INFLUENCE OF WATER STRESS AND RESTRICTED ROOT VOLUME ON GROWTH AND DEVELOPMENT OF URBAN TREES[1]

by Donald T. Krizek and Stephen P. Dubik

Abstract. Water stress and restricted root volume pose serious constraints to the successful establishment and maintenance of urban trees, especially in planters, median strips, and other confined spaces. This article describes factors influencing growth of plants in containers, summarizes major problems involved in growing plants in a restricted root volume, and compares the effects of water stress and root restriction on the morphology and physiology of plants. The importance of various stress interactions on plant growth and development in the urban environment is also discussed. Recommendations are given for possible genetic, cultural, and physiological approaches for enhancing plant growth in restricted root volumes and ameliorating the effects of environmental stress and for future research needs.

Water stress and restricted root volume are two of the most serious constraints to the successful establishment and maintenance of urban trees, especially in confined spaces such as in planters, along curbs, and in median strips (7, 142). Because of these and other urban stresses, the life span of trees in the city is relatively short.

Numerous studies have been carried out to determine the effects of root restriction on herbaceous plants (17, 18, 19, 76). The effects of water stress in the growth and development of forest trees are also well described (66, 71, 72, 74, 95, 106, 109). However, relatively little research has been conducted on the effects of water stress on trees growing in an urban environment, in containers, and other confined spaces (37, 111, 151).

The purpose of this article is to review some of the important considerations involved in the selection of urban trees for container plantings. Six topics are covered: a) factors influencing growth of trees in containers; b) major problems encountered in growing plants in a restricted root volume; c) comparative effects of water stress and root restriction; d) stress interactions; e) approaches to enhancing growth in containers and reducing environmental stress; and f) needs for further research.

Factors influencing growth in containers. Many factors influence successful growth of trees in containers. These include plant material; type, size, and shape of container; depth, volume, and color of container; type of medium; exposure and site; frequency of watering and fertilizing; time of transplanting; and prior treatment (e.g., whether or not the plants have been root pruned prior to transplanting) (3, 11, 29, 37, 46, 49, 51, 58, 61, 71, 84, 93, 125, 138, 146, 147, 157, 158, 159, 160, 161, 163, 164, 168).

If plants are pruned to maintain a proper balance between root and shoot growth as in the culture of bonsai trees or grape vines (15, 107), they may live indefinitely in a restricted volume. In most urban settings, however, trees in planters must be replaced after several years (41). The balance between transpiration and absorption determines whether or not internal water stresses develop (33, 34). Species with high top-root ratios tend to have low survival rates when outplanted (71). The root-shoot imbalance created by transplanting is one of the primary causes of transplanting shock with other physiological and pathological problems acting as secondary agents. Until the natural root-shoot balance of the tree is restored, some degree of transplanting stress will exist (153).

A well-branched root system is essential for effective water and nutrient uptake in containers (139, 140, 154). The distribution of roots in the soil is determined by both genetic and environmental conditions (35, 65, 86). Because of restrictions imposed by container walls, limited growth medium, and high water holding capacity of the medium, root growth of trees in containers differs from that in the field (61, 132).

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Some tree roots are able to grow in containers of any size and shape (8, 9). Others do better in a particular shape or configuration, depending on the nature of their root system (10, 16, 27, 43, 51, 61, 62). Red oak trees grown in containers that have a relatively low diameter to depth ratio outgrow those in containers with higher ratios (63).

Containers currently on the market for growing tree seedlings were developed primarily for the forest industry (50, 51, 104, 147, 152). Conventional containers, such as clay or plastic pots, are unsuitable for growing tree seedlings. They tend to cause poorly formed root systems, which later impede growth and survival of the trees.

Site and exposure are critical factors in the successful establishment of urban trees. Trees located close to the street are more likely to suffer from water deficits than those located in unpaved areas because of the intense amount of heat reradiated from parked cars and pavement and lower absolute humidity of paved sites (T. H. Whitlow, 1986, personal communication). Paved sites also frequently experience low oxygen exchange and high CO_2 levels. Trees that constantly get dessicated from high winds or frequently get waterlogged often develop abiotic leaf scorch (45) and are more likely to succumb to dieback. Street trees also experience salt damage from excess Na and Cl ions (30, 31, 56, 83, 155) which can be relieved to some extent by application of gypsum (5, 31, 116).

The average survival rate for sidewalk trees is about 10 years (41). Construction damage and altered, unsuitable environments left after construction are two of the main reasons for the poor survival rate of urban trees (39, 41). Available soil used in urban sites is often of poor quality, pH is frequently excessively high, and landfill gases are often present in toxic levels (39). The disturbed nature of urban soils with fill, concrete, refuse, and other artificial factors and different degrees of compaction, makes it difficult to draw any generalizations as to soil properties of a site (7).

Major problems in container growing. Various problems can arise from prolonged confinement of woody plants in a restricted root volume (48, 51, 107, 108, 119, 127). These include root distortion, girdling, and in extreme cases, even strangulation and death of the plant (48, 96). Water stress is one of the most serious problems experienced by container-grown plants and may occur from either an excess or deficit of water (67, 69, 73, 74, 90, 136, 137). Because of a perched water table, trees in planters frequently become waterlogged and experience aeration problems (132). These problems may be partly avoided by providing adequate drainage and a porous soil mix (131, 133). Other problems commonly encountered include compaction, deficiency and toxicity of nutrients and accumulation of soil gases (1, 40, 53, 94, 96, 97, 98, 99, 114, 117, 124, 125, 134, 143, 150, 167, 170).

