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Trees & Soil Compaction Stress:
A Workbook of Symptoms, Measures & Treatments

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This is a fourth revision over 25 years of a popular educational treatment for soil compaction and tree health care. This workbook is not designed for generating bidding specifications, standards, commercial marketing devices, or industrial consensus products. This is an educational workbook designed to assist tree health care providers appreciate and understand some of the complexities of soil compaction and its impact on tree health.

Information presented here is from research studies, field applications literature, and the professional experience of the author. The author has selected items to include and exclude based upon their value to forward different educational concepts and learning objectives for the student. Because of the complexity of this work, the author and this institution can not be held responsible for errors and omissions which may be present, or which may affect professional interpretation and associated field applications.

This revised publication is about learning basic information on soil compaction and tree interactions, not a "how to" on decompacting soils. Always seek the assistance of a professionally credentialed tree care provider to assure your tree receives the best possible care.

Contents

Introduction
Defining Soil Compaction
Root Health
Compaction Causes & Soil Results
Measuring Compaction
Tree Impacts & Site Renovation
Trees & Soil Compaction: A Selected Bibliography
Appendix 1: Compaction Tolerant Trees
Appendix 2: Field Data Sheet

Trees & Soil Compaction Stress: A Workbook of Symptoms, Measures & Treatments

Introduction

Health and structure of trees are reflections of soil health. The ecological processes which govern tree survival and growth are concentrated around the soil / root interface. As soils, and associated resources change, tree systems must change to effectively utilize and tolerate shifting resources quantities and qualities, as well as physical space available. Soil compaction is a major tree-limiting feature of many developed sites and a hidden stressor of community trees.

This workbook is a summary of soil compaction processes and tree growth impacts. In addition, some general renovation principles are reviewed. Understanding how soil compaction occurs, developing more accurate and precise definitions of soil compaction effects, and recognizing tree growth impacts stemming from compaction problems will be emphasized here. This workbook will concentrate entirely on negative growth constraints of soil compaction on trees.

Recognizing The Problem

Soil compaction is the most prevalent of all soil constraints on shade and street tree growth. Every place where humans and machines exist, and the infrastructures which support them are built, soil compaction is present. There are few soil areas without some degree of soil compaction. Soil compaction is a fact of life for trees and for tree health care providers. Unfortunately, prevention and correction procedures are not readily used nor recognized for their value.

There are many environmental constraints on tree survival and growth. All limitations for trees have impacts on daily and seasonal growth which can be measured and prioritized. Many people become obsessed by small constraints on trees, while major life-altering impacts are ignored. Soil compaction is one of those major problems causing significant tree stress and strain, and whose impacts are usually blamed on other things. Figure 1 shows the individual items causing the greatest growth limitations for tree growth. The top three constraints (by far!) are soil water availability, soil aeration, and soil drainage -- all three greatly disrupted by site compaction. Drought and soil compaction head the list of major tree growth stress problems.

As long as people continue to obsess about trivial tree and site growth limitations, they will continue to ignore the biggest items causing tree stress and strain! Tree care providers must help people understand soil compaction influences on tree growth, and the associated need for soil renovation treatments.

Bearing All

As a site is used by animals, people, and machines, the bearing surface for all activities is the top of soil. Soil is a composite material made of many different things, each interconnected physically and biologically in many ways. Site use applies force to the soil surface and this force is resisted and distributed locally in soil. The extent of soil impacts from site use depend upon many soil attributes, some inherent and some transient. For example, the size, shape, and geology of mineral components are long-term features of a soil, while moisture content greatly influences carriage of loads, but is in constant flux.

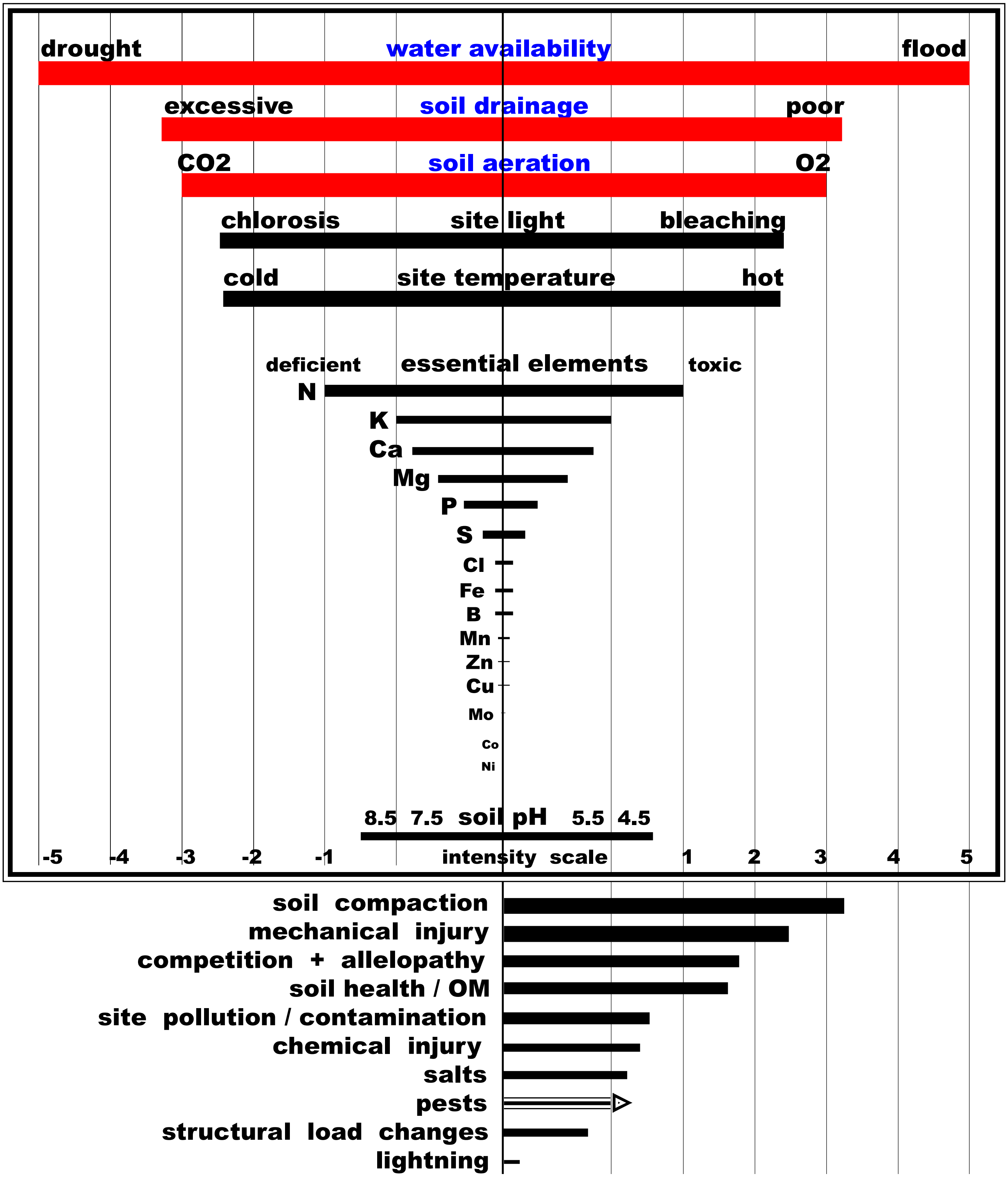

Figure 1: Occurrence priority of stress in trees.
(longer & thicker bars = greater tree imapct)

Compaction occurs when people allow light to moderate site useby people, animals, and machines on a relatively continuous basis, or periodically for heavy use. As compaction measures increase by 25-33%, soil health is seriously impacted. Tree health mirrors site health, and so negative compaction impacts in a soil negatively impact tree health and structure. As soil and tree health change, ecological health of the site declines and approaches exhaustion as both biologics and essential resources are lost. Soil compaction, although usually unnoticed and unmeasured as a site quality issue, leads to severe tree problems and is difficult to correct once applied onto a site.

Infrastructure Ecology

The small amount of land where we concentrate many thousands of people does not represent true carrying-capacity of natural resources on a site. We are forced to concentrate natural resource inputs and outputs from across a large surrounding area in order for our communities to exist. The means of concentrating resources is through building and maintaining engineered infrastructures such as streets, pipes, wires, curbs, buildings, parking lots, water collection and treatment systems, and environmental management devices for building interiors. Infrastructure waste-spaces (i.e. areas not needed for building or maintaining infrastructures) are delegated to "green" things.

Living systems are containerized and walled into small spaces adjacent and intertwined with massive infrastructure systems. The ecology of infrastructures involve resource and process constraints to such a degree that living systems are quickly damaged and exhausted. A summary of resource attributes around infrastructures include: many humans and machines functioning as sources for ecological disturbance and stress problems (both chronic and acute); fragmented and diminished self-regulating ecological states and processes (declining living things, organic matter, biotic interactions); and, less open soil surface and ecologically active volumes. Compaction is a leading stressor of trees under these resource conditions.

Summing Compaction

As infrastructure requirements increase and generate more ecological impacts, associated building, maintenance, demolition, and renovation processes cause natural resource quality and usability to decline. Key components of this decline are complex soil resource alterations including water availability, gas exchange, mechanical impedance, and pore space alterations. Soil compaction is a primary feature of ecological damage with which we are surrounded.

Defining Soil Compaction

Soil resources are always changing. Pore space, water, gas contents, and the electron exchange environment are dynamically changing in a soil every moment. Chemical, biological and physical soil features are always changing. Within this dynamically changing environment, tree roots use genetically crafted growth and survival strategies.

An ideal soil has 50% pore space, divided among air-filled pores and water-filled pores. In addition, 45% of an ideal soil is composed of mineral materials with 5% composed of living and dead organic materials. Figure 2. During genesis in an ideal soil, structural units and specific horizons develop. Unfortunately, soils surrounding infrastructures where we live are not ideal. Because ideal soils do not exist around infrastructures, tree health care providers must work with soils which could be

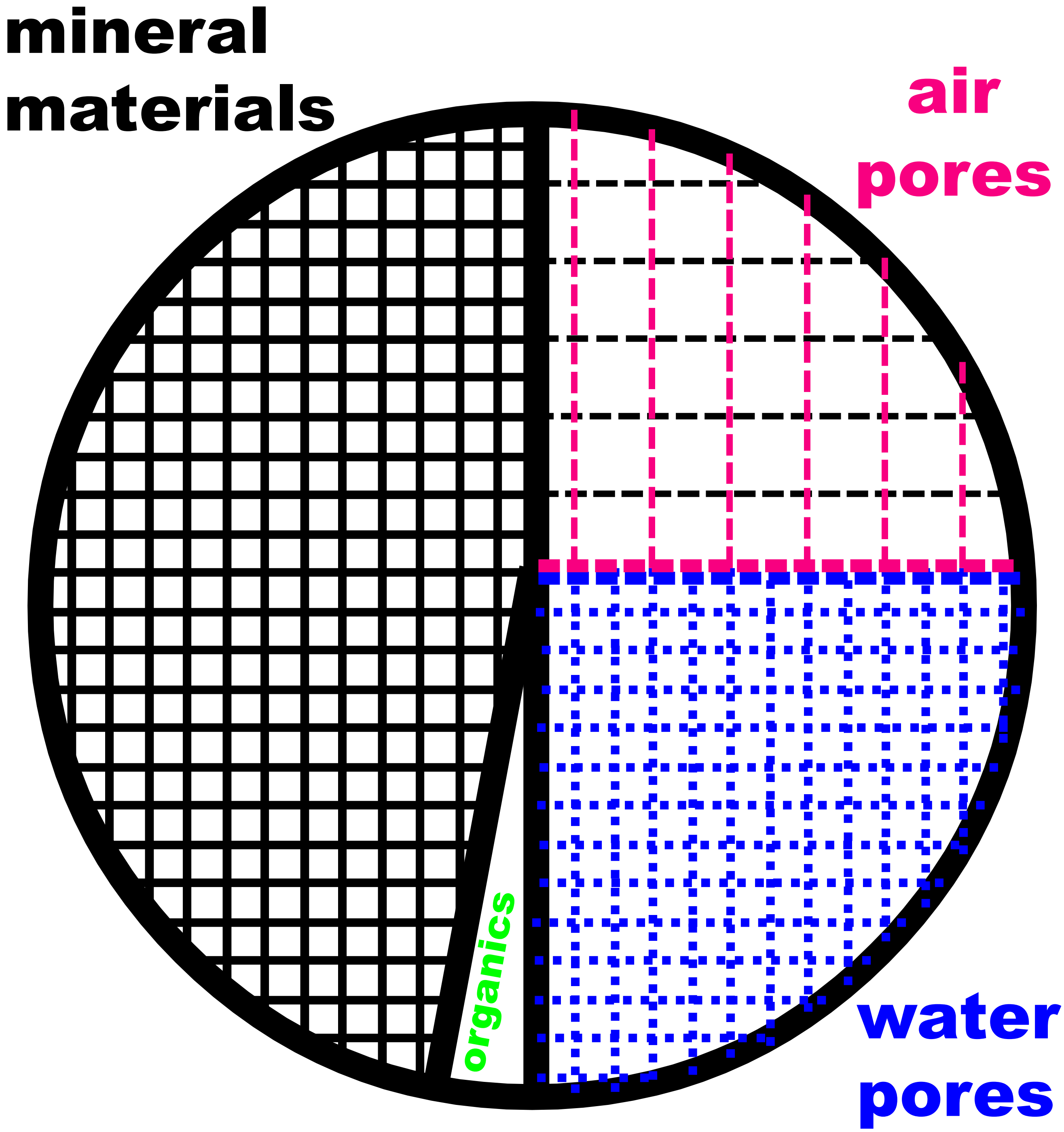

Figure 2: A classic diagram of component proportions for an idealized soil with a mineral matrix, organics (living & dead), and pore space (water-filled & air-filled).

fill-derived, trenched, cut, compacted, polluted, excavated, unstructured, crusted, desert-like, barren, and poorly developed. Figure 3.

Pore Spaces

Soil pore space exists around three primary components: individual particles (texture units) such as sand, silt, and clay; individual structural units (soil aggregates); and, as gaps and cracks at the interfaces of infrastructure and soil. Large sized soil pores are usually filled with air, and so provide good aeration but poor water holding capacity. Small soil pores are usually filled with water, but provide poor aeration. For a healthy soil, coarse textured soils dominated by large air-filled pores need more water availability -- fine textured soils dominated by small water-filled pores need more aeration for good root growth. Figure 4. Soils dominated by small soil pores (clay) have more total pore space than soils dominated by large pores (sand).

There are a series of physical and chemical differences among pore spaces based primarily on size. Aeration pores are filled with air at or below field capacity and capillary pores are filled with water. Figure 5 provides pore size definitions. Capillary pores are further divided into two sizes, tree-available water-filled pores, and tree-unavailable water-filled pores. The tree-unavailable water resides in the smallest soil pores where a tree cannot exert enough force through transpiration to remove pore held water. Figure 6.

Dead Zone

Along with pore space volumes, there are three additional soil concepts or attributes which must be appreciated: the deep dead zone; organic matter contents; and, soil structure. Tree-available resources change with soil depth. With increasing soil depth there is a natural increase in carbon dioxide (CO_2) concentrations and a decrease in oxygen (O_2) concentrations. The balance between these two gases change with water content and biological activity. Somewhere below the surface there is a functionally anaerobic zone (<5% O_2) where tree roots can not survive called the “dead zone.”

Dead Stuff

Organic matter, as it decays, provides cation and anion exchange capacity, water holding capacity, mineralization of essential elements, substrate and fuel for the detritus food web, and additional pore space. Organic matter in natural soil systems is deposited on the surface as plant litter or near the soil surface as roots die and decay. Decomposing materials are then washed downward through soil, moving pass living absorbing tree roots. Organic matter is important to soil health, but is transient, providing value for a time as it is consumed.

Bigger Clumps

Structural units, or soil aggregates, are the next order of soil unit above texture which yield pore space. The basic soil particles (sand, silt, and clay) are held together in clumps, clods, or structural units. These structural aggregates are held together with metallic, organic, or colloidal coatings. Between structural aggregates are soil pore spaces utilized by tree roots. Because of pore size and availability, tree roots heavily utilize pore spaces generated from structural aggregate development. Many compacted soils quickly loose structural based pores, and the soil structural units themselves.

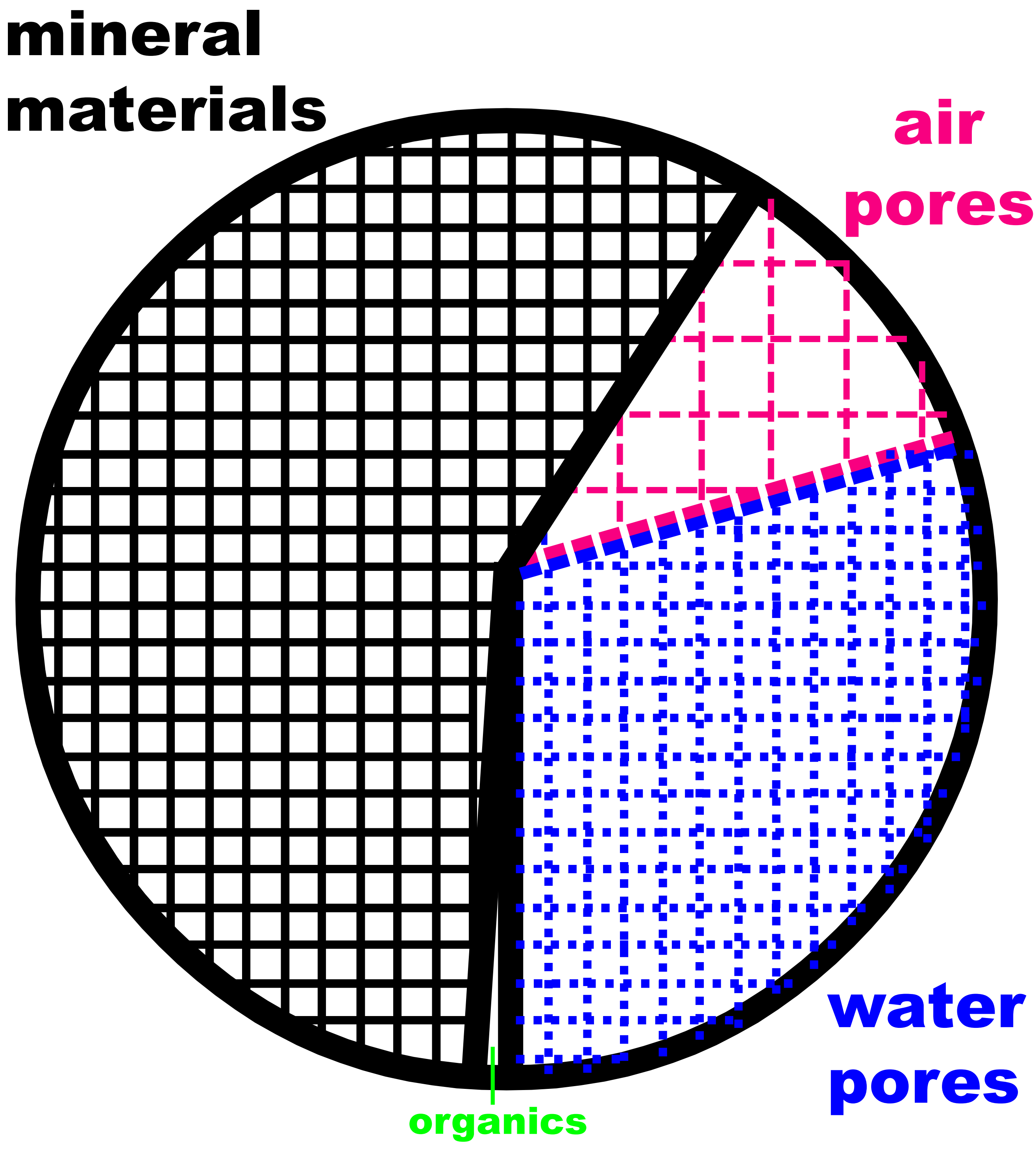

Figure 3: A diagram of the component proportions for an urban compacted soil with a mineral matrix, organics (living & dead), and pore space (water-filled & air-filled).

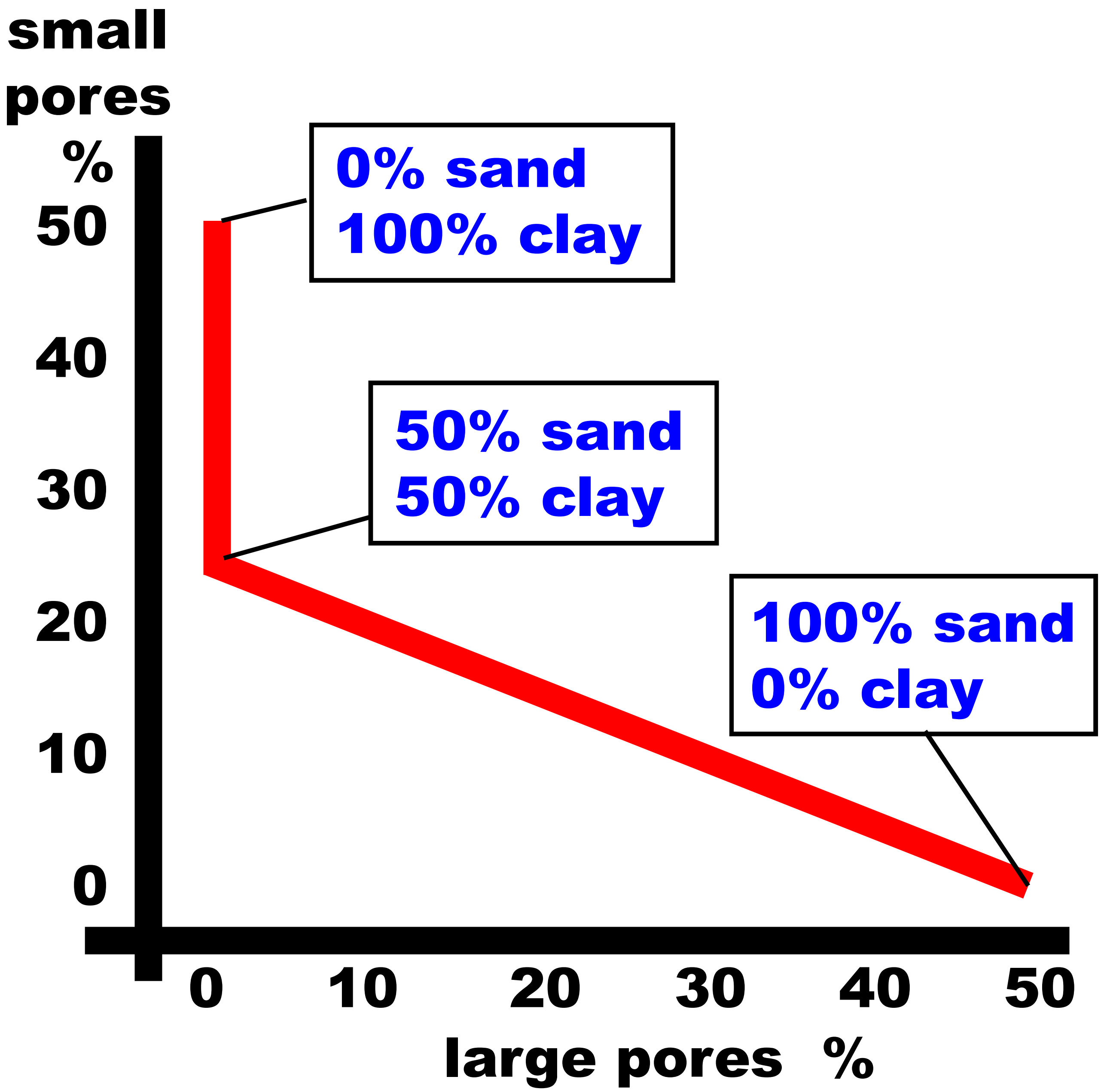

Figure 4: Large and small pore space percentages in various sand / clay mixtures at ~1.32 g/cc bulk density.
(after Harris et.al. 1999)

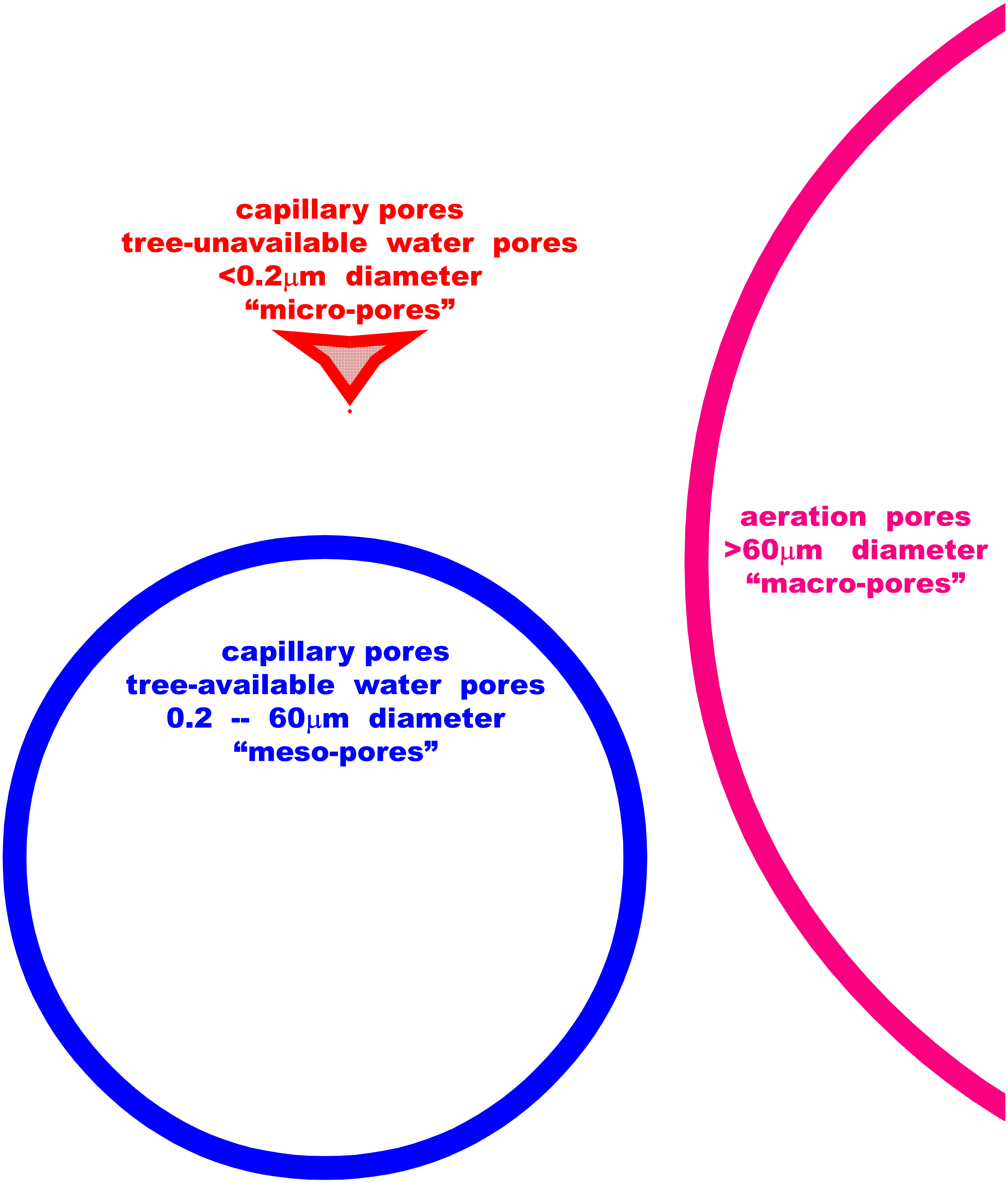

Figure 5: Proportional soil pore sizes.

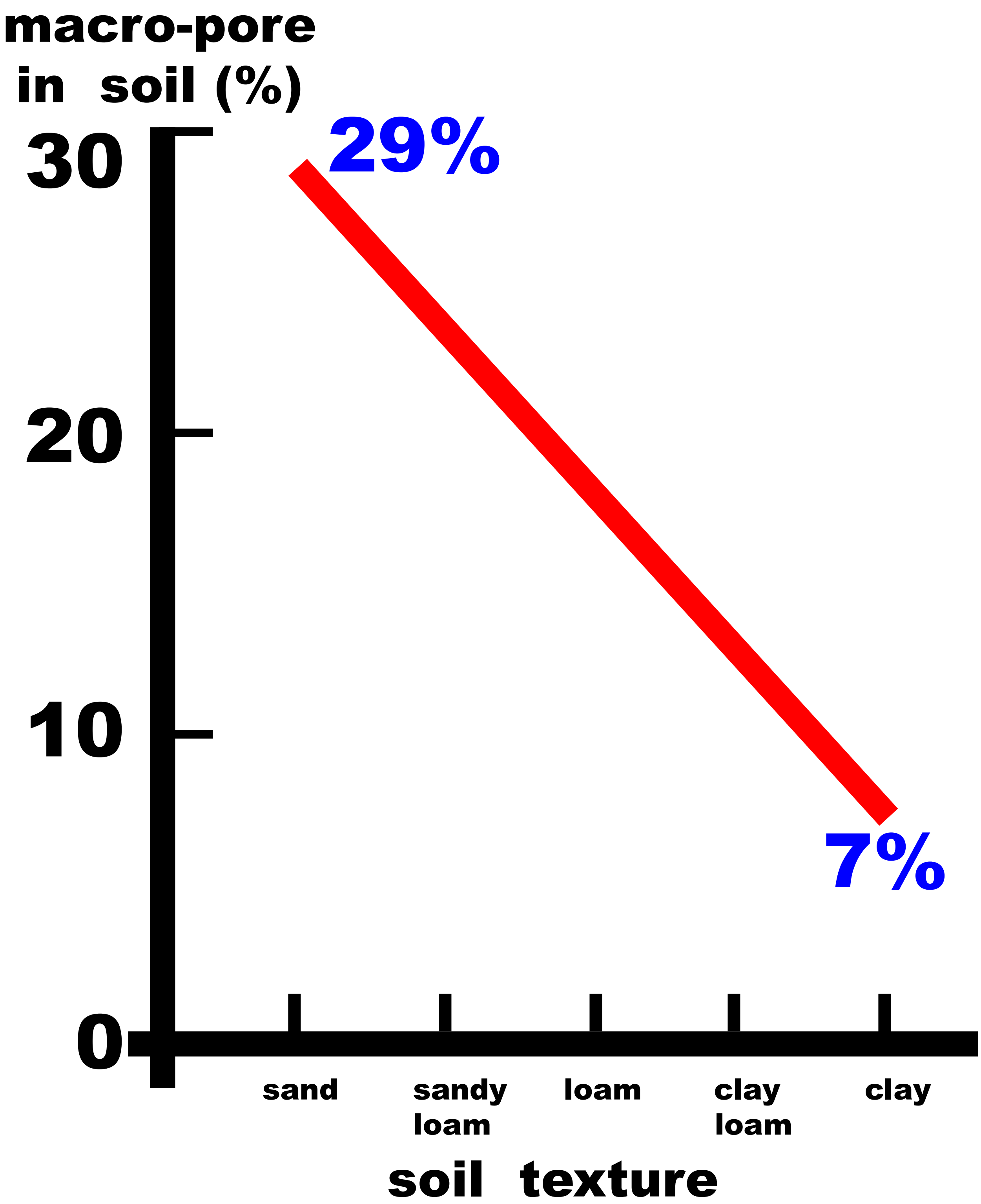

Figure 6: Macro-pore (air pore) space by soil texture.
(after Craul 1999)

Defining

A more precise and accurate definition of soil compaction, as seen in the field limiting and damaging tree health, is needed in order to discuss tree symptoms and managerial solutions. In this discussion the word "compaction" will be used as a composite, generic, negative impact on tree growth and soil health. This composite "compaction" concept used here includes three negative soil changes which include soil compression, soil compaction, and soil consolidation.

"C" Threesome

The process which damages soil around infrastructures called "compaction" starts with soil compressibility or loss of soil volume. Compression leads to a loss of total pore space and aeration pore space, and an increase in capillary pore space. In other words, large air-filled pore spaces are crushed leading to more small water-filled pores. Compression is most prevalent in soils used under wet conditions.

True compaction is the translocation and resorting of textural components in the soil (sand, silt, and clay particles), destruction of soil aggregates, and further loss of aeration pores. Compaction is facilitated by high moisture contents. Consolidation is the deformation of the soil, destroying any pore space and structure, by water squeezed from the soil matrix (hydraulic force). This process leads to increased internal bonding and soil strength as more particle-to-particle contacts are made and pore space is eliminated.

Adding CPR

In addition to the "3Cs" of compaction listed above (compression, compaction, consolidation), compaction problems often include crusting, puddling, and rutting. These processes are surface centered and affect the extent and depth of damage within the top surface layer of soil. These problems generate soil conditions difficult for effective tree health maintenance and remeadiation. Crusting, puddling and rutting generate soil and tree damage similar to applying a plastic sheet across the soil surface.

Crusting is the dislocation and packing of fine particles and organic matter on the soil surface. Natural oil and wax products, and pollutants, can be associated with the soil surface having a thin hydrophobic top layer which prevents water and oxygen infiltration. Primary causes of crusting is impacts of rain drops on open soil surfaces, sprinkler irrigation impacts, pollutant absorption, and animal and pedestrian traffic.

Puddling and rutting are both a cause and effect of a dense, thick crust or cap on the soil surface. The primary mechanism of this damage is from destruction of soil aggregates and aeration pores through particle movement. In saturated soils under a top load, there is no place for non-compressible water to go except to the side, squashing structure and pores. Foot and vehicle traffic under saturated soil conditions, and equipment movement on the soil surface over shallow saturated soil layers, facilitate puddling and rutting.

