Soil Compaction & Trees: Causes, Symptoms & Effects

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Introduction

The 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 changing resources quantities and qualities, as well as the physical space available. Soil compaction is a major tree-limiting feature of community forest managers and arborists.

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 that support them are built, soil compaction will be present. There are few soil areas without some form or extent of soil compaction. Soil compaction is a fact of life for trees and tree managers. Unfortunately, prevention and correction procedures are not readily used nor recognized for their value.

This paper is a summary of soil compaction processes and tree growth effects. In addition, some general renovation principles are proposed. Understanding how soil compaction occurs, developing more accurate and precise definitions of soil compaction effects, and recognizing tree growth effects stemming from compaction problems will be the primary emphasis here. This paper will concentrate entirely on the negative growth constraints of compaction. Figure 1.

Infrastructure Ecology

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

Living systems which remain 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 the resource attributes around infrastructures are: many humans and machines functioning as sources for 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 and ecologically active surfaces.

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As infrastructures requirements increase and generate more ecological impacts, the 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, gas exchange, mechanical impedance, and pore space alterations. Soil compaction is a primary measurable feature of the ecological damage with which we are surrounded.

Defining Soil Compaction

Ideal Soil Features – Soil resources are always changing. Pore space, water and gas contents, and the electron exchange environment are dynamically changing in a soil every moment. Chemical, biological and physical soil features are always under change. Within this continuing changing environment, tree roots must develop growth and survival solutions.

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. Within ideal soils, structural units and specific horizons develop. Because an ideal soil does not exist around infrastructures, tree managers must work with soils which are fill-derived, trenched, cut, compacted, polluted, excavated, unstructured, crusted, and poorly developed.

Pore Spaces -- Pore space exists around: individual particles (texture units) such as sand, silt, and clay; individual structural units (soil aggregates); and, gaps, cracks, and the interfaces of infrastructure and soils. There are a series of trade-offs across pore spaces. 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, and so have large water holding capacity but poor aeration. Soils dominated by small soil pores have more total pore space than soils dominated by large pores. For healthy soils, 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 2.

There are three primary forms of pore spaces in a soil: aeration pores filled with air at or below field capacity; and, capillary pores filled with water. Figure 3 provides semantic and size definitions. Capillary pores are further divided among two size subgroups: tree-available water-filled pores; and, tree-unavailable water-filled pores. The tree-unavailable water resides in the smallest soil pores where the tree can not exert enough force through transpiration to remove the pore water. Water is being held so tightly that the tree is unable to pull water into the roots. Figure 4.

Other Attributes -- Along with pore space volumes, there are three additional attributes of soils which must be appreciated. The first is resource changes with soil depth. With increasing soil depth there is a natural increase in CO2 concentrations and a decrease in O2 concentrations. The balance between these two gases change with water content and biological activity. The soil gas atmosphere directly impacts tree root growth.

A second attribute critical to soil and tree health is organic matter. Organic matter, as it decays, provides cation and anion exchange capacity, water hold capacity, mineralized essential elements, a substrate and fuel for the detritus food web, and pore space. Organic matter in natural soil systems is deposited on the surface as plant litter or near the soil surface as root breakdown / turnover. The decomposing materials then move downward through the soil and pass the absorbing roots.

A third soil attribute critical to tree root growth is a developed structure. Structural units, or soil aggregates, are the next order of particle yielding 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, and/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 space derived from structural aggregate development.

Compaction Definition(s)

To properly discuss soil compaction as seen in the field which limits and damages tree health, a clearer definition is needed regarding soil compaction. A more precise and accurate definition 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. My composite "compaction" concept will include soil compression, soil compaction, and soil consolidation.

Compression -- The process which damages soil around infrastructures called compaction starts with soil compressibility or loss of soil volume. Soil compression leads to a loss of total pore space and aeration pore space, and a 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 under wet conditions.

Compaction -- The next process soil undergoes is true compaction. Compaction is the translocation and resorting of textural components in the soil (sand, silt, and clay particles), destruction of soil aggregates, and collapse of aeration pores. Compaction is facilitated by high moisture contents.

Consolidation -- The third primary component of soil compaction is consolidation. Consolidation is the deformation of the soil destroying any pore space and structure, and water is squeezed from the soil matrix. This process leads to increased internal bonding and soil strength as more particle to particle contacts are made and pore space is eliminated.

The three components of the generic term "soil compaction" listed above do not necessarily occur in order, or on any given soil. A general summary of compaction as applied to tree and soil health problems would be a soil which has: loss of soil aggregates; destroyed aeration pore spaces; crushed or collapsed pore spaces; and, undergone extensive resorting and packing of soil particles.

The depth to which a soil is compacted is determined by the compacting agent or process. Every type of management which requires soil contact has a characteristic compaction zone / layer either at the surface or at some given depth below the surface. Cultivation or management pans or layers form from soil cultivation, packing of soil fills or lifts, and various types of traffic patterns. New compaction requirements may be developed over the top of past compaction problems.

Additional Components – In addition to the "3Cs" of compaction listed above (compression, compaction, consolidation), generic compaction problems can often also include crusting, puddling, and rutting. These latter components represent the extent and depth of a damaged top surface layer of the soil or a top seal on a soil column. In addition to compaction, these components can generate soil conditions difficult for tree health maintenance and for effective remediation. Crusting, puddling and rutting generate soil and tree damage similar to applying a plastic sheet to the soil surface.

Crusting is the dislocation and packing of fine particles and organic matter on the soil surface. In addition, natural products and pollutants can be associated with the surface making a hydrophobic surface, and preventing water and oxygen infiltration. Primary causes of crusting is the impact of rain drops on open soil surfaces, irrigation impacts, and animal and pedestrian traffic. Small local impacts on the soil surface help facilitate crusting.

Puddling and rutting develop a dense, thick crust or cap on the soil surface. The primary mechanism of damage is from destruction of soil aggregates and aeration pores through particle movements caused by hydraulic pressure. 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.

Measuring Compaction

Tree health management is limited in how easily and effectively we can measure absolute and relative soil compaction. The primary resources critical to tree growth in the soil are O2 availability, gas exchange with the atmosphere or circulation, and soil strength values. Because of the difficulty in simultaneously measuring these items quickly in the field, we have developed a number of approximate measures for soil compaction. The two measure most commonly used are bulk density and soil penetration force. Unfortunately both are soil moisture content and organic matter dependent. Additionally, bulk density and soil penetration force are not measures of the same features in the soil, and so, are not closely correlated.

Bulk density, when collected under the right soil conditions in the right soils can provide a great deal of information. Bulk density is the weight of the soil per unit volume (usually in g/cc). As bulk density increases, total pore space declines and aeration pore space is destroyed. In one soil for example, a 20% increase in bulk density initiated a 68% loss of aeration pores and an increase in 7% capillary pore space. Bulk density as a measure of soil compaction rapidly increases with the first few impacts on the soil surfaces 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 site. In other words, it is not years of traffic, but the first 4 trips that does the majority of compaction.

Table 1 provides bulk densities for selected construction materials and associated pore space. Some compacted soils have higher measured bulk densities than some common construction materials. It is possible to find soils around infrastructures which are more dense than the wall of the building they adjoin. Table 2 provides the formula calculation and table of values for the amount of pore space in a soil with a given bulk density.

Tree Root Survival & Growth

Roots utilize space in the soil. The more space controlled the more potential resources controlled. The volume of soil space controlled by tree roots is directly related to tree health. The resources required are water, oxygen, physical space for growth processes, and open soil surface area for replenishment of essential resources. Tree roots occupy the spaces and gaps around, under, and between infrastructures. In heavily compacted sites, roots will be concentrated around the edges of infrastructures and filling any moist air space. The soil matrix is only a significant concern for essential elements, surfaces holding biological cooperators, and frictional and inertial forces for structural integrity. Figure 5.

Tree roots and the soil surrounding them are an ecological composite of living, once-living, and abiotic features facilitating life. Compaction initiates many negative impacts in the soil including: decreases the volume of ecologically active space available; tree rootable space is decreased and made more shallow; the detritus food web, the ecological engine responsible for powering a healthy soil, is disrupted and modified; the diversity of living things decline, beneficial associates are eliminated, and a few ecological niche generalists succeed; and, pests favored by the new conditions (i.e. Pythium &

Phytophera) consume organisms and roots not able to defend themselves. Tree roots become more prone to damage and attack at a time when sensor, defense, growth regulation, and carbon allocation processes are functioning at reduced levels.

Root Requirements

Growth in trees may not be a positive increase in living mass, but does represent expansion of tissues into new spaces. For roots, the tips elongate and the tissues thicken in diameter. Lateral roots are developed adventitiously and allowed to elongate and radially thicken. Root density, mass, and activity vary with internal and external conditions. Resources required for root growth are summarized in Table 3.

Table 3: Brief list of root growth resource requirements.

root resource	requirements minimal	 maximum
oxygen in soil atmosphere (for root survival)	3%	21%
air pore space in soil (for root growth)	12%	60%
soil bulk density restricting root growth (g/cc)	-	1.4 clay
	-	1.8 sand
penetration strength (water content dependent)	0.01kPa	3MPa
water content in soil	12%	40%
root initiation (O2% in soil atmosphere)	12%	21%
root growth (O2% in soil atmosphere)	5%	21%
progressive loss of element absorption in roots (O2% in soil atmosphere)	10%	21%
temperature limits to root growth	40°F/4°C	94°F/34°C
pH of soil (wet test)	pH3.5	pH8.2

Roots utilize soil spaces for access to water and essential element resources, and to provide structural support. Roots grow following pathways of interconnected soil pores. Pore space can be the result of the space 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, and oxygen is present. Roots are generally shallow as limited by oxygen contents, anaerobic conditions, and water saturation in deeper soil. Near the base of the tree, deep growing roots can be found, but they are oxygenated through fissures and cracks generated as a result of mechanical forces moving the crown and stem under wind loads (sway).

Growth Forces

The ability of primary root tips to enter soil pores, further open soil pores, and elongate through soil pores is dependent upon the force generated by the root and the soil penetration resistance. Root growth forces are generated by cell division and subsequent osmotic enlargement of each new cell . Oxygen for respiration, and adequate water supplies are required. Figure 6. Tree roots can consume large amounts of oxygen during elongation. At 77°F (25°C) tree roots will consume nine times their volume in oxygen each day, at 95°F (35°C) roots can use twice that volume per day. The osmotic costs to cells of resisting surrounding forces and elongating can be significant.

In response to increased compaction, roots thicken in diameter. Compaction also 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. Thicker roots exert more force and penetrate farther into compacted soil areas. Figure 7. As soil penetration resistance increases in compacted soils, roots thicken to minimize their own structural failure (buckling), to exert increased force per unit area, and to stress soil just ahead of the root cap which allows for easier penetration.

For effective root growth, pore sizes in the soil must be larger than root tips. With compaction in a root colonization area, pore space diameters become smaller. Once soil pore diameters are less than the diameter of main root tips, many growth problems can occur. The first noticeable root change with compaction is morphological. The main axis of a root becomes thicker to exert more force to squeeze into diminished sized pores. As roots thicken, growth slows and more laterals are generated of various diameters. Lateral root tip diameters are dependent upon initiation by growth regulator and the extent of vascular tissue connections. If laterals are small enough to fit into the pore sizes of the compacted soil, then lateral growth will continue while the main axis of the root is constrained. If the soil pore sizes are too small for even the lateral roots, root growth will cease. Figure 8.

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 soils and associated responses to 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 mechanisms: reaction to mechanical damage is effective and fast; continuation of respiration under chronic O2 shortages; ability to continue to turnover, reorient, and adjust absorbing root systems; and, ability to deal with chemically reduced materials (toxics).

A list of trees meeting the above criteria for soil compaction tolerance can be found in: *Coder, Kim D. 2000. **Compaction Tolerant Trees.** University of Georgia School of Forest Resources Extension Publication FOR00-2. 1pp. (Download at WEB site www.forestry.uga.edu/efr under "tree health care.")*

Causes of Compaction

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

Conducive Moisture Contents – For every soil type and infrastructure situation there is a soil moisture content at which the soil can be severely compacted with minimal effort. These moisture content levels can be used to compact a soil for construction activities, but should be avoided when defending tree and soil health. Both direct impacts and vibrational energy will cause compaction when the soil is at or near its compaction moisture content maximum. Figure 9.

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

Vehicles – Conveyances with tracks, wheels, and glides provide a great deal of force on the soil surface. Narrow rubber tires can transfer many pounds of compaction force to the 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 tires, and reduce forces exerted per square inch.

Soil Handling – The movement, transport, handling, and stockpiling of soil destroys aeration pore spaces and disrupts soil aggregates. Soil cuts, fills, and leveling compacts the soil. Soil handling equipment can be large and heavy allowing compaction many inches deep.

Vibrations & Explosions – Any mechanical energy that impacts individual soil particles can cause compaction. Car and truck traffic can cause vibrations which compact soils effectively at higher moisture contents. One solution to compaction in the past was use of explosives to fracture soils. The end result was the explosive energy fractured the soil in areas but heavily compacted the soil in other areas. Explosives damaged the soil to a degree not offset by aeration pores formed.

Intentional Manipulations – In order for infrastructures to be built and maintained, the 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 build. This process assures that infrastructure edges, bases, and lifts (compacted fill layers) are heavily compacted. The only space available for tree root colonization are fracture lines and coarse building materials where large air spaces occur. The greater the compaction, the closer to the surface the soil anaerobic layer develops, decreasing effective rooting volume.

