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SOIL COMPACTION—EFFECTS ON URBAN VEGETATION [1]

by James C. Patterson

Abstract. The urban environment imposes severe stress upon vegetation. The problems are many, and interactions common, making simple solutions difficult. This paper on urban soils discusses basic soil physics and soil chemistry, reviews some existing literature, and describes several research efforts in Washington. Particular emphasis is placed on soil compaction and ways to minimize its deleterious effects upon vegetation.

This year is the 200th birthday of the United States and estimates of visitation to the Washington metropolitan area range between 15-60 million. Most of these visitors will presumably descend upon Washington between Memorial Day and Labor Day. Naturally National Capital Parks, National Park Service is aware of the extreme impact this number of visitors will have upon our urban parks and are taking some steps to minimize this impact. At present, National Capital Parks has jurisdictional and management responsibilities for nearly 23% of the land area within the District of Columbia's boundaries, including all of the National Monuments from the White House down through the lesser important monuments.

The Ecological Services Laboratory has been established to serve a primary mission of research and advisory capabilities to the Director and his staff of NCP. We are working solely with urban vegetation and soil relationships in hopes of providing the technical input vitally necessary to maintain Washington, D.C. as one of the most beautiful cities in the world; after all, the city is recognized as a World Capital. The program being reported on here deals principally with the soils research.

Natural Soils

Soils as they occur naturally provide the basis for a better understanding of urban soils. Of particular interest to our work are soil physics, the major components of a soil, and routine chemical characteristics.

Soils are very complex, naturally formed entities which vary widely with the natural landscape. The principal mineral fractions considered are three: sand, silt and clay. The sand fraction (2.0mm - 0.05 mm) is virtually *chemically inert but does provide vital structural* capabilities for the soil mantle and assists in reducing compaction. Silt (0.05mm - 0.002 mm) provides structural support as well as some minor contributions to fertility. The clay fraction (0.002mm and smaller) provides most of the nutrient or fertility capabilities as well as supplies much of the matrix of soil structure and tilth.

These three fractions combined from roughly 45% of a hypothetical or "ideal" soil. The remaining 55% is composed of 5% organic matter (decaying and decayed plant parts, organisms, etc.), 25% for air space (N_2 forming 79.2% of the soil atmosphere, O_2 20.6% and CO_2 0.2%), and 25% for water or moisture capabilities. Organic matter assists the clay fraction in maintaining the soil structure and provides nutrient exchange and food for microorganisms. The organic matter and clay content can each affect soil fertility (nutrient status) and pH. Pore space, ideally composed of equal amounts of air and water space, fluctuates widely depending upon rainfall, humidity, temperature, compaction or use.

The preceding simplistic discussion of soil physics forms the background of our discussion of soil compaction.

Similarly the chemical characteristics of a naturally occurring soil vary widely with the landscape and from one region to another. Some

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of the more important characteristics and the desirable range for many urban plantings as is follows: pH—(5.5-7.0), fertility expressed as the cation exchange capacity (greater than 12-15 meg/100 gms.), organic matter (3-5% or greater) and soluble salt content (less than 600 parts per million). For example, by knowing any one selected characteristic inference can be made of other soil parameters. The cation exchange capacity will roughly correlate with the soil texture and organic matter content. Sands and sandy loams are low in colloidal clay and are likely deficient in organic matter or humus. The finer textured soils, loams, silt loams, clays and clay loams are in marked contrast, always contain more clay and generally more organic matter. Hence, their cation exchange capacities are usually higher.

In the National Park Service we are concerned with the carrying capacity for an area or simply the number of visits an area can support without deterioration of the resource we are trying to conserve. Soils are the medium in which turf, ornamental shrubs, small trees, and large trees receive support, moisture, oxygen and nutrients. The soil also helps protect the root systems from the adverse effects of overuse. The purpose of vegetation in the city is different from that of forestry and agriculture — we are primarily interested in vegetation for aesthetic purposes, not food and fiber production.

