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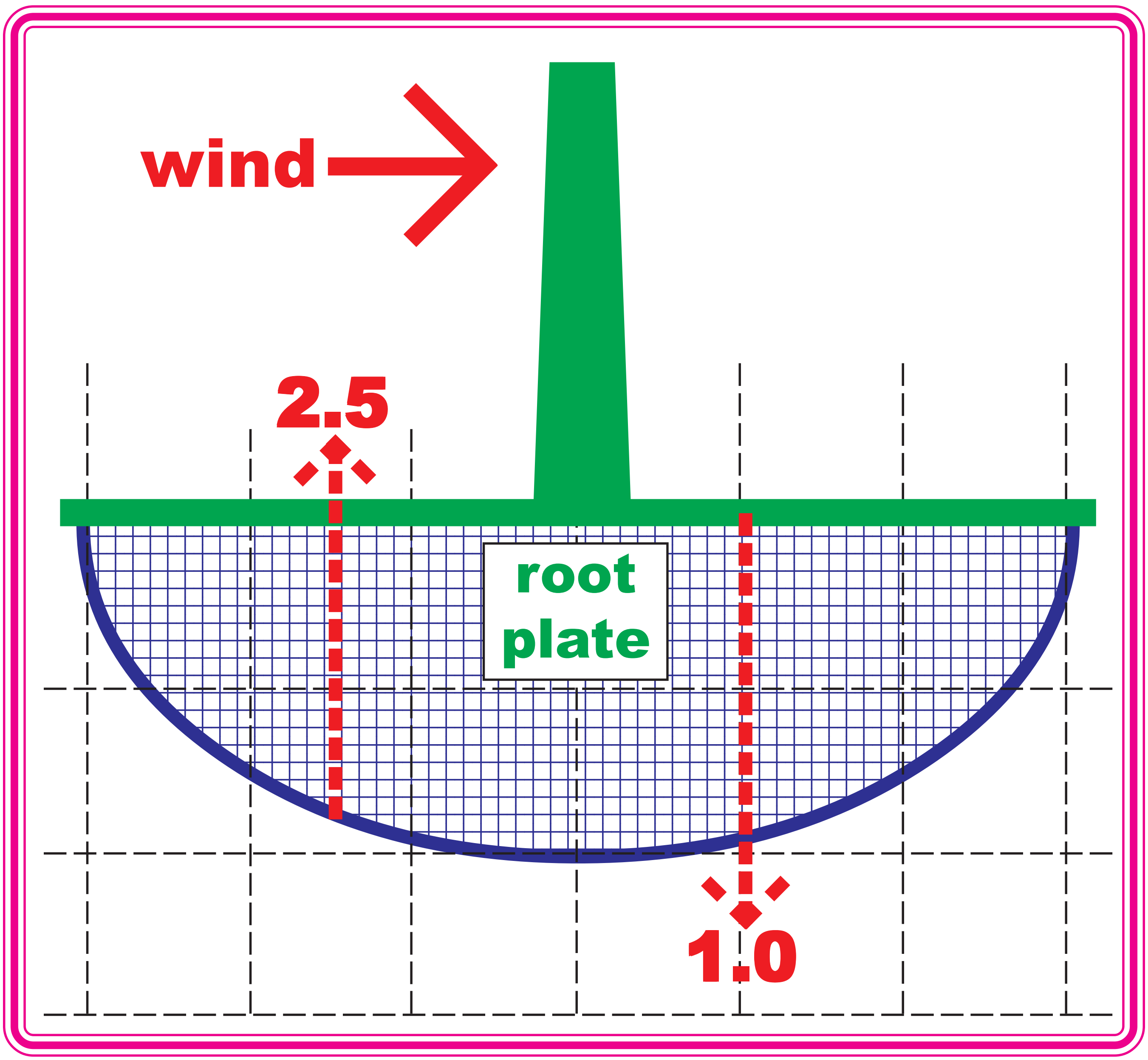
Tree Anchorage & Root Strength Manual

Dr. Kim D. Coder, Professor of Tree Biology & Health Care / University Hill Fellow
University of Georgia Warnell School of Forestry & Natural Resources



This publication is an educational product designed for helping tree professionals appreciate and understand a number of unique basic aspects of tree anchorage in a landscape soil. This manual is a synthesis and integration of peer-reviewed research and educational concepts regarding how tree root strength and geometry impact whole tree biomechanics. This educational product is for awareness building and professional development. This product does not represent tree rooting area specifications for preservation or tree anchorage standards.

At the time it was finished, this publication contained models of tree anchorage thought by the author to provide the best means for considering fundamental tree health care issues surrounding root strength and anchorage of trees. The University of Georgia, the Warnell School of Forestry & Natural Resources, and the author are not responsible for any errors, omissions, misinterpretations, or misapplications from this educational product. The author assumed professional users would have some basic tree and soil background. This educational product was not designed, nor is suited, for homeowner use. Always seek the advice and assistance of professional tree health providers for tree care and structural assessments.

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There has been a proliferation of tree anchorage research in the last decades. Most of the research published in the best peer-reviewed, scientific journals have focused on forest stands, steep slopes, and single tree failure risks. Research groups from the European Union (France, United Kingdom, and Italy in particular), Japan, Canada, and New Zealand have led the way in understandings regarding root strength and tree anchorage. This paper reviews and integrates a number of these research findings.

Root Attributes

Logically, successful tree anchorage depends upon the size of wind and gravity loading, and structural resistance to wind and gravity loads Tree structural resistance to wind and gravity loading is distributed and shared throughout a tree in various components. Figure 1. In this paper, only root strength and tree anchorage components resisting tree over-turning and up-rooting will be examined.

Trees have many roots of many sizes which all play some role in anchorage. For example, one spruce examined had a total of 82,500 roots. Of these roots, large roots (>1/5inch diameter) were estimated to be 62% of all roots, while small roots (<1/5inch diameter) comprised 38%. (Parr & Cameron 2004) In a different study, 85% of all tree roots were found to be smaller than 1/5 of an inch in diameter. (Abe & Ziemer 1991) Another study estimated 96% of tree roots are less than 2/5 inch in diameter. (Abernethy & Rutherfurd 2001) Dominant structural roots were found to provide more than 80% of total root mass, concentrated in 3-10 of the largest roots. (Coutts et al. 1999) Figure 2. In summary, there are a few large diameter roots and a host of small roots.

Mass & Friction

Tree anchorage is dependent upon friction between soil and root surfaces, and upon the shear weight and size of a tree and its root system. Anchorage of a tree has been found to be directly associated with tree size. As tree diameter (DBH) increases by 2X (two times), the energy required to cause failure increases by ~30X (thirty times). (Stokes et al.. 2005) Figure 3. Anchorage has been correlated with both stem weight (Figure 4; Figure 5), and tree diameter--height relationships (i.e. generic stem taper or shape factor). Figure 6; Figure 7.

Resistance to tree anchorage failure is also associated with structural attributes of root systems. Figure 8 presents three generic root types and two areas of interest beneath a tree. The rooting areas include: 1) root plate with large diameter, structural, rapidly tapering roots; 2) wide-ranging, woody transport roots structurally used under tension to resist higher wind speeds; and, 3) non-structural, shallow, horizontal absorbing root fans. The root plate edge and drip line edge are delineated in the figure.

Composite Values

Root value in tree anchorage is dominated by root number, root diameter, root density per soil volume, and associated root cross-sectional area. Root biomass is a composite of all these factors. Figure 9. Deeper into a soil, the smaller average root diameter becomes and the fewer roots are present (i.e. smaller roots and less root density). Figure 10; Figure 11. The decreasing number and size of roots

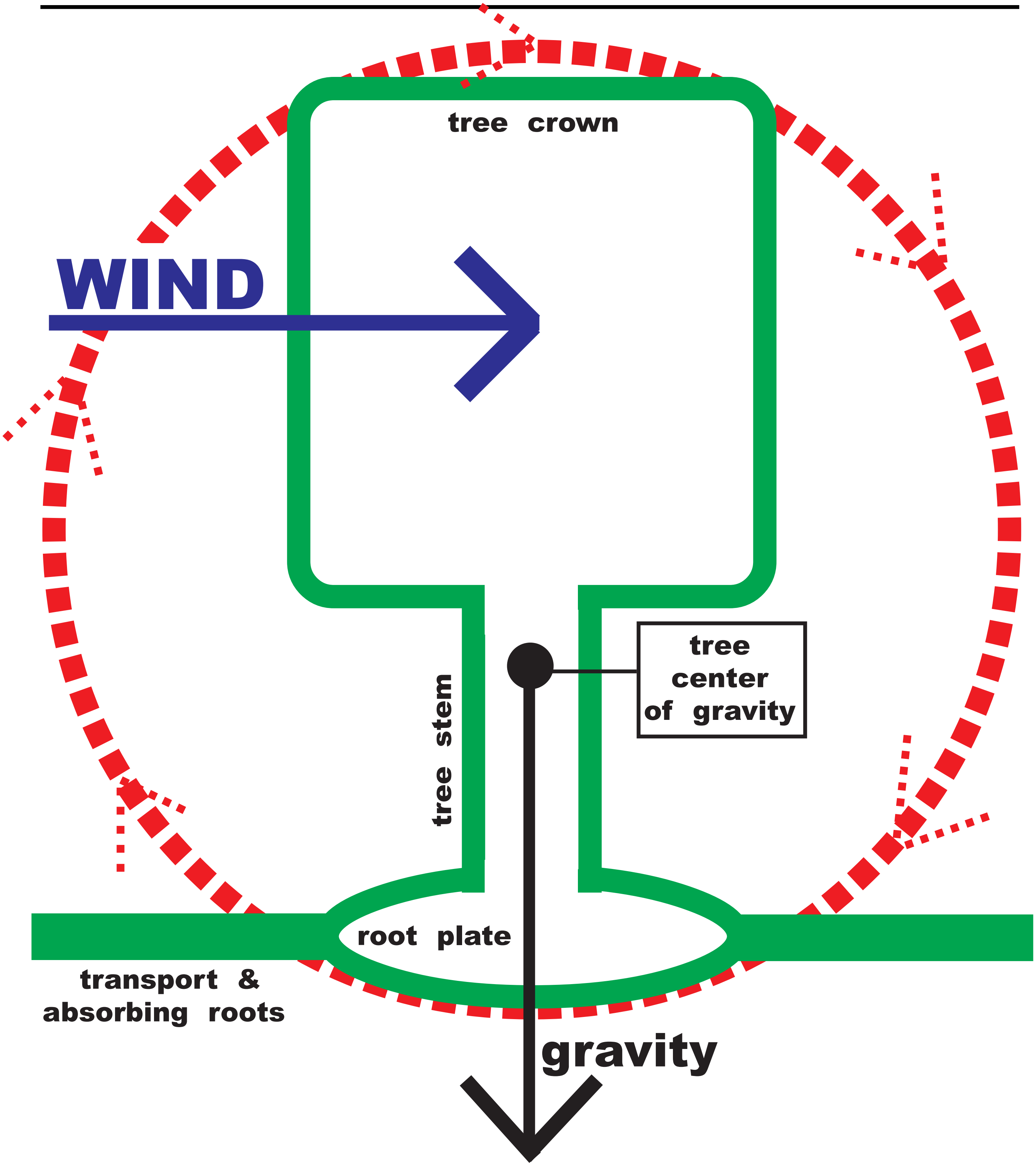

Figure 1: Simplified view of wind loading and gravity acting to rotate a tree out of a soil as a combined load wheel.