Generic "C"

All components of the generic term "compaction" listed above do not necessarily occur in any order, nor all occur on any given soil. A general summary of compaction as applied to tree and soil health problems would be: "A soil which has sustained a loss of soil aggregates, destruction of aeration pore spaces, crushing or collapse of pore spaces, and/or extensive resorting and packing of soil particles."

The depth to which a soil is compacted is determined by a compacting agent or process. Every type of site management or maintenance which requires soil contact has a characteristic compaction zone or layer, either at the surface or at some depth below the surface. Cultivation or management layers (pans) form from soil cultivation, packing of soil fills or lifts, and various types of traffic patterns. New compaction may develop over top of past compaction problems. One site may present several layers of compaction at various depths representing a history of site use and tree growth limitations.

Compacted Fast

The extent of soil compaction rapidly increases with the first few impacts on the soil surface under the right conditions, and then levels-off. Soils can be compacted to 90-95% of what they can be compacted to in as little as 3-4 trips over a single point. In other words, it is not years of traffic, but the first few trips over a site which does the majority of compaction damage. Figure 7.

Compaction stresses and strains trees, damages soils, and interferes with effective tree health management. Compaction is an unseen cause for many tree problems. Tree health care providers must better appreciate, quantify, and mitigate compaction.

Root Health

Roots utilize the space (pores) in soil. Volume of soil space controlled by tree roots is directly related to tree health. The more space controlled by roots, the more potential resources available. Healthy soil contains surfaces and spaces giving roots access to required resources including water, oxygen, physical space for growth processes, and open soil surface area for replenishment of essential resources.

The Matrix

After accounting for soil pore space, the rest of a soil is made of organic materials in the form of living organisms or dead materials, and a mineral matrix. The mineral matrix is only a significant concern for evolving essential elements, for surfaces holding biological cooperators, and for frictional and inertial forces for structural integrity. It is soil organic matter and pore space which are most critical for tree health.

In developed landscapes, compaction robs soil of viable rooting space and robs trees of healthy roots. Figure 8. Tree roots under soil space constraints occupy gaps and cracks around, under, and between hardscapes and supporting infrastructures. Because hardscapes, like pavements and foundations, expand and contract at different rates than soils, the interface between soil and infrastructures is usually an air filled crack. On heavily compacted sites, roots will be concentrated around the edges of infrastructures, running along hardscape edges, and filling any accessible moist air space.

Bad Things

Soil surrounding tree roots are an ecological composite of living, once-living, and abiotic features facilitating life. Soil compaction disrupts interconnections between ecological components in a soil. Compaction initiates many negative ecological impacts including: decreased volume of ecologically viable space available; decreased depth of tree rootable space; disruption of detritus food web -- the ecological engine responsible for powering a healthy soil; eliminating the diversity of living things

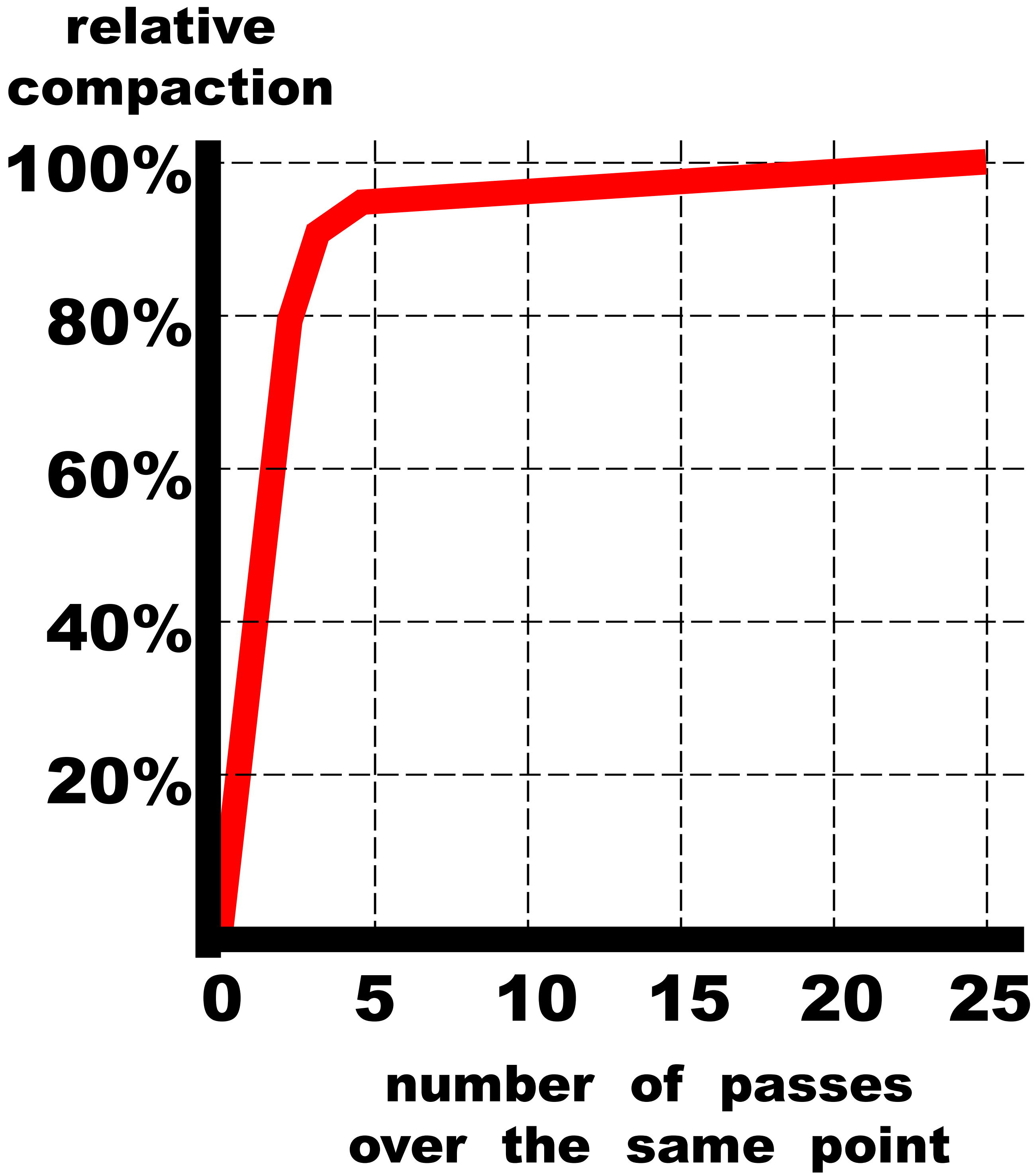

Figure 7: Number of passes / impact events over or on the same soil area generating compaction.

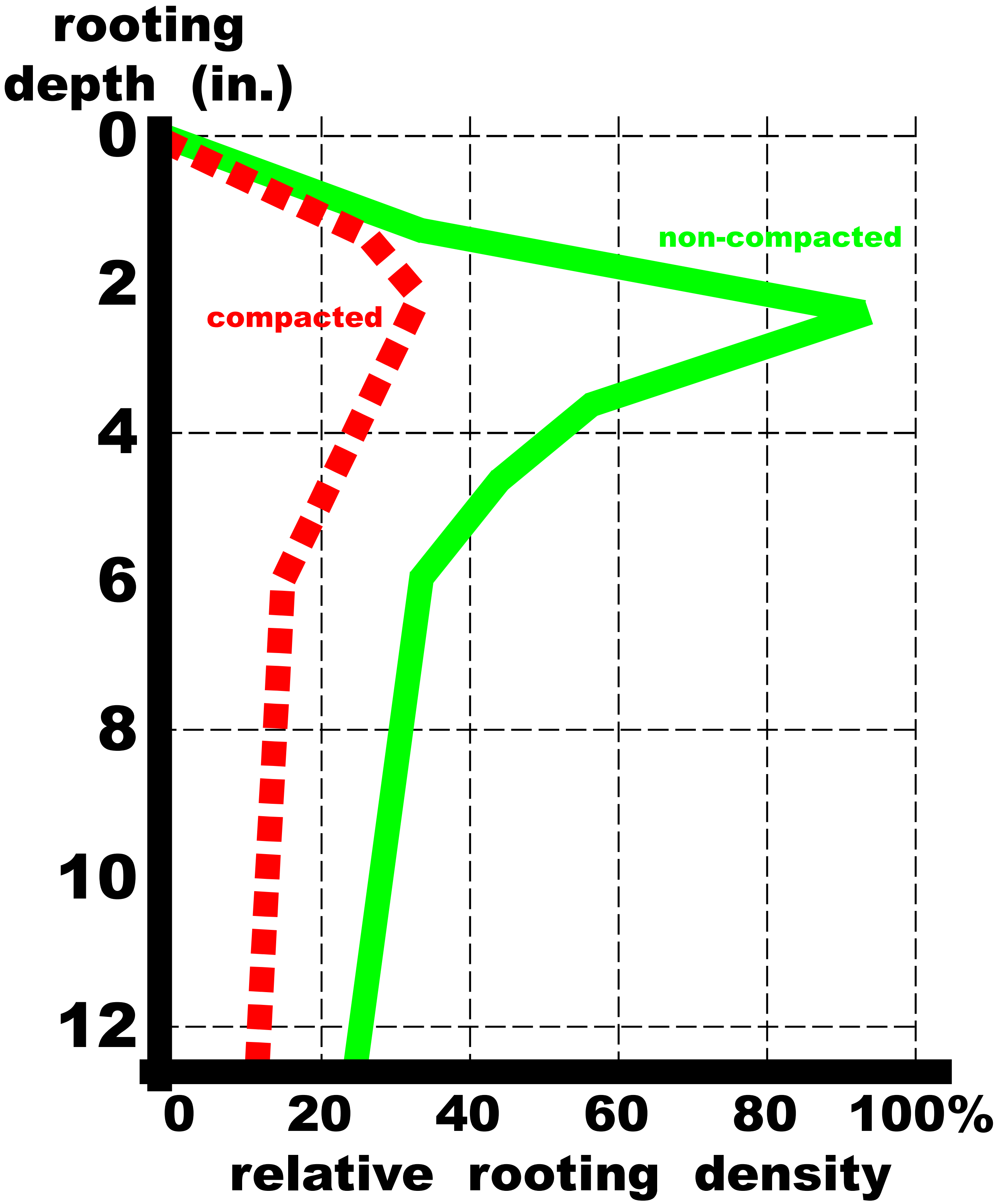

Figure 8: Relative rooting density of fine roots in pin oak (*Quercus palustris*) as depth in a soil increases, 4 years after compaction. (based upon Watson & Kelsey, 2006)

and beneficial associates, with only a few ecological niche-generalists succeeding; and, favoring pests which consume beneficial organisms and roots not able to defend themselves (i.e. *Pythium & Phytophthera* root rots). Compaction causes tree roots to become more prone to damage and attack at a time when their sensor, defense, growth regulation, and carbon allocation processes are functioning at marginal levels.

Root Requirements

Growth in trees may not be an increase in total living mass, but does represent expansion of tissues into new spaces. Tree roots develop adventitiously, expand into soil, and radially thicken. Root density, mass, and activity vary with internal and external conditions. Soil resources required for root growth are summarized in Figure 9.

Roots utilize soil spaces for access to water and essential elements, and for providing structural support. Roots grow following pathways of interconnected soil pores. Pores can be the result of spaces between textural units (sand, silt, and clay particles), between structural units (blocks, plates, grains, prisms, etc.), along fracture lines (shrink / swell clays, frost heaving, pavement interfaces, etc.), and through paths of biological origins (decayed roots, animal diggings, etc.).

Roots survive and grow where adequate water is available, temperatures are warm, light is subdued or blocked, and plenty of oxygen is present. Roots are generally shallow and extensive on sites, limited by oxygen contents, anaerobic conditions, and longterm water saturation. Near the base of a tree, deep growing roots can be found, but are oxygenated through fissures and cracks generated as a result of mechanical forces moving the crown and stem under wind loads (sway) causing root plate wobbling.

Growth Forces

The ability of root tips to enter soil pores, further open soil pores, and elongate through soil pores is dependent upon forces generated in the root and resisted by soil. Root growth forces are generated by cell division and subsequent osmotic enlargement of each new cell (hydraulic pressure). Oxygen and carbohydrate (food) for respiration, and adequate water supplies are required to produce root hydraulic pressure. Figure 10. Tree roots can consume large amounts of oxygen during elongation especailly at elevated temperatures as found on some developed sites. At 77°F (25°C) tree roots can consume nine times (9X) their volume in oxygen each day, at 95°F (35°C) roots can use twice that volume (18X) per day. The osmotic costs to root cells of resisting surrounding soil forces and elongating are significant.

Compaction forces roots to generate increased turgor pressures concentrated farther toward the root tip, to lignify cell walls quicker behind the growing root tip, and to utilize a shorter zone of elongation. In response to increased soil compaction, roots also thicken in diameter. Thicker roots exert more force and penetrate farther into compacted soil areas. Figure 11. As soil penetration resistance increases in compacted soils, roots must thicken to minimize structural failure (buckling), to exert increased extension force per unit area, and to stress soil just ahead of the root cap which allows easier penetration.

Size Matters

For effective root growth, many pores in a soil must be larger than root tips. With compaction, pore space diameters become smaller. Once soil pore diameters are less than the diameter of

root resource	requirements minimal	maximum
oxygen in soil atmosphere (for root survival)	**4 %**	**21 %**
air pore space in soil (for root growth)	**15 %**	**60 %**
soil bulk density restricting root growth (g/cc)	**1.4 clay**	**1.8 sand**
penetration strength (water content dependent)	**0.01 kPa**	**3 MPa**
water content in soil	**12 %**	**40%**
root initiation (oxygen % in soil atmosphere)	**12 %**	**21 %**
root growth (oxygen % in soil atmosphere)	**5 %**	**21 %**
progressive loss of element absorption in roots (oxygen % in soil atmosphere)	**<10 %**	**<21 %**
temperature limits for root growth	**40°F / 4°C**	**94°F / 34°C**
pH of soil (wet test)	**pH 3.5**	**pH 8.2**

Figure 9: Brief list of soil based root growth resource requirements and their relative range of values.

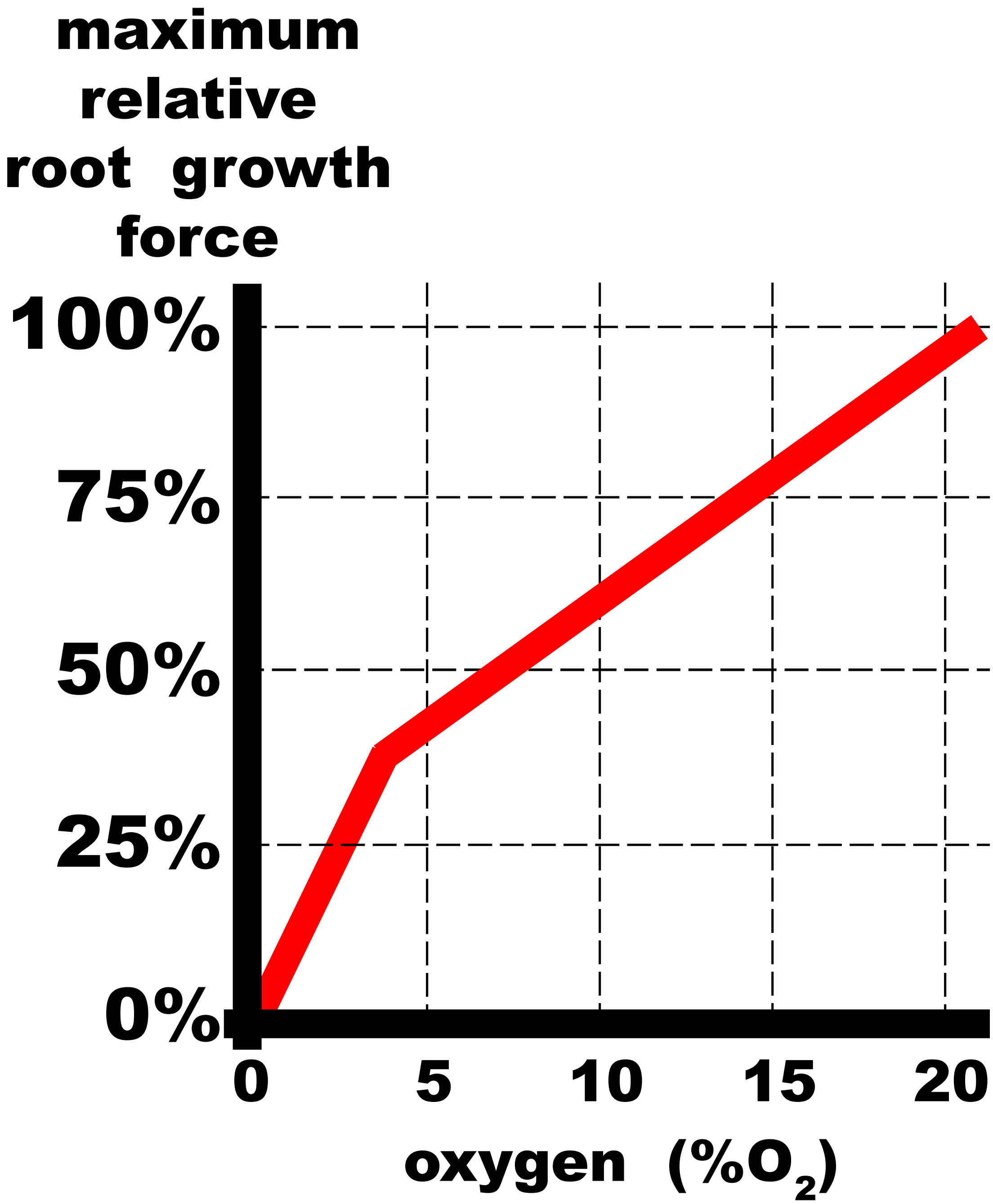

Figure 10: Maximum relative root growth force expressed by seedlings at various oxygen concentrations.
(after Souty & Stepniewski 1988)

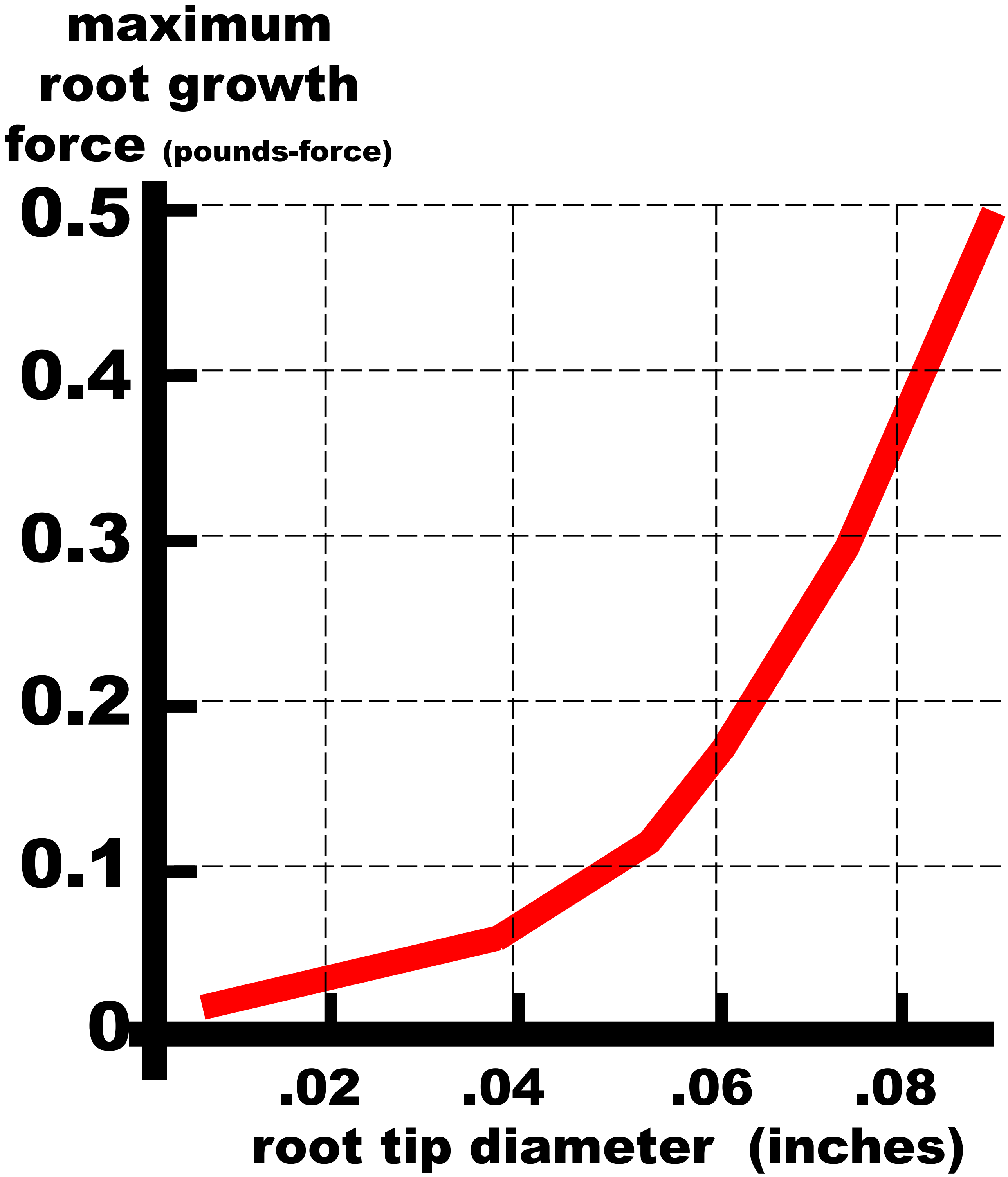

Figure 11: Maximum root growth force by root tip diameter.
(after Misra et.al. 1986)

main root tips, many growth problems occur. The first noticeable root change with compaction is morphological -- roots thicken, growth slows, and more lateral roots are generated of various diameters. Lateral root tip diameter is initiated by growth regulators and extent of vascular tissue connections. If laterals are small enough to fit into the pore sizes of a compacted soil, then lateral growth will continue while the main axis of a root is constrained. If soil pore sizes are too small for even lateral roots, root growth will cease. Figure 12.

Pavements

Soil is a complex material with unique thermal and moisture expansion and contraction patterns. Soil expands and contracts over a day, season, and year at different rates than does adjacent pavement or hard infrastructures. As a result, fracture lines filled with air occupy the interface between soil and infrastructures. These aeration pore spaces can be effectively colonized by tree roots. If infrastructure construction is not completed in an ecologically-literate way, tree roots can expand in these spaces generating enough mechanical force, and facilitating soil volume changes, to accentuate any structural / material faults present.

In addition to the aeration pore space available at structure / soil interfaces, coarse sub-grade and paving bed materials can provide pore space for tree root colonization. The interface between pavement and its bedding material can be a well aerated and provide a moist growing environment. Compaction may have caused anaerobic condition to be found close to the surface under pavement while the added pavement bed may provide a secure colonization space for tree roots. Physical or chemical root barriers may be needed to prevent root colonization of aeration spaces surrounding infrastructures.

Tree Species Tolerance

Across the gene combinations which comprise tree forms, there is a great variability in reactions to soil compaction. As there are many different soil conditions impacted by compaction, so too are there many gradations of tree responses to compaction. A tree’s ability to tolerate compacted soil conditions is associated with four primary internal root mechanisms: reaction to mechanical damage is effective and fast; continuation of respiration under chronic oxygen (O2) shortages; ability to regenerate, reorient, and adjust absorbing root systems; and, ability to deal with chemically reduced materials (toxins).

A list of trees with many of these compaction tolerance mechanisms are in **Appendix 1.**

Compaction Causes & Soil Results

In order to understand and visualize soil compaction more completely, underlying causes must be appreciated. Soil compaction is primarily caused by construction and development activities, utility installation, infrastructure use and maintenance, landscape maintenance activities, and concentrated animal, pedestrian, and vehicle traffic. Below are listed common individual causes of soil compaction.

Moisture Facilitation

For every soil type and infrastructure situation there is a soil moisture content at which soil can be severely compacted with minimal effort. Bringing soils to these optimum moisture content levels is

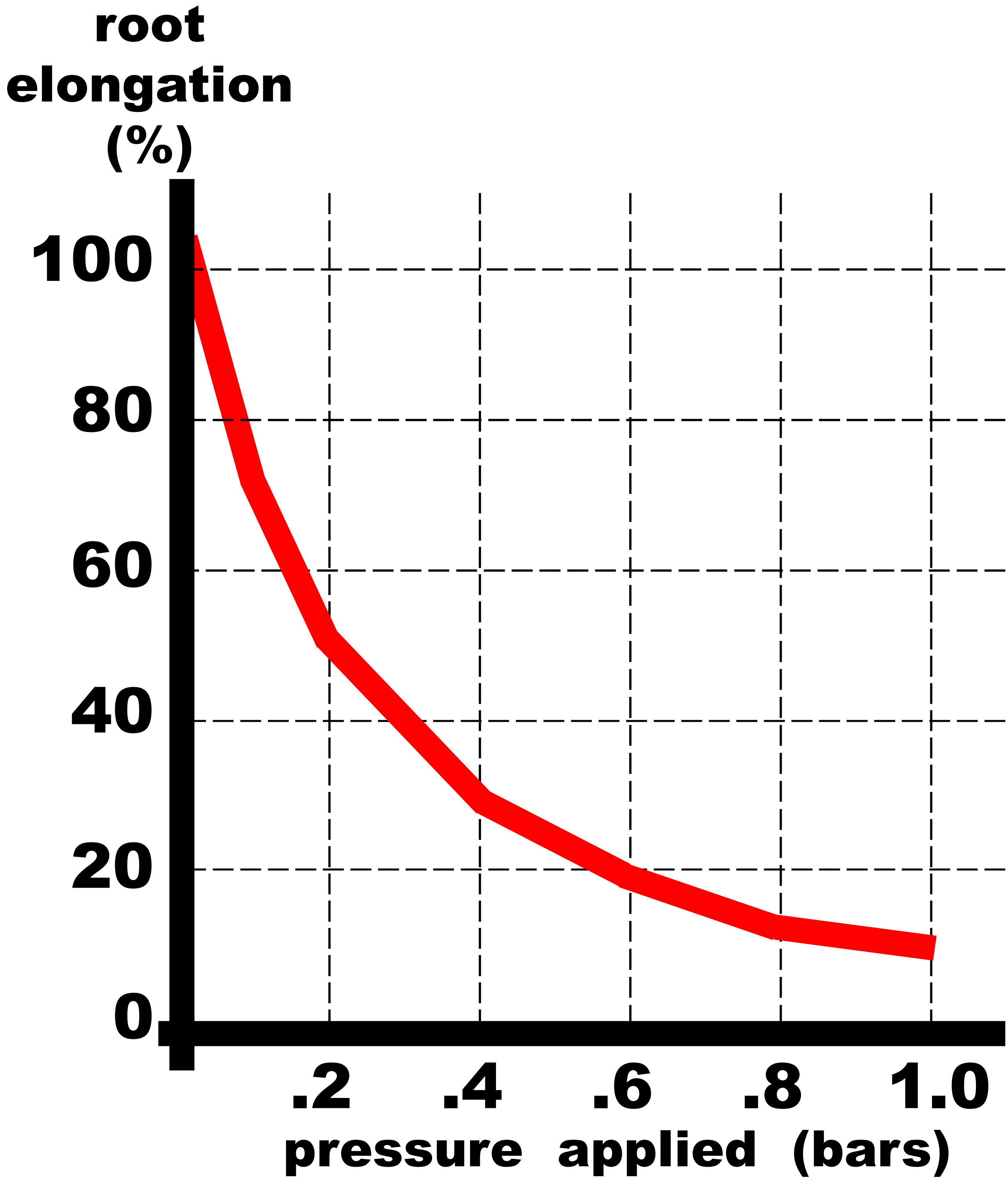

Figure 12: Pressure applied to root tips which limits elongation.
(1 MPa = 1,000 kPa or 10 bars) (after Rendig & Taylor 1989; Russell 1977)

used to compact soils for road construction. Compaction activities should be avoided on soils, especially near these moisture contents. Both direct impacts and vibrational energy will cause compaction when soil is at or near its compaction moisture content optimum. Figure 13.

Water can provide energy directly to the soil surface causing compaction. Direct irrigation impacts from sprinklers, or rainfall hitting open soil surfaces, can cause crusting and compaction. Piling of snow in winter when soil is frozen compacts little, but large snow drifts remaining on-site as soils begin to thaw can lead to compaction both from physical weight and from maintaining high moisture levels allowing for long periods of compaction susceptibility. Saturated soil contact allows hydraulic pressure to destroy soil aggregates and move fine particles into aeration pore spaces. Flooding events can dissolve soil aggregate coatings and lead to soil structure loss. Erosion processes across a soil surface, and fine particle movement within the top portions of soil, can lead to aeration pore space loss and crusting.

Trafficing

The pounds per square inch of force exerted on a soil surface by walking, grazing, standing, and concentrating humans and other animals can be great. Problems are most prevalent on edges of infrastructures such as fences, sidewalks, pavements, and buildings. Holding, marshaling, or animal concentration yards allow significant force to be delivered to soil surfaces. Paths and trails provide a guided journey to soil compaction.

Vehicles with tracks, wheels, and glides provide a great deal of force on soil surfaces. Narrow rubber tires can transfer many pounds of compaction force to soil. The classic example are in-line skates and high pressure bike tires. These wheels can impact soils beyond 60lbs per square inch. Broad, flat treads can dissipate compaction forces across more soil surface than thin tires, and reduce forces exerted per square inch.

Manipulations

The movement, transport, handling, and stockpiling of soil destroys aeration pore spaces and disrupts soil aggregates. Soil cuts, fills, and leveling compacts soil. Soil handling equipment can be large and heavy leading to compaction many inches deep. Anytime soil is moved, air pore space is destroyed and soil is compacted. The most extreme form of compaction force applied to a soil is by explosions. One solution to compaction in the past was use of explosives to fracture soils. The end result was explosive energy fracturing soil to the sides and above the charge, but heavily compacted soil below. Explosives damage soil to a degree not offset by any fracturing or aeration pores formed.

Any mechanical energy which impacts individual soil particles can cause compaction. Nearby car and truck traffic can cause vibrations which compact soils effectively at higher moisture contents. Wet, boggy sites are especially prone to transferring vibrational energy through soil. Vibrational compaction can be significant in rooftop, bridge, and train station planter boxes, for example.

Rooting Spaces

In order for infrastructures to be built and maintained, supporting soil must be properly compacted. Because of how forces in soil are distributed beneath infrastructures, a compacted pad with slanted base sides must be built. This process assures infrastructure edges, bases, and lifts (compacted fill layers) are heavily compacted. Under these standard construction conditions, the only space available for tree root colonization in or adjacent to these areas are fracture lines, interface zones between building materials, and any pore space in or under coarse building materials. The greater soil compac-

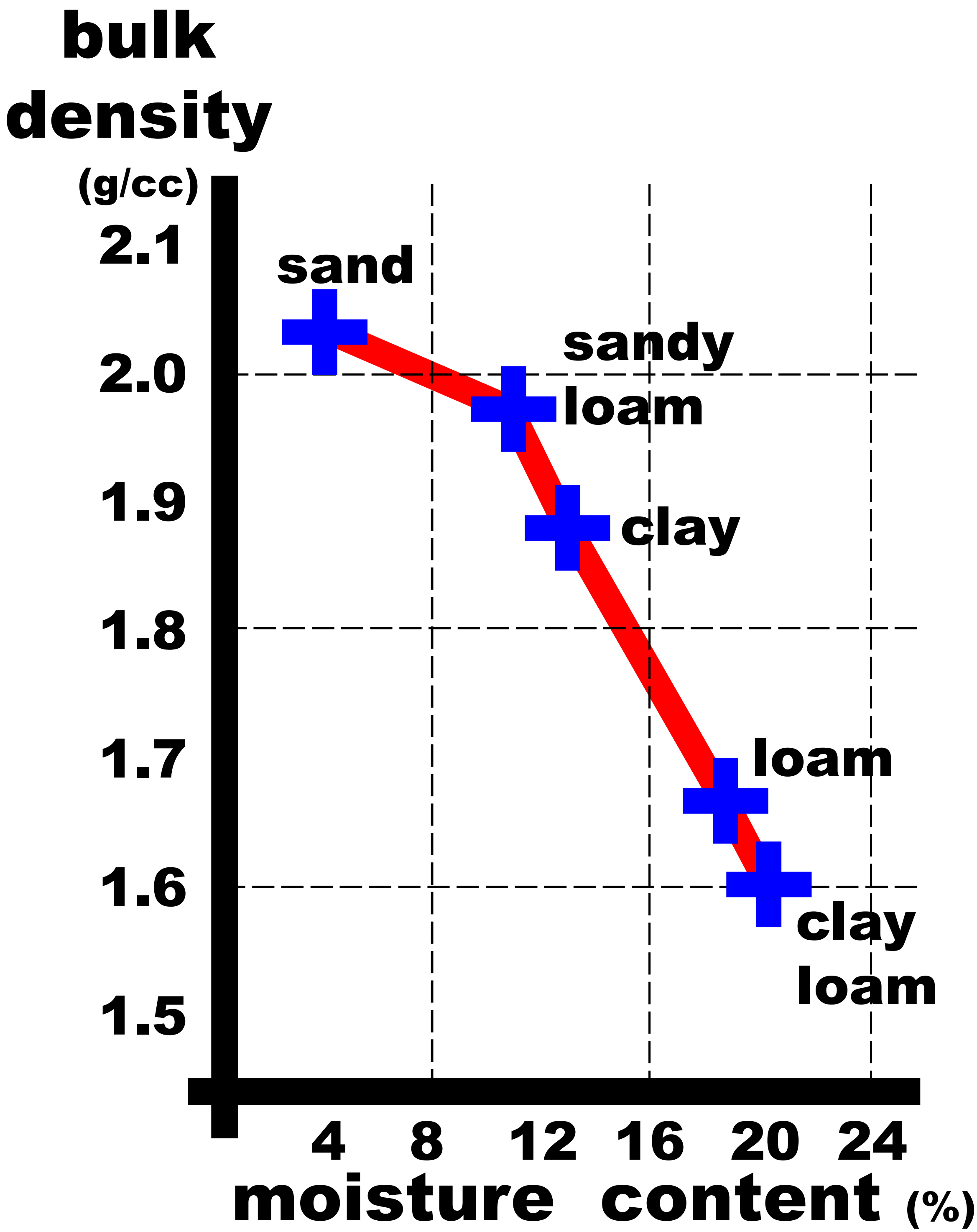

Figure 13: Maximum compaction capacity of soil by moisture content. (after Craul 1994)

tion, the closer to the surface functional anaerobic layers develop, the less ecologically viable space available for roots, and the smaller soil pore sizes become associated with mechanically stronger soil, all minimizing tree root growth.

