SOIL COMPACTION ON HEAVILY USED SITES

by Phillip J. Craul

Abstract. Compaction of soil is a detrimental result of heavy human use of a site. The destruction of the associated vegetation is an accompanying feature. Soil compaction commonly causes reduced water infiltration, loss of pore space and increased soil density, decreased waterholding capacity, reduced aeration, increased mechanical impedance to root growth with concomittant decrease in nutrient uptake, and reduction in soil microorganism activity. Amelioration of soil compaction under existing vegetative cover, especially trees, is difficult without some injury to the root systems. Some standard methods of surface soil aeration exist that can be applied to turf and some tree areas, but amelioration of compacted subsoils is very difficult in most cases. For existing trees and their root systems, radial trenching appears to be a promising technique for compaction amelioration.

Key words: Soil compaction, bulk density, infiltration, soil crusting, root penetration, heavy use site.

Soil compaction, defined as the compression of an unsaturated soil (4), is most often associated with heavy use of a site. Foot and vehicular traffic are common major causes of the compaction. Though soil compaction may occur without destruction of the covering vegetation, especially turf, it is often destroyed. Woody vegetation may persist longer under heavy use, but it soon succumbs as well. Trees will persist longer, but weakened vigor and greater susceptibility to insects and diseases sets in before actual mortality. Mechanical injury to stems, trunks or exposed roots is common.

A crust usually forms at the soil surface and becomes hydrophobic under urban conditions (2). Other physical effects include: reduced infiltration, increased density, loss of macropore space, decreased waterholding capacity and aeration. These physical conditions may create mechanical impedance to root penetration as well as reduce the oxygen concentration to levels below the minimum needed for root survival.

Causes of Compaction

Soil compaction develops as the result of shear and stress forces acting on soil particles and peds. Stress forces are those that are generally normal to the area over which it acts; thus, the force applied by the sole of the human foot. Shear forces are those that are parallel to the surface area, as the shear that occurs in the soil by the edge of the shoe sole making the sharp imprint. Stress forces occur below vehicle tire imprint, whereas the edge of the rut is produced by shearing forces.

There are several active and passive causes of soil compaction. The active causes of compaction include traffic over the soil surface. Foot traffic is characterized mainly by compressional stress but includes shear caused by "scuffing" of the soil by foot slippage or sliding on playgrounds or in other athletic activity. Vehicular traffic involves moving forces of stress and shear. Vibration is an important component of vehicular traffic.

Soil texture, or more precisely, particle size distribution, determines the self-compactability of a soil, a passive cause of compaction. A poorly graded soil with several of the finer particle sizes present (mainly fine sand, very fine sand and silt) in only small amounts or lacking (Figure 1a) will have less potential for compaction than a well graded soil with a rather uniform distribution of the particle sizes over the range of diameter classes (Figure 1b). Thus, a silt loam is more self-compacting than a coarse sandy loam soil. Passive vibrational forces caused by street or mass transit traffic are transmitted to soil surrounding plantings in urban areas. It is possible for soils to be compacted to high levels outside of heavily used areas where foot and vehicular traffic are absent. Craul and Klein (3) reported bulk density values approaching 1.88 Mg/m^3 in street-side silt loam subsoils.

Soil moisture influences the degree of compaction attained under a given set of applied

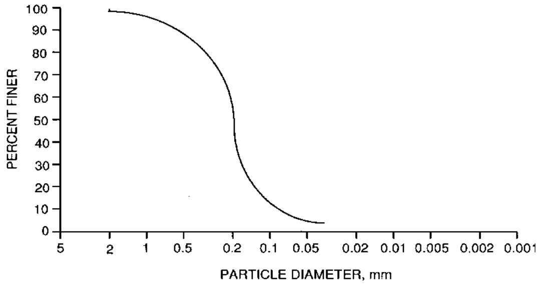


Figure 1a. A poorly graded soil.

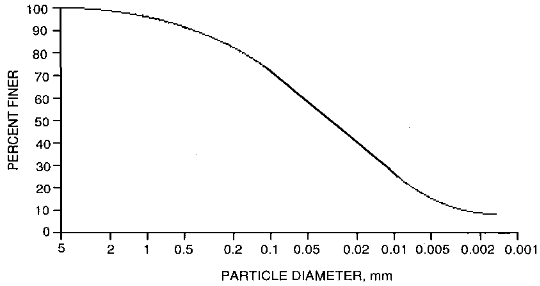


Figure 1b. A well-graded soil.

