TREES IN DIFFICULT SITES[1]

by Thomas H. Whitlow and Nina L. Bassuk

Abstract. Urban trees are thought to come under frequent water stress due to limited water supply and high evaporative demand. A three-year study of street trees in New York City suggests that soil water was not limiting to recently planted street trees and that periods of high demand are common, though infrequent. These findings underscore the need for research in tree physiology under urban conditions. Basic research will yield a more accurate picture of the urban tree habitat than will extrapolation from study conducted under non- or simulated urban conditions. Results from field research will provide an objective foundation for selection and management guidelines.

Key Words: Physiological ecology, urban horticulture, urban forestry, street trees, tree water relations, amenity trees.

A factorial approach to stress in the urban environment. This report provides an example of how we identify factors potentially limiting to tree growth in an urban environment, using as a case study the water balance of street trees in New York City. Details will be reported elsewhere. Two concepts need to be introduced at the outset. The first is the now-familiar People Pressure Disease (PPD), coined by Tattar (1980) to dramatize the complex and inter-related environmental and biological stresses a tree sustains in the urban habitat. Though useful because it forces recognition of complexity, too often this notion is used as a substitute for knowledge. For example, it is invoked to indicate that problems of urban trees are beyond science and non-researchable. This is an unfortunate situation which inhibits identification of causal relationships, promotes development of dogma, and ultimately interferes with problem identification and solution.

The second concept is perhaps less familiar to this audience but it deserves the attention of anyone dealing with plants in complex environments. Formally titled *A Functional, Factorial Approach to Plant Ecology* (Major, 1951), this paper argues that vegetation is the product of climate, soil parent material, topography, organisms, and time. Through a series of examples, Major illustrates how a researcher can isolate and quantitatively evaluate these various factors in relation to plant community development. With appropriate modifications to fit the system of interest, the concept is readily adapted to a species, an agricultural crop, or an individual plant. The central point is this: *given plants as dependent variables,* appropriate *independent variables in the environment can be identified* and studied in relation to plant performance. The advantages of this approach include: 1) explicit recognition of potential causal relationships; 2) quantitative evaluation of both site limitations and plant responses; 3) operational definitions of conditions which enable others to repeat or reinterpret the work. Clearly, too, the approach is experimental and thus begins with an unknown, but suspected, relationship between two variables and ends with either a confirmation or negation of these suspicions. Regardless of outcome, the end product is a better understanding of the system.

Water as a factor limiting tree growth and survival. Water is generally recognized as the major factor limiting the growth and survival of trees throughout the world (Kozlowski, 1982; Walter, 1973). It is therefore not surprising that many scientists and urban foresters rank drought or more generally, water stress, as one of the major problems encountered by urban trees (Berrang and Karnosky, 1983; Foster, 1978; Foster and Blaine, 1977; Gerhold et al., 1975; Green, 1980; Genetics Working Group, 1982; Roberts, 1977; Spirn, 1981; Staby, 1981; Steiner, 1980; Tattar, 1980; Wilson, 1977). Temporary water deficits occur in nature even with adequate soil moisture whenever *atmospheric demand* exceeds the *rate of supply* from the soil (Hinckley et al., 1978). These temporary deficits result from resistances in the transpiration stream through the soil-plant-atmosphere continuum (SPAC). Deficits are often apparent at midday when demand is highest and are alleviated in the late afternoon and evening when demand slackens. Though not lethal, temporary deficits impair virtually all plant

---

1. Presented at the annual conference of the International Society of Arboriculture in San Antonio in August 1986.

growth processes (Hsiao, 1973) and may lead to secondary injury resulting from high temperature via reduced transpirational cooling or by predisposing the plant to disease (Schoenweiss, 1978, 1981, 1982). Aside from this brief treatment, we will not detail water relations of trees here. The interested reader is referred to several recent reviews for a thorough discussion (Hinckley et al., 1978; Jones et al., 1985; Kaufmann, 1981; Kozlowski, 1982; Turner, 1986).