Soil Compaction and Pore Space

In the areas of intense use, the soil parameter that seems to be the best single barometer of soil conditions is bulk density. Soil bulk density has been used as the index of compaction (Pearson 1966). Bulk density is an expression of the mass per unit volume and can be an indicator of a wide variety of soil properties. Much has been accomplished to alleviate compaction in agricultural soils (Barnes *et al.* 1971) and one must begin with a brief review of literature to better understand the basic principles involved.

Pore space, ideally 50% is the portion of the soil matrix that is directly and adversely affected by heavy use (Cordell and James 1971). Pore space distribution, i.e. the distribution of macro and micropores does not remain constant, but is altered by compaction, cultivation, aggregation, fertilization, etc. (Waddington 1968). With compaction, for example, the solid phase of the soil increases per unit volume. In other words the pores that suffer most from compaction are the large macropores and there is a resulting increase in the smaller micropores. Compaction creates poorer soil moisture relationships, (less available moisture for plants), irregular soil temperature relationships, a less desirable soil atmosphere, resistance to root penetration, (a significant reduction in root weight/volume can occur), increased runoff and erosion, and other interrelated problems for plants. Total pore space can be calculated when the bulk density (BD) and particle densities (PD) are known: 100-(BD/PD x 100) = total percent pore space.

Reports vary when considering the percent pore space required for adequate plant growth. The percent pore space also varies with different plant species. For example: Van der Valk (1971) has suggested that when the percent total pore space is less than 44%, the growth of flower bulbs can be impaired. In contrast, Johnston and Wood (1971) noticed no significant reductions in sugar cane yield because of soil compaction. However, sugar cane is an exception and is generally able to grow under compacted conditions. Vigor of most plants suffers under compacted soil conditions and when the pore space volume drops below 30%, most plant growth is hampered. As implied, there is considerable variation among plants to exist under compacted conditions.

Both soil atmosphere and water movements are directly affected by, and related to, soil compaction. In general terms there is a balance between the soil atmosphere and soil water. After a saturating rain the soil pores are filled with water, leaving little pore space for soil gases. As water is lost to evaporation, percolation, transpiration, and other causes, the volume of the soil atmosphere increases. During very dry periods the gaseous phase predominates, and little water is available for plant use. Sekiguch (1973) noted that for street trees, moisture depletion can occur rapidly and can vary widely from location to location.

Soil Atmosphere. The soil atmosphere as indicated contains oxygen, carbon dioxide, nitrogen and various other gases. This phase of the soil is likewise adversely affected by compaction. According to Hady (1974), Dosberg and Bakker (1970) and Youngberg (1970), oxygen in the soil profile is the key to regulating plant growth. Youngberg indicated that the growth of scotch pine was hindered by an oxygen content of less than 10% by volume.

Within the soil profile the principal movement of oxygen and carbon dioxide is through diffusion (Wood and Greenwood 1971). Kays (1974) noted that an inverse relationship exists between concentrations of oxygen and carbon dioxide in the soil. In the surface soil oxygen will generally predominant over carbon dioxide. With increased depth in the soil profile, the relationship is altered so that carbon dioxide begins to predominate over oxygen.

The gaseous phase of the soil occurs in three principal forms: (1) a free state that is found within the pores, (2) a dissolved state in which the gases are dissolved in water, and (3) an absorbed state — on the mineral and organic fractions (Stolzy 1974). Stolzy concludes that, if internal drainage is good, the oxygen content of the soil will rarely drop below 15%, while the carbon dioxide content is rarely above 5 or 6%.

Yelenosky (1963, 1964) found that under poor aeration the oxygen concentration drops to as low as 1%, while the carbon dioxide content rises to 19% or higher. Soil aeration can be reduced by a layer of clay over existing soil, by compaction (as from heavy use), or by a paving operation. Under those treatments the soil atmosphere changes from aerobic to anaerobic, and the change can, seemingly, occur within a growing season. Once an area becomes compacted, re-creation of an aerobic soil condition is difficult.

