Growth and Physiology of Several Urban Tree Species in Soils Disturbed by Construction Fill or Compaction

by

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(Abstract)

Experiments were conducted to determine the effects of applying fill soil around existing trees and mechanisms for species tolerance to soil compaction, both common site disturbances in urban forestry. Groups of 22-year-old white oak (*Quercus alba*) and 13-year-old sweetgum (*Liquidambar styraciflua*) were subjected to one of three treatments: a control, fill (20 cm of subsoil spread over the root zones), and compacted fill (same as fill soil, but compacted). Additionally, individual trees had tree wells (fill soil pulled away from trunks), or not. After three years, treatments had no consistent effect on tree growth, chlorophyll fluorescence, or soil respiration. However, soil treatments disrupted normal soil moisture patterns at both sites. Roots of white oak grew into fill layers, although overall root growth was not significantly affected by treatment. Sweetgum roots grew very little into fill soils. However, root distribution shifted upward in the original soil under uncompacted fill. Other factors associated with raising the soil grade, such as soil trafficking and root severance, may be largely responsible for the tree decline often attributed to construction fill.

Another experiment investigated the relationship between tolerance of wet soils and the ability to grow in compacted soils. It was hypothesized that tree species tolerant of wet soils would have opportunities for root growth in compacted soil when high soil moisture reduced soil strength. Seedlings of flowering dogwood (*Cornus florida*), a species intolerant of inundation, and silver maple (*Acer saccharinum*), a bottomland species, were grown in a loam soil maintained at various combinations of soil strength and soil matric potential. In moderately compacted soil (1.5 g cm^{-3} bulk density), maple seedlings, but not dogwoods, had greater root growth rate, root length per plant, and ratio of root length to root dry weight in the wet soil (0.006 MPa soil matric potential) than in the moist and dry soils (0.026 and 0.06

MPa, respectively). No such effect was detected in highly compacted soil (1.7 g cm^{-3}). It can be concluded that silver maple roots can grow in moderately compacted soil when high soil water content decreases soil strength, whereas dogwood is unable to take advantage of this opportunity.

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Dedication

to Roger

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CHAPTER 1

Introduction

Growing urban trees to a size that provides maximum benefit to society has long been a challenge. Larger trees provide more of the environmental and economic benefits we expect from urban forests. Medium and large size trees have a greater positive effect on residential property values than small trees (Anderson and Cordell 1988). Residents respond most positively to more large trees and less undergrowth in suburban parks (Hull and Harvey 1989). People also feel happier and more cooperative when city streets have well-maintained landscaping (Sheets and Manzer 1991). Greater tree canopy, achieved by more and larger trees, also maximizes the economic benefits of urban trees. Properly placed trees can reduce cooling costs 33-50% through evapotranspirative cooling and shading (Huang et al. 1987). In addition, there is economic value to the carbon sequestration provided by urban trees. Even a moderate tree canopy of 21% is estimated to store 11 metric tons of carbon per hectare (Nowak 1993). Trees must survive, however, in order to provide these benefits.

In city streetside plantings, average tree lifespan has been estimated to be only about 10 years (Foster and Blaine 1978). In part, this is due to the difficult growing conditions found in cities and towns ranging from insufficient growing space and poor soils, to vandalism and vehicle damage. In the more rapidly changing suburbs and expanding towns, however, untimely tree death is also frequently due to construction activities: paving parking lots, burying or expanding utilities, and building in wooded areas. Street trees, trees in private yards and around commercial buildings, and woodland trees overtaken by urban expansion all become incorporated into urban forests. By increasing understanding of the effects of these environments on trees, the ability to achieve an urban forest dominated by healthy, full-grown trees will be improved. Soil compaction and construction fill are both particularly important factors which may severely affect urban tree health. Research in these areas can be applied immediately to improve the management and protection of urban and community trees.

Tree death following construction activity is frequently noted through anecdotal observation. Foresters and arborists attribute many such deaths to construction fill being spread over the root zone (e.g. Yelenosky 1963, 1964). Often, however, tree decline after fill is applied appears to be random, with some large trees dying or showing decline within a year, while others appear never to be affected. This is perhaps due to the many factors involved in grade changes (how the soil is graded; whether roots are severed; whether the soil is compacted; other site conditions; tree species, age, and condition; depth and type of fill; the installation of tree wells; and others) and the poor understanding of the relative importance of each factor and how it interacts with other conditions. Very little data are available at present to use as a guide. Consequently, it is impossible to determine the best management practices when grade changes are required. The two field experiments presented here were designed to untangle some of these factors so it can be learned which specific activities and techniques threaten tree health and vigor and which do not.

Grade changes and many other types of disturbance common to urban areas alter compaction levels and water movement in soils. Although the effects of soil compaction on plant growth are widely researched and well understood, compaction continues to plague our urban forests. By their very nature, cities and towns are densely populated and land is rarely undisturbed. As a result, soil compaction is nearly inevitable. Compaction can be minimized and alleviated to some extent, but, on the whole, urban foresters must attempt to maintain healthy trees in an environment with at least some degree of soil compaction. Consequently, one aspect of interest is species tolerance of compacted soils. Much research in soil compaction has focused on agronomic crop species where yield, rather than long term plant health, is of primary interest. Species' tolerances, especially as they relate to interactions with soil moisture, have rarely been investigated. The final experiment presented here is designed to investigate species tolerance to compaction as it relates to soil moisture.

Tree Protection During Construction

In recent years, tree protection has become a topic of intense interest to urban foresters and arborists. The value of mature trees is widely recognized and more information is available than ever before on the dollar value of urban trees, both in terms of increases in real estate values and attracting business, as well as in environmental contributions such as reducing energy use, runoff and certain types of air pollution (e.g. Dwyer et al. 1992). Tree protection workshops and conferences are now held around the country, and arborists specializing in this area are in demand as consultants. In developing tree protection plans, foresters must commonly assess the long-term risks associated with placing fill soil over areas where trees are growing. This is a difficult task, however, because of the many factors that come into play and the lack of research in this area.

Fill

Fill is soil that is placed on top of the existing soil in order to change the final grade or level of the ground. Some amount of *cutting* (lowering the grade) and *filling* (raising the grade) is necessary on virtually every construction site in order for the land to drain properly, to create the gentle inclines necessary for pedestrians and cars, and for other engineering needs. However, fill presumably alters the soil environment in the original ground beneath it, perhaps by making it wetter, dryer, or by altering the gas exchange with the surface air. Fill may also cause changes in soil microflora, reduce nitrogen availability, raise pH and result in improper drainage (Schoeneweiss 1982). It is also generally recognized that the grading process itself, as well as a variety of mostly unrelated construction activities, such as soil trafficking, stockpiling heavy materials, root severance, trunk damage, and chemical spills, may contribute to tree decline associated with fill (Duling 1969, Coder 1995b, Harris et al. 1999).

Fill is rarely applied without other site disturbance occurring. Furthermore, the fill soil itself is often degraded during application. In a cut area, the surface soil is often a subsoil that was once deep in the soil strata while in the filled area, surface soil may be a mixture of A, B and C horizons. As these soils can be very unproductive, stockpiling of topsoil is often recommended (Ishiwata et al. 1996). However, handling surface soil with heavy equipment during stockpiling and respreading results in considerable structural degradation (increased bulk density, decreased available water-holding capacity, and decreased macropore volume), especially in fine- or medium-textured soils (Ishiwata et al. 1996). Surface scraping has also been shown to result in long-term reduction in soil nutrient availability, which might additionally weaken stressed trees (Zabowski et al. 1996). Finally, as tree roots are often densely concentrated in the top 30 cm of soil (Gilman 1990), removal of surface soil around established trees will sever large numbers of roots and cannot be recommended in landscape situations where tree retention is an objective. Civil engineers also generally attempt to balance the cut and fill, in order to avoid the expense of transporting soil on or off site. In light of these factors, there is little chance of specifying soil type or completely eliminating other disturbances in most cases where fill is required.

The amount of fill that can be applied without damaging trees is generally considered to be no more than 15 cm. Schoeneweiss (1982) suggests that a fill of 10 cm is safe if the soil is a porous topsoil. Harris et al. (1999) indicate that a fill of 15 cm or less with good drainage is probably not harmful, but consider it far wiser to avoid fill altogether. Coder (1996) indicates that all types and amounts of fill can lead to root suffocation and other problems that will permanently damage the tree. He offers extremely detailed recommendations based on soil type, but notes that these are "highly variable values." For example, 10 cm of a sandy loam fill will initiate root damage, while 30 cm will result in massive damage to roots. For a clay fill, these depths are reduced to 2.5 and 7.6 cm, respectively. Others also suggest that as little as 2.5 to 5 cm of clay fill will damage sensitive trees (Schrock 1994).

Recommendations for protecting trees from the effects of fill have changed little in the last thirty years. In 1969, John Z. Duling, an influential arborist, recommended an aeration system of tile and stone (Duling 1969):

> A system of field tile is laid on the grade in the pattern of a wheel with the spokes running into the base of the tree where a tapered base of stone is laid around the tree trunk. We then lay a bed with stones about the size of a man's fist or larger. This stone is laid over all the root area, out to the drip line. Stone is placed to make a depth of six to twelve inches which will cover six-inch field tile. The tile is laid open-jointed, and at the intersection of each spoke and outer ring, a glazed bell-jointed tile is placed so it will extend to the top of the new grade when finished. The stone at the base of the tree is built up to the level of the new grade, and should be about eighteen to twenty-four inches in width around the tree trunk. When stone and tile are all in place, we cover the stone bed with burlap or straw to prevent the soil from filtering into the stone bed. The soil fill is then placed on top of this system to the desired grade. When the grade is finished, and settled, the vent tiles can then be pulled, and the lower end cut off so the vents will be flush with the new grade.
>
> When fertilization is needed in seasons following the installation, we have used liquid fertilizer solutions, and flushed it into the tile system through the

> vent pipes… …We have installed many of these aeration systems, and to our knowledge most of the trees have lived.

This recommendation has appeared, essentially unchanged, in various publications since then (e.g. Schoeneweiss 1982, Schrock 1994). Some authors, however, now primarily stress the importance of avoiding fill by changing grading plans or other means (Coder 1995a, Harris et al. 1999).

In addition to protecting root systems, consideration must be given to protecting the trunk of the tree. If fill is placed directly against the trunk of a tree, it is thought that this could damage the bark and lead to infection from soil-borne diseases such as *Phytopthora* and *Armillaria* root rots (Britton 1990, Smiley 1992). This belief has led, in part, to the widespread use of "root collar excavations" by arborists (Smiley and Fraedrich 1993). These are performed on trees where no root flare is visible, presumably due to overly deep planting or mulching, fill application, or sedimentation. The procedure removes soil from around the trunk of trees until the flare is visible. Eastern white pine (*Pinus strobus*) and sugar maple (*Acer saccharum*) are among those thought to especially benefit from these excavations (Smiley 1992). Employees of Bartlett Tree Research Laboratories (Charlotte, NC) excavated 363 recently planted trees and found 93% had buried root collars and 16% were showing signs of girdling due to "materials" around the trunk (Smiley 1991). When fill is applied, tree wells have traditionally been used to keep the soil away from the trunk (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. Occasionally, a tree well is constructed simply by piling large stones against the trunk in order to prevent contact with the surrounding fill soil. Many arborists consider any tree well to be detrimental because they can allow water to collect around the base of the trunk. Arborists therefore sometimes recommend partial tree wells or wells equipped with drainage systems.

