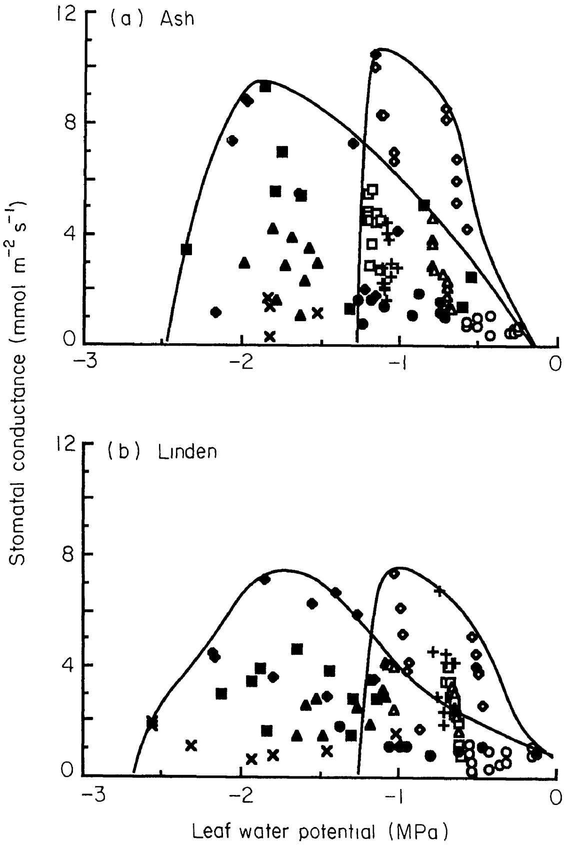

Fig. 6. Relationship between leaf water potential and stomatal conductance for in-ground and well watered potted trees during the 1984 growing season. The curves are hand drawn to show the boundaries between in-ground and potted trees. Potted trees are denoted by month as follows: ○, May; □, June; △, July; ◇, August; +, September. In-ground trees are denoted as follows: ●, May; ■, June; ▲, July; ◆, August; ×, September.

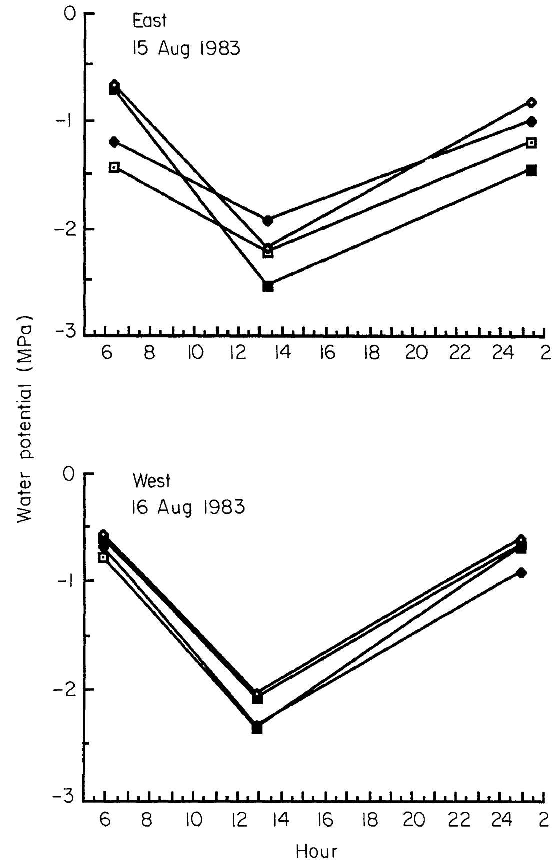

Fig. 7. Diurnal time course for leaf water potential, 15–16 August 1983. ——□——, irrigated ash; ——◆——, non-irrigated ash; ——■——, irrigated linden; ——◇——, non-irrigated linden.

