THE EFFECT OF TREES ON SUMMERTIME BELOW CANOPY URBAN CLIMATES: A CASE STUDY BLOOMINGTON, INDIANA

by C.A. Souch and C. Souch

Abstract. The objective of this study is to quantify the effects of trees in a Midwest urban area on air temperature and humidity to determine if the effects are significantly different for: different species of trees, trees of the same species in different environments, and whether the effects can be explained by physical characteristics of the individual trees. Replicate trees in each of five categories were studied: sugar maple, pin oak and walnut individuals over grass, sugar maple individuals along streets over concrete, and sugar maple clumps over grass. All the trees show a consistent effect: *temperatures are reduced and humidities are elevated under* the canopies. The greatest cooling effect (0.7 - 1.3°C) occurs *in the early afternoon. The difference between species is* insignificant, but street trees are significantly less effective in reducing temperature than either individual trees or clumps planted over grass. The clumps had no greater effect than the individual trees. The amount of cooling observed in this study was considerably less than that documented in many previous studies. No consistent linear relationships were determined between physical characteristics of the trees, such as leaf area index, and temperature reductions or humidity increases.

It is commonly observed that daily summer temperatures in urban areas are warmer (2 -5°C) than in their rural surroundings (2), a phenomenon referred to as the "urban heat island". In high latitude cities with cooler weather, heat islands can be an asset, but in mid and low latitude cities this results in increased electricity demand (for air conditioning), poorer air quality and human discomfort, especially in the summertime (6,9,11). One strategy that has been proposed to help overcome this is the strategic planting of trees, which it is argued will help lower summer temperatures (1,10). Trees can provide relief from high temperatures at two spatial scales. First, at the microscale through a direct shading effect, whereby incoming solar radiation is intercepted by the canopy and may be either absorbed or reflected. Second at the local scale through evaporative cooling, where energy is used for *transpiration rather than heating the surface and* the air. Trees act as a cool, moist surface dominated by larger scale warmer, drier surroundings (13). In the afternoon and evening the amount of energy needed to support the high evapotranspiration rates may exceed that which can be provided by incoming radiation, thus energy is derived from the sensible heat of the atmosphere and advection of this heat occurs toward the tree causing atmospheric cooling (8).

The impact of trees in urban areas on the microscale, below-canopy climate has been the subject of a number of studies. Preliminary measurements from suburban Sacramento in neighborhoods with mature canopies indicate daytime air temperatures 3 - 6°F (1.7 - 3.3°C) lower than in areas with no trees (16). An average, summer daytime temperature reduction of 6.4°F (3.6°C) has been documented in association with a large tree in Miami, Florida (14). Numerical simulations suggest that increasing tree cover by 25% in Sacramento and Phoenix would decrease summer temperatures by 6 - 10°F (3.3 - 5.6°C) (3). However, other studies show little or no effect on temperature within the urban canopy layer regardless of tree cover (7,9,15).

While general agreement exists that trees should bring about cooling, there remain many unanswered questions concerning the magnitude of the effects of trees on the micro-climate of urban areas. For example in the United States, few data are available on the effects of trees for areas outside of the arid southwest. Furthermore questions remain about the effect of planting different species, in different spatial arrangements (clumps as opposed to individual trees), or in different locations within a city (streets, gardens, parks).

The objective of this study is to empirically investigate the effects of trees on summer-time air temperature, relative humidity and vapor pressure in a small urban area in the Midwest, USA. The specific objectives of the study are to evaluate:

i) The effects of different species of tree in the same environment (isolated trees over grass).
ii) The effects of trees of the same species in different environments.
iii) The relationship between physical characteristics of the trees i.e. radius of the tree, diameter at breast height (dbh), or leaf area index (LAI), and observed differences in temperature and vapor pressure.

The study provides empirical data on the effectiveness of different planting strategies and baseline information for the evaluation of numerical simulation models.