If water deficits are ubiquitous, why, then, should they be especially significant to urban trees? Approaching the problem as one of supply and demand, it is readily apparent that cities have an unusual hydrologic cycle. On the supply side, precipitation falls on surfaces which are predominantly paved, so runoff rather than infiltration is the rule. This runoff is channeled away from sites where soil recharge could occur via a network of gutters and sewers. In this manner, groundwater and subsurface runoff are also intercepted, further reducing the available store of soil water. What water is in the soil may not be able to move very rapidly, owing to compaction and soil textural properties which contribute to decreased hydraulic conductivity. In addition, the amount of soil actually available to a tree as a reservoir may be quite small due to below-ground obstructions or the more obvious restrictions of raised containers.

On the demand side, cities are frequently warmer than open countryside (Landsberg, 1970; Oke et al., 1980). At the microsite level, radiation loads on a tree crown may be elevated because of reflection and re-radiation from buildings and pavement. All these factors increase leaf temperature and thereby increase transpiration demand. Too, the absolute humidity can be lower in a city which will also increase the demand. Finally, wind can be channelized and redirected around buildings, creating zones of increased velocity which also aggravates demand. Thus, in the urban habitat it is reasonable to suppose that water supply is limited and demand is increased, leading to more extreme and more frequent deficits. This is the conventional wisdom, yet we have only a limited number of studies to judge how broadly this scenario applies (Christensen and Miller, 1979; Potts and Herrington, 1982; Vrecenak and Herrington, 1984).

A Case Study

During the 1983, '84, and '85 growing seasons, we observed the water relations of a cohort of 20 street trees on Columbus Ave. in New York City. We set out explicitly to document frequency and severity of water deficits, the atmospheric conditions correlating with these events, and spatial variation in microclimate related to exposure. Tree performance was assessed by diurnal monitoring of leaf water potential, transpiration, and leaf temperature. Atmospheric water demand was monitored using a portable weather station and data logger.

Columbus Ave. is typical of the wide streets running SW-NE for the length of Manhattan. Buildings along the seven-block study area on the Upper West Side were 5-7 stories high, so the setting is a shallow urban canyon. We selected this site because it had a definite east-west exposure, two tree species (green ash, *Fraxinus pennsylvanica* 'Marshall's seedless' and littleleaf linden, *Tilia cordata* 'Greenspire'), and was recently planted. Trees were therefore reachable from the ground, and the site was close to an official weather monitoring station in Central Park.

We made a total of 16 diurnal observations over the three growing seasons, including five on a nearby north-south exposure on 72nd St. This relatively small number of samples was mandated by the logistics of conducting research at a site remote from Cornell. We could not leave equipment on site in our absence; weather stations required round-the-clock supervision even though they were automated. In addition to the "guard," observations of 20 trees as frequent as every three hours required a minimum of two people, preferably three. We operated on two 12-hour shifts, so a minimum of six workers was required for each sample period.

We observed tree water deficits once out of the 16 observations. This deficit occurred during the second of two consecutive days of observations in August 1983 and was characterized by partial stomatal closure during the midday period when leaf water potentials fell below −2.0 MPa (Fig. 1). The atmospheric demand, or vapor pressure deficit, at canopy level was exceptionally high during this period due to two contributing factors. The temperature maximum was 41°C (106°F) and the minimum relative humidity was 12% (Fig. 2). The low relative humidity was in part due simply to the high temperature. This does not account entirely for the low value, however. Also contributing was the low *absolute humidity*, or the amount of water vapor in the air.

It is apparent that the street environment can be more severe than that of a nearby open area. Central Park registered a maximum temperature of 32°C and a minimum relative humidity of 38% during the observation period. Absolute humidity on the street was up to 10.6 g m^{-3} below that of Central Park.