summer rain occurs. It is therefore reasonable to expect that this deficit would be accentuated under urban conditions involving both reduced supply and increased demand. Seasonal declines in both maximum and minimum water potentials were observed, but not every year, and their magnitude was less than expected in comparison with trees in native stands. Baseline data for water stress in trees growing in natural stands are scanty, but published data for *Fraxinus pennsylvanica* show that minimum water potentials reached −2·0 MPa in old fields near Ithaca, NY (Bunce, Miller & Chabot 1977). For other native hardwood species (*Acer rubrum*, *Liriodendron tulipifera* and *Cornus florida*) growing in North Carolina, minimum water potentials declined from *c.* −1·1 MPa to *c.* −1·6 MPa between May and August (Roberts, Knoerr & Strain 1979). When compared with these reports from forest trees in the eastern US, the street trees in the present study did not appear to experience unusual water stress. For comparison, the deciduous oak, *Quercus douglasii* growing in California (a summer dry, Mediterranean climate) reached predawn water potentials of −0·4 (June), −0·7 (July), −1·5 (August) and −2·6 MPa (September) following a wet winter and declined from −0·9 to −3·7 MPa between June and September following a dry winter (Griffin 1973). If the normal summer depletion of soil water were aggravated by reductions in supply and increases in demand caused by the urban environment, tree performance might be expected to resemble this pattern. Though daytime conditions on Columbus Avenue sometimes resembled a Mediterranean summer, the development of water deficits over the season were far less severe than those occurring in California. The picture given by seasonal patterns of water potential is that seasonal declines occur, though not every year, and that these declines are not unlike those observed in native hardwood stands in eastern North America.

Though the majority of trees showed midday depression in August 1983, and individual trees showed midday depression in July and August 1985, these events were uncommon in the context of this study. Further substantiation for street trees' ability to maintain open stomata is provided by the 1984 comparison of in-ground and well-watered trees in pots.

This general lack of dramatic evidence for water deficits was unexpected. The weight of the evidence suggests that soil supply was generally not sufficiently limiting to prevent nocturnal recovery. When mid-