Materials and Methods

The study area. The measurements were conducted in Bloomington, Indiana (39°10'N, 86° 31'W), a typical mid-size city in the Midwest, USA, with an active tree planting program. Summertime throughout the Midwest is hot and humid, consequently air conditioning demand is high. The data for this study were collected during a 15 day period August 7 - 21, 1991 (inclusive). The measurement period was very typical for August, with maximum daily temperatures between 28 and 30°C, minimum temperatures 18 - 20°C, and average dew point temperature 18.2°C (12). Most days in the period were sunny without clouds. A few days had afternoon cumulus, and one day was uniformly overcast with heavy rain in the morning. Measurements were not conducted on this day.

Adult, well established, healthy trees were chosen for the study. Where possible ten similar trees (replicates) were identified and studied in each of the following categories:

1) *Acer saccharum* (sugar maple) individuals over grass
2) *Acer saccharum* individuals along streets (over concrete)
3) *Acer saccharum* clumps of trees over grass (3 or 4 trees define a clump)
4) *Juglans cinera* (black walnut) individuals over grass
5) *Quercus palustris* (pin oak) individuals over grass

Sugar maple, pin oak and walnut were chosen because they are relatively common and are actively being planted in urban areas of the Midwest. The three environments studied: individuals over grass, clumps over grass, and individuals along streets over concrete, are common niches for trees within urban areas. Because of problems of finding well matched trees only 7 pin oak and 7 sugar maple in clumps were studied. The replicates in each category, the 44 trees overall, represent a trade-off between logistical constraints of manually taking measurements (see below) and the desire to maximize the number of replicates of each species in each environment. All individuals over grass and the clumps of sugar maple were located on the campus of Indiana University, located in the center of Bloomington (Figure 1). The sugar maple individuals along the roadside were located along a downtown street, in close proximity to the University, with mixed commercial and residential use (Figure 1).

Field measurements. All trees were physically described by measuring height (using a hand-held clinometer), diameter at breast height (dbh), height of the base of the canopy, and the radius of the canopy to the dripline (Table 1). The leaf area index (LAI) of each tree was determined using a Licor LAI 2000 Plant Canopy Analyzer (PCA). The PCA estimates of LAI (Table 1) are lower than expected. As yet this technique has not been independently tested for isolated trees in urban areas, so the absolute values must be treated with caution. However, the LAI data obtained provide a basis for relative comparison between the trees studied.

Measurements were taken below the tree canopy, at a height of approximately 1.5 m, representative of the environment in which humans live. Wet and dry bulb temperatures were taken simultaneously at the edge of the canopy and under the middle of the canopy cover (half distance from trunk to dripline). The circuit to measure the trees took approximately 2 hours to complete. To remove the effects of day to day variability in synoptic conditions and measurement time, reference data from the IU climate station were collected. All below tree-canopy readings were compared to these reference data and differences

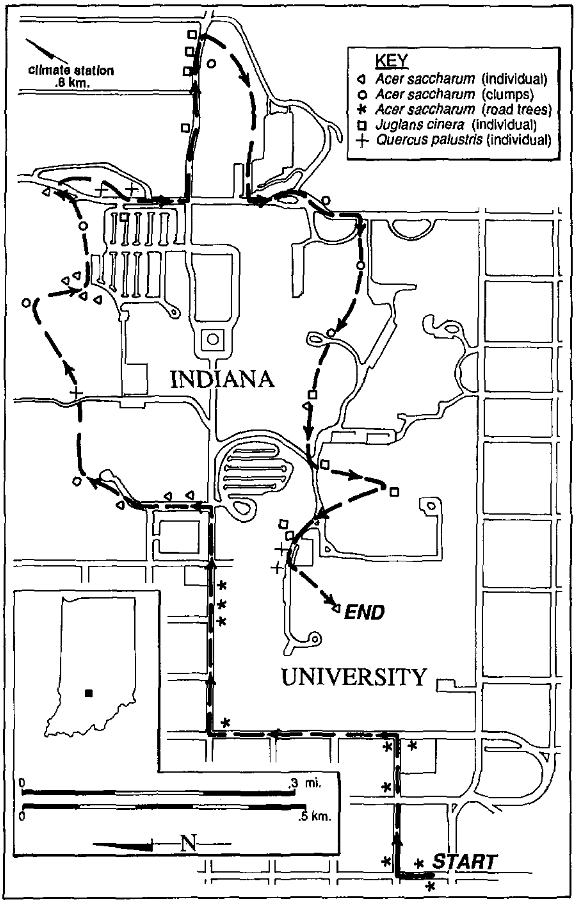

Figure 1: Location of each of the trees studied in relation to Indiana University, Bloomington, Indiana