These atmospheric conditions were exceptional in our study, as indicated by the synopsis of vapor pressure deficits (Fig. 3). Is this a sampling artifact or are water deficits exceptional for New York City? To explore this question, we used Central Park data to generate a profile of prevailing weather conditions likely to result in high evaporative demands on the street. We then searched the meteorological records for the June through August periods from 1972 to 1981. This analysis revealed a total of 40 occurrences of the "type

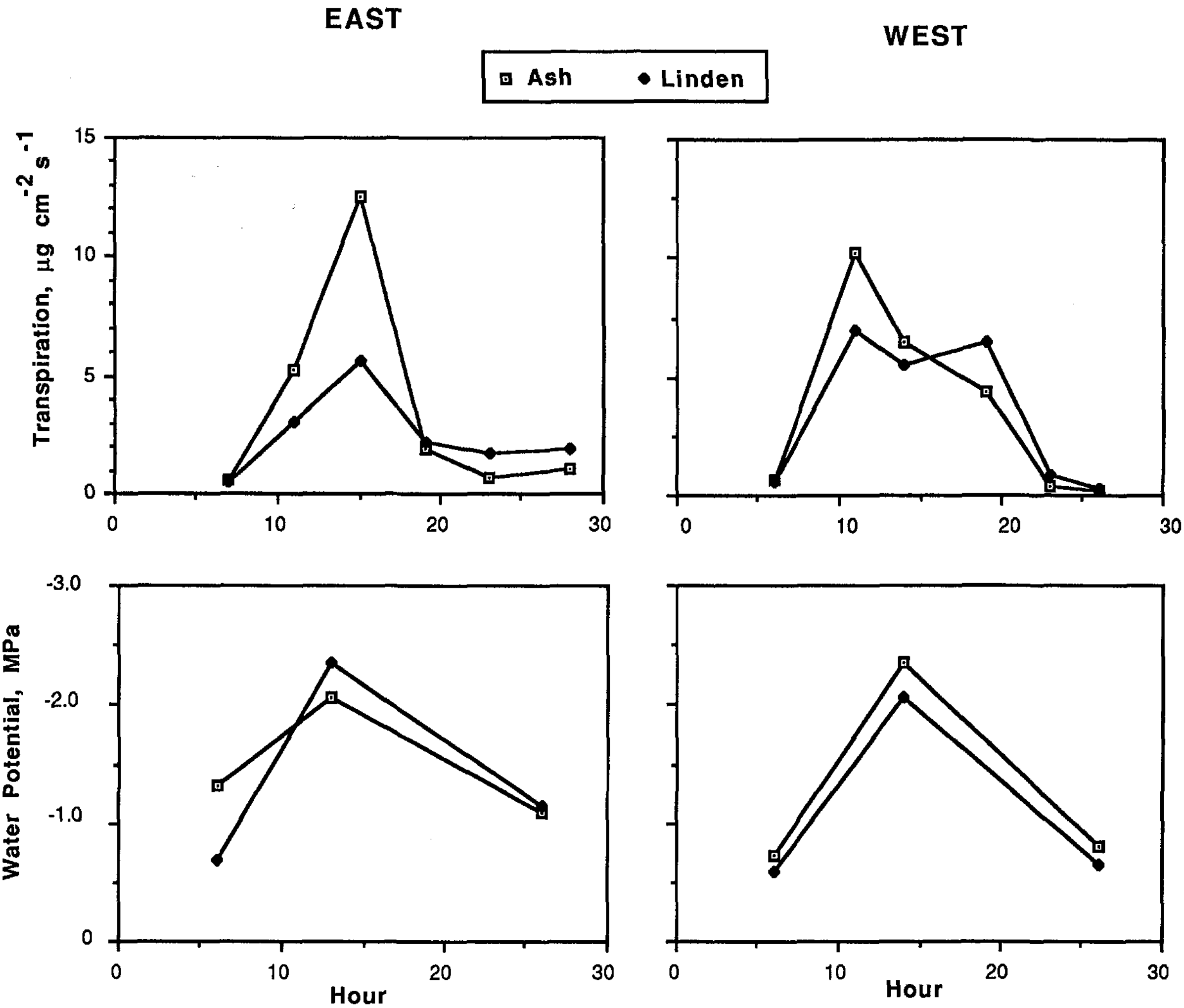

Figure 1. Average diurnal transpiration and water potential for 20 in-ground street trees on Columbus Ave., 15 August (east side) and 16 August (west side), 1983.

day" during this time period, or 4.35% of the total. Type days occurred every year except 1979 and occurred a maximum of eight times in 1977.