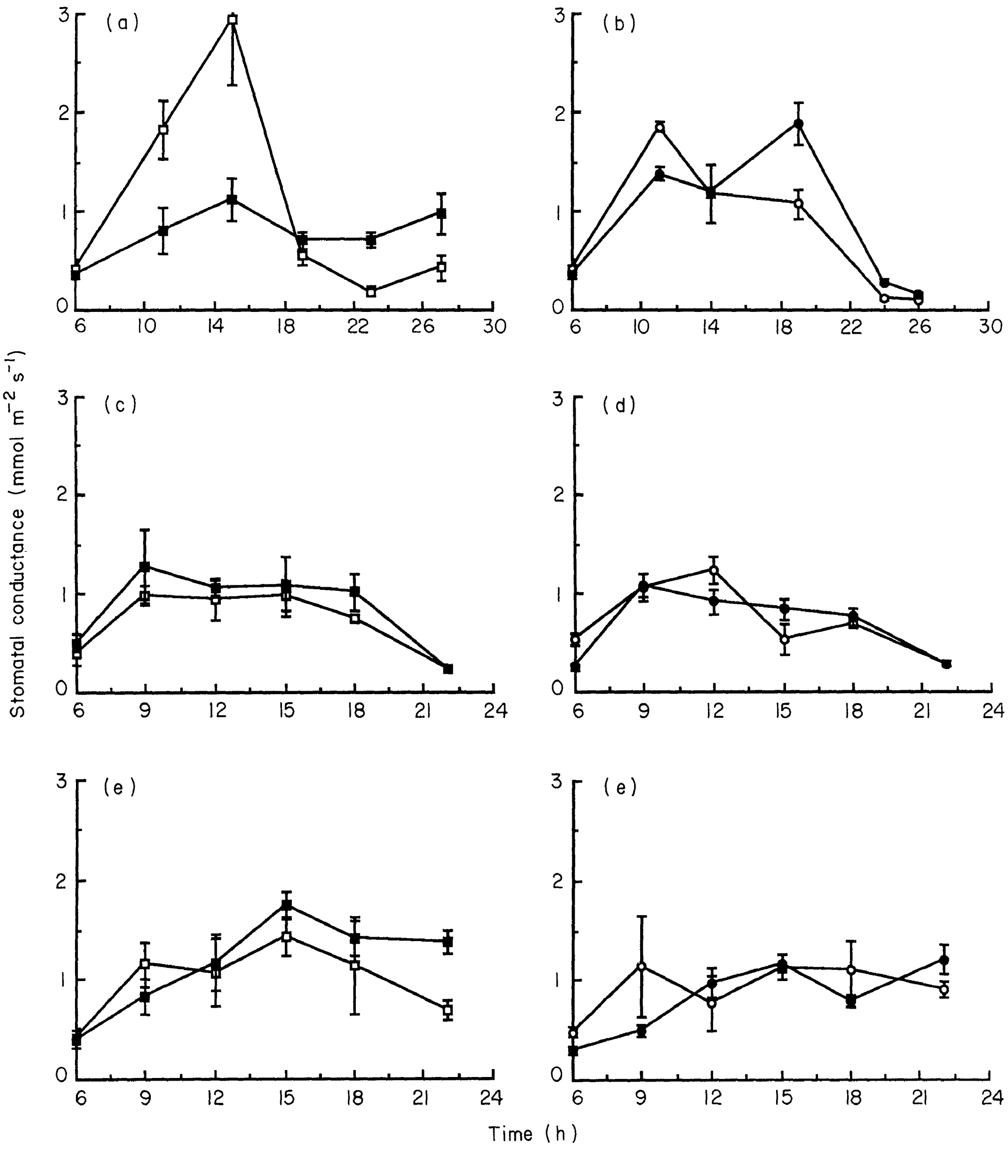

Fig. 8. Diurnal patterns of stomatal conductance showing varying degrees of stomatal closure: (a) 15 August 1983; (b) 16 August 1983; (c) & (d) 19 July 1985; (e) & (f) 20 August 1985. Plots are averages plus or minus one standard deviation. ——□——, ash on the east side; ——○——, ash on the west, ——■——, linden on the east side; ——●——, linden on the west.

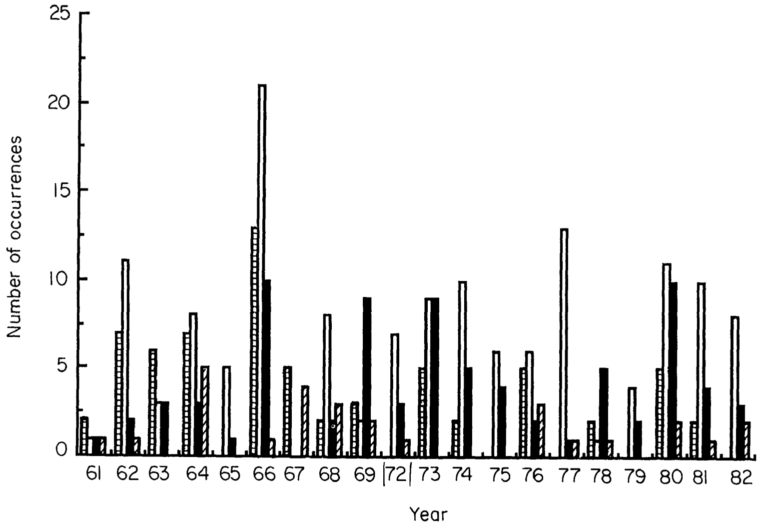

Fig. 9. Frequency of water stress type day conditions during the growing seasons for the years 1961–82. □, June; ▤, July; ■, August; ▨, September.

day depression was observed, it was apparently driven by high atmospheric demand such as during the August 1983 observations.

FREQUENCY OF WATER STRESS EVENTS

Symptoms of water stress do not prevail all the time and their occurrence will depend to a large degree on the weather. The 'water stress type day' is an empirical set of coincident weather conditions which correlate with observed water deficits in street trees. It must be emphasized that the type day characteristics are a first approximation which may not always correlate very precisely with tree water deficits. There are two reasons for caution. First, frequency of type days is sensitive to the selection criteria. A prior analysis (Whitlow & Bassuk 1988) using slightly more stringent temperature values resulted in a frequency of only 4·35% per season. Second, there is no way of knowing where the type day lies within a range of conditions which could cause water stress. For example, it is likely that less severe conditions could cause stomatal closure early in the growing season, especially if trees osmotically adjust over the season. However, because an extreme, late season observation (i.e. the most stringent observation) was chosen as the type day profile, the frequency estimate is probably conservative. To arrive at a more realistic predictor of plant water stress in the face of large between-year variation would require both a longer baseline and continuous monitoring of tree water status during the growing season.

