Overlaying compacted or uncompacted construction fill has no negative impact on white oak and sweetgum growth and physiology

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Abstract: Raising the soil grade, frequently required during building construction, is thought to damage trees and is of concern to foresters responsible for tree protection on such sites. We investigated the effects of applying fill over the roots of 22-year-old white oaks (*Quercus alba* L.) and 13-year-old sweetgums (*Liquidambar styraciflua* L.). Treatments included a control (no fill), fill (sandy loam C horizon soil spread 20 cm deep), and compacted fill (same as fill but compacted). Trees with fill had soil held away from trunks or not. After 3 years, there was no consistent treatment effect on growth, chlorophyll fluorescence, or soil respiration in either species. Fill disrupted normal soil moisture patterns. White oak plots with fills had lower soil water contents than controls. In sweetgum plots, soil underlying fill was typically drier than fill layers, whereas control plot soil moisture tended to increase with depth. Fills did not affect overall root density for either species. White oak grew roots well into fill soils, but sweetgum did not, although sweetgum root distribution shifted upwards under fills. Other factors associated with raising the grade, such as soil trafficking and root severance, may be responsible for much of the tree decline attributed to fill.

Résumé : L'élévation du niveau du sol qui est souvent rendue nécessaire lors de la construction d'un édifice est potentiellement dommageable pour les arbres et préoccupe les forestiers qui sont responsables de la protection des arbres sur ces sites. Les auteurs ont étudié les effets d'un ajout de sol au-dessus des racines de chênes blancs (*Quercus alba* L.) âgés de 22 ans et de copalmes d'Amérique (*Liquidambar styraciflua* L.) âgés de 13 ans. Les traitements incluaient un témoin (aucun remblai), un remblai (20 cm de sol provenant de l'horizon C d'un loam sablonneux) et un remblai compacté (le même sol compacté). Le tronc des arbres remblayés a été protégé ou non. Après 3 ans, il n'y avait pas d'effets consistants sur la croissance, la fluorescence de la chlorophylle ou la respiration dans le sol dus aux traitements chez aucune des espèces. Le remblai a perturbé les patrons d'humidité du sol. Les parcelles de chêne blanc remblayées avaient un contenu en eau du sol plus faible que les parcelles témoins. Dans les parcelles de copalme, le sol sous le remblai était typiquement plus sec que le sol du remblai, alors que dans les parcelles témoins l'humidité du sol avait tendance à augmenter avec la profondeur. Le remblai n'a pas affecté la densité globale des racines des deux espèces. Les chênes blancs ont formé des racines dans le sol du remblai. Ce n'était pas le cas des copalmes mais la distribution de leur système racinaire s'est déplacée vers le haut sous le remblai. Les autres facteurs associés à l'élévation du niveau du sol, tels que le transport du sol et les bris de racines, sont peut-être responsables de la majeure partie du dépérissement des arbres attribué au remblai.

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Introduction

Healthy mature trees are a valuable asset to the urban forest, often representing decades of community investment. Towns and cities, however, are not static. Infrastructure is continually replaced, buildings are constructed or remodeled, and new land is developed. These construction activities can result in extensive damage to existing trees. Some of the potentially most valuable urban trees are large forest trees that we intend to retain when forested land is converted to residential or commercial building sites. Protecting existing trees, whether they are already part of the urban forest or are selected specimens from land undergoing development, is difficult and expensive. Protection strategies could be more effective if we fully understood how construction affects trees. Unfortunately, there is little research available and we rely on educated guesses when assessing the long-term risk posed to a tree by a given construction process.

An integral part of land development and renewal is soil grading. Activities ranging from paving to new building construction usually require grading to meet design needs and drainage codes. Desired grade changes are often achieved by applying fill soil over the root zones of existing trees. This is considered extremely detrimental to tree health and recommendations for avoiding such damage abound (Yingling et al. 1979; Schoeneweiss 1982; Coder 1996). The amount of fill that can be applied without damaging trees is generally

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considered to be ≤15 cm and sometimes much less (Schoeneweiss 1982; Coder 1996; Harris et al. 1999). For a clay fill, depths of as little as 2.5 cm are thought to initiate root damage (Schrock 1994; Coder 1996). It is not clear, however, how grading causes tree decline. Research in this area is extremely limited; however, it appears that fill alone may not always be detrimental to tree health. When the root systems of 11-year-old eastern white pines (*Pinus strobus* L.) were covered with 20 cm of fill soil, no reduction in shoot growth or photosynthesis was observed after 2 years (Smith et al. 1995). However, the fill soil was not compacted, the root zone was not trafficked during application, soil was kept clear of tree trunks, and roots may have had access to soil beyond the filled area. Some authors have observed that the addition of soil over the root zone can alter drainage properties and be an impediment to gas exchange (Yelenosky 1963, 1964). Yelenosky also noted that two dogwoods (*Cornus florida* L.) partly buried by the fill, and several trees of other species in similar situations, appeared to be in decline. It is impossible, however, to judge if their decline was due to fill or to other factors. For example, grading also frequently results in soil compaction (Ishiwata et al. 1996) and root severance. Additionally, placing soil directly against tree trunks is thought to increase incidence of infection from soil-borne diseases such as *Phytophthora* and *Armillaria* root rots (Britton 1990; Smiley 1992), although there is little research to support or refute this belief. Nonetheless, tree wells have traditionally been used to keep the soil away from the trunk when fill is applied (Yingling et al. 1979; Morgan 1993). Tree wells are usually low retaining walls set anywhere from about 30 cm to several meters away from the trunk. Within the tree well, soil is maintained at the original grade.