There are means available to help re-create an aerobic soil atmosphere, although prevention of poor aeration by proper and adequate soil preparation has been most often emphasized (Martin 1971, Hiler *et al.* 1971, Grabert and Steinbrenner 1972). When a soil does become compacted, one of the most successful means to improve aeration is subsoiling (Grabert and Steinbrenner 1972). This method is often very costly and, in the urban environment, difficult to perform except on large open areas. When soils are poorly drained, the installation of tile drains may improve aeration. In areas that are difficult to drain, the use of plant species well adapted to moist conditions is advisable.

Pavements cause the soil atmosphere to change from aerobic to anaerobic, thereby reducing the vigor of plants (Yelenosky 1964, Franken 1969, Hartage and Bailly 1970, Hartage 1968). On the basis of observations in Washington, D.C., I believe that the soil beneath pavements is usually quite moist and the soil atmosphere is predominately anaerobic. Pirone (1972) stated that pavements prevent gaseous exchange with the atmosphere, and that a general anaerobic condition occurs beneath pavements. Normal gaseous exchange between the soil and the atmosphere is necessary for tree roots and microbes to respire. This exchange can be interrupted by pavements and compaction, thus retarding root growth essential to tree vigor.

I found limited information on the topic of species tolerance to soil compaction. Yelenosky (1964) reported that, of seven species of seedlings, American elm was the most tolerant to poor soil aeration, while the tuliptree (yellow-poplar) seedlings were the least tolerant. Littleleaf linden, 'Moraine' honeylocust, white oak, sugar maple, and flowering dogwood were intermediate between American elm and tuliptree. Pirone (1972), as reported by Kozlowski and Davies (1975), listed species affected by poor soil aeration, as follows: 1) most severely injured: sugar maple, beech, dogwood, oak, tuliptree, pines, and spruce; 2) less severely injured: birch, hickory, and hemlock; and 3) least injured: elm, poplar, willow, plane, pin oak, and locust. The two authors do not wholly agree in rating the susceptibility of various species.

Soil compaction and anaerobic conditions caused by paving, heavy use or flooding do cause an unfavorable rooting environment for most trees. Differences apparently exist in the tolerance of tree species and of individuals within species to compacted conditions within the urban environment. Plants most suited to such conditions have apparently undergone some selection simply through survival of stems of adapted species. However, much research still needs to be done as a basis for selecting suitable species or cultivars.

Yelenosky's (1964) summation of soil and plant relationships was succinctly stated: "there are no simple answers to meet all situations concerning tree growth and soil areation." This seems to be the case within the urban ecosystem.

Soil Compaction in Washington, D.C.

Tijmens (1973) indicated that planting should be an integral part of urban planning, and I believe that this is the direction we are all working toward.

Plants in urban areas exist under a myriad of environmental stresses and those in Washington are no exception. When you consider the effects of soil compaction, insects, disease, drainage, water pollution, deicing salt, and vandalism, which individually can reduce or prohibit tree growth, it is not surprising that their synergistic effects are quite severe (Seibert 1973 and others).

Determining Present Conditions. The soil program at the Ecological Services Laboratory of National Capital Parks has focused on soil heterogeneity, compaction and related physical properties, and recently has been examining the chemical properties. One significant endeavor has been a comprehensive survey of Washington's soils in cooperation with the Soil Conservation Service. This survey, the first comprehensive survey of urban soils, is nearly 90% completed (the field mapping is completed). It will be an exceptionally valuable aid in planning for Washington's plant scientists and urban planners.

Prior to the soil survey we did some soil characterization work on the Mall. The first urban soil profile I observed was dramatic. A distinct characteristic was realized with every swing of the pick, that of severe density or compaction. Analyses have been completed for that profile and for three others on the Mall. Data on bulk density and pore space in these samples verified the inadequate pore space for moisture and air exchange. Ideally the bulk density should range between 1.3 and 1.6 g/cc, while the pore space should range between 40 and 45%. For the Mall soils, the bulk-density range was 1.7 to 2.2 g/cc, while pore space was 13 to 36%. These data are indicative of the heterogeneity observed for the twenty soil profiles that the lab has characterized to date.

I conducted a small experiment to determine if in fact "urban soils are as dense as concrete." Four commonly used construction materials were tested: cinder block, brick, asphalt, and concrete. The data reveal that our urban soils are indeed as "dense as concrete"!