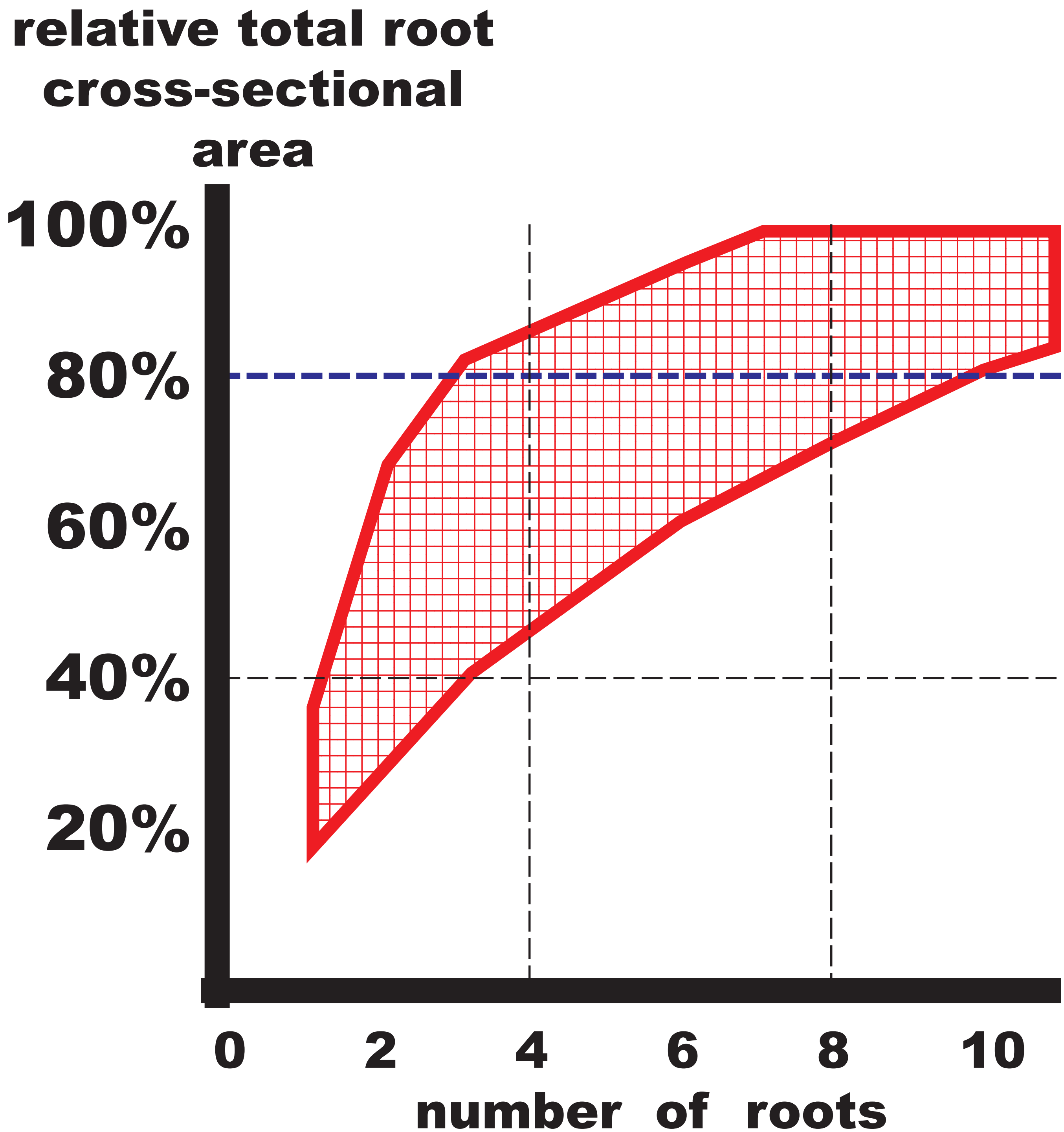

Figure 2: Range for total root cross-sectional area contained in the largest roots of *Picea sitchensis.*

For example: number of roots = 2, means the combined cross-sectional area of the first and second largest diameter roots. (after Coutts et al. 1999)

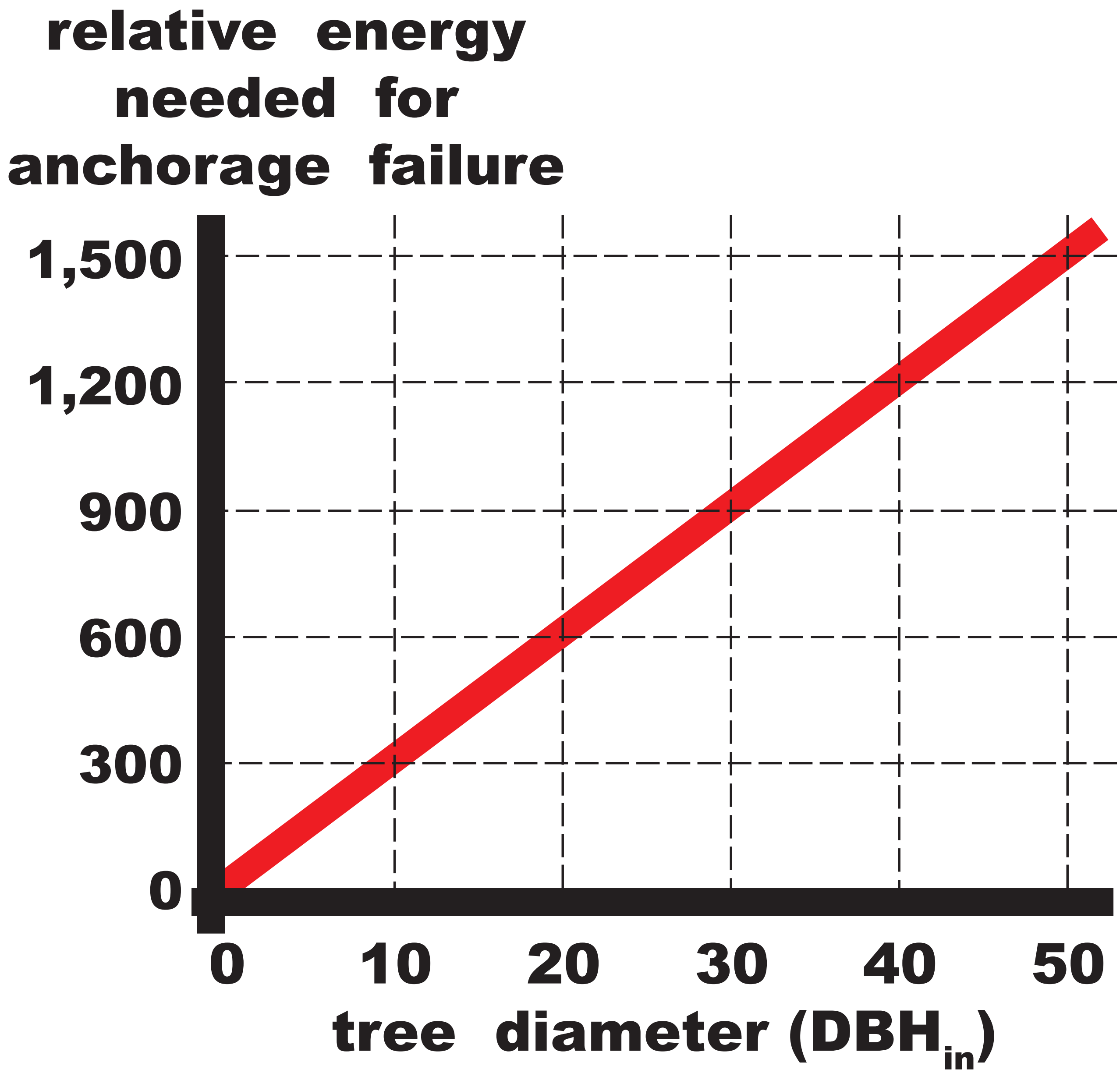

Figure 3: Relative amount of energy needed to over-turn or up-root a tree of a given diameter in inches.
(derived from Stokes 1999)

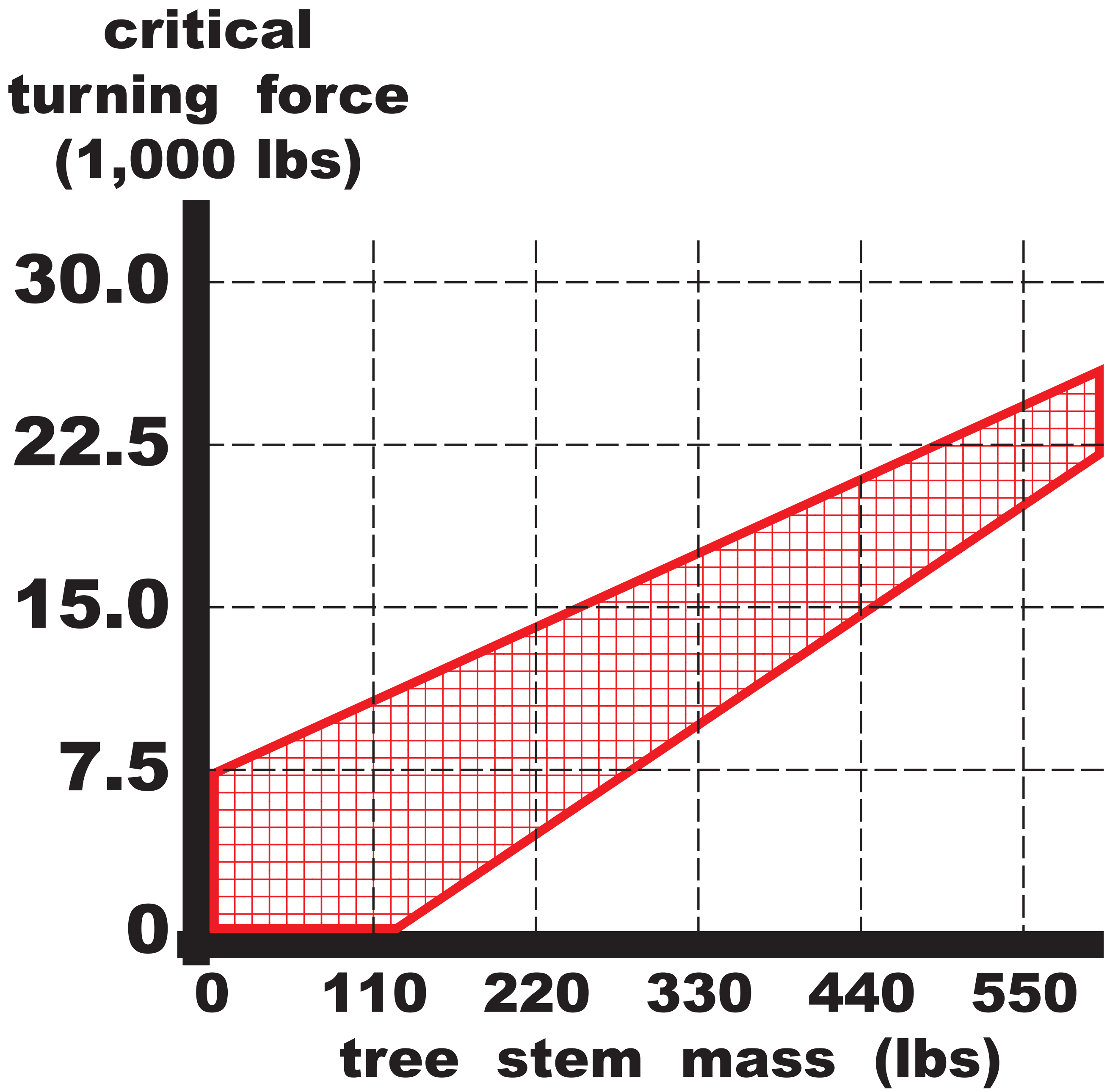

Figure 4: Range of critical turning force in 1,000 pounds for given tree stem mass in pounds. Data are from three studies for two spruces, one fir, and two pines. (derived from Elie & Ruel 2005)