In addition to differences in microclimate between Central Park and Columbus Ave., there are also exposure-related differences in the street environment. Our east/west measurements occurred on consecutive days in 1983, so temperature and relative humidity data are not directly comparable on a quantitative basis. However, the broad patterns were observed many times during the course of the study. The west exposure receives 3-5 hours per day more direct solar radiation than the east exposure, with the west side receiving morning sun and the east side receiving afternoon sun (Fig. 4). This is due to the N 30° E bearing of the street; building heights were the same on both sides where the monitoring stations were located. Had the street been oriented due north-south, the east side would still lag behind the west in receiving direct solar radiation but the total radiation received should be equal.

Surface temperatures show a diurnal pattern similar to solar inputs (Fig. 5). Leaves are generally the coolest surfaces measured, staying close to air temperature. Car roofs are the hottest surfaces, with temperature frequently in excess of 50°C (122°F). Car roofs cool quickly when the sun drops behind the buildings, probably owing to their low thermal mass. In contrast, massive ob-

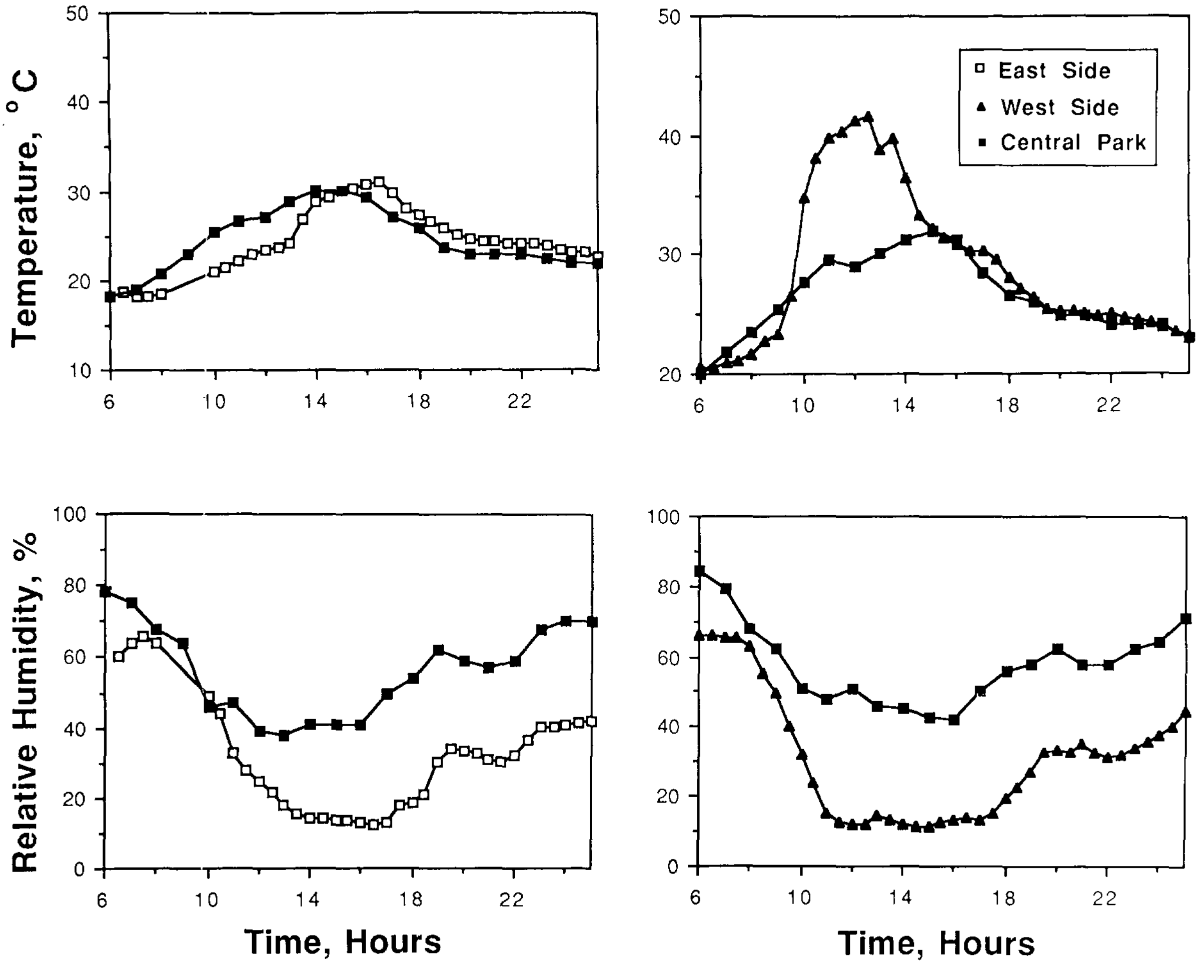

Figure 2. The atmospheric environment at the level of the lower canopy on Columbus Avenue compared with official observations from Central Park, for August 15-16, 1983.

jects like buildings and asphalt pavement cool slowly, re-radiating heat long into the evening.

