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Nitrogen fertilization during planting and establishment of the urban forest: A collection of five studies

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Abstract

Today's urban forest increasingly consists of planted trees, especially as native forest fragments yield to urban sprawl. These trees are usually larger (over 2-m tall) than typical reforestation trees and grow very little for the first few years after planting. Stressful urban sites exacerbate this effect and many practitioners hope to shorten the time required to reach environmentally functional size by fertilizing at planting. This is a controversial practice since nitrogen (N) application creates the potential for water quality impairment and effectiveness is uncertain. It is not clear how nitrogen application affects large trees with radically altered root:shoot ratios or how nursery production methods and restrictive sites affect response. In a series of five separate studies, we tested several N rates on ten shade tree species (both field- and container-grown) and transplanted to a range of urban sites, from a relatively undisturbed forest fragment to a highly compacted cutover soil with an absent A horizon. Trunk diameter increase, as an integrative metric of tree biomass accumulation, was followed for up to 4 years on each experiment. Overall, we saw little effect from fertilizing at planting at any rate we tested, regardless of location. Three studies that included leaf analysis with a SPAD-502 chlorophyll meter indicated that neither SPAD meter values or N concentration within leaves was increased by fertilizing at planting, suggesting that the newly planted shade trees took up very little of the applied N. Overall, SPAD-502 readings correlated well with actual leaf N concentration ($r = 0.692$). This group of studies indicates that fertilization at planting does not increase post-transplant growth, even in stressful urban sites and it is therefore not effective at shortening the establishment period of transplanted shade trees.

Keywords: Nursery production method; Site preparation; Soil compaction; Transplanting; Urban soil

Introduction

Shade tree fertilization has been studied for many years (see Struve, 2002, for a general review), although reports on fertilization of newly planted trees are few, especially on trees transplanted in the urban soils typical of many of today's landscapes (Craul, 1985). Although plant growth is very dependent on rhizosphere N (Mengel and Kirkby, 2001), it is not clear how plant response to N differs between newly transplanted and fully established trees. Normally, the functional equilibrium between roots and shoots can largely be explained by the production (i.e. through photosynthesis) and partitioning of carbon associated with the uptake and use of N (Argren and Ingestad, 1987). However, the root

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systems of large field-grown trees are often drastically reduced when transplanting (Gilman, 1988). The much altered root:shoot relationship and the resulting compromised ability to take up N likely interact to affect post-transplant growth. Although the response of container- and field-grown trees to N fertilizer at planting is poorly understood, many practitioners attempt to restore pre-transplant growth rates to newly transplanted trees through fertilization at planting.

Eleven species of bare-root trees showed no growth response to N during establishment, although leaves of fertilized trees were visibly darker green in the second year (Shoup et al., 1981). Silver maple (*Acer saccharinum* L.), a highly vigorous species, grew more rapidly with increased N when planted in a clay loam soil, but had no response when planted on a site with nutrient-deficient silt loam soil (Schulte and Whitcomb, 1975). After these mixed results, Whitcomb recommended fertilizing lightly at planting (Whitcomb, 1984). Neely (1980) found that established trees in fertile soil received only a small benefit from fertilization. In a recent study on two urban sites in Milan, Italy, fertilization increased photosynthesis rate of Japanese pagoda tree (*Styphnolobium japonicum* Schott) and sweetgum (*Liquidambar styraciflua* L.), but not European ash (*Fraxinus excelsior* L.) during the first year (Ferrini and Baietto, 2006). In subsequent years, this effect disappeared or was reversed and in no case was growth affected by fertilizer. In another recent study, there were no effects of fertilizing balled-and-burlapped (B&B) red maple (*Acer rubrum* L.) or linden (*Tilia cordata* Mill.) at recommended rates when transplanting into infertile, but uncompacted soil (Day and Harris, 2007). Unnecessary fertilizer is obviously not cost effective and raises concerns of degrading water resources through runoff or nitrogen leaching. It is apparent from the mixed results discussed above that fertilization research to date does not provide the definitive answers needed to make fertilization recommendations for newly transplanted urban trees. Few studies have included the less-than-ideal soils found in urban areas where rapid establishment could potentially provide significant financial and environmental benefits because of increased canopy cover and reduced tree replacement costs.

This group of studies seeks to determine if fertilization practices have potential to speed establishment rates in a broad cross-section of soil conditions typical of developed land. The five studies presented here all share the same objective: Can fertilizer be effectively used to improve the nutrient status of trees during the establishment period and thereby hasten their entry into the environmentally productive phase of their life? These studies include 10 deciduous shade tree species and 276 individual trees that were either field (transplanted B&B or bare root) or container grown (two container sizes) to full "landscape size" and transplanted into a variety of site conditions, including poor sites, typical of urban landscapes. This variety of planting sites, tree species, and production methods presents a broad look at the effect of fertilization at planting on the growth of shade trees.

Methods

Overview

All experiments were conducted at or near Virginia Tech's main campus in Blacksburg, VA, USA. The experimental design was completely random for all five experiments, and each species was analyzed separately. Trunk diameter was chosen as the most critical metric of establishment (Gilman and Beeson, 1996; Struve et al., 2000) and growth because it strongly correlates with total tree biomass (Avery and Burkhart, 2002). Trunk diameter increase was recorded annually for up to 4 years after transplanting. Soil characteristics were analyzed by Virginia Tech soil analysis laboratories within the Crop and Soil Environmental Sciences Department and can be found in Table 1. Total soil N and C were quantified using a Vario Max CNS elemental analyzer (Elementar Instrument, Mt. Laurel, NJ, USA). Experimental data were analyzed with multivariate repeated measures protocol and regression analysis within the GLM and REG procedures of SAS (vers. 9.1, SAS Institute, Cary, NC, USA) for Experiments 1 through 4 and for Experiment 5, respectively. Yearly tree size per treatment is presented for Experiments 1 through 4 (Figs. 1–4), and final post-transplant growth per treatment is presented for Experiment 5 (Fig. 5). *P*-values for treatment effects (Exp. 1–4) and parameter estimates from regression analysis (Exp. 5) are presented in Table 2. Experiments 1 and 5 were in soils that were undisturbed enough to be classified as a normal soil taxonomic series (described below), but Experiments 2, 3, and 4 were conducted in highly disturbed or "urban" soils (Craul, 1985) in which a normal soil series no longer accurately reflected its characteristics. Each experiment is individually described below.

