Root Growth Requirements and Limitations

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Minimizing tree root growth impacts on infrastructures requires an appreciation of how roots function and generate force. To control root growth, identification of growth limiting attributes of the soil environment is necessary. Tree-literate management will control growth, protect infrastructure from root-caused problems, and protect the values and quality of trees.

Root Growth

Growth is a permanent increase in whole organism size. 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 1. By understanding resource levels that limit root growth, better means of controlling growth can be developed.

Table 1: Brief list of root growth resource requirements.

	requirements	
root resource	minimal	maximum
oxygen in soil atmosphere (for root survival)	2.5% (17)	21%
air pore space in soil (for root growth)	12% (10)	—
soil bulk density restricting root growth (g/cc)	—	1.4 clay (10)
	—	1.8 sand (10)
penetration strength (water content dependent) (28,29)	0.01kPa	3MPa
water content in soil	12% (17)	40% (17,27)
root initiation (O_2% in soil atmosphere)	12% (17)	21%
root growth (O_2% in soil atmosphere)	5% (17)	21%
progressive loss of element absorption in roots (O_2% in soil atmosphere)	15% (17)	21%
temperature limits to root growth	40^{o}F/4^{o}C	94^{o}F/34^{o}C (12)
pH of soil (wet test)	pH3.5	pH8.2

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Roots utilize soil spaces for access to water and essential element resources, and to provide structural support. The mineral matrix of the soil surrounds small water-filled pores and larger air-filled pores. Many of these soil pores are continually filling and draining with water and air, depending upon water supplies, water uses, and the atmosphere above. 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.) (46).

Root Locations

Roots survive and grow where adequate water is available, temperatures are warm, and oxygen is present. Roots are generally shallow, 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 by fissures and cracks in the soil and around roots generated by the mechanical forces exerted on the crown and stem under wind loads (sway) (22).

Roots proliferate where essential resources are concentrated. Roots will traverse long areas of poor resources, as long as oxygen and moisture is available. Upon sensing (discovery) of organic materials and available resources, absorbing root fans will be generated to colonize and control resource space. Roots under pavements, for example, may grow across an area, close to the surface or cement underside in a relatively unbranched form, only to explode into absorbing root fans on the other side of the pavement (28).

Root Growth Mechanics

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 (48). Oxygen for respiration, and adequate water supplies are required (48). (Figure 1 (48)). Tree roots can consume large amounts of oxygen during this process. At 77^{o}F (25^{o}C) tree roots will consume nine times their volume in oxygen each day (17), at 95^{o}F (35^{o}C) roots can use twice that volume. The osmotic costs to cells of resisting surrounding forces and elongating can be significant.

As the diameter of an expanding root increases, both its strength to resist structural failure and the expansive force it can generate increases (31). As roots elongate against soil, their ability to resist structural failure is dependent upon root diameter and expansion length (7). The longer the root tip under elongation pressures and/or the smaller in diameter the root, the greater chance structural failure will occur (7). Short and thick roots generate significant force and minimize structural failure. Radial expansion of the roots immediately behind the tip also help fracture or reduce penetration resistance in the soil ahead of the elongating root tip (7, 31).

Growth Forces

Roots use the mass of the tissues behind the tip, including root hairs, lateral root formation, and microbial entanglements to minimize the length over which root elongation force is expressed, thus reducing structural failure potential (46). As the root elongates, only root tissue within approximately six root diameters of the tip will be involved with force generation (7). Root tissue further back will act as a anchor / support base in order to push against the soil (7).

If a root is compressed from the sides, it can exert significant force in elongation, depending upon its diameter (31,37). The greater the diameter, the more force available for elongation (31). The resistance of the soil to allow penetration is dependent upon the force exerted by the root over its cross-sectional area (7). The bigger the root, the slower the growth for an equivalent amount of force applied, or the greater the force that can be applied (7, 37).

Maximum Forces

The maximum force that roots can exert range from 9-15 bars (9-15 MPa), with 10 bars (1MPa) being most cited (17,42,46). This pressure value is a maximum, with roots instantaneously sensing root tip progression and osmotically adjusting elongation to barely push through soil pore spaces. Note that tree roots can not generate enough pressure to push into cement, pipes, asphalt, wood, most plastics, or most metals. Roots can only take advantage of cracks and faults already in materials, or exacerbate cracks and faults by growing root mass within, beneath or around materials (19).