A note needs to be made here regarding pavements. Soil is a complex material with a unique thermal and moisture expansion and contraction pattern. Soil expands and contracts over a day, season, and year at different rates than adjacent pavement or hard infrastructures. As a result, fissures and fracture lines filled with air occupy the interface between soil and infrastructures. These aeration pore spaces can be effectively colonized by tree roots. If infrastructures are not ecologically-literate in their construction, tree roots can generate enough mechanical force to accentuate any faults present.

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

Water Interactions – Water influences soil conditions conducive for compaction as well as providing energy directly to the soil surface for compaction. Direct irrigation impacts from sprinklers or rainfall hitting the soil surface can cause crusting and compaction. Piling of snow in winter when the soil is frozen compacts little, but large snow drifts remaining on-site as soils begin to thaw can lead to compaction from direct contact as well as from maintaining high moisture concentrations allowing for long periods of compaction susceptibility.

Soil saturation allows for hydraulic pressure to destroy soil aggregates and move fine particles into aeration pore spaces. Flooding events can lead to dissolved aggregate coatings and aggregate stability loss. Erosional processes across the surface of the soil and particle movement within the top portions of the soil (dislocated fine particles) can lead to aeration pore space loss and crusting.

Organic Matter Loss – Organic matter is the fuel, short-term building blocks of soil structure, and supply warehouse for living things in the soil. As organic matter decomposes and mineralizes without adequate replacement, soil becomes more compacted. Bulk density increases and aggregate stability declines as organic matter is "burned " out of the soil.

Functional Results of Compaction

Having reviewed the primary means by which soils become compacted, the results of compaction can be estimated for tree and soil health.

Destruction of soil aggregates and large pore spaces – The pore spaces from cracks, interface surfaces, biotic excavations, organic particle decomposition, and normal soil genesis processes help oxygenate the soil matrix. By definition, compaction results in the destruction of soil aggregates and aeration pore spaces. Pore spaces filled with O2 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.

Resorting / redistribution of particles – (Change in particle distribution) Particles of soils are redistributed into new locations, many of which are open pore spaces in the soil matrix. Through processes of packing, erosion, and cultivation many fine particles can fill-in the spaces surrounding other particles, as well as the 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.

Total pore space changes – (Change in pore space distribution) Compaction initiates a redistribution of pore sizes within the soil matrix. Large pores are destroyed and small pore are generated. The total pore space of the compacting soil initially increases as more capillary pores are created as aeration pores are lost. With increasing compaction, soil strength increases and pore space declines. Figure 10.

Aeration pore space destruction – The crushing collapse of aeration pores facilitates the upward movement of the anaerobic layer. There are always anaerobic and aerobic micro-sites in and around soils aggregates within the 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 the soil to anaerobic sites. With further compaction, aerobic sites are concentrated closer and closer to the surface until little available rooting volume remains. Table 4 lists root-limiting aeration pore space percentages in soils of various textures. Air pore space less than 15% is severely limiting.

Table 4. Root growth limiting air-pore space values by soil texture.

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

Increased mechanical impedance – 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 decrease, the ability of roots to grow and colonize soil spaces declines rapidly. With compaction, soil strength reaches a level where roots can not exert enough force to push into pore spaces. Pore space average diameters significantly smaller than average root diameters are not utilized by tree roots. Figure 11. Table 5 lists root-limiting bulk densities by soil texture. The texture and bulk density must be known to estimate compaction impacts.

Table 5. Root growth limiting bulk density values by soil texture.

soil texture	root-limiting bulk density (g/cc)
sand	1.8 g/cc
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

Connectivity of aeration pores decreased – The aeration pathway (lifeline) from the atmosphere to the root surface through all the interconnected aeration pores declines quickly with compaction. As the tortuosity of the oxygen supply path increases, the closer to the surface the anaerobic layer moves. As pore sizes become smaller with compaction, more of the pore space is filled with water. Water-filled pores diffuse O2 at rates 7,000 to 10,000 times slower than air-filled pores. With all the other aerobes and roots in the soil competing for the same oxygen, oxygen limitations become severe. Figure 12.

<u>Poor aeration</u> – Compaction constrains O2 movement in the soil and shifts soil toward anaerobic conditions. Less O2 diffusion into the soil leads to a chemically reducing soil environment (both the soil solution and soil atmosphere). Under these conditions, toxins and unusable essential element forms are generated. In addition, organic matter is not mineralized or decomposed.

A soil anaerobic respiration sequence is initiated among bacteria starting with nitrogen and moving through manganese, iron, and sulfur, ending with carbon (fermentation of roots). Tree roots are aerobes as are root symbionts and co-dependent species of soil organisms. Less oxygen prevents growth, defense, and survival in aerobes. Roots use available food 20 times 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 O2 concentration falls below 5% in the soil atmosphere, severe root growth problems occur. Figure 13. Figure 14. Figure 15.

<u>Poor gas exchange with atmosphere</u> – Compaction prevent gas exchange with the atmosphere. Compaction prevent O2 from moving to root surfaces, but also prevents CO2 and toxics (both evolved and resident) from being removed from around the roots and vented to the atmosphere. Poor gas exchange allows the anaerobic layer to move closer to the surface and reduce rooting volume. As CO2 comprises more than 5% of the soil atmosphere, problems of aeration become compounded. As CO2 climbs above 15% in soils, root growth dysfunctions accelerate. Figure 16.

<u>Less tree available water / Less water holding capacity</u> – One of the most ignored result of compaction is it effects on soil water availability. Soil compaction reduces the tree available water held in the large capillary pores and increases the volume of small capillary pores which hold water unavailable to trees. With the decreasing number of large capillary pores and increasing number of small capillary pores, the total water holding capacity of the soil declines. Irrigation scheduling and monitoring becomes critical around trees in compacted soils. Figure 17. Figure 18. Figure 19. Figure 20.

<u>Decreased infiltration rates / Increased surface erosion</u> – Compaction leads to smaller pore spaces and slower infiltration rates. With increasing residency time at the soil surface, water can horizontally move 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 it infiltrates easily.

<u>Poor internal drainage</u> – Compaction prevents effective drainage of soils. Poor internal drainage limits tree available water, prevents O2 movement, and increases production and residence time of CO2 and toxics.

<u>Increased heat conductance</u> – Compaction changes the energy and water balance near the surface of the soil. With more particle to particle contact, heat transfer is greater into the 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 path – for every 18°F (10°C) increase in temperature, respiration doubles.

Tree Root Impacts of Compaction

Compaction impacts tree in many ways. Generally, compaction associated physiological dysfunctions cause systemic damage and decline, as well as failures in dealing with additional environmental changes. Physical / mechanical constraints negatively modify responses in the tree resulting in inefficient use of essential resources. The symptoms we see in trees under compacted soil conditions have causes stemming from disruptions of the internal sense, communication, and response process.

Biological Disruptions

Compaction disrupts respiration processes which power every function of the tree. Growth regulators are destroyed prematurely or allowed to buildup, causing wild changes in tissue reactions. Carbon 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, and ineffective food use, is slow to react and incomplete in response. With compaction, short-term fluctuations in resource quality and quantity must be effectively dealt with and resulting chronic stress must be tolerated.

The presence of toxic materials can be highly disruptive to soil health. As oxygen concentrations decline, more reduced compounds (only partially oxidized) are generated by the tree roots and associated soil organisms. These reduced compound can buildup and damage organisms and move the 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, the more damage.

The structure of the 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 wood development. Whole tree stress can result in tissue shedding internally to heartwood and externally. Top and root dieback as well as branch drop can be the result. Reduced rooting volume mechanically destabilizes the whole tree.

Compaction Effects

Major soil compaction effects on trees are defined below:

Reduced elongation growth – As compaction increases, roots are physically prevented from elongating into the soil by lack of O2, by decreasing pore size, and by increased soil strength. As roots are put under greater than 1.2 MPa of pressure, elongation slows and stops. Figure 21.

Reduced radial growth – Trees begin to generate thick and short roots with many more lateral roots as surrounding soil pressure exceeds 0.5 Mpa. O2 shortages and soil strength are major limitations.

Essential element collection and control problems – 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 in active element uptake (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.

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

<u>*Constrained size, reach, and extent of root systems*</u> – Compaction limits the 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 the reach of the root system also prevents effective reactions to changes in mechanical loads on the tree and concentrates stress and strain in smaller areas.

<u>*Stunted whole tree form*</u> – As resources are limited by soil compaction and more effort is required to seek and colonize resource volumes, trees are stunted. The 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 and with limited ability to take advantage of any short-term changes in resource availability.

<u>*Seedling establishment and survival problems*</u> – Micro-site variability in compaction levels and a limited resource base constrain young and newly planted trees. Less of a bulk density increase and crusting effect are needed for failure of new trees compared with older, established trees.

<u>*Root crushing and shearing-off*</u> – The mechanical forces generated in compacting a soil can crush roots, especially roots less than 2 mm in 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, soil organic material, and depth to the saturated layer (for rutting). Figure 22.

<u>*Fewer symbionts / codependents*</u> – Soil compaction puts selective pressure against aerobes and favors low O2 requiring organisms, like <u>Pythium</u> and <u>Phytophera</u> root rots, or anaerobes. Because of the destruction of the detritus energy web coupled with successional changes, recovery of soils to pre-compaction conditions may not be possible. Management must move forward to new solutions for resource availability and deal with new patterns of pest management since returning to the soil microbiology and rhizosphere of pre-compaction is impossible.

Renovation of Sites

<u>*Principles*</u> -- A summary of this discussion of soil compaction lies with those general principles and renovation techniques managers must use to reclaim a part of the ecological integrity of the site, as well as soil and tree health. General soil compaction renovation principles are listed below in a bullet format:

– Soil compaction should be considered permanent. Studies demonstrate that after one-half century, compaction still afflicts soils under natural forest conditions. Recovery times for significant compaction is at least two human generations. Soils do not “come back” from compaction.
– 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.

– Management activities should concentrate on moving forward to increased aeration space and reduced soil strength as best you can, rather than trying to recover past ecological history.

– Measure bulk density, penetration force, O2 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 expensive and difficult to make.

– Alleviation of soil compaction is part of a good soil health management plan.

– Use extreme caution in management of water over and in compacted soils. Compaction provides little margin for error for drainage, aeration, infiltration, and water holding capacity of tree available water. (Wet soil / dry tree problems).

– Seek the assistance of a tree and soil specialist to avoid tree-illiteracy problems on compacted soils.

Techniques – Once the general principles of working with compacted soils are digested, the next requirement is to identify some techniques for renovating compacted soils. These recommendations are generic across many situations and soil types. General techniques are listed below in a bullet format:

– Restrict site access to the soil surface as soon as possible with fences and fines (legal penalties). Try to be the first one on the site and setup anti-compaction protection.

– Defend the ecological "foot print" of the tree rooting area. Select working conditions (dry, dormant season, surface mulch, etc) that minimizes compaction.

– Restrict where possible vibrational compaction.

– Carefully design tree growth areas using "biology-first" design processes rather than the common (and damaging) "aesthetics-first" design processes.

– Try to soften and distribute compaction forces with temporary heavy mulch, plywood driving pads, and soil moisture content awareness planning.

-- Restart or improve the detritus energy web in the soil including addition of organic matter and living organisms, as well as trying to change soil physical properties by increasing aeration pore space.

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 the greening of inter-infrastructural spaces in our communities, we will spend most of our budgets and careers treating symptoms and replacing trees. Understanding the hideous scourge of soil compaction is essential to better, corrective management.

For more information on this subject review papers listed in the following reference: *Coder, Kim D. 2000.* ***Trees and Soil Compaction: A Selected Bibliography.*** *University of Georgia School of Forest Resources Extension Publication FOR00-1. 2pp. (Download at WEB site www.forestry.uga.edu/efr under "tree health care.")*