Experiment 1: 55-L container-grown trees in average soil conditions (1-CON-AVG)

6 replications $\times$ 4 fertilization rates $\times$ 4 species = 96 trees

Container-grown (55-L) swamp white oak (*Quercus bicolor* Wild.), shingle oak (*Quercus imbricaria* Michx.), pear (*Pyrus calleryana* Decne. "Cleveland Select"), and Freeman maple (*Acer* $\times$ *freemanii* Autumn Blaze®) trees were obtained from Dewis Nursery (Bedford, VA, USA) and planted approximately 4 m apart in rows at Virginia

Table 1. Soil characteristics at the five experimental sites

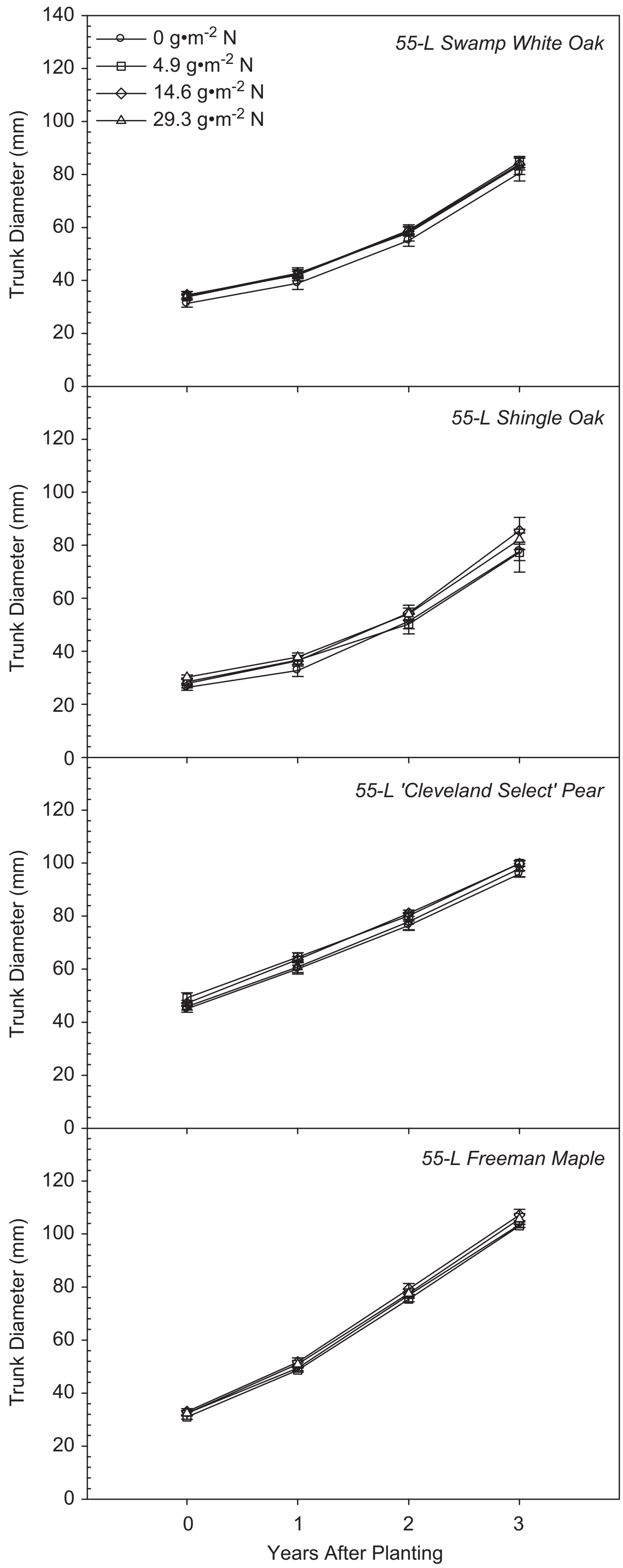
Experiment	Depth[a] (cm)	Bulk density (g cm^{-3})	pH	Sand (%)	Silt (%)	Clay (%)	Class[b]	N[c] (%)	C (%)	C/N
1	0–5	1.05	6.1	40.6	49.8	9.6	SL			
1	5–10	1.12	6.2	37.3	50.4	12.3	SL			
1	10–15	1.35	6.5	32.1	48.9	19.0	L	0.15	2.34	15.3
1	15–20	1.14	6.7	35.5	53.1	11.5	SL			
2	0–5	1.49	6.8	36.9	38.0	25.1	L			
2	5–10	1.52	7.3	42.1	36.1	21.9	L			
2	10–15	1.49	7.3	48.2	33.8	18.0	L	0.29	3.83	14.7
2	15–20	1.50	7.4	47.0	28.0	25.0	L			
3	0–5	1.25	6.5	27.6	53.4	18.9	SL			
3	5–10	1.35	6.5	33.5	42.1	24.4	L			
3	10–15	1.48	6.5	29.8	52.4	17.9	SL	0.14	1.68	12.0
3	15–20	1.45	6.9	39.7	38.0	22.4	L			
4	0–5	1.24	6.3	26.1	45.1	28.8	CL			
4	5–10	1.45	6.3	22.8	42.1	35.2	CL			
4	10–15	1.47	5.8	22.1	40.8	37.1	CL	0.18	2.14	12.6
4	15–20	1.56	6.1	23.2	40.3	36.5	CL			
5	0–5	1.13	6.2	20.9	64.9	14.2	SL			
5	5–10	1.15	5.9	21.8	61.5	16.7	SL			
5	10–15	1.13	5.8	20.3	67.1	12.6	SL	0.36	5.98	16.8
5	15–20	1.24	6.2	21.3	61.2	17.5	SL			

[a]$n = 3$, 3, 6, 6, and 3 for experiments 1, 2, 3, 4, and 5, respectively.
[b]SL, L, and CL = silt loam, loam, and clay loam, respectively.
[c]$n = 3$ for all experiments. N and C were analyzed from a well-mixed core that was 15 cm deep.