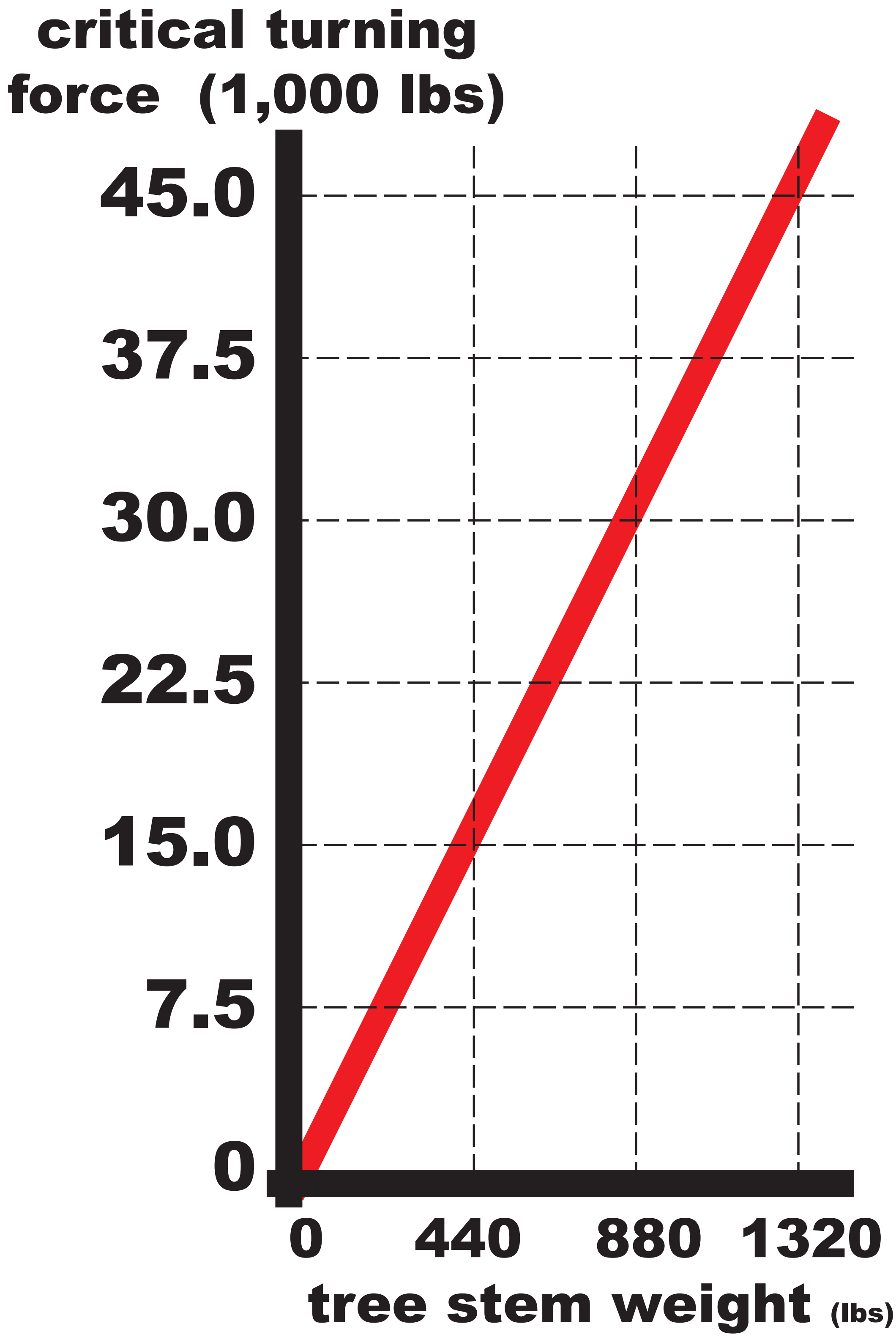

Figure 5: Critical turning force in 1,000 of pounds needed for a given stem weight in pounds -- spruce and fir on different sites. (modified from Achim et al. 2005)

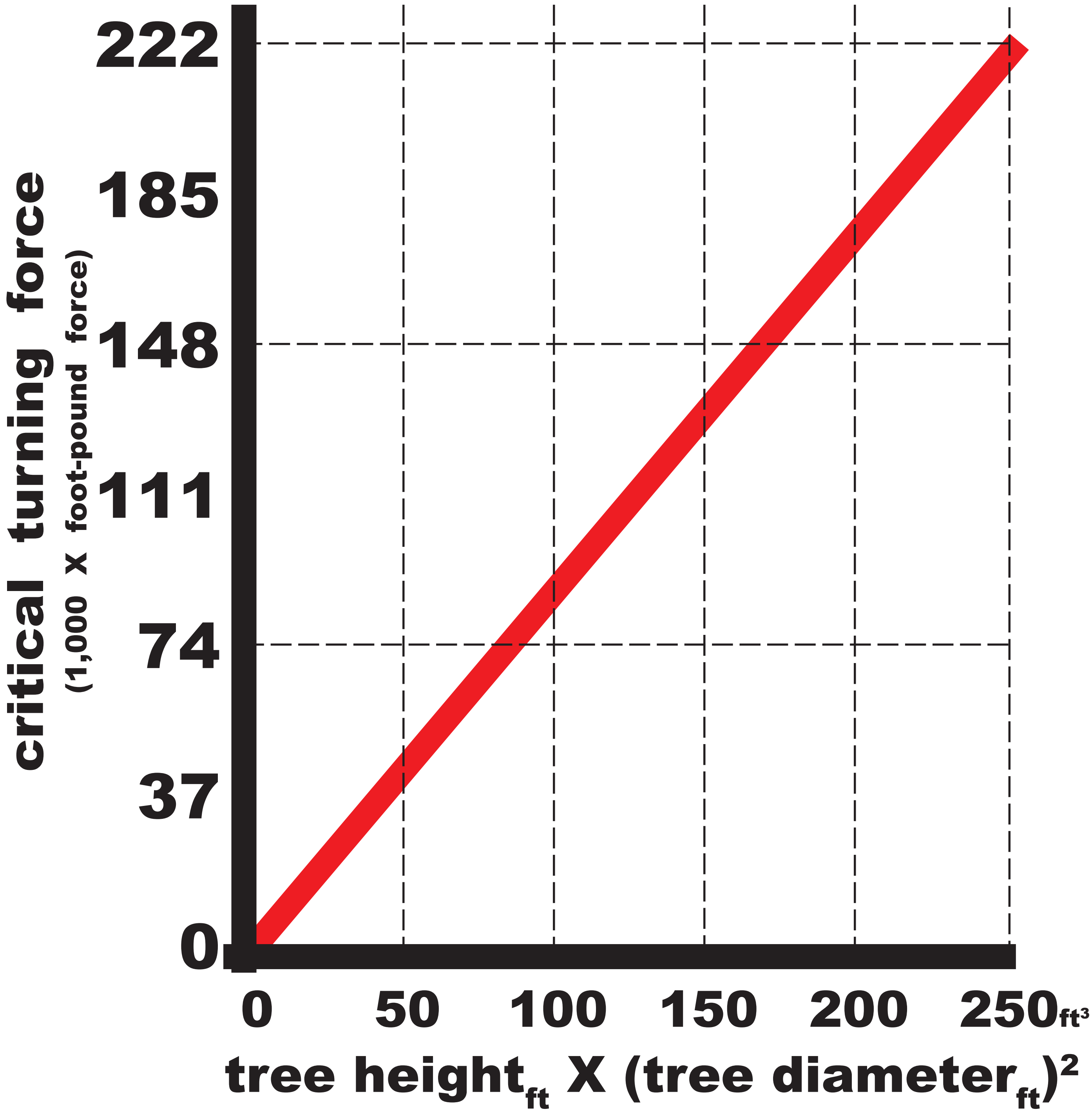

Figure 6: Critical turning force required as stem form changes. Stem form is measured as: (tree height in feet) X (tree diameter in feet)^2 = graph axis value in cubic feet. (from Cucchi et al. 2004)