Because generation of root elongation force is an energy requiring process, only as much force as is needed is brought to bear. The foundation force used in elongation arises from osmotic forces using solutes and water. When water is in short supply, or when temperatures increase, diameter of roots are sacrificed to facilitate more elongation (42). Roots can loose more than 1/3 their diameter under dry conditions, leaving roots thinner and elongating at a slower rate (42). (Figure 2 (42)) The loss of contact with the soil, and potential for mechanical failure (buckling) of elongating roots, can lead to poor tree support.

Morphology Changes

Root thickening, or an increase in diameter, is controlled through growth regulation signals emulating from shoot and root tips, and associated changes in cellulose microfibril angles within expanding cell walls (7). Root radial growth under poor soil conditions is stimulated by small amounts of ethylene. Ethylene is generated by excessive auxin build-up in the roots caused by oxygen shortages, flooding and hot temperatures. Less than 10ppm ethylene can stop root elongation and can lead to radially thickened roots (42,46).

In response to increased compaction, roots thicken in diameter (31,53). 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 (7). Thicker roots exert more force and penetrate farther into compacted soil areas (31). As soil penetration resistance increases in compacted soils, roots thicken to minimize structural failure (buckling), to exert increased force per unit area, and to stress soil just ahead of the root cap to allow easier penetration (31). (Figure 3 (37)).

Changing Pore Spaces

Many soils in developed areas are compacted. Compaction is the reduction in size of soil pore spaces by pressure from the surface, like feet, bikes, vehicles, and vibrations. As soils become more compacted, root growth is modified. The physical features of the soil impacting root growth under compaction are increasing soil strength, increasing soil density, and less air containing soil pores.

For effective root growth, pore sizes in the soil must be larger than root tips (17). 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. 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 (46). If the soil pore sizes are too small for even the lateral roots, root growth will cease.

Conclusions

Tree roots are opportunistic in the colonization and control of resource space. The attributes which make a root an ideal resource gatherer for the tree, conspire to make roots infrastructure explorers and fault exploiters. To eliminate roots from infrastructure interactions, an understanding of environmental features that limit root growth is required

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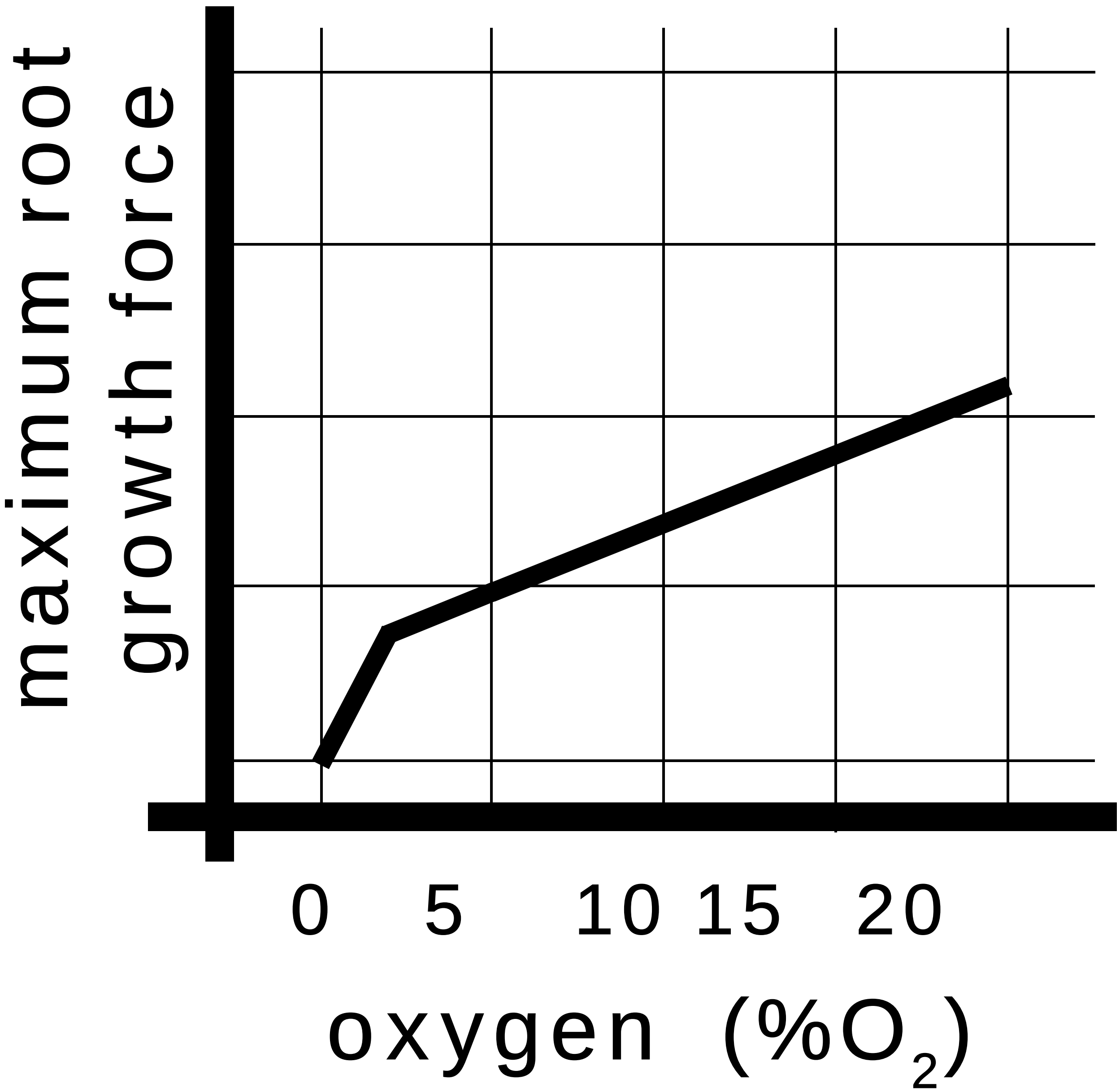