Tree wells also, presumably, prevent the formation of adventitious roots on the trunk at the new soil level. Adventitious roots have been considered desirable by some, and troublesome by others. Adventitious root systems are considered responsible for the survival of coast redwood (*Sequoia sempervirens*) in alluvial flats where massive floods deposit sometimes as much as 1.2 m of new soil at one time (Stone and Vasey 1968). In Rochester, New York, it is reported that trees scheduled to be buried with two to fourteen feet of fill soil in the 1930s were intentionally wounded with an axe in several places around the trunk with the intention of stimulating adventitious root growth (Duling 1969). Trees included such diverse species as Norway spruce (*Picea abies*) black oak (*Quercus velutina*) and a number of unnamed maples and poplars. After 27 years, not a single tree had died. On the other hand, adventitious roots are blamed for poor anchorage of Coast live oak (*Quercus lobata*) in California (Britton 1990). Britton recommends tree wells in order to prevent the hidden hazard caused by adventitious roots that "keep the foliage green, but may not be large or extensive enough to support and anchor the tree."

There is little controlled research available on the effects of fill on trees. A recent study with 11-year-old Eastern white pine (*Pinus strobus*) showed that photosynthesis rates, pre-dawn water potentials, and shoot growth were unaffected over two years following the application of 20 cm of clayey fill soil over the root zone (Smith et al. 1995). This research, however, looked at what might be a best-case scenario. 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.

More so than the detrimental effects of fill, the benefits of aeration systems have been questioned in recent years. Aeration systems sometimes recommended to arborists for compacted soil did not improve tree growth and were found to decrease, rather than increase, soil air oxygen content, presumably because they acted as sumps, collecting surface water (Day et al. 1995). Two recent experiments have indicated no benefit from aeration systems under fill. Smith et al. (1995) found no benefit from using crushed rock fill with aeration pipes similar to the setup described by Duling (1969). In a non-replicated study with six-year-old cherry trees (*Prunus mahaleb*), 30 cm of clay loam fill soil was applied both with and without an extensive pipe aeration system (Tusler et al. 1998). Oxygen diffusion rates were monitored over a two-year period at 1-, 15-, and 60-cm depths, but no consistent differences were found. The researchers also noted that the cherry trees appeared unaffected by the treatments, although they did not make any physiological or growth measurements. Recommendations for aeration systems may be on the decline. In fact, the most recent edition of *Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines*, an authoritative arboriculture textbook, notes in bold type that "The aeration systems [under fill soil] are expensive to construct, and to date there is no scientific evidence that they have a positive effect on trees"(Harris et al. 1999).

Because the research is so limited, and the possible variables in a field situation so numerous, it is difficult to draw many conclusions concerning fill at this point. It does appear, however, that 30 cm or less of uncompacted fill applied to root zones of young trees, in the complete absence of other construction damage, probably does no harm—at least in the short term.

Current research considerations

Primary factors considered in the two field experiments presented here include the effect of soil compaction after fill is applied (which would typically occur during machine grading), and the effect of tree wells. Additional concerns were the responses related to tree species and age, although an experiment to test specifically for these two factors could not be conducted. Nonetheless, two separate experiments were carried out, one with white oak (*Quercus alba*), an upland species, and the other with sweetgum (*Liquidambar styraciflua*), a bottomland species. It was fortunate that stands of these trees that were 22 and 13 years old, respectively, at the beginning of the experiment were available. These trees were considerably larger than those typically available for this type of experiment. Many developers and arborists are attempting to protect and retain trees much older than this, however, and these experimental results may not be fully applicable in these cases.

Species Tolerance for Compacted Soils

It is well known that some tree species are better adapted than others to urban soil conditions. "Urban" conditions can include poor drainage, compacted soils, high soil pH, limited rooting space, and other mostly disadvantageous characteristics. By understanding how some species are more successful than others in this environment, it may be possible to better manage urban soils and construction activity for particular trees species.

In most cities, compacted soil is very difficult to avoid. Soil compaction and moisture interact to affect soil strength and soil aeration (Tackett and Pearson 1964) which, in turn, affect root growth. It would be useful to understand how different species respond to these soil characteristics. In Chapter 3, an hypothesis is developed and evaluated that suggests that trees more tolerant of flooding might also tend to be those more tolerant of soil compaction because of their tolerance for poor soil aeration. According to this hypothesis, this would occur because soil strength is usually lowest when the soil is very wet. Thus, an opportunity for root growth would occur in compacted soils when conditions were excessively wet. Bottomland trees with some degree of flood tolerance could be better adapted to take advantage of this opportunity.

Although this research can only partially evaluate this hypothesis, information in this area could help in many urban forestry management decisions. First, although the flood tolerance of many species has been thoroughly researched, tolerance to compaction has not. If flood tolerance is relevant to success as an urban tree, research for evaluating new street tree species might include numerous North American bottomland species (e.g., Carolina ash (*Fraxinus caroliniana*), water-elm (*Planera aquatica*), etc.) that are not currently available in the landscape nursery trade. There are extensive swamplands and bottomlands in the Eastern United States that are rich in tree species. Naturally, there are numerous other requirements for urban tree success besides tolerance of compacted soil, depending on the site conditions where trees will be planted. For example, desirable characteristics can include tolerance of de-icing salt, high soil pH, and heat; disease resistance; and lack of messy or slippery fruit. Furthermore, a successful tree must be sufficiently cold hardy as well as easy to propagate and transplant at a landscape size. Still, almost all successful urban trees must grow in compacted soils, and many urban foresters would welcome the evaluation of additional native trees for such use.

Many trees evaluated and promoted for urban areas have been chosen because of their tolerance to drought (e.g., Amur corktree (*Phellodendron amurense*), hardy rubber tree (*Eucommia ulmoides*), and Turkish hazelnut (*Corylus colurna*)). These trees have not always been as successful as expected and, consequently, many are not widely planted in urban settings. A new avenue of approach via native bottomland trees could add many species to the palette of trees currently available for urban plantings. Native trees have several distinct advantages over exotics. Invasiveness is of little concern, they are helpful in meeting the quotas sometimes set by certain planting ordinances, and they can lend a “sense of place” to a town or city.

In addition to tree introduction, research concerning the interaction of soil compaction and moisture and tree root growth could add to the available management tools for plantings in compacted soil. For example, in addition to alleviating and preventing compaction, it might prove especially useful to irrigate plantings if dry periods occurred at times when significant root growth would be expected to occur.

Objectives

The studies presented here cover topics that are relatively new to urban forestry research. Consequently, one objective of this work is to gather information that will guide future research projects in the areas of construction fill and species tolerance to soil compaction. The primary research objectives of this work, however, were centered around three experiments as follows:

Sweetgum and white oak field experiments with construction fill (Chapter 2)

1. Determine growth and physiological responses of *Quercus alba* and *Liquidambar styraciflua* to the application of fill.
2. Determine if compacting or not compacting the fill affects these responses.
3. Determine if keeping fill soil off the trunks of trees affects their responses under these conditions.
4. Gain some understanding of how the construction processes replicated in this field study can affect the soil environment.

Silver maple and flowering dogwood experiment with compacted soils at varying soil water contents (Chapter 3)

1. Investigate differences between *Acer saccharinum* and *Cornus florida* in root and shoot response to soil compaction as it relates to reported flood tolerance.
2. Make an initial evaluation (within the confines of the two species studied here) of the hypothesis presented in Chapter 3 that flood tolerant species might take advantage of wet periods when the soil is soft to grow roots, while flood intolerant species would not.

CHAPTER 2

Effects of Construction Fill and Soil Compaction on White Oak (*Quercus alba*) and Sweetgum (*Liquidambar styraciflua*) Growth and Physiology

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 developers intend to protect and retain when forested land is converted to residential or commercial buildings. 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 could be more effective if it were fully understood how construction affects trees. Unfortunately, there is little research indicating the best strategies for tree protection and educated guesses are relied upon 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). It is not clear, however, which aspect of grading, if any, 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*) were covered with 20 cm of fill soil and soil held away from trunks, no reduction in shoot growth or photosynthesis was observed after two years when compared to control trees with no fill (Smith et al. 1995). Many authors suggest, however, that the addition of soil over the root zone (construction fill) can alter drainage properties and be an impediment to gas exchange. Such an effect was noted in an observational study where soil oxygen levels were monitored under 30-90 cm of clay fill, under an unpaved road and in a nearby forest. Soil air oxygen content ranged from 3-12% under the fill, 4-20% under the road and stayed at 18% or higher in the undisturbed forest, with oxygen contents generally being in the lower ranges during the growing season (Yelenosky 1963 and 1964). Yelenosky also noted that two dogwood trees partly buried by the fill, and several trees of other species subjected to similar environments in other sites 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 disease and tree decline, although there is little research to support or refute this belief.

In certain natural forests, tree root systems and trunks are occasionally covered by the periodic deposition of soil. Coast redwood trees (*Sequoia sempervirens*) 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*) 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 per 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 water or nutrient status of the soil. Adventitious roots under soil buildup have also been documented in black spruce (*Picea mariana*) (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.

The aim of this research was to gain insight into which aspects of applying construction fill injure trees and how. This pair of experiments 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 tree physiology and growth?

Materials and Methods—Oak Experiment

Site description and maintenance

This experiment was conducted in a stand of white oaks (*Quercus alba* L.) on the Reynolds Homestead Forest Resources Research Center, Critz Virginia. The oaks were planted as 1-0 seedlings in 1975 into a 0.24-ha plot. In late spring of 1996, 154 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). Herbaceous plants and remaining woody vegetation were removed via repeated mowing and applications of glyphosate. After treatments were installed, plots were maintained weed-free via two or three herbicide treatments 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 5m X 7m to 12m X 18m and included from 5 to 19 trees (see Appendix 1). Because of the uneven arrangement of the trees within the stand, some plots were contiguous with others, while some abutted on wide buffer zones maintained in the same manner as controls but typically devoid of trees.

Three soil treatments were assigned in a completely random design and applied in June 1997: 3 treatments X 5 replications = 15 plots. Soil treatments included: 1) Control (C), no fill treatment; 2) 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 3) Compacted Fill (CF), same as Fill, but two passes from a sheep's-foot compactor with the vibrator engaged (Model RT 820, Wacker Corp., Menomonee Falls, WI) were made over the fill soil when gravimetric soil moisture was 36%. The compactor weighed 697 kg and had an 81-cm wide drum. 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.

In addition, two trunk treatments were randomly assigned within plots to equal numbers of individual trees in the F and CF treatments. These treatments were: 1) Tree Wells (TW), tree wells, constructed of 57-l plastic nursery pots (44 cm diameter at the top) 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 2) No Tree Wells (NTW), soil was spread 20 cm deep against trunks. Five permanent stakes (polyvinyl-chloride 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 (DBH) was measured 1.35 m above the original soil level 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 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, MA) was used to measure initial (F_0) and maximum (F_m) leaf fluorescence in 5 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 (PSII) electron transport and a low value can thus indicate tree stress. One, fully mature sun leaf 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 minute dark adaptation period, leaves were subjected to 800μmol m^{-2} s^{-1} of light, and fluorescence kinetics recorded for 10 s. Measurements were taken every 2 to 4 weeks at the end of the growing season in 1997 in order to detect any premature leaf senescence and 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

A relative measure of leaf chlorophyll content was made on September 19 1998 with a chlorophyll meter (SPAD-502, Minolta, Japan). 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 spots, 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 poly-vinylchloride pipe caps fitted with closed-cell foam gaskets were placed over stationary rings placed 5 cm deep in the soil and enclosing 79 cm^2 of soil surface. Air was circulated via tygon tubing using a portable photosynthesis system (LI-6200, LI-COR, Lincoln, NE) programmed to measure soil respiration. The rate of CO_2 evolution at near ambient CO_2 concentration was measured. In conjunction with each pair of soil respiration measurements, soil temperature at 10-cm and 30-cm depths were measured with thermocouples. Soil respiration can respond sharply to short-term changes in temperature, especially in moist soil (Bryla et al. 1997). Consequently, soil respiration readings were standardized 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, CA), volumetric water content in the top 15 cm of soil and at 15-30 cm deep was measured 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.