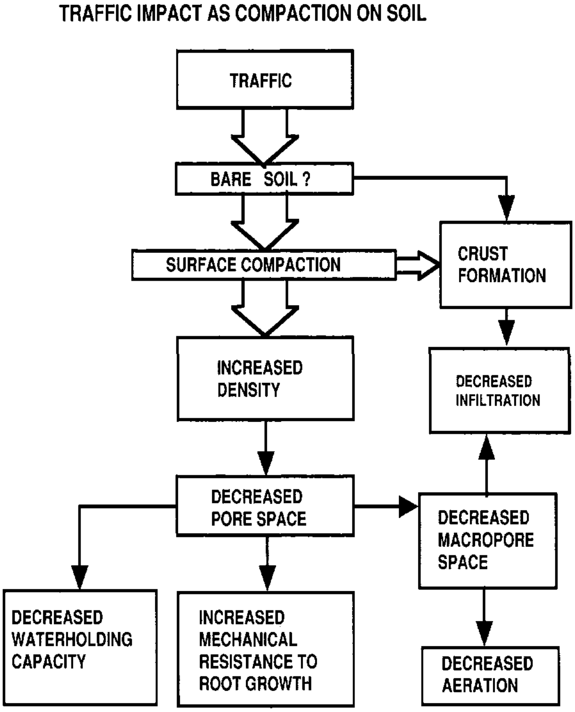


Figure 2. The general effects of soil compaction.

forces. When the soil is dry and hard, little compaction will occur. As moisture content increases from dry to moist, the aggregates are softened and may be more easily compressed with a loss of airfilled pore space (macroporosity). The water also acts as a lubricant, reducing friction of aggregates slipping over each other. Eventually, as the soil moisture content nears saturation, there is less airfilled pore space and the degree of compaction is reduced as water is imcompressible. As the soil reaches the liquid limit, it becomes puddled and flows under compressive forces (4).

The Effects of Compaction

As illustrated in Figure 2, there are significant effects of soil compaction as they affect tree growth and management of the site.

Crusting. Crusting occurs when the soil aggregates are pulverized and the fines fill the smaller pores. In addition, the surface under traffic is compacted to a greater degree than at lower depths. There is also a tendency for soil particles to be horizontally oriented within the crust. The deposition of petroleum residues on the crust and the tranformation of organic compounds into esters and fatty acids causes it to become hydrophobic.

Decreased Infiltration. The crust formation coupled with the reduced pore space and its smaller average pore size reduces the infiltration capacity of the compacted soil. Thus, small amounts of precipitation infiltrate only to shallow depths in the crusted soil or may be converted mostly to runoff.

Increased Density. Compaction has been defined as the compression of unsaturated soil. As such, the pore space volume is decreased in compressed soil. Due to the aggregate (ped) makeup of the soil, the peds are crushed and fragments fill the voids, which are reduced in effective size. Thus, not only is total pore space lost upon compaction but also the larger pores are destroyed or at least reduced in size. These changes all have significant influence on other soil physical characteristics.

Reduced Waterholding Capacity. Since water is held in the pore space, any decrease will generally decrease waterholding capacity; however, there are some instances where a loose soil with a low bulk density soil may show an increase in waterholding capacity because of an increase in the percentage of water-retaining micropores.

Reduced Soil Aeration. With the decrease in total and macropore space coupled with the shift in the proportion of macro- to micro-pore space, the diffusion of gases, such as oxygen and carbon dioxide, into and out of the soil can be greatly reduced. Interconnected pores become discontinuous which increases the complexity of the diffusion pathway. A greater proportion of the pores are waterfilled which acts as a barrier to the diffusion process (5). Even though the surface soil may be the only portion compacted, the entire profile may exhibit decreased gaseous diffusion similar to the analogous idea of putting a lid on a garbage can.

Increased Mechanical Root Impedance. Roots penetrate only pores that have the same or larger diameters as their root tips. The rootcap of the tip consists of a certain minimum number of cells which occupy a certain minimum diameter. The root will penetrate a smaller pore only if the soil is loose and the root can make the pore larger by nutational motion. If the soil is firm, the root simply cannot penetrate the smaller pore. Root penetration is inhibited at a bulk density of about 1.55 Mg/m^3 in fine textured soils and about 1.75 Mg/m^3 for sandy soils (11). The bulk density of many urban soils approach or exceed these values (3,6,9). It should be apparent that reduced root elongation will reduce nutrient and water uptake by the roots.