Organic Matter Loss

Organic matter is fuel, short-term building blocks of structure, and supply warehouse for living things in a soil. As organic matter decomposes and mineralizes without adequate replacement, soil becomes more compacted. Soil density increases and aggregate stability declines as organic matter is "burned" out of a soil through elevated temperatures and lack of replacement. The organic matter cycle spirals down as a compacted soil system is exhausted and becomes less capable of sustaining life.

Resulting Problems

The actions of people compact soils in intentional and unintentional ways. Whatever the cause of compaction, soil's ability to fully sustain tree growth is diminished. Ecological results of compaction lead to severe tree stress and strain, of which only acute and severe impacts are usually ever recognized. The chronic problems of soil compaction remain on-site as a plague to current and future trees. The functional results of soil compaction on trees and their sites are many and complexly interconnected.

Aggregate Destruction

Air pore spaces from soil cracks, interface surfaces, biotic excavations, organic particle decomposition, and normal soil genesis processes help oxygenate the soil matrix. By definition, compaction results in destruction of soil aggregates and aeration pore spaces. Pore spaces filled with oxygen, and interconnected with other aeration spaces exchanging gases with the atmosphere, are critical to a healthy soil and tree root system. The destruction of aeration spaces surrounding soil aggregates can be unrecoverable.

Under compaction, particles of soil are redistributed into new locations, many into open pore spaces within the soil matrix. Through packing, erosion, and cultivation processes, many fine particles can fill-in spaces surrounding other particles, as well as spaces between structural aggregates. Some soil types can be compacted more easily through this process than others. Mid-textured soils with a mix of particle sizes can be strongly compacted due to particle size availability to fill any size of pore space.

Pore Space Destruction

Compaction initiates a redistribution of pore sizes within a soil matrix. Large pores are destroyed and small pore are generated. The total pore space of soil being compacted initially increases as more capillary pores are created and as aeration pores are lost. With continuing compaction, total porosity declines and oxygen diffusion rates plumate. Figure 14. The mid-size pores, which fill and empty with water and air, are most impacted by compaction. Figure 15.

The crushing collapse of aeration pores facilitates the upward movement in a soil of a functionally anaerobic layer. Figure 16. There are always anaerobic and aerobic micro-sites in and around soils aggregates within surface layers of soil. The dynamic proportions of each type of micro-site changes with each rainfall event and each day of transpiration. Compaction shifts proportional dominance in a soil toward anaerobic sites. With further compaction, aerobic sites are concentrated closer and closer to the surface until little available rooting volume remains. Figure 17. Figure 18 lists root-limiting aeration pore space percentages in soils of various textures. Air pore space less than 15% is severely limiting.

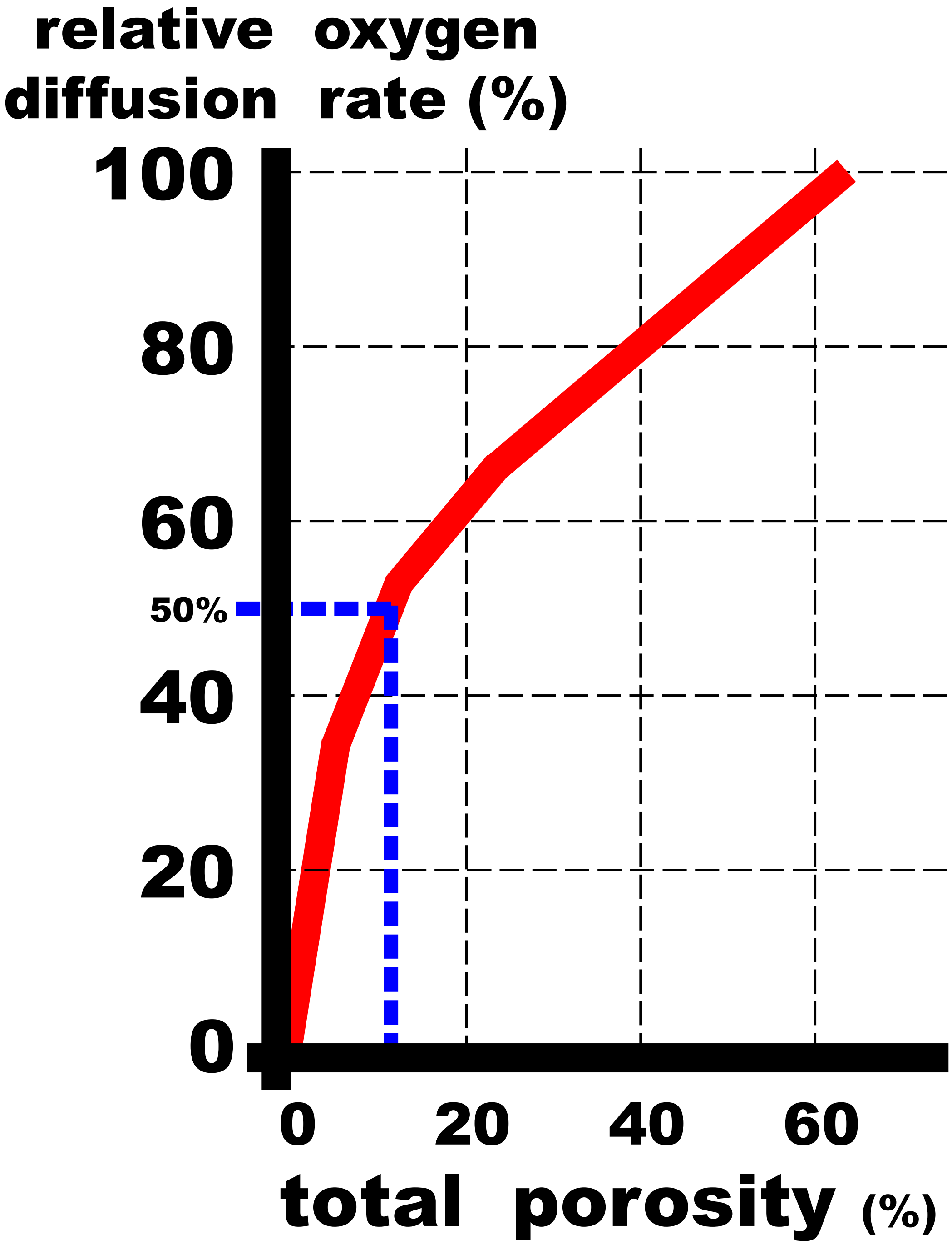

Figure 14: Relative oxygen diffusion rates as total soil pore space changes. (derived from Cook & Knight, 2003)

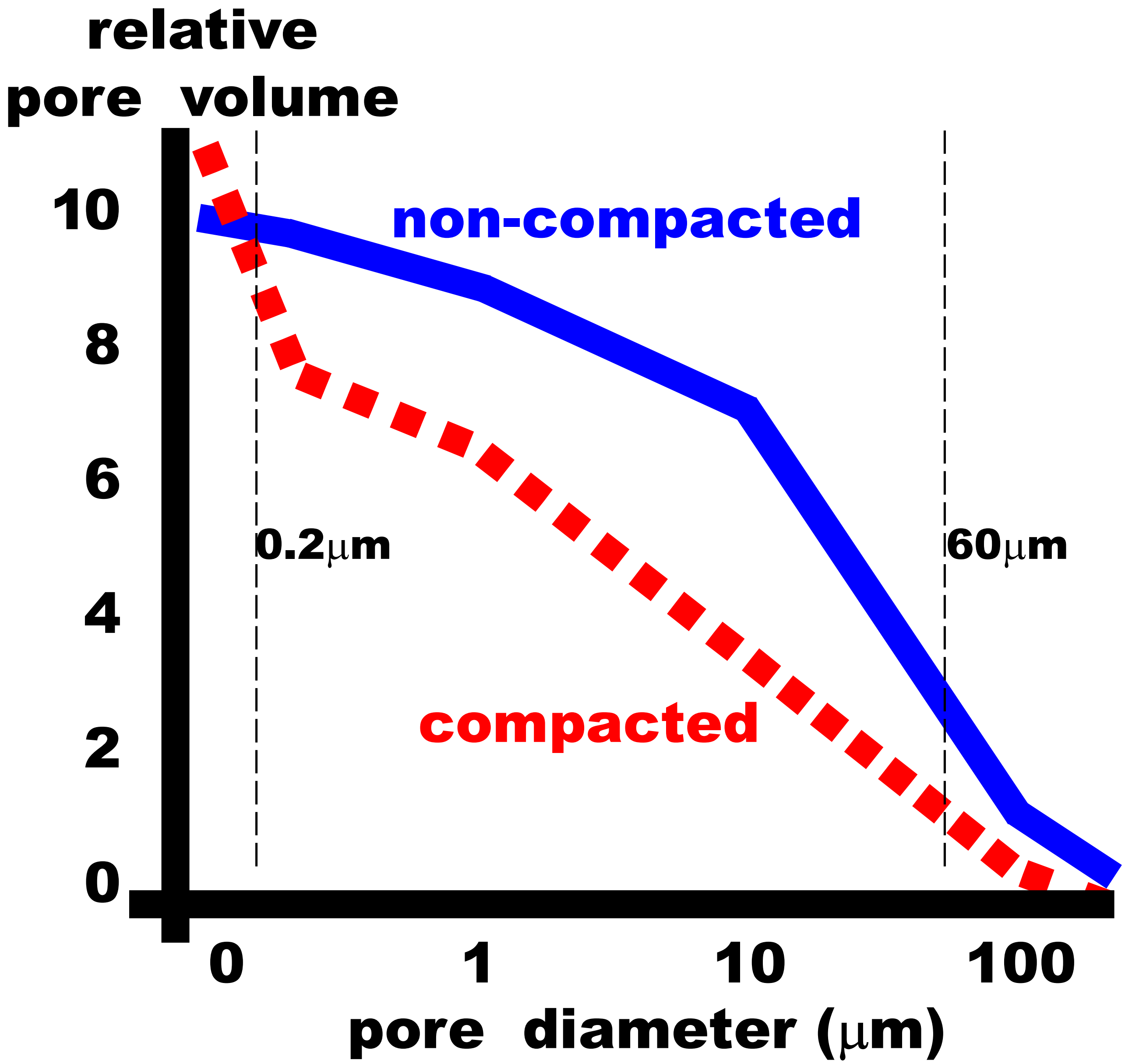

Figure 15: Soil pore diameters and relative volumes under non-compacted (1.4 g/cc) and compacted (1.8 g/cc) conditions. (after Jim 1999)

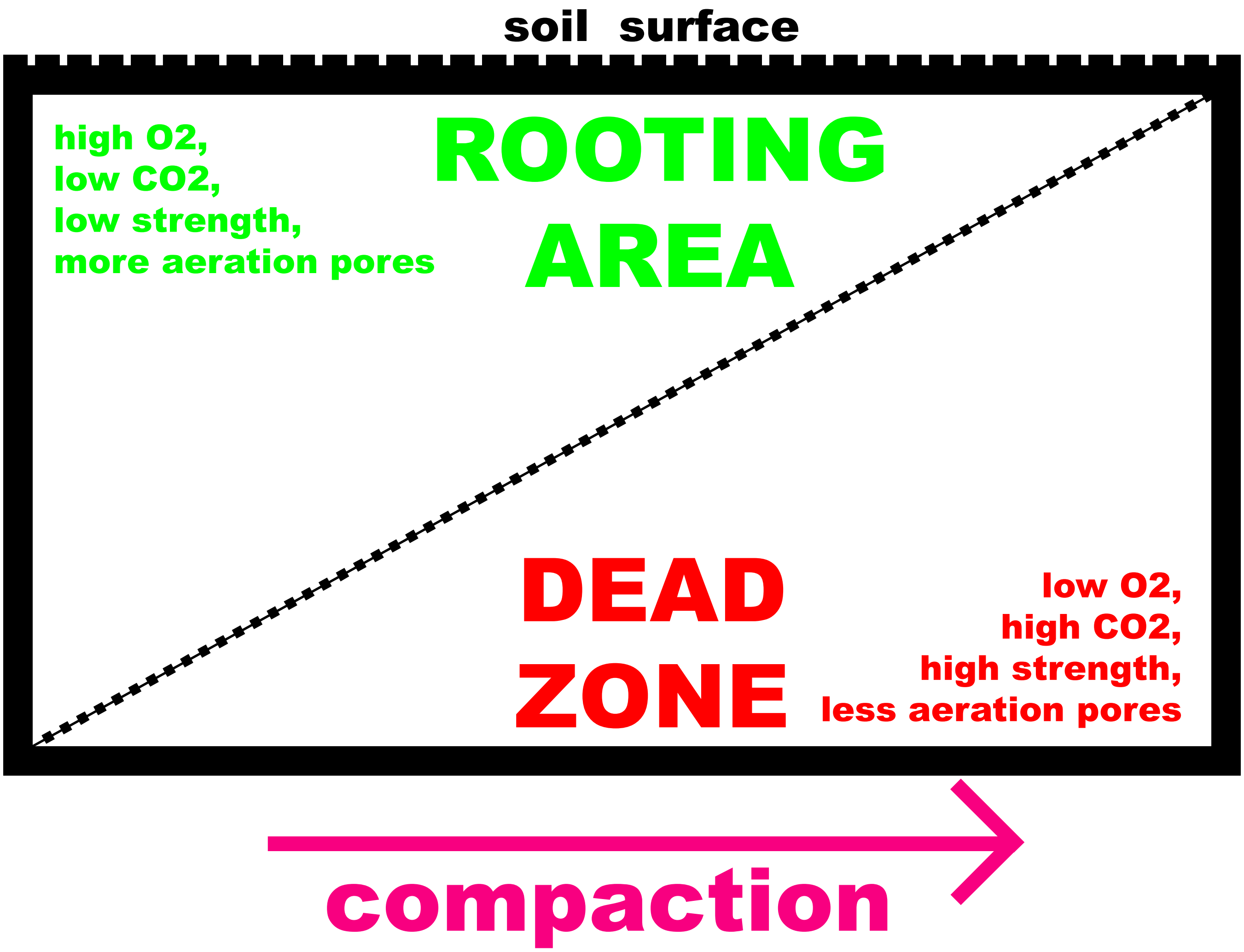

Figure 16: Graphical representation of compaction impacts on soil.

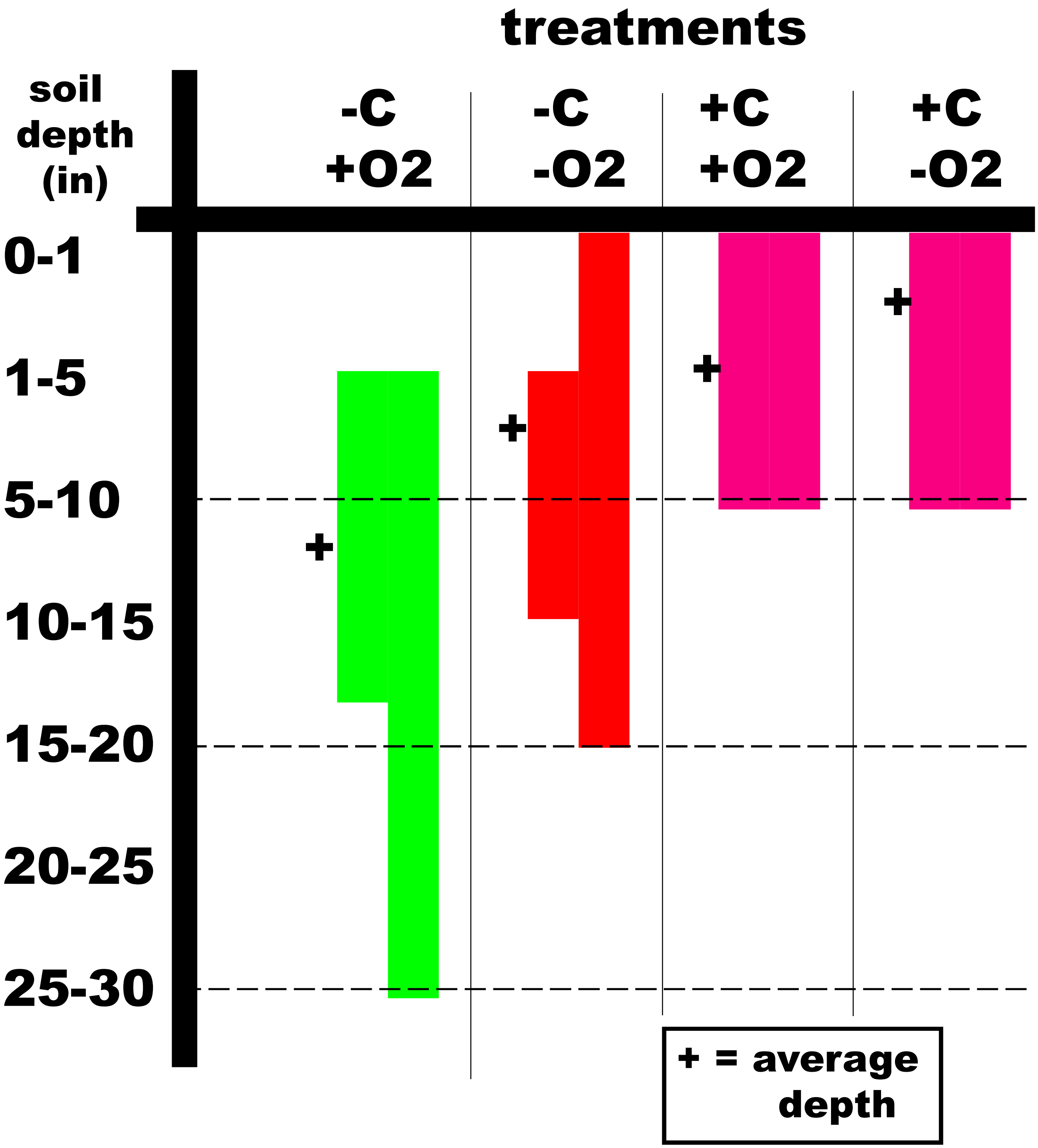

Figure 17: Compaction (C = + 28%) and oxygen (O2 = - 5%) impacts on tree rooting depths. (after Gilman et.al. 1987)

soil texture	root-limiting air pore %
sand	24 %
fine sand	21
sandy loam	19
fine sandy loam	15
loam	14
silt loam	17
clay loam	11
clay	13

Figure 18: Root growth limiting air-pore space values by soil texture. Pore space percentages at or less than the value given are limiting to tree root growth.
(Daddow & Washington 1983)

Increased Strength

Compaction brings soil particles into closer contact with each other (less moisture and/or greater bulk density). Closer contact increases surface friction and soil strength. As soil strength increases, and pore sizes and numbers decrease, the ability of roots to grow and colonize soil spaces decline rapidly. Average diameters of pores significantly smaller than average root diameters are not utilized by tree roots.

With compaction, soil strength reaches a level where roots can not exert enough force to push into pore spaces. Figure 19. Figure 20. Figure 21 lists root-limiting soil densities by texture. Soil texture and density must both be determined to estimate compaction impacts on tree health. Figure 22 shows a soil texture graph with root growth constraining soil density values. Regardless of soil texture, soil density values greater than 1.75g/cc severely limits growth.

Suffication

The aeration pathway (lifeline) from the atmosphere to a root surface through all the interconnected aeration pores declines quickly with compaction. Figure 23. Figure 24 demonstrates as air pore space falls below 15%, the pore interconnectiveness becomes highly convoluted and highly resistive to gas exchange. As tortuosity of the oxygen supply path increases, the closer to the surface the anaerobic layer moves.

As pore sizes become smaller with compaction, more pore space is filled with water. Water-filled pores diffuse oxygen at rates 7,000 to 10,000 times slower than air-filled pores. With all the aerobes and roots in a soil competing for the same oxygen, oxygen limitations can quickly become severe. Figure 25 shows oxygen diffusion rates declining in a soil under increasing (line 1 to 3 in figure) compaction.

Compaction constrains oxygen movement in soil and shifts soil aggregates toward more anaerobic conditions. Less oxygen diffusing into soil leads to a chemically reducing soil environment (both in soil solution and soil atmosphere) closer to the surface. Figure 26. Under these conditions, toxins and unusable essential element forms are generated. In addition, organic matter is not mineralized or decomposed effectively. As oxygen is consumed, an anaerobic respiration sequence begins among bacteria starting with the use of nitrogen and moving through manganese, iron, and sulfur, ending with carbon (i.e. fermentation of organic matter including roots).

Limited Gas Exchange

Tree roots are aerobes, as are root symbionts and co-dependent species of soil organisms. Less oxygen minimizes root growth pressure, defense, and survival. Figure 27. Tree roots use available food twenty times (20X) more inefficiently under near anaerobic conditions. Less oxygen also allows common pathogenic fungi, which have oxygen demands must less than tree roots, to thrive. As oxygen concentrations fall below 5% in the soil atmosphere, severe root growth problems occur even at low soil densities. Figure 28. Figure 29.

Compaction prevents gas exchange with the atmosphere. Figure 30. Compaction prevents oxygen from moving to root surfaces, but also prevents carbon-dioxide and toxics (both evolved and resident) from being removed from around roots and vented to the atmosphere. Poor gas exchange allows the anaerobic layer to move closer to the surface and reduces rooting volume. As carbon-dioxide comprises more than 5% of the soil atmosphere, problems of aeration become compounded. As carbon-dioxide climbs above 15% in soils, growth problems accelerate. Figure 31.

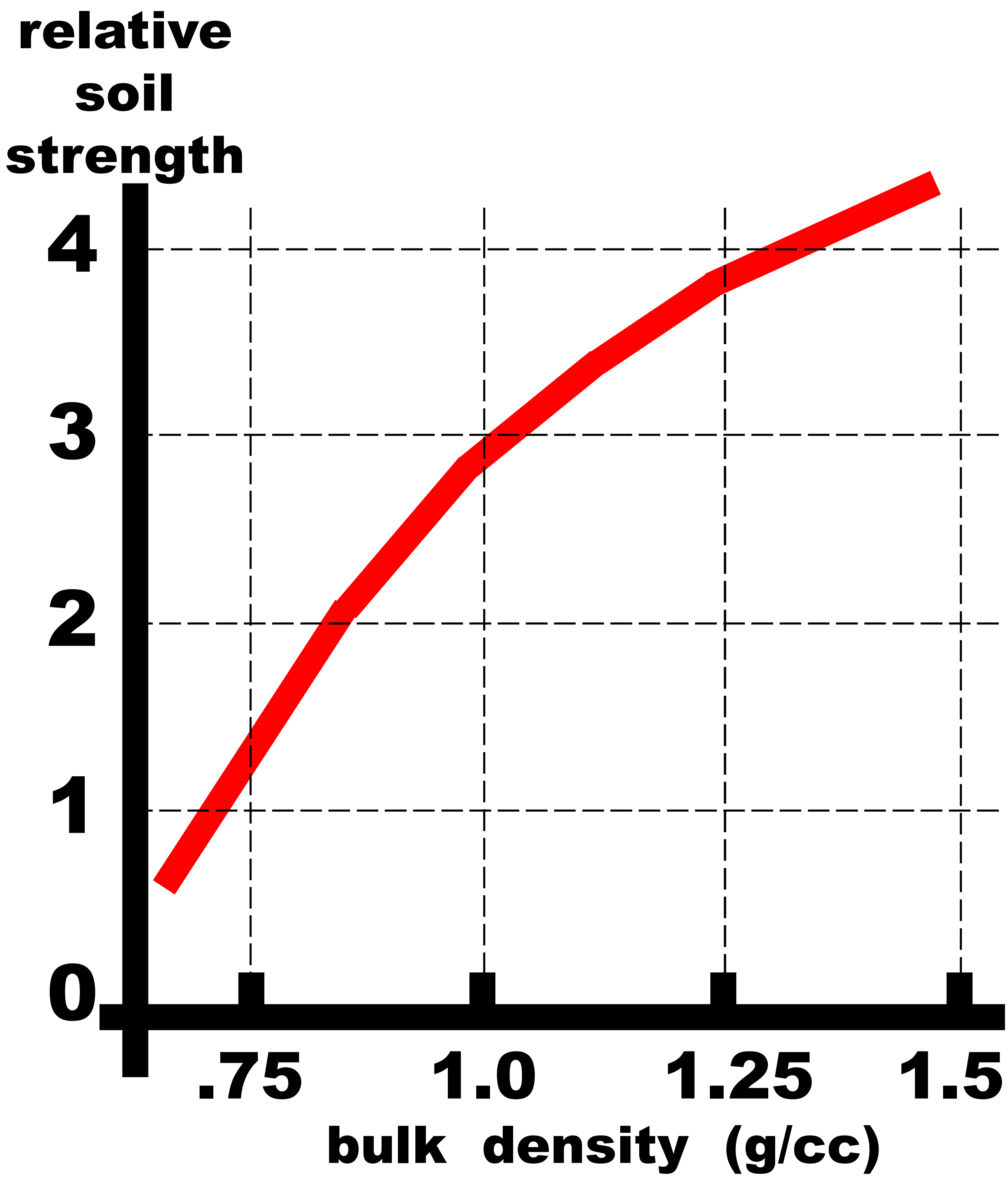

Figure 19: Relative soil strength with increasing density values. (after Craul 1994)

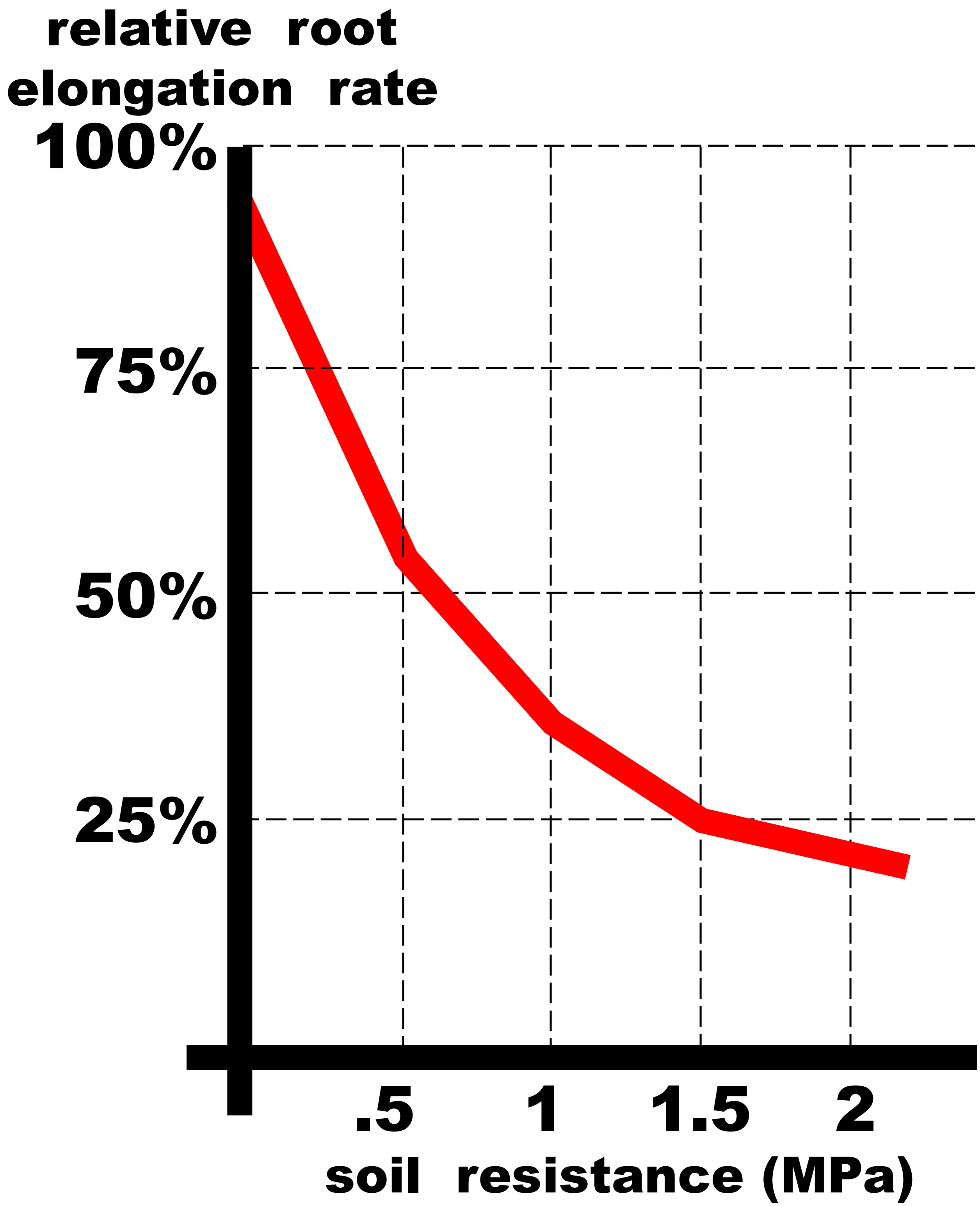

Figure 20: Soil penetration resistance & root elongation rate.
(1 MPa = 1,000 kPa or 10 bars) (after Rendig & Taylor 1989)

soil texture	root-limiting bulk density (g/cc)
sand	1.8
fine sand	1.75
sandy loam	1.7
fine sandy loam	1.65
loam	1.55
silt loam	1.45
clay loam	1.5
clay	1.4

Figure 21: Root growth limiting bulk density values by soil texture. Soil density values equal to or greater than listed values are limiting to tree root growth.
(Daddow & Washington 1983)

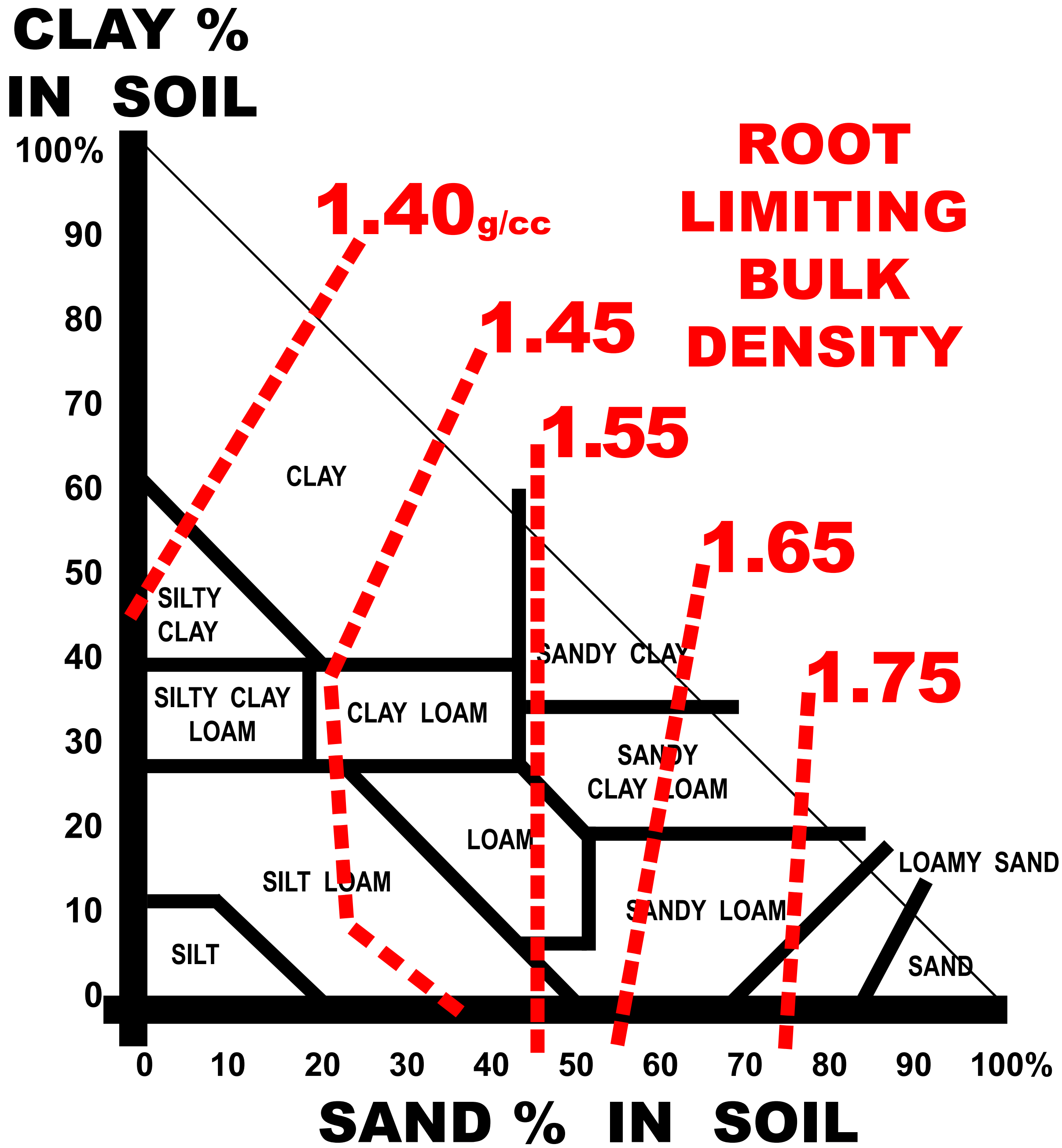

Figure 22: Soil texture graph showing texture classifications based upon sand and clay proportions, and dotted lines showing root-limiting bulk densities (g/cc). Values equal to or greater than listed density value will significantly constrain tree root growth. (Daddow & Washington 1983)