Comparative effects of water stress and root restriction. Since plants grown in confined root volumes are frequently subjected to water stress, it is difficult to know how much of the reduction in growth is caused by drought or excess water and how much is caused by root restriction (2, 17, 18, 19, 89, 100, 112, 113, 149, 156). Under natural conditions, it is difficult to answer this question because plants are seldom irrigated frequently enough during the day to eliminate water deficits. In the greenhouse and growth chamber, however, the effects of these two stresses have been separated by use of an automatic watering system (75).

The results of greenhouse and growth chamber studies indicate that the physiological effects of water stress and restricted root volume may be quite different from one another even though the morphological responses may be similar (76). When soybean plants were subjected to water stress or root restriction, restricted root volume had little or no effect on the rate of leaf initiation or photosynthesis. In contrast, water stress greatly reduced both rate of leaf initiation and photosynthesis. Under both water stress and root restriction, branching of the shoot and total plant dry matter accumulation were greatly reduced (76). Root/shoot ratio was increased in water-stress treated plants but was unaffected by root restriction. These studies have been extended to tomato (M. S. Ruff et al., unpublished) and Euonymus (S. P. Dubik et al., unpublished) with similar results.

Stress interactions. Research is needed to identify the most common urban stresses and to evaluate the comparative tolerances of different species and cultivars to specific stresses (82). Greater plant diversity is possible if trees are selected for tolerance to stresses at a specific site, rather than for tolerance to all urban stresses (7). Many municipalities and private companies maintain computer inventories of their tree plantings. However, these systems are usually oriented toward management rather than research. Consequently, biologically important parameters such as soil moisture, soil type, and nutrient content, are often excluded as site characteristics.

The phenomenon of cross-protection in woody (68, 91, 92, 126) and herbaceous plants (77, 78, 110) is well known. Several workers have shown that trees subjected to low temperature (68, 91, 126) or flooding (68, 92) prior to SO_2 fumigation, were less damaged by SO_2 than were unstressed control plants. Krizek et al. (77, 78) observed similar protective effects of water stress and temperature pretreatment against SO_2 injury in selected herbaceous species.

One of the ways in which drought, flooding, low temperature, salinity, and air pollution appear to provide cross protection is by increasing the level of abscisic acid (ABA) in the plant; this in turn closes the stomates and reduces water loss through transpiration (12, 77, 144).

Root restriction has an adverse effect on hormone metabolism in the plant. Since plant hormones such as cytokinins and gibberellins are synthesized in the root system (20, 128, 129, 148), one of the primary ways in which root restriction may suppress plant growth is by altering the synthesis and/or transport of these substances in the plant.

Plants subjected to prolonged periods of drought, flooding, salt damage, and other environmental stresses are frequently predisposed to attack by insects and invasion by various disease causing organisms (21, 55, 57, 70, 85, 103, 115, 120, 121, 122, 123, 166) and may exhibit either biotic or abiotic leaf scorch (45). For example, elm trees subjected to drought or soil compaction are more likely to succumb to Dutch elm disease than unstressed trees. Similarly, sweet gum trees grown in water-logged or compacted soils are likely to be more vulnerable to canker than unstressed trees (R. Hammerschlag, 1986, personal communication). Although quantitative data are generally lacking, empirical observation indicates that the effects of drought, flooding, transplanting shock, extreme temperature fluctuation, or compaction may have significant additive effects in reducing lifespan of urban trees, particularly if they occur for prolonged periods.

Approaches to enhancing growth in containers and reducing stress effects. A multidisciplinary approach is required to establish and maintain a successful planting of urban trees. This will necessitate enlisting the assistance of persons trained in horticulture, landscape architecture, agronomy, soil science, genetics, plant physiology, and plant pathology. By utilizing various genetic, cultural, morphological, and physiological approaches, one can greatly enhance the growth of trees in a restricted root volume and increase the chances for survival under urban stress.

One of the most important needs is to make a careful site assessment. This should include a thorough study of exposure, climate, size, area usage, history of the site (e.g., type of land fill), drainage conditions, and physical and chemical properties of the soil (e.g., type, pH, electrical conductivity of the soil solution, prior pesticide use). If plants are balled and burlapped, prior knowledge of their cultural conditions may be helpful.

Species and cultivars should be chosen that have wide, shallow, and highly branched roots because deep-rooted plants, with little branching, are much less adaptable to container growing (8, 9). Since container volume rapidly becomes restricting to root growth, slow growing plants should be chosen over rapidly growing species and cultivars (47). Cultivars tolerant to air pollutants, salt damage, drought, waterlogging, extreme cold, and other urban stresses should be selected wherever possible (22, 59, 60, 70, 130). The Metropolitan Tree Improvement Alliance (METRIA) has served as a clearinghouse for information on selecting trees for urban landscapes since 1973 (42, 60).

Cultural approaches include the use of appropriate media and amendments, addition of mulch, installation of an automated irrigation system, selected pruning during drought to reduce water loss, and possible application of antitranspirants. Ideally, native soil should be used. If too many amendments are added, the soil may act like a sponge reducing aeration and causing flooding injury (96). If trees or long-lived shrubs are to be grown in containers, a high proportion of humus in the mix should not be used. Once the humus is decomposed by soil bacteria and fungi, and disappears finally as carbon dioxide, the soil subsides and becomes compact causing aeration problems (37). Chances for survival are greatest if plants are transplanted while they are still relatively small, and if the size of the root ball is large in relation to plant size (7). Inoculation with mycorrhizae may also be needed when tree seedlings are outplanted (169).