In certain natural forests, tree root systems and trunks are occasionally covered by the periodic deposition of soil. Coast redwood trees (*Sequoia sempervirens* (D. Don) Endl.) on alluvial flats along the Eel river in California have been subjected to periodic flooding for thousands of years. As a result, as much as 1.2 m of silt has been deposited on the forest floor at one time. Initially, trees respond by growing roots vertically upward into the new soil. These are later replaced by a new, adventitious root system originating from the trunk near the new soil surface (Stone and Vasey 1968). These responses are presumably species specific as they are considered partly responsible for the dominance of coast redwood in these areas; however, the death and decline of competitor species is also partly due to flooding and fire, rather than to sedimentation alone. New adventitious root systems were also formed in white spruce (*Picea glauca* (Moench) Voss) after sand deposition over the root zone due to dune movement in subarctic Canada (Filion and Marin 1988). Tree dieback occurred when sedimentation surpassed 8 cm/year or when it exceeded 1.25 m in total, but these effects appeared to be at least partly related to the extremely cold temperatures beneath the soil surface, rather than to changes in soil water or nutrient status. Adventitious roots under soil buildup have also been documented in black spruce (*Picea mariana* (Mill.) B.S.P.) (DesRocher and Gagnon 1997) and poplar (*Populus* spp.) (Telewski and Lynch 1991). In landscape situations, the use of tree wells would presumably make the formation of adventitious root systems extremely unlikely.

We wanted to determine which aspects of applying construction fill injure trees and how. We selected white oak (*Quercus alba* L.), an upland species, and sweetgum (*Liquidambar styraciflua* L.), a bottomland species, for evaluation. In natural forests, sweetgum is more likely to experience some alluvial soil deposition and is more tolerant of poor drainage than white oak. In this pair of experiments we sought to answer the following questions. Is raising the grade around established white oak and sweetgum trees detrimental to their health and survival in the absence of other site disturbance? When the grade is raised, does keeping construction fill away from trunks (i.e., using tree wells) benefit these trees? Does the soil compaction that typically occurs during grade changes play a significant role in the effect of the grade change on trees? We monitored height and diameter growth to provide an integrated measurement of tree vigor after grade changes. Physiological measurements including chlorophyll fluorescence and soil respiration were used to detect early tree response to construction fill treatments. To explain tree response to the grade change, we used soil moisture and bulk density measurements to characterize the new soil environment and compared root distribution in this new environment (fill treatments) to that in the existing soil (controls).

Materials and methods

Oak experiment

Site description and maintenance

We conducted this experiment in a stand of white oaks on the Reynolds Homestead Forest Resources Research Center in Patrick County, Virginia, U.S.A (36°38.04′N, 80°16.02′W). The oaks were planted as 1–0 seedlings in 1975 into a 0.24-ha plot. In early June 1996, one hundred and fifty-four oaks remained, and all other tree species were removed. Although the spacing of the oaks was highly variable, virtually all trees were open on one or more sides and had a growth habit typical of open-grown trees. The native soil is a Lloyd sandy clay loam (50.7% sand, 26.6% silt, and 22.7% clay; fine, kaolinitic, thermic Rhodic Kanhapludults). The site is eroded and of low to medium quality for white oak. Herbaceous plants and remaining woody vegetation were removed via repeated mowing and applications of glyphosate. After treatments were installed the following year, plots were maintained weed free via two or three herbicide applications per year (glyphosate and a combination of glyphosate and sulfometuron methyl).

Experimental layout and treatments

The stand was divided into 15 roughly rectangular plots, which served as experimental units. Plots ranged in size from 5 × 7 m to 12 × 18 m and included from 5 to 19 trees. Because of the uneven arrangement of the trees within the stand, some plots were contiguous with others, while some abutted wide buffer zones maintained in the same manner as controls but typically devoid of trees. Plots extended 3.6 m beyond the edge trees of each plot in most cases to encompass the root zone of the trees. This was not possible, however, where trees in contiguous plots were close together.

Three soil treatments were assigned in a completely random design and applied in June 1997: three treatments × five replications = 15 plots. Soil treatments included (*i*) control (C), no fill treatment; (*ii*) fill (F), a sandy loam C horizon soil (54.7% sand, 26.4% silt, and 18.9% clay; Clifford series, clayey, kaolinitic, mesic Typic Hapludults) brought from a nearby site was spread 20 cm deep over the entire plot; and (*iii*) compacted fill (CF), same

as F, but two passes from a 697-kg sheep's-foot compactor (Model RT 820, Wacker Corp., Menomonee Falls, Wis.) with a 81 cm wide drum and the vibrator engaged were made over the fill soil when gravimetric soil moisture was 36%. Traffic from heavy equipment (loaders, etc.) was excluded from C and F treatment plots and kept to a minimum in CF plots. Soil was graded manually, using shovels and rakes, in F plots. In CF plots, soil was also spread primarily by hand, but loaders were used where there was no possibility of hitting trees or greatly trafficking the soil. Bulk density measurements were taken the following May using a slide hammer undisturbed core sampler (inline AMS slide hammer, AMS, Inc., American Falls, Idaho) and a 92-cm^2 sleeve. Two samples were taken per replication centered at 10 cm deep and also at 10 cm deep in the native soil underlying the compacted fill in CF plots. Samples were dried to a constant mass at 105°C, and bulk density was calculated. Mean bulk densities indicated that the compaction process did not affect the underlying native soil (CF (underlying native soil) 1.27 ± 0.05 $g \cdot cm^{-3}$ (mean ± SE); C = 1.27 ± 0.03 $g \cdot cm^{-3}$). The mean bulk densities of the compacted and uncompacted fill showed that the treatment of fill in CF plots resulted in moderate compaction of the fill layer (CF = 1.35 ± 0.03 $g \cdot cm^{-3}$; F = 1.12 ± 0.02 $g \cdot cm^{-3}$).