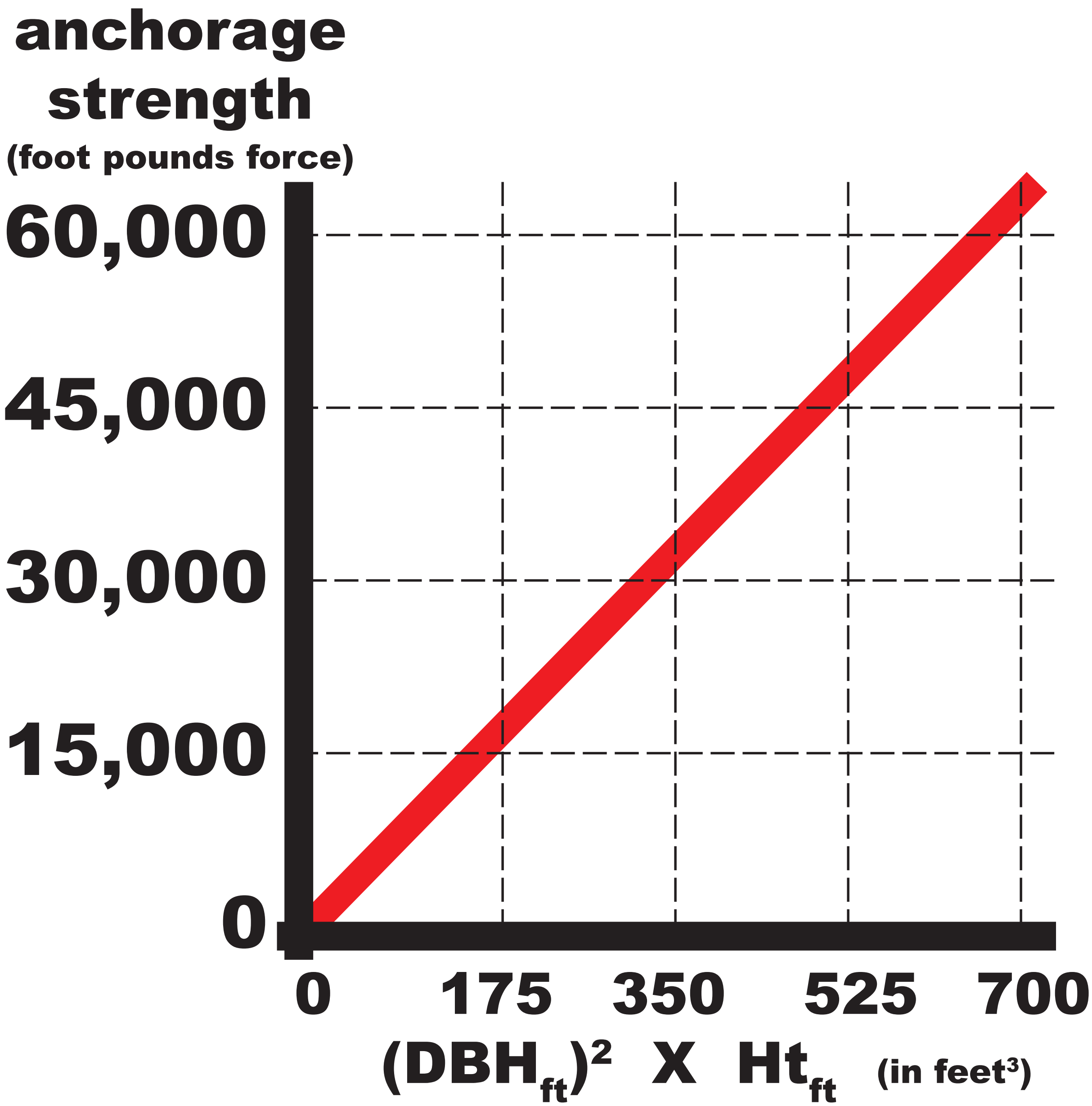

Figure 7: Anchorage strength of conifers in thousands of foot pounds of torque with increasing tree size, as measured by stem diameter in feet squared multiplied by stem height in feet.
(from Lundstrom, et al. 2007)

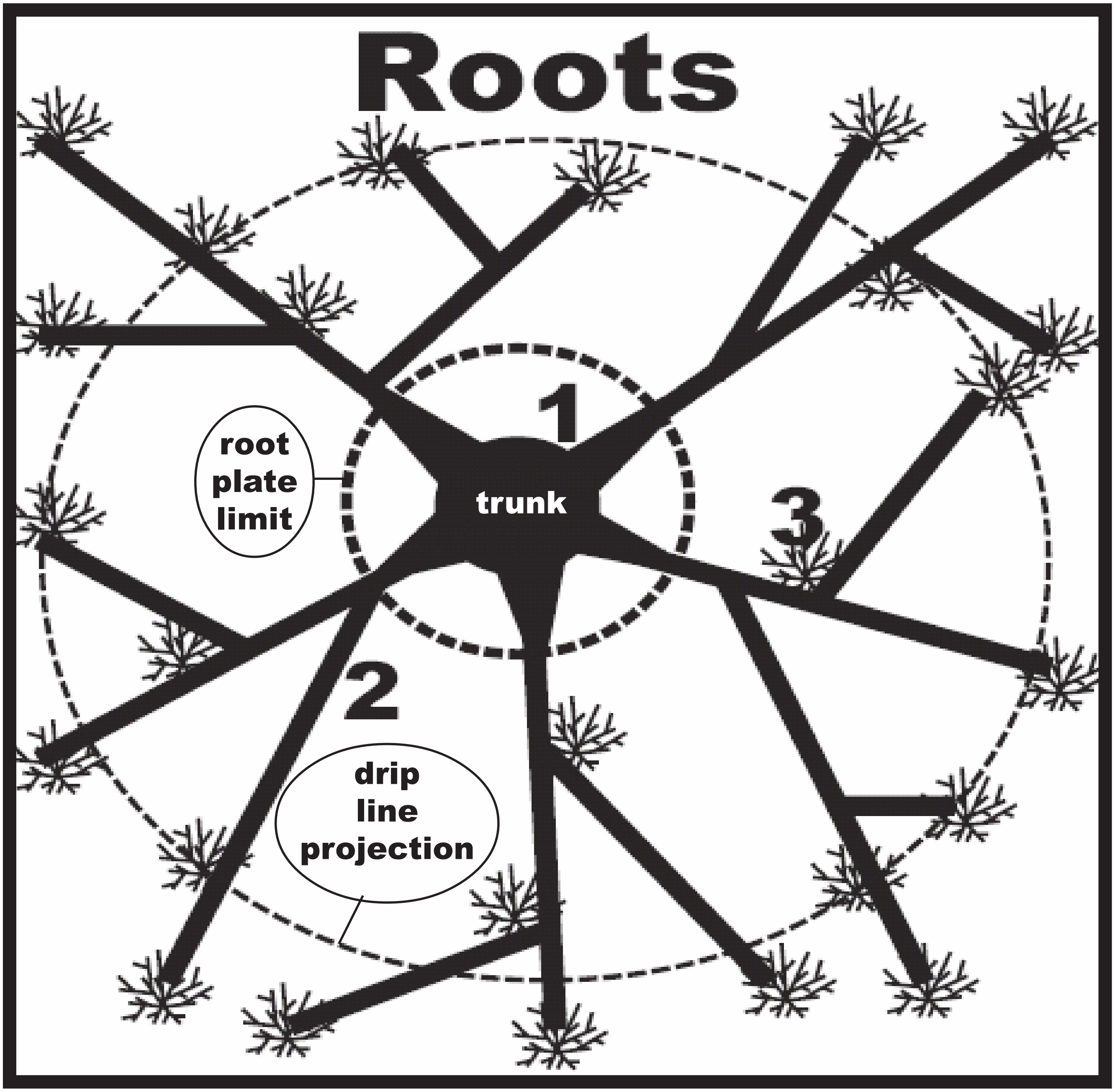

Figure 8: Stylized view from above of three different tree root zones (not to scale and not representing root sizes, number, and density): 1) structural roots and root plate; 2) woody transport roots; and, 3) ephemeral horizontal absorbing root fans. The outer dotted line representing crown projection onto soil surface (i.e. drip line) contains ~65% of active roots found on average sites.

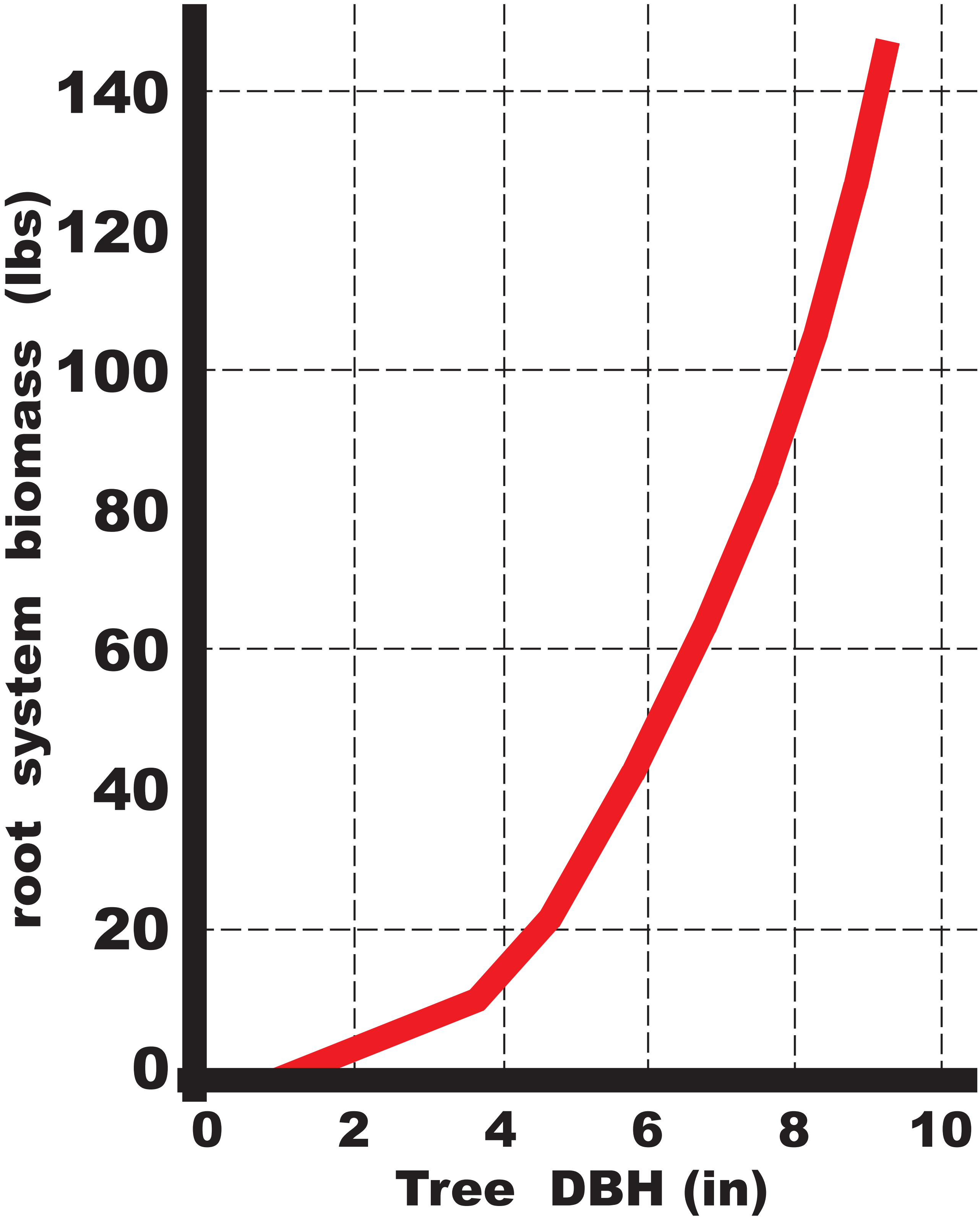

Figure 9: Root system biomass for *Pinus sylvestris* excluding fine roots. Composite data from five different studies.
(modified from Tobin et al. 2007)