Plant production practices at the nursery contribute to some of the problems involved in transplanting (135). If tree roots are pot bound, fracturing of the roots may be needed prior to planting. If trees are maintained too long in a restricted root volume, the roots may become girdled and root pruning may be necessary. Methods of handling trees in transit, storage, and at the planting site are also important in assuring survival. Plant losses may result from failing to soak the root ball (96). Excessive soil moisture and mounding of soil on roots in the nurseries also contribute greatly to tree losses during transplanting.

Physiological approaches include the use of plant growth regulators to inhibit shoot elongation and antitranspirants to reduce water loss (24, 25, 26, 71). The triazoles and other growth retardants are attractive as possible candidates for tailoring growth and increasing tolerance to urban stress (4, 6, 14, 32, 38, 54, 79, 80, 88, 141, 165). These compounds inhibit gibberellin and sterol biosynthesis, increase root branching, and have been found to be effective in providing protection against SO_2, drought, and other environmental stresses (38, 79, 80, 81). Increasing the Al concentration in the soil has also been shown to reduce shoot growth by causing dwarfing of the root system (13, 64), although this method is not recommended.

Research Needs

It is difficult to extrapolate from data obtained on trees growing in the forest to trees growing in an urban environment. Thus, in-depth studies are needed on urban trees to determine the morphological, physiological, and biochemical effects of water stress (both deficits and excesses) and root restriction on plant growth and development. These should be conducted under both controlled-environment conditions and under actual field conditions. They should be accompanied by careful measurements of such parameters as leaf, air, and soil temperatures, radiation conditions, stomatal behavior, water potential, and mineral status (52, 87, 145).

Studies should be focused on mechanisms of adaptation to water stress, root restriction, and other urban stresses (e.g., high pH, Fe stress, Pb pollution) including both avoidance mechanisms and detoxification mechanisms (102). Experiments should be carried out to determine the extent to which urban trees experience osmotic adjustment and other possible mechanisms of stress adaptation. Information is needed to determine the changes in root permeability of trees during drought stress and recovery (162). Efforts should be made to determine the hormonal basis for differences in growth reduction caused by water stress and root restriction. Studies should be conducted to identify trees that can withstand high temperatures as well as those that continue to transpire, thereby maintaining cooler leaf temperatures which may enable them to avoid leaf injury.

Careful studies are also needed to determine the influence of various stress interactions, e.g., drought and air pollutants, drought and mineral stress, water stress and plant pathogens to determine their possible synergistic and antagonistic effects.

Further efforts should also be made to develop computer models of transpiration from individual tree crowns (151). Such information could be used to predict water use, to schedule irrigation, to monitor plant water stress conditions, and to assess the whole plant energy balance. Additional information is also needed to establish minimum irrigation requirements for urban trees (23, 36, 44, 101, 118).

Conclusions

In order to reduce losses from environmental stress and to increase the longevity of urban plantings, it is clear that an interdisciplinary approach is needed. This should involve the cooperation of researchers and arborists. Greater attention should be given to conducting a thorough examination of the biological and edaphic factors at each proposed site and to selecting species and cultivars that are resilient to environmental stress.