In addition, all trees in the F and CF treatments were randomly assigned to equal numbers of individual trees within plots. These treatments were (*i*) tree wells (TW), constructed of 57-L plastic nursery pots (44 cm diameter) with the bottoms cut out and turned upside down, were placed around the trunks of the trees before the fill was applied to hold the soil off the trunks, and (*ii*) no tree wells (NTW), with soil spread 20 cm deep against trunks. Five permanent stakes (polyvinylchloride schedule-40 pipe, 1.3 cm diameter), marked at the final soil depth, were placed in each plot to monitor soil settling throughout the experiment.

Tree growth

Trunk diameter at breast height (DBH) was measured 1.35 m above the original soil level on all trees on July 13, 1996 (after removal of competing vegetation, but before treatments were applied), and on June 22, 1999. Height was measured with a digital hypsometer (Forestor Vertex, Forestor Instrument AB, Sweden) on all trees on July 27, 1997, shortly after treatments were applied, and again on April 1, 1999.

Chlorophyll fluorescence

A portable chlorophyll fluorescence meter (CF-1000, P. K. Morgan, Inc., Andover, Mass.) was used to measure initial (f_0) and maximum (f_m) leaf fluorescence in five trees selected randomly from each plot. A synthesis of these two measurements, $f_v/f_m = (f_m - f_0)/f_m$, estimates the maximum quantum yield of photosystem II electron transport, and a low value can thus indicate tree stress (Mohammed et al. 1995). One, fully mature sun leaf that could be reached from the ground was selected from each subsample tree for measurement. Readings were taken while the leaf was shaded to avoid measurement error due to excessive heating of the cuvettes (Marler and Lawton 1994). After a 15- to 20-min dark-adaptation period, leaves were subjected to 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ of light, and fluorescence kinetics was recorded for 10 s. Measurements were taken every 2–4 weeks until the end of the growing season in 1997 to detect late-summer stress, and then occasionally throughout the experiment. Measurements were made on August 1, September 6, September 20, and October 11, 1997; July 21, 1998; and July 1, 1999.

Leaf chlorophyll content

We made a relative measure of leaf chlorophyll content on September 19, 1998, with a chlorophyll meter (SPAD-502, Minolta, Japan). Three fully developed leaves were measured on each tree. This measurement was intended to detect early fall leaf color change (i.e., chlorophyll loss) that can occur in trees under stress.

Soil respiration, moisture, and temperature

Soil respiration was measured in two locations, 30 cm apart, at each of two stations in each plot, resulting in four measurements per plot. Each station was positioned 1 m towards the interior of the plot from a randomly selected tree. For each measurement, cuvettes constructed of polyvinylchloride pipe caps fitted with closed-cell foam gaskets were placed over stationary rings embedded 5 cm deep in the top soil layer and enclosing 79 cm^2 of soil surface. Air was circulated via tygon tubing using a portable photosynthesis system (LI-6200, LI-COR, Lincoln, Nebr.) programmed to measure soil respiration. We measured ambient CO_2 concentration at the soil surface frequently during data collection and measured the rate of CO_2 evolution when chamber levels were close to that concentration. In conjunction with each pair of soil respiration measurements, we measured soil temperature at 10 and 30 cm depths with thermocouples. Soil respiration can respond sharply to short-term changes in temperature, especially in moist soil (Bryla et al. 1997). Consequently, we standardized soil respiration readings to a soil temperature of 23°C, which was close to the average temperature on all measurement dates, using a Q_{10} of 2 (Bouma et al. 1997) and temperature readings from the 10-cm depth. Using time domain reflectometry (Trase 6050XI, Soilmoisture Equipment Corp., Santa Barbara, Calif.), we measured volumetric water content in the top 15 cm of soil and at 15–30 cm deep in conjunction with each pair of soil respiration measurements and at other times during the 1998 growing season. Soil respiration was measured on June 23, July 28, and September 19, 1998; and on June 24, 1999. Measurements made in 1999 followed the same technique but used a larger chamber (covering 366 cm^2 of soil surface) without stationary rings, and were taken at only two subsamples per plot. Additional soil moisture measurements were made on April 2, June 3, and August 11, 1998.

Root distribution

On June 17, 1999, we dug a pit in each plot next to one of the soil respiration sites to expose a vertical face of soil 60 cm wide and 40 cm deep. We then placed a wire grid against each face and counted the severed roots visible through each 10 × 5 cm square of the grid. Roots were classed as either coarse (≥2 mm diameter) or fine (<2 mm diameter). The position of the interface between fill and original soil was also noted, if applicable.

Sweetgum experiment

Site description and maintenance

This experiment was conducted in a stand of sweetgums in a bottomland site at the Reynolds Homestead Forest Resources Research Center. Trees were planted as 1–0 seedlings in 1984 with a 0.6-m spacing in eight rows 1.8 m apart in a Chewacla sandy loam (50.7% sand, 26.6% silt, and 22.7% clay; fine-loamy, mixed, active, thermic Fluvaquentic Dystrudepts). This is a bottomland site of medium to high quality for sweetgum. In 1996, trees had long ago achieved full canopy closure, and little other vegetation was present. The stand was surrounded by a meadow of which a 3.6-m band was cleared on all sides using glyphosate. Plots were maintained weed free as in the oak experiment.

Experimental layout and treatments

The stand was divided into nine rectangular plots, each with some trees forming the edge of the stand. Three soil treatments and two trunk treatments were applied in September 1996. Soil treatments extended 3.6 m beyond the edge of the stand to cover as much of the root zone as possible. Two rows of trees extended beyond the main block and were designated a control plot because of

Table 1. Analyses of variance for height and DBH increases of all white oak trees.