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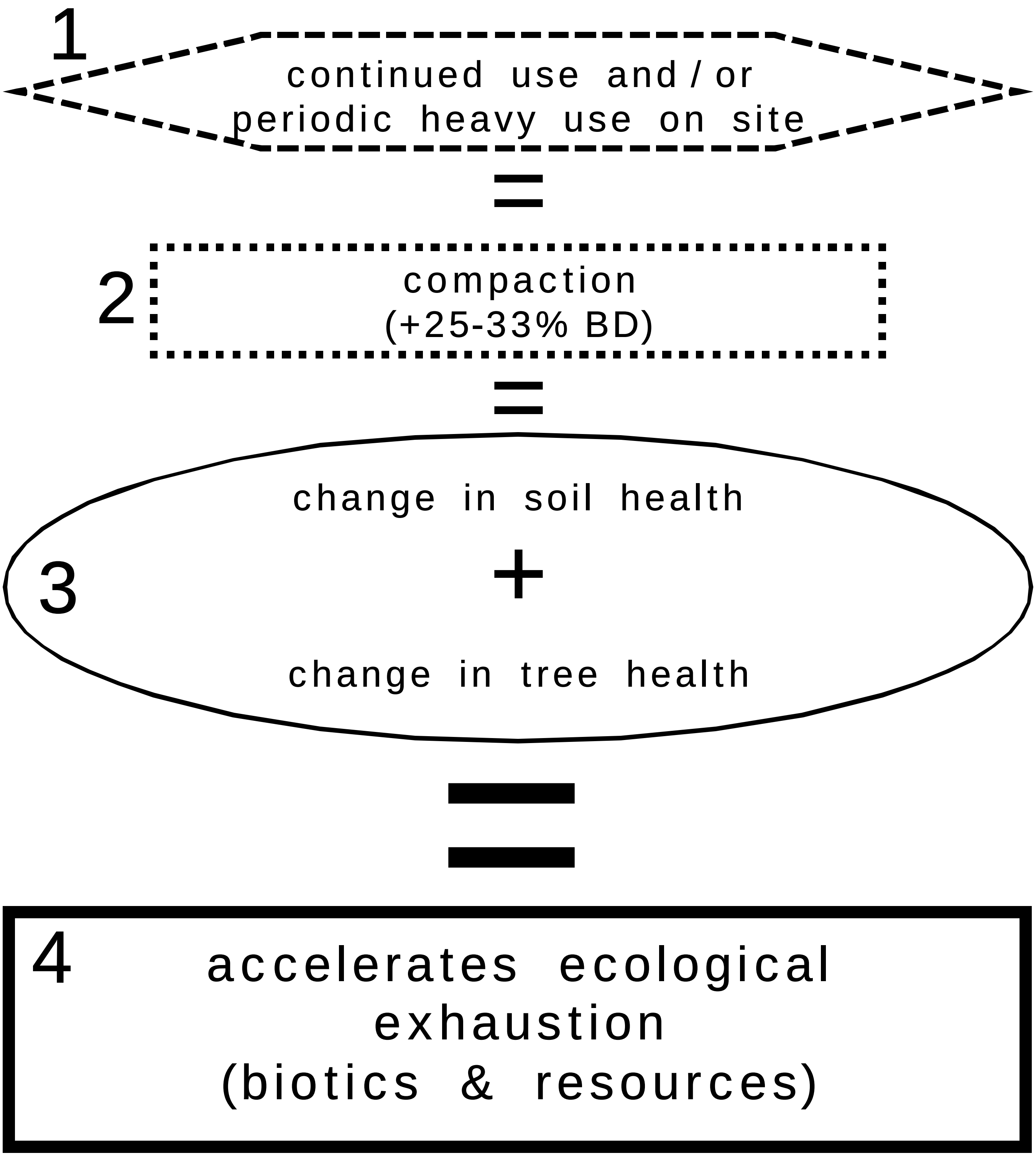
Figure 1: Cause and effect processes under soil compaction.



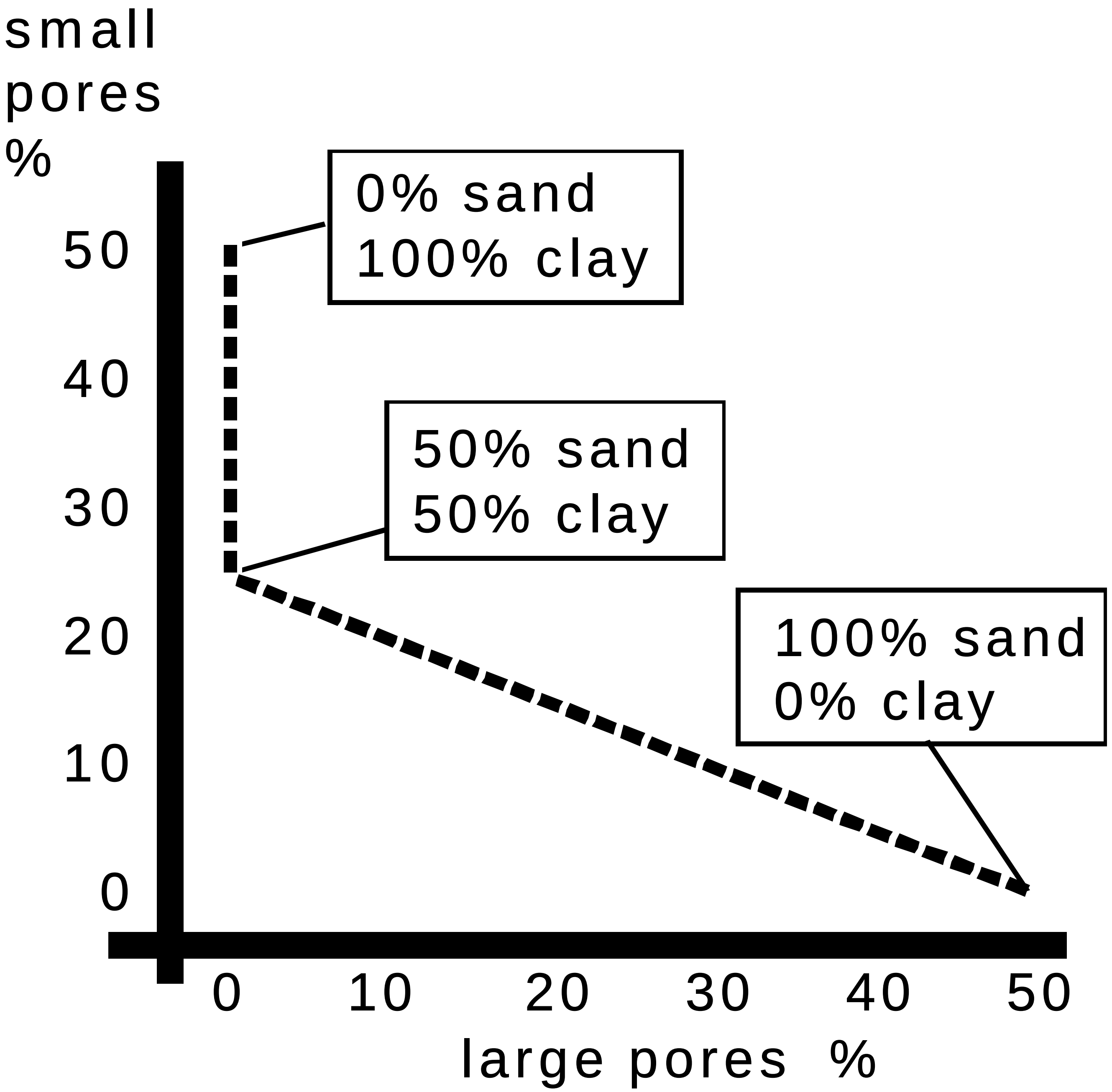


Figure 2: Large and small pore space percentages in various sand / clay mixtures.
(after Harris et.al. 1999)

Figure 3: Pore size definitions.

I. AERATION PORES

aeration pores
>60mm diameter
“macro-pores”

II. CAPILLARY PORES

1. available water pores
0.2 -- 60mm diameter
“meso-pores”

2. unavailable water pores
<0.2mm diameter
“micro-pores”

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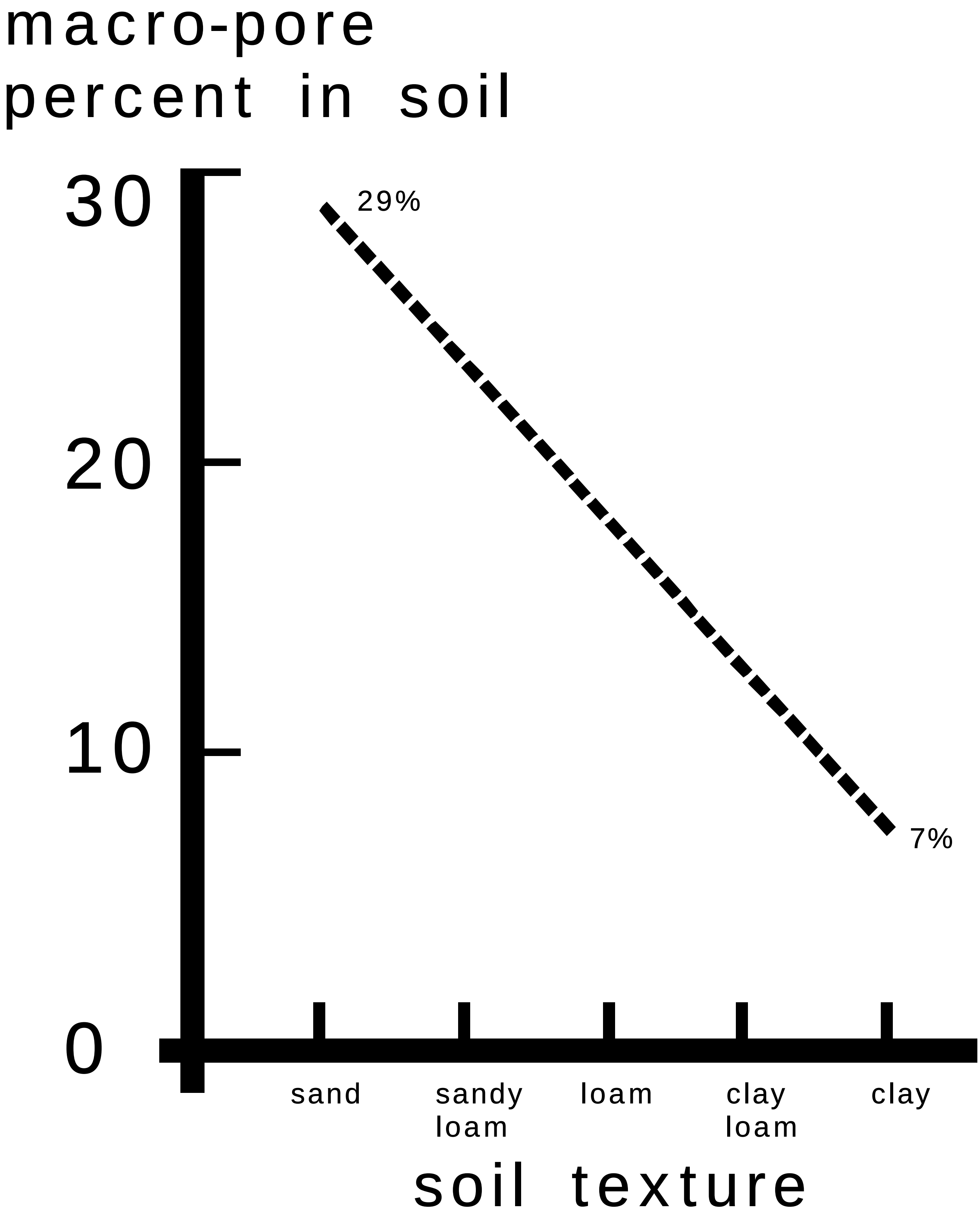

Figure 4: Macro-pore space by soil texture. (after Craul 1999)

Table 1: Physical attributes of selected construction materials.

(from Patterson)

material	BD	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	% volume

Table 2: Calculation of pore space from bulk density and avaerage mineral density.

$$\% \text{ pore space} = (1 - BD / 2.65) \times 100$$

BD (g/cc)	% pore space
0.9	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

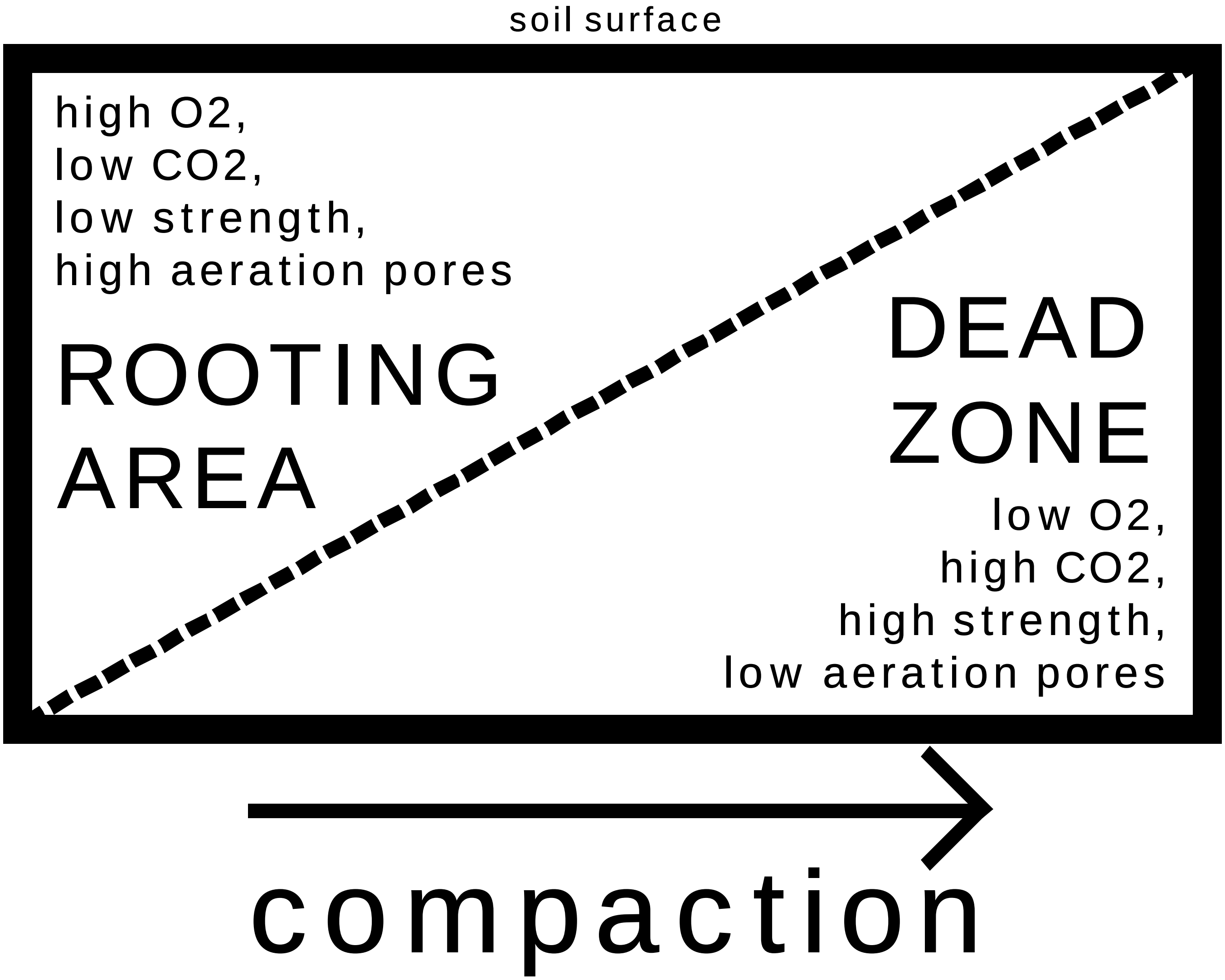

Figure 5: Graphical representaion of compaction effects on soil.