Figure 1: Maximum root growth
force expressed by seedling at
various oxygen concentrations.
(48)

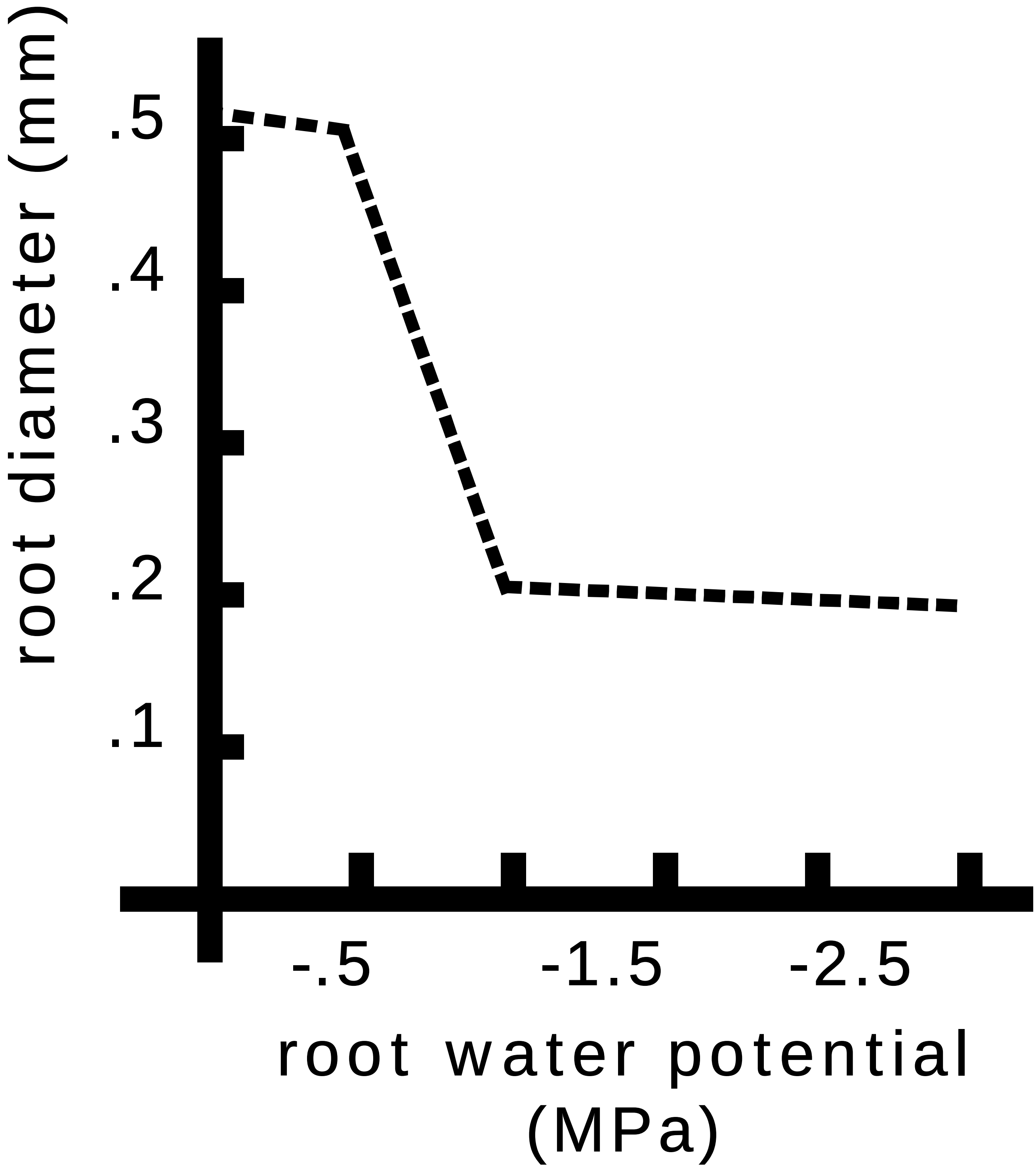

Figure 2: Root tip diameter and root water potential. (42)