Source and treatment	Height 7/24/97 (m)	Height 4/1/99 (m)	Height increase (%)*	DBH 7/13/96 (cm)	DBH 6/22/99 (cm)	DBH increase (%)*
Soil treatments						
C	5.4 (0.45)	5.6 (0.43)	5.1 (1.6)	6.7 (0.77)	8.8 (0.70)	43.9 (12.0)
F	5.5 (0.41)	5.8 (0.40)	7.8 (1.5)	6.7 (0.71)	8.8 (0.64)	39.7 (11.1)
CF	5.3 (0.45)	5.6 (0.42)	7.3 (1.6)	7.1 (0.79)	9.1 (0.72)	30.2 (12.4)
$p > F$	0.94	0.89	0.45	0.91	0.93	0.74
Trunk treatments						
TW	5.3 (0.16)	5.7 (0.17)	7.7 (0.51)	6.9 (0.15)	8.9 (0.22)	35.2 (1.9)
NTW	5.4 (0.17)	5.8 (0.18)	7.3 (0.55)	7.0 (0.16)	9.1 (0.23)	34.5 (2.1)
$p > F$	0.72	0.75	0.60	0.67	0.54	0.81
Fill treatments × trunk treatments						
FTW	5.4 (0.22)	5.8 (0.23)	7.6 (0.69)	6.9 (0.21)	9.1 (0.30)	40.7 (2.6)
FNTW	5.5 (0.23)	5.9 (0.24)	8.0 (0.73)	6.6 (0.22)	8.7 (0.31)	38.4 (2.7)
CFTW	5.3 (0.23)	5.6 (0.25)	7.8 (0.75)	6.9 (0.23)	8.8 (0.32)	29.7 (2.9)
CFNTW	5.3 (0.26)	5.6 (0.27)	6.5 (0.83)	7.4 (0.25)	9.6 (0.35)	30.7 (3.1)
$p > F$	0.89	0.76	0.46	0.40	0.41	0.61

Note: Values are least squares means with standard errors given in parentheses. C, control; F, fill; CF, compacted fill; TW, tree wells; NTW, no tree wells; FTW, fill with tree wells; FNTW, fill without tree wells; CFTW, compacted fill with tree wells; CFNTW, compacted fill without tree wells.

*Increases are measured as a percentage of the initial height or DBH.

the difficulty of applying soil treatments there. Growth and initial size of trees in this plot were later compared with those of other control plots with analysis of variance, and no differences were found. The remaining soil treatments were assigned randomly, resulting in three soil treatments with three replications for a total of nine plots. Treatments were as described for the oak experiment. However, because of the close spacing of the trees, somewhat more trafficking from a small loader occurred on CF plots during fill application than on oak plots. Bulk-density measurements were made as in the oak experiment in May 1998. Again, the compaction process did not affect the mean bulk density of the underlying native soil (CF (underlying native soil), 1.20 ± 0.07 $g \cdot cm^{-3}$; C, 1.20 ± 0.04 $g \cdot cm^{-3}$). The mean bulk densities of the compacted and uncompacted fill showed that the treatment of fill in CF plots resulted in moderate compaction of the fill layer (CF, 1.34 ± 0.03 $g \cdot cm^{-3}$; F, 1.10 ± 0.06 $g \cdot cm^{-3}$). Also, the trunk treatment TW was achieved by pulling fill soil approximately 20 cm away from the trunks by hand rather than by using nursery pots.

Tree growth

We measured the DBH of all trees on June 17, 1997, and June 22, 1999. Height was measured on July 27, 1997, and on April 1, 1999.

Chlorophyll fluorescence

Chlorophyll fluorescence measurements were made on eight trees selected randomly from the edge trees in each plot. Only edge trees were used because the leaves of interior trees were inaccessible. Sample leaves were selected as in the oak experiment. Measurements were made on August 16 and September 6, 1997; July 21, 1998; and July 1, 1999.

Soil and root measurements

Soil respiration, moisture, and temperature were measured as in 1998 data for the oak experiment. Soil respiration stations, however, were located in the center of the plots between the first and second rows and between the third and fourth rows of trees. Soil respiration was measured on July 14 and August 11, 1998. Additional soil moisture measurements were made on April 2, June 3, and September 19, 1998. Root distribution was measured on the same dates and using the same procedures as in the oak experiment.

Statistical analysis

We used the same methods of statistical analysis for both experiments. Soil treatment and trunk treatment effects on trees were analyzed using the general linear methods (GLM) procedure in SAS version 6.12 (SAS Institute Inc., Cary, N.C.) and Fisher's protected least significant difference (LSD), when appropriate. Trees within a plot with a given trunk treatment were treated as subsamples. The effects of soil treatments on soil conditions and root distribution were analyzed using GLM procedures and *t* tests in SAS and Minitab version 12 (Minitab, Inc., State College, Penn.). One-sided, paired *t* tests were used to evaluate differences in rooting in fill layers and in the underlying soil. The four soil respiration measurements in each plot were treated as subsamples.

Results and discussion

White oak growth

During the course of the experiment, DBH and height increase did not vary among oak trees by soil or trunk treatment (Table 1). Most trees appeared to be healthy and growing well with the exception of two trees in a CF plot that showed top dieback and one tree in a C plot that was very chlorotic.

Sweetgum growth

When all trees were considered, DBH and height growth percentages were not affected by soil or trunk treatment (C, 10.9 ± 1.5%; F, 6.4 ± 1.5%; CF, 6.9 ± 1.4%; $p = 0.15$). Because sweetgums were tightly spaced, their trunks had very little taper. Consequently, we integrated growth measurements by calculating $DBH^2 \times$ height as an index of volume. This index indicated a greater percentage increase in volume for control trees than for trees with fill treatments (C, 36.7 ± 3.7%; F, 19.0 ± 3.7%; CF, 23.0 ± 3.3%; $p = 0.03$).

However, the stand had developed many smaller trees that showed little or no growth because of competition from the dominant and codominant trees. Furthermore, trees in control plots tended to be larger at the beginning of the experiment and have fewer of these suppressed trees (mean initial

Table 2. Analyses of variance for height, DBH, and estimated volume increases of dominant and codominant sweetgums between 1997 and 1999.