A high bulk density and low amount of pore space seem to exist in most of the soils examined and probably form the most restrictive characteristic of urban soils for plant growth. Other characteristics I have observed as common in urban soils are extreme heterogeneity from area to area, variability in percentages of organic matter with profile depth, unoriented coarse fragments (rock and stones), highly variable fertility and pH, a wide variation in textural distribution (% of sand, silt and clay) with depth of profile, and a tendency for the compacted soils to repel moisture or exhibit a hydrophobic nature.

Improving Present Conditions. Part of the soils work is directed toward finding economical ways to alleviate deleterious effects of soil compaction upon plants. Major areas needing renovation are heavily used: playgrounds, picnic sites, concession areas, athletic centers, etc. Soils of these areas undergo severe compaction that in all likelihood reduces the longevity of vegetation, particularly trees. A soil-amending process should assist in reducing compaction over the long term, 5 to 10 years or longer. However, soil renovation is difficult once trees are established — because of the predominance of roots in the surface A1 and A2 soil horizons.

At Hains Point, plots have been laid out under conditions of very heavy use in a picnic-playground area. The number of daily visits to the area is estimated at 800, and visitors are permitted unrestricted use of the area. The Park Service staff maintains the grounds as a part of their regular duties.

Soil amendments used in this study were four: (1) sintered fly-ash (a by-product of the hydroelectric power industry, fly-ash is heat-treated or sintered to produce a porous, inert and rigid, light-weight aggregate with about 70% pore space); (2) expanded slate (a commercially available material produced by a heat-expansion process so the slate, too, is porous (about 50% pore space, inert and rigid); (3) coarse construction sand (not a light-weight aggregate, but an age-old and commercially available material); and (4) an organic material, digested sewage sludge.

After four years — even with continued visitor use — there are significant differences between treatments. The soil mix having 33% by volume of expanded slate has the lowest bulk density and the most pore space. Sintered fly-ash was not so effective an amendment as expanded slate except at volumes of 20%. The four treatments utilizing sintered fly ash did produce the best overall performance. Coarse construction sand was not so effective an addition as either of the two aggregates, while the use of sewage sludge with the other materials had little or no effect. Effective soil amendments offer a partial solution for alleviating some of the deleterious effects of compaction. The best treatment gave an increase of 7% for pore space in the rooting zone, an increase that improves the air and water relationships for the growth of trees.

Infiltration and percolation data are not yet completed, but initial indications are that the modified plots handle more water per unit time than the controls. This is particularly important in reducing runoff and erosion during rain storms and in getting the moisture into the soil so it is available for plant use. We have noticed that the plots exhibit a hydrophobic or water-repellant tendency. This characteristic can apparently develop when soils become compacted. Further work will hopefully substantiate these indications and suggest possible amelioration measures.

Within the environment of the city and its parks, the general procedure has been to remove leaves and other naturally produced organic matter. This practice removes nutrients and organic matter from city soils (Meyer 1973 and personal observations). Organic materials should be included in maintenance operations as urban soil amendments. Use of these materials is economically feasible, partly because of the number of brush and log chippers currently available and partly because of the high cost of purchasing adequate amounts of topsoil, fertilizer and peat moss. The materials can be composed with sewage sludge, as the USDA has demonstrated at Beltsville, and provide a very desirable organic material for modifying urban soils. Such organic wastes do not, of course, totally replace topsoil and fertilizer in amending urban soils.