Case Study: The National Mall, Washington, D.C.

The National Mall between the Capitol and the Washington Monument probably receives as heavy a use as any other landscape in the United States with over 2,000 permits issued each year for various events and demonstrations. About 23,000,000 people visit the Mall annually. During the summers of 1989 and 1990 various soil and vegetation observations were made on eight of the 52 panels of trees and turf that comprise the National Mall (1). Loss of turf and changes in bulk density (18 sample points per panel) were measured on five heavily impacted American elm panels (100,000 people per day for about 10 days each June-July since 1976) and compared with two panels receiving light or casual impact and one with moderate impact (Table 1). Results show that surface soil (2-inch depth) bulk density on the five heavily impacted panels was an average of 1.53 Mg/m^3 and at the 6-inch depth was an avearge of 1.62 Mg/m^3 as measured by a nuclear density probe. The nuclear density probe was locally calibrated using the Saran-coated clod method. Short, et. al. (9), using the clod method earlier found surface bulk density of 1.61 Mg/m^3 for the surface horizon and 1.74 Mg/m^3 at the 12-inch depth. Patterson showed similar results (6). The discrepancy (lighter in the former case) between the two sets of averages may be partially due to the cracking of the compacted soil from driving the steel access probe into the soil for the 6-inch depth measurement. About 14 to 45 percent of the soil surface on the heavily impacted panels was laid bare and 9 to 34 percent of it was bare and later invaded by goosegrass (*Polygonum aviculare*). No direct evidence of impact on the trees could be obtained other than past mortality history.

Methods of Compaction Amelioration

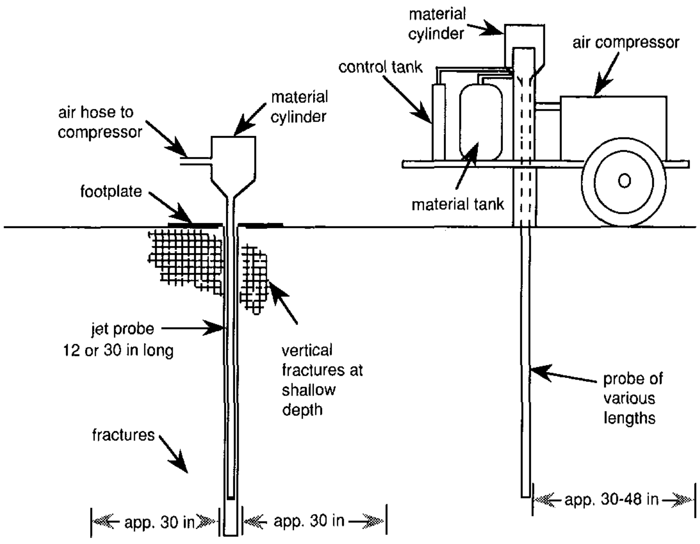
The various methods or techniques to reduce soil compaction are derived from agricultural or turf soil management systems. Many of these methods may be applied to urban situations but are not always applicable to treed sites because of

Table 1: Soil bulk density values for three levels of impact (1).

	Degree of impact		
Soil depth	Light (2)[a]	Moderate(1)	Heavy(5)
		Mg/m^3	
2 inches	1.45	1.49	1.55
6 inches	1.58	1.57	1.63

a Number of panels with 18 sample points per panel.

Figure 3. Deep jetting: (a) Hydrojet; (b) Terralift. After (10).



the inherent danger of injury to the woody root systems of the trees. Hence, a certain degree of discretion must be used or other methods must be employed. Since nearly 90 percent of tree roots occur within the upper 6 to 12 inches of soil (2), it is difficult to avoid tree root damage by several of the compaction amelioration methods.

Surface compaction. *Spike and Core Aeration.* These techniques punch holes into the soil, removing a soil core in the case of the core aerator or creating a hole surrounded by compressed soil with a solid spike aerator. The core method is the preferred method on turf areas such as golf courses, etc. However, the core penetrates the soil only several inches and does not affect compacted soil below that depth. Frequent use of the aerator can create a compacted layer just below the level of maximum core penetration. In some cases the soil is compacted to such a great degree that the cores or spikes cannot penetrate the soil surface such as the Washington Mall. Even the spike aerator is used with difficulty on this site (J.C. Patterson, National Park Service, Center for Urban Ecology, personal communication).