Source and treatment	Height 7/24/97 (m)	Height 4/1/99 (m)	Height increase (%)*	DBH 6/17/97 (cm)	DBH 6/22/99 (cm)	DBH increase (%)*	$D^2H^\dagger$ increase (%)*
Soil treatments							
C	14.5 (0.24)	15.6 (0.32)	8.1 (1.4)	14.2 (0.41)	16.5 (0.36)*a*	16.1 (1.3)	47.4 (4.6)
F	15.0 (0.28)	15.9 (0.37)	6.2 (1.6)	13.1 (0.48)	14.6 (0.42)*b*	11.5 (1.5)	30.9 (5.4)
CF	14.7 (0.24)	15.9 (0.31)	8.5 (1.4)	13.7 (0.41)	15.4 (0.36)*ab*	12.3 (1.3)	35.5 (4.6)
p >*F*	0.47	0.84	0.54	0.31	0.04	0.10	0.12
Trunk treatments							
TW	15.0 (0.09)	15.7 (0.21)	6.0 (1.3)	13.7 (0.42)	15.3 (0.51)	11.6 (0.66)	30.5 (2.4)
NTW	14.6 (0.11)	15.9 (0.24)	9.0 (1.5)	13.0 (0.50)	14.7 (0.61)	12.2 (0.78)	35.8 (2.9)
p >*F*	0.04	0.65	0.20	0.35	0.44	0.62	0.24
Fill treatments × trunk treatments							
FTW	15.1 (0.14)	15.7 (0.33)	5.4 (2.0)	13.7 (0.66)	15.3 (0.81)	11.8 (1.0)	29.8 (3.9)
FNTW	14.8 (0.17)	15.7 (0.39)	6.5 (2.4)	12.3 (0.79)	13.7 (0.96)	10.6 (1.2)	29.3 (4.6)
CFTW	15.0 (0.11)	15.8 (0.25)	6.6 (1.6)	13.8 (0.51)	15.4 (0.63)	11.4 (0.81)	31.2 (3.0)
CFNTW	14.4 (0.13)	16.1 (0.30)	11.5 (1.9)	13.8 (0.61)	15.6 (0.74)	13.8 (0.96)	42.1 (3.5)
p >*F*	0.47	0.72	0.32	0.32	0.27	0.16	0.12

Note: Values are least squares means with standard errors given in parentheses. Dominant and codominant trees are the 25% of trees in each treatment with the greatest initial height. Means within a given source and column with different letters are significantly different at $\alpha = 0.05$ using Fisher's protected LSD. C, control; F, fill; CF, compacted fill; TW, tree wells; NTW, no tree wells; FTW, fill with tree wells; FNTW, fill without tree wells; CFTW, compacted fill with tree wells; CFNTW, compacted fill without tree wells.

*Increases are measured as a percentage of the initial height, DBH, or volume.

†Estimated volume increase calculated as $(\text{diameter})^2 \times \text{height}$.

DBH: C, 10.7 ± 0.48 cm; F, 8.8 ± 0.48; CF, 9.2 ± 0.43). For these reasons, growth of dominants and codominants (the top 25% of trees by initial height) was considered separately. Although final DBHs of dominants and codominants in control plots were greater than those in uncompacted fill plots, percentage increases in height, DBH, and volume did not vary among soil or trunk treatments (Table 2). Survival was close to 100%; only four highly suppressed trees died during the experiment, presumbably because of natural thinning of the stand. Overall, no consistent differences were evident among trees, indicating that soil and trunk treatments did not affect sweetgum growth during this period.

White oak chlorophyll fluorescence and chlorophyll content

Because of the short duration of the current experiments (3 years), we made chlorophyll fluorescence measurements to detect early signs of stress that might not be immediately reflected in growth measurements. Chlorophyll fluorescence has been used as a rapid, nondestructive technique for detecting stress in trees in the field or greenhouse (Epron and Dreyer 1990; Percival and Dixon 1997; Peterson et al. 1999). Fluorescence readings have been correlated with a number of stresses, including nutrient deficiencies (Peterson et al. 1999), waterlogging and NaCl spray (Percival and Dixon 1997), and drought (Conroy et al. 1986). Although fluorescence has consistently detected nutrient stress, its ability to detect drought stress is variable and, likely, species related. Fluorescence of sweetgum trees is not affected by drought (Peterson et al. 1999), and only very severe drought stress affects fluorescence in willow (Ögren 1990) and in three European oak species (Epron and Dreyer 1990). On the other hand, f_v/f_m is lower in droughted Monterey pine (*Pinus radiata* D. Don) (Conroy et al. 1986) and loblolly pine (*Pinus taeda* L.) (Peterson et al. 1999).

Soil and trunk treatments had no effect on chlorophyll fluorescence of white oak trees on most measurement dates. On September 6, 1997, however, mean f_v/f_m was higher for trees in uncompacted fill compared with controls and compacted fill using Fisher's protected LSD at $\alpha = 0.05$ (C, 0.80 ± 0.007; F, 0.82 ± 0.007; CF, 0.79 ± 0.007). Late 1997, 1998, and 1999 were drier than normal. The higher f_v/f_m ratio in the oak trees in uncompacted fill plots at this time could be due to a mulching effect or a result of the increased resources available because of the additional rooting space provided by the fill, although the magnitude of the increase in f_v/f_m was very slight. Additionally, measurements made July 1, 1999, indicated a trunk treatment effect on trees in the compacted fill plots. Mean f_v/f_m values were higher for trees in compacted fill without tree wells than for those with tree wells when tested using Fisher's protected LSD at $\alpha = 0.05$ (CFTW, 0.79 ± 0.01; CFNTW, 0.84 ± 0.01; FTW, 0.82 ± 0.01; FNTW, 0.83 ± 0.01). It is unclear why not having tree wells might result in higher f_v/f_m ratios. The greater number of comparisons needed for the trunk treatment analysis, however, increases the possibility of error in the mean separation. Neither soil nor trunk treatments affected relative chlorophyll content of oak leaves when measured in September 1998. Overall, there were no indications that fill resulted in tree stress as detected by measurements of chlorophyll fluorescence or content, suggesting that growth rates will continue to be unaffected by treatment in the near future.