Tech's Urban Horticulture Center in early November 2001. Soil was uncompacted Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludults) and relatively unfertile (Table 1), typical of regional soils. Electrical conductivity (EC) measurements of rootball leachate was measured for each tree with the pour through (PT) method (Wright, 1986) to assess the fertility of rootballs at transplanting. Container substrate was nursery industry-standard semi-composted pine bark. Planting holes were dug at the same depth and twice the width of the original rootball on this and all subsequent experiments (approximately 45-cm deep × 90-cm wide for Exp. 1). Although not excessively pot bound, rootballs were sliced on opposite sides, approximately 2-cm deep and along the entire height according to common industry practice. Backfill on this and all other experiments was existing (native) backfill only. Fertilizer was a slow-release, sulfur-coated product from Southern States Cooperative Inc. (Richmond, VA) with a 27N–0.9P–9.9K analysis (5.0% ammonical N, 1.8% water insoluble N, 17.6% urea N, and 2.6% other water soluble N), described by the manufacturer as having a 4-month release time. Fertilizer was applied at 0, 4.9, 14.6, or 29.3 g m^{-2} N over a 1 m^2 area centered above the rootballs on top of the ground after planting. The same fertilizer regime was repeated in early November the following year and yearly throughout the experiment. After fertilizing, the nursery rows were mulched with a 5-cm deep × 2-m wide layer of shredded hardwood bark. Trees were irrigated to apparent field capacity at planting and twice a week for the following month. Irrigation was withheld thereafter. Trunk diameter was measured 15 cm above the ground at planting for the following 3 years. Foliar N levels were determined in early August 2003 (2nd growing season after transplanting) using three, randomly selected replications of each treatment. Five randomly selected matured leaves from separate branches throughout the canopy of each tree were pooled to make one sample. Chlorophyll meter readings were taken with a hand-held dual wavelength meter (SPAD 502, Minolta Camera Co. Ltd., Tokyo, Japan). SPAD-502 values have been reported to correlate with foliar N levels of deciduous hardwood trees (Chang and Robison, 2003). One reading per leaf was made on each leaf before detaching to use as described above for N analysis. Total Kjeldahl N in leaves (Peterson and Chesters, 1964) was determined with a Lachat autoanalyzer (QuicChem method 13-107-06-2-D; Lachat Instruments, Milwaukee, WI). Treatment effect on nitrogen concentration and SPAD-502 values were analyzed by analysis of variance within the GLM procedure of SAS. Correlation between nitrogen concentration and SPAD-502 values was determined within the CORR procedure of SAS.

Experiment 2: 55-L container-grown red maple along a highway (2-CON-HWY)

5 replications × 5 fertilization rates = 25 trees



Container-grown (55-L) red maple (*Acer rubrum* L. October Glory®) were grown in the Urban Horticulture Center nursery in industry-standard pine-bark substrate and planted approximately 6 m apart in a single row along the adjacent highwayside ditch in early May 2004. The soil at this site was compacted cut-and-fill from the road and drainage ditch with high pH (Table 1). Planting holes and rootball handling were the same as described in Experiment 1-CON-AVG. Fertilizer was a POLYON®-coated slow-release product from Harrell's Inc. (Lakeland, FL, USA) with a 19N–1.2P–6.6K (6.9% ammonical N, 5.9% nitrate N, and 6.2% urea N) analysis, described by the manufacturer as having a 5–6-month release time. Fertilizer was scattered within and just outside of the planting hole (1 m^2 area) as the trees were being backfilled at amounts equal to rates of 0, 14.6, 29.3, 58.6, or 117.2 g m^{-2} of actual N. All trees were mulched with a 5-cm deep, 1 m^2 area layer of shredded hardwood bark after fertilization. Trees were irrigated as in Experiment 1-CON-AVG. Trunk diameter was measured 30 cm above the ground at planting and for the following 3 years.

Experiment 3: 14-L container-grown trees on a cutover site (3-SM-CONT-CUT)

10 replications × 2 fertilization rates × 2 species = 40 trees

Sweetgum and red maple grown in 14-L containers were obtained from Lancaster Farm Nursery (Suffolk, VA) and planted along an intensely disturbed urban site at the Virginia Tech sports practice field in early April 2003. All trees were produced in industry-standard pine-bark substrate. Before planting, EC measurements were taken for a randomly selected subsample of five trees per species with the PT method (Wright, 1986) to assess pre-transplant fertility of rootballs. Planting holes were 30-cm deep × 60-cm wide and rootball handling was the same as described in Experiment 1-CON-AVG. This was a compacted (Table 1) cut-and-fill area. Fertilizer was the same as that described in Experiment 1-CON-AVG and was evenly spread within and outside of the planting hole (1 m^2 area) as the trees were being backfilled at amounts equal to rates of 0 or 29.3 g m^{-2} N (i.e. unfertilized or fertilized). All trees were mulched as in Experiment 2-CON-HWY. Trees were irrigated to apparent field capacity soon after planting and weekly

Fig. 1. Experiment 1-CON-AVG. Trunk diameter at transplanting and for 3 consecutive years thereafter for not fertilized 55-L swamp white oak (*Quercus bicolor* Wild.), shingle oak (*Quercus imbricaria* Michx.), pear (*Pyrus calleryana* Decne. "Cleveland Select"), and Freeman maple (*Acer × freemanii* Autumn Blaze®) trees and for trees fertilized at planting with three N rates ($n = 6$). See Table 2 for statistics.

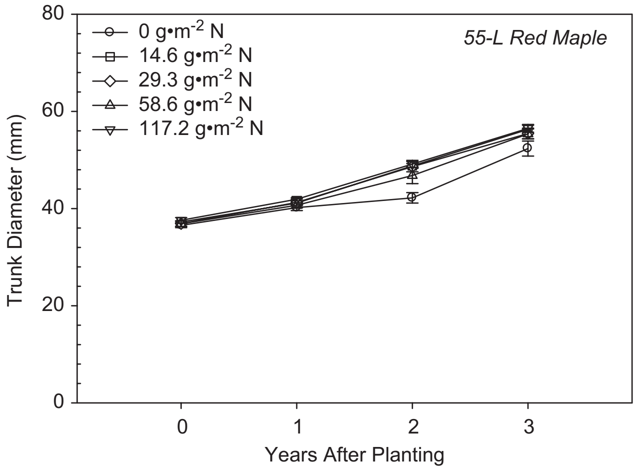


Fig. 2. Experiment 2-CON-HWY. Trunk diameter at transplanting and for 3 consecutive years thereafter for not fertilized 55-L red maple (*Acer rubrum* L. October Glory®) and for trees fertilized at planting with four N rates ($n = 5$). See Table 2 for statistics.