Soil bulk density

Soil bulk density was measured on May 20 1998 using a slide hammer undisturbed core sampler with a double cylinder (Inline AMS Slide Hammer, AMS, Inc., American Falls, ID). Two cores (92 cm^3) were taken from each plot centered at 10 cm deep. Two additional cores were taken in CF plots at 10 cm below the original soil level. Samples were dried to a constant mass at 105 ºC and bulk density calculated.

Root distribution

On June 17 1999, a pit was dug in each plot to expose a vertical face of soil 60 cm wide and 40 cm deep. A wire grid was placed against each face and the severed roots visible through each 10 X 5-cm square of the grid were counted. Roots were visually 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. These excavations were made immediately next to one of the sites where soil respiration was measured.

Statistical analysis

Soil treatment and trunk treatment effects on trees were analyzed using the GLM procedure in SAS v. 6.12 (SAS Institute, Inc., Cary, NC) and Fisher's Protected 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 v. 12 (Minitab, Inc., State College, PA). 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.

Materials and Methods—Sweetgum Experiment

Site description and maintenance

This experiment was conducted in a stand of sweetgums (*Liquidambar styraciflua* L.) on a bottomland site at the Reynolds Homestead Forest Resources Research Center, Critz, Virginia. Trees were planted as 1-0 seedlings in 1984 with a 0.6 m spacing in 8 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). 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 9 rectangular plots, each with some trees forming the edge of the stand (see Appendix 1). Three soil treatments and two trunk treatments were applied in September 1996. Two rows of trees extended beyond the main block and were designated a control plot because of 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 3 soil treatments X 3 replications = 9 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 (Bobcat) occurred on CF plots during fill application than did on oak plots. 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

The DBH of all trees was measured 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 8 trees selected randomly from the edge trees in each plot. Only edge trees were used because the leaves of interior trees were inaccessible. 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. Soil bulk density and root distribution were measured on the same dates and using the same procedures as in the oak experiment.

Statistical analysis

The same methods of statistical analysis were used as in the oak experiment.

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 2.1). Percentage increases are expressed because trees varied considerably in size and spacing. However, an analysis of actual increases in height and DBH gave similar results. 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 did not vary by soil treatment or trunk treatment (Table 2.2). Final DBHs, however, were greater in control trees than for other soil treatments and final heights were greater in control trees than in trees with uncompacted fill. Because sweetgums were tightly spaced, their trunks had very little taper. Consequently, DBH^2 X height was calculated as an index of volume. This index

Table 2.1. Analyses of variance for height and DBH increases of all trees in the white oak stand. The stand was located in Virginia's Upper Piedmont. Least squares means are given with standard errors in parentheses.

Source	Treatment[z]	Height 7/24/97 (m)	Height 4/1/99 (m)	Height Increase (%)[y]	DBH 7/13/96 (cm)	DBH 6/22/99 (cm)	DBH Increase (%)[y]
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 X 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

[z] 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.

[y] Percent increase of the initial height or DBH.

Table 2.2. Analyses of variance for height, DBH, and estimated volume increases of all sweetgum trees from 1997 to 1999. This stand was located in Virginia's Upper Piedmont. Least squares means are given with standard errors in parentheses.

Source	Treatment[z]	Height 7/24/97 (m)	Height 4/1/99 (m)	Height Increase (%)[y]	DBH 6/17/97 (cm)	DBH 6/22/99 (cm)	DBH Increase (%)[y]	D^2H[x] Increase (%)[y]
Soil Treatments	C	11.5 (0.37)	12.7a[w] (0.41)	11.5 (1.6)	10.7 (0.48)	12.2a (0.58)	10.9 (1.5)	36.7a (3.7)
	F	10.2 (0.37)	10.7b (0.41)	6.7 (1.6)	8.8 (0.48)	9.5b (0.58)	6.4 (1.5)	19.0b (3.7)
	CF	10.6 (0.33)	11.4ab (0.37)	8.4 (1.4)	9.2 (0.43)	10.0b (0.52)	6.9 (1.4)	23.0b (3.3)
	p>F	0.13	0.04	0.18	0.06	0.04	0.15	0.03
Trunk Treatments	TW	10.7 (0.35)	11.2 (0.41)	7.1 (1.0)	9.2 (0.25)	10.0 (0.37)	7.0 (0.28)	21.1 (1.8)
	NTW	10.2 (0.33)	10.9 (0.39)	7.8 (1.0)	8.8 (0.24)	9.4 (0.35)	6.2 (0.27)	20.0 (1.7)
	p>F	0.36	0.67	0.68	0.30	0.31	0.10	0.80
Fill Treatments X Trunk Treatments	FTW	10.6 (0.53)	10.9 (0.62)	5.8 (1.6)	9.0 (0.37)	9.9 (0.56)	6.7 (0.43)	18.4 (2.7)
	FNTW	9.9 (0.49)	10.5 (0.58)	7.2 (1.5)	8.5 (0.36)	9.1 (0.53)	6.0 (0.40)	18.8 (2.5)
	CFTW	10.8 (0.45)	11.5 (0.53)	8.5 (1.3)	9.4 (0.33)	10.2 (0.48)	7.4 (0.37)	23.9 (2.3)
	CFNTW	10.5 (0.45)	11.4 (0.53)	8.3 (1.3)	9.1 (0.32)	9.8 (0.48)	6.4 (0.36)	22.1 (2.3)
	p>F	0.65	0.80	0.49	0.85	0.77	0.87	0.72

[z] 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.

[y] Percent increase of the initial height, DBH or volume.

[x] Estimated volume increase. Estimated volume was calculated as *(diameter)*^{2} *X height.*

[w] Means within a given source and column with different letters are significantly different at alpha = 0.05 using Fisher's protected LSD.

indicated a greater percentage increase in volume for control trees than for trees with fill treatments. However, the stand had developed many smaller trees that showed little or no growth because of competition from the dominant and co-dominant trees. Furthermore, trees in control plots tended to be larger at the beginning of the experiment (Table 2.2). For these reasons, growth of dominants and co-dominants (considered to be the top 25% of the trees by initial height) was considered separately. Although final DBHs of dominants and co-dominants in control plots were greater than those in uncompacted fill plots, percentage increases did not vary among soil or trunk treatments (Table 2.3). Overall, no consistent growth differences were evident among trees in the various soil and trunk treatments.

White oak chlorophyll fluorescence and chlorophyll content

Because of the short duration of the current experiments (three years), chlorophyll fluorescence measurements were made in order to detect early signs of stress. 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. 1997). Fluorescence readings have been correlated with a number of stresses, including nutrient deficiencies (Peterson et al. 1997), 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. Drought does not affect PSII function in several herbaceous species (Havaux 1992) and fluorescence therefore might not be expected to respond to drought. Fluorescence of sweetgum trees is not affected by drought (Peterson et al. 1997); 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*) (Conroy et al. 1986) and loblolly pine (*Pinus taeda*) (Peterson et al. 1997).

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 to controls and compacted fill using Fisher's protected LSD at alpha = 0.05 (C = 0.80, SE 0.007; F = 0.82, SE 0.007; CF = 0.79, SE 0.007). Late 1997, 1998 and the first half of 1999 were dryer than normal. The higher F_v/F_m ratio in the

Table 2.3. Analyses of variance for height, DBH, and estimated volume increases of dominant and co-dominant[z] sweetgum trees between 1997 and 1999 in a stand in Virginia's Upper Piedmont. Least squares means are given with standard errors in parentheses.

Source	Treatment[y]	Height 7/24/97 (m)	Height 4/1/99 (m)	Height Increase (%)[x]	DBH 6/17/97 (cm)	DBH 6/22/99 (cm)	DBH Increase (%)[x]	D^2H[w] Increase (%)[x]
Soil Treatments	C	14.5 (0.24)	15.6 (0.32)	8.1 (1.4)	14.2 (0.41)	16.5a[v] (0.36)	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)	14.6b (0.42)	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)	15.4ab (0.36)	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 X 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

[z] Dominant and co-dominant trees are defined as the 25% of trees in each treatment with the greatest initial height.

[y] 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.

[x] Percent increase of the initial height, DBH or volume.

[w] Estimated volume increase. Estimated volume was calculated as *(diameter)*^{2} *X height.*

[v] Means within a given source and column with different letters are significantly different at alpha = 0.05 using Fisher's protected LSD.

oak trees in uncompacted fill plots at this time may indicate that the fill was acting as a mulch, conserving moisture and reducing temperatures at the original soil surface and thereby reducing stress. However, the top 15 cm of original soil in control plots consistently had greater volumetric soil water content during 1998 than did the original soil underlying the uncompacted fill treatment (Fig. 2.1). Still, it is possible that an extremely wet year would yield different results. 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 = 0.84, SE 0.01; CFNTW = 0.79, SE 0.01; FTW = 0.82, SE 0.01; FNTW = 0.83, SE 0.01). It is unclear why not having tree wells might result in higher F_v/F_m ratios.

Initially, chlorophyll fluorescence was measured in order to detect early leaf senescence as a sign of overall tree stress. Measurements made several times during August, September and October 1997, however, did not indicate a trend towards lower F_v/F_m ratios or any discernable patterns in F_0, F_v, or F_m. Research comparing a mutant of *Festuca pratensis*, "stay-green", in which chlorphyll does not degrade during leaf senescence, with the wild type found that F_v/F_m decreased only very slightly during senescence with no significant differences between genotypes (Kingston-Smith et al. 1997). Chlorophyll fluorescence may not necessarily reflect many of the changes normally associated with leaf senescence, such as chlorophyll degradation. Consequently, relative chlorophyll content of oak leaves was measured in September 1998 as an alternative means of quantifying stress. Neither soil nor trunk treatments, however, affected relative chlorophyll content of oak leaves at this time.

Sweetgum chlorophyll fluorescence

No differences in F_v/F_m of trees in the various soil or trunk treatments were found on any measurement date. In sweetgums, chlorophyll fluorescence measurements may detect nutrient stress, but not drought stress (Peterson et al. 1997). Consequently, these results probably do not reflect any changes or lack of changes in the water relations of the trees, but could indicate that roots were not damaged by any treatment to a degree that would result in nutrient stress.

White oak soil bulk density

Soil bulk density measured approximately one year after soil treatment application confirmed that compacted fill soil had a higher bulk density than uncompacted fill soil (CF = 1.35 g cm^{-3}, SE 0.03; F = 1.12 g cm^{-3}, SE 0.02; p = 0.0001). The density of the original soil under CF treatments was not significantly different from that of the original soil in the control plots (CF = 1.27 g cm^{-3}, SE 0.05; C = 1.27 g cm^{-3}, SE 0.03), indicating that the compaction process did not affect the underlying native soil.

Sweetgum soil bulk density

Similar results were found in the sweetgum plots. Compacted fill soil had a significantly greater bulk density than uncompacted fill (CF = 1.34 g cm^{-3}, SE 0.03; F = 1.10 g cm^{-3}, SE 0.06; p = 0.01). Again, the density of the original soil under CF treatments was not significantly different from that of the original soil in the control plots (CF = 1.20 g cm^{-3}, SE 0.07; C = 1.20 g cm^{-3}, SE 0.04).

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. However, there was no consistent pattern in soil respiration among treatment plots (Table 2.4). Data from 1999 indicated lower soil respiration in plots with compacted fill. This could be due to restricted gas diffusion through the compacted soil layer, but such an effect was not observed on other measurement dates. 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. 2.1).

Table 2.4. Soil respiration standardized to 23 °C (Q_{10} = 2) from white oak plots on various dates in 1998 and 1999. Plots were located in Virginia's Upper Piedmont. Means[z] are given with standard errors in parentheses.