Sweetgum chlorophyll fluorescence

We found no differences in f_v/f_m of trees in the various soil or trunk treatments on any measurement date. In sweetgum, chlorophyll fluorescence measurements may detect nutrient stress but not drought stress (Peterson et al. 1999). Consequently, our results probably do not reflect any changes or lack of changes in the water relations of the trees

Table 3. Soil respiration standardized to 23°C (Q_{10} = 2) from white oak plots on various dates in 1998 and 1999.

Soil treatment	Soil respiration ($\mu mol \cdot m^{-2} \cdot s^{-1}$)			
	6/23/98	7/28/98	9/19/98	6/24/99
C	3.98 (1.25)	1.32 (0.08)	1.01 (0.60)	2.71 (0.32)*a*
F	5.42 (0.85)	2.70 (0.45)	1.09 (0.52)	2.97 (0.37)*a*
CF	3.07 (0.69)	4.13 (1.54)	1.11 (0.34)	1.37 (0.20)*b*
p >*F*	0.26	0.14	0.99	0.006

Note: Values are means with standard errors given in parentheses. For 1998 data, n = 5 with each replicate including four subsamples. For 1999 data, n = 5 with two subsamples. Means within a given column with different letters are significantly different at α = 0.05 using Fisher's protected LSD. C, control; F, fill; CF, compacted fill.

Table 4. Soil respiration standardized to 23°C (Q_{10} = 2) from sweetgum plots in July and August 1998.

Soil treatment	Soil respiration ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	
	7/14/98	8/11/99
C	2.39 (0.48)	1.94 (0.34)
F	3.65 (0.94)	1.19 (0.50)
CF	2.88 (0.63)	1.91 (0.80)
p >*F*	0.49	0.61

Note: Values are means with standard errors given in parentheses (n = 5 with each replicate including four subsamples). C, control; F, fill; CF, compacted fill.

but could indicate that roots were not damaged by any treatment to a degree that would result in nutrient stress.

White oak soil respiration

From 23 to 90% of forest soil respiration has been attributed to live root respiration (Tate et al. 1993; Thierron and Laudelout 1996), although the higher estimates may include some CO_2 efflux from decaying roots and other coarse organic material. In this study, one goal in measuring soil respiration was to detect any large-scale root mortality as a result of the fill. This might then be confirmed during the root excavations carried out at the end of the experiment. There was no consistent pattern in soil respiration among treatment plots (Table 3). Data from 1999 did indicate lower soil respiration in plots with compacted fill. This could be due to restricted gas diffusion through the compacted soil. There are many other factors that might affect soil respiration in the white oak plots. Plots were cleared of competing vegetation before treatment installation, leaving behind many roots and shoots of dead plants that would presumably decay over time and thus contribute to soil respiration. Soil moisture also varied between treatment plots and may have increased variation among respiration measurements (Fig. 1). This lack of effect on soil respiration suggests that no major shifts in root turnover occurred as a result of fill.

Sweetgum soil respiration

Soil treatments did not affect soil respiration rates in sweetgum plots on any measurement date (Table 4).

White oak soil moisture

Because white oak plots were located on an eroded, upland site in Virginia's Upper Piedmont, fill and original soils in the white oak plots were somewhat similar. For all soil treatments, the deeper soil usually remained wetter than the surface soils (Fig. 1). On all measurement dates in 1998 except September 19, both the 0- to 15-cm and the 15- to 30-cm soil regions were wetter in control plots than in fill and compacted fill plots (Fisher's protected LSD, α = 0.05). On September 19, soil water contents in control plots were greater than in uncompacted fill only. This could perhaps be attributed to greater runoff and reduced percolation through the fill soils. Compacted fill soil water contents were also greater than uncompacted fill on April 2, June 3, and July 28, 1998 (Fisher's protected LSD, α = 0.05). Compacted fill may have remained wetter than uncompacted fill because of its pore size distribution or perhaps partly as an artifact of the measurement process. We measured the top 15 cm of soil, which, in the compacted fill, may have included a very small portion of original soil, whereas in the uncompacted fill it would not.

Of interest is the disruption in water recharge of the original underlying soil in the fill and compacted fill treatments when rainfall followed a dry period as shown by the August 11, 1998, measurements (Fig. 1). On July 28, 1998, differences between volumetric water content in the 15- to 30-cm and the 0- to 15-cm ranges were similar among treatments (C, 8.1 ± 2.3%; F, 5.6 ± 1.8%; CF, 6.0 ± 1.7%; values represent (percent volumetric soil water content at 15–30 cm) – (percent volumetric water content at 0–15 cm)). When measurements were made on August 11, 1998, however, only control plots maintained a similar difference between deep and shallow regions, while the differences in fill and compacted fill treatments were significantly less using Fisher's protected LSD at α = 0.05 (C, 9.2 ± 3.1%; F, –4.5 ± 1.9%; CF, –1.0 ± 1.0%). Water movement into the lower soil regions may have been slowed by the interface of two soils of differing structures (Miller and Gardner 1962).