The minimum average pre-dawn leaf water potential was −1.07 MPa, while the minimum average midday value was −2.41 MPa. Both these observations occurred during the August 1983 sampling. There was frequently a 1.0 MPa difference between pre-dawn and midday water potentials but we nearly always saw recovery to maximum values by late evening. No seasona decrease in maximum potentials was observed.

It is apparent that the 1984 season was relatively mild in terms of evaporative demand (Fig. 3). During 1984, we brought containerized trees of the same species as the in-ground trees to provide a comparison with well-watered material. Both in-ground and containerized plants showed similar transpiration rates, but in-ground trees generated more negative midday water potentials. This suggests that though in-ground trees were under more stress on an absolute level, they were still able to maintain high transpiration rates. We also have an indication that ash and linden have different water economies. Frequently ash had higher transpiration rates. Studies presently underway in a controlled environment growth chamber support this field observation.

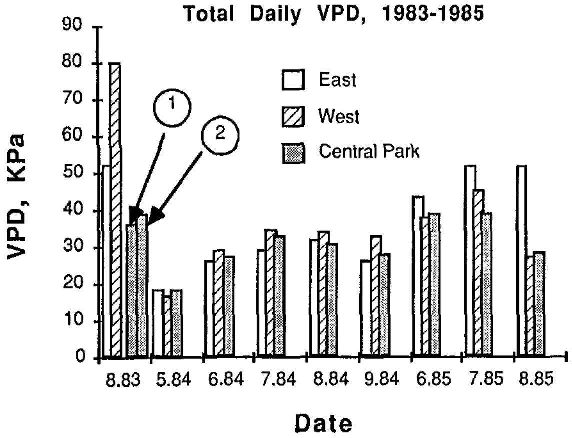

Figure 3. Total daily vapor pressure deficit for Columbus Ave. and Central Park for days during which tree water balance was monitored, 1983-1985.

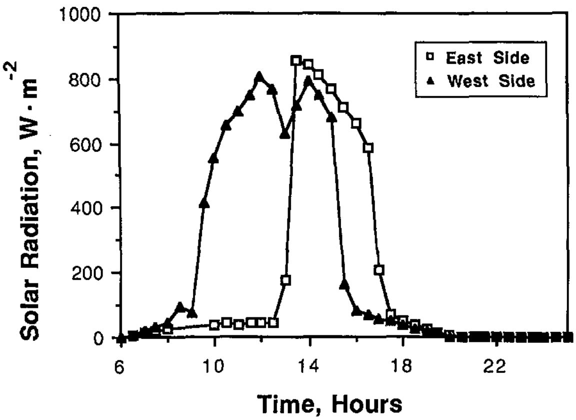

Figure 4. Diurnal pattern for solar radiation received by the eastern and western exposures of Columbus Avenue during late summer.