Soil Treatment[y]	Soil respiration (μmol m^{-2} 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)	2.71a[x] (0.32)
F	5.42 (0.85)	2.70 (0.45)	1.09 (0.52)	2.97a (0.37)
CF	3.07 (0.69)	4.13 (1.54)	1.11 (0.34)	1.37b (0.20)
p>F	0.26	0.14	0.99	0.006

[z] For means from 1998 data, n=5 with each replicate including 4 subsamples. For 1999 data, n=5 with 2 subsamples.

[y] C=control, F=fill, CF=compacted fill

[x] Means within a given column with different letters are significantly different at alpha = 0.05 using Fisher's protected LSD.

Sweetgum soil respiration

Soil treatments did not affect soil respiration rates in sweetgum plots on any measurement date (Table 2.5). Although almost no other vegetation was present in these plots, a dense layer of leaf litter was present when treatments were applied. This organic material was sandwiched between the original soil and the applied fill. Its decay presumably contributed to soil respiration to some degree.

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 regions usually remained wetter than the surface soils (Fig. 2.1). On all measurement dates in 1998 except September 19, both the 0-15-cm and the 15-30-cm soil depths were wetter in control plots than in fill and compacted fill plots (Fisher's protected LSD, alpha = 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,

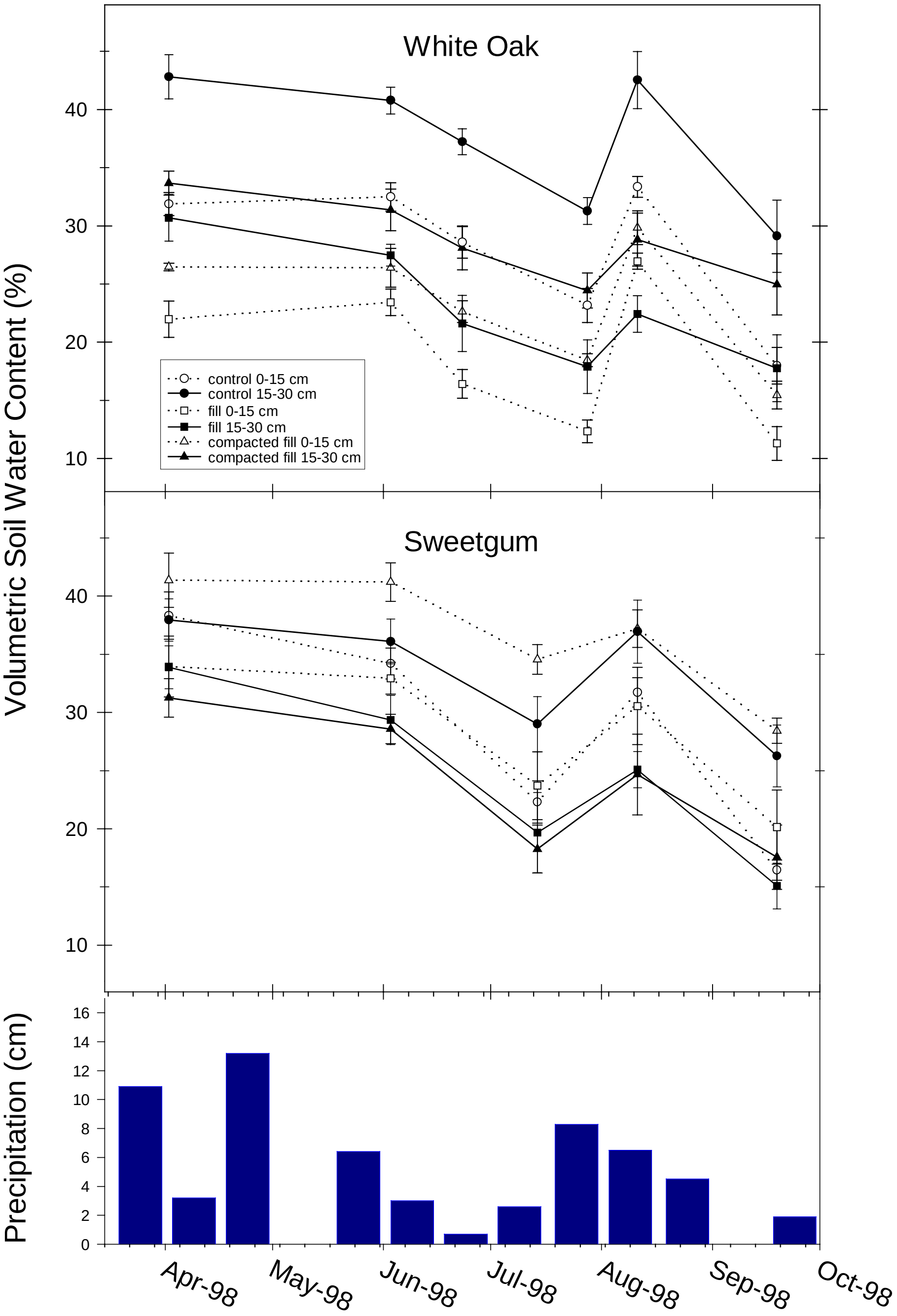

Figure 2.1. Volumetric soil water content at white oak and sweetgum plots and precipitation during the 1998 growing season at the Reynolds Homestead Forest Resources Research Center in Critz, Virginia. Data for the 15-30 cm depths in fill and compacted fill treatments correspond closely to the first 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) and the bars indicate standard errors. Each column in the precipitation bar graph represents total rainfall for the first or second half of each month.

Table 2.5. Soil respiration standardized to 23 °C (Q_{10} = 2) from sweetgum plots in July and August 1998. Means[z] are given with standard errors in parentheses.

	Soil respiration (μmol m^{-2} s^{-1})	
Soil Treatment[y]	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

[z] n=5 with each replicate including 4 subsamples.

[y] C=control, F=fill, CF=compacted fill

alpha = 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. The top 15 cm of soil was measured, which, in the compacted fill, may have included a tiny region 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 measurements from August 11 1998 (Fig. 2.1). On July 28 1998 differences between volumetric water content in the 15-30 cm and the 0-15 cm ranges were similar among treatments (C = 8.1%, SE 2.3; F = 5.6%, SE 1.8; CF = 6.0%, SE 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 uncompacted fill treatments were significantly less using Fisher's protected LSD at alpha = 0.05 (C = 9.2%, SE 3.1; F = -4.5%, SE 1.9; CF = -1.0%, SE 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 greater soil depths were typically wetter than surface horizons, were disrupted by the application of fill (Fig. 2.1). Mean volumetric soil water content was consistently the same or greater at the 15-30 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. The interface may thus 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 2.6)) remained consistently drier than the first 15 cm of the original soil in control plots.

White oak root distribution

Numbers of roots and root distribution in the original soil were mostly unaffected by soil treatment (Table 2.7). There was some root growth, however, into the fill and compacted fill layers. Both the fill and compacted fill layers appeared to have fewer roots/cm^2 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. Only one coarse root (≥ 2 mm) was uncovered in the excavations of compacted fill layers and just five in the uncompacted fill soil. All of these were within a few centimeters of the interface with the original soil.

When the percent of roots in the top 5 cm of the top 25 cm of original soil (as an indication of degree of surface rooting) was examined, it appeared that there may have been a change in root distribution resulting in increased rooting just below the original soil surface

Table 2.6. Root distribution based on numbers of roots intersecting a 60 X 40 cm excavated soil face in sweetgum plots in June 1999. Plots were located in Virginia's Upper Piedmont. Means are given with standard errors in parentheses.

Soil Treatment[z]	All roots (roots/cm^2)	Roots in top 25 cm of original soil (roots/cm^2)	Coarse[y] roots in top 25 cm of original soil (roots/cm^2)	Percent surface roots in original soil[x] (%)	Roots in fill soils (roots/cm^2)
C	0.138 (0.015)	0.167 (0.019)	0.015(0.002)	27.6b[w] (1.6)	-
F	0.121 (0.012)	0.170 (0.016)	0.018 (0.002)	44.3a (4.1)	0.035 (0.010)
CF	0.112 (0.008)	0.170 (0.008)	0.013 (0.002)	40.0ab (4.4)	0.012 (0.006)
p>F	0.38	0.99	0.20	0.04	0.30

[z] C=control, F=fill, CF=compacted fill.

[y] Coarse roots are defined as those greater than approximately 2 mm in diameter.

[x] Surface roots are those in the top 5 cm of the original soil. Percent is based on the top 25 cm of original soil in all treatments.

[w] Means within a given column with different letters are significantly different at alpha = 0.05 using Fisher's protected LSD.

Table 2.7. Root distribution based on numbers of roots intersecting a 60 X 40 cm excavated soil face in white oak plots in June 1999. Plots were located in Virginia's Upper Piedmont. Means are given with standard errors in parentheses.

Soil Treatment[z]	All roots (roots/cm^2)	Roots in top 25 cm of original soil (roots/cm^2)	Coarse[y] roots in top 25 cm of original soil (roots/cm^2)	Percent surface roots in original soil[x] (%)	Roots in fill soils (roots/cm^2)
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

[z] C=control, F=fill, CF=compacted fill.

[z] Coarse roots are defined as those greater than approximately 2 mm in diameter.

[y] Surface roots are those in the top 5 cm of the original soil. Percent is based on the top 25 cm of original soil in all treatments.

in the fill treatments as compared to the control; but, again, the statistical support for this is not very strong (Table 2.7). Likewise, there is some indication of fewer coarse roots in the native soil underlying the compacted fill than in other treatments (Table 2.7). Overall, however, there is little evidence of changes in root distribution or density due to fill during this three-year period, 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 2.6). 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/cm^2 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 2.6). Only two coarse roots ($\geq$ 2mm) were found 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). However, it does not appear that the change in distribution of the sweetgum roots is an indication that this is beginning to take place here. First, it was not observed 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 A and B horizons with considerable organic matter; and presumably higher fertility than the fill soil. If growing conditions in the original soil remained adequate for sweetgum roots, it is possible that they would be unlikely to 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, vigorous white oaks and sweetgums appears to have had no detrimental effects on tree growth and physiology during the three years of these experiments. This is in agreement with the results of Smith et al. (1995) from their experiment with Eastern white pine. Furthermore, there did not appear to be any benefit to the use of tree wells. It is possible that 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, both a bottomland species, sweetgum, and an upland species, white oak, were evaluated 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 did appear 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 in order 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.

CHAPTER 3

A Comparison of Root Growth Dynamics of Silver Maple and Flowering Dogwood in Compacted Soil at Several Moisture Levels

Introduction

Many of the most successful street trees have been bottomland species and their hybrids, e.g.: American elm (*Ulmus americana* L.), London plane tree (*Platanus* X *acerifolia* (Ait.) Willd.), pin oak (*Quercus palustris* Muenchh.), willow oak (*Quercus phellos* L.), water oak (*Quercus nigra* L.), green ash (*Fraxinus pennsylvanica* Marsh.), and many others. Urban soils are typically compacted (Patterson 1977, Alberty et al. 1984) and, therefore, in many regions, trees must be tolerant of compacted soils to function successfully as street trees. These observations suggest there may be an association between tolerance of excessive soil moisture and the ability to grow in compacted soils.

Based on the limited literature available on woody plants, 2.3 MPa has been suggested as a threshold soil penetration resistance, where the reduction in tree root growth due to mechanical impedance becomes severe (Day and Bassuk 1994). In a severely compacted soil, the soil strength would likely only fall below this threshold when the soil is very wet. It is possible that the decrease in soil strength that accompanies an increase in water content for most soils (Taylor and Gardner 1963) creates an opportunity for root growth that could explain bottomland species' tolerance for compacted soil. According to this hypothesis, a bottomland species could exploit this period of reduced soil strength for root growth, while the growth of an upland or mesic species would be inhibited by excessive moisture and the associated impaired gas exchange. When the soil dries and gas exchange improves, the soil would once again be too hard for roots to penetrate. The upland or mesic species would, therefore, have very limited opportunity for root growth.