Sweetgum soil moisture

Moisture patterns seen during the 1998 growing season in the control plots, where the deeper soil regions were typically wetter than surface regions, were disrupted by the application of fill (Fig. 1). Mean volumetric soil water content was consistently the same or greater at the 15- to 30-cm depth in controls than at 0–15 cm. In contrast, in fill and compacted fill plots, this pattern was reversed, most dramatically in the compacted fill plots. Unlike the soil at the oak site, the native soil in the sweetgum stand was not eroded, had a lower bulk density, and was considerably darker in color than the fill soil, likely indicating a higher organic matter content. Consequently, the difference in soil structure between the fill and original soils may have been greater than in the oak experiment. Thus, the interface may have created a greater impediment to water movement as occurs when there is an abrupt change in soil pore size. Furthermore, the mean volumetric water content at 15–30 cm deep in the fill and compacted fill plots, which is approximately the first 15 cm of the original, underlying soil, and where the majority of roots were concentrated (Table 5) remained consistently drier than the first 15 cm of the original soil in control plots.

Fig. 1. Volumetric soil water content at white oak and sweetgum plots and precipitation at the Reynolds Homestead Forest Resources Research Center in Patrick County, Virginia, during the 1998 growing season. Data for the 15- to 30-cm depths in fill and compacted fill treatments correspond closely to the first 15 cm of the underlying native soil. For soil water content, each data point represents the mean (n = 5 for oaks, n = 3 for sweetgums, with two subsamples in each replication). Error bars are SE. Each column in the precipitation bar graph represents total rainfall for the first or second half of each month.

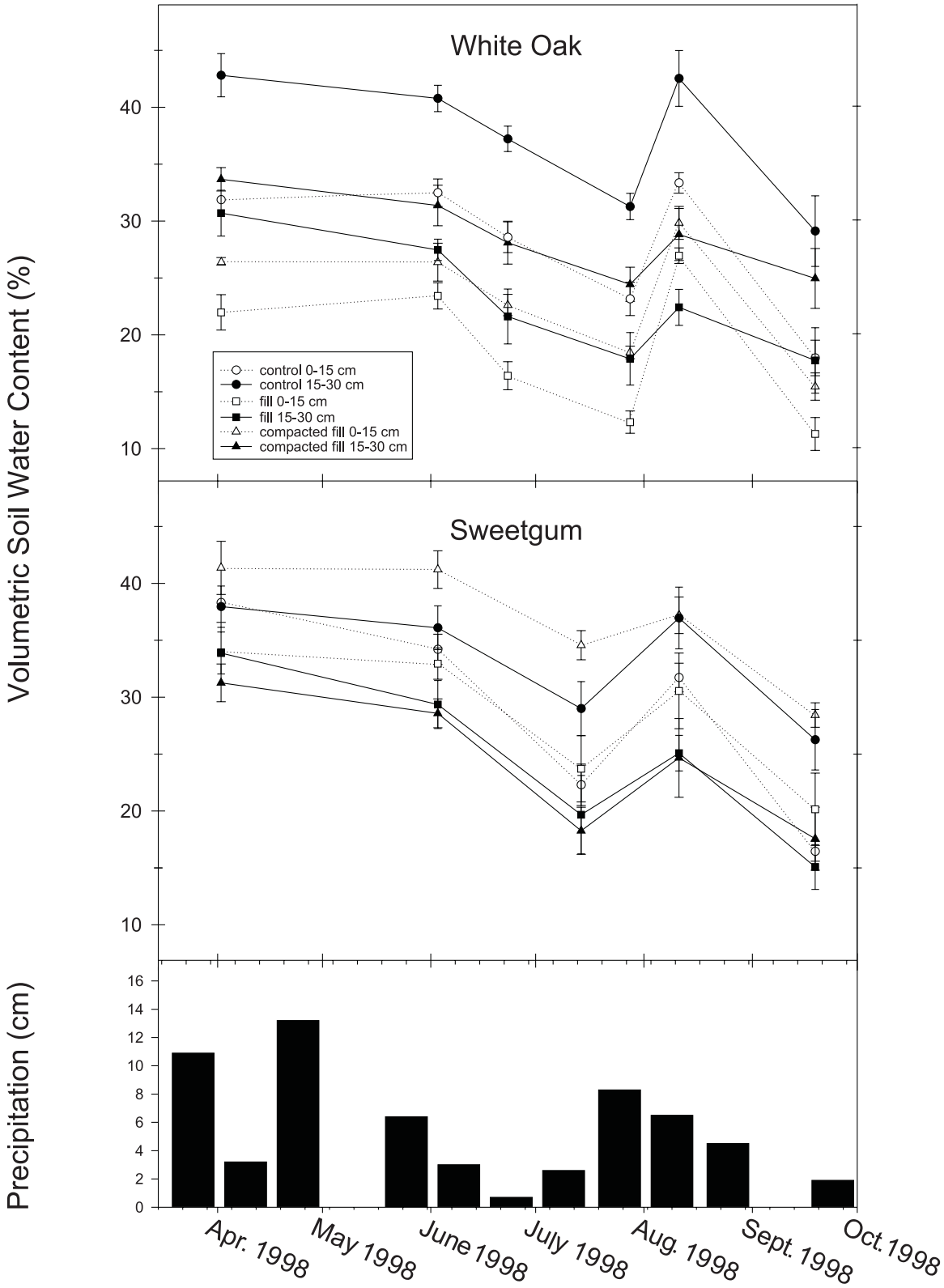

Table 5. Root distribution based on numbers of roots intersecting a 60 × 40 cm excavated soil face in sweetgum and oak plots in June 1999.