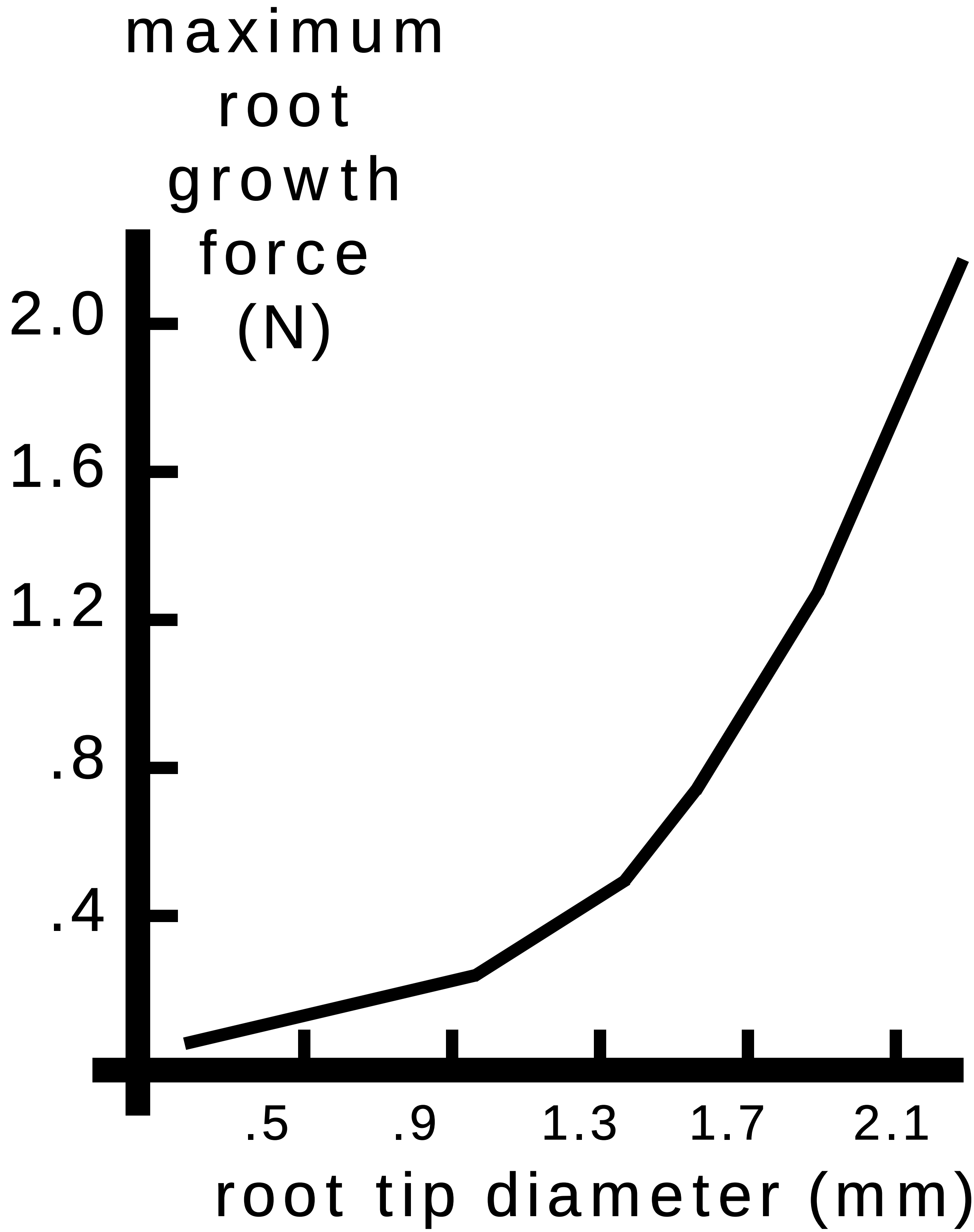

Figure 3: Maximum root growth force by root tip diameter. (37)