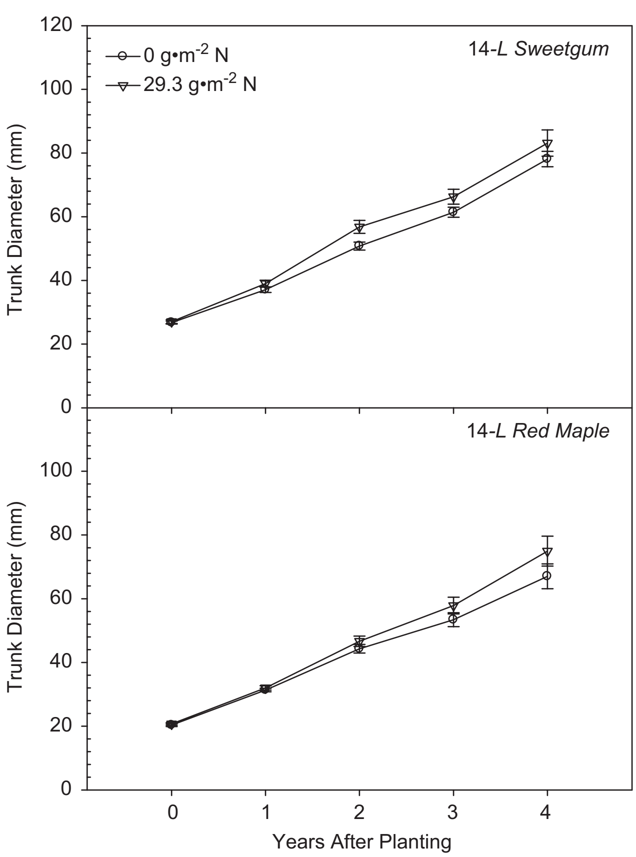


Fig. 3. Experiment 3-SM-CON-CUT. Trunk diameter at transplanting and for 4 consecutive years thereafter for not fertilized 14-L red maple (*Acer rubrum* L. October Glory®) and sweetgum (*Liquidambar styraciflua* L.) and for trees fertilized at planting with 29.3 $g\,m^{-2}$ N ($n = 10$). See Table 2 for statistics.

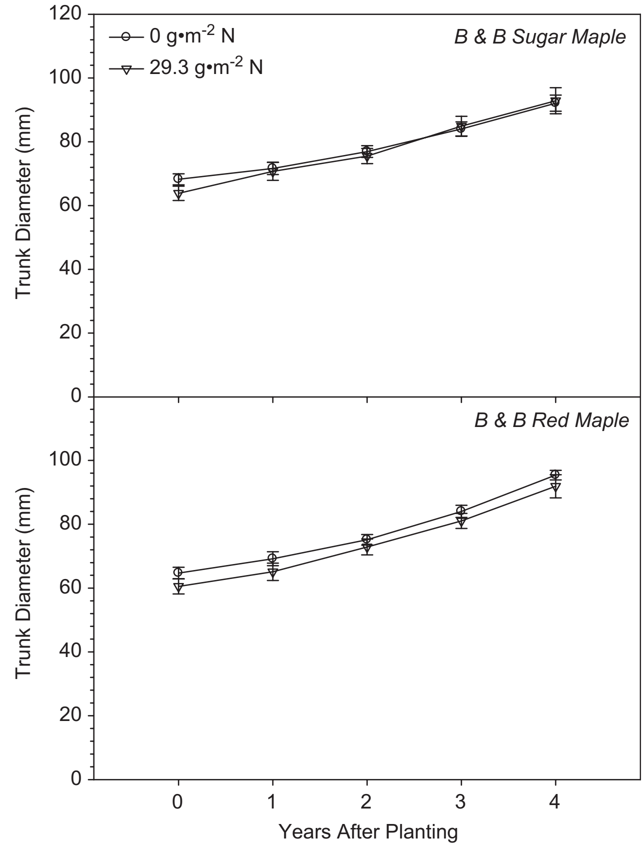


Fig. 4. Experiment 4-BB-URB. Trunk diameter at transplanting and for 4 consecutive years thereafter for not fertilized balled-and-burlapped red maple (*Acer rubrum* L.) and for trees fertilized with 29.3 $g\,m^{-2}$ N ($n = 10$). See Table 2 for statistics.

for the following month. Irrigation was withheld thereafter. Trunk diameter was measured 15 cm above the ground at planting and annually for the following 3 years. Foliar nitrogen levels were determined in early August 2003 (approximately 4 months after transplanting) using three, randomly selected replications of each treatment. Leaf sampling, SPAD-502 readings and analysis were the same as described in Experiment 1-CON-AVG.

Experiment 4: Balled and burlapped trees on an urban roadway (4-BB-URB)

10 replications × 2 fertilization rates × 2 species = 40 trees

Sugar maple (*Acer saccharum* Marsh. Green Mountain®) and red maple trees were field grown at the Urban Horticulture Center nursery in Groseclose silt loam soil (clayey, mixed, mesic, Typic Hapludults) and transplanted with intact rootballs wrapped in burlap (balled and burlapped; B&B) with 71-cm wide, machine-dug rootballs in early April 2003. The planting site was compacted, low-fertility soil (Table 1) along the Virginia