between the open reference site and under the trees calculated. The IU climate station is located at the edge of the campus of Indiana University (Figure 1), at an open site over grass. Intercomparison of the instruments at the climate station and those used to study the trees showed combined systematic and unsystematic measurement errors on the order of the resolution of the instruments (temperature ±0.12 °C). Consequently the data were not adjusted.

Under the trees, temperature and relative humidity were determined using sling psychrometers, which measure wet (T_w) and dry (T_d) bulb air temperatures (°C). From these two temperatures actual (e_a) and saturation (e_s) vapor pressure (mb), and relative humidity (%) can be calculated:

formula $$e_a = e_s \frac{C_p}{EL_v} p(T_d - T_w)$$

where e_a is actual vapor pressure (mb), e_s is saturation vapor pressure (mb) calculated (5):

formula $$e_s = 6.112 \exp \frac{17.68 T_w}{T_w + 243.5}$$

C_p is specific heat of air at constant pressure (1010 J/kg/K), E is 0.622, the ratio of the molecular weight of water vapor to that of dry air, L_v is latent heat of vaporization (J /kg):

Table 1: Physical characteristics of the trees studied

		LAI# (m^2/m^2)		**dbh** (m)		**Ht of tree** (m)		**Radius*** (m)	
	n	*Mean*	*sd*	*Mean*	*sd*	*Mean*	*sd*	*Mean*	*sd*
Pin oak	7	3.71	0.84	0.83	0.13	22.83	3.6	7.68	2.27
Walnut	10	4.06	1.10	0.64	0.19	15.99	3.75	6.96	1.19
Sugar maple: individuals	10	4.35	0.54	0.49	0.17	15.34	2.97	5.33	1.33
Sugar maple: street trees	10	4.00	0.98	0.55	0.11	18.82	3.65	6.45	0.99
Sugar maple: clumps	7	3.99	0.50	0.59	0.11	18.74	2.21	-	-

see cautionary comments in text about absolute LAI values

* Rad - radius of the tree to the dripline; n sample size; sd standard deviation

$$L_V = 1.92846 \times 10^6 \, (T_d/(T_d - 33.91))^2$$

with T_d dry bulb temperature (K), and p atmospheric pressure (mb). Relative humidity (%) can then be calculated:

$$RH = (e_a/e_s) \times 100$$

Relative humidity is strongly inversely correlated with temperature because of the temperature dependence of the saturation vapor pressure (e_s). For this reason, in the subsequent analysis, actual vapor pressure (e_a) is also considered to investigate the effect of the trees on the vapor content of the atmosphere.

Results are grouped into three times of the day: early morning (0700 - 0900 LAT); midday/early afternoon (1200 - 1400 LAT); and late afternoon-early evening (1700 -1900 LAT). Four or five sets of readings for each time of day were taken over the 15 day period. Thus there are 24 - 50 measurements for each category of tree at each time of day, 614 observations in total.

Results and Discussion

The average temperatures, relative humidities and vapor pressures, and their standard errors for each species of tree, in each environment, for each time of day (morning, midday, early evening) are presented in Tables 2, 3 and 4. From these tables comparisons between trees in terms of the absolute readings should be undertaken with cau-

Table 2: Temperatures (°C) below trees and deviations from reference site for morning, midday and evening measurement periods.