Although an increased water supply has been shown to alleviate some of the effects of compaction (Buttery et al. 1998), species specific tolerances have not been directly addressed. Taylor and Ratliff (1969) found peanut and cotton roots to be affected by soil strength rather than water content *per se*. They did not, however, evaluate growth in the nearly saturated soils required to achieve low soil strength in highly compacted soils. Wolfe et al. (1995) attributed species differences in yield response of vegetables to soil compaction, in part, to differing sensitivity to secondary effects such as poor drainage and greater pest populations. However, tolerance for excessively wet soils has not been specifically tested as a means by which certain species might achieve greater root growth in compacted soils.

This experiment was designed to investigate this hypothesis by comparing the root growth dynamics of a bottomland and a mesic tree species under a range of soil strengths and water contents. Urban foresters generally consider flowering dogwood (*Cornus florida* L.), a mesic species native to Eastern North America and widely planted as an ornamental, to be intolerant of compacted soils. Silver maple (*Acer saccharinum* L.) has a similar native range, but is a bottomland species considered highly tolerant of compacted soils. According to the hypothesis, these two species would be similarly affected by increases in soil strength, but would respond differently to changes in soil water content, even when soil strength was low. Furthermore, this hypothesis states that as soil moisture increases in a given compacted soil, silver maple will be able to take advantage of the resulting low resistance, while dogwood will not.

Materials and Methods

Preliminary soil analyses

Several preliminary preparations and tests of the experimental soil were required before the final experimental pots could be prepared. A Unison loam soil (fine, mixed, semiactive, mesic Typic Hapludults; 48.5% sand, 39.4% silt, 12.1% clay, pH 5.8) was screened through 0.6-cm mesh hardware cloth to remove organic debris and then air dried. Equal numbers of metal sleeves (approx. 89 cm^3 each) were packed with screened soil to each of three bulk densities (1.2 (uncompacted), 1.5 and 1.7 g cm^{-3}). A soil moisture release curve was established for each bulk density using these samples (n = 5), a tension table and pressure plate. These curves established the volumetric water content required to maintain specified matric potentials at each compaction level. Further tests were then performed to establish soil penetration resistance-matric potential relationships for each compaction level. For these tests, larger soil samples (500 cm^3) were prepared for each compaction level as described below for the experimental pots. For each compaction level, three samples were brought to each of four (five for the uncompacted soil) soil matric potentials, ranging from 0.005 to 0.06 MPa (3 replications X 3 bulk densities X 4 (5 for uncompacted) matric potentials = 37 cores). Soil penetration resistance of each core was then tested with a Proctor penetrometer (Model CN-433, Soiltest, Inc.) complying with ASTM standard D1558 (ASTM 1999). Using a 1.6 cm^2 flat tip, measurements were taken at four locations (subsamples) within each core. These data were fitted to establish separate penetration resistance-matric potential curves for each of the three compaction levels. This information allowed for the preparation of experimental pots with soil of known penetration resistance by varying the compaction level and water content of the soil.

Preparation of experimental pots

Sifted, air-dried soil was pre-weighed, moistened to 16% gravimetric water content, and packed into pots made of schedule 40 polyvinyl-chloride pipe (10-cm diameter, 15-cm length), with the bottom end sealed with cellophane and secured with a rubber band. The soil was packed in three layers to one of three bulk densities (1.2 (uncompacted), 1.5 and 1.7 g cm^{-3}) using a specially designed compaction chamber and a Proctor hammer. Through several trial runs, a repeatable compaction protocol was determined, specifying the number of blows and the force of each blow required to reach the desired compaction level for each layer. After compaction, all pots contained 500 cm^3 of soil. Water was then added to bring each pot to the desired average matric potential and the top was tightly sealed with cellophane to prevent water loss before the experiment began the next day. Treatments consisted of soil prepared in 8 different combinations of soil matric potential and soil penetration resistance (Table 3.1). Together these comprise an incomplete factorial (seven missing cells) with three levels of matric potential (0.006, 0.026, and 0.06 MPa) and 5 levels of penetration resistance (0.6, 1.75, 2.0, 2.3, and 3.1 MPa). A complete factorial structure was

Table 3.1. Incomplete factorial treatment structure for the experiment. Numbers in parentheses indicate bulk density in g cm^{-3} used to create that soil moisture-soil strength combination. Cells with *na* indicate no treatment for that combination of factor levels. Each combination was replicated 4 times for each species.

Soil matric potential (MPa)	Soil penetration resistance (MPa)				
	0.6	1.75	2.0	2.3	3.1
0.006	(1.5)	(1.7)	na	na	na
0.026	(1.2)	(1.5)	na	(1.7)	na
0.06	(1.2)	na	(1.5)	na	(1.7)

not possible because space considerations limited the number of treatments and the soil physical properties did not allow certain soil moisture and soil strength combinations.

Plant material

Flowering dogwood (*Cornus florida*) seeds collected in Michigan were soaked in water for 24 h and stratified in moist paper for 95 days at 3 ˚C. Seeds were then placed on blotting paper on a day/night regimen of 30 ˚C (16 h)/20 ˚C (8 h) for 14 days, by which time the majority had germinated. Silver maple (*Acer saccharinum*) seeds collected from a landscape tree in Blacksburg, VA were dewinged, soaked in water for 24 h, and stratified at 3 ˚C for approximately 30 days. Seeds germinated while under stratification. At the beginning of the experiment, seeds at the same stage of germination were selected (radicle emerged from 1 to 3 mm from seed coat for dogwoods, 2 to 5 mm for maples) and placed them in the prepared pots in small depressions on the soil surface. Three seeds were placed in each pot. Soil was pressed carefully around each seed to ensure good seed-soil contact.

Placement and maintenance of experimental pots

The open-bottomed pots were weighed and placed in a completely random design (8 treatments X 2 species X 4 replications = 64 pots) on large glass plates set on black corrugated plastic in a growth chamber (Conviron Model E15, Controlled Environments Ltd., Winnipeg, Manitoba, Canada). The chamber was set at a day/night regimen of 22 ˚C (16 h)/16 ˚C (8 h) with a relative humidity of 90%. PAR light levels were maintained at 400-

425 μmol m^{-2} s^{-1}. This was measured occasionally during the experiment with a portable photosynthesis system (LI-6200, LI-COR, Lincoln, NE) to ensure consistency over time. At the same time each day, pots were weighed and distilled water added to bring each pot back to its original weight. Maples were harvested after 21 days and the slower-growing dogwoods after 30 days. After 11 days, all the seeds in 1 maple pot and 8 dogwood pots had died. These were replaced and allowed to grow the full 21 and 30 days, respectively.

Plant measurements

At the same time each day, the glass trays were removed from the growth chamber and the bottoms of the pots were examined for roots through the glass, using a hand lens when necessary. Each new root that appeared at the bottom of a pot was recorded. The number of days needed for the first root to reach the bottom of a given pot divided by the depth of the soil was the downward daily root growth rate. At the end of the experiment, pots where no roots had yet appeared were carefully excavated from the bottom and the depth of the deepest root of the three plants was determined. This depth was then used to calculate the downward root growth rate for these pots. At harvest, the number of surviving plants in each pot was noted, and the soil was gently washed away from each plant. The root systems were spread out to a single layer, and the plants were photocopied for later determination of root length. Shoots and roots were dried separately to a constant mass at 60 °C, and dry weights recorded. Total root length for each pot was determined by scanning the photocopied images using computer imaging software (Desk-Scan II, Hewlett Packard Co., Mountain View, CA) and a computer-image analyzing system (Delta-T SCAN, Delta-T Devices Ltd., Cambridge, England). Root and shoot dry weights and root lengths are expressed on a per-surviving-plant basis for each pot.

Oxygen diffusion rate measurements

At the end of the experiment, the soil in the remaining dogwood pots was sampled for oxygen diffusion rate. Dogwood pots were selected because they had relatively few roots that might affect measurements. Eight platinum electrodes were inserted approximately 3.0 cm deep into each pot and the oxygen diffusion rate to each electrode was calculated (Oxygen Diffusion Ratemeter, Model E, Jensen Instruments, Tacoma, WA).

Data analysis

Data for treatments with soil matric potentials of 0.006 and 0.026 MPa and soil penetration resistances of 0.6 and 1.75 MPa formed a complete 2 X 2 factorial and were analyzed via contrast statements in SAS (SAS Institute, Cary, NC). The general linear models procedure (GLM) in SAS was used to determine significant trends where treatments occurred at more than two levels of soil strength or soil matric potential with the other factor constant. Regression analysis was used to model the relationship between soil strength and downward root growth rate, independently of other factors. In the two compacted soils, the effects of bulk density and soil matric potential were analyzed separately via analysis of variance using the GLM procedure in SAS. Multiple comparisons were made by Fisher's protected least significant difference (LSD, $\alpha = 0.05$) where appropriate. Data for the two species were analyzed separately since an initial analysis indicated compaction level and soil matric potential and species interacted. Subsamples of oxygen diffusion rate measurements were averaged and tested for correlation with soil matric potential and soil strength using Pearson's correlation coefficient.

Results

Increasing soil strength reduced the downward root growth rate in both species (Fig. 3.1). Because of the incomplete factorial treatment structure, interactions with soil moisture could not be calculated across the entire data set. In the wetter soils and lower penetration resistance levels (which made up a complete 2 X 2 factorial), however, there were no significant interactions between soil moisture and strength on rate of root growth for either species. Under these conditions, increased soil strength reduced root growth rate for both species ($p = 0.0002$ and $p = 0.0035$ for maples and dogwoods, respectively), but increased soil moisture adversely affected dogwoods only ($p = 0.02$) (Table 3.2). At low soil strength (0.6 MPa), dogwood root growth rate slowed when soil became excessively wet or dry, whereas maple root growth rate increased linearly with soil moisture (Fig. 3.2).

Many dogwoods died during the experiment. Although no statistically significant cause could be identified, only 38% of the pots with soils at matric potential 0.006 MPa had

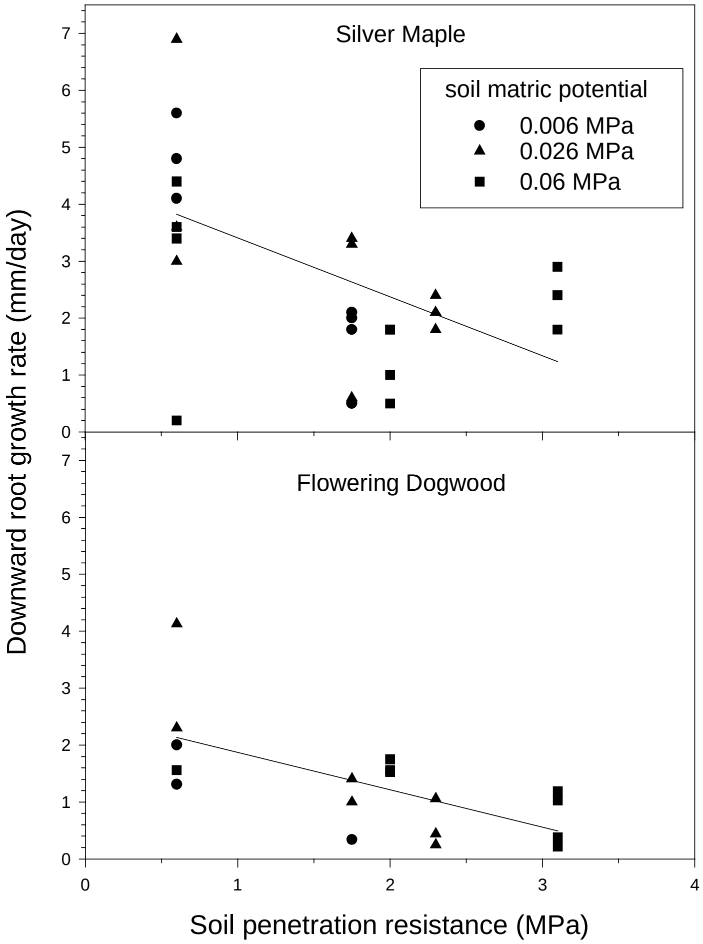

Figure 3.1. Downward root growth rate of dogwoods and silver maples as a function of soil strength for all soil matric potentials. Lines represent least squares regressions for all data points (maples: $y = 4.44 - 1.03x$, $r^2 = 0.29$; dogwoods: $y = 2.53 - 0.656x$, $r^2 = 0.42$).