However, the value of these organic wastes is demonstrated by their use in Constitution Gardens, a 42-acre site located between the Lincoln Memorial and Washington Monument (Patterson 1975). Nineteen-hundred trees, numerous shrubs and other vegetation are being used to create an informal park where Bicentennial visitors can relax. Typical urban soil existed at this site, so National Capital Parks had to choose between purchasing adequate topsoil to support the trees and other vegetation and building a soil using the existing soil, 3 inches of USDA compost (digested sewage sludge and wood chips), 4 inches of leaf mold collected within the Washington area, and a small amount of topsoil. The existing soil, compost, and leaf mold were thoroughly mixed to form a soil mantle of 14 inches, over which a 3- to 4-inch layer of topsoil was placed. The results of soil data indicate that the fertility is mostly adequate to date. Nitrogen will have to be added because of the very low amount in the organic amendment. (Nitrogen analyses show 4 to 18 lbs. of available N per acre.) Another added benefit of building soils in the urban area is one of economics. By and large, a dollar savings of about $200-$250,000 was realized by "building" the soil at Constitution Gardens. Another benefit not calculated into the savings was the value of recycling urban produced "wastes" such as leaves, wood chips and sewage sludge. Further, if "topsoil" were purchased for a site such as this a large amount of fertilizer, organic matter and other additives would need to be added to the soil. By and large, the term topsoil is a meaningless term, particularly in the urban environment. To me, the term topsoil simply means the soil on the surface, regardless of it's soil chemical and physical characteristics.

Another similar area where we plan to utilize wood chips, leaves and sewage sludge will be the 1976 Bicentennial Folk Life Festival. We anticipate about 10,000 persons per week will visit this 20 acre site between Memorial Day and Labor Day 1976. At present we are planning to broadcast wood chips over the entire site to a depth of 3-4 inches for the duration of the Festival. In September when the Festival is over, Beltsville compost (the wood chip-sewage sludge compost) will be applied to the surface of the wood chips and the wood chips, compost and underlying soil will be thoroughly mixed to form a homogeneous mixture which will be seeded to grass. Some experimental plots have indicated that this is a desirable approach for the renovation of this area. The costs have not been estimated as yet, however, by approaching the renovation in this manner, the costs will be significantly reduced over sodding or some other technique.

In the future we are looking toward composting of our urban produced organic materials for use as soil amendments. These materials will be used along with existing soils to "build" our own topsoil materials. This procedure seems quite attractive and sensible particularly when one considers the cost of peat moss and other mulches, fertilizers and topsoil which is generally of low quality and costly.

Conclusions

Soil compaction imposes severe stress upon urban vegetation. Treatments tested by the Ecological Services of the National Capital Parks have produced a significant reduction in soil compaction as measured by bulk density. Lightweight aggregates rotary-tilled into plots reduced soil compaction, even though the area was continually used as a playground-picnic area. Composts of leaves, wood chips and sewage sludge help reduce compaction of urban soils and also increase their fertility and content of organic matter. Wood chips, when used on heavily compacted soils in shaded areas, reduce damage to soil and to tree roots from continued heavy use. Such applications of organic materials aid the development of a "natural" soil profile.

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Research Agronomist,
Ecological Sciences Laboratory,
National Capital Region,
National Parks Service,
Washington, D.C.

HERBICIDE INJURY TO TREES[1]

by John A. Meade

A herbicide is a chemical used to kill unwanted plants. Often these plants are growing in association with desirable plants. To kill one plant growing in close association with another is difficult and relies on the property of selectivity. This selectivity depends on several things, such as the herbicide, temperature, rainfall, and species of plant involved. When selectivity fails, we have tree injury.

Those herbicides generally involved in tree injury fall into two classes: 1) compounds used to kill broadleaf weeds in turf; and 2) total vegetation control agents.

The first group causes injury in three ways:

Drift. Movement of spray particles through the air. These particles contact the leaves of desirable plants and injury results. This, of course, shows up only during the growing season. Conifers are more resistant that deciduous plants.

Volatility. These compounds are usually used when air temperatures are high (60-85 deg. F). At elevated temperatures, some formulations will evaporate into a gas. This gas then moves through the air to contact desirable plants. The herbicide is absorbed and injury occurs.

Root absorption. While the life of these compounds in soil is short (2-3 weeks) and they do not penetrate deep into the soil (1-4"), tree roots can intercept some of these compounds and move them up into the tree where injury symptoms show up.

The second group causes injury usually by root absorption. These herbicides are designed to be long-lived in the soil and indeed some persist for a year or more. Since they are there longer, they move deeper into the soil with rainfall. Hence, they have more chance of coming into contact with tree roots.

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