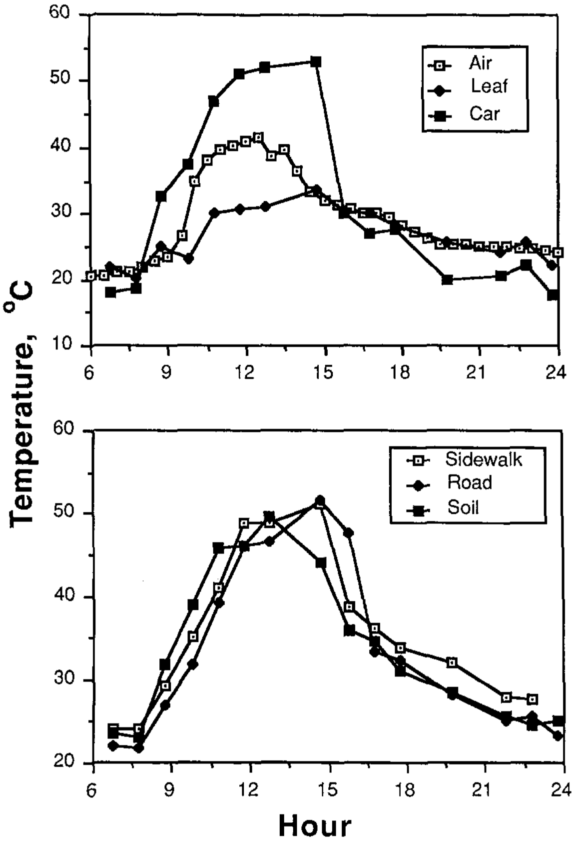

Figure 5. Diurnal temperature fluctuations for leaves and selected environmental surfaces on Columbus Avenue, August 16, 1983.

Discussion

Our findings are contrary to some of our expectations. Most obvious is the low frequency of water stress events in Columbus Ave. street trees. This should not be misinterpreted: though they occur infrequently, water deficits are *common* in the sense that they occur an average of four times each summer.

Also surprising is the indication that soil water is not limiting. We infer this from the facts that trees recovered to pre-dawn water potentials, did not show a seasonal decrease in pre-dawn water potential, and maintained high transpiration rates despite relatively low midday water potentials. Others have made qualitative observations that soil water frequently is not limiting for street trees (Karnosky, 1985, citing Perry, 1982) but ours are the first field data indicating the relative contributions of supply and demand to street tree water balance.

We have several explanations for the apparently adequate water supply in soils on Columbus Ave. The first is that it is not a supply phenomenon at all, but rather that the trees we observed had small enough leaf areas that soil water is adequate to meet the demand placed on the canopies. If this is the case, we would predict that water deficits would become more severe and more frequent as leaf area increases. This hypothesis has obvious implications for frequency estimations. To provide some context, average leaf area in the October 1983 season was 9.4 m^2 and the trees were 5-6 m tall. These trees were planted in 1982 and were thus in their establishment period throughout our study. With relatively large leaf areas and possibly limited root systems, these trees may have been even more susceptible to water stress than established trees. Reports of post-transplanting survival list drought as the prime cause of mortality (Foster, 1978a&b; Foster and Blaine, 1978). At present, we think that our estimates of "drought" frequency (as interpreted to mean high atmospheric demand) should be taken as a lower limit.

The second explanation is that the pavement provides more access to water than we frequently assume. There are many cracks, both accidental and planned, and as pavement ages these become more numerous and increasingly pervious to water. Buildings may act as rain collectors and funnel water into expansion joints at the junction with the sidewalk.

Thirdly, underground sewers may leak or trees may have roots which penetrate the sewers. These last two explanations would be difficult to document directly without detailed engineering studies outside the usual scope of urban horticulture. A more feasible alternative would be to install relatively invulnerable access holes for a neutron probe or gamma probe and then follow soil water status beneath the pavement for several growing seasons.

While leaf temperatures track air temperature, we observed no temperatures over 40°C even when air temperature reached this level. In all probability, this is not a lethal tissue temperature. This is not to say that higher temperatures were not reached somewhere in the canopy, however. Higher transpiration rates in ash suggest the possibility that ash can cool its leaves better than linden under high demand conditions where soil water is non-limiting. It is also interesting to consider leaf temperature data with temperatures of other environmental surfaces. Car tops are not only the hottest surfaces measured, they are also the surfaces closest to the tree canopies. Changing the thermal characteristics of materials used to construct buildings and streets is impractical. Is it more realistic to restrict parking under small street trees to times when solar radiation is less intense? Perhaps even this is too radical a suggestion to put forth seriously, but it is an indication of the kind of relationships that we can expect to find through systematic study of the urban habitat. At the very least we can begin to suggest design specifications for tree lawns and median strips so that trees are not subjected to intense heat from car roofs.