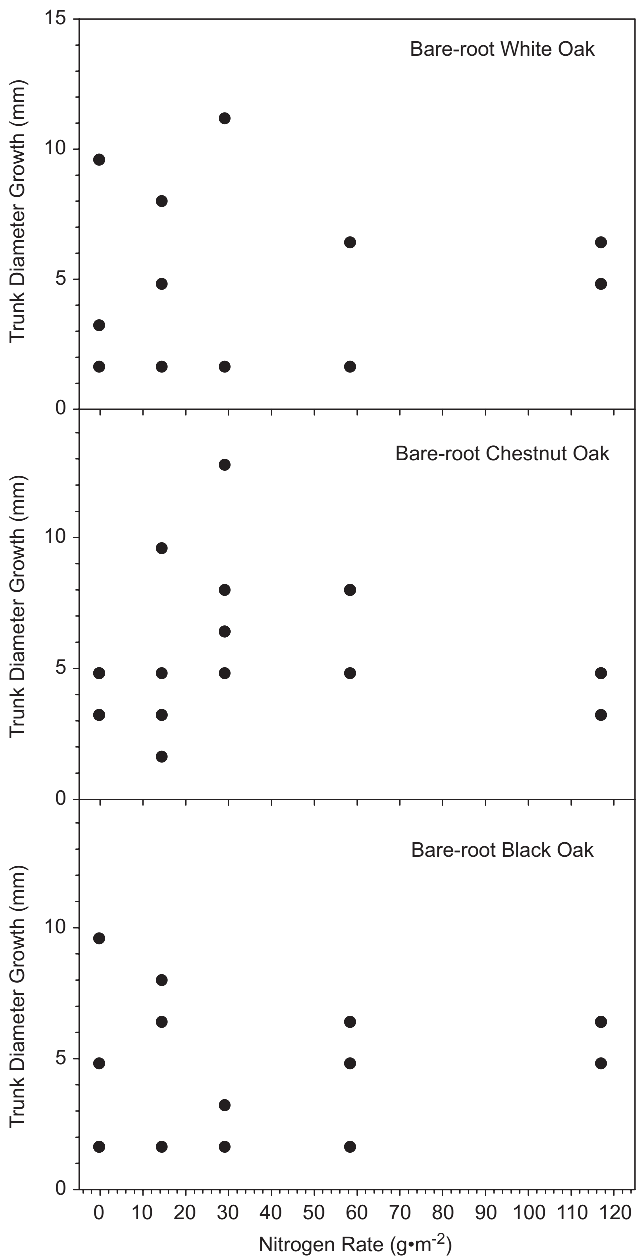


Fig. 5. Experiment 5-BR-FF. Two-year trunk diameter increase for individual trees of white oak (*Quercus alba* L.), chestnut oak (*Quercus prinus* L.) and black oak (*Quercus velutina* Lam.), not fertilized or fertilized at 14.6, 29.3, 58.6, or 117.23 g m^{-2} N. See Table 2 for statistics.

Tech baseball field and approaching roadway. Planting holes were approximately 45-cm depth × 150-cm wide. Fertilizer was the same as described in Experiment 1-CONT-AVG and was applied at 0 or 29.3 g^{-2} N over a 1 m^2 area within the excavated planting hole and over the rootballs when the holes were approximately 2/3 backfilled (i.e. unfertilized or fertilized). All trees were mulched with a 5-cm deep layer of shredded hardwood bark after fertilization. Trees were irrigated to apparent field capacity soon after planting and irrigated regularly with drip irrigation bags (i.e. "Gator" bags) for the following 3 months. Irrigation was withheld thereafter. Trunk diameter was measured 30-cm above the ground at planting and for the following 3 years. Controversy and misunderstanding abounds concerning the effect of nitrogen fertilization of trees on pest attack, particularly insects (Kyto et al., 1996). Experiment 4-BB-URB included systematic monitoring of insect and pathogen damage on all trees of both species, beginning 1 month after transplanting. We sampled each tree by collecting a twig with at least five leaves on it from the top and bottom of the canopy every other week for 9 weeks in May through July. Each canopy was divided into 4 quarters and the twigs were sampled from a randomly selected quarter. Foliar nitrogen levels were determined in mid August 2003 (approximately 4 months after transplanting) using three, randomly selected replications of each treatment. Leaf sampling, SPAD-502 readings and analysis were the same as described in Experiment 1-CON-AVG.

Experiment 5: Bare-root trees in a forest fragment (5-BR-FF)

5 replications × 5 fertilization rates × 3 species = 75 trees

White oak (*Quercus alba* L.), chestnut oak (*Quercus prinus* L.) and black oak (*Quercus velutina* Lam.) trees were field grown at the Urban Horticulture Center nursery in Groseclose silt loam soil (clayey, mixed, mesic, Typic Hapludults) and transplanted bare root in mid April 2003. Trunk diameters, measured 15 cm from ground, (S.E. mean in parentheses) averaged 2.6 (0.13), 3.5 (0.13), and 3.3 (0.10) cm for white oak, chestnut oak, and black oak, respectively. Rootballs on all trees were approximately 36 cm deep × 55 cm wide. Trees were planted into the understory of widely spaced hardwoods, dominated by white oak, at the Virginia Tech amphitheater (a little-frequented glade) in Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludults). The soil was uncompacted with higher carbon and nitrogen than the other four sites (Table 1), presumably because of accumulated leaf litter. Planting holes were approximately 36 cm deep × 110 cm wide. Fertilizer was the same as described in Experiment 2 and was applied over a 1 m^2 area at 0, 14.6, 29.3, 58.6, or 117.23 g m^{-2} N on top of the ground after planting. All trees were irrigated to apparent field capacity soon after planting and irrigation was withheld thereafter.

Results

Experiment 1-CON-AVG

Survival was 100% for all species throughout the 3 years of this experiment. Overall, fertilizer regime had

Table 2. *P*-values from five experiments testing the effectiveness of fertilizing landscape trees produced in the ground and transplanted bare root or balled and burlapped (B&B) or produced and transplanted from containers on post-transplant trunk diameter growth

	Experiment	$P>F$[a] Time period (post-transplant growing season)			
		1	2	3	4
Container grown					
55-L swamp white oak	1	0.882[a]	0.806	0.997	NA
55-L shingle oak	1	0.636	0.106	0.604	NA
55-L pear	1	0.796	0.245	0.378	NA
55-L Freeman maple	1	0.617	0.588	0.439	NA
55-L red maple	2	0.636	0.474	0.312	NA
14-L sweetgum	3	0.260	0.053	0.568	0.963
14-L red maple	3	0.712	0.423	0.251	0.260
Balled and burlapped					
Sugar maple	4	0.028	0.680	0.214	0.812
Red maple	4	0.918	0.250	0.715	0.849
Bare root[a]		Linear	Quadratic		
White oak	5	0.731[b]	NA		
Chestnut oak	5	0.024	0.021[c]		
Black oak	5	0.467	NA		