	Pin Oak	Walnut	Sugar maple Individual	Sugar maple Clump	Sugar maple Street trees
Morning:					
Sample size	30	50	50	35	50
Average temperature					
Mid-canopy	22.7 (0.31)	22.9 (0.21)	21.7 (0.25)	22.2 (0.27)	20.2 (0.28)
Edge canopy	23.0 (0.33)	23.3 (0.03)	22.0 (0.26)	22.5 (0.30)	20.4 (0.30)
Reference site	22.1 (0.27)	23.0 (0.21)	21.8 (0.21)	22.1 (0.30)	19.5 (0.28)
Average deviation					
Mid-canopy	-0.6*(0.11)	0.1 (0.09)	0.1 (0.01)	-0.1 (0.02)	-0.7*(0.01)
Edge canopy	-0.9*(0.13)	-0.3*(0.10)	-0.2*(0.02)	-0.4*(0.02)	-0.9*(0.01)
Midday					
Sample size	30	50	50	35	50
Average temperature					
Mid-canopy	28.0 (0.49)	28.0 (0.38)	27.6 (0.37)	27.4 (0.44)	27.9 (0.39)
Edge canopy	29.0 (0.25)	28.7 (0.58)	28.3 (0.16)	28.7 (0.25)	28.2 (0.18)
Reference site	28.7 (0.27)	28.9 (0.14)	28.5 (0.21)	28.7 (0.18)	27.8 (0.14)
Average deviation					
Mid-canopy	0.7*(0.20)	0.9*(0.11)	0.9*(0.14)	1.3*(0.14)	-0.1 (0.16)
Edge canopy	0.3 (0.24)	0.2 (0.14)	0.2 (0.15)	0.0 (0.20)	-0.4*(0.16)
Evening					
Sample size	24	40	50	30	40
Average temperature					
Mid-canopy	27.0 (0.16)	26.6 (0.19)	27.1 (0.17)	26.9 (0.18)	28.4 (0.17)
Edge canopy	27.1 (0.31)	27.0 (0.19)	27.4 (0.20)	27.0 (0.19)	28.5 (0.15)
Reference site	26.9 (0.15)	26.2 (0.25)	27.0 (0.28)	26.8 (0.22)	27.8 (0.13)
Average deviation					
Mid-canopy	-0.1 (0.16)	-0.4*(0.10)	-0.1 (0.08)	-0.1 (0.18)	-0.6*(0.11)
Edge canopy	-0.2 (0.18)	-0.8*(0.10)	-0.4*(0.08)	-0.2*(0.13)	-0.7*(0.11)

( ) standard error
* indicates statistically significant difference (T-test, significance level 0.95)

Table 3: Relative humidity (%) below trees and deviations from reference site for morning, midday and evening measurement periods.

	Pin Oak	Walnut	Sugar maple Individual	Sugar maple Clump	Sugar maple Street trees
Morning:					
Sample size	30	50	50	35	50
Average relative humidity					
Mid-canopy	72 (0.60)	89 (0.44)	91 (0.44)	90 (0.52)	93 (0.41)
Edge canopy	71 (0.63)	88 (0.07)	89 (0.41)	89 (0.49)	91 (0.35)
Reference site	79 (0.77)	76 (0.64)	80 (0.64)	80 (0.65)	84 (0.42)
Average deviation					
Mid-canopy	7.0 (6.44)	-12.7* (0.41)	-10.7* (0.38)	-10.7* (0.37)	-9.3* (0.32)
Edge canopy	8.4 (6.32)	-11.9* (0.35)	-9.2* (0.40)	-9.6* (0.42)	-6.8* (0.31)
Midday					
Sample size	30	50	50	35	50
Average relative humidity					
Mid-canopy	79 (1.52)	79 (1.53)	79 (1.10)	79 (1.34)	80 (1.03)
Edge canopy	77 (0.85)	79 (1.32)	78 (0.58)	81 (0.68)	77 (0.53)
Reference site	50 (1.15)	49 (0.92)	50 (0.85)	48 (1.01)	53 (0.78)
Average deviation					
Mid-canopy	-29.1* (0.53)	-29.8* (0.40)	-29.3* (0.41)	-30.0* (0.41)	-27.2* (0.44)
Edge canopy	-27.3* (0.55)	-29.3* (0.48)	-27.5* (0.45)	-33.0* (0.49)	-24.0* (0.38)
Evening					
Sample size	24	40	50	30	40
Average relative humidity					
Mid-canopy	78 (0.80)	79 (0.38)	78 (0.47)	79 (0.68)	75 (0.44)
Edge canopy	77 (0.56)	78 (0.49)	76 (0.90)	77 (0.98)	74 (0.51)
Reference site	47 (1.27)	49 (1.07)	46 (0.99)	47 (0.93)	43 (0.51)
Average deviation					
Mid-canopy	-31.3* (0.90)	-30.0* (0.68)	-32.3* (0.50)	-32.3* (0.57)	-32.1* (0.28)
Edge canopy	-30.0* (0.90)	-28.8* (0.72)	-30.2* (0.51)	-30.4* (0.70)	-31.0* (0.30)