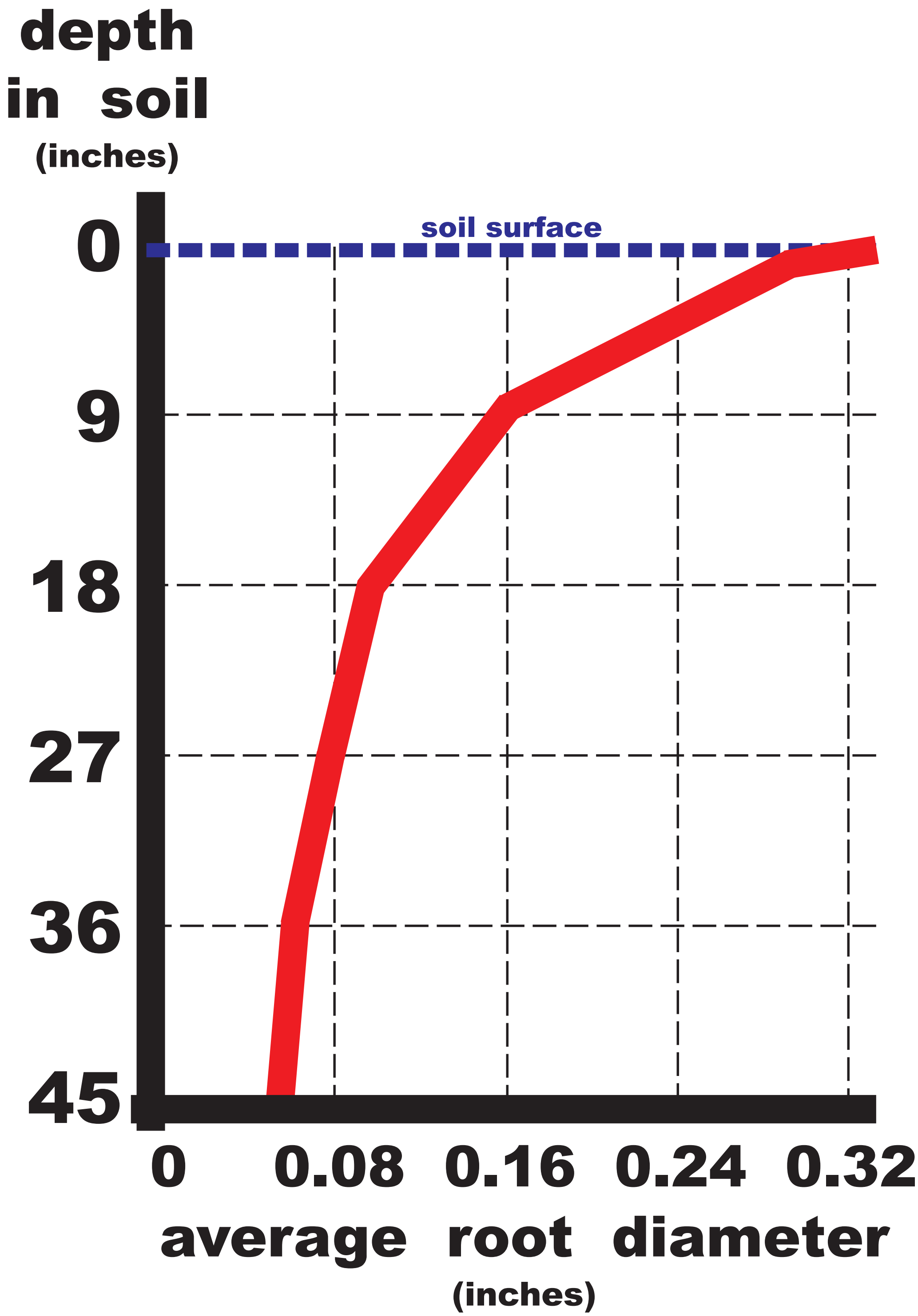

Figure 10: Average tree root diameter in inches with increasing depth in soil.
(from Tosi 2007)

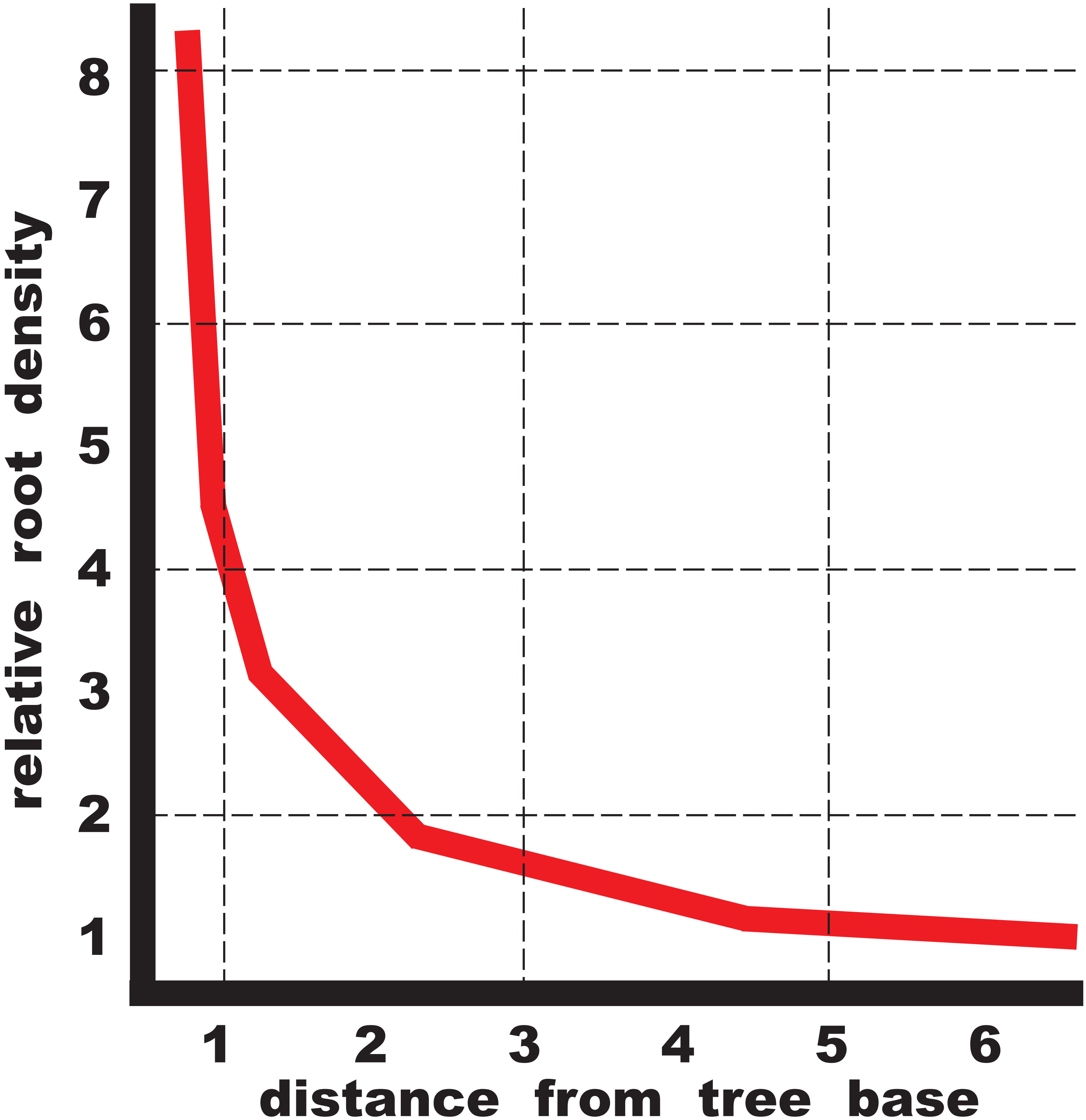

Figure 11: Relative value of root density with increasing distance from tree base. (derived from Abernethy & Rutherfurd 2001)

with soil depth generate a declining total cross-sectional area of roots in soil with depth. Figure 12. A greater number of larger roots are concentrated closer to the soil surface. (Abernethy & Rutherfurd, 2001; Danjon et al. 2008; Tosi 2007) Tree anchorage is a composite of many tree structural attributes.

Push & Resist

Tree root systems are responsive to changes in wind loading. Trees continually challenged by wind are better adapted and reactive to their wind load environment. (Nicoll et.al. 2006) Wind movement of a tree top initiates an increase in total cross-sectional area of roots and induces greater biomass development in roots proportional to the forces applied to the top. More and larger roots are generated parallel to the wind loading direction close to the stem. (Mickovski & Ennos 2003)

Wind Force

For roots to fail anchoring a tree, significant force must be applied to the crown. Force developed in the tree top and focused at the stem base depends upon several factors. The formula normally used is: (Koizumi et.al. 2007)

wind force developed on tree top =
0.5 X (drag coefficient) X (air density) X (wind velocity)^2 X
(projected frontal crown area) X (height wind pressure center in crown).

Tree roots must successfully resist any wind forces developed to avoid breaking, bending, pulling, and tree toppling. Of the factors in the formula above: drag coefficient can be assumed to be between 0.2 and 0.4 under moderate wind speeds; air density under average conditions can be assumed to be 1.2 kg/m^3 ; wind velocity is always a squared term; projected frontal area of the crown is the dimensions of height, width and shape facing into the wind; and, height of wind pressure center in the crown is assumed to be 0.33 of crown length above crown base. (Koizumi et.al. 2007)

By inserting more easily measured tree crown geometry values, and assuming a constant wind velocity (where the wind is not gusting and calming, or rapidly changing), the wind force formula can be redefined as: (Koizumi et.al. 2007)

wind force developed on tree top =
0.5 X (wind velocity)^2 X (air density) X
[((drag coefficient) X (crown length) X (crown width)) / 2 X
((height to crown base) + (crown length / 3))].

In addition to crown width and length, a crown shape coefficient could be included to more accurately represent the frontal cross section or resistance volume of a tree crown toward the wind. Figure 13 provides Coder tree crown shape coefficients.