[a] $P>F$ for overall treatment effect during post-transplant periods from multivariate repeated measures analysis of variance.
[b] $P>t$ for parameter estimates from regression analysis.
[c] $R^2=0.275$.

very little effect on tree growth throughout the 3 years of observation (Fig. 1; Table 2). Although the *P*-value for the treatment effects test dropped to 0.106 for the second growing season for shingle oak, any possible treatment effect did not persist through the third year. These trees were planted in soil that would be considered favorable for agricultural production, although it is fairly infertile, as is typical of the region. EC readings (S.E. of means in parentheses) of rootballs at transplanting were 0.30 (0.03), 0.35 (0.05), 0.17 (0.02), and 0.15 (0.01) $\mathrm{ds\,m^{-1}}$ for Freeman maple, pear, shingle oak, and swamp white oak, respectively. These readings indicate relatively low residual nitrogen within their rootballs from production (Stanley et al., 2003), so trees might have been expected to respond to fertilization. A temporary growth reduction from the rootball slicing (Gilman et al., 1996) and a general acclimation to transplanting (i.e. transplant shock) (Close et al., 2005) may have masked a fertilization response. Swamp white oak and shingle oak showed a growth that is typical of many transplanted trees where growth is low in the first year, greater in the second year, and still greater in the third year. Freeman maple had a lag in growth the first post-transplant year, but "Cleveland Select" pear grew steadily after transplanting (Fig. 1). In this experiment, we continued with a yearly fertilizer application. We did not increase the area fertilized so as to minimize foraging from adjacent trees. It is unlikely that roots from adjacent trees could effectively forage within the immediate zone that we fertilized because of the high density of roots in the original rootball and just beyond. We saw no roots of adjacent trees when we moved several trees at the termination of the experiment. Therefore, as trees grew, they received less N relative to tree size. Fertilizer application rates in this experiment represented the mean recommended rate by ANSI of $14.6\,\mathrm{g\,m^{-2}}$ N (American National Standards Institute (ANSI, 1998) and a lower and higher rate.

Experiment 2-CON-HWY

In this experiment with container-grown red maples, survival was 100% and, as also seen in Experiment 1-CON-AVG, overall evidence for a fertilizer effect was weak throughout the experiment. These trees were planted along a drainage ditch for a two-lane highway in front of the Urban Horticulture Center. This soil was the dredge from the roadside ditch and is compacted with high pH (Table 1), conditions unfavorable for tree growth. A bulk density of 1.4 severely limited root expansion of conifers growing in similar-class soil (Zisa et al., 1980). With adequate irrigation, early top growth is not necessarily restricted (Halverson and Zisa, 1982), but dry conditions, common to roadside sites such as this dramatically increase soil resistance to root impedance, further limiting root extension (Day et al., 2000). Unfertilized trees appeared to lag behind fertilized trees the second growing season (Fig. 2), but a P-value of 0.474 (Table 2) gives no indication that this was a treatment effect. A contrast between fertilized and unfertilized trees resulted in $P = 0.230$, and unfertilized vs. fertilized at $14.6\,g\,m^{-2}$ resulted in $P = 0.160$. Any evidence of a fertilization effect appears transitory since evidence for overall treatment effect for post-transplant growing season was $P = 0.312$ (Table 2), although unfertilized trees appeared to catch up somewhat with fertilized trees during post-transplant growing season three (Fig. 2; $P = 0.130$). In this experiment, rates that represent four and eight times (58.6 and $117.2\,g\,m^{-2}$ N) the recommended rate ($14.6\,g\,m^{-2}$ N) were tested, but no negative or positive effect was evident.

Experiment 3-SM-CON-CUT

For these smaller container-grown trees, survival was again 100% for both species throughout the 4 years of this experiment. EC values (S.E. mean in parentheses) of rootballs at transplanting were 0.11 (0.01) and 0.17 (0.03) $ds\,m^{-1}$ for red maple and sweetgum, respectively, indicating very low native fertility levels in the rootballs at planting (Stanley et al., 2003). There was evidence of a fertilizer effect during post-transplant season two for sweetgum, but no effect was evident during seasons three and four (Fig. 3; Table 2). For red maple, little evidence exists for a fertilizer effect. These trees were planted in a random and highly scattered fashion adjacent to the Virginia Tech sports practice field. Soil was compacted (Table 1) cut-and-fill. Trees of both species grew steadily throughout the 4 years of this experiment, with or without fertilization at planting. Root penetration in this soil would likely be restricted, especially when dry (Day et al., 2000; Zisa et al., 1980). Because of inherent variability in field experiments, we chose to maximize the number of replications by testing only fertilized or unfertilized treatments. We chose a high fertilization rate ($29.36\,g\,m^{-2}$ N), but no clear effect was evident by the fourth post-transplant growing season.

Experiment 4-BB-URB

Survival was 100% for sugar maple throughout the 4 years of this experiment with large balled and burlapped trees, and nearly so for red maple. One red maple was damaged by a truck and excluded from the analysis. Fertilizing sugar maple at planting resulted in a slight, but definite increase in growth compared to unfertilized trees the first season after transplanting (Fig. 4; Table 2). However, growth remained similar to unfertilized trees for the remaining 3 years of the experiment. Fertilized and not-fertilized red maples grew at almost identical rates. Trees were planted along the approach to Virginia Tech's main campus in a compacted site (Table 1) subjected to past cut-and-fill and grading operations. Results from this experiment agree with our recently published study (Day and Harris, 2007) on transplanted B&B red maple and linden, where response to fertilization at planting had very little effect. In that study fertilizer was applied at $14.6\,g\,m^{-2}$ N, whereas in the present study fertilizer was applied at $29.3\,g\,m^{-2}$ N. In addition, the site was considerably more favorable in the maple and linden study than the present study. For all trees throughout the 9 weeks of observation only 14 incidences of "heavy" damage (i.e., $>50\%$ of leaf surface area was affected) from insects or pathogens was observed, and none occurred on the same tree. Damage was restricted to leaf spots, but the pathogen was not identified; insect damage was only classified as "minor" (i.e., $<25\%$ of leaf surface area was affected). This lack of an increase in insect predation due to nitrogen fertilization agrees with the general consensus reached by Kyto et al. (1996) for established trees in their review. However, we could not detect an increase in foliar nitrogen due to fertilization in our transplanting experiment (discussed below), so nutrient-enriched plant tissue was likely not an inducement to predation.