( ) standard error
* indicates statistically significant difference (T-test, significance level 0.95)

tion because the readings were not undertaken simultaneously (see comments above). The average deviations between the trees and the reference "open" site and standard errors also are presented in Tables 2, 3 and 4. In all cases the below tree reading was subtracted from the open "reference" reading. Thus a positive deviation indicates the open reference site had a higher reading, a negative deviation the measurement under the tree was higher. T-tests were conducted to determine the statistical significance of the differences between the trees and open site. Significant differences (confidence level 95% or greater) are indicated in the Tables with an asterix.

The effects of trees. Morning temperatures under all of the other trees were close to the reference site (0.7°C warmer to 0.1°C cooler) (Table 2). By midday all trees are significantly cooler than the open site by the order of 0.7 - 1.3°C (Table 2). The notable exception is the street trees, which in the middle of the day are only slightly cooler on average (0.1°C). In the evening it is slightly warmer under all the trees, significantly so under the sugar maple street trees and walnut (0.4 - 0.6°C). The warming in the evening is likely due to the reduced sky view factor under the trees: longwave radiation emitted by the ground to the tree is reflected, absorbed and re-emitted back to the ground.

The midday reductions in temperature under the trees in this study, while statistically significant, are lower than those documented in previous studies. However, this reduced effect is to be expected. Bloomington is located further north than the previous study sites (Sacramento, Phoenix, Miami, etc). Consequently solar radiation is lower, and the trees would be expected to have less of a shading effect. More importantly, the humidity in the Midwest is much greater than the southwest, resulting in reduced vapor gradients and evaporative cooling.

Relative humidities were statistically higher under all the trees than at the open site (Table 3), except for pin oak in the morning. Relative humidity was highest in the morning, due to the combination of lower temperatures and the evaporation of dew. Through midday and evening, relative humidity under the trees was 27-33% greater than at the open site.

The absolute level of vapor pressure at all sites decreased through the day (Table 4). Most evaporation (as opposed to transpiration) occurs in the morning when solar radiation is coming from a low sun angle and there is dew on the surface which can be readily evaporated. By midday evaporation of soil and grass moisture decreases as less than 20% of the incoming solar radiation may penetrate the canopy (13). Vapor pressure continues to decrease in the late afternoon-early evening as evaporative demand induces the trees' stomata to close. Vapor pressure is greater at the open site in the morning. The difference by the middle of the day becomes significantly greater below the trees and remains so through the

Table 4: Vapor pressure(mb) below trees and deviations from reference site for morning, midday and evening measurement periods.