Rototilling. This method is satisfactory only where tree roots do not occur in the soil surface and the destruction of the turf is not a problem. Frequent rototilling to the same depth tends to form a smoothed tine compaction layer that may be detrimental to root extension and vertical water movement even though the soil above may be temporarily loosened. Frequent rototilling of low organic matter content soils may reduce macropore space volume. Thus, routine rototilling is not always beneficial.

Subsurface compaction. *Deep-jetting.* This technique involves the injection into the soil of air or water at high pressure to fracture the soil (Figure 3). Compost, fertilizer, or a soil lightener (Styrofoam) is injected into the fracture voids. Both Rolf (8) and Smiley, et. al.(10) have experienced mixed results with these machines. Apparently, soil profile conditions, such as texture, moisture content, presence of one compacted layer below another, etc. influence their effectiveness. Perhaps with more applied research this technique may have wider application.

Subsoiling. The plowing of the soil at depth with a subsoiler or chisel plow to break up plow pans or clay pans has been done in agricultural soil management for many years (Figure 4). Its use in urban soil situations has been limited. Its best application in urban soils is on newly constructed

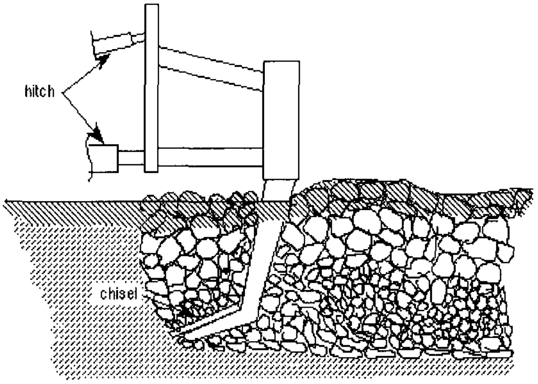


Figure 4. Subsoiling or deep plowing.

sites that have suffered compaction from construction equipment, etc. It must be used before the installation of plant stock as the plowing can do much harm to existing tree root systems. Turf areas are disturbed only along the line of the plow shaft. Agricultural experience shows that the effects of subsoiling are short-term, lasting only several years after which the soil recovers its compacted nature. Experience in urban soils may be better. Rolf (7) uses a backhoe to loosen the subsoil with favorable results on new construction sites before final grading and installation of the plant stock.

Trenching. This method was described by Watson (12) after a Chinese technique. It consists of a series of trenches dug radially outward from the trunk with each trench located to avoid the the pathways of the major lateral roots (Figure 5). The trenches are backfilled with specified soil containing high organic amendment. An aeration system may be installed in each trench. Preliminary results by Watson show real promise.

Conclusions

One of the major detrimental effects of heavy site use is soil compaction and its attendant effect on the vegetation. Though evidence directly linking soil compaction to the reduced vigor and mortality of trees on heavily used sites is scarce, there is a large body of circumstantial evidence that indicates to the practicing eye that there are detrimental conditions present in the compacted soil.

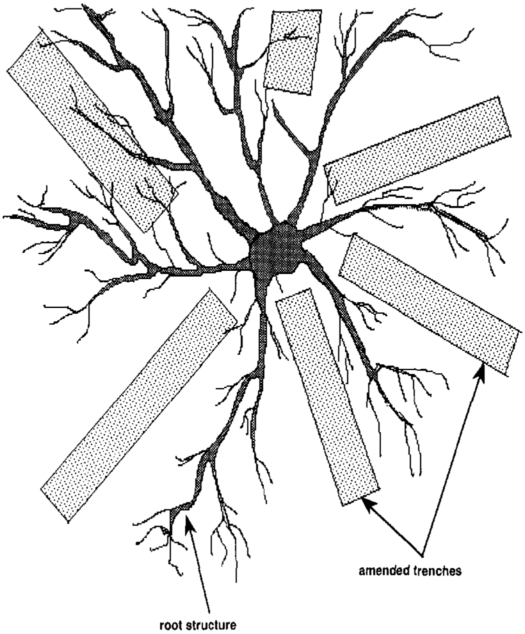


Figure 5. Radially trenching: an old Chinese technique (12).