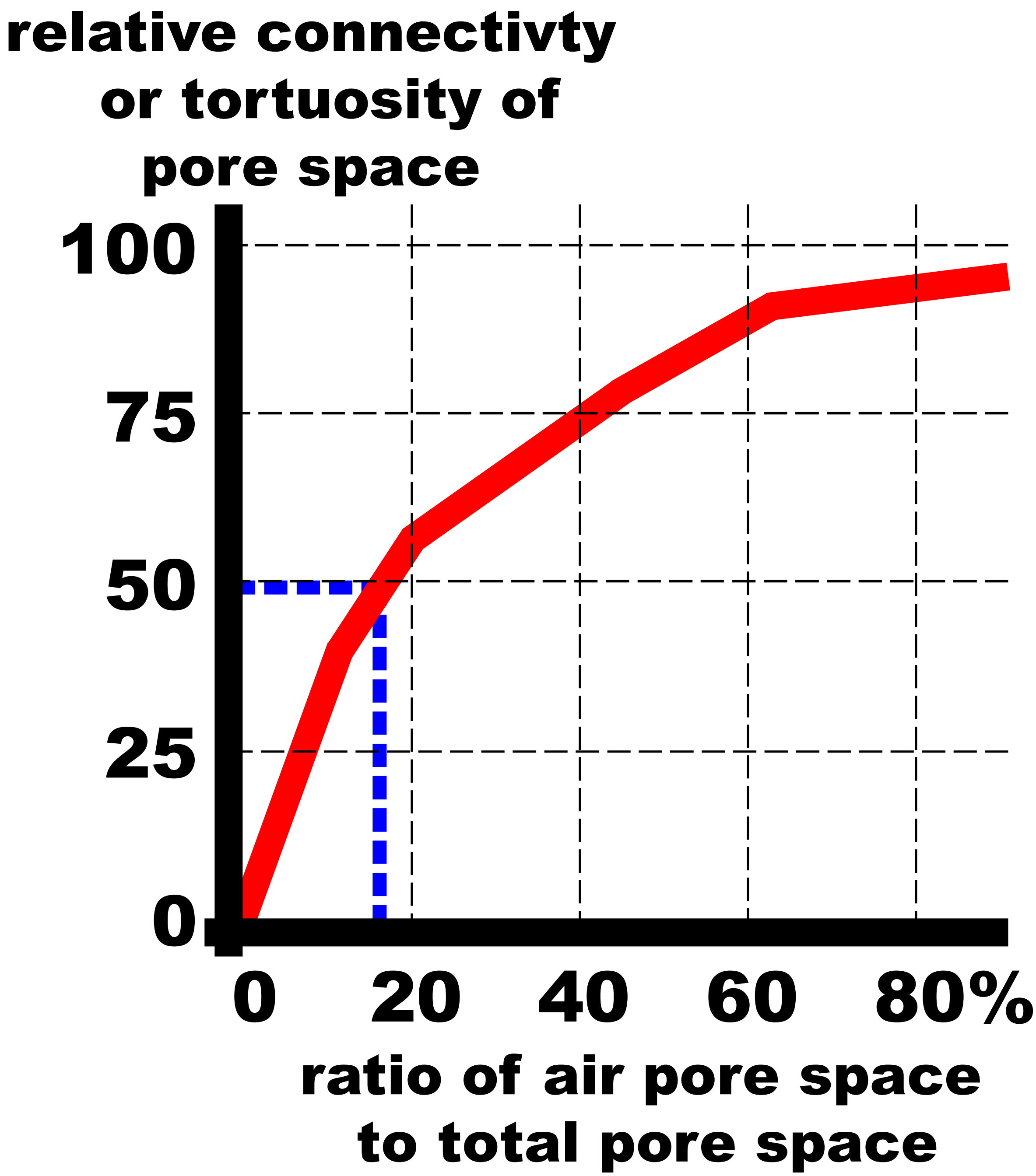

Figure 23: The relative interconnectedness or tortuosity of pore space for aeration in soils. The ratio of air pore space to total pore space (%) = (air porosity % in soil) / (total porosity % in soil). Heavy dotted lines represent one-half loss of pore space connectivity at an air pore to total pore space ratio of 18%. (derived from Moldrup et.al. 2004)

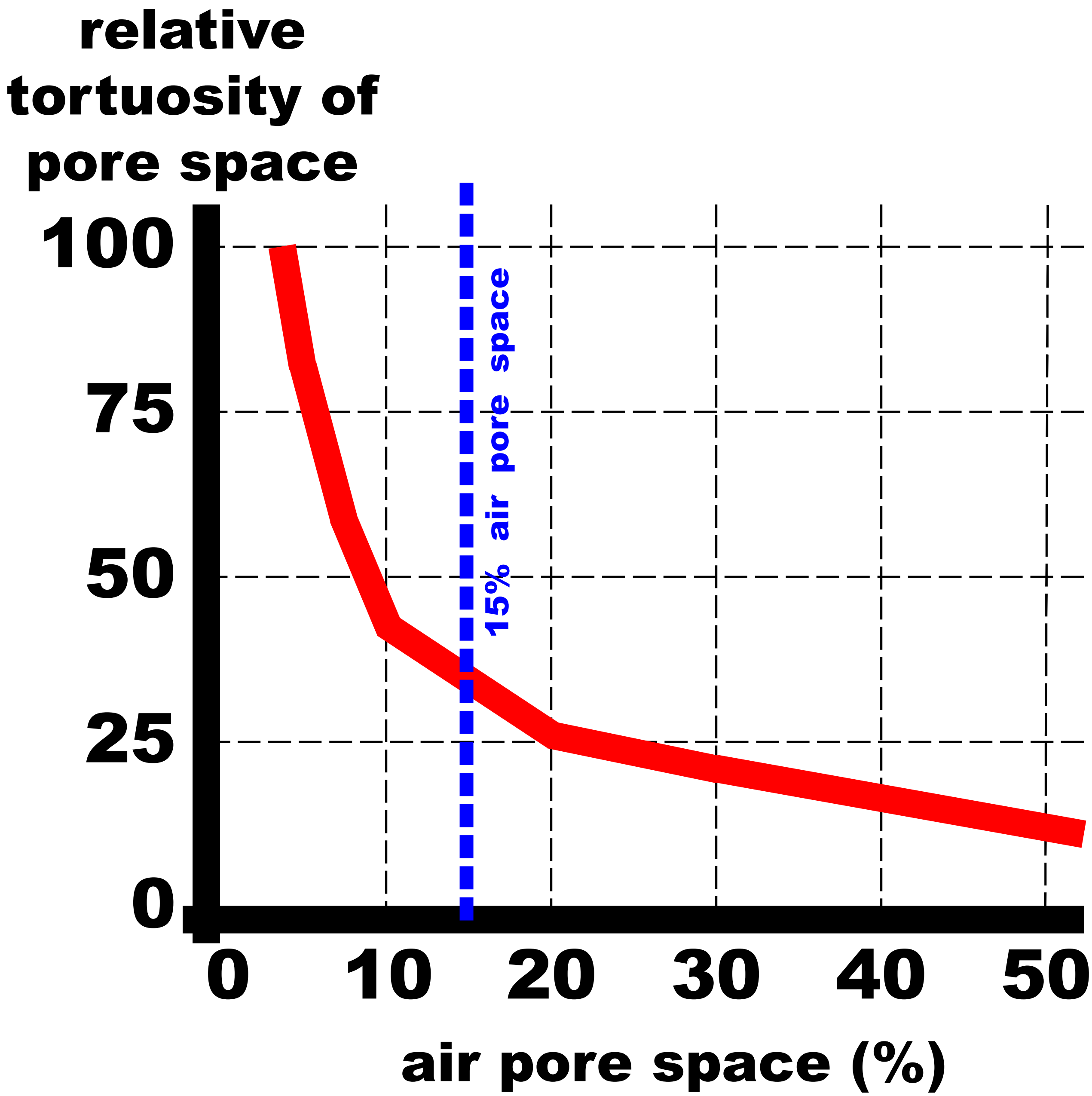

Figure 24: The relative interconnectedness or tortuosity of pore space for aeration in soils.
(derived from Moldrup et.al. 2001).

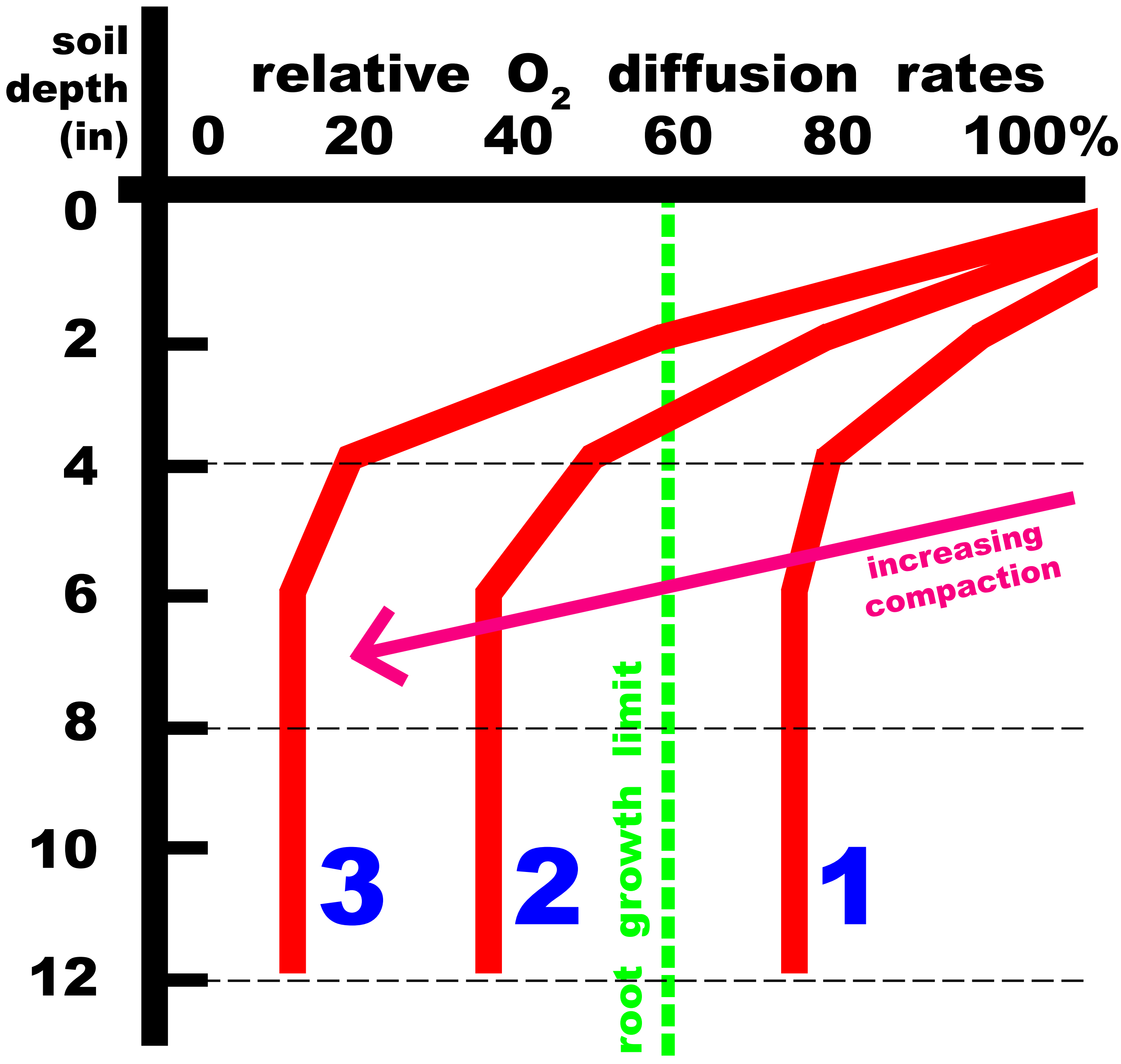

Figure 25: Relative oxygen (O_2) diffusion rates with increasing soil compaction. (after Kelsey 1994)

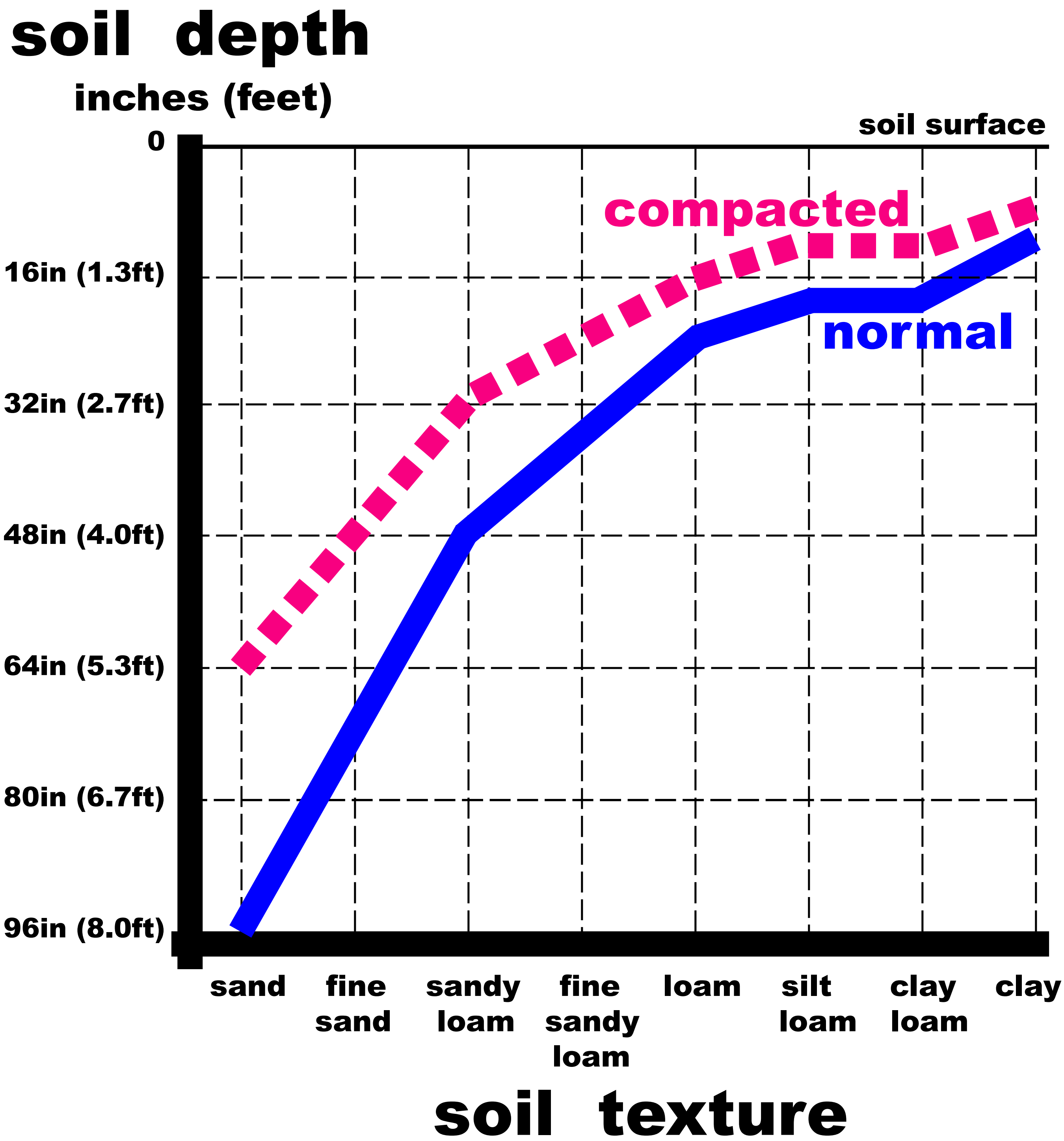

Figure 26: Constrained effective soil depth of biologically available resources in soils of various textures under compacted and non-compacted conditions.

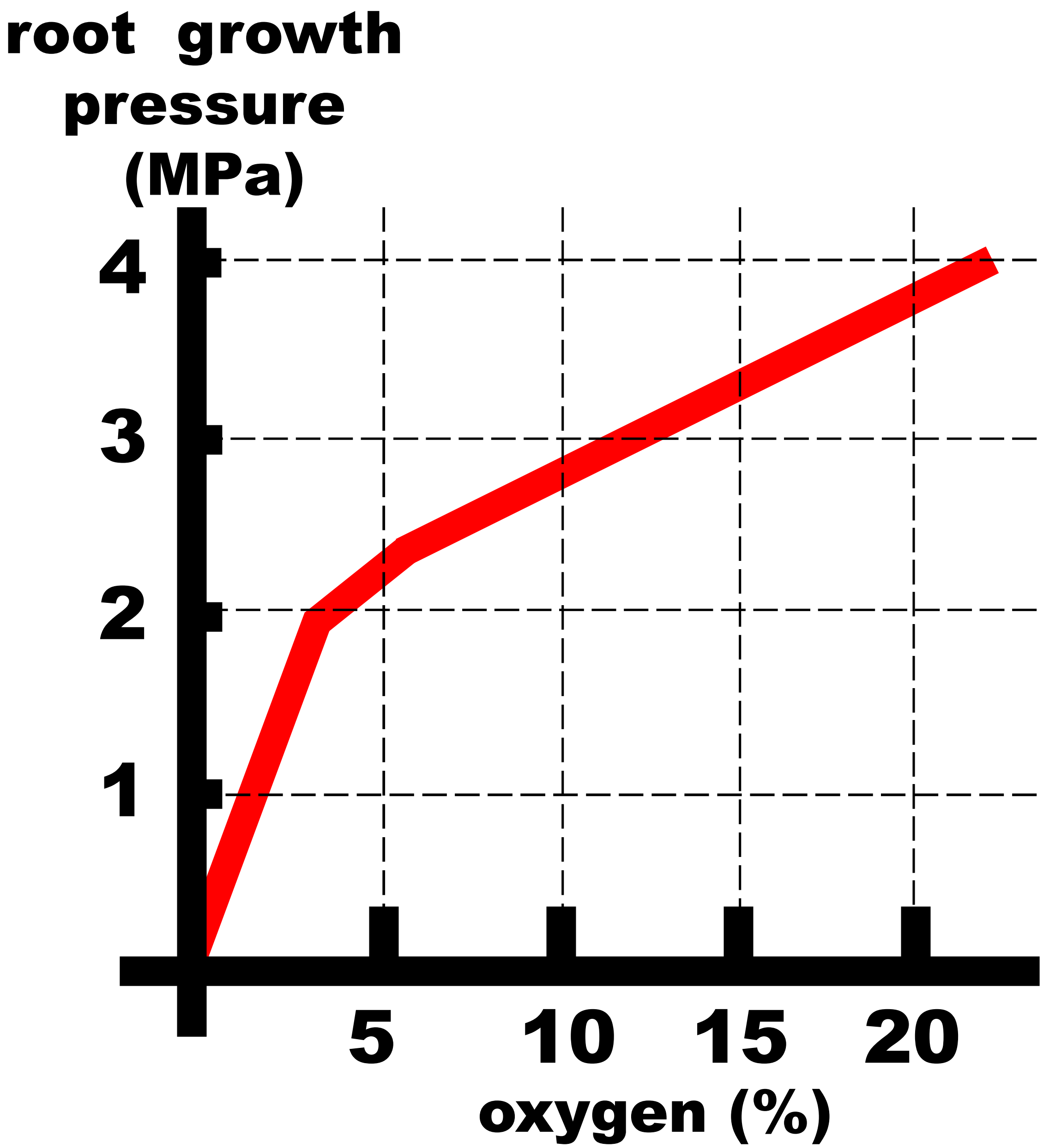

Figure 27: Root growth pressure by oxygen concentration.
(after Souty & Stepniewski 1988)

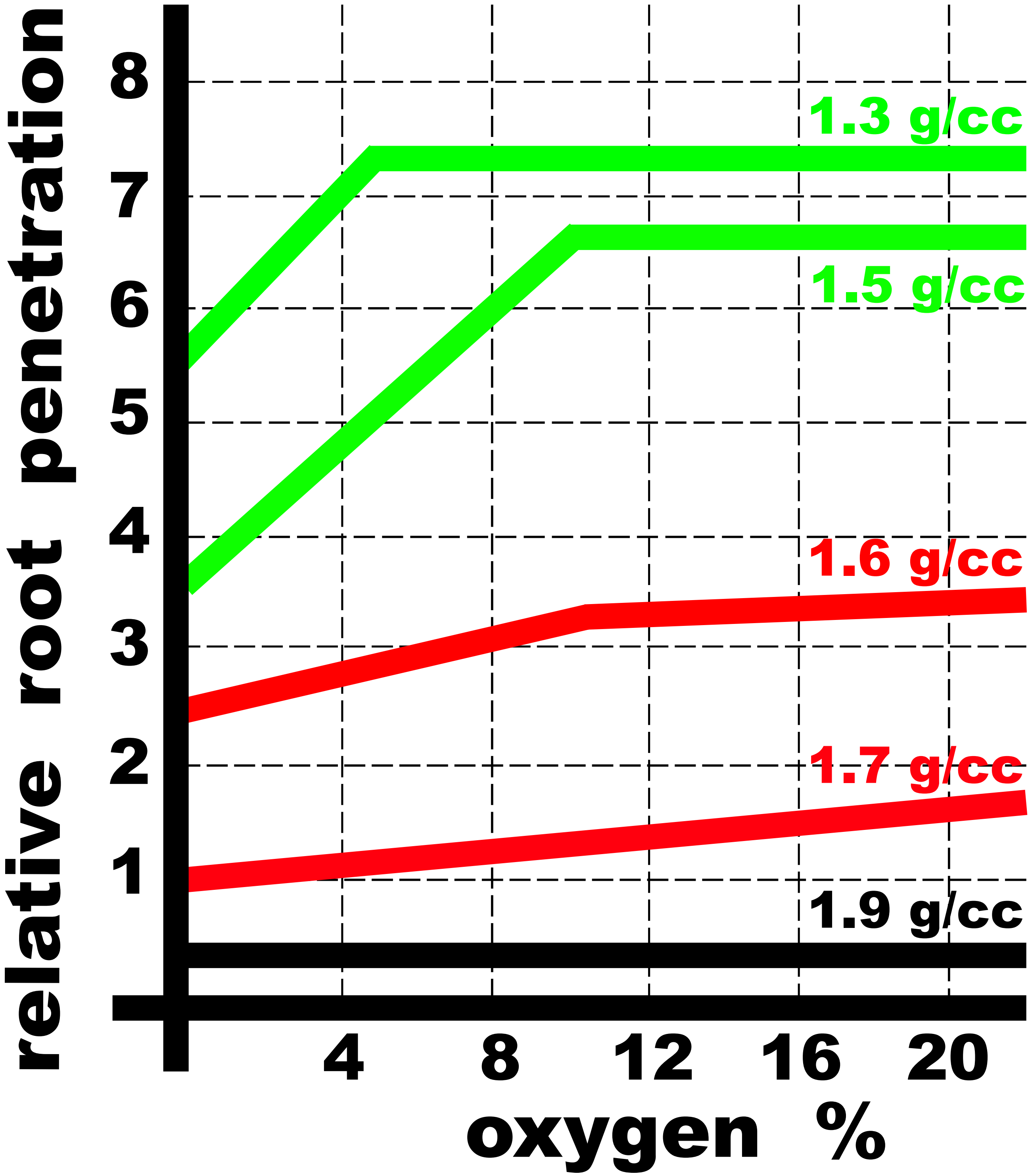

Figure 28: Percent oxygen and soil density (bulk density values) effects on root penetration.
(after Rendig & Taylor 1989)

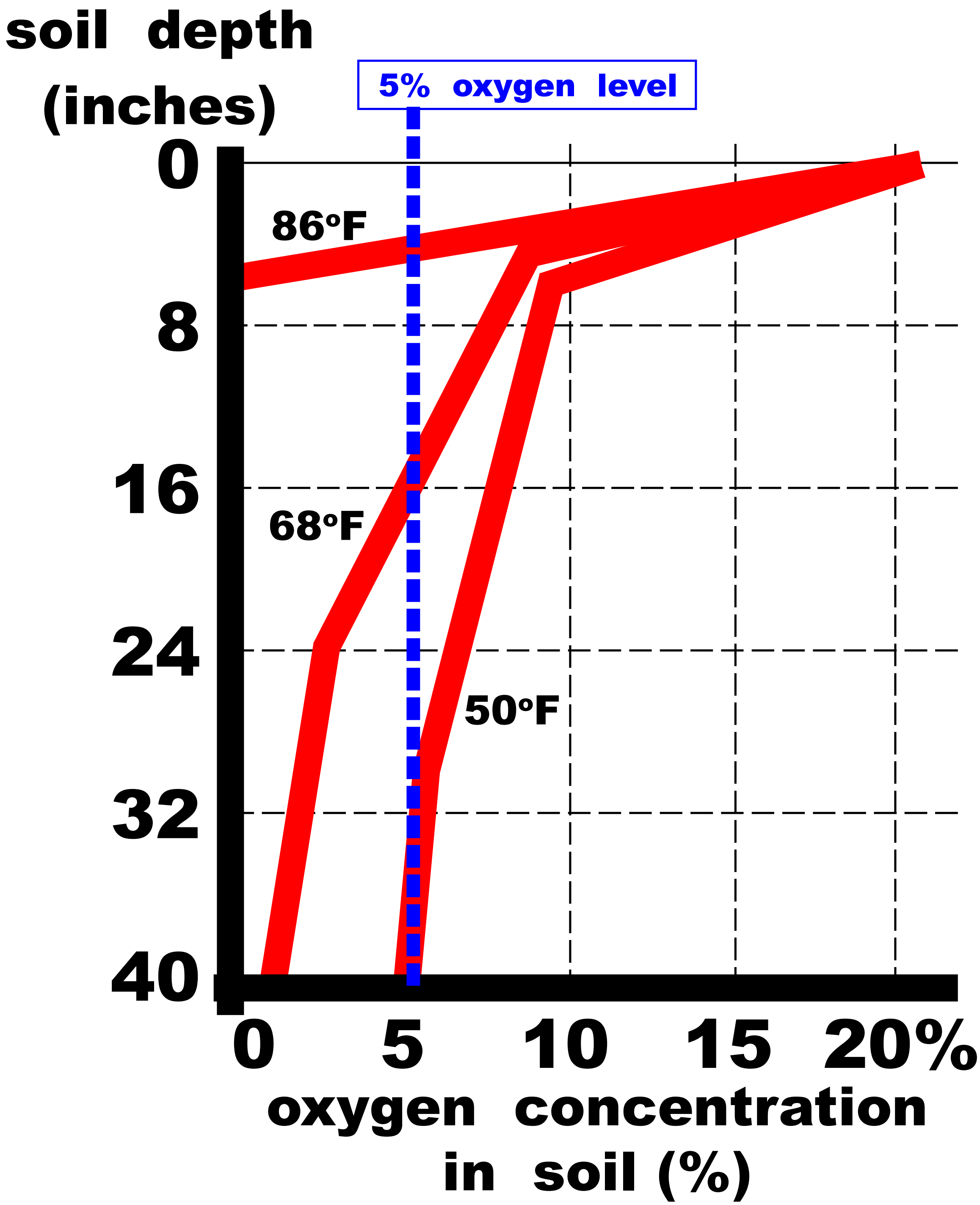

Figure 29: Oxygen concentration (percent) in soil with increasing depth for three different temperatures.
(derived from Cook & Knight 2003)

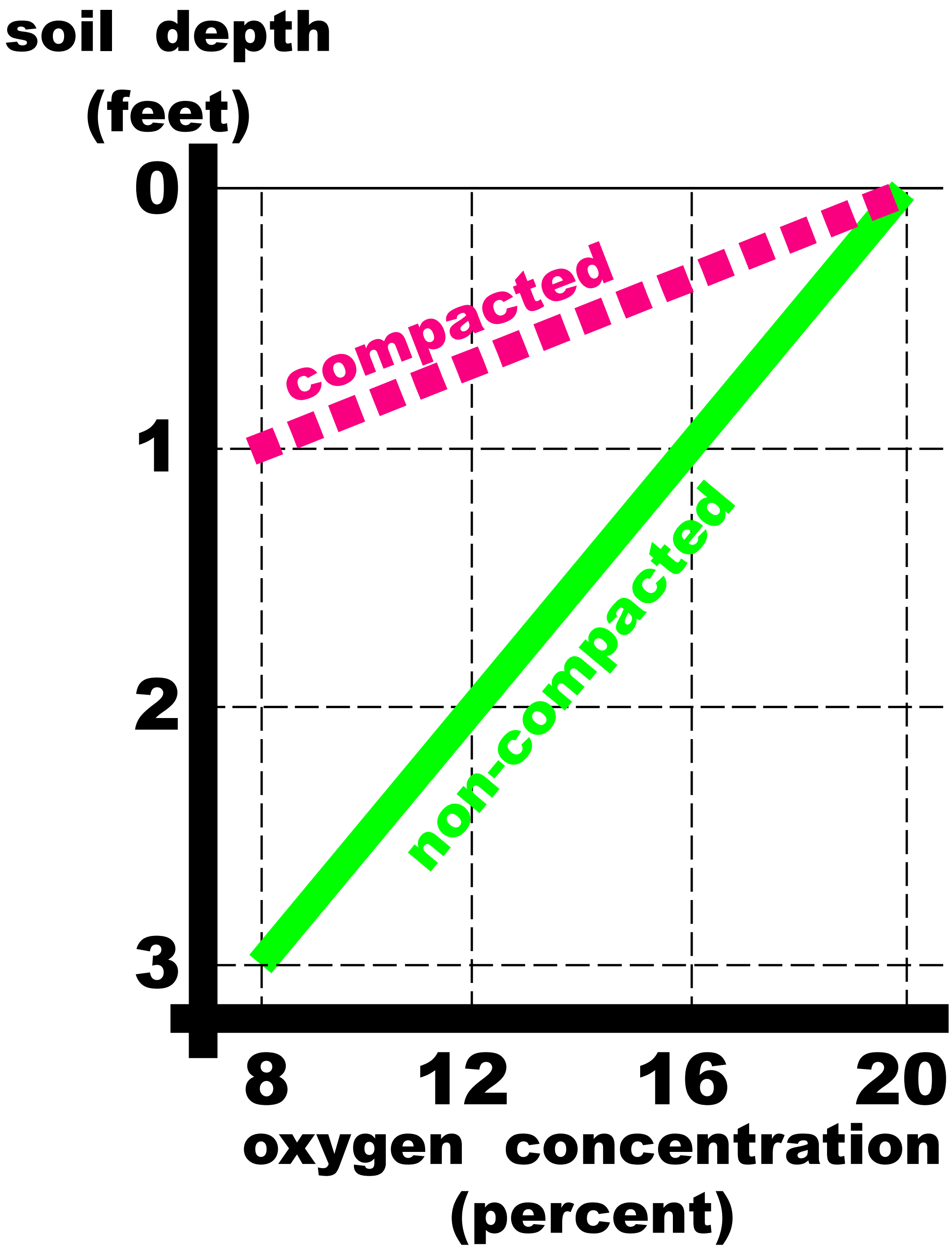

Figure 30: Oxygen concentrations (percent) with increasing soil depth (in feet) under compacted and non-compacted conditions.
(non-compacted data derived from Kalita, 1999)

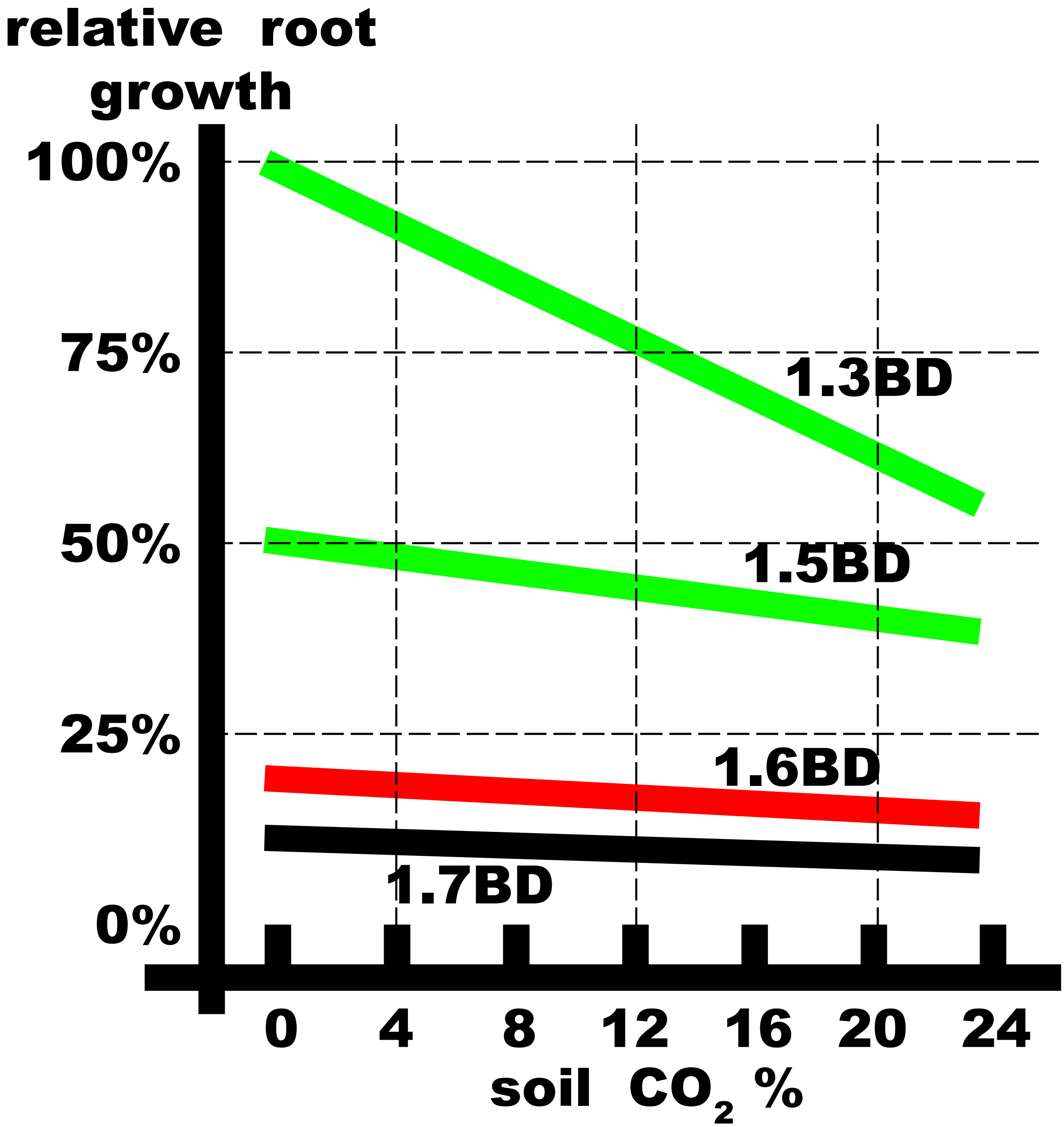

Figure 31: Carbon dioxide (CO_2) concentrations in soil and soil density (bulk density values) impacts on root growth. (after Patterson, 1976)

Less Water

One of the most ignored result of compaction is it effects on soil water availability. Figure 32. Soil compaction reduces tree available water held in large capillary pores and increases the volume of small capillary pores which hold water unavailable to trees. Figure 33. With a decreasing number of large capillary pores and increasing number of small capillary pores, the total water holding capacity of the soil declines. Compare Figure 34 and Figure 35.