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Literature Cited

1. Aliabod, S., and S. Sandi. 1983. *Effect of restricted watering and its combination with root pruning on root growth capacity, water status and food reserves of Pinus caribaea var. hondurensis seedlings.* Plant and Soil. 71:123-129.
2. Alberty, C. A., H. M. Pellett, and D. H. Taylor. 1984. *Characterization of soil compaction at construction sites and woody plant response.* J. Environ. Hort. 2:48-53.
3. Appleton, B. L., and C. E. Whitcomb. 1983. *Effects of container size and transplanting date on the growth of tree seedlings.* J. Environ. Hort. 1:89-93.
4. Atkinson, D., and C. M. Crisp. 1983. *The effect of some plant growth regulators and herbicides on root system morphology and activity.* Acta Hort. 136:21-28.
5. Ayoub, A. T. 1975. *Effect of some soil amendments on sodium uptake and translocation in dry beans (P. vulgaris L.) in relation to sodium toxicity.* J. Agr. Sci. 84:537-541.
6. Bausher, M. G., and G. Yelenosky. 1986. *Sensitivity of potted citrus plants to top sprays and soil applications of paclobutrazol.* HortScience 21:141-143.
7. Berrang, P., D. F. Karnosky, and B. J. Stanton. 1985. *Environmental factors affecting tree health in New York City.* J. Arboric. 11:185-189.
8. Biran, I., and A. Eliassaf. 1980a. *The effect of container shape on the development of roots and canopy of woody plants.* Scientia Hort. 12:183-193.
9. Biran, I., and A. Eliassaf. 1980b. *The effect of container size and aeration conditions on growth of roots and canopy of woody plants.* Scientia Hort. 12:385-394.
10. Birchell, R. S., and C. E. Whitcomb. 1977. Effects of container design on root development and regeneration. pp. 39-45. In Okla. Agric. Expt. Sta. Res. Rept. P-760. Oklahoma State University, Stillwater, OK.
11. Blake, T. J. 1983. *Transplanting shock in white spruce: effect of cold storage and root pruning on water relations and stomatal conditioning.* Physiol. Plant. 57:21-216.
12. Blake, T. J., T.J.L. Tschaplinski, and A. Eastham. 1984. *Stomatal control of water use efficiency in poplar clones and hybrids.* Can. J. Bot. 62:1344-1351.
13. Borkenhagen, J. E., and J. G. Iyer. 1972. *Aluminum sulphate as a stabilizer of nursery stock development.* J. For. 70:33-34.
14. Bowles, G. 1985. *Growth retardant use by utility companies.* J. Arboric. 11:59-60.
15. Buttrose, M. S., and M. G. Mullins. 1968. *Proportional reduction in shoot growth of grapevines with root systems maintained at constant relative volumes by repeated pruning.* Aust. J. Biol. Sci. 21:1095-1101.
16. Carlson, L. W., and F. Endean. 1976. *The effect of rooting volume and container configuration on the early growth of white spruce seedlings.* Can. J. For. Res. 6:221-224.
17. Carmi, A., J. D. Hesketh, W. T. Enos, and D. B. Peters. 1983. *Interrelationships between shoot growth and photosynthesis, as affected by root growth restriction.* Photosynthetica 17:240-245.
18. Carmi, A., and B. Heuer. 1981. *The role of roots in control of bean shoot growth.* Ann. Bot. 48:519-527.
19. Carmi, A., and Y. Shalhevet. 1983. *Root effects on cotton growth and yield.* Crop Sci. 23:875-878.
20. Carr, D. J., and W. J. Burrows. 1966. *Evidence of the presence in xylem sap of substances with kinetin-like activity.* Life Sci. 15:2061-2077.
21. Colhoun, J. 1973. *Effects of environmental factors on plant disease.* Ann. Rev. Phytopathology 11:343-364.
22. Conaway, M. A., and R. L. Thayer, Jr. 1981. Evaluation of new species of drought-tolerant plants for highways. Dept. of Transportation Tech. Rept. Proj. E73LA03, National Technical Information Service, Springfield, VA.
23. Cotter, D. J., and F. Chavez. 1979. *Factors affecting water application rates on urban landscapes.* J. Amer. Soc. Hort. Sci. 104:189-191.
24. Davies, W. J., and T. T. Kozlowski. 1974. *Short- and long-term effects of antitranspirants on water relations and photosynthesis of woody plants.* J. Amer. Soc. Hort. Sci. 99:297-304.
25. Davies, W. J., and T. T. Kozlowski. 1975a. *Effects of applied abscisic acid and plant water stress on transpiration of woody angiosperms.* For. Sci. 22:191-195.
26. Davies, W. J., and T. T. Kozlowski. 1975b. *Effects of applied abscisic acid and silicone on water relations and photosynthesis of woody plants.* Can. J. For. Res. 5:90-96.
27. Davis, R. E., and C. E. Whitcomb. 1975. *Effects of propagation container size on development of high quality seedlings.* Proc. Inter. Plant Prop. Soc. 25:448-453.
28. Davis, W. D., S. T. Besemer, and D. H. Close. 1964. Landscaping in planters without natural drainage. Univ. Calif. Agric. Ext. Serv. AXT 124. pp. 1-3.
29. Dickinson, S., and C. E. Whitcomb. 1982. *Root development of transplanted seedlings initially in bottomless milk cartons.* J. Arboric. 8:323-324.
30. Dirr, M. A. 1976. *Selection of trees for tolerance to salt injury.* J. Arboric. 11:209-216.
31. Dirr, M. A., and J. Biedermann. 1980. *Amelioration of salt damage to cotoneaster by gypsum.* J. Arboric. 6:108-110.
32. Domir, S. C. 1978. *Chemical control of tree height.* J. Arboric. 4:145-153.
33. Evans, P. S., and J. E. Klett. 1984. *The effects of dor-*