Conclusions

Serious scientific study of plant problems peculiar to urban areas is relatively new. We need to be especially careful not to be dogmatic at this stage because the foundation for research is still incomplete; there are unique possibilities to either lead or *mis*lead. We need to exercise caution in interpreting results of studies and not overlook the significance of apparently negative findings. For example, some published reports maintain that urban conditions promote water stress in trees even though the results indicate high plant water potentials, transpiration rates, and reasonably normal environmental conditions. Let us not be so eager to generalize that we obscure results interesting in their own right. The first goal of our studies should be accurate description, not perpetuation of strongly held beliefs, no matter how logical they appear. This mandates the use of quantitative methods and explicit hypothesis testing wherever possible so that complex results may be interpreted in light of the questions being asked.

The second goal should be cumulative understanding. We should strive to build on previous work and leave the stage ready for the next step. If we merely cite conventional wisdom that urban sites are stressful, it is not long before we lose sight of the limited experimental foundation from which some of our generalities originate and accept them as undisputed truth. When we abandon critical observation, real problem solving and advances in understanding both cease.

Environmental stresses facing urban trees, complex and severe as they may be at times, are not necessarily unique. Rather, they should be viewed as a subset of a larger range of environmental conditions affecting the physiological responses of trees. Researchers dealing with urban trees need to take a basic approach to street tree problems. We need to draw on the literature and research models of plant physiology, ecology, forestry, and pomology, and then be certain to relate our findings to the broader context of tree physiology.

There is also a need for operational definitions of what we mean by "difficult," "stressful," and other qualitative terms which are often used to describe urban conditions. These may have no unique definition which applies to all cities and all species, but at least within the scope of individual studies we should strive for operationality so that others may interpret the work.

People Pressure Disease as a concept sets before us the challenge of unraveling a complex of maladies affecting the growth and survival of urban trees. It is a problem statement, not a problem solution. We have a tool for slicing this Gordian Knot, however. By taking a factorial approach to the problem, we can sequentially understand the relationships among the environmental factors, set priorities, and arrive at practical solutions.

Literature Cited

1. Berrang, P. and D. F. Karnosky. 1983. Street Trees for Metropolitan New York. New York Botanical Garden Institute of Urban Horticulture. Cary Arboretum, Millbrook, New York.
2. Christensen, T. W. and D. R. Miller. 1979. Sap flow in honeylocust (*Gleditsia triacanthos* L.) on urban stress sites. Final Report, U.S. Forest Serv. N.E. Exp. Sta. Project FS-NE-1651.
3. Foster, R. S. 1978. *Bio-engineering for the urban ecosystem.* Metro. Tree Improvement Alliance (METRIA) Proc. 1:13-17.
4. Foster, R. S. and J. Blaine. 1978. *Urban tree survival: trees in the sidewalk.* J. Arboric. 4:14-17.
5. Genetics Working Group. 1982. Genetic improvement and urban trees. A problem analysis for environmental forestry research. USDA Forest Serv. NE/NA, Broomall, PA.
6. Gerhold, H. D., A. J. Long, and M. E. Dermitt. 1975. *Genetic information needed for metropolitan trees.* J. Forestry 73:150-153.
7. Green, B. C., Jr. 1980. Comments reported in Metro. Tree Improvement Alliance (METRIA) Proc. 2:38.
8. Hinckley, T. M., J. P. Lassoie, and S. W. Running. 1978. Temporal and spatial variation in water status of forest trees. Forest Sci. Monog. 20.
9. Hsiao, T. C. 1973. *Plant response to water stress.* Ann. Rev. Plant Phys. 24:519-570.
10. Jones, H. G., A. N. Lakso, and J. P. Syvertsen. 1985. *Physiological control of water status in temperate and subtropical fruit trees.* Hort Reviews 7:301-344.
11. Karnosky, D. F. 1985. Abiotic stress of urban trees. **In**: D. F. Karnosky and S. L. Karnosky (eds.), Improving the quality of urban life with plants. Proc. Internat'l. Symp. on Urban Hort. June, 1983. New York Botanical Gardens.
12. Kaufmann, M. R. 1981. *Development of water stress in plants.* HortScience 16:34-36.
13. Kozlowski, T. T. 1982. *Water supply and tree growth. Part I. Water deficits.* Forestry Abstracts 43:57-95.
14. Landsberg, H. E. 1970. Micrometereological temperature differentiation through urbanization. Urban Climates World Meteorological Organization Tech. Note 108. Geneva, Switzerland.
15. Major, J. 1951. *A functional, factorial approach to plant ecology.* Ecology 32:392-412.
16. Oke, R. T., B. D. Kalanda and D. G. Steyn. 1980. *Parameterization of the heat storage in urban areas.* Urban Ecology 5:45-54.
17. Potts, D. F. and L. P. Herrington. *Drought resistance adaptations in urban honeylocust.* J. Arboric. 8:75-80.
18. Roberts, B. R. 1977. *The response of urban trees to abiotic stress.* J. Arboric. 3:75-78.
19. Schoenweiss, D. T. 1978. *The influence of stress on diseases of nursery and landscape plants.* J. Arboric. 4:217-225.
20. Schoenweiss, D. T. 1981. *The role of environmental stress in diseases of woody plants.* Plant Disease 65:308-314.
21. Schoenweiss, D. T. 1982. Environmental stresses in