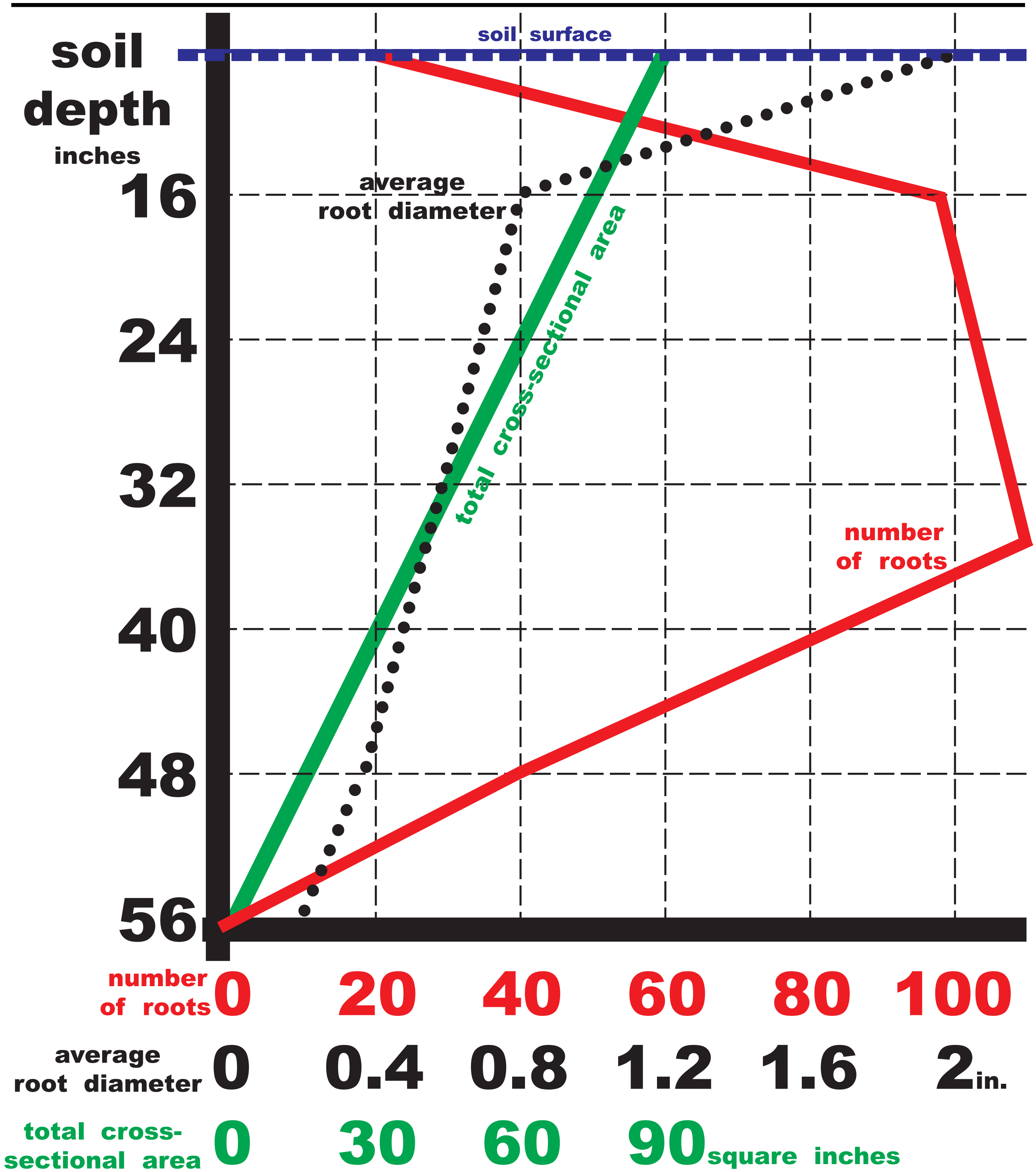

Figure 12: Tree root distribution in a well-drained, sloped soil showing number of roots, average root diameter in inches, and total cross-sectional area of roots in square inches.
(from Danjon et al. 2008)

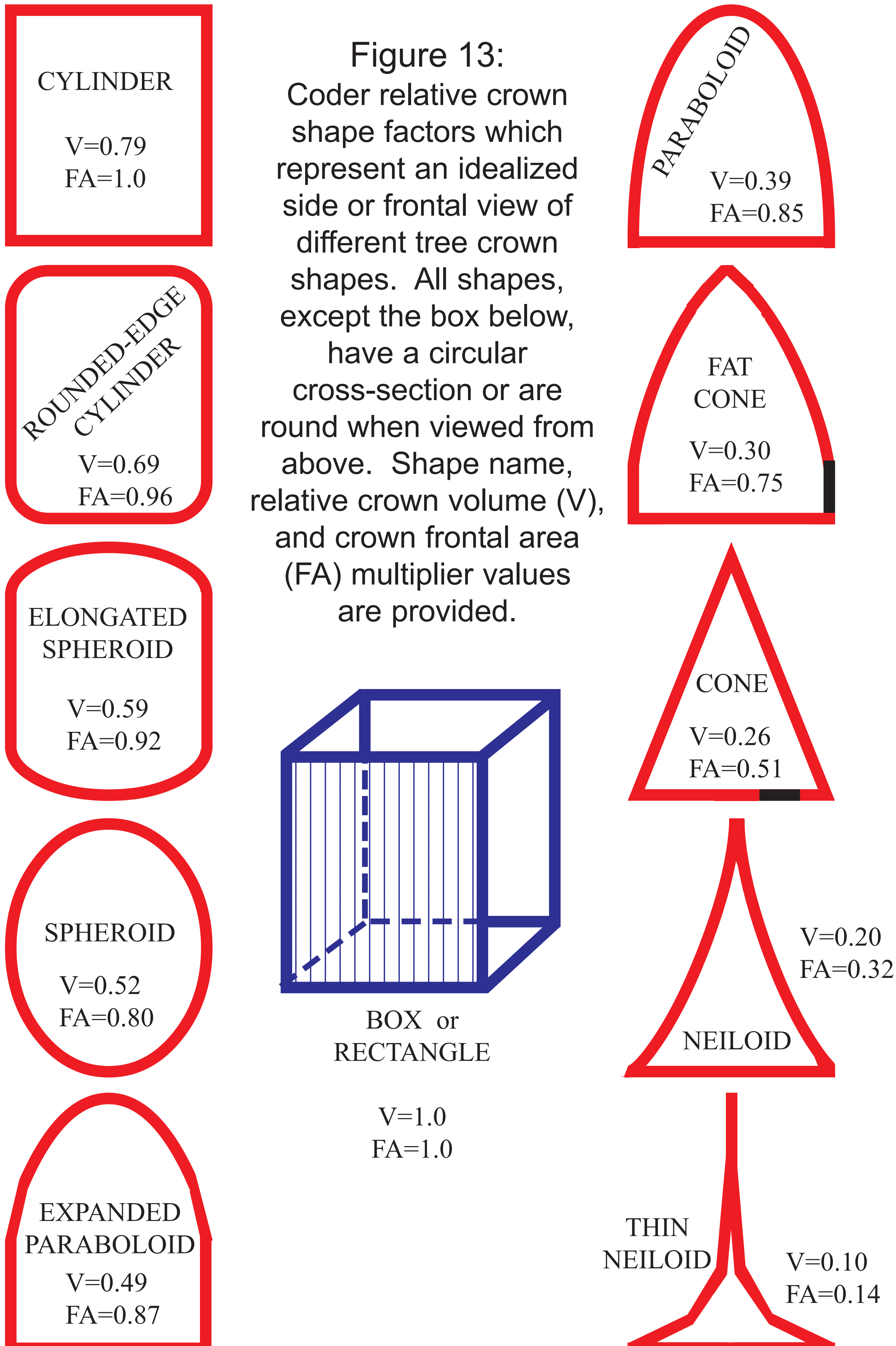

Figure 13:
Coder relative crown shape factors which represent an idealized side or frontal view of different tree crown shapes. All shapes, except the box below, have a circular cross-section or are round when viewed from above. Shape name, relative crown volume (V), and crown frontal area (FA) multiplier values are provided.

Wind Impacts

Wind applied forces on tree crowns and resisted by tree root systems have three components: A) average wind speeds; B) gust speeds above average wind speeds; and, C) turbulence. The scale of gusts and turbulence, including periodicity and duration, can quickly and catastrophically place unrecoverable loads onto trees which were previously handling average steady wind speeds. (England et.al. 2000)

Resistance of a tree to over-turning is challenged by forces placed on the crown by wind loading. Figure 14 shows the proportion of various stresses applied to a tree. Wind has roughly 10X the impact of a tree lean of 5^o, and lean has 10X the impact of top weight with tree height increases. In the end, it is wind loading which dominates the stress and strain on the tallest trees.

With Age

Over time, trees grow larger with more soil area colonized and larger stems, taper, and root surface area. The relative change in tree resistance to over-turning remains roughly the same until old age constraints begin to limit tree reactions to its wind environment. (Achim et.al. 2004) Figure 15.

As trees age, structural investment differences between stem and roots occur. Note both root plate resistance and wind force applied (i.e. an up-rooting resistance index) increase with tree age and size, suggesting up-rooting resistance can be stable over years unless something catastrophic occurs. (Koizumi et.al. 2007) As a general rule when young, trees are more likely to break stems, and with age more up-rooting occurs. (Koizumi et.al. 2007; Stokes 1999) Figure 16 shows stem resistance to failure with age out-pacing root resistance over time.

Failings

Uprooting resistance of tree roots depends upon the strength and stiffness of roots, and susceptibility of roots to failing under wind forces presented on a site. Tree roots will fail in one of two ways, depending upon soil characters. In shallow soils, windward side horizontal roots will tend to fail in tension. In deep soils, the root plate will tend to shear, slip and rotate out of the soil. (Koizumi et.al. 2007) The roots not in-line with the wind or force direction, (or perpendicular to the force along a root plate) are placed in torsion by the wind forces (twisted). These roots under torsion have little resistance to add in preventing up-rooting. (Danjon et.al. 2005)

Tree root failure under wind loading is comprised of root breakage, soil breakage or shifting due to plasticity, and roots shearing off and sliding out of soil. (Dupuy et.al. 2005) Individual roots tend to fail in one of three patterns: (Norris, 2005)

Failure pattern #1 occurs as a straight root is pulled directly from soil. This failure pattern occurs relatively suddenly as frictional forces between soil and a tapered root are exceeded.

Failure pattern #2 occurs as a lateral root with many small lateral roots attached is pulled. This failure pattern occurs after major force is applied and causes gradual failure as small laterals are progressively broken.

Failure pattern #3 occurs as large branched or forked roots are pulled. This failure pattern occurs in abrupt steps as major root components break away.