Table 3.2. Downward root growth rate (mm/day) for dogwoods and maples in the wetter soils and lowest soil strengths. Standard errors are in parentheses.

	Soil penetration resistance (MPa)			
	0.6		1.75	
Soil matric potential (MPa)	Dogwood	Maple	Dogwood	Maple
0.006	1.65 (0.35)	4.83 (0.43)	0.34 (n=1)	1.60 (0.37)
0.026	3.22 (0.92)	5.10 (1.05)	1.21 (0.21)	2.43 (0.92)

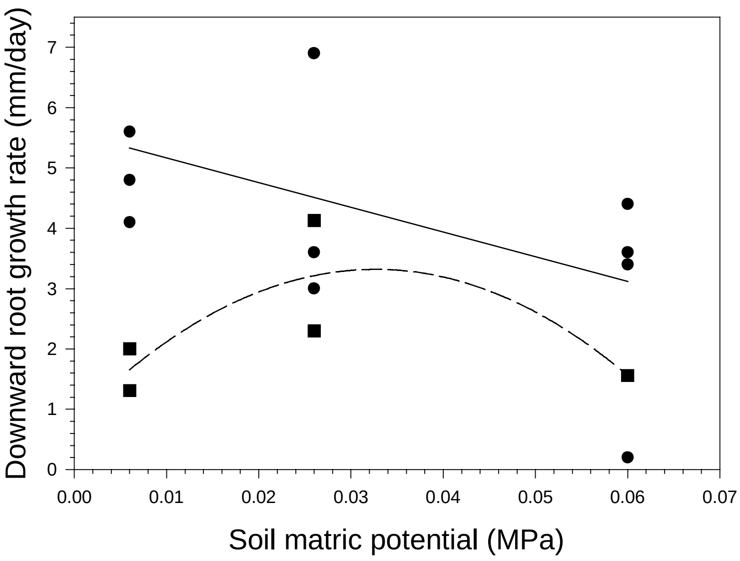

Figure 3.2. Downward root growth rate for maples (● ——) and dogwoods (■ — —) at low soil strength (0.06 MPa) across soil matric potentials. Lines are least squares regressions reflecting the significant trends identified: a linear trend for maples ($p = 0.011$) and a quadratic trend for dogwood ($p = 0.003$).

surviving plants at the end of the experiment. At 0.026 and 0.06 MPa, 58% of pots had survivors. In contrast, all but one maple pot had surviving plants.

Analysis of root growth in compacted treatments suggests that silver maple was able to take advantage of the low soil strength that resulted when the moderately compacted soil (1.5 g cm^{-3}) was very wet (Fig. 3.3). Dogwoods did not show this response. Analysis of variance of the effects of bulk density of the compacted soils (bulk densities 1.5 and 1.7 g cm^{-3}), soil matric potential, and species showed a three-way interaction for several of the root growth variables measured ($p = 0.02$ for rate of root growth, $p = 0.01$ for root length, and $p = 0.02$ for ratio of root length to root dry weight), indicating that species responded differently across these levels of soil moisture and compaction. No such interaction was evident for root and shoot dry weights. When species were analyzed separately, root growth rate of maples showed a strong interaction between bulk density and soil moisture ($p = 0.0003$) (Fig. 3.3). These factors also interacted in their effect on root length ($p = 0.0001$). Although soil moisture did not affect maple root growth rate or length in the highly compacted soil (1.7 g cm^{-3}), root growth rate and length increased rapidly with soil moisture level for the moderately compacted soil (1.5 g cm^{-3}) ($p = 0.008$ and $p = 0.004$, respectively). Multiple comparisons using LSD at $\alpha = 0.05$ indicate that root growth rate and root length in the wet soil (0.006 MPa) were significantly greater than that in the moist (0.026 MPa) or dry (0.06 MPa) soils.

High bulk density (1.7 g cm^{-3}) reduced rate of root growth for dogwoods ($p = 0.002$) (Fig. 3.3). In contrast to maples, however, root growth rate was unaffected by soil matric potential ($p = 0.54$) and no interaction was evident. No significant interactions or main effects were detected in dogwoods in any of the other variables measured (root length, root and shoot dry weights, and ratio of root length to root dry weight) when subjected to this analysis (data not shown).

The ratio of root length to root dry weight provides an index of root morphology. A low ratio represents a higher degree of stubbiness, a root morphology sometimes associated with roots grown in compacted soil or low oxygen levels (Hook et al. 1971, Eavis 1972). As described earlier, bulk density and soil matric potential interacted in their effects on this ratio ($p = 0.023$) in maples, while in dogwoods they did not (Fig. 3.4). In maples, soil moisture affected root stubbiness at bulk density 1.5 g cm^{-3}, but not at the higher compaction level.

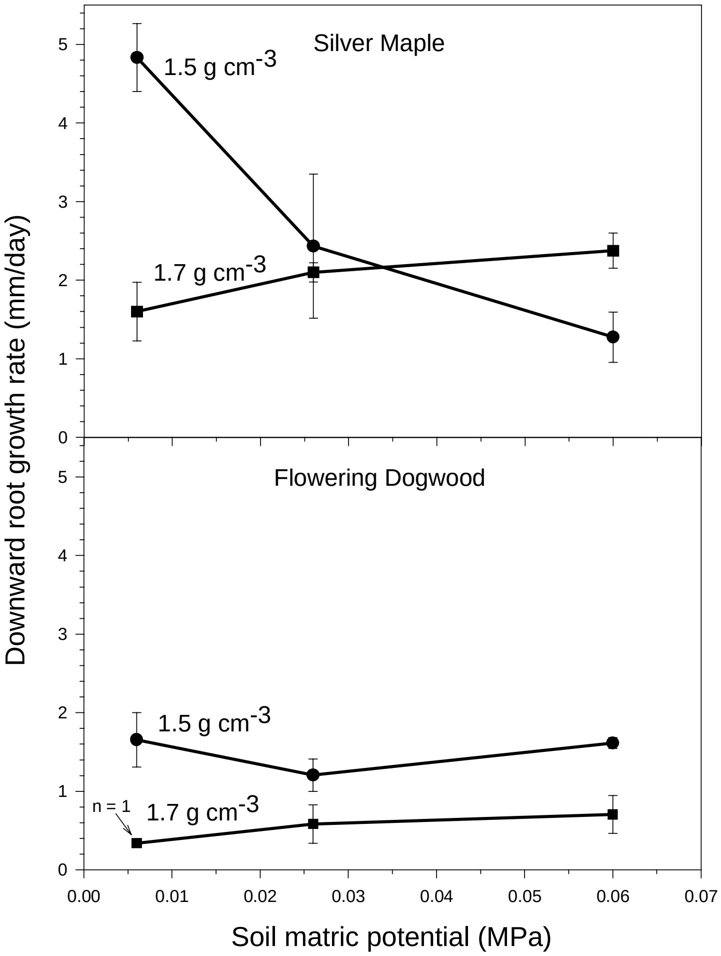

Figure 3.3. Downward root growth rate for dogwoods and maples at two compaction levels (bulk densities 1.5 and 1.7 g cm^{-3}) across soil matric potentials. Bars indicate standard error.

Again, multiple comparison by LSD at $\alpha = 0.05$ showed that root stubbiness was reduced in the wet soil compared to the moist and dry soils. This corresponds with visual observations that the root systems of that treatment (0.006 MPa matric potential, 0.6 MPa penetration resistance, 1.5 g cm^{-3} bulk density) appeared more spreading and fibrous with thinner roots. For dogwoods, the ratio of root length to root dry weight was not significantly affected by any factor, although there was some indication that the higher bulk density (1.7 g cm^{-3}) may have tended to increase root thickness ($p = 0.066$).

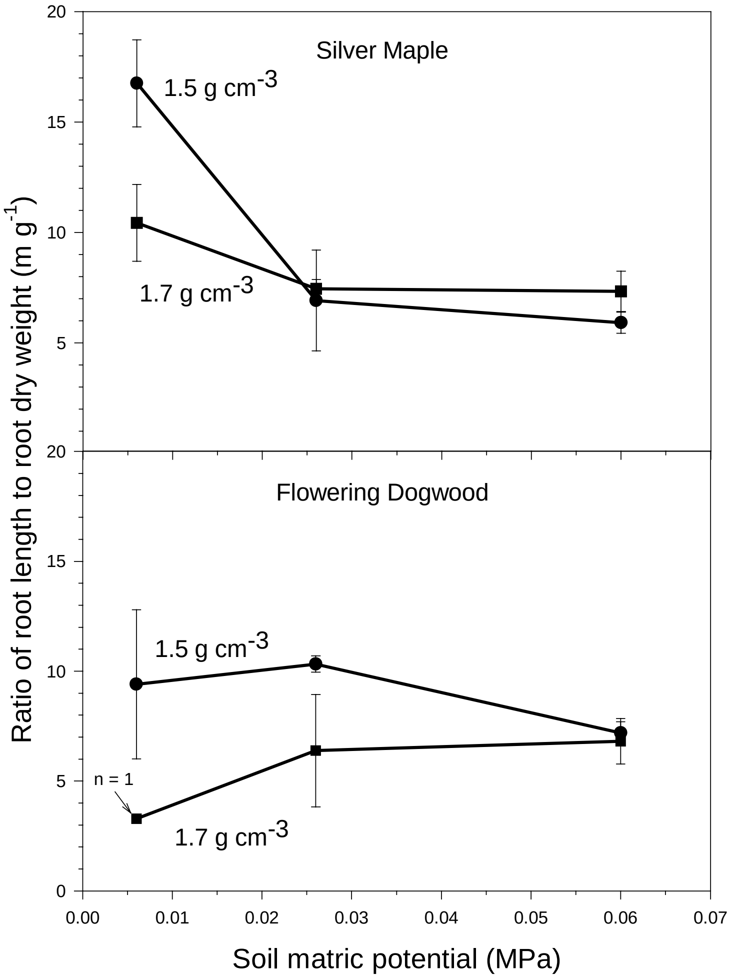

Figure 3.4. Ratio of root length (m) to root dry weight (g) for maples and dogwoods at two compaction levels (bulk densities 1.5 and 1.7 g cm^{-3}) across soil matric potentials. Bars indicate standard error.

A decrease in soil moisture showed a weak positive correlation (r = 0.40) with oxygen diffusion rate (ODR) (p = 0.07). Variation among replicates was large, mainly because low ODR (less than 0.4 μg cm^{-2} min) occurred at all soil moisture levels. In the wet soils, however, average ODR were less than 0.5 μg cm^{-2} min for all replications, whereas levels reached well above 0.8 μg cm^{-2} min in the moist soils and 1.0 μg cm^{-2} min in the dry soils. ODR was unrelated to soil strength.