	Pin Oak	**Walnut**	**Sugar maple** Individual	**Sugar maple** Clump	**Sugar maple** Street trees
Morning:					
Sample size	30	50	50	35	50
Average vapor pressure					
Mid-canopy	16.4 (1.64)	20.1 (0.01)	19.7 (0.28)	19.8 (0.37)	19.2 (0.20)
Edge canopy	17.2 (1.32)	19.7 (0.05)	19.7 (0.31)	19.4 (0.40)	18.6 (0.21)
Reference site	21.1 (0.33)	21.6 (0.28)	20.9 (0.28)	21.2 (0.36)	19.3 (0.28)
Average deviation					
Mid-canopy	4.7*(1.55)	1.5*(0.09)	1.2*(0.11)	1.4*(0.17)	0.1 (0.16)
Edge canopy	3.9*(1.46)	1.9*(0.13)	1.2*(0.11)	1.8*(0.15)	0.7*(0.11)
Midday					
Sample size	30	50	50	35	50
Average vapor pressure					
Mid-canopy	19.7 (0.66)	19.6 (0.52)	19.9 (0.47)	19.8 (0.58)	19.9 (0.38)
Edge canopy	19.9 (0.65)	19.6 (0.56)	19.8 90.42)	19.5 (0.50)	19.5 (0.38)
Reference site	19.3 (0.66)	19.4 (0.50)	19.3 (0.50)	19.2 (0.59)	19.3 (0.35)
Average deviation					
Mid-canopy	-0.4*(0.15)	-0.2 (0.11)	-0.6*(0.17)	-0.6*(0.15)	-0.6*(0.16)
Edge canopy	-0.6*(0.20)	-0.2 (0.17)	-0.5*(0.17)	-0.3 (0.21)	-0.5*(0.17)
Evening					
Sample size	24	40	50	30	40
Average vapor pressure					
Mid-canopy	18.0 (0.26)	18.1 (0.16)	18.0 (0.16)	18.1 (0.09)	17.4 (0.14)
Edge canopy	17.4 (0.16)	17.5 (0.14)	17.3 (0.14)	17.9 (0.25)	17.0 (0.12)
Reference site	16.5 (0.15)	16.6 (0.13)	16.4 (0.21)	16.5 (0.11)	16.0 (0.08)
Average deviation					
Mid-canopy	-1.5*(0.20)	-1.5*(0.13)	-1.6*(0.11)	-1.6*(0.13)	-1.4*(0.11)
Edge canopy	-0.9*(0.18)	-0.9*(0.11)	-0.9*(0.13)	-1.4*(0.24)	-1.0*(0.13)

( ) standard error
* indicates statistically significant difference (T-test, significance level 0.95)

evening.

Conditions at the edge of the tree canopy. Higher temperatures are observed at the edge of the canopy than under the middle of the tree (Table 2). Where significant cooling occurs under the tree in the middle of the day, no such effect is observed at the edge of the canopy (Table 2). At all times of the day the conditions at the edge of the street trees are warmer than the reference site. However, this is to be expected given that the reference site is located over grass and the street trees grow over concrete.

Very similar results are observed both under the tree and in the middle of the tree for relative humidity and vapor pressure (Tables 3 and 4), i.e. moisture is significantly enhanced around, not just under the tree. In general, there is greater variability at the edge of the canopy (greater standard errors, see Tables 3 and 4). These results suggest that there is a marked gradient away from the trees, and the edge is less affected by shade and more by small scale advection of heat.

Effects of tree species. In terms of deviations from the refernce site, in the morning, under the middle of the canopy, pin oaks are significantly warmer than both sugar maple and walnut (Table 5), and the reference site. A distinguishing feature of pin oak is the drooping of their lower branches toward the ground, which may reduce overnight long-wave radiative losses from under the canopy. In contrast, Sugar maple has a longer trunk, with branches that extend straight out, thus there should be a greater movement of air through the canopy, reducing the temperature. By midday/early afternoon there are no significant differences between the species (Table 5a). By evening walnut and sugar maple are significantly different, with walnut warmer on average, although neither of the two species is significantly different from pin oak.

In terms of relative humidity and vapor pressure, all the trees are significantly different from one another in the morning (Table 5a). Walnut and

Table 5: Results of T-tests to assess the statistical significance of differences between measurements:

a) Comparison of different species in the same environment (individual trees over grass)

	Walnut: Individual				**Pin oak: Individual trees**			
Sugar maple: Individual								
	T	**RH**	**Ea**		**T**	**RH**	**Ea**	
Morning	0.66	4.98*	2.57*	n=50	4.72*	2.69*	2.36*	n=30
Midday	0.30	1.51	0.81	n=50	1.31	0.51	0.88	n=30
Evening	3.39*	4.39*	1.01	n=40	0.28	0.04	0.79	n=24\
Walnut: Individual								
Morning					5.81*	3.19*	2.07*	n=30
Midday					1.93	1.37	1.26	n=30
Evening					1.27	2.35	0.91	n=24

b) *Comparison of one species in different environments*: Sugar maple

	Sugar maple: Clumps				**Sugar maple: Street trees**			
Sugar maple: Individuals								
	T	**RH**	**Ea**		**T**	**RH**	**Ea**	
Morning	0.16	1.95	1.75	n=50	5.99*	4.54*	9.07*	n=35
Midday	0.99	2.71	1.03	n=50	3.98	4.96*	0.53	n=35
Evening	1.26	1.02	0.70	n=40	3.24	0.26	1.25	n=30
Sugar maple: Clumps								
Morning					3.40*	5.40*	11.02*	n=35
Midday					3.24	6.06	1.66	n=35
Evening					4.52	0.61	1.17	n=30