mant pruning treatments on leaf, shoot and root production from bare-root Malus sargentii. J. Arboric. 10:298-302.
34. Evans, P. S., and J. E. Klett. 1985. *The effects of dormant branch thinning on total leaf, shoot and root production from bare-root Prunus cerasifera 'Newportii.'* J. Arboric. 11:149-151.
35. Feldman, L. J. 1984. *Regulation of root development.* Ann. Rev. Plant Physiol. 35:233-242.
36. Fitzpatrick, G. 1983. *Plant growth response to water rationing in a container nursery.* HortScience 18:187-189.
37. Flemer, W. III. 1973. *Growing street trees in containers.* Garden J. 23:83-88.
38. Fletcher, R. A. 1985. Plant growth regulating properties of sterol-inhibiting fungicides. **In** S. S. Purohit (ed.), Hormonal Regulation of Plant Growth and Development. Vol. 2. Agro. Bot. Publ., India.
39. Flower, F. B., E. F. Gilman, and I. A. Leone. 1981. *Landfill gas, what it does to trees and how its injurious effects may be prevented.* J. Arboric. 7:43-52.
40. Foil, R. R., and C. W. Ralston. 1967. *The establishment and growth of loblolly pine seedlings on compacted soils.* Soil Sci. Soc. Amer. Proc. 31:565-568.
41. Foster, R. S., and J. Blaine. 1978. *Urban tree survival: trees in the sidewalk.* J. Arboric. 4:14-17.
42. Gerhold, H. D. 1978. *History and goals of METRIA, the Metropolitan Tree Improvement Alliance.* J. Arboric. 4:62-66.
43. Gibson, J. D., and C. E. Whitcomb. 1980. *Producing tree seedlings in square bottomless containers.* Orn. South 2:12-15.
44. Halverson, H. G., and D. F. Potts. 1981. Water requirements of honeylocust in the urban forest. USDA For. Serv. Res. Paper NE-487. 4 pp.
45. Hammerschlag, R., J. Sherald, and S. Kostka. 1986. *Shade tree leaf scorch.* J. Arboric. 12:38-43.
46. Harris, R. W. 1967. *Factors influencing root development of container-grown trees.* Proc. Intern. Shade Tree Conf. 43:304-314.
47. Harris, R. W. 1983. Arboriculture: Care of Trees and Shrubs in the Landscape. Prentice-Hall, Inc.
48. Harris, R. W., D. Long, and W. B. Davis. 1967a. Root problems in nursery liner production. Calif. Agric. Ext. AXT 244:1-4.
49. Harris, R. W., D. Long, and W. B. Davis. 1967b. *Root pruning improves nursery tree quality.* J. Amer. Soc. Hort. Sci. 96:105-108.
50. Hathaway, R. D., and C. E. Whitcomb. 1976. Growth of tree seedlings in containers. Okla. Agric. Expt. Sta. Res. Rept. Oklahoma State University, Stillwater, OK. pp. 33-38.
51. Hathaway, R. D., and C. E. Whitcomb. 1977. *Propagation of Quercus seedlings in bottomless containers with Osmocote.* J. Arboric. 3:208-212.
52. Havis, J. R. 1980. *Container moisture state and stomatal resistance in nursery plants.* HortScience 15:638-639.
53. Heilman, P. 1981. *Root penetration of Douglas-fir seedlings into compacted soil.* Forest Sci. 27:660-666.
54. Hield, H., R. M. Sachs, and R. A. Backhaus. 1978. *Bark banding with morphactin to inhibit tree growth.* J. Arboric. 4:58-61.
55. Himelick, E. B. 1976. Disease stresses of urban trees. pp. 115. **In** F. S. Santamour, Jr., H. D. Gerhold, and S. Little (eds.), Better Trees for Metropolitan Landscapes. U.S. Govern. Print. Off., Washington, D.C.
56. Hofstra, G., and R. Hall. 1971. *Injury on roadside trees: leaf injury on pine and white cedar in relation to foliar levels of sodium and chloride.* Can. J. Bot. 49:616-622.
57. Houston, D. R. 1981. Stress triggered tree diseases—the diebacks and declines. U.S.D.A. Forest Service Pub. N. E. INF-41-81. 36 pp.
58. Karlsson, I., and M. Kovats. 1974. Effects of rooting medium, container size, cover and planting time on container-grown Douglas-fir seedlings. B. C. Forest Service Res. Note 69.
59. Karnosky, D. F. 1981. Selecting trees for the urban environment. Proc. "Plants in Our Lives" Symp. at the New York Botanical Garden, June 1981.
60. Karnosky, D. F., H. D. Gerhold, and W. H. Collins. 1982. *METRIA projects on species trials and cultivar testing.* J. Arboric. 8:178-181.
61. Keever, G. J., G. S. Cobb, and R. B. Reed. 1985. *Effects of container dimension and volume on growth of three woody ornamentals.* HortScience 20:276-278.
62. Klingaman, G. L., and J. H. King. 1981. *Influence of container design on harvestability of field-grown oaks.* New Horizons 21-23.
63. Klingaman, G. L., and J. H. King. 1983. *What size and shape of container are best for growing seedlings?* Amer. Nurs. 158:87-93.
64. Ko, W. H., and F. K. Hora. 1972. *Identification of an Al ion as a soil fungitoxin.* Soil Sci. 113:42-45.
65. Kozlowski, T. T. 1971. Growth and Development of Trees. Vol. II. Academic Press, New York. pp. 196-250.
66. Kozlowski, T. T. 1985. *Tree growth in response to environmental stresses.* J. Arboric. 11:97-111.
67. Kozlowski, T. T. 1986a. *Responses of woody plants to environmental pollution. Part I. Sources and types of pollutants and plant responses.* For. Abstr. 47:5-52.
68. Kozlowski, T. T. 1986b. *Environmental pollution and tree growth. Part II. Factors affecting responses to pollution and alleviation of pollution effects.* For. Abstr. 47:105-132.
69. Kozlowski, T. T. 1986c. *Soil aeration, flooding, and tree growth.* J. Arboric. 11:85-96.
70. Kozlowski, T. T. 1986d. *The impact of environmental pollution on shade trees.* J. Arboric. 12:29-37.
71. Kozlowski, T. T., and W. J. Davies. 1975. *Control of water balance in transplanted trees.* J. Arboric. 1:1-10.
72. Kozlowski, T. T., and T. Keller. 1966. *Food relations in woody plants.* Bot. Rev. 32:293-382.
73. Kramer, P. J. 1969. Plant and Soil Water Relationships: A Modern Synthesis. McGraw-Hill Book Co., New York.
74. Kramer, P. J., and T. T. Kozlowski. 1979. Physiology of Woody Plants. Academic Press, NY. pp. 277-280.
75. Krizek, D. T. 1985. *Methods of inducing water stress in plants. Proc. ASHS Symposium on Water Stress Measurement Techniques—Instrumentation and Procedures.* HortScience 20:1028-1038.
76. Krizek, D. T., A. Carmi, R. M. Mirecki, F. W. Snyder, and J. A. Bunce. 1985. *Comparative effects of soil moisture stress and restricted root zone volume on morphogenetic and physiological responses of soybean [Glycine max (L.) Merr.].* J. Exp. Bot. 36:25-38.
77. Krizek, D. T., R. M. Mirecki, and P. Semeniuk. 1986a. *Influence of soil moisture stress and abscisic acid pretreatment in modifying SO_2 sensitivity in poinsettia.* J. Amer. Soc. Hort. Sci. 111:446-450.