Irrigation scheduling and soil water monitoring becomes much more critical around trees in compacted soils. Compaction leads to smaller pore spaces and slower infiltration rates. With increasing residency time at the soil surface, water can move horizontally across the surface of the soil initiating erosion. Over the top of compacted soil, water can reach faster velocities (more erosion potential) than in areas where infiltration is eased. Inside a soil, compaction prevents effective drainage. Poor internal drainage limits tree available water, prevents oxygen movement, and increases production and residence time for carbon-dioxide and toxics. Figure 36.

More Heat

Compaction changes the energy and water balance near a soil surface. With more particle to particle contact, heat transfer is greater into soil. Results include burning-out of organic matter quicker, acceleration of evaporative and transpirational water loss, and increased respiration of roots and soil organisms. As temperature increases, respiration responds along a doubling sequence – for every 18°F (10°C) increase in temperature, root and soil microbe respiration doubles.

Compaction Kills!

Soil compaction impacts tree and soil health in many ways. Generally, compaction associated physiological dysfunctions cause systemic tree damage and decline, as well as failures in dealing with additional environmental changes. Physical / mechanical constraints impact tree responses resulting in inefficient use of essential resources. The symptoms of compaction expressed by trees under compacted soil conditions are derived from disruptions of internal sense, communication, and response processes.

Compaction disrupts respiration processes which power every function of a tree. Growth regulators are destroyed prematurely or allowed to buildup, causing wild changes in tissue reactions. Carbon (food) allocation patterns, following highly modified growth regulation patterns, change food production, storage, use, and transport processes. Defensive capabilities with degraded sensor functions, associated growth regulator communications failures, and ineffective food use, are slow to react and incomplete in response. With compaction, short-term fluctuations in resource quality and quantity in a tree must be effectively dealt with, and resulting chronic stress must be tolerated, in order to survive.

Poisoning

The presence of toxic materials can be highly disruptive to soil health. As oxygen concentrations decline, more reduced compounds (partially oxidized) are generated by tree roots and associated soil organisms. These reduced compounds can build-up, damage organisms, and move soil toward anaerobic conditions. In normal soils, these materials (if produced at all) are quickly oxidized or removed from near tree roots. In compacted soil, normally produced materials, materials produced under low oxygen conditions, and anaerobically produced compounds, are not oxidized nor removed from where they are produced. The longer the residence time of some of these materials near roots, the more damage to tree roots.

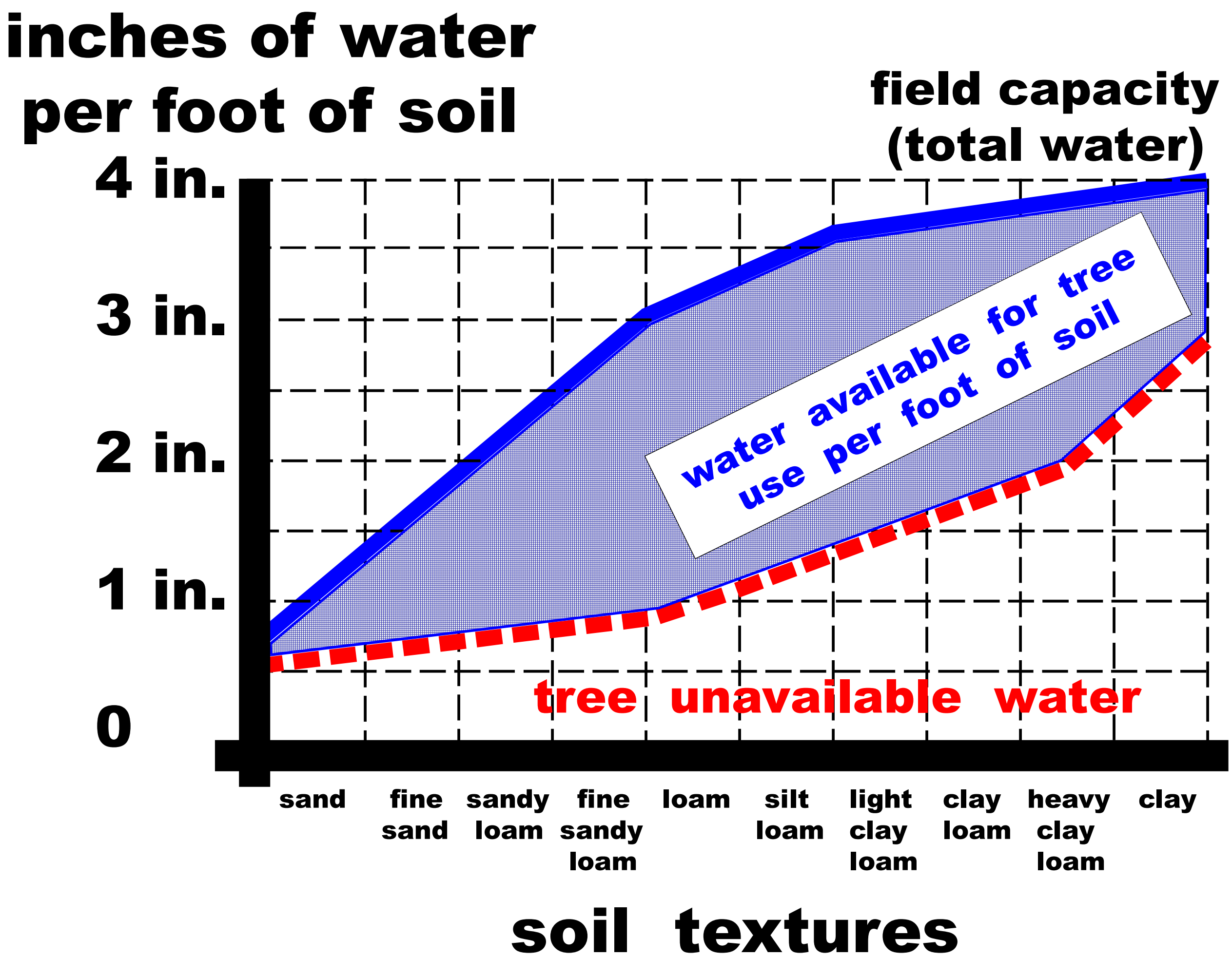

Figure 32: Tree available water is the difference between total water at field capacity and unavailable water held tightly by soil.

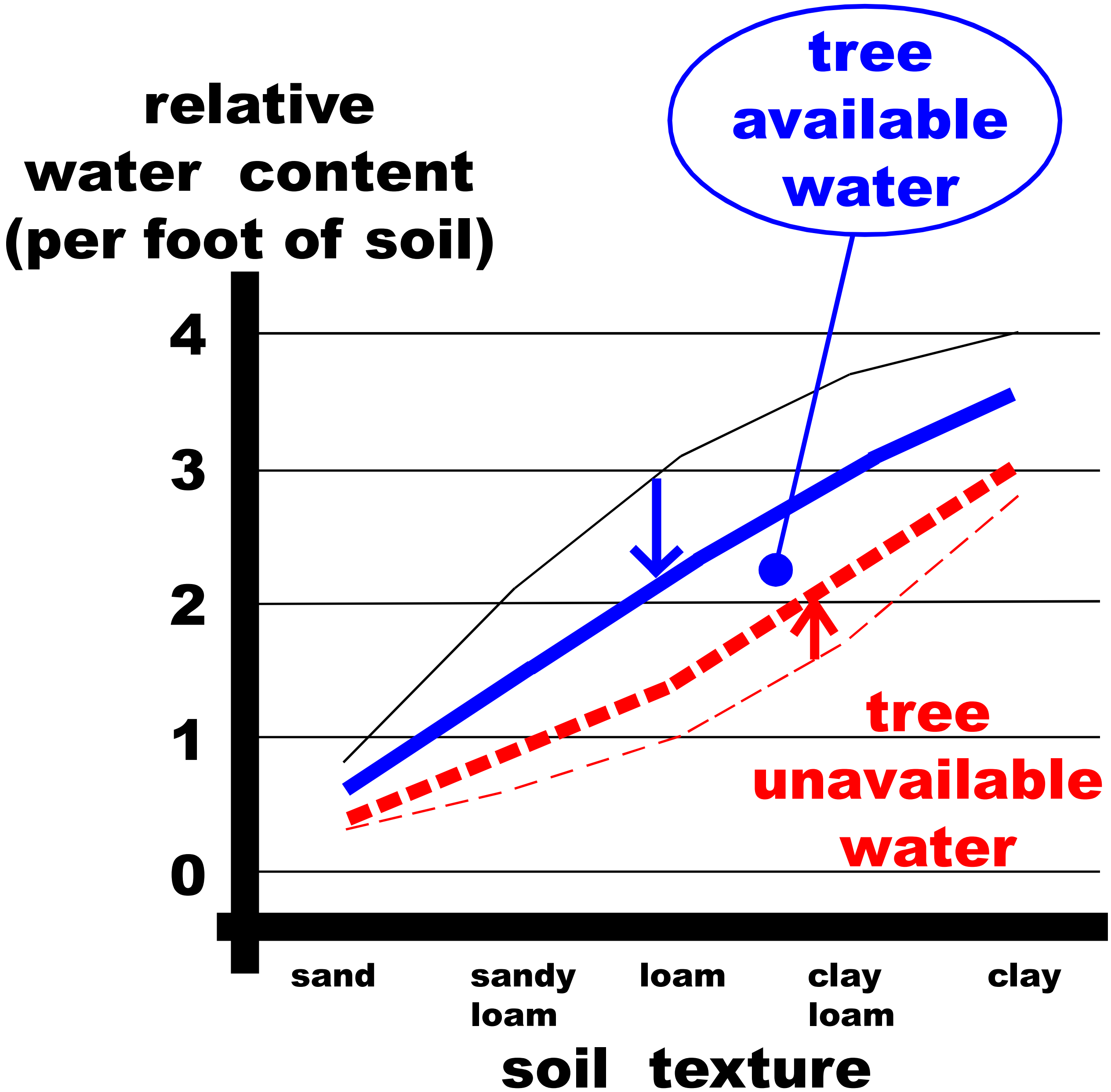

Figure 33: Declining tree-available water present in a soil as compaction is applied for different soil textures.

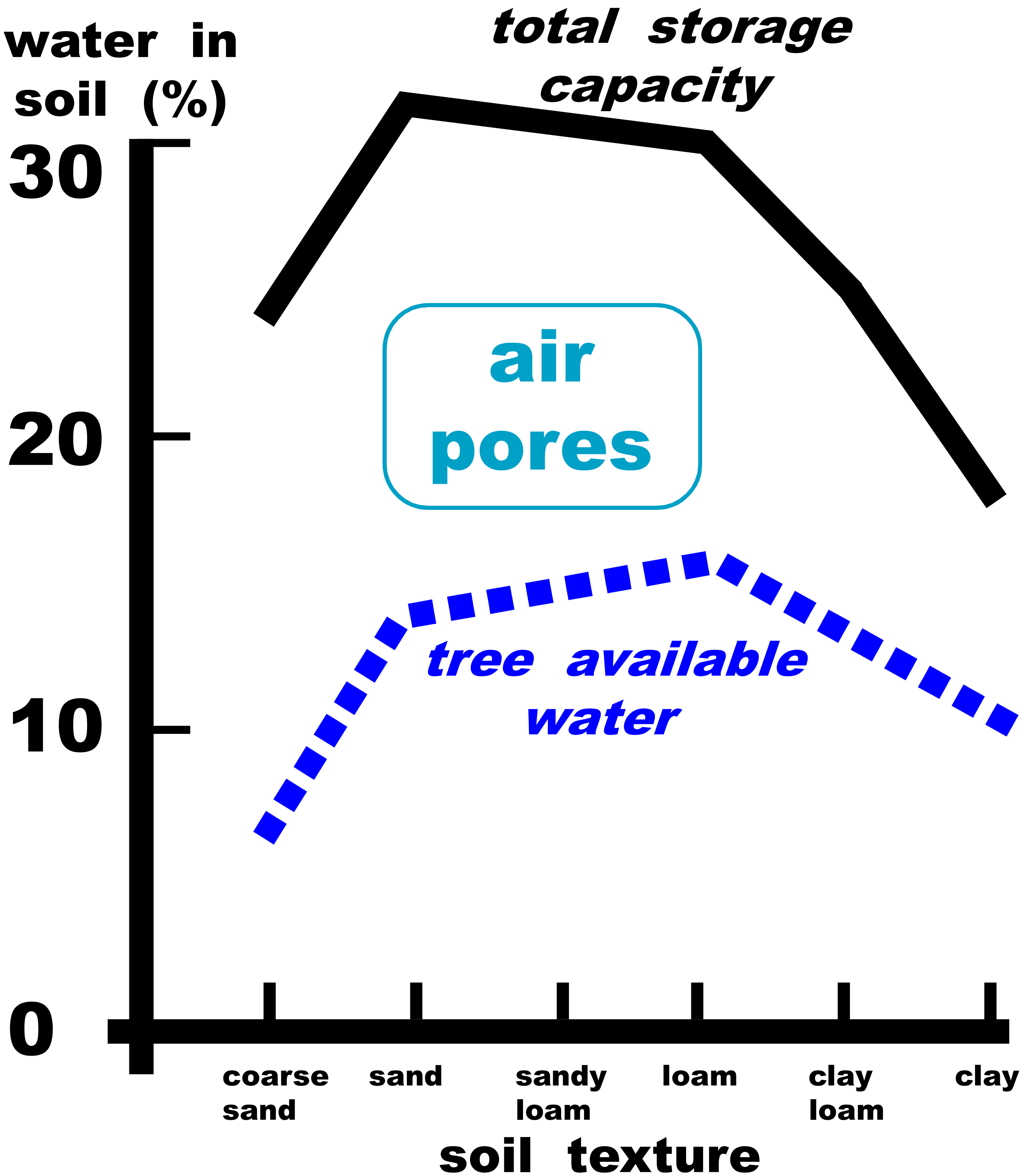

Figure 34: Water storage capacity in normal soil.
(after Craul 1999)

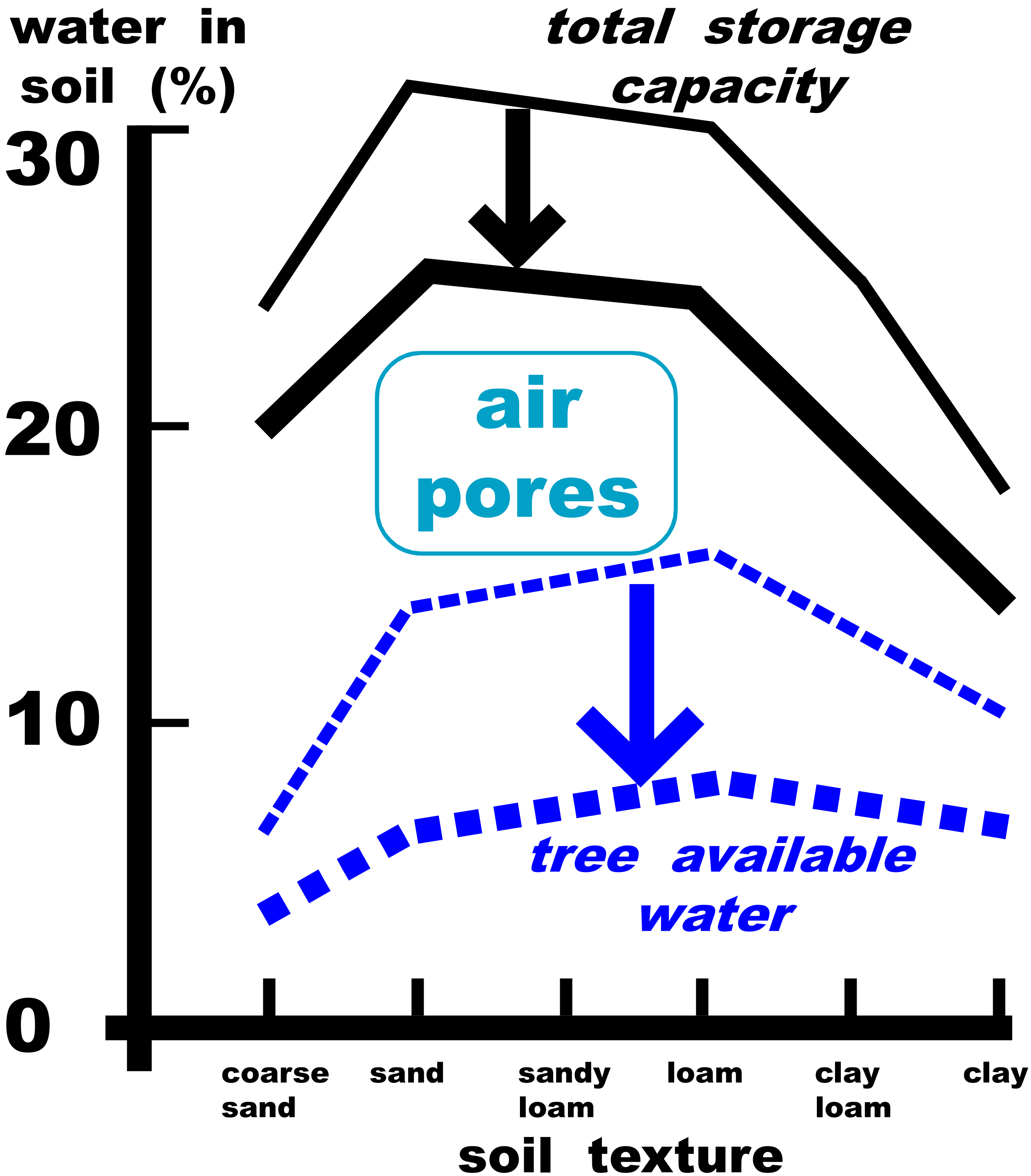

Figure 35: Water storage capacity under compaction.
(after Craul 1999)

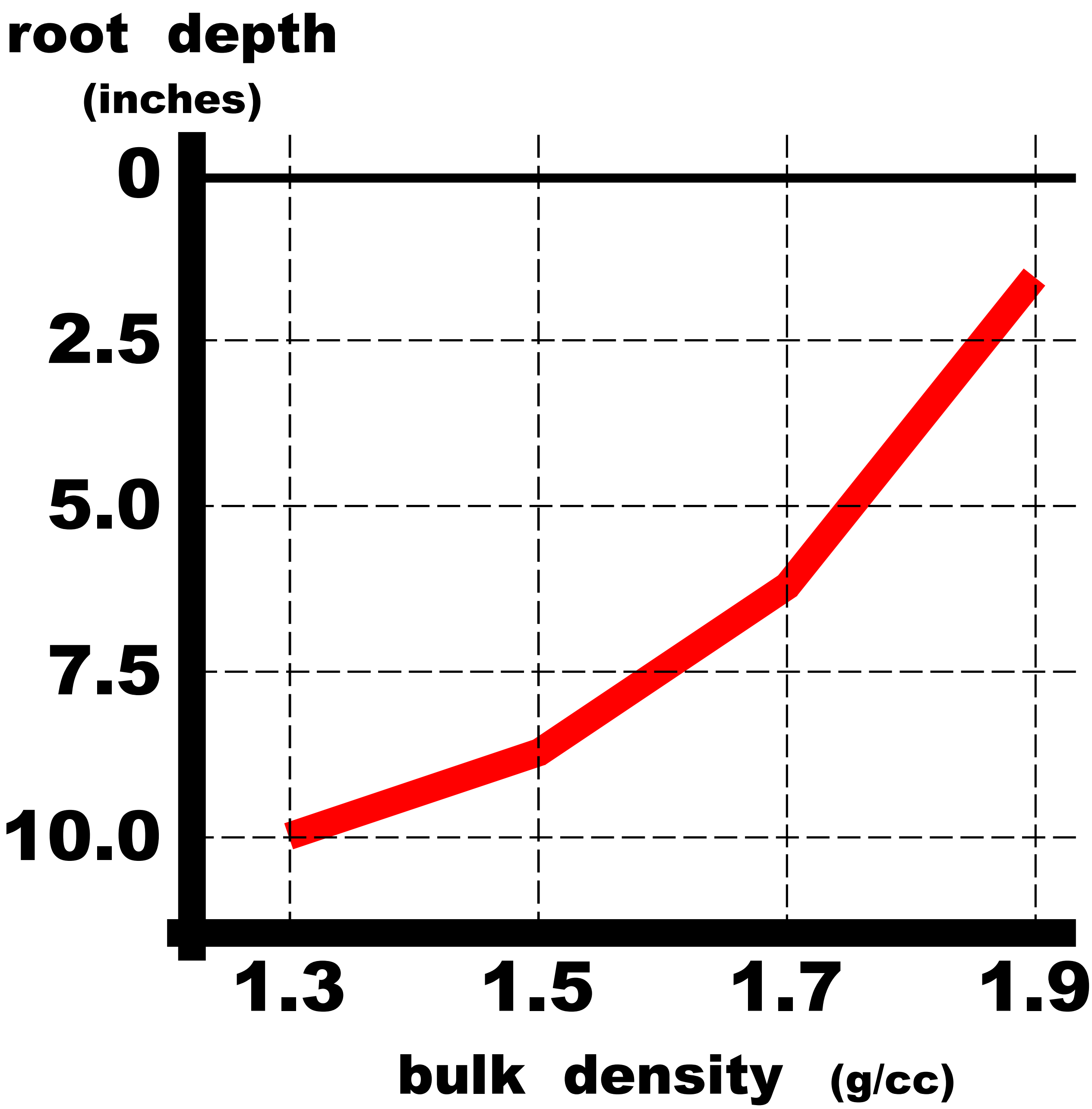

Figure 36: Rooting depth (in inches) limit on young pine (*Pinus taeda*) in controlled rooting experiments by soil bulk density (g/cc). (derived from Torreano, 1992 -- PhD dissertation)

Structural Decline

The structure of a tree can also be directly and indirectly impacted by compacted soils. Root decline and death can lead to catastrophic structural failures. Tissue death and subsequent compartmentalization processes can compound mechanical faults. Growth regulation and carbon allocation changes can modify stem and root collar taper and reaction and flexure wood development. Whole tree stress can result in tissue shedding both internally to heartwood and externally as shown in crown and root dieback. Branch drop and root failures can result. Reduced rooting volume mechanically destabilizes the whole tree.

Measuring Compaction

Tree health management is limited to how easily and effectively we can measure absolute and relative soil compaction. Measures can be used which approach actual values and suggest impacts on essential tree resources. Primary resources impacted by compaction and critical to tree growth in soil are oxygen availability, gas exchange with the atmosphere, and root mechanical growth through pore volumes. These resources are severely limited by soil compaction. Mechanical impedance and gas movement in a soil for tree health is difficult to measure directly.

Because of the difficulty in simultaneously measuring soil resource limitations quickly in the field, a number of approximate measures for compaction have been developed. Two measures most commonly used are bulk density and soil penetration force. Unfortunately, both measures are soil moisture content and organic matter dependent. Additionally, bulk density and soil penetration force are not measuring the same features in a soil, and so, are not necessarily closely correlated. Bulk density is usually considered the best estimate of soil compaction on a site.

Bulk Density

Bulk density is a relative measure of soil density (weight of a given volume of soil). The most commonly used tool for measuring bulk density is a soil core slap-hammer which carefully drives a metal sleeve of a known volume down into soil. The driving force used in sampling is shifted to soil surrounding the sample volume. Minimizing any disruption of collected soil volume during sampling is critical for an accurate measure. In addition, gravel, moisture content and percent of organic matter can all disrupt collection of an accurate sample. Bulk density cores consistently provide higher than actual (true) bulk density values for any sampled soil.

Dry & Wait

The collected soil volume must be dried in an oven until all measurable moisture (by weight) is removed. Oven-dry weight of collected soil is recorded and divided by the known volume of sample taken from the collection site. Clearly bulk density measures are not immediately available, but require drying and weighting time, usually a minimum of one day.

Bulk density characterizes both the mineral portion and pore space portion of a soil. Most mineral soils share similar densities of solid mineral components (~2.65g/cc). Organic soils and soils generated from parent materials with mineral densities significantly different from 2.65g/cc, will have different bulk densities simply due to different matrix component densities.

Open Spaces

If most soils share similar mineral densities, then any variability in their bulk density will be due to differences in pore space volume. Pore space volumes (composed of water-filled "micro" pores and air-filled "macro" pores) are measured in a bulk density sample. Figure 37 provides a calculation of soil bulk density and percent of total pore space present for average mineral density soils. Note, the larger bulk density values, the smaller pore space volumes must be.

Bulk density, when collected under the right soil conditions in the right soils can provide critical management information. Because tree roots utilize soil spaces, any measure of these pore space volumes can help better manage tree growth. As soil bulk density increases (compaction increases), total pore space declines and aerated pore spaces collapse. For example in one soil, a 20% increase in bulk density initiated a 68% loss of aerated pore space and an increase in 7% capillary (water-filled) pore space. In another soil, compaction from a bulk density of 1.25g/cc (~50% total pore space) to 1.5g/cc (~40% total pore space) left the soil with 45% fewer large pores, 98% fewer intermediate sized pores, 1% fewer small pores, and 14% more extremely small pores.

Dense As A Brick

Many materials can be measured using bulk density. Figure 38 provides bulk densities for selected construction materials and associated pore space. Some compacted soils have greater measured bulk densities than some common construction materials. It is possible to find soils around infrastructures which are more dense than the walls and sidewalks of the building they adjoin.

As discussed earlier, bulk density, as a measure of soil compaction, rapidly increases with the first few impacts on the soil surface and then only incrementally increases. Soils can be compacted to 90-95% of what they can be compacted to in as little as 3-4 trips over a single site under the right conditions. As tree rooting space is compacted, root growth declines and stops. Figure 39 shows the bulk density and associated air pore volume, by soil texture type, where tree root growth becomes limiting. Note bulk density limits root growth at different values for each soil texture type. Figure 40 demonstrates it is not simply bulk density and total pore space which should be examined for tree health but air pore space in particular. There is not a single magic number, but trends in several measures under varying conditions which should govern management decisions

Figure 41 provides a list of bulk density measurement units and their interconversion.

Penetrometer Pressure

The second primary means used to measure soil compaction and estimate resulting tree available resources is by using a penetrometer. A penetrometer measures the energy (pressure) required to push a metal rod into soil. Penetrometers can be simple devices used to estimate packing density of mulch, surface compaction of roads beds, and bulk density of soils. Penetrometers provide immediate estimates without laboratory drying and weighting of samples, as needed with bulk density measures. But, penetrometers measure penetrative force not density of soil. Penetrometer measures are much more sensitive to soil moisture contents and associated soil strength values than bulk density measures.

As a penetrometer is pushed into a soil, the soil resists. This resistance is measured on a dial or slide scale. As the penetrometer is inserted farther, different resistances are measured for different layers of soil, some significantly compacted and some not. Figure 42. Depending upon site history, different compacting events may have occurred and have left unique soil compaction signatures. The heavier the compacting items, the deeper into soil measurable compaction will occur. Figure 43.

BD (g/cc)	% pore space
0.9 g/cc	66
1.0	62
1.1	58
1.2	55
1.3	51
1.4	47
1.5	43
1.6	40
1.7	36
1.8	32
1.9	28
2.0	25
2.1	21
2.2	17

% pore space =
[(1 - BD) / 2.65] X 100

Figure 37: Calculation of pore space within a soil. Value derived from bulk density (BD) and average mineral density (2.65 g/cc).

material	bulk density	particle density	pore space
cinder block	1.70	2.64	36%
clay brick	1.75	2.72	36%
asphalt	2.19	2.35	7%
concrete	2.26	2.47	9%
units =	g/cc	g/cc	percent volume

Figure 38: Physical attributes of selected construction materials. (Patterson, 1976)

soil texture	root-limiting bulk density (g/cc)	root-limiting % pores normally filled with air (%)
sand	1.8 g/cc	24%
fine sand	1.75	21
sandy loam	1.7	19
fine sandy loam	1.65	15
loam	1.55	14
silt loam	1.45	17
clay loam	1.5	11
clay	1.4	13

General tree root growth limits:

A) physical limit = bulk density greater than 1.75 g/cc.

B) aeration limit = air pore volume less than 15%.

Figure 39: Root growth limiting bulk density and percent air pore space values by soil texture.
(Daddow & Washington 1983)

texture = bulk density =	sand 1.52 g/cc	silt 1.20	clay 1.05
mineral matrix	55%	50%	45%
total pore space	45%	50%	55%
air pore	30%	25%	10%
water pore	15%	25%	45%

Figure 40: Relative proportion of air, water and mineral materials in the top foot of soils with different textures and bulk densities (g/cc).

Mg/m^3 g/ml g/cc g/cm^3	kg/m^3	g/m^3	lbs/ft^3	lbs/in^3
1	1,000	1,000,000	62.43	.036
.001	1	1,000	.0624	3.61×10^{-5}
1.0×10^{-6}	.001	1	6.2×10^{-5}	3.6×10^{-8}
.016	16.02	16,018	1	5.77×10^{-4}
27.8	27,778	27,777,778	1,734.2	1

[1.0×10^{-3} = .001; 1.0×10^{3} = 1,000]

Figure 41: Estimated interconversion factors for bulk density values. Columns represent given measurement units. Lines represent interconversions between measurement units.

NOTE: Use table horizontally (along one line) only, not vertically (along a column). Conversion factor estimates are rounded for ease of use.

For example, all units of measure in the first column (Mg/m^3, g/ml, g/cc, and g/cm^3) are equivilent to each other. Reading across the first line in the table: 1 g/ml is approximately equal to 1,000 kg/m^3, or 1 million g/m^3, or 62.43 lbs/ft^3, or 0.036 lbs/in^3. Always read across one line.