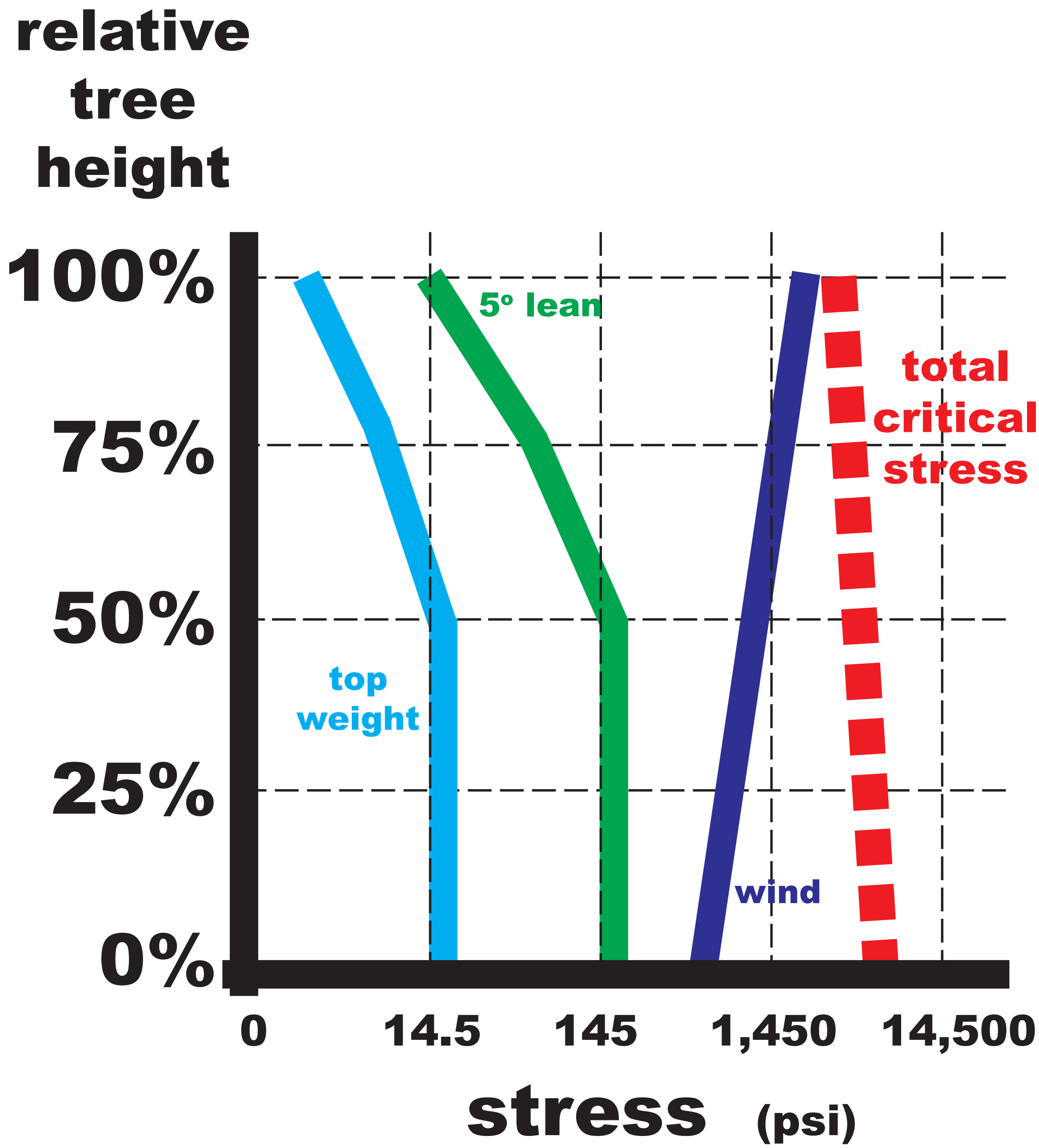

Figure 14: Proportion of total critical stress in pounds of force per square inch across three structural components with increasing relative tree height. Note the log scale for stress.
(derived from Spatz & Bruechert 2000)

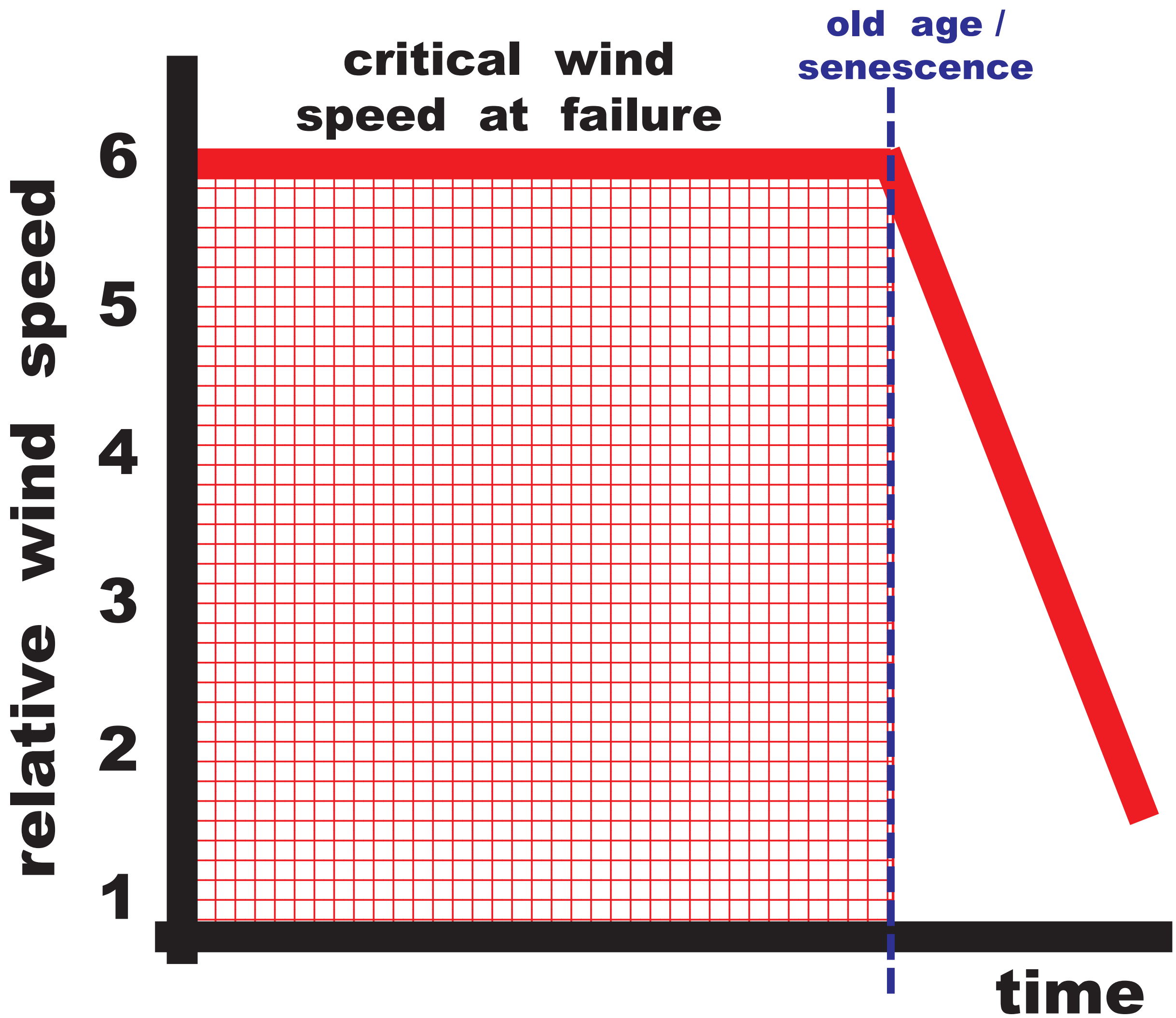

Figure 15: Relative changes in tree resistance to anchorage failure with time at peak wind speeds.
(Achim et al. 2004)

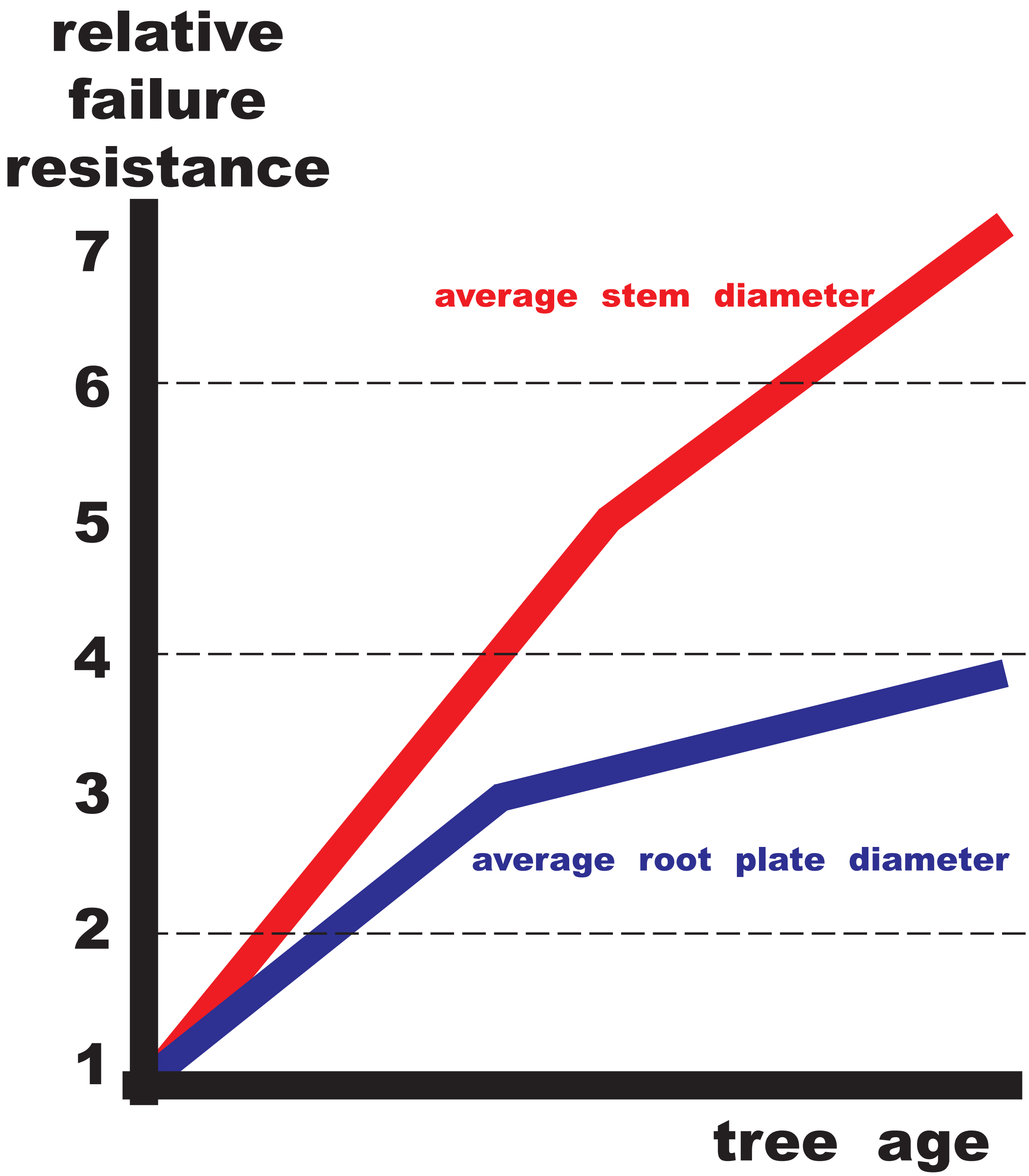

Figure 16: Change in root plate and stem resistance to failure for average diameters as trees age.
(after Koizumi et al. 2007)

These failure patterns are not discrete because of tapered root forms with various sizes of swelled nodes and lateral branch sizes all breaking or bending under different forces and then being pulled through the soil. (Norris, 2005)

Ideally

Tree roots with circular cross-section are stiff proportionally to root diameter to the 4th power ($diameter^4$). Resistance to breakage of tree roots with a circular cross-section are proportional to root diameter to the 3rd power ($diameter^3$). As roots grow in diameter, stiffness to resist bending greatly increases compared with potential breakage. (Danjon et al. 2005) Figure 17. Root diameter growth assures stiffness and resistance to hinging or bending.