Discussion

Silver maple is known to be tolerant of even prolonged submergence (Hosner 1960, Loucks and Keen 1973), while flowering dogwood shows poor survival on poorly drained soils (McLemore 1990). The greater sensitivity of dogwood to poor drainage was also evident in this experiment (Table 3.2 and Fig. 3.2). Root growth is expected to be severely restricted when the ODR is below 0.4 μg cm^{-2} min (Erickson 1982), yet silver maple produced extensive root systems in wet soil with low resistance where average ODR was only 0.28 μg cm^{-2} (SE 0.05).

Both species appeared to be similarly affected by increasing soil resistance (Fig. 3.1), indicating that the ability to penetrate harder soils is not a factor in the success of silver maple in compacted soils when compared to dogwood. Other researchers have noted few differences between species in their ability to penetrate hard soil. For example, when the growth of 22 crop species was evaluated in very strong soil (4.2 MPa), all had root elongation reduced between 92.2 and 97.5 % (Materechera et al. 1991). At lower soil strengths, on the other hand, peanut root elongation was somewhat less affected than was cotton root elongation by increases in soil strength from 0 to 1.0 MPa (29% reduction vs. 62%) (Taylor and Ratliff 1969). Taylor and Ratliff also found that soil strength, rather than bulk density, was the primary factor restricting root growth. This effect was independent of soil moisture except in dry soils. Others have noted an interaction between aeration and soil strength on root growth (Tackett and Pearson 1964). Because of the treatment structure, an interaction effect across the entire range of data could not be tested for. Consistent with the findings of Taylor and Ratliff, however, there was no interaction across the moist and wet soils at the two lowest soil strengths. Interactions may have occurred at higher soil strengths, but as root growth is already severely restricted at this point, it is not likely to be a factor in the success of particular species in compacted soils.

There is strong evidence that silver maple, but not flowering dogwood, was able to take advantage of reduced soil strength caused by a higher soil moisture level when the soil was compacted to bulk density 1.5 g cm^{-3} (Fig. 3.3). When wet, this moderately compacted soil had a soil strength of 0.6 MPa, a very low resistance. At this same moisture level, however, the highly compacted soil (1.7 g cm^{-3}) still maintained a soil strength of 1.75 MPa, and no increase in rate of root growth or root length occurred. This soil strength is already fairly restrictive to root growth (Fig. 3.1). Consequently, it may be that the soil was simply not soft enough to create an opportunity for root growth. Even when saturated, the soil used in this experiment, compacted to 1.7 g cm^{-3}, has a soil strength of 1.56 MPa, suggesting that opportunities for root growth would be few in most highly compacted soils regardless of moisture level.

Although many bottomland species tolerate inundation, they rarely make their best growth under these conditions. Their success has sometimes been attributed to their ability to maintain a certain level of normal function when oxygen is low. Some flood-tolerant tree species have been shown to maintain higher root starch concentrations after prolonged flooding than less tolerant species (Gravatt and Kirby 1998). In the genus *Myosotis*, wetland species were found to maintain a fructan/starch ratio that could allow roots to continue to function as a sink for photosynthate while their non-wetland counterparts did not (Albrecht and Biemelt 1998). Many wetland species develop aerenchymatous tissue, thereby increasing root porosity as a means to improve oxygenation of the root tissues when flooded (Justin and Armstrong 1987). These authors found that, unlike most wetland species, many non-wetland species could not be induced to form this type of tissue by applying exogenous ethylene. Although flooding tends to reduce secondary thickening of roots (Justin and Armstrong 1987), the anatomical changes associated with flooding can result in greater root diameters (Hook et al. 1971). High levels of mechanical impedance also result in greater root diameters (Tackett and Pearson 1964, Materechera et al. 1991). In this experiment, maple roots growing in soil of bulk density 1.5 g cm^{-3} were significantly less thickened at the high soil moisture level where soil strength was low (Fig. 3.4). This agrees with the findings of Bengough and Young (1993) who found that root diameter of peas only increased significantly when soil was compacted to 1.4 g cm^{-3} and soil strength was above 1.5 MPa. In this same situation, however, dogwood root thickness was unaffected. In fact, the ratio of root length to root dry weight was greatest (i.e. roots were thinnest) for dogwoods in the moist uncompacted soil (15.67 m g^{-1}, SE 1.37 m g^{-1}). For maples, however, the wet soil of the same soil strength (0.6 MPa) produced the thinnest roots. This may indicate differing responses to soil moisture. Greater root thickening has been associated with increased ability to exert pressure (Materechera et al. 1991), but there is no evidence of that in this experiment.

In the field, soil moisture fluctuates on a daily and a seasonal basis. On the one hand, this presents the opportunity for silver maple roots to grow in compacted soils. Soils are frequently near saturation in spring, which is also an optimum time for root growth for many species (Harris et al. 1995). Because water moves more slowly through compacted soils, they are more likely to remain wet, extending the opportunity for root growth for silver maple. On the other hand, other factors may also contribute to the poor success of flowering dogwoods in urban areas. Dogwoods may not be able to survive long periods of wet soil. Furthermore, compacted and poorly drained soils typically result in shallower root systems (Voorhees et al. 1975, Gilman et al. 1987, Justin and Armstrong 1987), making the already shallow root system of the dogwood (McLemore 1990) more susceptible to drought.

Conclusions

There is strong evidence that supports the hypothesis that silver maple trees would be able to take advantage of low soil strength resulting from wet soils, while flowering dogwoods would not. This could enable silver maples to achieve greater success in compacted soils in the field, just as they did under the conditions of this experiment. Although silver maple and dogwood are bottomland and mesic tree species, respectively, it is possible that their responses to the conditions of this experiment may be specific for these species and not indicative of the responses of other trees of these classes. Nonetheless, because of the clear role of excessive soil moisture in limiting root extension of dogwoods, these results are highly suggestive that this hypothesis could be applicable to a broader range of bottomland and mesic tree species.

CHAPTER 4

Conclusions

The Effects of Construction Fill on Existing Trees

Fill and the absence or presence of tree wells had no discernible effects on the growth and physiology of white oak and sweetgum trees. There was, however, some disruption of water movement through the soil, even though the fill and original soils were not vastly different in texture or structure. The species selected for these experiments represent the two extremes of sensitivity to fill according to published recommendations (Schoeneweiss 1982, Schrock 1994). Schrock lists oaks as "very sensitive" to fill while sweetgum, as a bottomland tree, would fall in the category of "fairly tolerant." These categorizations are presumably based on the accumulated experience of arborists and give some credence to the belief that the results of the present work would be applicable to a wide range of deciduous trees. It is reasonable to assume that applying the amount of fill used in these experiments (20 cm) or less to trees of similar ages or younger would yield similar results. The effect of deeper fills on older trees, or previously damaged trees, is still a matter of speculation. There is certainly anecdotal evidence of trees surviving long periods under very deep fill with no apparent ill effect (Duling 1969), but others have reported swift declines in trees with deep fill (Yelenosky 1964, Schoeneweiss 1982). When deep fills are applied, the formation of a new root system originating higher on the trunk might be a necessary part of successfully adapting to the new conditions, as suggested by the excavation of coast redwoods subjected to alluvial deposition (Stone and Vasey 1968). This would suggest that tree wells could be detrimental in deep fills because they would prevent the formation of this type of root system. On the other hand, anecdotal evidence has linked disease entry into the trunk to the presence of fill (Harris et al. 1999). In sum, the results of the experiments presented here will allow better recommendations to be made for protecting trees when fill is needed, but still leave many questions unanswered.

Recommendations to urban foresters

The results of this work add considerably to existing knowledge of how fill affects trees. Enormous gaps still remain in our understanding of this issue and educated guesses will continue to be relied upon in order to formulate best management practices (BMPs) for tree protection that can be used by arborists and urban foresters. Also, where the protection of valuable trees is concerned, it may be best to err on the side of caution in formulating BMPs. The following recommendations can be useful to tree care professionals, but it must be kept in mind that such recommendations should be reevaluated as more scientifically based information becomes available.

There are essentially two situations where applying fill over the root zones is considered. The first is when soil has eroded around existing trees exposing roots to the degree that they are unsightly or have become a tripping hazard. The second is when fill is a product of building construction or similar activity.

In the first case, arborists could be advised to feel free to apply up to 20 cm of soil over the roots of these trees, regardless of the trees age or species. This level of fill would be more than adequate to cover any exposed roots. The soil should preferably be similar in texture to the original soil to allow normal water movement through the profile. Because the soil level has been lowered in the past, leaving the trunk on higher ground, the question of whether to use a tree well does not need to be considered. Soil could be kept away from the trunk just by gradually lessening the depth of fill near the trunk. The issue then arises as to how to prevent the new soil from eroding. If the cause of the erosion has been removed (for example, a roof drainpipe rerouted), or the erosion pressure is very slight, well-maintained mulch will probably be adequate. If more protection is needed, landscape cloth could be used under the mulch. Another option is to plant a dense groundcover provided that no tilling or other activity that might mechanically damage existing roots was employed. The groundcover could be turf or any of the many others available as long as it was suited to the site conditions. There are disadvantages to having ground covers under trees, but this may be the best solution if erosion is a problem.

In the second situation, there are more difficult choices to make and decisions would have to be based on a number of untested assumptions. In construction of any kind, trees are exposed to many hazards not directly related to fill, such as soil compaction, trunk wounds, root severance from trenching or trafficking, chemical spills, and more. The first recommendation would be to eliminate all these possible sources of damage to the extent possible. When fill is applied in grading, specifying soil type is not always an option. Again, however, a fill soil similar to the existing soil would be preferable. The fill should be applied in such a way as to reduce compaction and tree damage as much as possible. For example, grading near the trunk should be done by hand and overall grading should be done when the soil is relatively dry. The number of passes over the fill soil with grading equipment should be minimized, even if this requires a more flexible grading plan.

If fill of 15-20 cm or less is applied, the question of a tree well can probably be avoided, just as in the first scenario, where exposed roots are being covered. In the research presented here, tree wells were neither beneficial nor detrimental. In situations with different soil conditions, tree species, ages and time frames, the effect of tree wells is unknown. If a deeper fill is needed, no tree well would be recommended unless there was reason to suppose that the particular tree would never form adventitious roots along the submerged trunk. In the case of very deep fill, 90 cm or more, a tree well is a major undertaking. Consequently, the best course of action is probably to provide no tree well. If the tree is extremely valuable and large, a more conservative approach might be needed. For example, it would likely be worthwhile to redesign grading plans to avoid steep grade changes. Very valuable small trees are uncommon, but such trees can usually be moved with a tree spade and then replaced after the grade change is complete.

Future research

The many unanswered questions concerning the effects of fill suggest two primary areas where considerable research is needed. First, it is necessary to determine the relation of other construction activities to fill. Some questions that arise include:

- Does applying fill using typical construction practices (grading with heavy machinery) result in tree damage?
- Does trafficking the original soil before fill is applied result in tree damage? This might occur in order to clear out underbrush or simply because it provides

convenient access to the construction site. Is such damage related to the age, species or condition of the tree?

- Is there an interaction effect between soil trafficking and fill?

A second area of interest concerns the depth of fill and the pros and cons of placing soil against the trunk. Questions in this area include:

- Do very deep fills damage trees and if so, is the effect related to the age or species of the tree?
- Can fill against the trunk cause the introduction of disease into the trunk?
- How readily do trees form adventitious roots when fill is applied? What factors (species, age, vigor, soil moisture, depth, climate, etc.) affect such root formation?
- If adventitious roots do not form (for example, if a tree well is used), is there a limit to the depth of fill that the existing root infrastructure can explore?
- Can the production of adventitious roots be stimulated by wounding or another treatment?