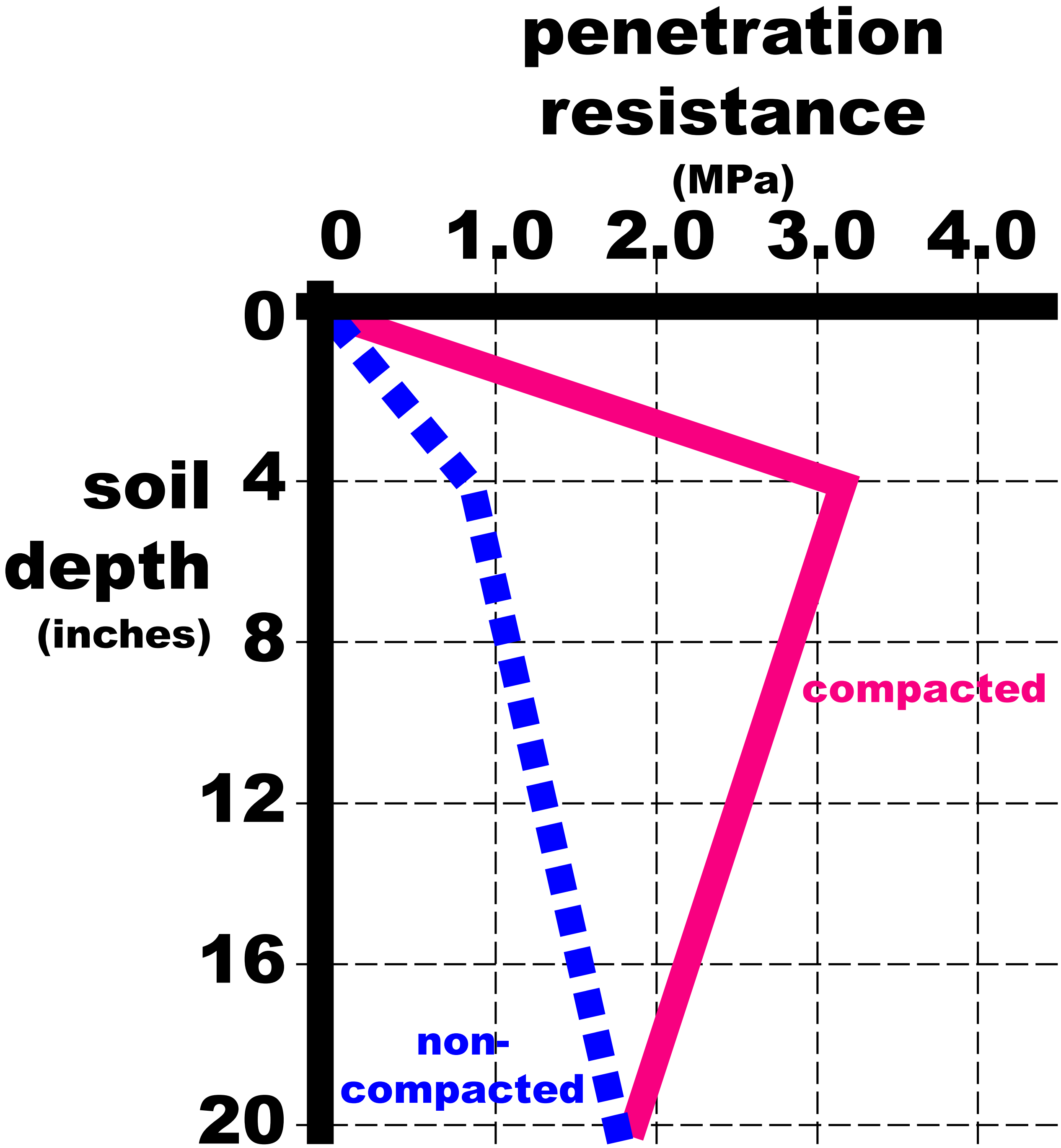

Figure 42: Example penetration resistances (MPa) by soil depth for a compacted soil and a non-compacted soil.

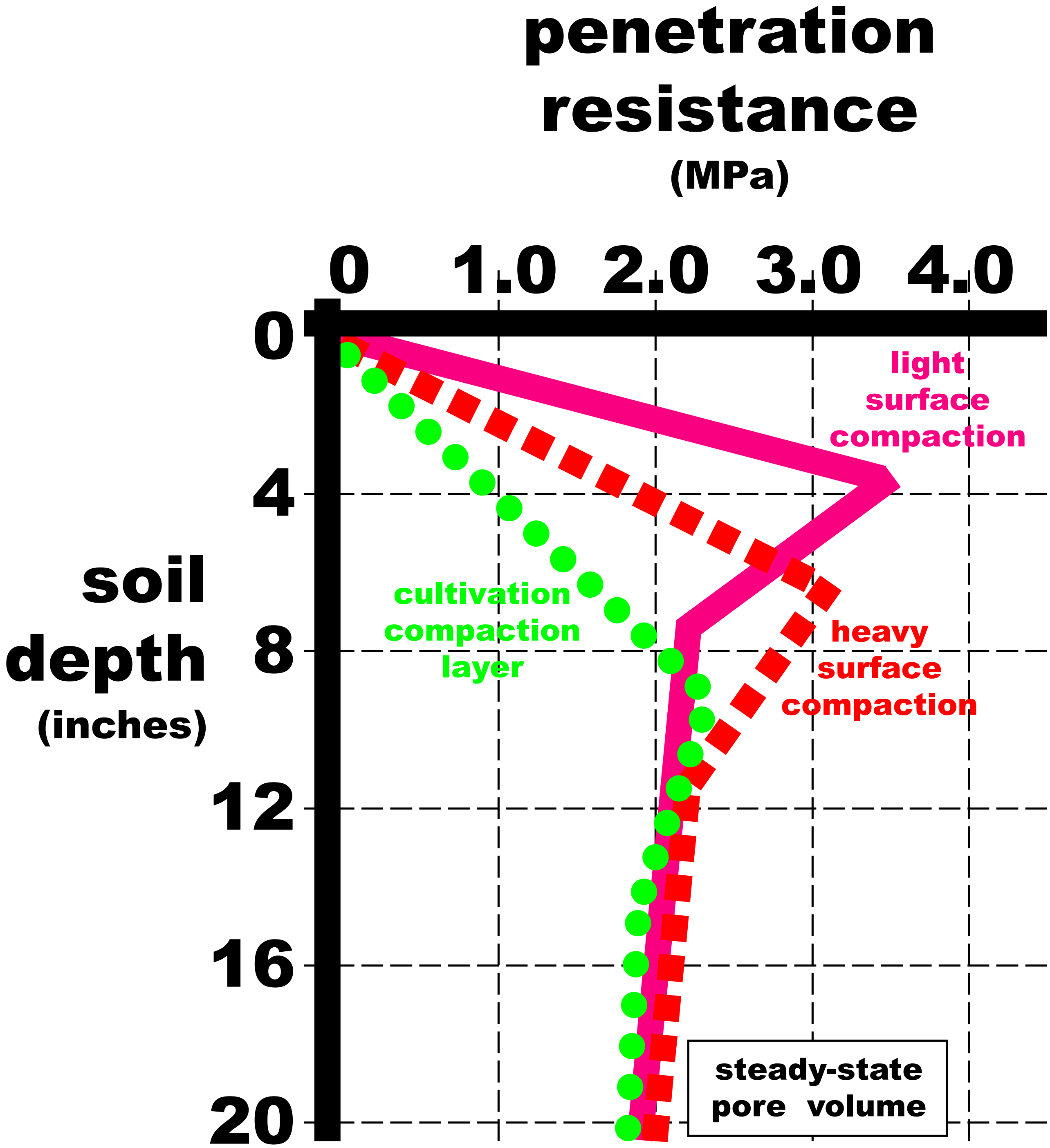

Figure 43: Example penetration resistances with increasing soil depth for three different types of soil compaction.
Note all three eventually reach some steady-state resistance at some soil depth.

Pushing On

Penetrometers are unique tools, easy to use for estimating a single-number composite of soil features and values. Penetrometers estimate resistance of a soil to root penetration (resistance = compression of soil in front of probe plus soil/metal friction around probe). In soils with uniform physical characteristics across all dimensions, the penetrometer measure is well correlated to tree root elongation. Soils which contain large pores, fracture lines, cracks, gravel or stones are not good candidates for accurate and precise penetrometer use.

Penetrometers do not displace soil in a manner like a tree root. Tree roots are soft, flexible, and mucilaginous with a rounded cap. The penetrometer probe is rigid, large in cross-sectional area, and usually has a conical point on its end. Penetrometers with a tapered tip having approximately a 30° angle point have 40% less friction moving through soil than a blunt tip, and more closely mimic root penetrations.

Steady & Vertical

Because of displacement and frictional forces on a penetrometer as it is pushed into soil, penetrometers tend to overestimate impacts of penetration resistance on tree root growth. The deeper a penetrometer is pushed into soil, the greater soil / metal friction. When pushing a penetrometer into a soil always keep the probe vertical, do not wobble, and apply a constant pressure. A steady, moderate pressure is preferable over a suddenly-exerted high pressure.

Pushing Roots

Traditionally a penetration resistance of 0.5 MPa begins to constrain root growth, 2.0 MPa cuts root growth by 60%, and 3.5 MPa of penetration resistance prevents elongation or expansion of tree roots. Two recent studies show root growth limitations at much smaller pressures. These studies provide two views of relative tree root penetration of a soil (in percent) compared with measured penetrometer resistance values (in MPa).

The first study (Figure 44) shows a comparison among values of penetration resistance which have been transformed into natural logarithms (base e) for preparing a linear regression model. This figure suggests penetration resistances above 2.3 MPa are extremely limiting and penetration resistances below 0.6 represent few root growth impediments. The second study (Figure 45) provides a field-usable comparison between penetration resistance and relative root penetration percent. Remember, extremely large penetration resistances in soil allow for root growth only along fractures (cracks), along the soil surface, and along infrastructures boundaries.

Water Problems

When using penetrometers, it is critical to account for moisture contents. All sites measured should have roughly the same soil moisture content in order to be comparable. The lower water content of a soil, the greater soil strength values become, and the greater penetration resistance values become. As an approximation in average soils -- for every one percent reduction in moisture below 35% soil moisture content, soil strength is increased by 0.11 MPa (a reduction of 10% moisture content in a soil would increase soil penetration resistance by 1.1 MPa. Site irrigation the day before sampling with adequate drainage provided would be ideal.

When water contents are at saturation, penetration resistances are reduced by a lubrication effect and ease of hydraulic deformation of soil. Heavily compacted, uniform soils saturated with water will

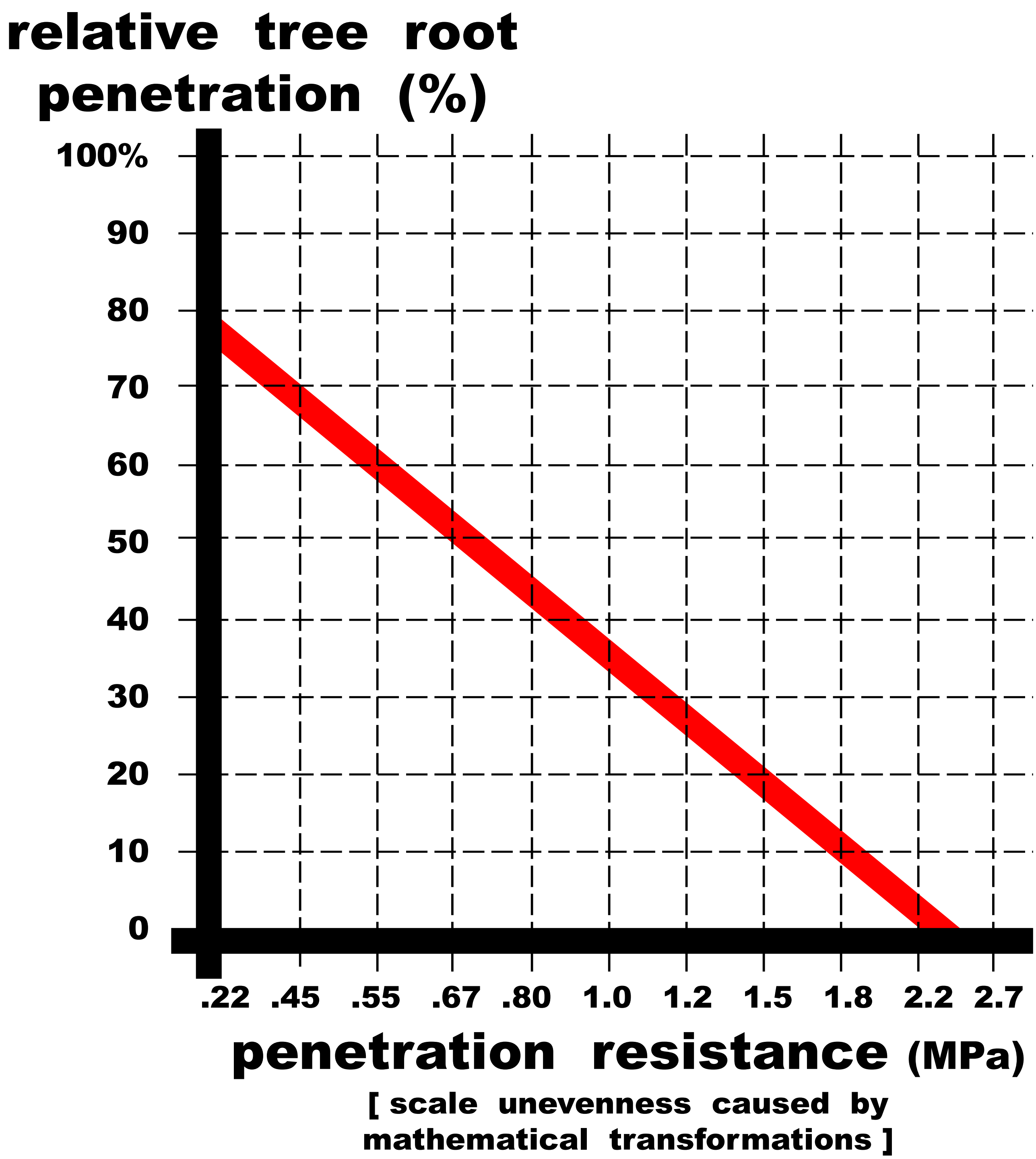

Figure 44: Linear model comparision of relative tree root penetration percentages with penetrometer resistance (MPa).
Regression is: $y = 35.5 - 43(\ln x)$ r-square = 0.967.

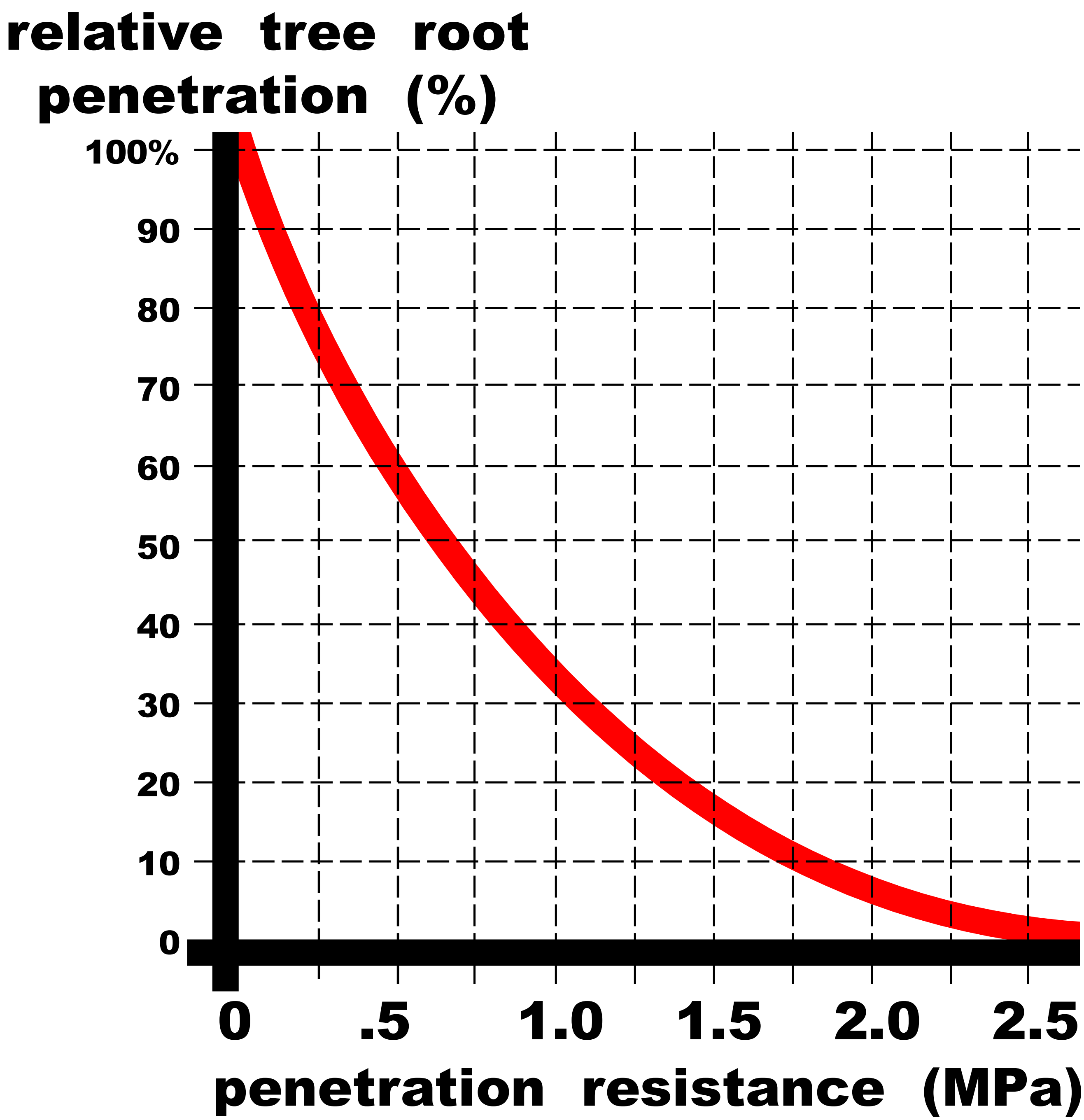

Figure 45: Comparision of relative tree root penetration percentages with penetrometer resistance (MPa).

read a much lower penetration resistance value than expected, given the known level of soil compaction. For soil at or near saturation for long periods (or short periods with relatively hot soil temperatures) penetration resistances have little value in determining biological ability for roots to colonize new soil volumes. As total pore volumes fill with water (>85% water-filled), and oxygen in the soil drops below ~5%, soil provides major constraints to root growth which has little correlation to penetration resistance.

Figure 46 provides a list of penetrometer measurement units and their interconversion.

Using Penetrometers To Estimate Bulk Density

Both penetration resistance and bulk density values provide good relative, composite (multifactor) estimates of soil compaction for use by tree health care providers and landscape managers. There are a number of growth estimating tables, figures, or rules for each estimated measure. Some tree health care providers would like to rely on one easily determined value to estimate both. Because of laboratory drying and weighting time involved with bulk density measures, and the ease of which many penetrometer measures can be made in a given amount of time, use of penetrometer resistance values as an approximation of bulk density would be ideal for field estimates.

Bulk density is a weight to volume measure while penetrometer resistance is a pressure measure. Geometrically, bulk density is a three-dimension based value while penetration resistance is a two dimension value. The correlation between these two types of measures is roughly 50-60% across all soils under various conditions. The correlation between these measures is much more closely related in mineral soils with more uniform textures without gaps, cracks, or gravel.

Appreciating Correlations

Remembering correlations between bulk density values and penetration resistances are not strong for every sampled condition, a set of interconversion figures have been prepared. Figure 47 provides the graphical definition of a linear regression model comparing penetration resistance with soil bulk density, where penetration resistance values have been mathematically transformed using natural logarithm (base e). Figure 48 presents field data for comparing penetration pressure values with soil bulk density values under good soil moisture content values. See **Appendix 2** for a field worksheet.

Soil resources are constraining on tree growth. Soil compaction is a major stressor of trees. Tree health care providers must realize the qualitative and quantitative values associated with compaction. Using a bulk density sampler or a penetrometer provide a means of more fully appreciating tree growth limitations.

Tree Impacts & Site Renovation

Soil compaction lingers as an abiding stress on developed sites from which there is no escape by trees unless tree health care providers actively renovate soil. Soil compaction can quickly limit tree reactions under other stress events, making them worse. Compaction is not usually visible nor measured, but controls most significant tree resources on a site. Tree health care providers must begin measuring compaction and making clients aware of severe problems arising from increased soil density. Tree symptoms of compaction come in many forms and severities. A selected number of major tree damaging impacts from soil compaction are reviewed here.

Figure 46: Estimated interconversion factors for different soil penetration pressure units.

NOTE: Use table horizontally (along one line) only, not vertically (along columns).
Conversion factor estimates are rounded for ease of use.
[1.0×10^{-3} = 0.001; 1.0×10^{3} = 1,000]

atmospheres	bars	lang units (blue)	pds/in² PSI	pds/ft²	tons/ft² (short)	pascals (Pa)	kilopascals (KPa)	megapascals (MPa)	kg/cm²
1	1.01	.288	14.7	2,130	1.06	101,325	101.3	.101	1.03
.987	**1**	.284	14.5	2.089	1.04	100,000	100	.10	1.02
3.47	3.52	**1**	51.0	7,347	3.67	353,701	353.7	.354	3.61
.068	.069	.020	**1**	144	.072	6,895	6.9	.007	.07
4.74×10^{-4}	4.8×10^{-4}	1.35×10^{-4}	.007	**1**	4.97×10^{-4}	47.9	.048	4.8×10^{-5}	4.9×10^{-4}
.945	.958	.272	13.9	2013	**1**	95,761	95.8	.096	.98
9.87×10^{-6}	1.0×10^{-5}	2.84×10^{-6}	1.45×10^{-4}	.021	1.04×10^{-5}	**1**	.001	1.0×10^{-6}	1.02×10^{-5}
.01	.01	.0028	.145	20.9	.010	1000	**1**	.001	.01
9.9	10	2.84	145	20,890	10.4	1,000,000	1000	**1**	10.2
.968	.981	.279	14.2	2,061	1.02	98,067	98.1	.098	**1**

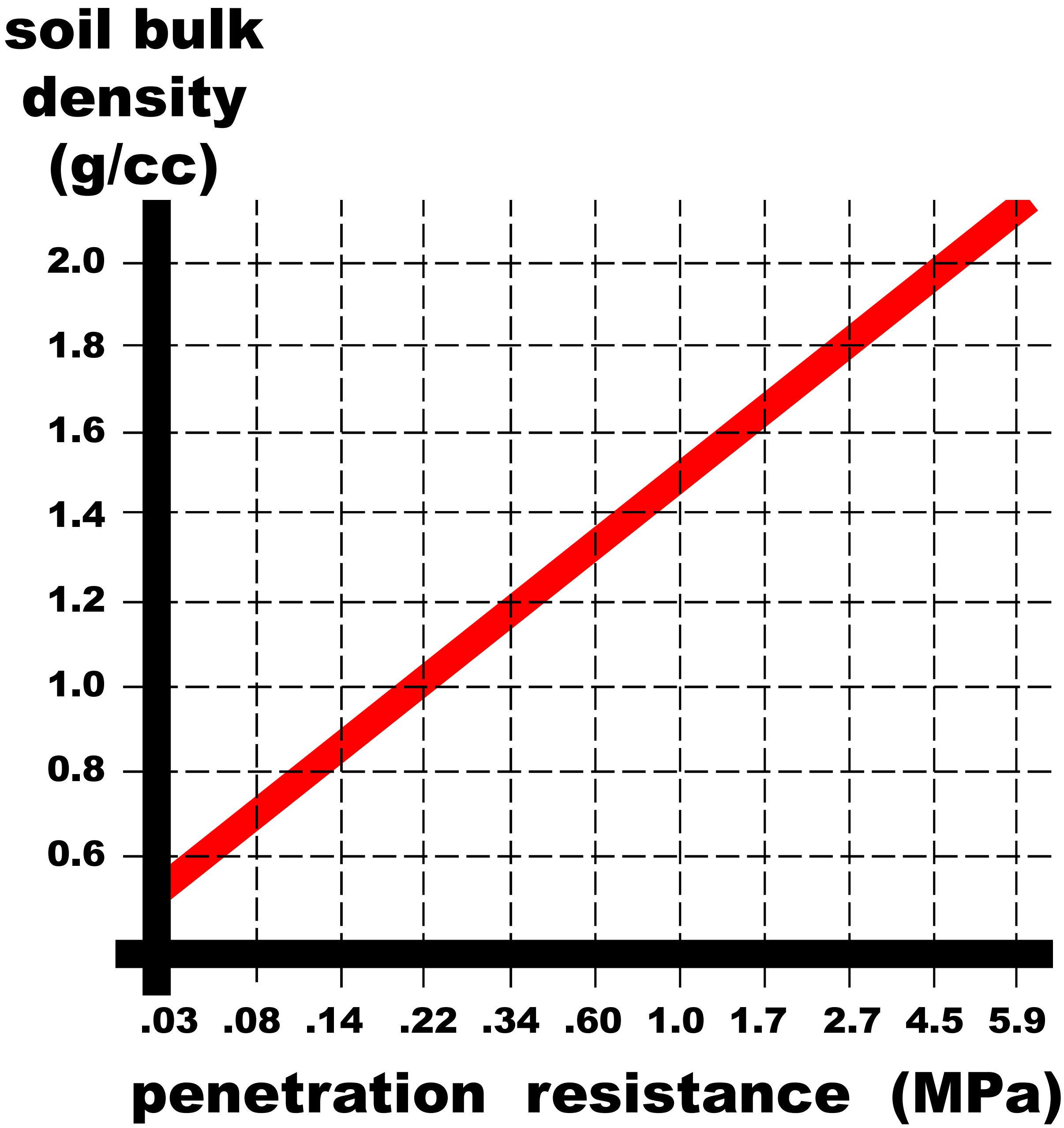

Figure 47: Linear model comparision of soil bulk density (g/cc) with penetrometer resistance (MPa).
Regression is: $y = 1.5 + 0.3 (\ln x)$. r-square = 0.97.
[scale unevenness caused by mathematical transformations]

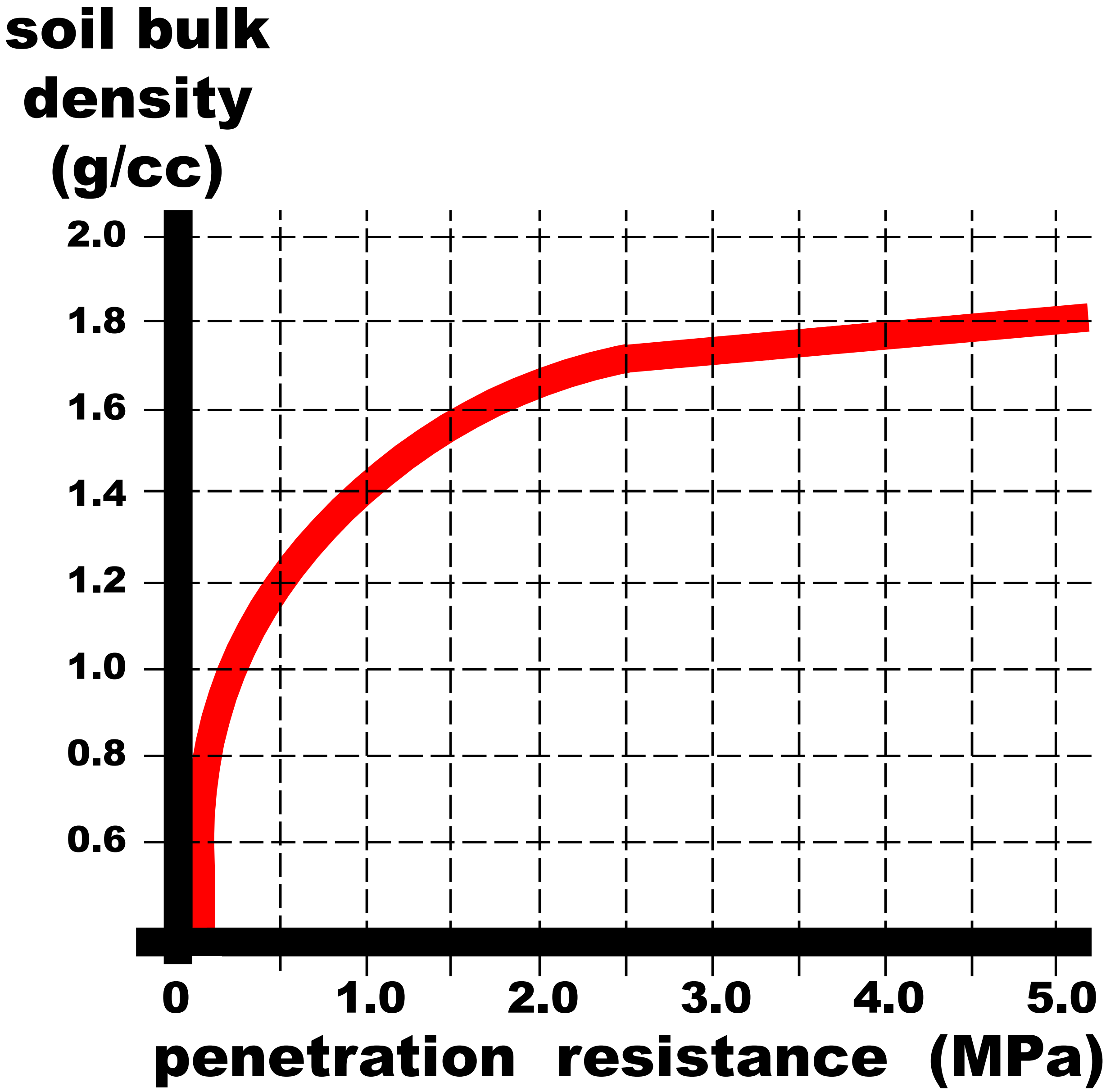

Figure 48: Comparision of soil bulk density (g/cc) with penetrometer resistance (MPa).

Reduced Growth

As compaction increases, roots are physically prevented from elongating into soil by lack of oxygen, by decreasing pore size, and by increased soil strength. As roots are put under greater than 1.5 MPa of pressure, elongation slows. Trees begin to generate thick, short roots with many more lateral roots as surrounding soil pressure exceeds 1.0 MPa. Oxygen shortages and soil strength increases are major limitations to both elongation and radial growth.

Less Resource Space

With less colonizable soil volume, there is less physical space to collect resources from and less resources within that space. With declining respiration processes, energy requiring steps within active element uptake processes (i.e. N, P, S) fail. Part of the difficulty in collecting essential resources is a buildup of toxics which pollute any existing essential resource supply.

As roots survive in a steadily diminishing aerobic layer, and as the anaerobic layer expands toward the soil surface, physical space available for living roots declines. The consequences of having smaller volumes of colonizable space at the surface of a soil means tree roots and their resources are subject to much greater fluctuation in water content, heat loading, and mechanical damage. Drought and heat stress can quickly damage roots in this small shallow layer of oxygenated soil.

Constrained & Stunted

Compaction limits depth and reach of tree root systems leading to greater probability of windthrow and accentuating any structural problems near the stem base / root collar area. Limiting reach of a root system also prevents effective reactions to changes in mechanical loads, and concentrates stress and strain in smaller areas. Micro-site variability for compaction levels and a limited resource base, constrain young and newly planted trees. It requires less soil density (compaction) and crusting impacts for failure to occur in new trees compared with older, established trees.

As resources are limited by soil compaction, and more effort is required to seek and colonize resource volumes, trees are stunted. Disruption of growth regulation produces stunting as auxin / cytokinin ratios shift resource allocations and use. In addition, carbohydrate and protein synthesis rates enter decline cycles interfering with nitrogen and phosphorous uptake, which in-turn disrupts carbohydrate and protein synthesis. The result is a tree with a small living mass, with limited ability to take advantage of any short-term changes in resource availability, and with reduced resistance to other environmental stresses.

Root Injury

The mechanical forces generated in compacting a soil can crush roots, especially roots less than 1/10 inch diameter. Larger root can be abraded and damaged. Rutting can shear-off roots as soil is pushed to new locations. The amount of crushing is dependent on root size and depth, weight of the compacting device, organic material, and depth to the saturated layer (for rutting). Figure 49
.

Life Decline

Soil compaction puts selective pressure against aerobes and favors low oxygen requiring organisms, like *Pythium* and *Phytophthera* root rots, or anaerobes. Destruction of the detritus energy web, coupled with successional changes, assures renovation of soils to pre-compaction conditions is not possible. Management must move forward to new solutions for resource availability and deal with new

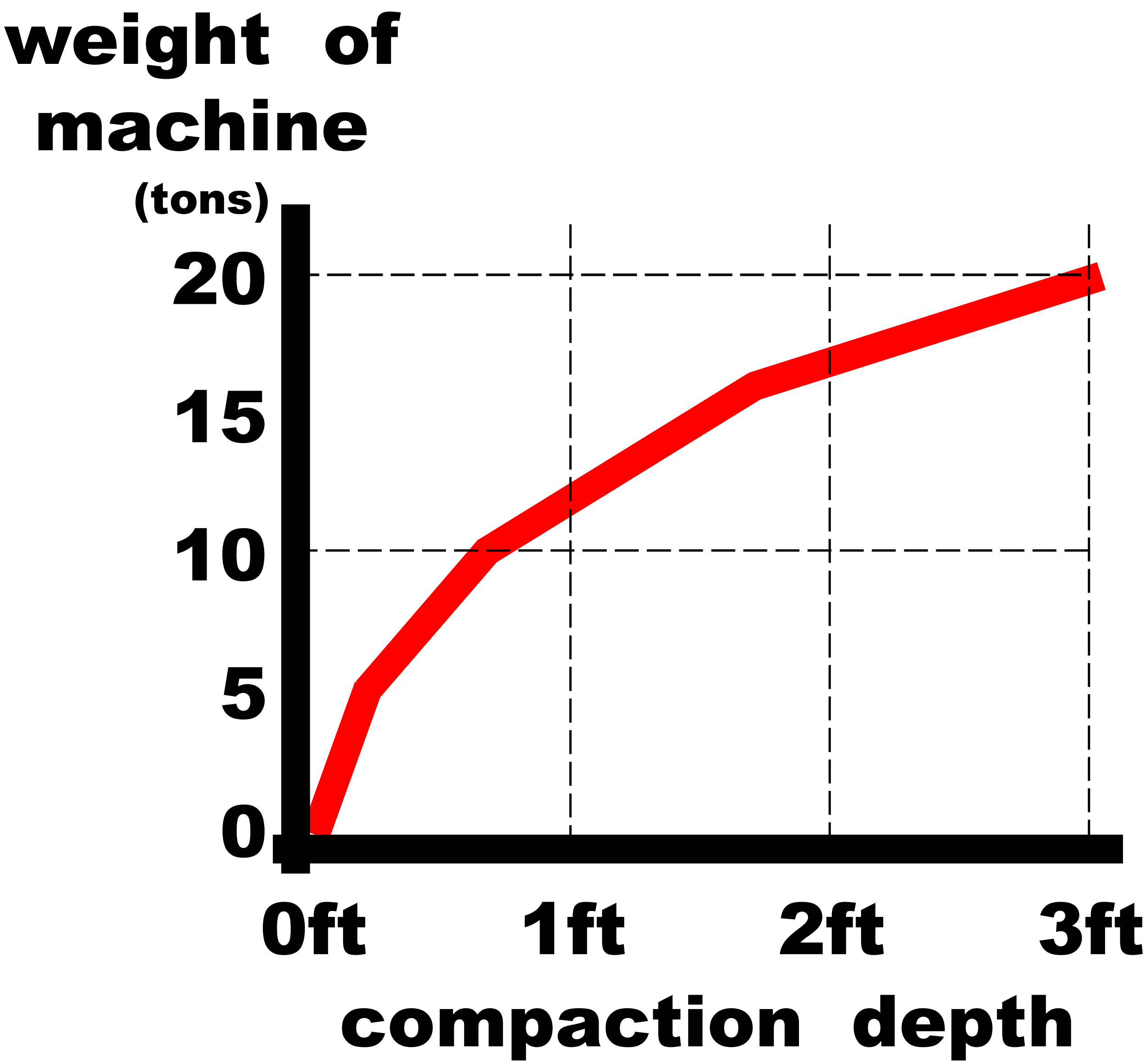

Figure 49: Concentration depth of soil compaction under machines of various weights.
(after Randrup 1999)

patterns of pest management, since returning to the soil microbiology and rhizosphere of pre-compaction is impossible.