Soil	All roots (roots/cm^2)	Roots in top 25 cm of original soil (roots/cm^2)	Coarse roots in top 25 cm of original soil (roots/cm^2)*	Percent surface roots in original soil (%)†	Roots in fill soils (roots/cm^2)
Sweetgum					
C	0.138 (0.015)	0.167 (0.019)	0.015 (0.002)	27.6 (1.6)*b*	—
F	0.121 (0.012)	0.170 (0.016)	0.018 (0.002)	44.3 (4.1)*a*	0.035 (0.010)
CF	0.112 (0.008)	0.170 (0.008)	0.013 (0.002)	40.0 (4.4)*ab*	0.012 (0.006)
p >*F*	0.38	0.99	0.20	0.04	0.30
Oak					
C	0.064 (0.007)	0.076 (0.006)	0.006 (0.001)	20.5 (2.9)	—
F	0.064 (0.006)	0.072 (0.009)	0.007 (0.001)	29.1 (4.5)	0.050 (0.007)
CF	0.072 (0.008)	0.081 (0.012)	0.003 (0.001)	30.5 (1.5)	0.055 (0.009)
p >*F*	0.64	0.64	0.09	0.10	0.67

Note: Values are means with standard errors given in parentheses (n = 5 with each replicate including four subsamples). Means within a given column with different letters are significantly different at α = 0.05 using Fisher's protected LSD. C, control; F, fill; CF, compacted fill.

*Coarse roots are those greater than approximately 2 mm in diameter.

†Surface roots are those in the top 5 cm of the original soil. Percentage is based on the top 25 cm of original soil in all treatments.

White oak root distribution

Numbers of roots and root distribution in the original soil were mostly unaffected by soil treatment (Table 5). There was root growth, however, into the fill and compacted fill layers. The *t* tests suggested that both the fill and compacted fill layers may have fewer roots per square centimetre than the top 25 cm of the original soil in the same treatment, although the statistical evidence was not strong (p = 0.06 and p = 0.09 for F and CF, respectively). Most of the roots in the fill layers, however, were fine roots that appeared to be branching off larger roots that were still located in the underlying native soil or at the soil interface. We uncovered only one coarse root (≥2 mm) in our excavations of compacted fill layers and just five in the uncompacted fill soil. All of these were within a few centimetres of the interface with the original soil.

When we looked at the percentage of roots in the top 5 cm of the top 25 cm of original soil (as an indication of degree of surface rooting), it appeared that there may have been a change in root distribution resulting in increased rooting just below the original soil surface in the fill treatments as compared with the control, but again, the statistical support for differences among treatments is not very strong (Table 5). Likewise, there is some indication of fewer coarse roots in the native soil underlying the compacted fill than in other treatments (Table 5). Overall, however, there is little evidence of changes in root distribution or density due to fill, with the exception that roots clearly did grow upwards into both the fill and compacted fill layers.

Sweetgum root distribution

Although no soil treatment affected total root density, the uncompacted fill resulted in a shift in root distribution in the original soil towards the surface 5 cm (Table 5). Unlike the oak roots, sweetgum roots appeared heavily concentrated at and below the surface of the original soil, and comparatively few roots were growing in the fill soils. Both the fill and compacted fill layers had fewer roots per square centimetre than the top 25 cm of the original soil in the same treatment (p = 0.008 and p = 0.001 for F and CF, respectively) (see also Table 5). We found only two coarse roots (≥2 mm) in all of the compacted and uncompacted fill soil layers combined. New systems of adventitious roots have been observed to form when natural sedimentation raises the soil level around existing coast redwoods (Stone and Vasey 1968) and white spruce (Filion and Marin 1988), but the change in distribution of the sweetgum roots is probably not an indication that this is beginning to take place here. First, we did not observe that roots in the lower regions might be dead or dying, and new root growth into the applied fill soils was minimal and hardly indicative of a new root system. Roots of sweetgum, more so than some other tree species, have been shown to markedly proliferate in areas of high nutrient supply (Mou et al. 1997). The Chewacla series soil in the sweetgum plots has formed in recent alluvium and has Ap and Bw horizons that presumably have higher fertility than the fill soil. If growing conditions in the original soil remained adequate for sweetgum roots, possibly they would not grow into the fill layers because of its relatively poor nutrient availability.

Conclusions

In the absence of other construction damage, 20 cm of sandy loam subsoil fill, compacted or not, applied to the root systems of healthy white oaks and sweetgums had no detrimental effects on tree growth and physiology during the 3 years of these experiments. Oak roots grew well into the overlaid soil whether it was compacted or not, although no benefit from this additional soil resource was apparent in terms of tree growth. Sweetgum roots remained mostly in the original soil, yet no detrimental effect to tree growth was apparent. Chlorophyll fluorescence, chlorophyll content (oaks only), and soil respiration measurements detected no signs of tree stress that would suggest that decline might occur in the near future. There was no mortality in the oak experiment and virtually none in the sweetgum experiment. This is in agreement with the results of Smith et al. (1995) from their experiment with eastern white pine. Furthermore, there was no observed benefit or detriment to the use of tree wells. The disruption of soil moisture patterns by fill treatments

was most notable in the CF sweetgum plots. Here, there was an abrupt change of soil type at the fill – native soil interface and the deeper soil regions remained dry when the fill was wet, a complete reversal of the pattern in control plots. Thus the soil environment was clearly altered for these trees, but with no apparent effect on above- or below-ground growth.

Possibly, different results would be seen if the experiments were conducted for a longer period or if there were any extreme changes in the weather patterns during such a time. However, we have evaluated both a bottomland species, sweetgum, and an upland species, white oak, in two sites with differing soil types and water relations. Consequently, the results of the present experiment are likely applicable to a fairly broad range of urban forestry situations in the eastern United States.

Fill appeared to disrupt water movement through the soil profiles to some degree. In construction situations, this could potentially have some effect on long-term tree growth, depending on the specific site conditions, although no evidence of that was revealed in the present experiment. Tree decline after construction activity is probably largely due to factors other than fill. Possibilities include compaction of the original soil by vehicle traffic, root severance during clearing of underbrush or grading, trunk damage from machinery, and surface tilling large areas under trees to establish a grass lawn, all common occurrences during construction. The rapidity of decline may be related to the severity of the damage as well as to the health, size, and reserves of the trees in question. More information is needed to develop best management practices for tree protection during construction. Future research could evaluate the relative contributions of the above-mentioned construction activities to tree decline and their interaction with each other and with weather effects such as drought or storm damage.

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