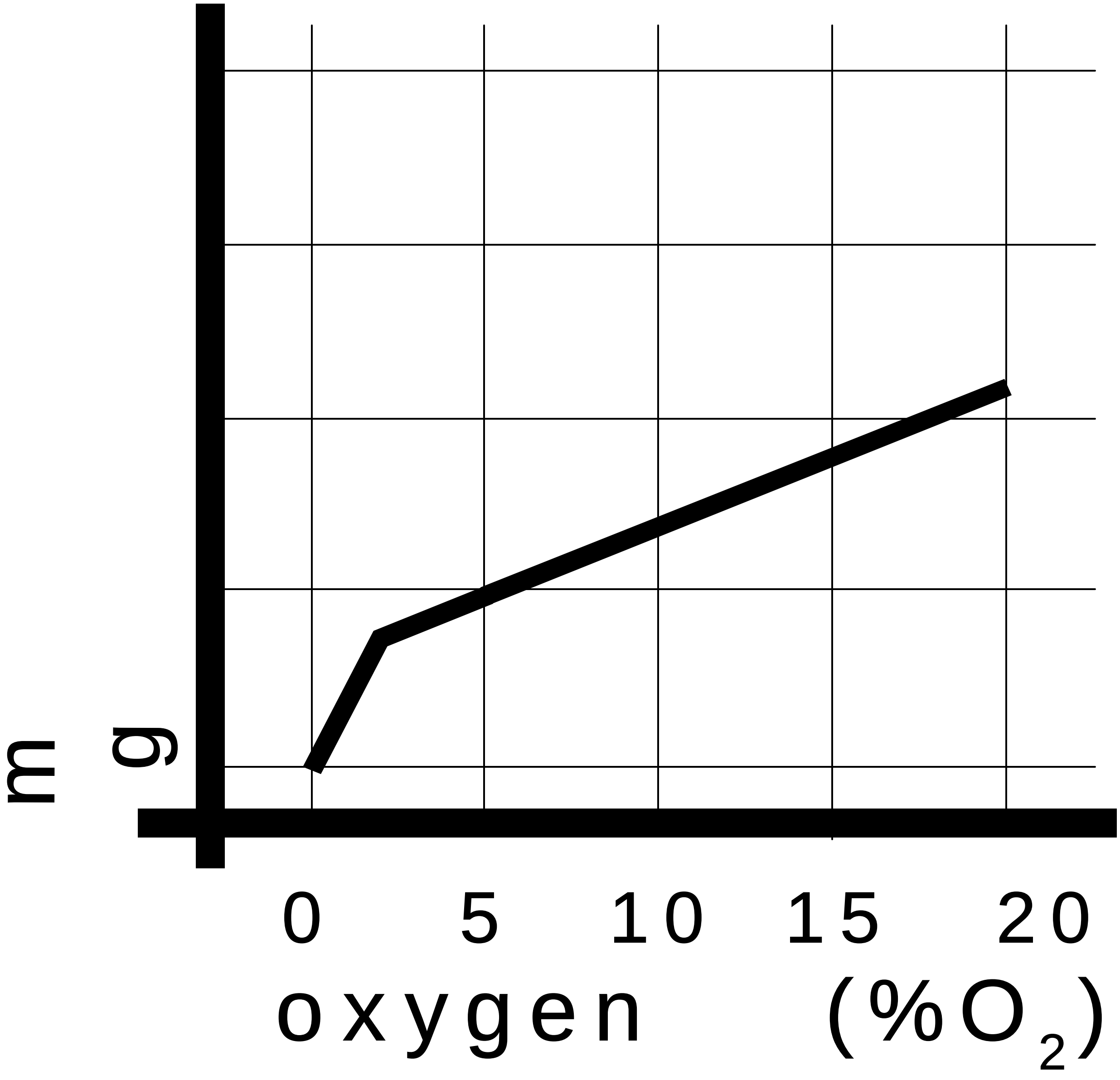

Figure 6: Maximum root growth force expressed by seedlings at various oxygen concentrations.

(after Souty & Stepniewski 1988)

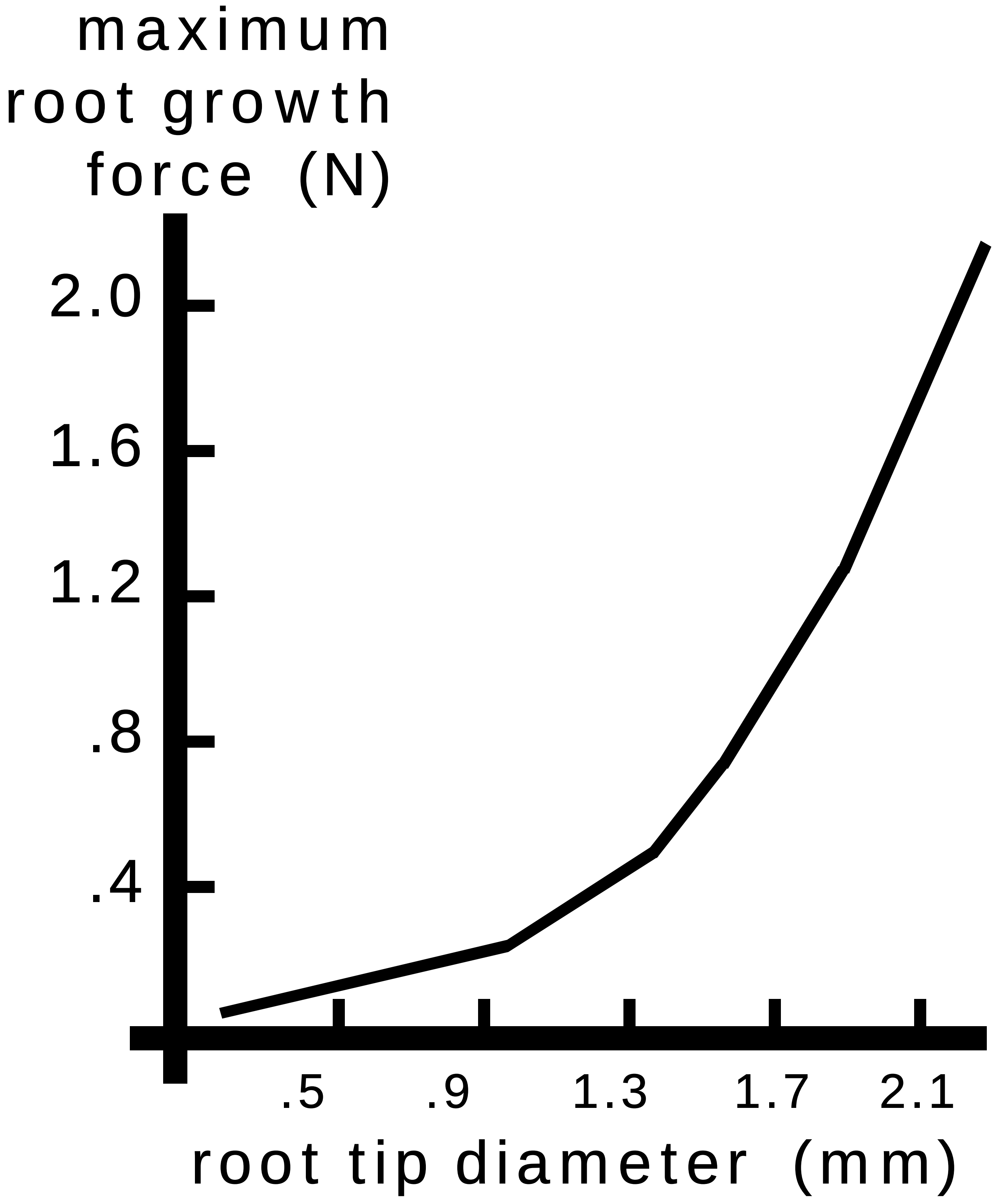

Figure 7: Maximum root growth force by root tip diameter.

(after Misra et.al. 1986)

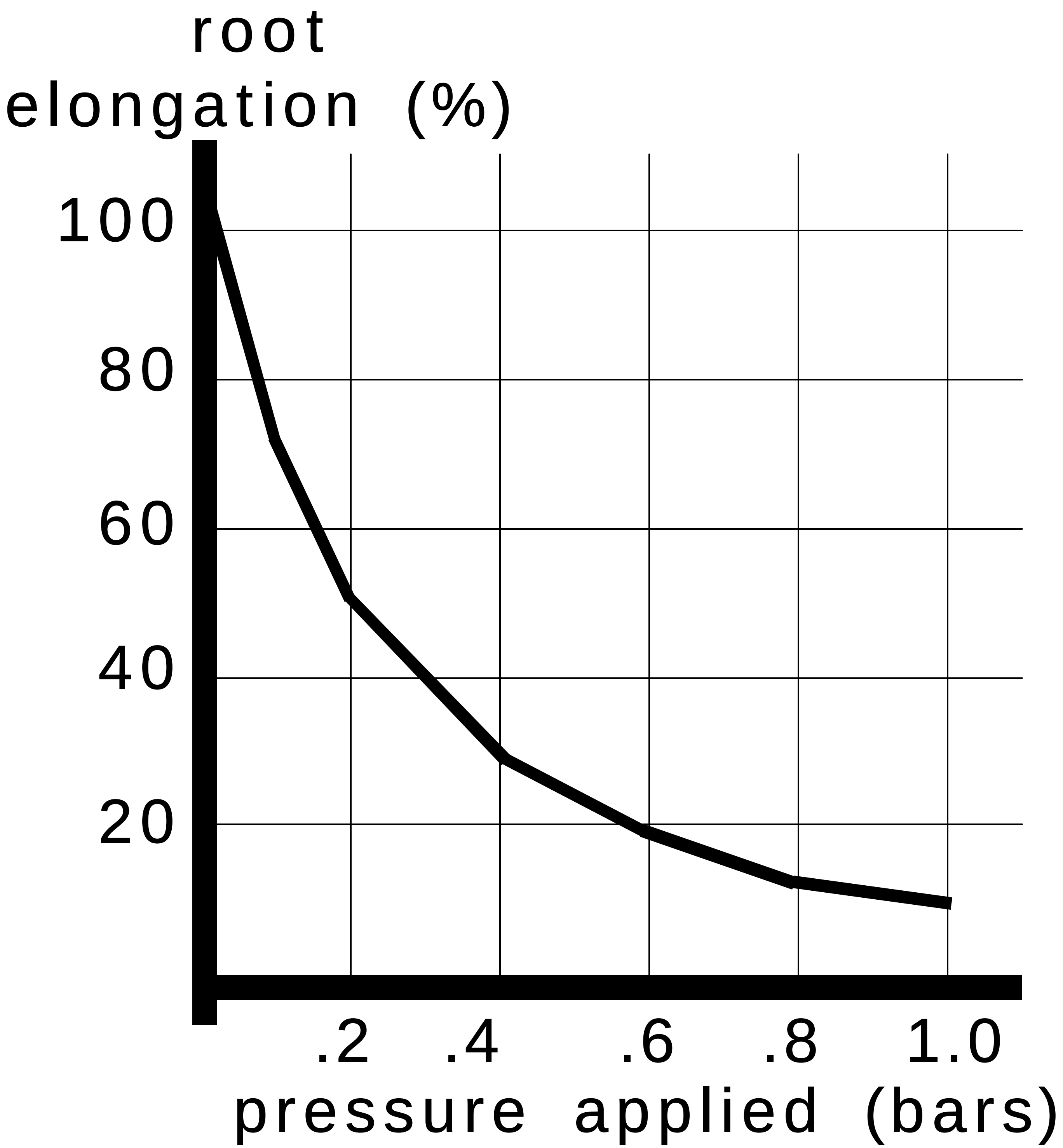

Figure 8: Pressure applied to roots that limit elongation.
(after Rendig & Taylor 1989; Russell, 1977) (1 MPa =100 kPa ■ 1 bar)