T - temperature, RH - relative humidity, Ea vapor pressure, n - sample size
* indicates statistically significant difference (T-test; significance level 0.95)

sugar maple have different relative humidities in the evening (as with temperature) but no difference in vapor pressure, indicating the difference in relative humidity is likely an artifact of a temperature control.

Trees of the same species in different environments. Differences between environments are more significant than between species in the same environment (compare Tables 5a and 5b). In terms of mid-canopy temperature, trees growing along streets are warmer than trees growing alone or in clumps. By evening, the street trees are approximately 0.5°C warmer (Table 2). At this time the surrounding concrete may be reflecting and re-emitting radiation back onto the trees resulting in higher temperatures. There are no significant differences between the clumps and individuals.

The vapor pressures below the canopy in all three environments are remarkably similar (Tables 4 and 5). The street trees are consistently lower, although only significantly so in the morning, probably due to the absence of evaporation of dew from grass. In the morning and evening, vapor pressure is less variable under the street trees than in the other environments, a pattern indicative of more uniform stress for all the street trees. The pattern of relative humidity largely reflects (inversely) the pattern of temperature. It is highest under street trees in the morning then decreases as temperature rises, even though the moisture content of the air (vapor pressure) is increasing. By evening it decreases, despite decreasing temperatures, as a consequence of changes in vapor pressure.

Correlation of effects with physical characteristics of the trees. Linear correlations were determined between the temperature and vapor pressure reductions for each time period and physical characteristics of the trees (dbh, LAI, and radius of the tree to dripline). Firstly for each of the five classes of tree separately, and secondly for all the trees together (Table 6). Caution should be exercised in interpreting the first set of results because of the small sample size.

No consistent significant correlations were determined between temperature reduction under the trees and their physical characteristics. The only significant correlations were with LAI for sugar maple clumps in the morning, and sugar

Table 6: Linear correlation coefficients (r) between average temperature and vapor pressure deviations and selected physical characteristics of the trees.

	n	LAI			dbh			Radius		
		am	mid	ev	am	mid	ev	am	mid	ev
(a) Temperature deviations										
Pin oak	7	0.81	0.66	0.82	-0.04	0.50	0.17	0.41	0.20	0.40
Walnut	10	0.62*	0.17	0.35	0.33	-0.20	0.24	0.47	0.26	0.41
Sugar maple: ind	10	0.05	0.09	0.40	0.39	-0.05	0.10	0.40	0.28	-0.14
Sugar maple: st	10	0.61	0.69*	0.26	0.27	0.20	0.06	0.24	0.47	0.51
Sugar maple: clmp	7	0.80	0.17	0.17	-	-	-	-	-	-
All trees combined	44	0.22	0.03	0.12	0.04	-0.08	0.14	0.04	-0.02	0.32
b) Vapor pressure deviations										
Pin oak	7	0.20	0.20	0.52	0.37	0.37	0.57	0.17	0.17	-0.09
Walnut	10	0.62*	-0.17	0.35	0.33	0.20	0.24	0.47	0.26	0.41
Sugar maple: ind	10	0.17	0.53	0.49	0.14	0.09	0.49	0.26	0.37	0.35
Sugar maple: st	10	0.14	-0.03	0.04	0.67*	0.36	0.17	0.57	0.26	0.57
Sugar maple: clmp	7	0.64	0.71	0.71	-	-	-	-	-	-
All trees combined	44	0.09	0.01	0.13	0.12	0.28	0.04	0.21	0.10	-0.06

n = sample size, LAI = leaf area index, dbh = diameter at breast height, Radius = radius of crown to dripline, ind = individual trees, st = street trees, clmp = clumps, am = morning period, pm = early afternoon, ev =early evening (see text for details).
* significant at 0.95 level

maple street trees in the middle of the day. The only significant correlations for vapor pressure were with LAI for walnut in the morning. These results suggest that factors such as the exact location of the tree are more important than physical characteristics of the tree, at least in the urban situation, in determining the microclimate under a tree canopy.