disease predisposition. **In**: B. O. Parks (ed.), Urban and Suburban Trees: Pest Problems, Needs, Prospects, and Solutions. Proc. Conf. held April 18-20, 1982. Michigan State Univ. East Lansing.
22. Spirn, A. W. 1984. *Design for survival.* Arnoldia 44:29-36.
23. Staby, G. 1981. *Water stress on plants.* Metro Horticulture 16:1-3.
24. Steiner, K. C. 1980. *Developing tree varieties for urban soil stresses.* Metro. Tree Improvement Alliance (METRIA) Proc. 3:57-69.
25. Tattar, T. A. 1980. *Non-infectious diseases of trees.* J. Arboric. 6:1-4.
26. Turner, N. C. 1986. *Adaptation to water deficits: a changing perspective.* Aust. Jour. Plant Phys. 13:143-160.
27. Vrecenak, A. J. and L. P. Herrington. 1984. *Estimation of water use of landscape trees.* J. Arboric. 10:313-319.
28. Walter, H. 1983. Vegetation of the Earth. Springer-Verlag, Berlin.
29. Wilson, C. L. 1977. *Emerging tree diseases in urban ecosystems.* J. Arboric. 3:69-71.

Department of Floriculture
and Ornamental Horticulture
Cornell University
Ithaca, New York 14853

Abstracts

PETROVIC, A.M. 1986. **Approaches to correcting soil compaction.** Grounds Maintenance 21(1):96,98,100.

Soil compaction comes from three primary sources. On recreational turfs, foot traffic is the primary cause. On many other sites, however, vehicular traffic may be the villain. To a lesser degree, the impact of droplets from rain or irrigation can compact the soil, a fact that can be important during seedling establishment. Compaction can be a problem on newly constructed sites where large, heavy equipment with poor weight distribution has been used during the soil preparation. In most cases, however, compaction is a greater problem after establishment. There are numerous approaches to correcting compacted soil conditions: 1) reduce the amount of traffic, 2) change the traffic pattern, 3) partially modify the soil, 4) completely modify the soil, 5) cultivate, 6) use chemical amendments and 7) use other approaches.

REINERT, J.A. 1986. **How insecticides work.** Grounds Maintenance. 21(1):90-91.

To be effective, insecticides must contact or penetrate the insect's body. Although the exact mechanism of penetration is not completely understood, it is known that most organic insecticides easily pass through the cuticle and body wall of the insects. Other avenues of entry are ingestion or gaseous intake through the spiracles and tracheae of the respiratory system. The most important consideration in understanding the toxicity of a pesticide is the inability of the insect's nervous system to tolerate even the briefest disruption. Tampering with a system that regulates such vital functions as breathing and heartbeat has fatal consequences. Chemicals that act briefly on other tissues have relatively little effect on the insect, unless they directly affect the functioning of the nervous system. Insecticides, depending upon the type, act primarily upon the mechanisms of transmission in the nervous system.