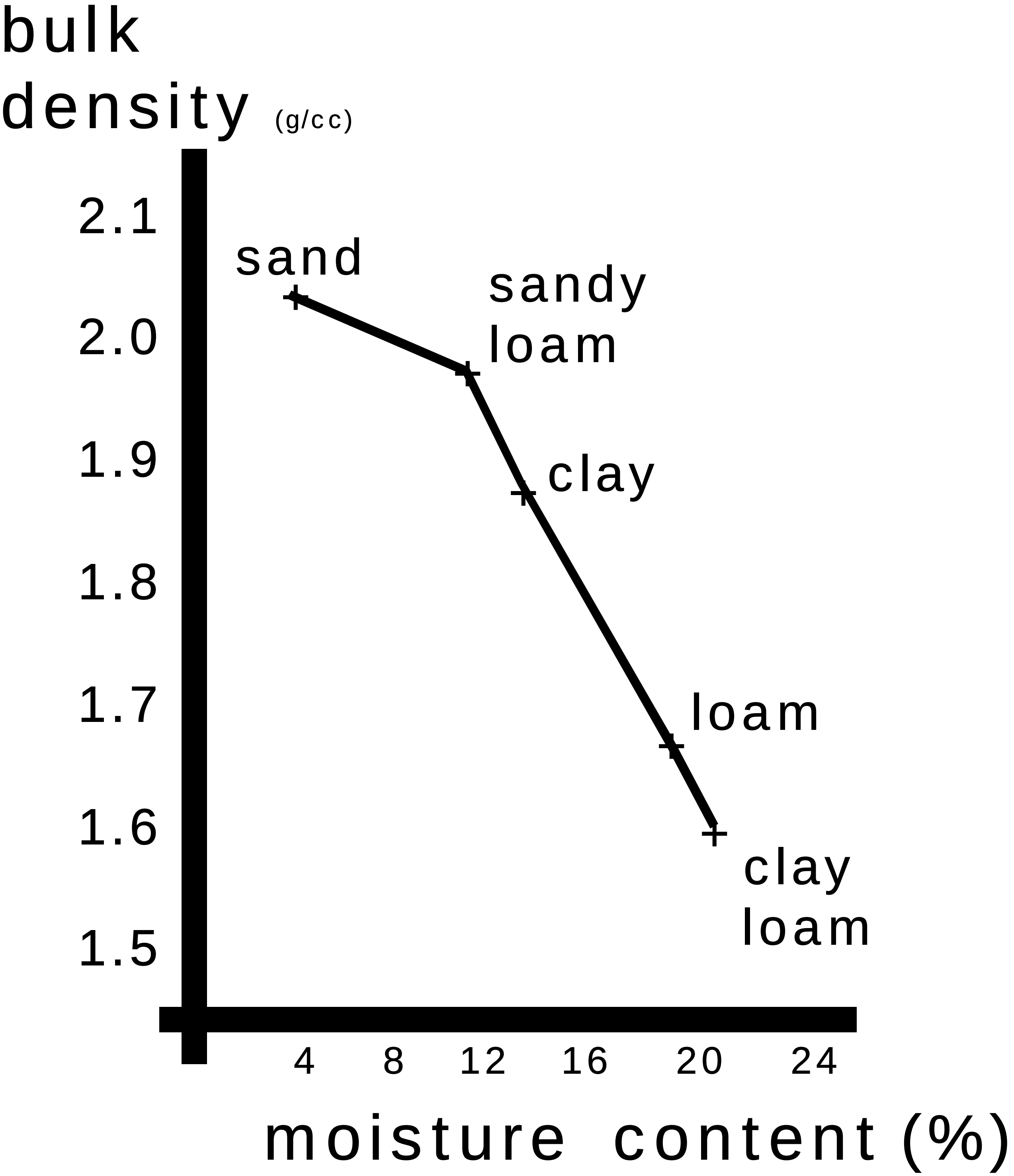

Figure 9: Maximum compaction capacity by moisture content.
(after Craul 1994)

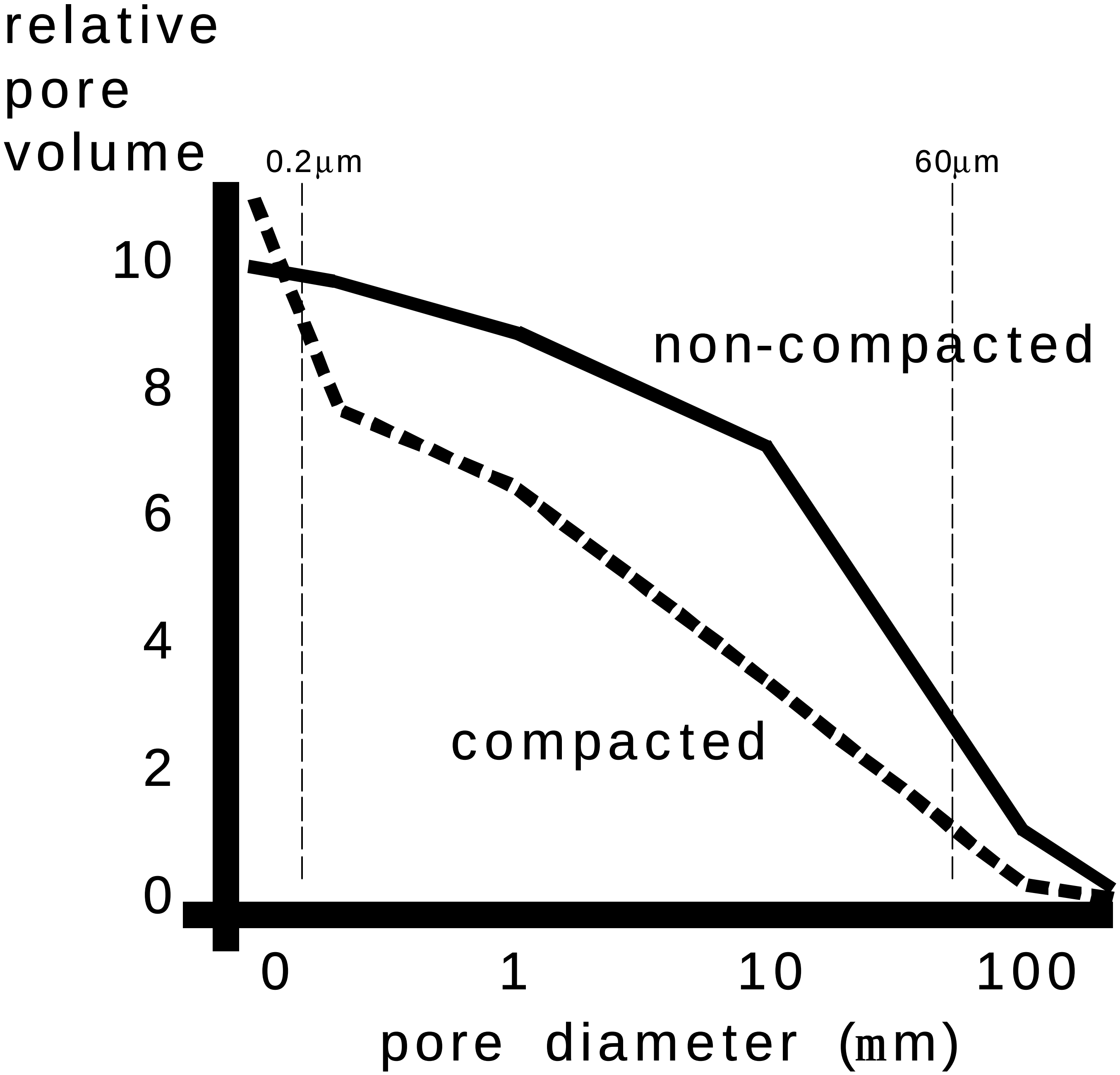

Figure 10: Soil pore diameters and relative volumes under non-compacted (1.4 g/cc) and compacted (1.8 g/cc) conditions.
(after Jim 1999)

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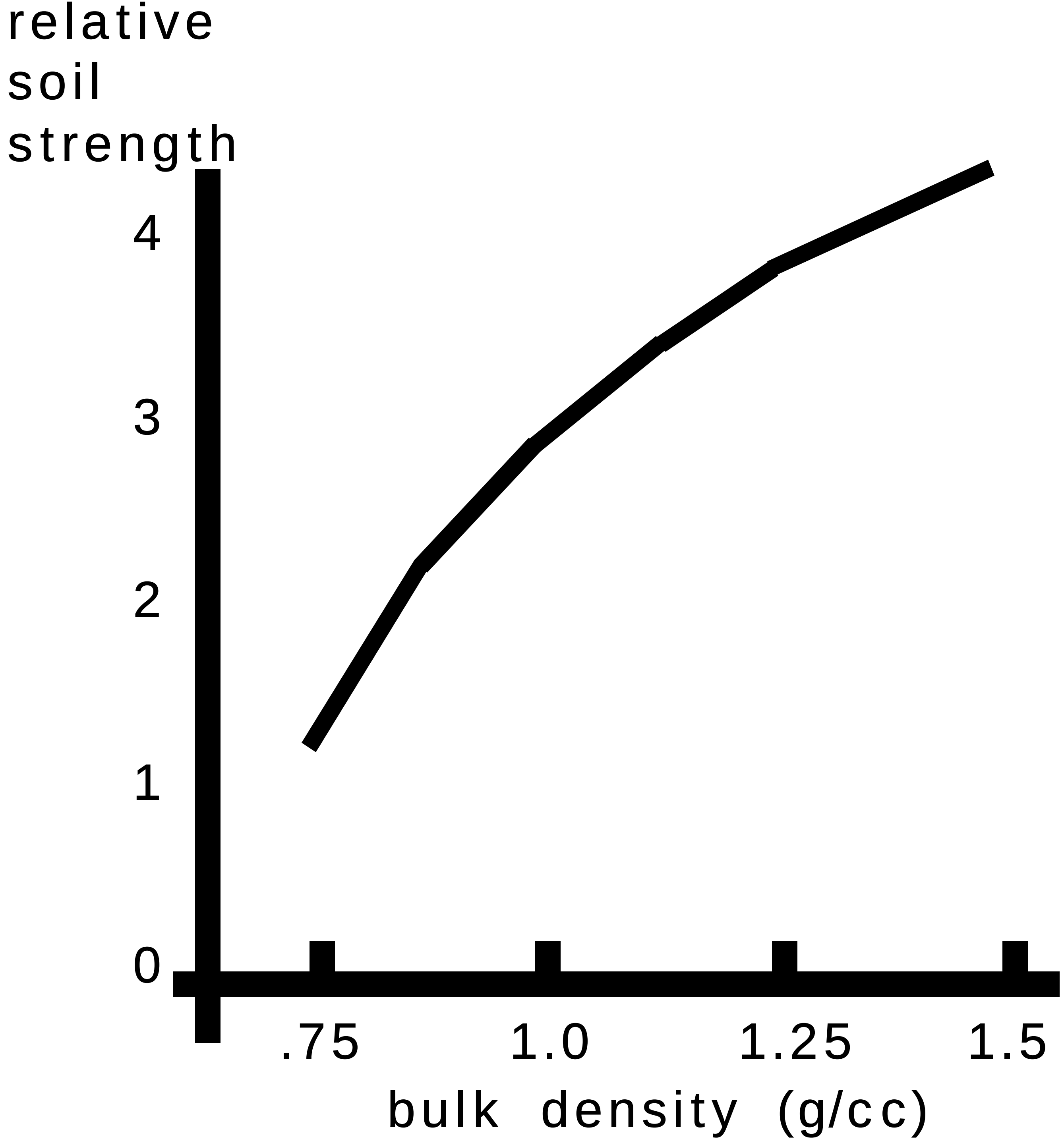

Figure 11: Relative soil strength with increasing bulk density values.
(after Craul 1994)

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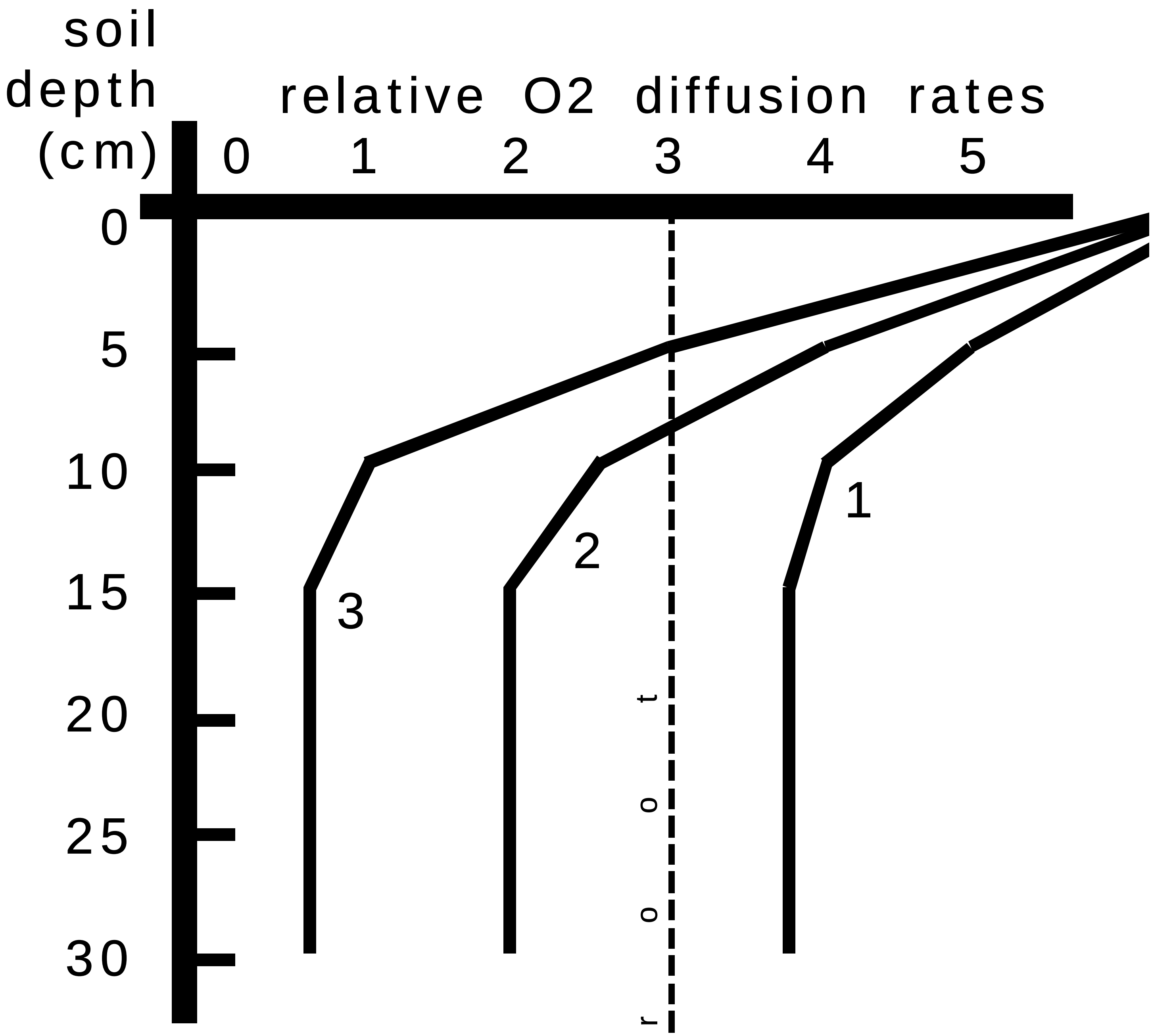