Renovation Principles

Tree health care providers and site managers must correct compaction and its limitations on tree growth. Compaction is "forever," being reduced by natural processes at such a slow rate (~1% reduced bulk density per six (6) years) as to be unseen in tree health changes. Compaction must be actively prevented and actively corrected. There are a number of renovation principles to consider when reclaiming part of the ecological integrity of a site, as well as soil and tree health.

Principle 1 -- Past soil compaction should be considered a permanent management constraint. Studies demonstrate after one-half century, compaction still afflicts soils under natural forest conditions. Recovery times for significant compaction is at least three human generations, if no further site impacts occur. Soils do not "come back" from compaction. Soil must be actively renovated.

Principle 2 -- Every soil used by humankind has a representative compacted layer, zone, area, or crust. Changing management may not change the current compacted zone, but may well add an additional compacted zone in a new position. A site is a composite of many compaction events over many years, all needing remediation.

Principle 3 -- Management activities should concentrate on moving forward to increase aeration space and reduce soil strength, rather than trying to recover past ecological history.

Principle 4 -- Estimate soil compaction now as a bench-mark for gauging effectiveness of any treatment. Do not suggest compaction problems exist until confirmed by measurements.

Principle 5 -- Measure compaction using any or all resource availability approximations, like bulk density, penetration force, oxygen diffusion rates, and tree available water. These are the best proxy measures we have to understand soil compaction and its impacts on trees. More careful and direct measures of soil compaction constraints on tree growth are possible but are expensive, time consuming, and difficult to make.

Principle 6 -- Alleviation of soil compaction is part of a good tree and soil health management plan. Any soil renovation is a positive investment in the future.

Principle 7 -- Use extreme caution in water management over and in compacted soils. Compaction provides little margin of error for drainage, aeration, infiltration, and water holding capacity of tree available water. For example, a moist soil area may contain a dry tree, or a wet soil area may contain a root-suffocated tree under compaction.

Principle 8 -- Optimize tools and site renovation processes which have minimal negative tree biology impacts for the greatest soil compaction reduction.

Principle 9 -- Seek assistance of a tree and soil health specialist to avoid tree-illiteracy problems on compacted soils. Always seek to educate clients about compaction. Awareness of the problem is critical to initiation and maintenance of a renovation program.

Renovation Techniques

Once general principles of working with compacted soils are digested, the next requirement in tree health care is to identify general techniques for renovating compacted soils. These recommendations are generic across many situations and soil types. Specific actions must be crafted for specific sites and tree situations.

One of the most important decision points in decompacting soil and facilitating tree root health is setting the treatment objective. The two objectives are: 1) remove enough soil volume from compacted soil to make a significant difference in soil bulk density, fracturing, and soil lightening; or 2) pierce the soil enough to significantly impact gas exchange with the atmosphere and oxygen diffusion. Selecting either a soil volume or oxygen diffusion treatment will depend upon soil texture, water saturation conditions over time, extent of current compaction, and potential compaction in the future.

Technique 1 -- Restrict site access to the soil surface as soon as possible with fences and fines (legal penalties). Try to be the first one on-site and setup anti-compaction protection. Prevention is the best way of minimizing compaction impacts on trees.

Technique 2 -- Defend the ecological "foot print" of a tree rooting area. Select working conditions (dry, dormant season, surface mulch, etc) that minimizes compaction in a tree rooting area. Figure 50. The closer to a tree compaction occurs, the geometrically greater impact of any damage. For example, a 20 inch diameter tree (D=20") has an ecological root print of 80 feet in diameter, a critical root zone of 50 feet in diameter, and a structural root zone of 18 feet in diameter.

Technique 3 -- Carefully design tree growth areas or compartments using "biology-first" design processes rather than the common (and damaging) "aesthetics-first" design processes. Assure well aerated and drained, ecologically viable space is provided, as well as adequate water supply, under the conditions present.

Technique 4 -- Try to soften and distribute any new compaction forces applied by using: 1) temporary coarse, thick organic mulch, plywood or rubber driving pads; 2) designated non-tree rooting areas as material and vehicle storage / parking; and, 3) develope soil moisture content awareness planning. Restrict and minimize, where possible, any vibrational compaction.

Technique 5 -- Restart or improve the detritus energy web in soil, including addition of composted organic matter, living organisms, essential elements in short supply, and water (both supply & drainage). Pursue soil health by changing physical, chemical and biological soil conditions.

Technique 6 -- If tree roots are not present on-site, use deep tilling and/or sub-soiling to fracture and aerate soil before other activities are begun for planting trees.

Technique 7 -- In some locations, especially where soils are containerized or are required to carry light to intermediate loads, consider either amending the soil with large sized, porous, low density solids, or

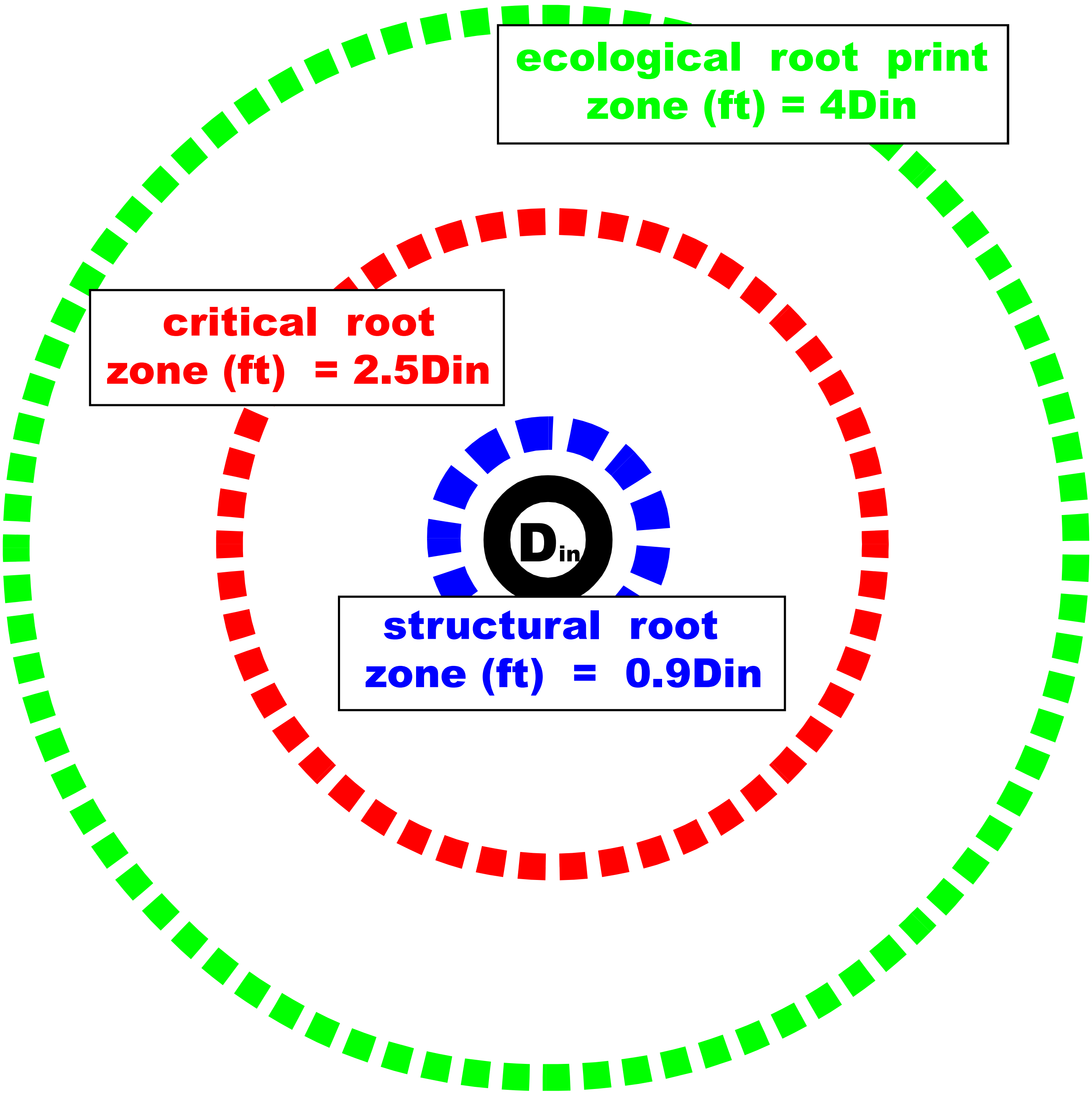

Figure 50: View from above a tree rooting area showing the ecological root print area (ecological root print zone), critical root zone, and structural root zone (root plate) surrounding a tree.

All distance measures are diameters centered on the tree in feet and based upon tree diameter (Din) measured at 4.5 feet above the ground in inches.

replacing the soil with structural / constructed soils. Utilize porus paving materials, soil binding materials, or root aggregation structures, where possible, to avoid further compaction. (See excellent text by Ferguson, 2005.) Structurally bridge-over soils which contain tree roots. Constructed soils and porous pavements are both distinct subject areas not further reviewed here.

Technique 8 -- Use core (not punch) aerators designed for compacted areas which reach 8-14 inches in depth. These are large hydraulic powered core aerators, not shallow surface aerators as used in turf culture. Figure 51 shows two holes excavated into a soil. These holes could have been generated by a punch aerator, core aerator, drill, water gun, or air gun. A punch aerator, and to a lessor extent a water gun, would have generated more compaction and disrupted addition pore space, and are not recommended. There is an aerated soil volume near the soil surface which has always existed to some depth, and two new aerated soil volumes around the excavated holes which have been produced.

Figure 52 is a diagram of an excavated hole. There is both a volume of soil removed and an additional surface area of soil exposed inherent in any hole excavation. Figure 53 presents estimated aeration diameters and radii for different soil textures. Under compaction, aeration is greatly limited by air pore space in clay textured soils while aeration distances in sandy textured soil can be relatively deep, depending upon water saturation levels. The aeration diameter distance is the maximum distance apart holes can be in soil in order to aerate soil volumes in-between. Deep core aeration, to be effective, must have great enough hole density and depth to impact aeration and break through surface compaction.

Technique 9 -- In highly limited areas, vertical mulching can be used to increase ecologically viable space. Vertical mulching is, in essence, deeper and more impactful core aeration as listed in Technigue 8 above. Drill or blow out small diameter vertical holes 12-24 inches deep into a soil. Figure 54 shows a vertical mulching hole field from above. Note this treatment is applied away from the tree stem base at some distance to prevent large root damage. Keep the treatment zone away from the tree base at least 3.5 times tree diameter measured in inches, if not farther, especially in large trees or trees on very shallow soils. Figure 53 lists aeration distances for soils with different textures. Use these values to determine how far apart vertical holes should be placed.

Figure 55 provides the center-to-center distance apart holes should be for different soil textures and for different hole diameters. In the field, there is little real difference in distances within a single soil texture class. Figure 56 provides the estimated amount of additional soil surface area exposed by excavating holes of various sizes and to various depths. Note, each value is how many times greater the new surface area generated from a single hole is larger than the previous surface area of the soil. For example, a 2 inch diameter hole excavated to 20 inches in depth would add 41 times more surface area of soil to a site than the surface area before excavation.

Figure 57 lists the amount of soil volume removed and the amount of soil surface area added by excavating a single hole with a given diameter and depth. For example, a 2 inch diameter hole excavated to a depth of 20 inches would remove 63 cubic inches of soil and expose an additional 129 square inches of soil surface area than before excavation. Figure 58 provides an estimate of how many holes of a given size and depth would be needed to remove one cubic yard of soil. This value can be used to compare this treatment with other treatments and how each impacts soil volume changes. Note it takes tens-of-thousands of small shallow holes to have any significant impact on soil volume aerated. For example, it would take 743 separate holes, two inches in diameter and 20 inches deep, to remove one cubic yard of soil from a site. As usually applied, vertical mulching does not influence much soil volume per treatment.

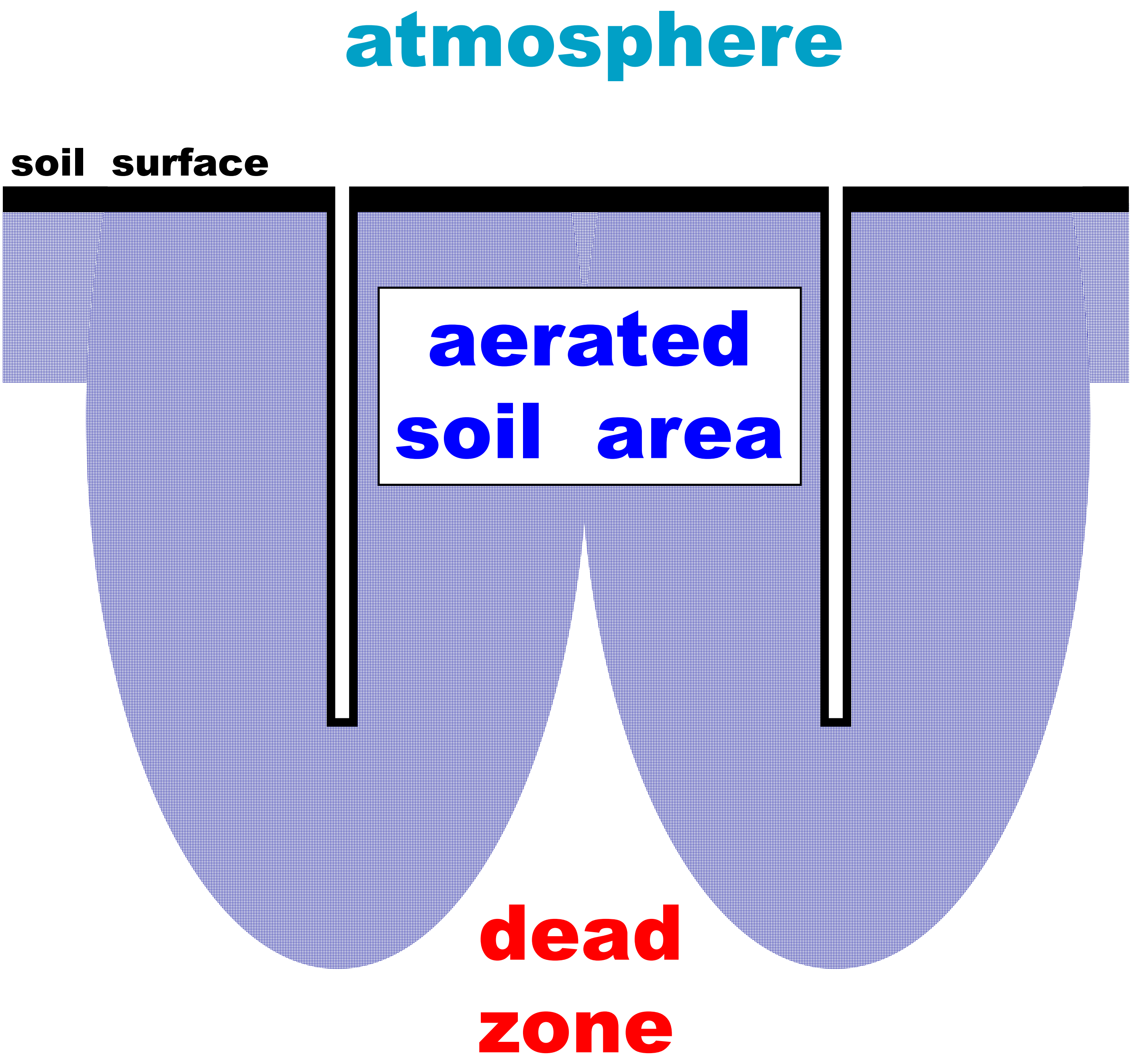

Figure 51: Diagrammatic side view of aerated soil area (shaded) with a compacted soil surface. Newly aerated space is a result of excavating two holes.

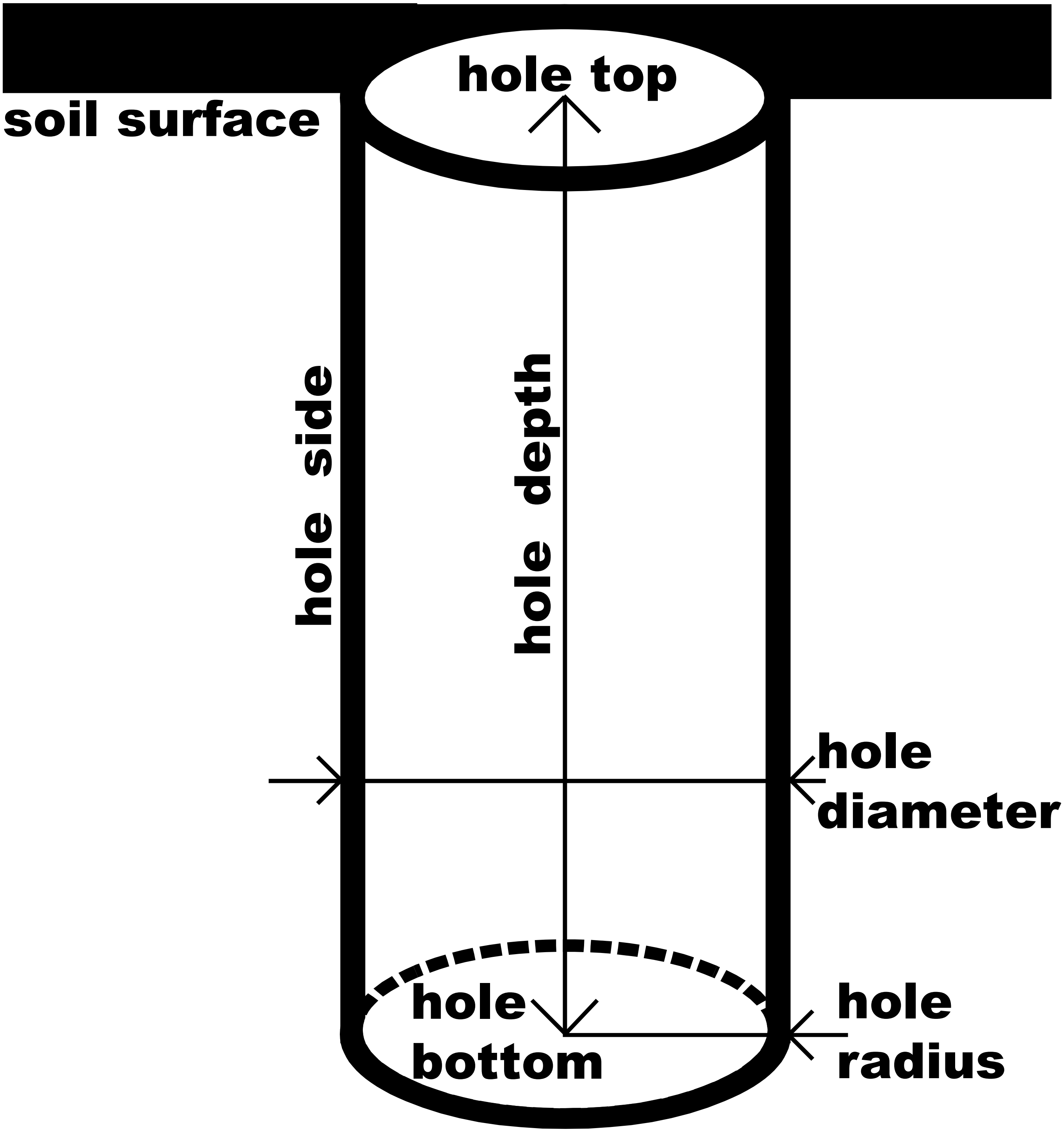

Figure 52: Diagrammatic definition of a round vertical excavated hole in soil. Volume of the hole is a right cylinder volume. Surface area of the hole is a right cylinder surface area minus the area of the hole top.

soil texture	aeration distance (in) diameter	radius
clay	12"	6"
clay loam	16	8
silt loam	16	8
loam	24	2
fine sandy loam	30	15
sandy loam	36	18
fine sand	48	24
sand	48	24

Figure 53: Estmated aeration (oxygen diffusion and flow) diameter and radius (in inches) around an excavated hole within different soil textures not under continuous saturation or continuous air dry conditions. Aeration rates were estimated based upon minimum oxygen diffusion rates needed for tree root health and at a soil temperature of 68°F. Aeration radius is also the depth in soil of aeration from the surface.

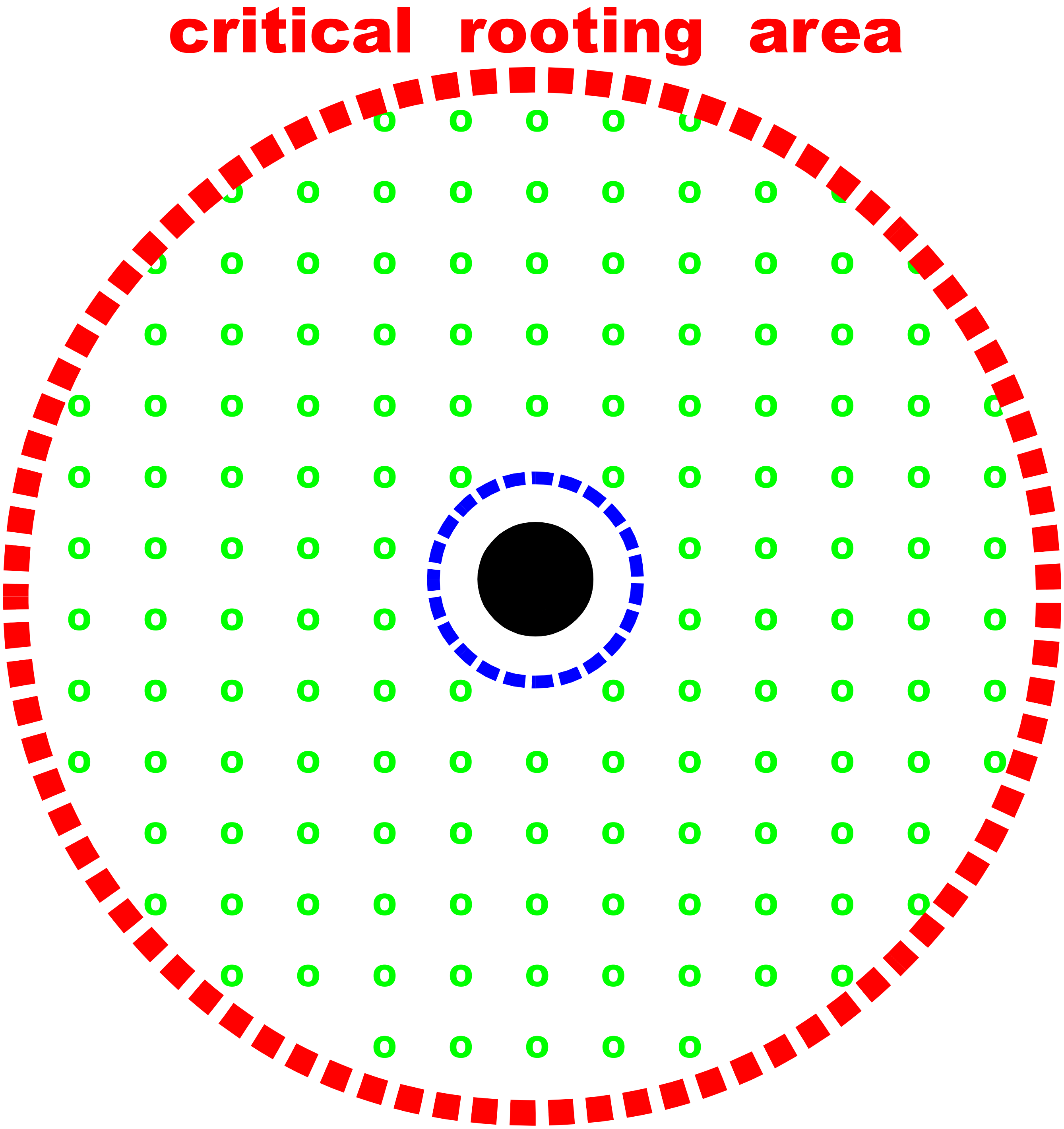

Figure 54: Diagrammatic view from above a vertical mulching field of holes systematically distributed within the critical rooting area of a tree. The distance between hole centers are specified when the treatment is installed. The center black circle represents the tree trunk.

soil texture	hole size in inches 0.5”	1”	1.5”	2”	2.5”	3”	4”
clay	13”	13	14	14	15	15	16
clay loam	17	17	18	18	19	19	20
silt loam	17	17	18	18	19	19	20
loam	25	25	26	26	27	27	28
fine sandy loam	31	31	32	32	33	33	34
sandy loam	37	37	38	38	39	39	40
fine sand	49	49	50	50	51	51	52
sand	49	49	50	50	51	51	52

Figure 55: Distance apart (in inches), center-to-center, excavated holes should be for adequate aeration (oxygen diffusion and flow) supporting tree root health in various soil textures and for various sized holes (diameter inches). Values rounded to next highest whole number.

hole depth (inches)	hole diameter in inches 0.5"	1"	1.5"	2"	2.5"	3"	4"
8"	65X	33	22	17	14	12	9
12"	97	49	33	25	20	17	13
16"	127	65	44	33	27	22	17
20"	161	81	54	41	33	28	21
24"	193	97	65	49	39	33	25
28"	225	113	76	57	46	38	29X
soil surface area removed (in^2)	0.2	0.8	1.8	3.1	4.9	7.1	12.6

table value = { [6.283 X radius X depth] + [3.142 X (radius)^2] } / [3.142 X (radius)^2]

Figure 56: Approximate amount of additional soil surface area exposed by excavating a round vertical hole of a given diameter (in inches) and depth (in inches) into soil. Value shown is the number of times greater the surface area would be increased by excavating a hole versus the existing soil surface area.

hole depth (inches)	diameter of hole in inches 0.5"	1"	1.5"	2"	2.5"	3"	4"
8"	1.6 in^3	6.3	14	25	39	57	101
	13 in^2	26	40	53	68	83	113
12"	2.4	9.4	21	38	59	85	151
	19	39	58	79	99	120	163
16"	3.1	13	28	50	79	113	201
	25	51	77	104	131	158	214
20"	3.9	16	35	63	98	141	251
	32	64	96	129	162	196	264
24"	4.7	19	42	75	118	170	302
	38	76	115	154	193	233	314
28"	5.5	22	50	88	137	198	352
	44	89	134	179	225	271	364

upper table value =
[3.142 X (radius)^2 X depth] = volume in cubic inches
lower table value =
[6.283 X radius X depth] + [3.142 X (radius)^2] = surface area in square feet

Figure 57: Approximate open volume (upper value in cubic inches) and increased surface area of soil (lower value in square inches) exposed by excavating a round vertical hole of a given diameter (in inches) and depth (in inches) into soil.

hole depth (inches)	hole diameter in inches						
	0.5”	1”	1.5”	2”	2.5”	3”	4”
8”	29,717	7,406	3,309	1,859	1,187	826	464
12”	19,769	4,963	2,201	1,238	792	550	309
16”	14,859	3,703	1,649	928	594	413	232
20”	11,872	2,972	1,322	743	475	330	186
24”	9,906	2,482	1,100	620	396	275	155
28”	8,483	2,121	943	530	340	236	133

Figure 58: Number of round vertical holes of a given depth (in inches) and diameter (in inches) needed to remove one (1) cubic yard of soil volume.
1 cubic yard ($yard^3$) volume = 46,656 cubic inches ($inch^3$) volume

Figure 59 lists additional soil volume aerated below the soil surface aeration zone by a single vertical hole 24 inches deep. Note, in more coarsely textured soils, the surface aeration zone descends far enough into soil to make vertical mulching useless for aeration objectives, but can begin to impact soil density. Vertical mulching holes should be backfilled with a non-compressible material, small amounts of composted organic material, and some native soil materials. Assure holes are immediately filled and periodically checked for settling.

A derivation of vertical mulching is the use of compresed air probes. Air probes are inserted at specified intervals into the soil generating a hole field across a site. High pressure air is then used to fracture soil. Some devices require pre-excavation for the probe while others can be driven into and through compacted soil. With some probes, additional materials can be added into the hole and along any fracture lines created in a soil. Materials added could be either liquid or granular, and include fertilizers, organic matter, biologics, and porous solids for holding soil fractures apart. As in vertical mulching, it is the volume of soil impacted which comprise the value of the technique.

Technique 10 -- With large established trees on-site which can not have the soil surface greatly disturbed through sub-soiling to alleviate compaction, radial trenching can be utilized. A trencher, soil saw, or air gun device can be used to excavate radially aligned trenches around a tree. Trenches can be inserted starting at a distance away from a tree of 3.5 times tree diameter in inches (3.5D). Primary radial trenches (1^o) can be placed close together for aeration diffusion objectives, based upon aeration radii in soil of different textures, or can be placed farther apart and made wider in size to disturb and remove more soil volume.

Figure 60 gives the number of primary trenches required for trees of various sizes and for distances between initiation points of primary trenches. For example, with a tree diameter of 10 inches, a multiplier from this figure of 0.47, and an initial distance apart of 4 feet (i.e. 0.47 X 10), there should be five (5) primary radial trenches installed (value rounded to nearest whole number).

As a further example, if soil compaction and tree root health warrants increasing aeration (oxygen diffusion and flow), the number of primary trenches can be determined by multiplying tree diameter in inches by 0.94. These primary trenches would be placed with starting points every two feet around the tree at a distance of 3.5 times the diameter of the tree in inches away from the tree.

Alternatively, if general soil volume disturbance and removal is sought, using a factor of 0.31 times tree diameter would determine the number of primary trenches to install every 6 feet along a circumference of a circle whose radius is 3.5 times tree diameter. Note the minimum number of primary trenches is three for any small tree.

Additional trenches (secondary = 2^o; tertiary = 3^o) will need to be placed between primary radial trenches at set distances from the tree. Figure 61. Replace soil removed from trenches with non-compressible materials, small amounts of composted organic material, and some native soil. French drain materials could also be installed. Assure trenches are immediately filled and checked periodically for settling.

For example, for a 9 inch diameter tree (D=9”), four 1^o trenches begin at 31.5 inches or 2.6 feet [3.5D] away from the tree with four 2^o trenches begining at 63 inches or 5.3 feet [7D] away from the tree and eight 3^o trenches begin at 126 inches or 10.5 feet [14D] away from the tree, all running out to 234 inches or 19.5 feet [26D] or beyond.

Figure 62 shows the estimated volume in cubic inches and the surface area in square inches generated along each linear foot of trench for a given width and depth. For example, a trench excavated 4 inches wide and 3 feet deep would generate 1,728 cubic inches of soil volume removed and

soil texture	hole diameter in inches 0.5"	1"	1.5"	2"	2.5"	3"	4"
clay	3.5in³	14	32	57	88	127	226
clay loam	3.1	13	28	50	79	113	201
silt loam	3.1	13	28	50	79	113	201
loam	2.4	9.4	21	38	59	85	151
fine sandy loam	1.8	7.1	16	28	44	64	113
sandy loam	1.2	4.7	11	19	29	42	75
fine sand	0	0	0	0	0	0	0
sand	0	0	0	0	0	0	0

aerated soil volume in^3 =

(hole radius)^2 X [(hole depth - diffusion radius) X 3.142]

Figure 59: Additional soil volume (in cubic inches) aerated below the surface aeration zone by a vertical hole of a given diameter by soil texture class. Depth of hole is set at 24 inches.

multiplier value for number of primary radial trenches needed	initial (closest) distance between primary trenches	reason for & type of trench
0.94 X tree diameter in.	2 ft	diffusion / texture thin trenches
0.63 X tree diameter in.	3 ft	diffusion / texture thin trenches
0.47 X tree diameter in.	4 ft	diffusion / texture thin trenches; soil volume wide trenches
0.31 X tree diameter in.	6 ft	soil volume wide trenches
0.24 X tree diameter in.	8 ft	soil volume wide trenches
0.19 X tree diameter in.	10 ft	soil volume wide trenches
0.16 X tree diameter in.	12 ft	soil volume wide trenches

NOTES:

Concentrate on either volume of soil removed or diffusion facilitation.
Minimum approachable distance to tree is 3.5 x D.
Minimum number of trenches is 3.
Excavate trenches out as far as 26 x D away from tree if possible.

Figure 60: Number of primary trenches required radiating from around base of a tree either for increasing effective oxygen diffusion and flow in different soil textures, or for removal of specific target soil volumes. Table values are multipliers of tree diameter (in inches) yielding the number of primary trenches needed.