Considerable research is needed to even begin to answer these questions. Experiments to determine the effects of very deep fills and tree age- or size-related questions are very difficult to carry out, the main limitations being the extreme expense and space required to move large volumes of soil and the lack of older trees available for experimentation. For the fill experiments reported here, 500 cubic yards of soil were hauled in and spread. For a similar experiment with fill 100 cm deep and using older trees, that volume would easily reach 5,000 cubic yards, an impossibly large quantity in most circumstances. However, much information can still be gained through smaller scale projects. At the very least, this will greatly refine research questions allowing the formulation of more efficient experiments.

The Effect of Soil Moisture on Species Response to Compacted Soil

The work presented here offers excellent supporting evidence for the hypothesis that trees tolerant of wet soil might also be more tolerant of compacted soil because they can exploit the periods of soft soil that result when soil is very wet. However, this study included only one bottomland tree species, silver maple, and one species intolerant of wet soils, flowering dogwood. Results cannot be extrapolated to other species without further information. Also of interest is that the results add support to the concept that root growth of different species does not vary greatly in its response to soil strength. Furthermore, the study trees were young seedlings maintained in a highly controlled environment, rather than grown trees subject to the fluctuating conditions of an urban parkway. Keeping these limitations in mind, however, the results of this work have some immediate applications for urban forestry practice and research.

Practical implications for urban forestry

Urban foresters use many approaches to alleviate tree stress caused by soil compaction. This research suggests that irrigation may be another possible tool in alleviating compaction problems where trees tolerant of wet soil are concerned. Irrigation is not a long-term solution and there is no conclusive proof that it would be beneficial. However, irrigating inundation-tolerant trees when soil is dry holds few risks and is not normally particularly expensive. Hence, the possible benefits make this a worthwhile recommendation.

The similar responses of silver maple and dogwood to soil strength and the lack of increased maple root growth even in the wettest soil at the highest bulk density (1.7 g cm^2) suggest that urban foresters must continue to work to protect soil from compaction. Although one can choose to plant species that will better tolerate compacted soils in the field, there is surely no perfect urban tree that can grow freely in extremely hard soils. Even the now mythologized American elm (*Ulmus americana*) presumably suffers from extreme soil compaction.

A final practical implication of this work lies in suggesting a future course in shade tree evaluation and introduction. It could be recommended to urban foresters that they more often consider planting bottomland species. Many urban planting sites are hot and dry much of the time and planting bottomland species seems counterintuitive. For a given municipality, the mix of soil conditions, climate, microclimate, insect and disease problems, use of deicing salt, etc., yield an environment that is probably not replicated in nature, or even in the next town. Urban foresters typically learn through experience which trees thrive under what conditions in their particular climate and circumstances. The results of this research indicate that bottomland species could be suggested for planting in areas where they have not always been considered in the past.

Future research

The research presented in Chapter 3 suggests many avenues for future study. The most obvious would be the evaluation of a much greater selection of species in a similar type of experiment. Another direction would be to evaluate a number of bottomland tree species for use as urban trees. As suggested in the first chapter of this dissertation, there are a number of native species, such as Carolina ash and water-elm, which would be possible candidates and are now essentially unknown as landscape trees. These could be evaluated in field trials for tolerance of soil compaction. One aspect of interest would be to compare them with upland species such as white oak and scarlet oak (*Quercus coccinea*). More immediately useful would be a series of trials to select species for introduction into the nursery trade for use as shade trees. Such evaluations should consider a host of other factors besides tolerance of soil compaction. In addition, the best means of propagation and production of landscape-size trees and appropriate transplanting techniques would need to be studied.

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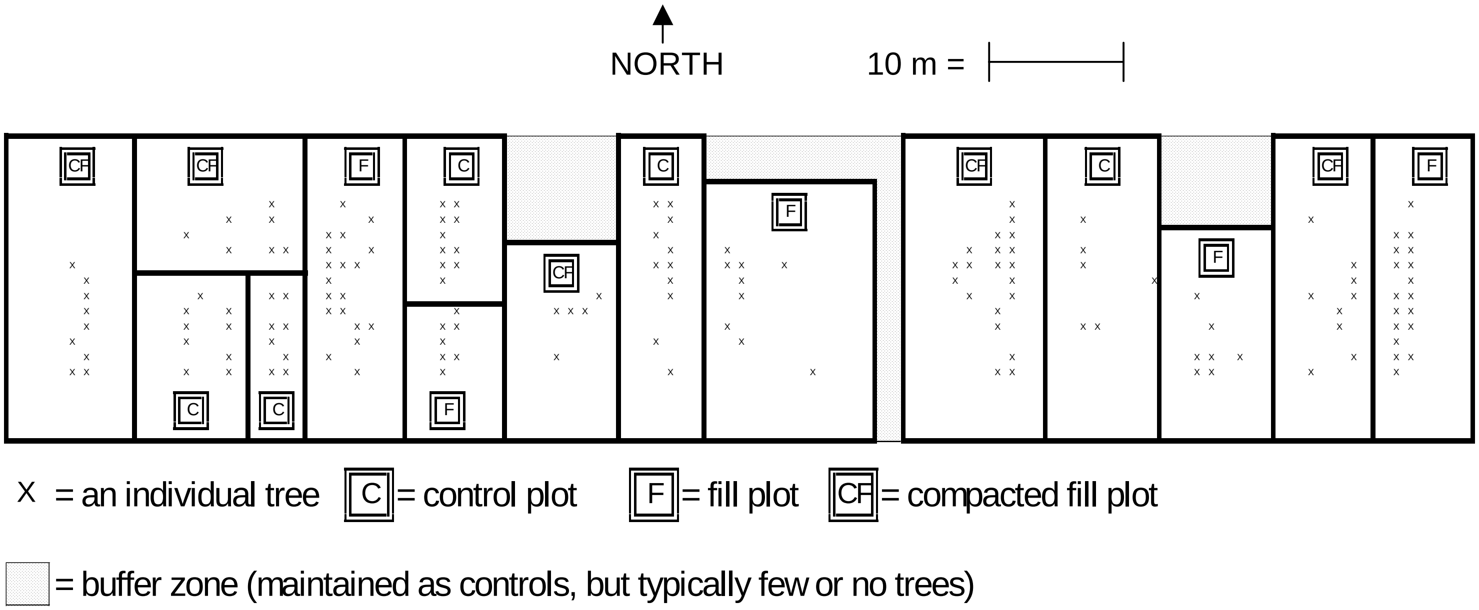
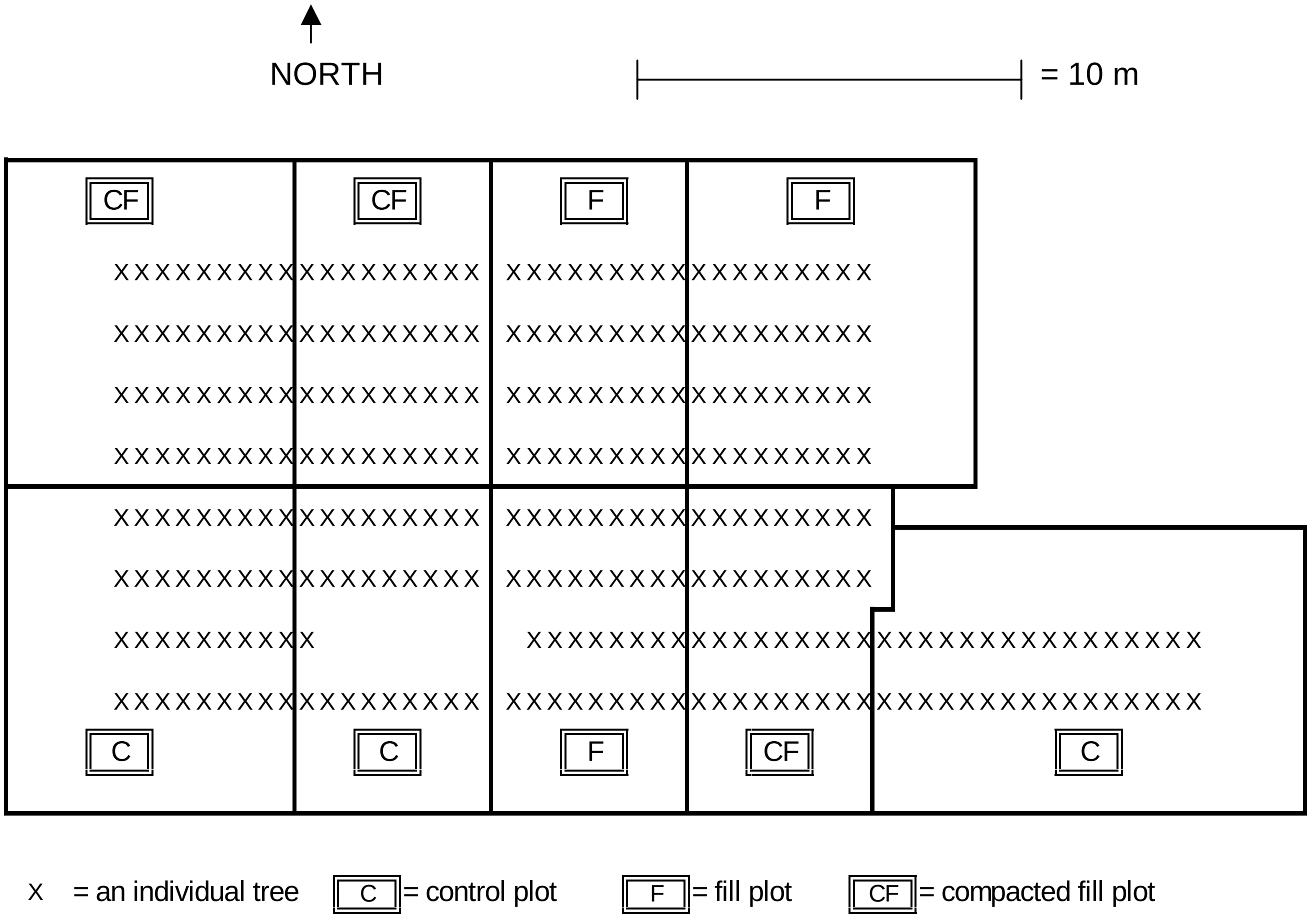
Appendix 1

Maps of Sweetgum and White Oak Stands



Map 1. White oak plots at Reynolds Homestead Forest Resources Research Center in the Upper Piedmont region of Virginia. The map is only very roughly to scale, with 1 cm = approximately 6 m.



Map 2. Sweetgum plots at Reynolds Homestead Forest Resources Research Center in the Upper Piedmont region of Virginia. The map is only roughly to scale (1 cm = approximately 2 m) and all individual tree locations may not correspond to the map.

Vita

Susan Downing Day's interest in urban forestry began when she lived in Chicago, Illinois during the late 1980s. Chicago's system of connected parks and the simple parkways for tree planting that line the streets of most residential neighborhoods make the city more comfortable and relaxing than many others of its size. Ms. Day completed a Master of Science degree in Urban Horticulture with Dr. Nina Bassuk at Cornell University in Ithaca, New York in 1993. She moved to Blacksburg, Virginia that same year when her husband, J. Roger Harris, took a faculty job in the Horticulture Department at Virginia Polytechnic Institute and State University. A few years later, she decided to pursue her Ph. D. at the university's College of Forestry and Wildlife Resources. She feels that being educated in both horticulture and forestry has broadened her outlook on urban forestry issues and practices. Ms. Day was born in Wilmington, Delaware in 1963, and lived in Pacific Palisades, California and Hinsdale, Illinois during her childhood. She holds a Bachelor's degree in Philosophy from Yale University in New Haven, Connecticut. She and her husband have one daughter and are expecting another child soon.