Figure 12: Relative oxygen (O2) diffusion rates with increasing soil compaction. (after Kelsey 1994)

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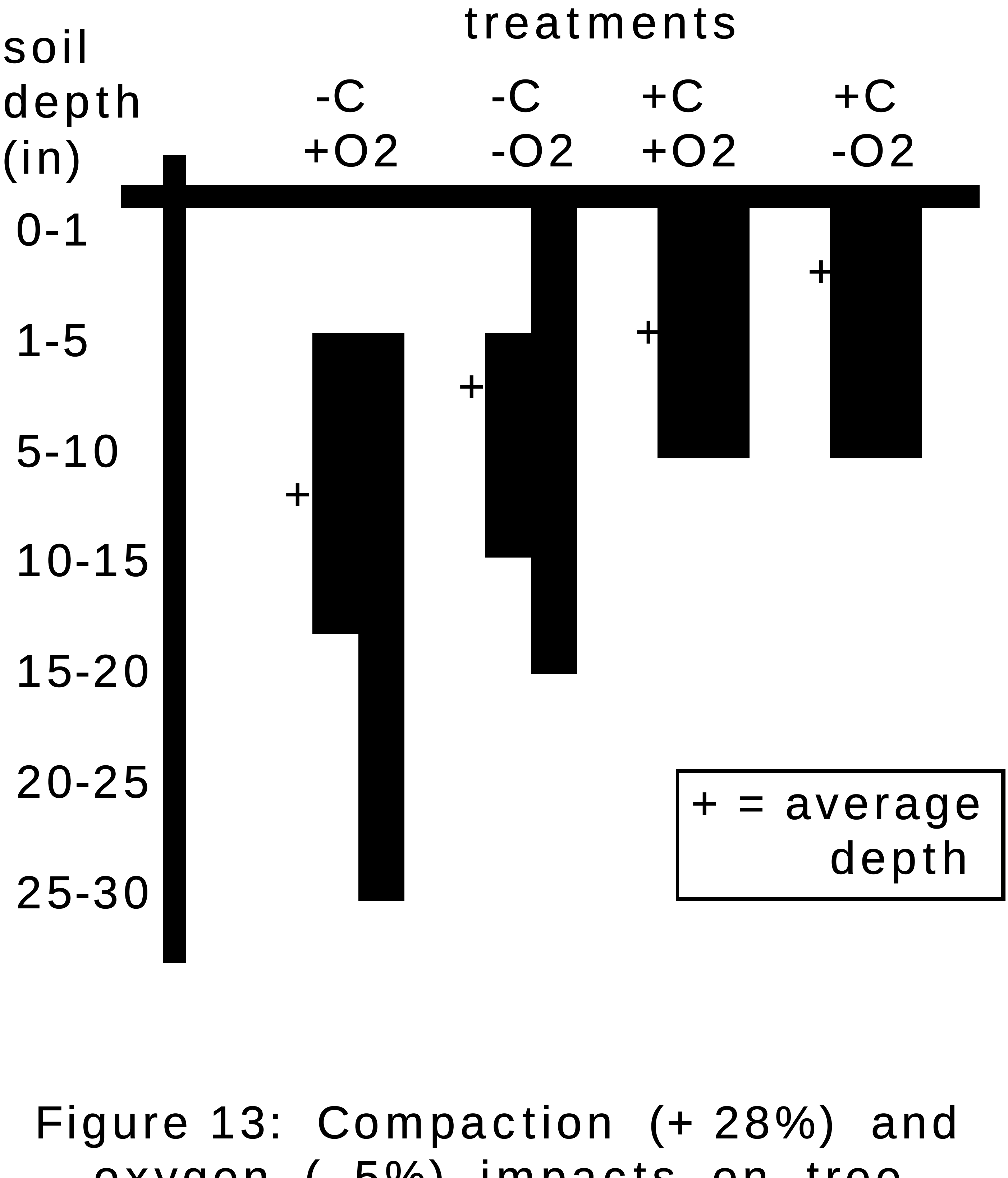

Figure 13: Compaction (+ 28%) and oxygen (- 5%) impacts on tree rooting depths. (after Gilman et.al. 1987)

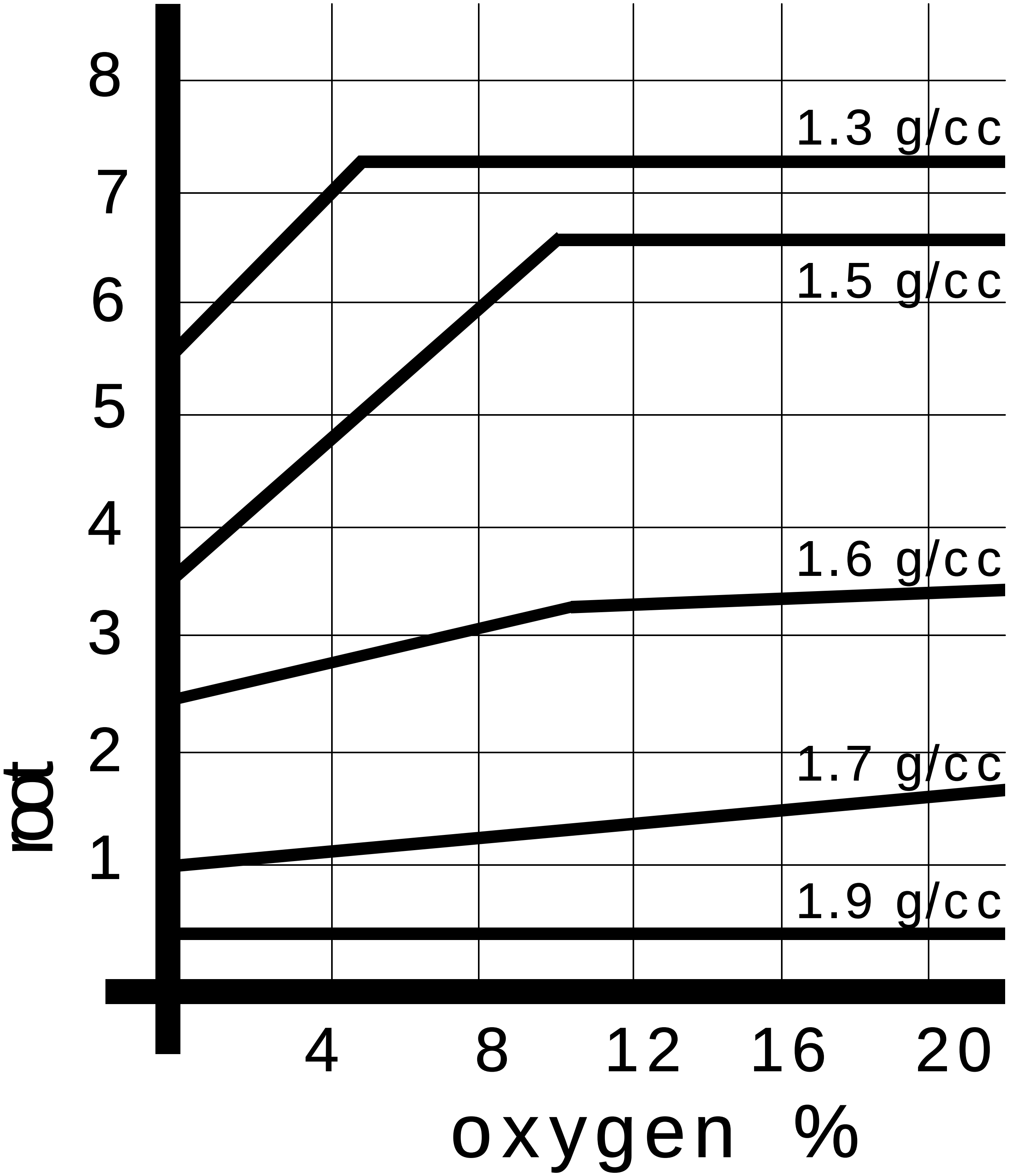

Figure 14: Percent oxygen and bulk density effects on root penetration. (after Rendig & Taylor 1989)

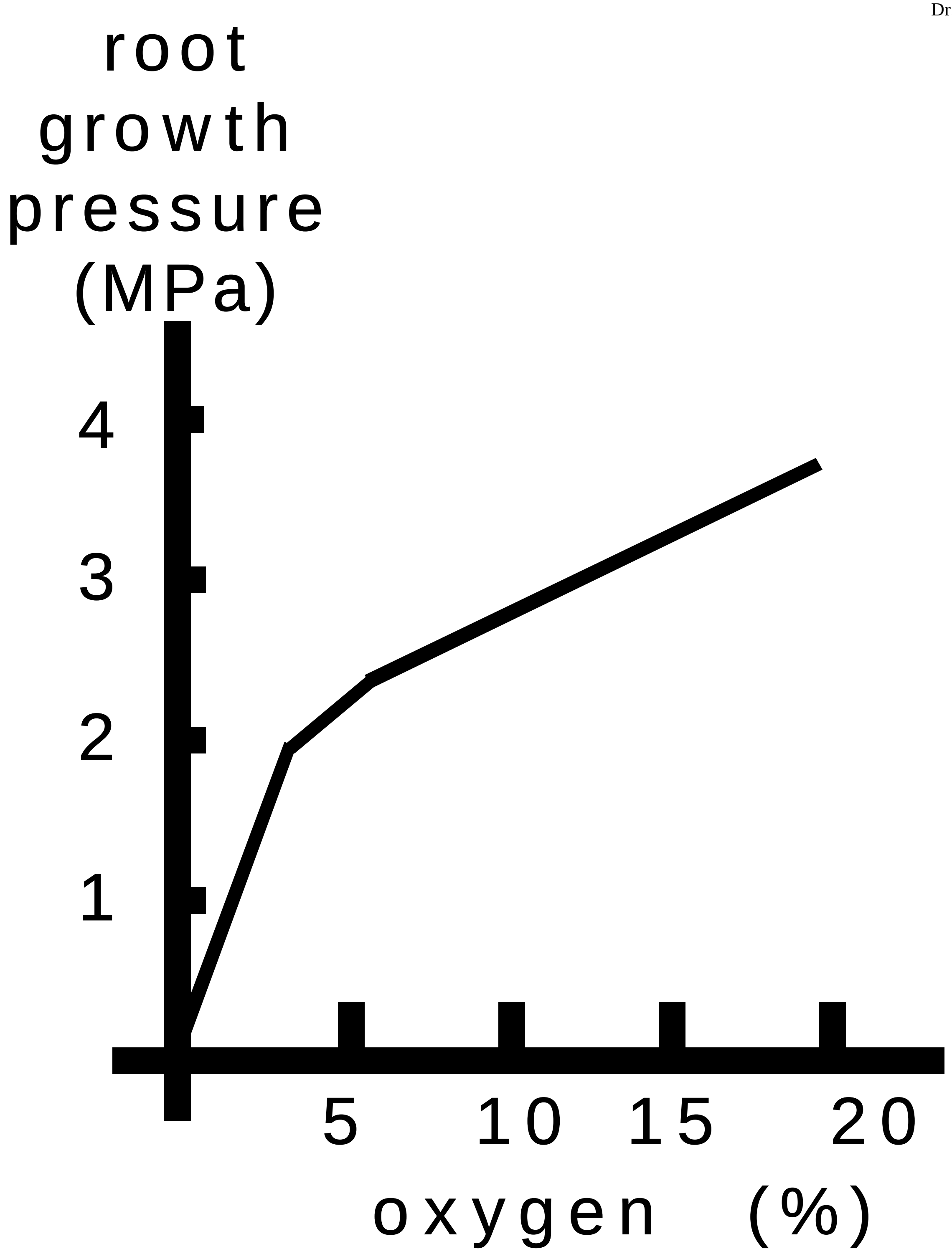

Figure 15: Root growth pressure by oxygen concentration.
(after Souty & Stepniewski 1988)