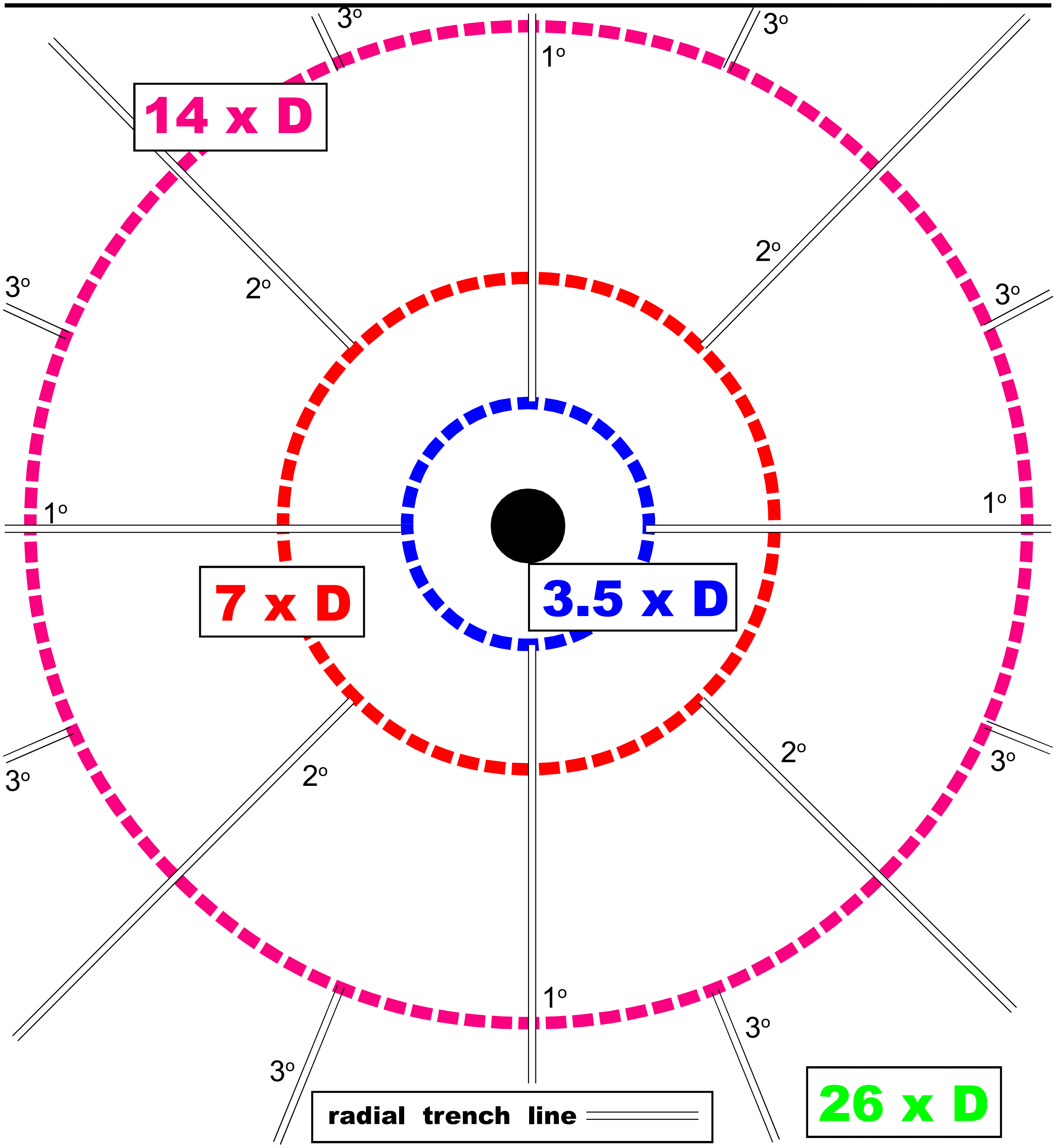

Figure 61: View from above a tree rooting area showing distances away from a tree where primary (1°), secondary (2°), and tertiary (3°) radial trenches begin.

All distance measures are multipliers of tree diameter (D in inches at 4.5 feet above the ground) yielding the distance in inches away from tree.

NOTE: These values are per foot of trench.

trench depth inches (ft)	width of trench in inches 1"	2"	4"	6"	8"	10"
12"(1')	144in³ 324in²	288 360	576 432	864 504	1,152 576	1,440 648
24"(2')	288 636	576 696	1,152 816	1,728 936	2,304 1,056	2,880 1,176
36"(3')	432 948	864 1,032	1,728 1,200	2,592 1,368	3,456 1,536	4,320 1,704
48"(4')	576 1,260	1,152 1,368	2,304 1,584	3,456 1,800	4,608 2,016	5,760 2,232

upper volume value = [width X depth X 12]
lower surface area value =
[(2 X depth X width) + (12 X width) + (24 X depth)]

Figure 62: Approximate volume (upper value in cubic inches) and increased surface area of soil (lower value in square inches) exposed for each linear foot by trenching at a given trench depth (in inches & feet) and trench width (in inches).

replaced, and 1,200 square inches of soil surface area exposed, per linear foot of trench. The amount of soil influenced by radial trenching is much greater than in vertical mulchng.

Technique 11 -- Use soft excavation techniques like air guns to cultivate (stir-up) soil in selected areas under a tree over several months or growing seasons (i.e. Bartlett renovation technique). The soil area for treatment can be divided into subdivisions and each segment eventually treated down to 6-12 inches of depth. Soil moisture content and level of compaction is critical for effective cultivation.

Figure 63 shows the critical rooting area of a tree divided into eight equal areas with every other area treated this year and the remaining areas treated the following year for a 50% area per year treatment process. Figure 64 shows the critical rooting area of a tree from above divided into 12 equal areas with every third area treated this year and each neighboring area to the left (counterclockwise in this example) treated in year two, and the remaining areas treated in year three, for a 33% area per year treatment process. Immediately after cultivation, watering is essential.

Figure 65 provides an estimate of how many square feet of the pretreatment soil surface area would be impacted in any one year for various sized trees. This figure lists 100%, 50%, 33%, and 25% treatment intensity. For example, a 40 inch diameter tree would have 3,927 square feet of soil surface beneath its canopy treated each year for two years (50% of the area treated per year.)

Figure 66 shows the volume of soil decompacted beneath every square foot of a treatment area for a variety of soil depths. For example, if the decompaction treatment depth was 8 inches, then 1,152 cubic inches (0.67 cubic feet) of soil is influenced for every square foot treated. Deep decompaction treatments using soft excavation techniques become progressively more difficult and variable in application below 8 inches. Composted organic matter and other soil and growth materials can be incorporated during this operation. Note this technique greatly exceeds the soil impact volume of radial trenching.

Technique 12 -- As seen is the previuos techniques, increasing depth of aeration and volume of soil impacted are key elements in successful compaction renovation. For extremely compacted soils where air gun decompaction is inadequate and complete soil removal is not warranted, a more invasive process can be used. Micro-slits or mini-trenches can be excavated deeply (>24 inches) in a thin radial line away from the trunk base with a soil saw or thin-kerf trencher (mini-trencher) in large treatment fields around a tree (i.e. Coder renovation technique).

Figure 67 shows micro-slits installed in four wedge shaped areas around a tree. These treatment segements or wedges do not begin until the distance from the tree is 3.5 times tree diameter in inches (3.5D). This technique is designed for extreme compaction and does have potential to significantly increase root damage and tree structural failures. The trade-off between biology and biomechanics must be evaluated. Micro-slits begin at 3.5D distance and slit number are increased at 6D and 10D distances away from a tree. The micro-slits should be installed out to at least a distance of 15D from a tree.

Micro-slits must be inserted deep into soil for best effect and placed close together. Figure 68. For example, if a tree diameter is 35 inches and is growing in heavily compacted clay soil, the micro-slit number per treatment segement is “5+4+6.” The first number (5) denotes five micro-slits are started at the 3.5D distance and run radially out to at least the 15D distance. At the 6D distance, four (4) new micro-slits are started and ran out to at least the 15D distance. At the 10D distance,

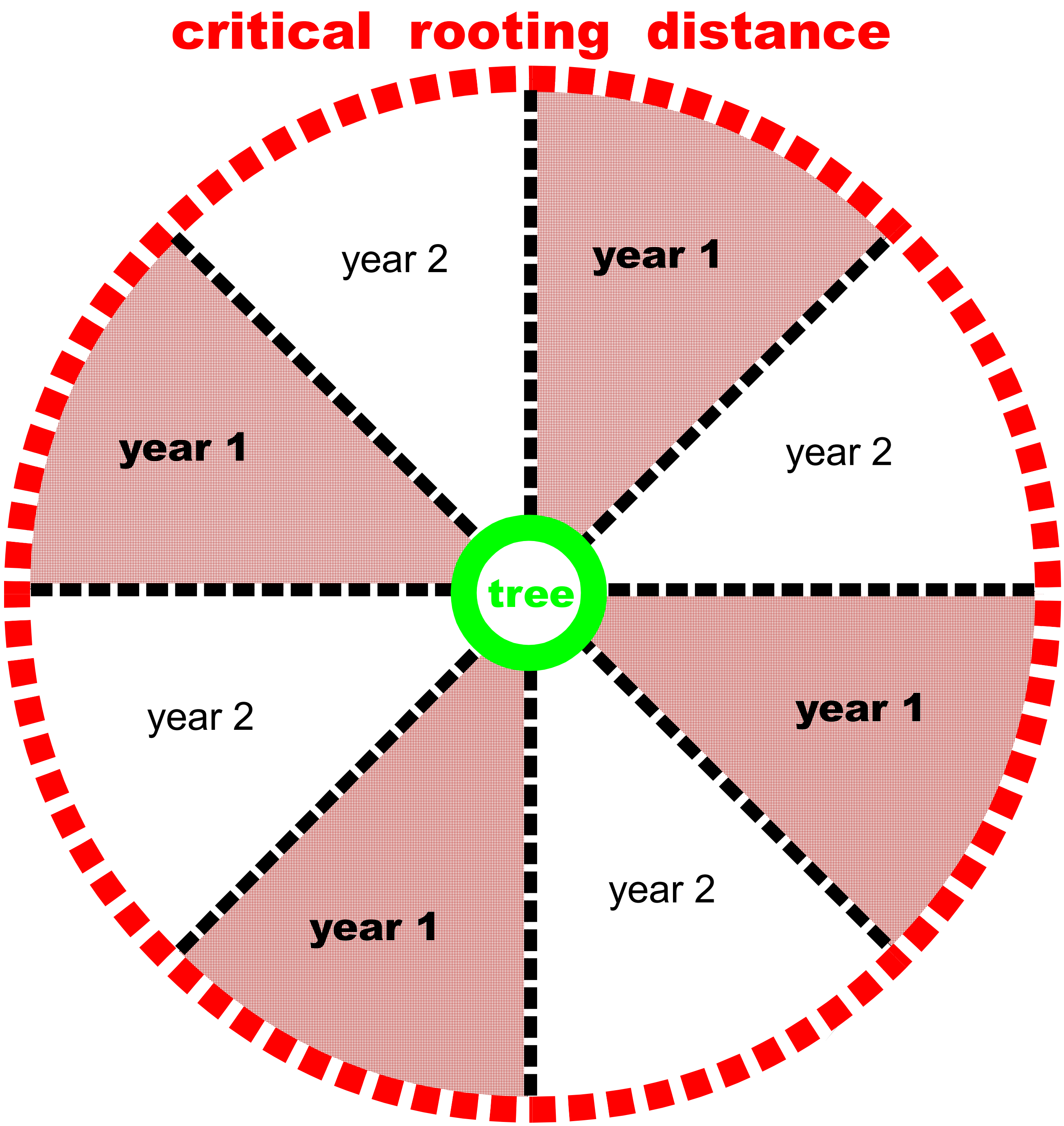

Figure 63: Radial wedges of equal area representing soil around base of a tree for decompaction treatment over two years (one-half of critical rooting area decompacted per year).

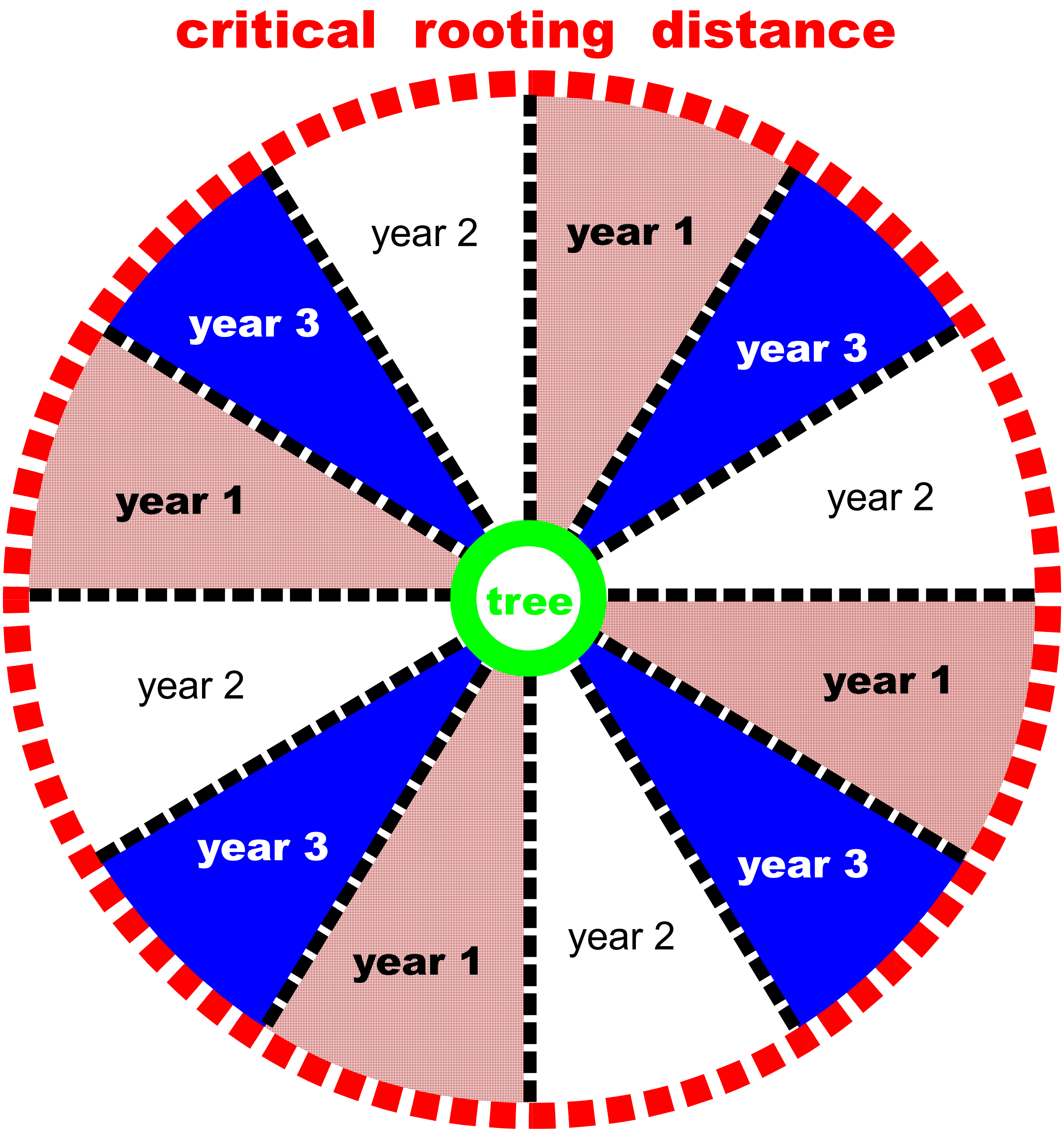

Figure 64: Radial wedges of equal area representing soil around the base of a tree for decompaction treatment over three years (one-third of critical rooting area decompacted per year in a counter-clockwise progression).

tree diameter (inches)	critical rooting area decompacted per treatement (ft^2) 100%	50%	33%	25%
10"	491 ft^2	246	162	123
15	1,105	553	365	276
20	1,964	982	648	491
25	3,068	1,534	1,012	767
30	4,418	2,209	1,458	1,105
35	6,013	3,007	1,984	1,503
40	7,854	3,927	2,592	1,964
45	9,940	4,970	3,280	2,485
50	12,272	6,136	4,050	3,068
55	14,849	7,425	4,900	3,712
60	17,671	8,836	5,831	4,418
65	20,739	10,370	6,844	5,185
70	24,053	12,027	7,938	6,013
75	27,611	13,806	9,112	6,903
80	31,416	15,708	10,367	7,854

$[(\text{diameter} \times 2.5)^2 \times 0.785] \times \text{treatment percent} = \text{table value}$

Figure 65: Surface area of soil (in square feet) within the critical rooting area of a tree decompacted in any one year or treatment.

depth of decompaction treatment (in)	volume below one (1) square foot of soil surface cubic inches	cubic feet
2”	288 in^3	0.17 ft^3
4	576	0.33
6	864	0.50
8	1,152	0.67
10	1,440	0.83
12	1,728	1.00
14	2,016	1.17
16	2,304	1.33
18	2,592	1.50
20	2,880	1.67
22	3,168	1.83
24	3,456	2.00
26	3,744	2.17
28	4,032	2.33

table value in cubic inches = depth X 144
table value in cubic feet = cubic inch value / 1,728

Figure 66: Volume (in cubic inches & cubic feet) of soil decompacted below each square foot of soil surface for different soil treatment depths (in inches).

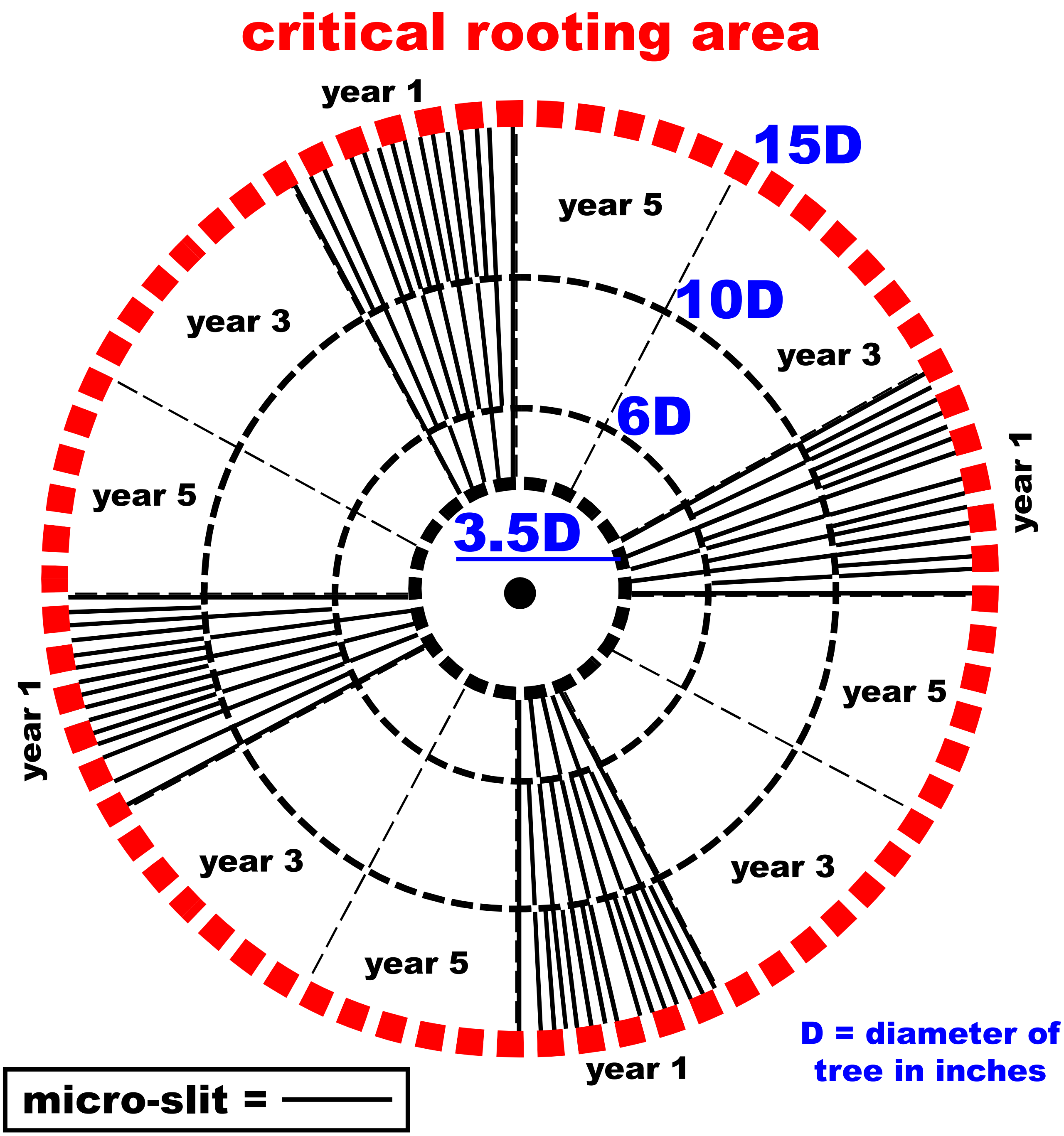

Figure 67: View from above of micro-slit fields arranged in radial patterns around a tree. Only one-third of the critical rooting area is treated every other year.
This example shows a 35-inch diameter tree in the center growing in compacted clay soil surrounded by micro-slit fields in the pattern 5+4+6.

soil texture

tree diameter	clay	clay loam	silt loam	loam	fine sandy loam	sandy loam	fine sand	sand
5 in	0+1+1	0+1+0	0+1+0	0+0+1	0+0+0	0+0+0	0+0+0	0+0+0
10	1+1+2	1+1+1	1+1+1	0+1+1	0+1+1	0+0+1	0+0+1	0+0+1
15	2+2+2	1+2+2	1+2+2	1+1+1	1+1+1	0+1+1	0+1+1	0+1+1
20	3+2+3	2+2+2	2+2+2	1+1+2	1+1+1	1+1+1	0+1+1	0+1+1
25	3+3+5	3+2+3	3+2+3	2+1+2	1+1+2	1+1+1	1+1+1	1+1+1
30	4+4+5	3+3+3	3+3+3	2+2+2	1+2+2	1+1+2	1+1+1	1+1+1
35	5+4+6	4+3+4	4+3+4	2+2+3	2+2+2	1+2+2	1+1+1	1+1+1
40	6+4+7	4+4+5	4+4+5	3+2+3	2+2+3	2+2+2	1+1+2	1+1+2
45	7+4+8	5+4+5	5+4+5	3+3+3	2+2+3	2+2+2	1+2+2	1+2+2
50	7+6+8	5+4+7	5+4+7	3+3+5	3+2+3	2+2+3	2+2+2	2+2+2
55	8+6+10	6+4+8	6+4+8	4+3+5	3+2+4	2+2+4	2+2+2	2+2+2
60	9+6+11	7+4+8	7+4+8	4+4+5	3+3+4	3+2+4	2+2+2	2+2+2
65	10+7+11	7+5+9	7+5+9	5+4+5	4+3+4	3+2+4	2+2+3	2+2+3
70	10+8+12	8+5+10	8+5+10	5+4+6	4+3+5	3+3+4	2+2+3	2+2+3
75	11+8+13	8+6+10	8+6+10	5+4+7	4+4+5	3+3+5	3+2+3	3+2+3

3.5D # = (0.153D) / diffusion value. 6D # = (0.262D) / diffusion value.
10D # = (0.436D) / diffusion value.

Figure 68: Number of radial micro-slits in each segment wedge (one of four wedges installed) within critical rooting area of a tree of a given diameter (in inches). First number is micro-slits per segment between 3.5 times tree diameter inches (3.5D) and 15 times tree diameter inches (15D) away from a tree. Second number is additional micro-slits added beyond 6D radial distance per segment. Third number is additional micro-slits added beyond 10D radial distance per segment. Micro-slits should run out to at least 15D radial distance, if not beyond.

another six (6) micro-slits are started and ran out to at least the 15D distance.

For each soil texture (based upon oxygen diffusion and flow level), and for each tree diameter, three numeric values are provided giving the number of micro-slits to install and where each should be started. It is not critical the micro-slits are perfectly aligned, spaced, or even straight. It is the soil volume impact which is critical. Note, the value of this technique is concentrated in the finer textured soils which are heavily compacted.

Only one-third of a tree's critical rooting area should be treated in every other year. No soil distrubance should occur closer than 3.5 times the tree diameter in inches (3.5D) from the tree tunk. Figure 69 provides the surface area of soil impacted by this technique. Figure 66 provides the volume of soil impacted for various treatment depths for each square foot of surface area. Micro-slits can be filled by raking in non-compressable materials, some composted organic material, and some native soil.

Additional tree growth and soil health materials can be added to the soil surface and raked in. Watering should be completed immediately after treatment. In heavily compacted soils which are dry, thin-kerf micro-trenchers and soil saws will usually provide quicker and more effective treament than soft excavation methods.

Figure 70 provides a general summary of the relative effectiveness of the decompaction techniques previously listed here based upon site soil volume manipulated and disrupted, and the amount of tree roots damaged when the technique is applied.

Other Techniques -- Other methods for decompacting sites are being developed and tested. Complete soil and tree replacement may be realities for some extremely damaged and growth constraining sites. Artificial soil support structures may also be of value.

tree diameter (inches)	individual segment / wedge surface area (ft^2)	combined (all 4) segments / wedges surface area (ft^2)
5	9.7 ft^2	38.7 ft^2
10	38.7	155
15	87	348
20	155	619
25	242	967
30	348	1,392
35	474	1,895
40	619	2,475
45	783	3,133
50	967	3,867
55	1,170	4,680
60	1,392	5,569
65	1,634	6,536
70	1,895	7,580
75	2,175	8,702

table value of individual segment =
$\{ [3.142 \times (\text{tree diameter} \times 1.25)^2] - [3.142 \times (\text{tree diameter} \times 0.292)^2] \} / 12.$
table value of all combined segments = individual segment value X 4.

Figure 69: Treatment surface areas (in square feet) per treatment for micro-slit technique.
Second column lists area of single segment / wedge between 3.5D (3.5 times tree diameter) & 15D (15 times tree diameter). Third column lists area of all treated segments / wedges under one tree in a single year.

decompaction technique	relative site impact	first year root damage
vertical mulch	11%	5%
radial trench	20%	20%
1/3 root area air cultivation	33%	10%
1/2 root area air cultivation	50%	15%
micro-slit (heavy compaction only)	33%	33%
complete soil removal	100%	100%

Figure 70: Relative effectiveness of decompaction techniques based upon site volume disrupted and tree roots damaged when applied.

Conclusions

Soil compaction is a hidden stressor which steals health and sustainability from soil and tree systems.

Causes of compaction are legion and solutions limited.

Without creative actions regarding sustainable greening of inter-infrastructural spaces in our communities, we will spend most of our budgets and careers treating compaction symptoms and replacing trees.

Understanding the hideous scourge of soil compaction is essential to better, enlightened, and corrective tree health management.

Citation:

Coder, Kim D. 2024. Trees & Soil Compaction Stress: A Workbook of Symptoms, Measures & Treatments. University of Georgia, Warnell School of Forestry & Natural Resources Outreach Manual WSFNR-24-3C. Pp.99.

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Appendix 1: Compaction Tolerant Trees

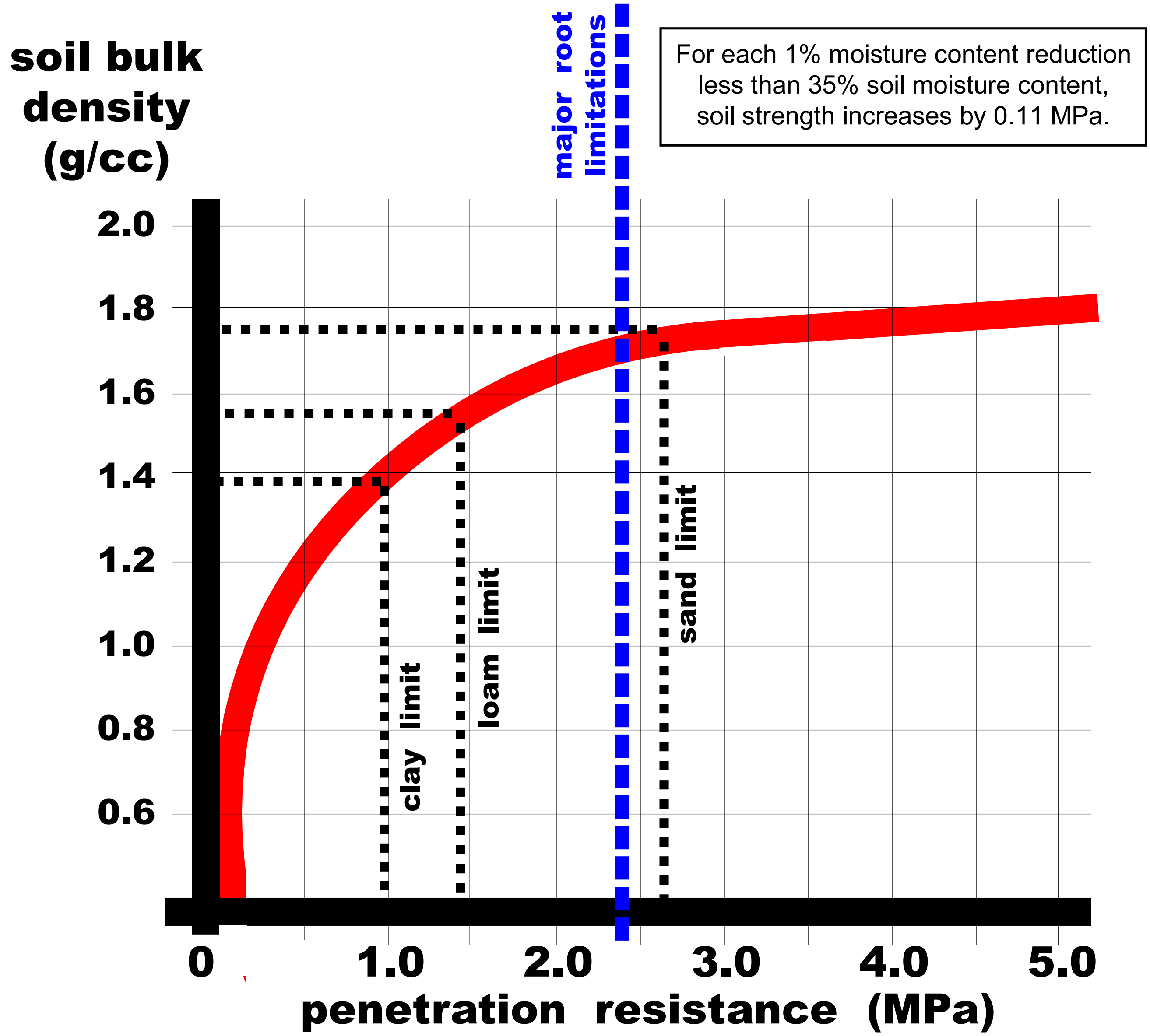
Soil compaction is a complex set of physical, chemical, and biological constraints on tree growth. Principle components leading to limited growth are the loss of aeration pore space, poor gas exchange with the atmosphere, lack of tree available water, and mechanical impedance of root growth. There are significant genetic differences between tree species for tolerating various levels of soil compaction.

This is a select list of compaction tolerant trees. Tolerant species were selected for their effectiveness in reacting to mechanical damage quickly, in surviving anaerobic soil conditions, and in adjusting their root systems to new conditions. This is not a comprehensive list and is only provided to show average species examples. Chronic and severe compaction will kill any tree. Some species, varieties, and individuals may tolerate various compacted soil conditions better than others.

scientific name	common name
Acer negundo	boxelder
Acer rubrum	red maple
Acer saccharinum	silver maple
Alnus spp.	alders
Betula nigra	river birch
Carya aquatica	water hickory
Carya illinoensis	pecan
Carya laciniosa	shellbark hickory
Catalpa spp.	catalpa
Celtis laevigata	sugarberry
Celtis occidentalis	hackberry
Cephalanthus occidentalis	button-bush
Cercis canadensis	redbud
Chamaecyparis thyides	Atlantic whitecedar
Cliftonia monophylla	buckwheat tree
Crataegus spp.	hawthorns
Diospyros virginiana	persimmon
Fraxinus spp.	ash
Gleditsia spp.	water / honeylocust
Ilex spp.	holly
Juglans nigra	black walnut
Juniperus spp.	junipers / redcedar
Leitneria floridana	corkwood
Lindera benzoin	spicebush
Liquidambar styraciflua	sweetgum
Magnolia virginiana	sweetbay
Maclura pomifera	Osage-orange
Nyssa spp.	tupelo / blackgum

scientific name	common name
Persea borbonia	redbay
Pinus elliottii	slash pine
Pinus glabra	spruce pine
Pinus serotina	pond pine
Pinus taeda	loblolly pine
Planera aquatica	planer-tree
Platanus spp.	sycamore / planetree
Populus spp.	cottonwood / aspen
Pyrus calleryana	callery pear
Quercus bicolor	swamp white oak
Quercus falcata	Southern red oak
Quercus imbricaria	shingle oak
Quercus laurifolia	laurel oak
Quercus lyrata	overcup oak
Quercus macrocarpa	bur oak
Quercus michauxii	swamp chestnut oak
Quercus nigra	water oak
Quercus nuttallii	Nuttall oak
Quercus palustris	pin oak
Quercus phellos	willow oak
Quercus rubra	red oak
Quercus shumardii	Shumard oak
Robinia pseudoacacia	black locust
Salix spp.	willows
Taxodium spp.	bald / pondcypress
Thuja occidentalis	arborvitae
Ulmus spp.	elms
Viburnum spp.	viburnum

Appendix 2: Field Data Sheet



COMPACTION FIELD SHEET

soil samples

1 ____________ # 6 ____________

2 ____________ # 7 ____________

3 ____________ # 8 ____________

4 ____________ # 9 ____________

5 ____________ #10 ____________

average penetration resistance

____________ **MPa**

estimated bulk density value = ____________ **g/cc**

estimated tree root growth reduction = ____________ **%**