Literature Cited

1. Craul, P.J. 1990. Report to the Regional Director on the conditions of the soil and vegetation on the National Mall, Washington, D.C. U.S. Dept. of Interior-National Park Service, National Capital Region. 46 pp.
2. ________ . 1992. Urban Soil in Landscape Design. John Wiley, New York. 396 pp.
3. ________ , and C.J. Klein. 1980. *Characterization of streetside soils of Syracuse, New York.* METRIA 3:88-101.
4. Hillel, D. 1980. Fundamentals of Soil Physics. John Wiley, New York. 413 pp.
5. MacDonald, J.D., L.R. Costello and T. Burger. 1993. *An evaluation of soil aeration status around healthy and declining oaks in an urban environment in California.* J. Arboric. 19(4):209-219.
6. Patterson, J.C. 1976. Soil compaction and its effects upon urban vegetation. **In** Better Trees for Metropolitan Landscapes Symposium Proc. USDA Forest Serv. Gen. Tech. Rep. NE-22.
7. Rolf, Kaj. 1991. *Soil improvement and increased growth response from subsoil cultivation.* J. Arboric. 17(7):200-204.
8. ________ . 1992. *Soil physical effects of pneumatic subsoil loosening using a Terralift soil aerator.* J. Arboric. 18(5):235-240.
9. Short, J.R., D.S. Fanning, M.S. McIntosh, J.E. Foss, and

J.C. Patterson. 1986. Soils of the Mall in Washington, D.C: I. *Statistical summary of properties.* Soil Sci. Soc. Am. J. 50:699-705.
10. Smiley, E.T., G.W. Watson, B.R. Fraedrich, and D.C. Booth. 1990. *Evaluation of soil aeration equipment.* J. Arboric. 16(5):118-123.
11. Veihmeyer, F.J., and A.H. Hendrickson. 1948. *Soil density and root penetration.* Soil Sci. 65:487-493.
12. Watson, G.W. 1990. *Tree growth revisited.* Golf Course Manage. 58(6):8-10, 12-14, 16, 18, 22, 24-25.

Professor of Soil Science
Faculty of Forestry
SUNY-College of Environmental Science and Forestry
Syracuse, New York 13210
and
Visiting Professor of Landscape Architecture
The Graduate School of Design
Harvard University
Cambridge, Massachusetts 02138

Résumé. La compaction du sol est le résultat dommageable de l'utilisation humaine d'un site. La destruction de la végétation qui y est associée est un trait qui accompagne une telle situation. La compaction du sol cause communément une réduction de l'infiltration de l'eau, une perte de porosité, un accroissement de la densité du sol, une diminution de la capacité de rétention en eau, une réduction de l'aération, un accroissement de la résistance mécanique à la croissance des racines en concomitance avec une décroissance dans l'assimilation des éléments nutritifs et une réduction de l'activité des microorganismes du sol. Diminuer la compaction du sol sous un couvert végétal existant, spécialement des arbres, est difficile à réaliser sans endommager ou blesser les systèmes racinaires. La diminution de la compaction des couches de sol plus profondes est extrêmement difficile à faire. Lorsqu'il y a déjà présence d'arbres, la technique d'une tranchée radiale apparaît être prometteuse.

Zusammenfassung. Die Bodenverdichtung ist ein verhängisvolles Ergebnis von starker Beanspruchung des Standortes. Die Zerstörung der damit verbundenen Vegetation ist eine Begleiterscheinung. Die Bodenverdichtung verursacht gewöhnlich reduzierte Wasserinfiltration, Verlust von Proenvolumen und verstärkte Bodendichte, verminderte Wasserhaltekapazität, reduzierte Belüftung, verstärkte mechanische Behinderung des Wurzelwachstums mit gleichzeitiger Verminderung der Nährstoffaufnahme und Reduktion der Bodenmikroorganismenaktivität. Eine Verbesserung der Bodenverdichtung unter existierender Vegetation, besonders unter Bäumen, ohne das Wurzelsystem zu verletzen oder zu zerstörch, ist schwierig. Die Verbesserung von verdichtetem Unterboden ist sehr schwer. Für existierende Bäume und ihr Wurzelsystem scheint das Anlegen von seitlichen Gräben eine veilversprechende Technik zu sein.