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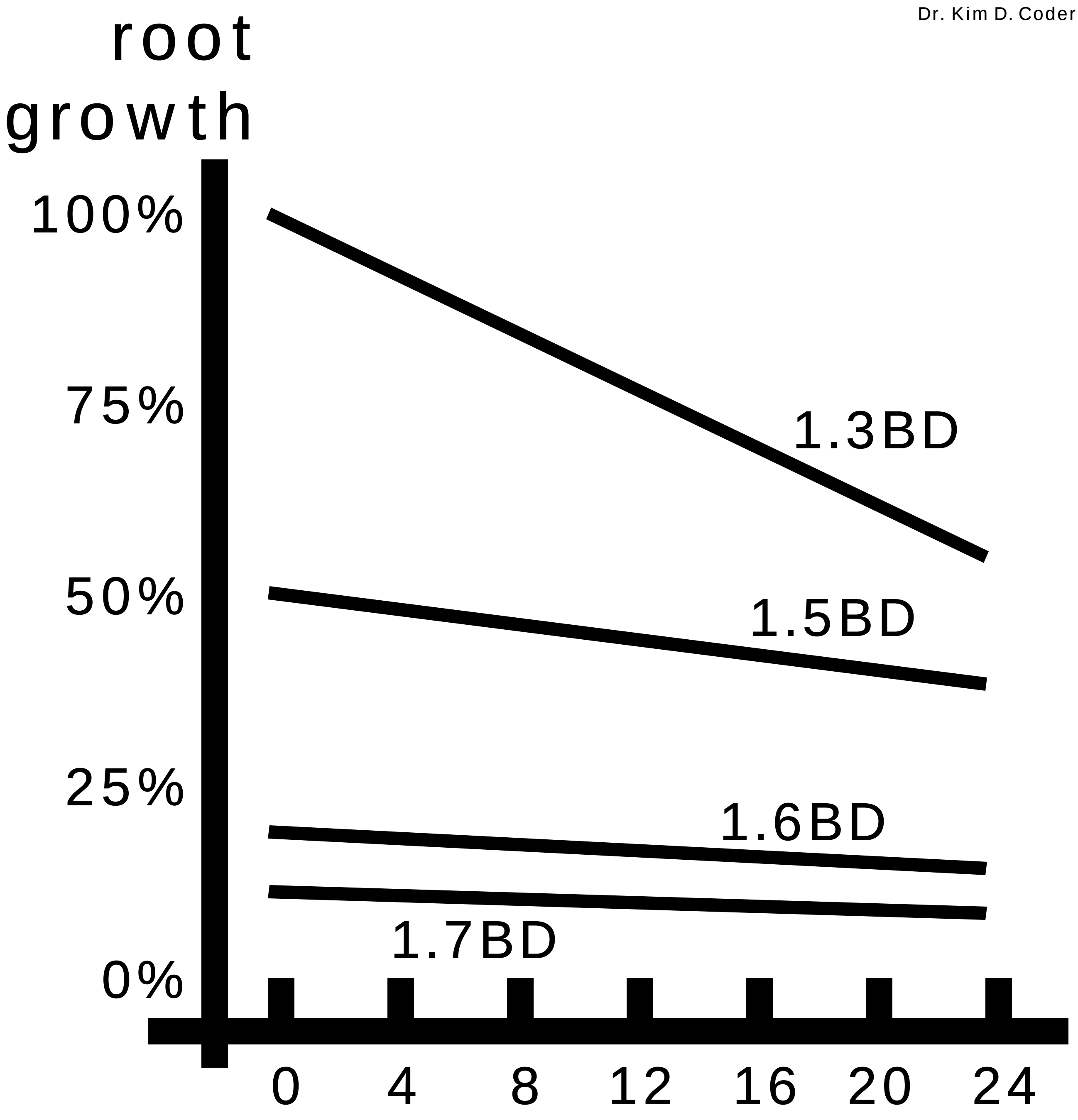

Figure 16: Carbon dioxide (CO2) concentrations in the soil and bulk density impacts on root growth. (after Patterson)

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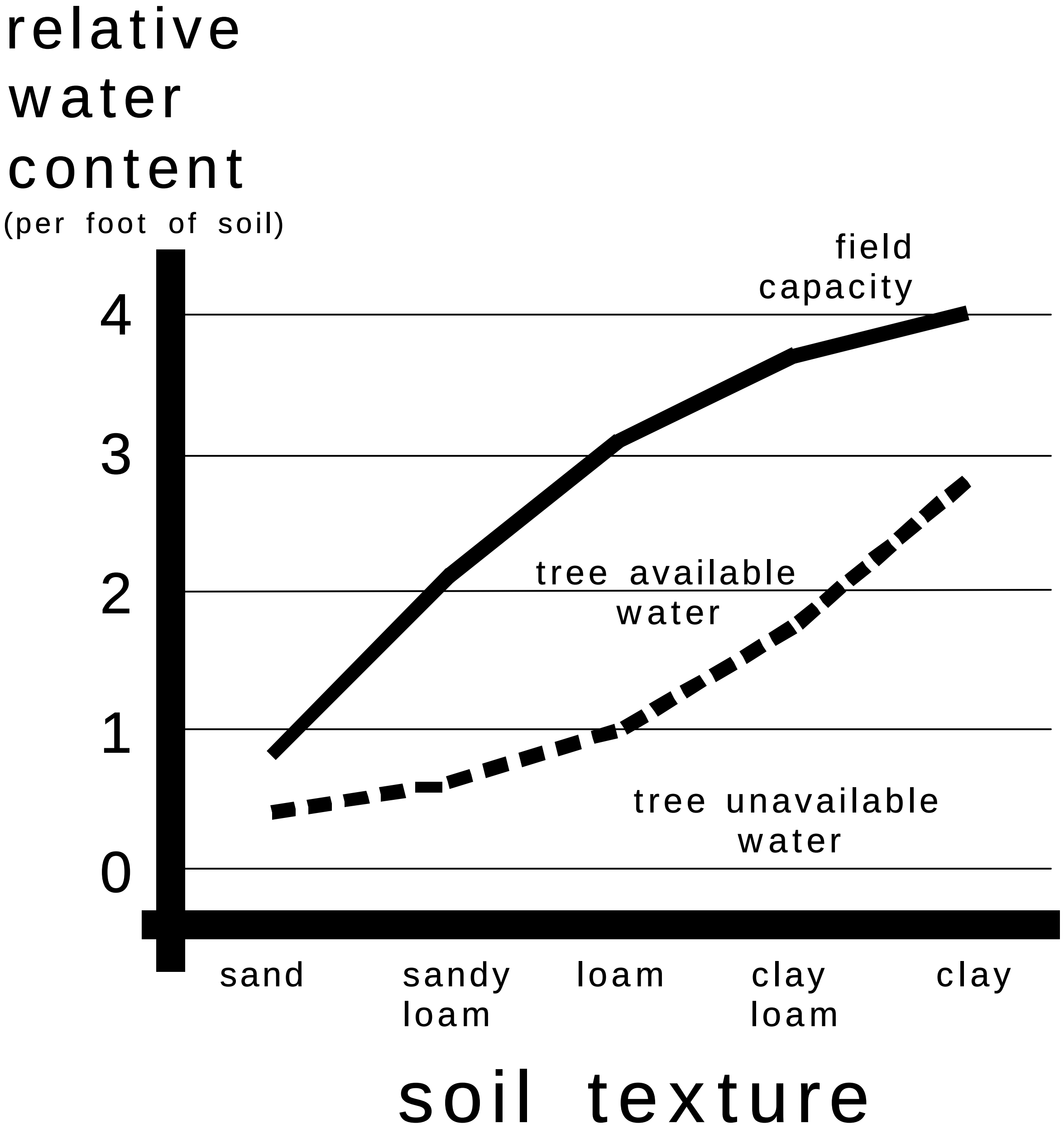

Figure 17: Tree-available water present at different soil textures.

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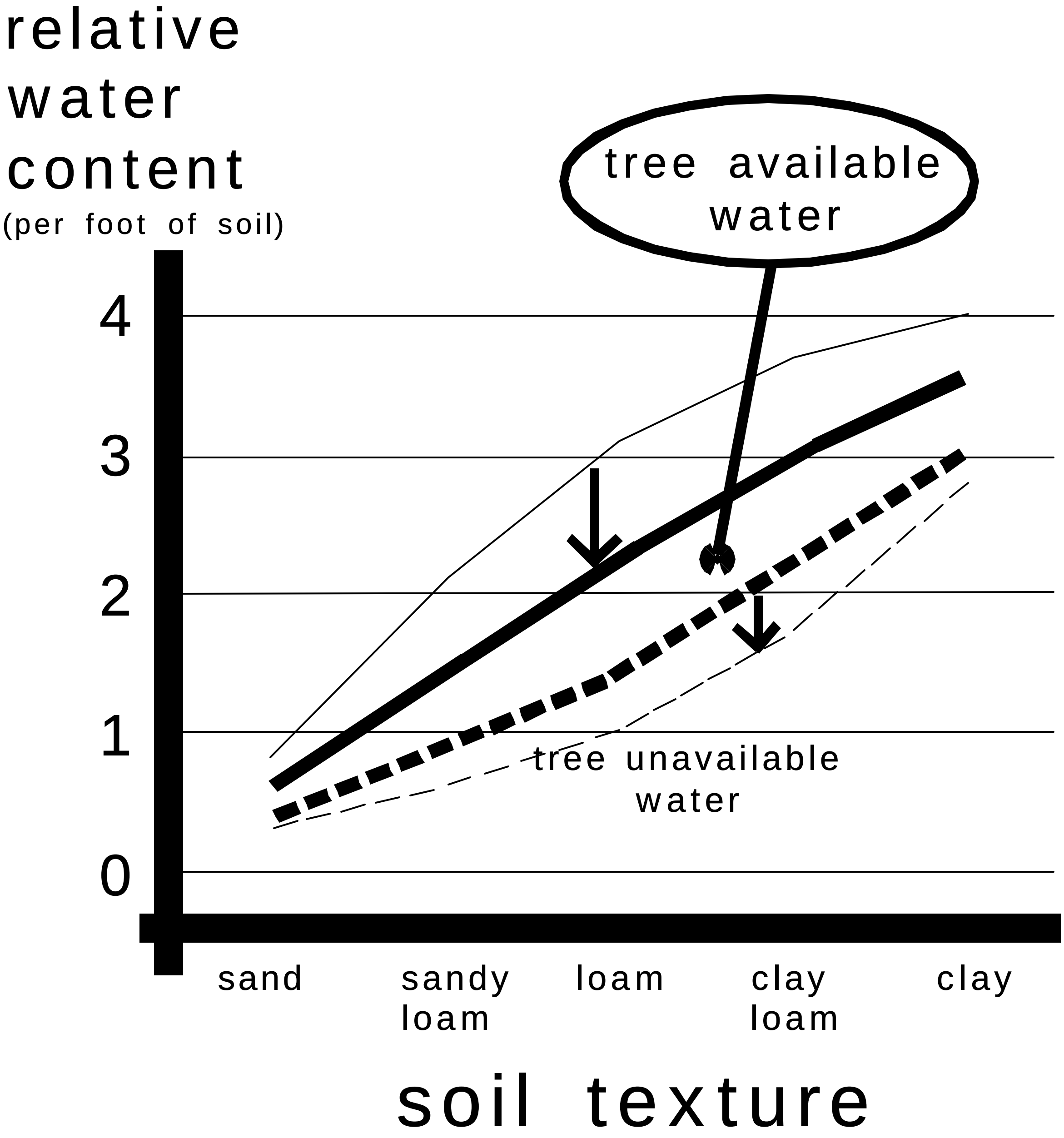

Figure 18: Tree-available water present at different soil textures under compaction.

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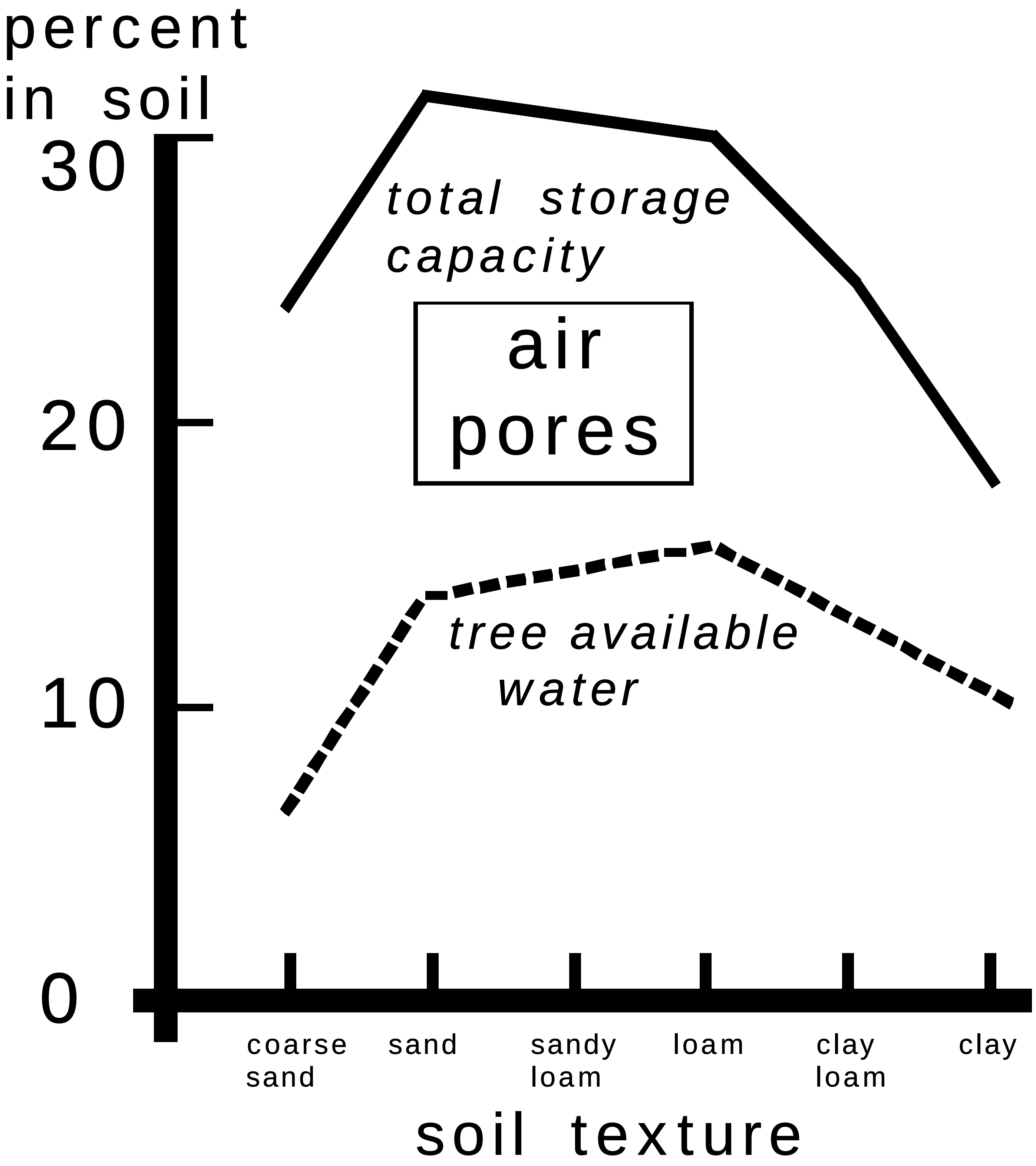