78. Krizek, D. T., P. Semeniuk, and R. M. Mirecki. 1986b. *Influence of temperature and PPF pretreatment in modifying SO_2 sensitivity in coleus.* HortScience 21:816.
79. Krizek, D. T., P. Semeniuk, and R. M. Mirecki. 1986c. *Influence of paclobutrazol concentration and time of pretreatment in ameliorating SO_2 injury in coleus.* Plant Physiol. 80S:125.
80. Krizek, D. T., P. Semeniuk, R. M. Mirecki, and G. L. Steffens. 1986d. Influence of triazoles in ameliorating SO_2 injury in coleus. Abstracts, Phytochemical Soc. North Amer.
81. Lee, E., J. K. Byun, and S. J. Wilding. 1985. *A new gibberellin biosynthesis inhibitor, paclobutrazol (PP_{333}) confers increased SO_2 tolerance on snap bean plants.* Env. Exp. Bot. 25:265-275.
82. Levitt, J. 1980. Responses of plants to environmental stresses. Vol. II. Academic Press, New York. pp. 93-128.
83. Lumis, G. P., G. Hofstra, and R. Hall. 1975. *Salt damage to roadside plants.* J. Arboric. 1:14-16.
84. McDavid, C. B., G. R. Sagar, and C. Marshall. 1973. *The effect of root pruning and 6-benzylamino-purine on the chlorophyll content, $^{14}CO_2$ fixation and the shoot/root ratio in seedlings of Pisum sativum L.* New Phytol. 72:465-470.
85. MacDonald, J. D. 1982. *Role of environmental stress in the development of Phytophthora root rots.* J. Arboric. 8:217-223.
86. Merritt, C. 1968. *Effect of environment and heredity on the root growth pattern of red pine.* Ecology 49:35-40.
87. Miller, M. N., D. L. Gunta, B. E. Melton, C. R. Johnson, and J. T. Midcap. 1980. *Selecting economically optimal levels of fertilization and irrigation for container production of woody ornamentals.* J. Amer. Soc. Hort. Sci. 105:766-768.
88. Miller, S. S. 1982. *Growth and branching of applied seedlings as influenced by pressure-injected plant growth regulators.* HortScience 17:775-776.
89. Mutsaers, H.J.W. 1983. *Leaf growth in cotton (Gossypium hirsutum L.), 2. The influence of temperature, light, water stress and root restriction on the growth and initiation of leaves.* Ann. Bot. 51:521-529.
90. Nelms, L. R., L. A. Spomer, C. W. Boast, and J. S. Vandelmark. 1978. *Water loss from container soils after transplantation to field.* Ill. Res. 20:8-9.
91. Norby, R. J., and T. T. Kozlowski. 1981. *Relative sensitivity of three species of woody plants to SO_2 at high or low exposure temperature.* Oecologia 51:33-36.
92. Norby, R. J., and T. T. Kozlowski. 1983. *Flooding and SO_2 stress interaction in Betula papyrifera and B. nigra seedlings.* For. Sci. 29:739-750.
93. Owston, P. W., and K. W. Seidel. 1978. *Container and root treatments affect growth and root form of planted ponderosa pine.* Can. J. For. Res. 8:232-236.
94. Pan, E., and N. Bassuk. 1985. *Effects of soil type and compaction on the growth of Ailanthus altissima seedlings.* J. Environ. Hort. 3:158-162.
95. Parsons, L. R. 1982. Plant responses to water stress. pp. 175-192. **In** M. N. Christiansen and C. F. Lewis (eds.), Breeding Plants for Less Favorable Environments. Wiley, NY.
96. Partyka, R. E. 1982. *The ways we kill a plant.* J. Arboric. 8:57-66.
97. Patterson, J. C. 1976. Soil compaction and its effects on urban vegetation. Pp. 91-102. **In** J. Santamour, H. D. Gerhold, and S. Little (eds.), Better Trees for Metropolitan Landscapes. Symposium Proceedings. USDA For. Serv. Gen. Tech. Rep. NE-22.
98. Patterson, J. C. 1977. *Soil compaction—effects on urban vegetation.* J. Arboric. 3:161-167.
99. Perry, T. O. 1982. *The ecology of tree roots and the practical significance thereof.* J. Arboric. 8:197-211.
100. Peterson, C. M., B. Klepper, F. V. Pumphrey, and R. W. Rickman. 1984. *Restricted rooting decreases tillering and growth of winter wheat.* Agron. J. 76:861-863.
101. Ponder, H. G., and A. L. Kenworthy. 1976. *Trickle irrigation of shade trees growing in the nursery: I. Influence on growth.* J. Amer. Soc. Hort. Sci. 101:100-103.
102. Potts, D. F., and L. P. Herrington. 1982. *Drought resistance adaptations in urban honeylocust.* J. Arboric. 8:75-80.
103. Powell, C. C. 1985. *Tree health from top to bottom.* J. Arboric. 11:129-131.
104. Reiger, R., and C. E. Whitcomb. 1983. *Growers can now confine roots in field containers.* Amer. Nurseryman 158:33-34.
105. Richards, D. 1977. *Root-shoot interactions. A functional equilibrium for water uptake in peach [Prunus persica (L.) Batsch].* Ann. Bot. 41:279-281.
106. Richards, D., and B. Cockroft. 1974. *The effect of soil water on root production of peach trees in summer.* Aust. J. Agric. Res. 26:173-180.
107. Richards, D., and R. N. Rowe. 1977a. *Effects of root restriction, root pruning, 6-benzylaminopurine on the growth of peach seedlings.* Ann. Bot. 41:729-740.
108. Richards, D., and R. N. Rowe. 1977b. *Root-shoot interactions in peach: The function of the root.* Ann. Bot. 41:1211-1216.
109. Richards, L. A., and C. H. Wadleigh. 1952. Soil water and plant growth. Pp. 73-251. **In**: Soil Physical Conditions and Plant Growth. Academic Press, NY.
110. Rikin, A., A. Blumenfeld, and A. E. Richmond. 1976. *Chilling resistance as affected by stressing environments and abscisic acid.* Bot. Gaz. 20:1537-1546.
111. Roberts, B. R. 1977. *The response of urban trees to abiotic stress.* J. Arboric. 3:75-78.
112. Rook, D. A. 1969. *Water relations of wrenched and unwrenched Pinus radiata seedlings on being transplanted into conditions of water stress.* New Zealand J. For. 14:50-58.
113. Rook, D. A. 1972. *Conditioning of radiata pine seedlings to transplanting, by restricted water.* New Zealand J. For. Sci. 3:54-69.
114. Ruark, G. A., D. L. Mader, and T. A. Tattar. 1982. *The influence of soil compaction and aeration on the root growth and vigor of trees—A literature review.* J. Arboric. 6:251-265.
115. Ruark, G. A., D. L. Mader, P.L.M. Veneman, and T. A. Tattar. 1983. *Soil factors related to urban sugar maple decline.* J. Arboric. 9:1-6.
116. Rubens, J. M. 1978. *Soil desalination to counteract maple decline.* J. Arboric. 4:33-42.
117. Russell, R. S., and M. J. Goss. 1974. *Physical aspects of soil fertility the response of roots to mechanical impedance.* Neth. J. Agri. Sci. 22:305-318.
118. Sachs, R. M., T. Kretchum, and T. Mock. 1975. *Minimum irrigation requirements for landscape plants.* J. Amer. Soc. Hort. Sci. 100:499-502.