Experiment 5-BR-FF

In contrast to the other four experiments, mortality approached 50% for all species in this forest fragment site. This high mortality was likely a combination of difficult-to-transplant species, bare-root methodology, lack of adequate post-transplant irrigation, and site occupation by pre-existing trees. In addition, a few of the missing trees may have been removed by the Virginia Tech grounds crew to make room for other plantings. Because of this high mortality, we regressed 2-year trunk diameter growth against N rate applied at planting (Fig. 5; Table 2). Trunk diameter growth was generally small, with no relationship between growth and rate of N for white oak and black oak. A quadratic relationship was evident, however, for chestnut oak. Although the relationship was clearly present ($P = 0.021$), little variation was described ($R^2 = 0.275$).

Discussion

The objective of all five studies was to test if fertilizing at planting facilitated establishment of shade trees. Each study represented a different combination of production method and transplant site. Although 10 species were studied, there was no indication of anything beyond a transitory benefit (at most) from fertilization. Three sites could be considered very common to urban areas (topsoil removed, compacted) and generally inhospitable to tree establishment, whereas two sites (1-CON-AVG and 5-BR-FF) could be considered to be similar to many older residential sites (not compacted agricultural or forest soil). The post-transplant growth period studied in each experiment meets or exceeds the period generally considered adequate for full establishment of trees of these sizes (Watson, 1985). Even though there were small responses to fertilizing at planting (sweetgum in Experiment 3-SM-CON-CUT, sugar maple in Experiment 4-BB-URB, black oak in Experiment 5-BR-FF), these results probably do not warrant prescribing fertilizer at planting as a general practice. Instead of fertilizing at planting, other site treatments, such as improving overall conditions of surrounding soil by adding organic matter and reducing compaction (Day et al., 1995), and increasing soil volume (Grabosky and Gilman, 2004), may be the most worthwhile investments to speed establishment and long-term growth.

Several of the rates used in this experiment exceed the current recommendations of between 9.8 and 19.5 $g\,m^{-2}$ N for newly transplanted trees (American National Standards Institute (ANSI), 1998). The rootball of a transplanted tree (container, B&B, or bare root) occupies only a small fraction of the ground surface area that would be occupied by an established tree of the same size (Gilman, 1988). For example, for a 7.5-cm trunk diameter B&B tree that is 2.4 m tall tree, the *transplanted* root ball is generally 0.71 m diameter, yielding a rooting ground surface area of 0.4 m^2 (American Nursery and Landscape Association, 2004). The same size, fully established tree planted in open ground (using the rule of thumb that root spread is 1.5–2 times tree height) would have a root system ground surface area between 10.4 and 18.6 m^2. Thus, when fertilization is based on ground surface area of the root system, a tree that has not been transplanted would receive roughly 20–40 times as much fertilizer as the same tree after transplanting. It has been suggested that one possible reason for the lack of tree responses to fertilization in most cases is that the recommended rates and practices may not deliver sufficient N to spur a measurable response, either because of insufficient rates or inability of compromised root systems to take up nutrients (Day and Harris, 2007). However, Experiments 2-CON-HWY and 5-BR-FF tested N fertilization rates of up to 117.2 $g\,m^{-2}$, with no apparent growth response, indicating that increased rates do not address this problem.

High-fertility regimes are usually employed during production since rapid growth is profitable. Productive soil and attention to detail combine to maximize production and profits. Nursery production employs a fertilizer regime that maximizes top growth while maintaining a balance with root development. Compared to rates for container production in particular, the recommended N rates for post-transplant application are extremely low. The manufacturer's recommended medium rate for production of 55-L trees for the POLYON® coated slow-release product utilized in Experiments 2-CON-HWY and 5-BR-FF is 148 g of product. Converted to a per unit surface area, this equals 185 $g\,m^{-2}$ N, dramatically higher than the recommended rate of 14.6 $g\,m^{-2}$ N for newly transplanted trees. A container-grown tree with the same canopy size as a field-grown tree would have approximately the same nutritional requirements as the field-grown tree, but fertilizer must be applied at a higher rate to the smaller rootball. Transplanted container rootballs should theoretically be able to take up similar rates at planting as was applied during production, whereas, the much lower root density of field-grown transplants may impose a much lower limit to uptake potential. Therefore, higher rates of fertilizer should be effective if applied to newly transplanted, container-grown trees. Yet we did not observe any growth response to N in the experiments with container-grown trees. Removal of the container at planting changes the moisture dynamics within the container (Spomer, 1980) and pine-bark rootballs can quickly become very dry (Hanson et al., 2004). This change in container solution likely impacts nutrient delivery to roots, but such an interaction between the change in rootball solution at transplanting and tree nutrition has apparently not been studied. The generally accepted rate for field production is 28 $g\,m^{-2}$ N (Ingram et al., 1998), a rate that is twice as high as the mean recommended rate in the landscape, but a rate that we tested in all five of our experiments.

Neither concentration of N within leaves nor SPAD-502 values were increased by fertilizing at planting (Table 3). This fact, coupled with no increase in growth due to fertilizing, suggests that trees took up very little nitrogen from the fertilizer. Our data indicate that the positive relationship between SPAD-502 readings and laboratory-derived nitrogen concentrations varied among species (Table 3). As reported by others (Sibley et al., 1996), red maple had the lowest correlation. Very strong correlation ($r = 0.921$) was evident for sweetgum. Considering our entire data set, SPAD-502 readings correlated well with actual N concentration ($r = 0.692$), although one should realize that there were distinct differences within the seven species tested (Table 3). The small container-grown trees in Experiment 3-SM-CON-CUT and the B&B trees in Experiment 4-BB-URB were tested only 4 months after fertilization. Nitrogen uptake may have been suppressed by the root severance (Dong et al., 2003) that occurs during harvesting for B&B trees. Slicing container rootballs of shade trees is a common industry practice because of concern of persistent girdling roots. Many growers utilize specially constructed containers that chemically (Arnold and Struve,