SPATIAL VARIATION IN STREET TREE WATER STATUS

Given a simple east–west exposure difference on Columbus Avenue, the initial expectation was that the east side of the street would be hotter due to reflected and re-radiated energy during the afternoon when the air was already warm. Instead, because of the orientation of the street, the west exposure received more direct sun and had correspondingly higher maximum temperatures. Differences in VPD between the two sides of the street, however, were frequently negligible. Furthermore, there were frequently only modest differences between the street and Central Park. During type day conditions, however, the differences were extreme. In the Park, maximum temperatures were 9 °C cooler, maximum VPDs 5·5 kPa lower and minimum vapour pressures 0·75 kPa above those of the street. Given the proximity of the street site to the Central Park observation station, it is reasonable to expect that both sites would be influenced by the same air mass and should therefore have similar vapour pressures (Campbell 1977). Observations from this study indicate that small-scale spatial variation in atmospheric water content is at times dramatic in the urban habitat, most likely because of the radically different surface areas contributing water vapour to the atmosphere. Therefore, data from standard meteorological observation stations may not pertain to the urban street regardless of proximity. Without a baseline study to cross-tabulate street conditions with the observation site, official observations would be unreliable as aids for scheduling street tree irrigation or other purposes (Johnson, Bell & Sipp 1975).

INTERSPECIFIC VARIATION IN WATER BALANCE

Both species observed in this study are currently favoured for urban plantings in the north-eastern United States, in part because they have proven successful in urban areas (Kozel, Jansen & Hettel 1978). It is particularly interesting, then, that this study suggests that Marshall's seedless ash and little-leaf linden have somewhat different stomatal conductances. Under street conditions this difference was not absolute, but both potted and in-ground trees under a wide variety of street conditions showed that ash had higher conductances and hence greater transpiration rates than linden. This difference is also apparent under controlled laboratory conditions and is expressed most markedly when soil water begins to be limited (T.H. Whitlow, unpublished). Other studies have also shown that *Fraxinus* species have higher stomatal conductances than species occurring in the same habitat. For example, during an imposed drought, *Fraxinus americana* maintained higher conductances than *Ulmus americana*, *Acer rubrum*, *A. saccharum*, and *Cornus florida* 4–16 days after watering (Davies, Kozlowski & Pereira 1974). On a continuum of drought avoidance to drought tolerance (Kozlowski 1976; Levitt 1980), linden tends to avoid drought (maintaining lower transpiration rates and higher water potentials) while ash tends to avoid drought (sustained transpiration rates despite decreasing water potentials). From the standpoint of selecting and improving cultivars for urban use, both water-balance strategies could have a place in urban habitats and artificial classifications of plant response to water stress may not be especially useful as screening tools. At the level of intraspecific selection, there is a need to develop an ideotype which includes the ability to maintain carbon uptake in the face of high evaporative demand.

RESPONSE OF TREES TO IRRIGATION

Supplying in-ground ash trees with 18·9 l (5 gal) of water per week throughout the 1983 growing season resulted in slightly higher conductances and slightly more negative midday water potentials while irrigated linden showed no response. However, neither of these differences was statistically significant.

In all likelihood, the amount of water supplied in this study was far below both potential and actual weekly transpirational demand experienced by the trees. In practice, irrigation of street trees is rare, logistically difficult to accomplish, and is often discounted as unfeasible given the enormous demand by each tree. For example, Vrecenak & Herrington (1984b) calculated that $31\,\mathrm{h}^{-1}$ would be required by a tree with crown radius of 2 m, leaf area index of 4 and transpiration rates of $1{\cdot}67 \times 10^{-6}\,\mathrm{g}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (comparable to the trees in this study). At this rate, the supplements used in this study would supply 6 h of transpiration under the model assumptions of these workers. Increasing the crown radius to 3 m reduces the supply to 2·7 h of transpiration. While the Columbus Avenue study cannot assess the duration of the effect of irrigation, indications are that the effects of minimal irrigation last less than 1 day.

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