119. Salem, B. B. 1967. Root strangulation: A neglected factor in container grown nursery stock. MS Thesis, Univ. of California, Berkeley, CA. 50 pp.
120. Schoeneweiss, D. F. 1975. *Predisposition, stress, and plant disease.* Ann. Rev. Phytopathol. 13:193-211.
121. Schoeneweiss, D. F. 1978a. Water stress as a predisposing factor in plant disease. pp. 61-99. **In** T. T. Kozlowski (ed.), Water Deficits and Plant Growth, Academic Press, NY.
122. Schoeneweiss, D. F. 1978b. *The influence of stress on diseases of nursery and landscape plants.* J. Arboric. 4:217-225.
123. Schoeneweiss, D. F. 1981. *Infectious diseases of trees associated with water and freezing stress.* J. Arboric. 7:13-18.
124. Schoeneweiss, D. F. 1982. *Prevention and treatment of construction damage to shade trees.* J. Arboric. 8:169-175.
125. Schulte, J. R., and C. E. Whitcomb. 1975. *Effects of soil amendments and fertilizer labels on the establishment of silver maple.* J. Arboric. 1:192-195.
126. Shanklin, J., and T. T. Kozlowski. 1984. *Effect of temperature preconditioning on responses of Fraxinus pennsylvanica seedlings to SO_2.* Environ. Pollut. Ser A. 36:1-16.
127. Shaw, K. 1977. *Girdling roots.* Arnoldia. 37:242-247.
128. Skene, K.G.N. 1967. *Gibberellin-like substances in root exudate of Vitis vinifera.* Planta 74:250-262.
129. Skene, K.G.N. 1975. Cytokinin production by roots as a factor in control of plant growth in the development and function of roots. pp. 365-396. **In** J. G. Torrey (ed.), The Development and Function of Roots. Academic Press, NY. 618 pp.
130. Smith, G. C., and E. G. Brennan. 1984. *Response of honeylocust cultivars to air pollution stress in an urban environment.* J. Arboric. 10:289-293.
131. Spomer, L. A. 1979. *Three simple demonstrations of the physical effect of soil amendment.* HortScience 14:75-77.
132. Spomer, L. A. 1980. *Container soil water relations: production, maintenance, and transplanting.* J. Arboric. 6:315-320.
133. Spomer, L. A. 1981. *The effect of soil container volume on plant growth.* HortScience 17:680-681.
134. Spomer, L. A. 1983. *Physical amendment of landscape soils.* J. Environ. Hort. 1:77-80.
135. Stone, E. C. 1955. *Poor survival and the physiological condition of planting stock.* For. Sci. 1:90-94.
136. Stone, E. C., and J. L. Jenkinson. 1970. *Influence of soil water on root growth capacity of ponderosa pine transplants.* For. Sci. 16:230-239.
137. Studer, E. J., P. L. Steponkus, G. L. Good, and S. C. Wiest. 1978. *Root hardiness of container-grown ornamentals.* HortScience 13:172-174.
138. Stupendick, J. T., and K. R. Shepherd. 1980. *Root regeneration of root pruned Pinus radiata seedlings. II. Effects of root pruning on photosynthesis and translocation.* New Zealand J. For. Sci. 10:148-158.
139. Sutton, R. F. 1969. Form and development of conifer root systems. Fornham Royal, Bucks, England, Commonwealth Agricultural Bureaux. 131 pp.
140. Sutton, R. F. 1980. *Planting stock quality, root growth capacity, and field performance of three boreal conifers.* New Zealand J. For. Sci. 10:54-71.
141. Swietlik, D., and S. S. Miller. 1983. *The effect of paclobutrazol on growth and response to water stress of apple seedlings.* J. Amer. Soc. Hort. Sci. 108:1076-1080.
142. Tattar, T. A. 1983. *Stress management for trees.* J. Arboric. 9:25-27.
143. Taylor, H. M. 1974. Root behavior as affected by soil structure and strength. pp. 27-291. **In** E. W. Carson (ed.), The Plant Root and Its Environment. University Press of Virginia, Charlottesville.
144. Terry, P. H., D. T. Krizek, and R. M. Mirecki. 1986. *Influence of photosynthetic photon flux, spectral quality, and temperature on chlorophyll and abscisic acid concentrations in leaves of coleus plants.* Proc. Plant Growth Reg. Soc. Amer. 13: *In Press.*
145. Teskey, R. O., and T. M. Hinkley. 1981. *Influence of temperature and water potential on root growth of white oak.* Physiol. Plant. 27:435-459.
146. Tinus, R. W. 1978. *Root system configuration is important to long tree life.* Proc. Intern. Plant Prop. Soc. 28:58-64.
147. Tinus, R. W., and S. E. McDonald. 1979. How to grow tree seedlings in containers in greenhouses. Tech. Report RM-60. Rocky Mountain For. and Range Expt. Sta., U.S. Forest Service, Bottineaus, ND. 256 pp.
148. Torrey, J. G. 1976. *Root hormones and plant growth.* Ann. Rev. Plant Physiol. 27:435-459.
149. Tschaplinski, T. J., and T. J. Blake. 1985. *Effects of root restriction on growth correlations, water relations and senescence of alder seedlings.* Physiol. Plant. 64:167-176.
150. Vomocil, J. A., and W. J. Flocker. 1961. *Effect of soil compaction on storage and movement of soil air and water.* Trans. Amer. Soc. Agr. Eng. 4:242-245.
151. Vrecenak, C. J., and L. P. Herrington. 1984. *Estimation of water use of landscape trees.* J. Arboric. 10:313-319.
152. Wall, S., and C. E. Whitcomb. 1980. A comparison of commercial containers for growing tree seedlings. Okla. Agr. Expt. Sta. Res. Rept. P-803:72-75.
153. Watson, G. 1985. *Tree size affects root regeneration and top growth after transplanting.* J. Arboric. 11:37-40.
154. Watson, G. W., and E. B. Himelick. 1982. *Root distribution of nursery trees and its relationship to transplanting success.* J. Arboric. 8:225-229.
155. Westing, A. H. 1969. *Plants and salts in the roadside environment.* Phytopathology 59:1174-1181.
156. Weston, L. A., and B. H. Zandstra. 1986. *Effect of root container and location of production on growth and yield of tomato transplants.* J. Amer. Soc. Hort. Sci. 111:498-501.
157. Whitcomb, C. E. 1981a. Growing tree seedlings in containers. Okl. Agr. Exp. Sta. Bull. 755. Stillwater, OK.
158. Whitcomb, C. E. 1981b. *A vertical air-root-pruning container.* Proc. Intern. Plant Prop. Soc. 31:591-596.
159. Whitcomb, C. E. 1984. *Reducing stress and accelerating growth of landscape plants.* J. Arboric. 10:5-7.
160. Whitcomb, C. E. 1985. *Innovations and the nursery industry.* J. Environ. Hort. 3:33-38.
161. Whitcomb, C. E., A. Storjohann, and J. Gibson. 1977. Effects of time of transplanting container grown tree seedlings on subsequent growth and development. Okla. Agr. Expt. Sta. Res. Rept. P-777:37-39.
162. Wiersum, L. K., and K. Harmanny. 1983. *Changes in water permeability of roots of some trees during drought*