Table 3. N concentration within leaves, SPAD-502 values, and correlation between N concentration and SPAD-502 value for each species and N fertilizer rate, applied at planting in Experiments 1, 3, and 4

Experiment	Fertilization rate ($g\,m^{-2}$ N)	N[a] (% dry mass)	N[b] $P>F$	SPAD-502[c]	SPAD $P>F$	R^d (N-SPAD)
1	55-L Freeman maple		0.261		0.627	0.268
	0	1.90 (0.03)		36.04 (0.73)		
	4.9	2.02 (0.04)		37.19 (0.37)		
	14.6	2.07 (0.14)		37.45 (2.14)		
	29.3	2.13 (0.05)		38.25 (0.46)		
1	55-L swamp white oak		0.994		0.695	0.423
	0	2.80 (0.11)		46.11 (1.17)		
	4.9	2.81 (0.06)		44.29 (1.82)		
	14.6	2.81 (0.23)		45.00 (1.09)		
	29.3	2.76 (0.13)		43.88 (1.34)		
1	55-L shingle oak		0.053		0.290	0.568
	0	2.71 (0.04)		40.78 (1.13)		
	4.9	2.16 (0.25)		37.03 (0.91)		
	14.6	2.60 (0.07)		39.22 (1.53)		
	29.3	2.73 (0.04)		40.31 (1.75)		
1	55-L pear		0.304		0.081	0.353
	0	2.24 (0.03)		43.83 (0.58)		
	4.9	2.34 (0.07)		42.92 (0.39)		
	14.6	2.18 (0.08)		41.31 (0.86)		
	29.3	2.18 (0.06)		43.05 (0.86)		
3	14-L sweetgum		0.667		0.979	0.921
	0	1.45 (0.12)		30.54 (1.02)		
	29.3	1.99 (0.13)		34.55 (1.45)		
3	14-L red maple		0.220		0.086	0.693
	0	1.80 (0.04)		30.54 (1.02)		
	29.3	2.00 (0.13)		34.55 (1.45)		
4	B&B sugar maple		0.362		0.790	0.328
	0	1.37 (0.10)		33.13 (2.70)		
	19.3	1.50 (0.09)		32.24 (1.64)		
4	B&B red maple		0.685		0.266	0.697
	0	1.77 (0.10)		35.07 (0.80)		
	19.3	1.72 (0.05)		33.83 (0.53)		

[a]Five randomly selected leaves pooled for analysis per replication; three replications; S.E. of means in parentheses.
[b]$P>F$ for overall treatment effect.
[c]Five subsamples; one reading per subsamples (same five leaves as were pooled for N analysis); three replications. Units for SPAD-502 values are dimensionless.
[d]Pearson correlation coefficients. Overall r for entire data set was 0.692.

1989) or mechanically (Whitcomb and Williams, 1985) prune roots as they grow so that slicing is unnecessary. Slicing 55-L rootballs of shade trees at planting would likely remove 30–35% of the root mass and many if not most of the intact root tips (Struve, personal communication). If indeed 35% of the root system was removed at planting, nutrient uptake may have been compromised.

Since rootball EC readings were low at planting for the 14-L trees, it was somewhat surprising that tissue N levels did not reflect fertilization. N rates may have been too low to result in a detectable increase in leaf N 4 months after application. We tested foliar nitrogen on the 55-L trees in Experiment 1-CON-AVG during the second season after transplanting. Trees were fertilized again at the same rate and over the same area 1 year later, so they had been fertilized twice before tissue analysis. Any nitrogen that was taken up may have been utilized, although its use did not result in additional trunk growth compared to unfertilized trees. For B&B red maple in Blacksburg, VA, new root growth into the backfill soil may not be visible until 38 days after spring transplant, but other species can take much longer (Kelting et al., 1998). For example, fringe tree

(*Chionanthus virginicus* L.) roots may not be visible until 110 days after spring transplant (Harris et al., 1996). Thus, delivery of nutrients to the newly transplanted tree may be hindered by both the reduced physical size of the root system and its physiological state, especially for B&B and bare-root trees.

Three of our sites (Experiments 2-CON-HWY, 3-SM-CON-CUT, 4-BB-URB) were compacted to bulk densities that are probably typical for many urban landscapes (Day and Bassuk, 1994) and can severely limit root extension, especially when dry (Day et al., 2000; Zisa et al., 1980). Flood tolerant species such as the sweetgum, red maple, and swamp white oak used in our experiments should be able to exploit the softening of the soil during rainy periods. Rapid growth during such periods would be very desirable, since conditions radically change when soil dries. Favorable nutrient status would be required for best growth in these periods, yet we saw almost no benefit to fertilizing at planting.

Other techniques for improving establishment rates for urban trees, such as nutrient-loading during production (Lloyd et al., 2006), or improvement in long-term soil productivity are avenues that needs further exploration. Intensive site preparation that includes mechanical operations such as harrowing and disking has been demonstrated to be effective at improving initial tree growth in sites compacted by timber harvesting (Miwa et al., 2004). In sandy soils, Burger and Pritchett (1988) found that intensive site preparation that included harrowing increased nutrient levels in the soil solution, even though overall nutrient levels at the site were reduced when compared to control plots. In many urban sites, extreme soil compaction may be a primary factor limiting tree establishment and root exploration. However, traditional site preparation techniques or other large-scale soil manipulation is impractical in confined urban spaces and where underground infrastructure (e.g. utilities) is present. In contrast to Simcock et al. (2006), we did not find that fertilization was effective in compacted sites. However, because urban trees can lose the majority of their roots during harvesting for transplanting into their final site, the recovery period is much greater and results for small seedlings may not be applicable. Reduced canopy growth (transplant shock) can be expected even in the best of conditions until an equilibrium between roots and shoots (i.e. the root:shoot ratio) is restored by compensatory growth of the root system (Wareing, 1970; Borchert, 1973; Abod and Webster, 1989). Besides compromised water uptake ability, loss of roots at transplanting also likely reduces shoot growth due to loss of root physiological functions such as food storage and hormone production. These effects of root loss were not overcome by fertilization at planting. Although we did not compare fertilization practices with soil remediation practices, fertilizing at planting and during the establishment period does not appear to be an effective way of speeding establishment of urban trees, even on stressful sites.

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