Figure 19: Water storage capacity in normal soil. (after Craul 1999)

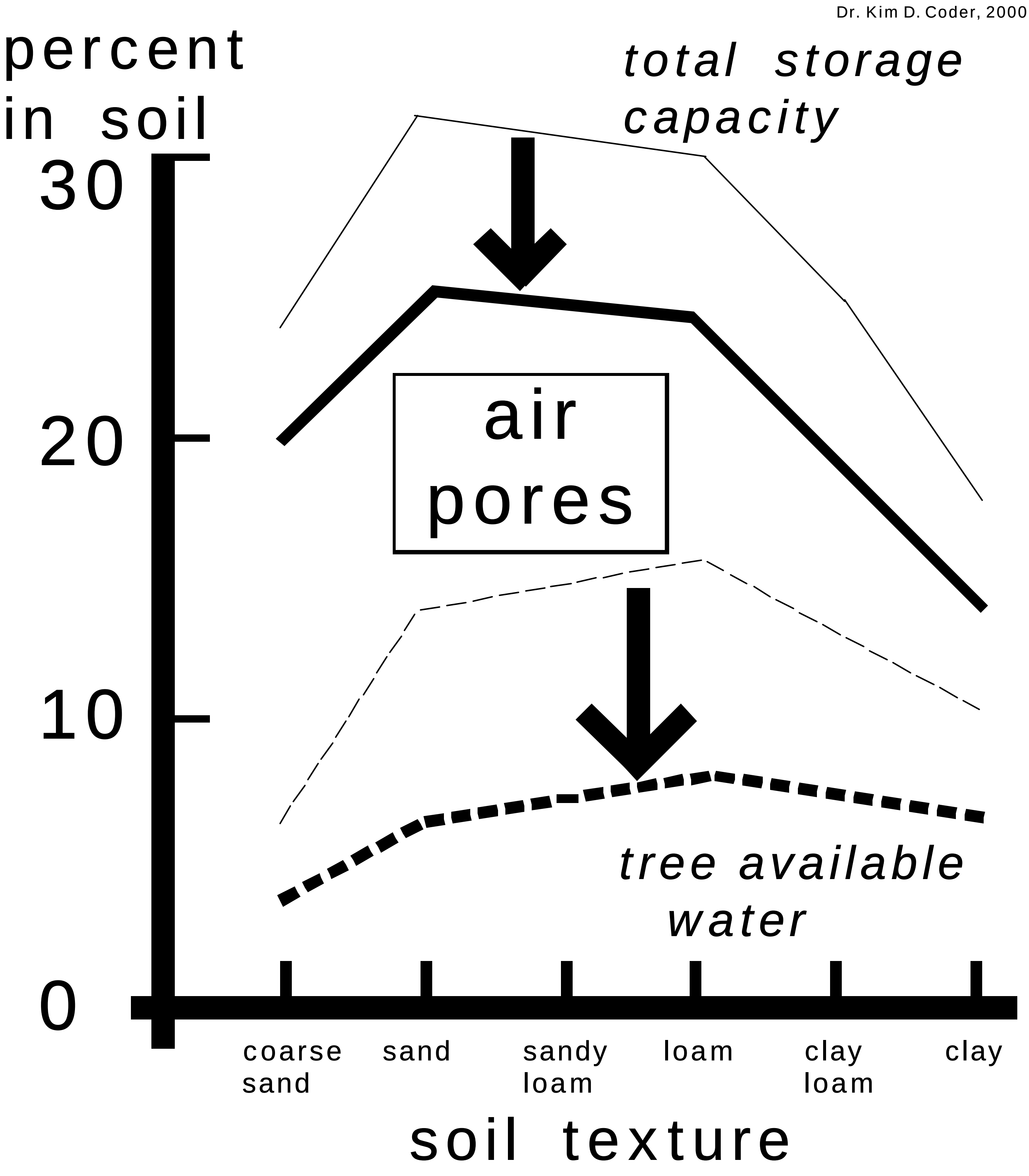

Figure 20: Water storage capacity under compaction. (after Craul 1999)

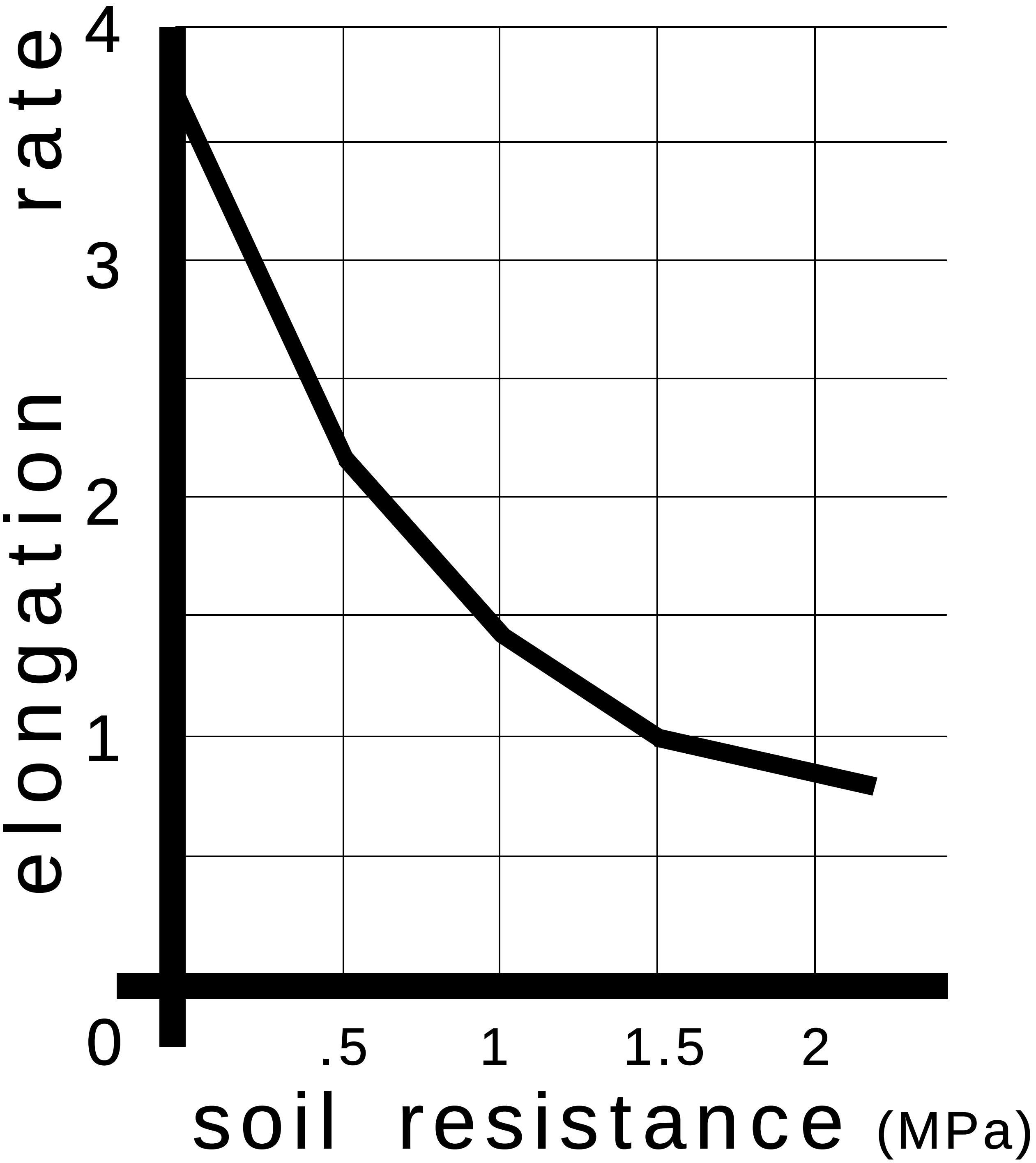

Figure 21: Soil penetration resistance and root elongation rate. (after Rendig & Taylor 1989)

(1 MPa =100 kPa ≈ 1 bar)

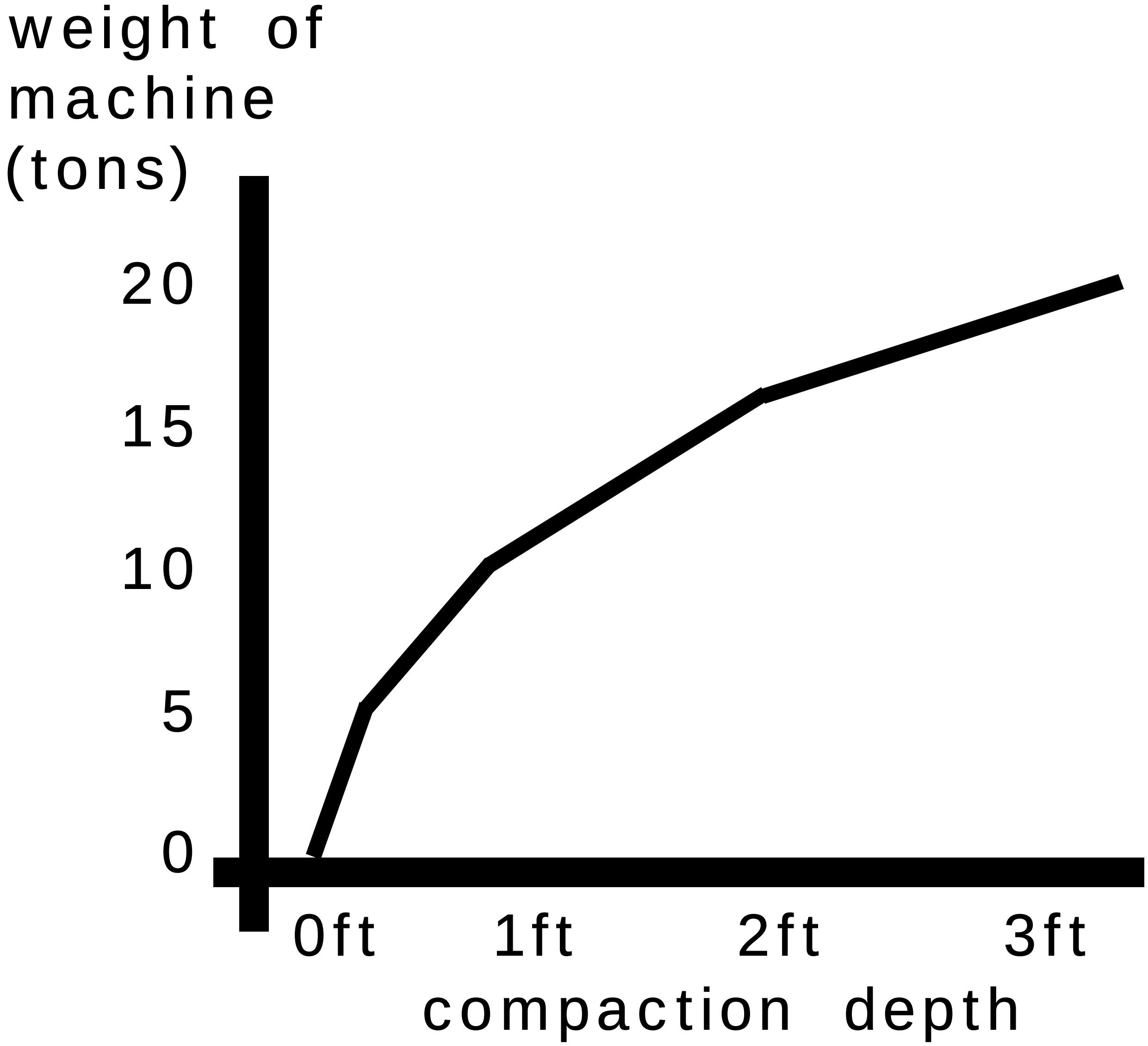

Figure 22: Depth of soil compaction under machines of various weights. (after Randrup 1999)