stress and recovery, as related to problems of growth in an urban environment. Plant and Soil 75:443-448.

163. Williams, D. J. 1978. *Handling plants in landscape containers.* J. Arboric. 4:184-186.
164. Williams, E., and Whitcomb, C. E. 1979. Effects of growing media and container design on growth of tree seedlings. Okla. Agr. Exp. Sta. Res. Rept. P-79:40-43.
165. Williams, M. W., and L. J. Edgerton. 1983. *Vegetative growth control of apple and pear trees with ICI PP-333 (paclobutrazol) a chemical analog of bayleton.* Acta Hort. 13:111-116.
166. Wilson, C. L., and C. W. Ellett. 1980. *The diagnosis of urban tree disorders.* J. Arboric. 6:141-145.
167. Yelenosky, E. 1964. *Tolerance of trees to deficiencies of soil aeration.* Proc. Inter. Shade Tree Conf. 40:127-146.
168. Young, H.E.L., and P. J. Kramer. 1982. *The effect of pruning on the height and diameter growth of loblolly pine.* J. For. 50:474-479.
169. Zak, B. 1977. *Mycorrhizae and container seedlings.* J. Arboric. 3:178-179.
170. Zisa, R. P., H. G. Halverson, and B. B. Stout. 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA For. Serv. Res. Pap. NE-451.

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Abstract

TATTAR, T.A. 1986. **How to prevent transplant failures.** Am. Nurseryman. 163(6):143-144,146,148-151.

Due to the high value of plants at the time of sale and to the importance of the customers, post-sale failures are important to nurserymen, landscapers and garden center operators. No one expects plant materials that have been recently sold to fail. Customers expect the trees or shrubs they purchase to remain healthy and vigorous after they have been transplanted. Usually, they receive a written or oral guarantee to that effect. Replacing trees and shrubs that fail is a costly practice and does not provide a practical solution to the problem. Three general causes account for most post-sale failures: 1) poor-quality plant material, 2) poor placement in the soil or container, and 3) lack of follow-up care. Nurserymen who believe that the work is done after the plant is set in the ground are overlooking a major cause of transplant failure--a lack of post-planting follow-up care. Post-planting problems fall into two categories: continual care, which is needed during the plant's transition to independent growth; and protection from biotic and abiotic stresses.