Summary and Conclusions

The objective of this study was to quantify the effects of trees in urban areas on temperature and humidity to determine if the effects are different for different species of trees, trees of the same species in different environments, and whether the effects could be explained by physical characteristics of the individual trees.

All the trees show a consistent effect on the microclimate in terms of temperature and humidity: temperatures are reduced and humidities are elevated under the canopies. There was a smaller effect at the edge of the canopy. The greatest cooling occurs in the early afternoon. Overall, the difference between the species is insignificant. However, street trees are significantly less effective in cooling than either individual trees or clumps planted over grass. Humidities are higher under the trees than in the open. They show a gradual decrease in difference through the day, as the trees become stressed and stomata close. No simple relationship was determined between temperature reduction and physical characteristics of the trees, such as leaf area index, of the trees. Clumps of trees have no greater effect on the microclimate than individual trees.

The results indicate that in terms of minimizing site-specific temperatures within urban areas the best strategy is to plant any of the tree species either as individuals or clumps over grass. Although street trees do bring about cooling in the middle of the day, the effects are lesser and not significant when compared to open grass temperatures. Obviously the temperatures over concrete, in streets, are elevated and the cooling effect of the street trees is not truly documented here.

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School of Biological and Molecular Sciences,
Oxford Brookes University
Oxford, OX3 0BP, England,
and
Department of Geography,
Indiana University,
Indianapolis, IN, 46202, USA

Résumé. L'objectif de cette étude est de quantifier l'influence des arbres sur la température et l'humidité des zones urbaines du Centre des États-Unis (Midwest américain). Plus spécifiquement, c'est de déterminer si les effets sont significativement différents dans le cas de différentes espèces d'arbres et de celui d'arbres de même espèce mais dans des environnements différents, et si ces effets peuvent être expliqués par des paramètres des arbres individuellement pris. Tous les arbres montrèrent des effets logiques et conséquents, soient la réduction des températures et l'augmentation de l'humidité relative sous le couvert. L'effet maximal de refroidissement (1.5 à 2.0°C) se produit tôt en après-midi. La différence entre les espèces est insignifiantes, mais les arbres de rues sont significativement moins efficaces que leurs homologues plantés sur des surfaces gazonnées. Le refroidissement observé lors de cette étude est considérablement inférieur à celui reporté lors d'études antérieures. L'humidité de l'air est supérieure sous les arbres qu'à l'extérieur de ceux-ci, mais une décroissance graduelle de cette différence est observée au cours de la journée au fur et à mesure que l'arbre devient stressé et que les stomates se referment.

Zusammenfassung. Ziel dieser Studie ist es, die Wirkung von Bäumen eines Stadtgebietes im mittleren Westen auf die Temperatur und Feuchtigkeit zu quantifizieren. Besonders galt es, zu bestimmen, ob die Effekte signifikant unterschiedlich sind für; verschiedene Baumarten, Bäume der gleichen Art in verschiedenen Umgebungen, und ob diese Effekte anhand von physikalischen Parametern der einzelnen Bäume erklärt werden kann. Alle Bäume zeigten einen übereinstimmenden Effekt: die Temperaturen sind reduziert und die relative Luftfeuchte ist angehoben unter dem Kronendach. Der größte Abkühlungseffekt (1.5 - 2.0°C) ereignet sich am frühen Nachmittag. Der Unterschied zwischen den arten ist nicht signifikant, aber Strassenbäume nehmen weniger Einfluß auf ihre Umwelt als Bäume, die über Gras gepflanzt sind. Der in dieser Studie untersuchte Kühlungseffekt ist wesentlich geringer als bei vielen früheren Untersuchungen. Unter Bäumen ist die Luftfeuchtigkeit höher als im Freien, nimmt aber während des Tages allmählich ab, wenn der Baum Stress ausgesetzt ist und seine Stomata schließt.