Idealized rooting structure for strong anchorage include: 1) many small, long, shallow, windward roots (better resisting tension); and, 2) a few large, gently tapering, deeper leeward roots (better resisting compression and bending). (Danjon et al. 2005)

Tensile Strength

In considering tree anchorage and resistance of roots to failure, root tensile strength must be a factor. Root tensile strength averages for trees vary by species. A range of tree root tensile strengths is shown in the components of the following formula: (Genet et al. 2005)

$$\textbf{root tensile strength coefficient ranges} = (23 \text{ to } 64) \times (\text{root diameter})^{(-0.5 \text{ to } -1.0)} .$$

Specific root tensile strength for a number of different tree species are given in Figure 18. There is a trend for angiosperms to have an exponential value near "-1," and for gymnosperms to have an exponential value near "-0.75." There are many notable exceptions. (Bischetti et al. 2005)

Mighty Mite

Tensile strength within a species varies by root diameter. Greater root strength per cross-sectional area lies in smaller roots and root stiffness lies with the larger roots. Figure 19. It is estimated 96% of tree roots are less than 2/5 inch diameter. (Abernethy & Rutherfurd 2001) The seeming conflict in root strength among small and large root diameters comes from significantly larger cellulose contents (i.e. larger proportion of cellulose in cell walls) in the smallest roots. Cellulose content in root cell walls is directly responsible for root tensile strength. Small roots less than 1mm (1/25 inch) in diameter have high relative tensile strength due to a proportionally high cellulose content. (Tosi 2007)

As root diameters increase, percent of cellulose in cell walls declines. Cellulose is highly resistant in tension but has low resistance to bending. Small roots, with proportionally more cellulose, are much more resistant to tensile forces than large roots per cross-sectional area. (Genet et al. 2005) Larger root diameter, and associated cross-sectional area, cause progressively smaller tensile strength per cross-sectional area. Larger roots as a unit can resist greater total tensile forces simply because of their size. (Tosi 2007)

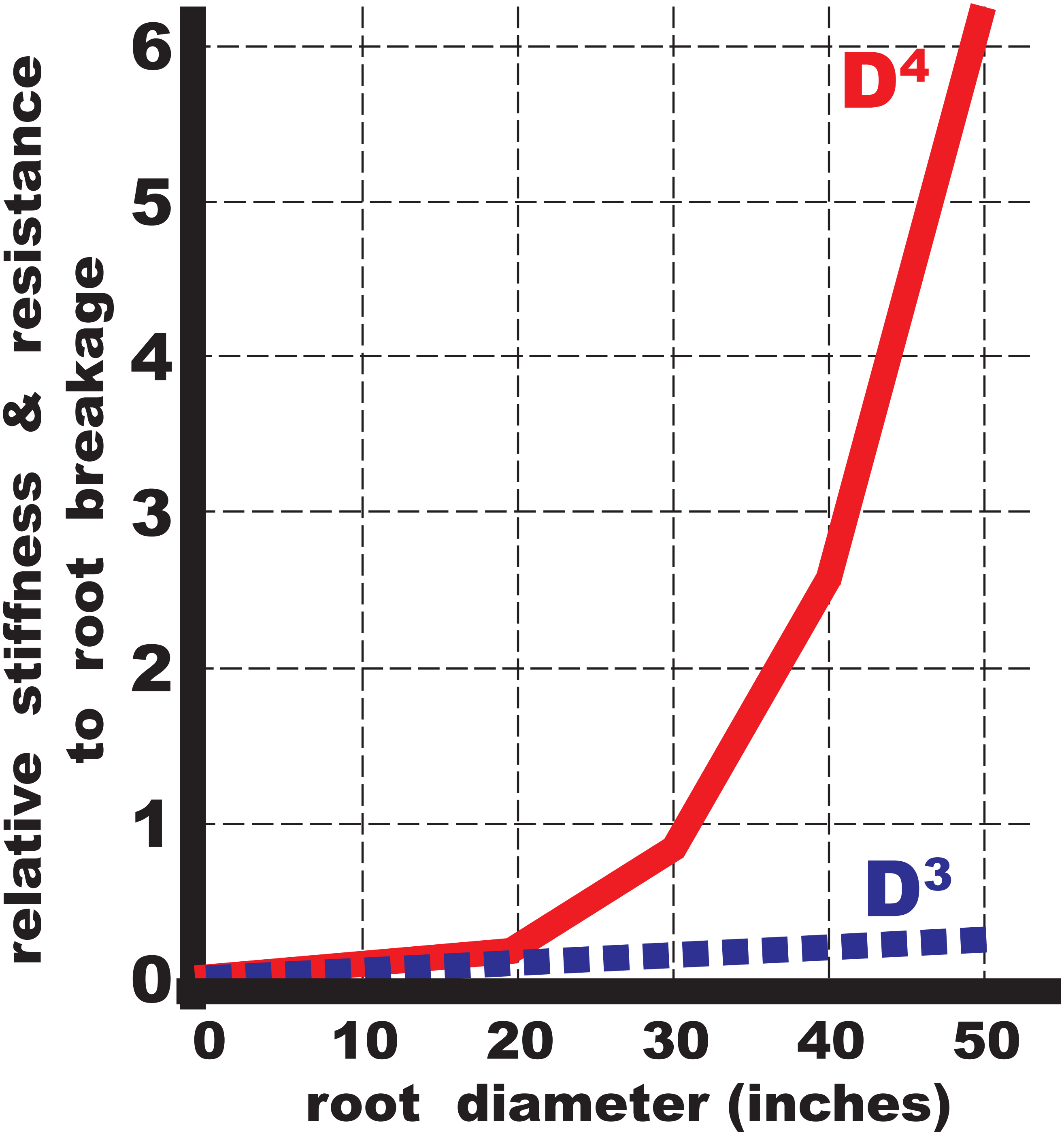

Figure 17: Comparison of roots with a circular cross-section and various diameters (D) for relative stiffness (solid line D^4) and resistance to breaking (dotted line D^3).
(Danjon et al. 2005)

species	root tensile strength	citation
spruce	$28\ D^{-0.7}$	1
general trees	$29\ D^{-0.52}$	2
willow	$31\ D^{-1}$	1
salt-tree	$32\ D^{-0.89}$	3
Euro. mt. ash	$35\ D^{-1}$	1
alder	$35\ D^{-0.75}$	1
larch	$34\ D^{-0.75}$	1
beech	$42\ D^{-1}$	1
eucalyptus	$50\ D^{-0.75}$	4
hazel	$60\ D^{-0.75}$	1

Figure 18: Example formula for estimating tree root tensile strength by species. Note root diameter (D) measures are in millimeters.
(Sources: 1 = Bischetti et al. 2005; 2 = Danjon et al. 2008; 3 = DeBaets et al. 2008; 4 = Abernethy & Rutherfurd 2001).

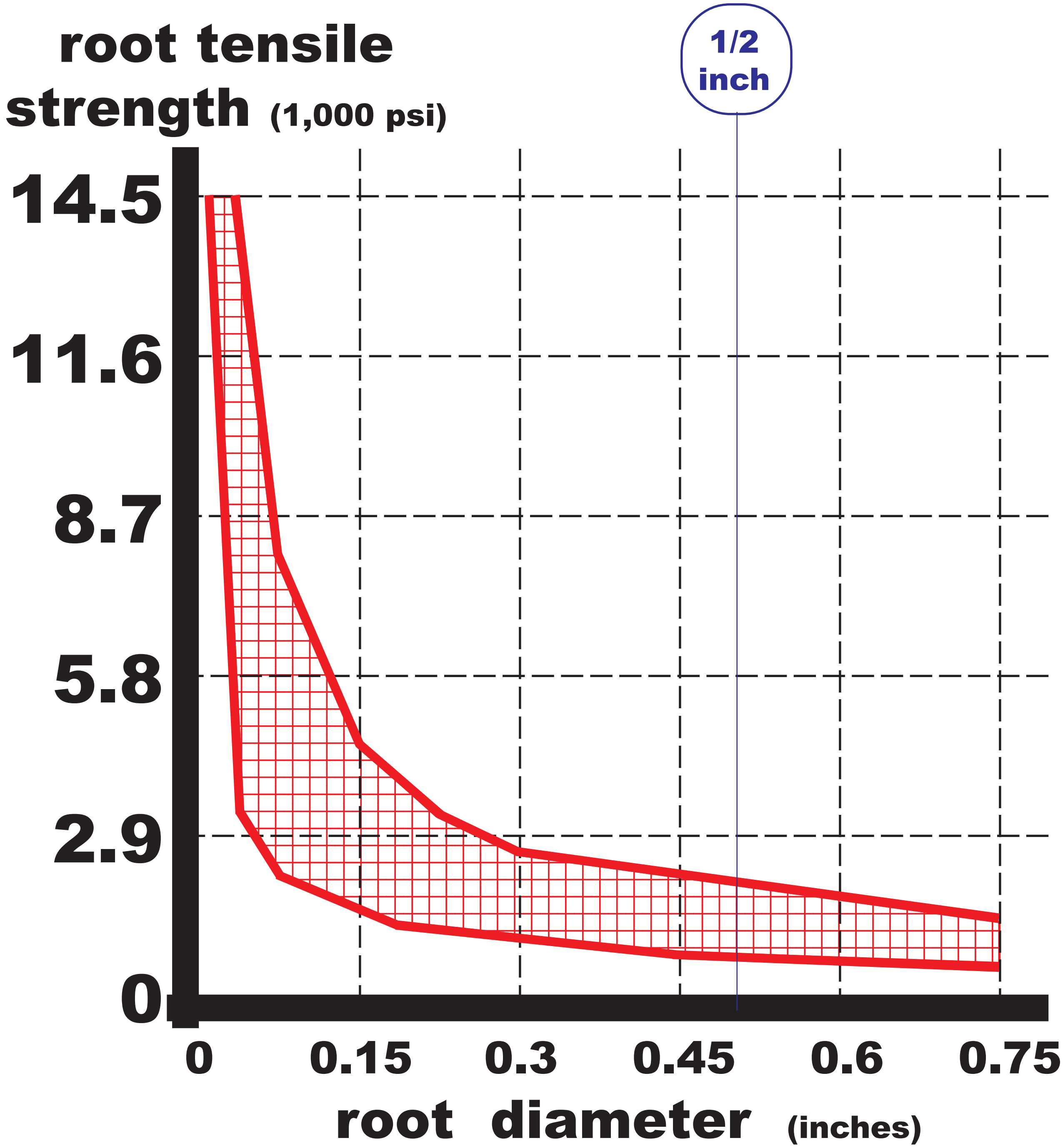

Figure 19: Range of root tensile strength from several studies on trees based upon root diameter. Root tensile strength is species dependent, but most species follow similar trend lines and curve shapes.
(Derived from Abernethy & Rutherfurd 2001; Bischetti et al. 2005; & Tosi 2007.)

Yank!

One way to estimate root tensile strength is to longitudinally pull roots out of soil. A maximum pull-out resistance is proportional to root tensile strength. Pull out resistance is shown in Figure 20. Root pull-out forces can be estimated by multiplying root tensile strength times 0.65 (Norris 2005), or by 0.60 (Greenwood 2006). Resistance to root pull-out for a conifer is shown in Figure 21. (Abe & Ziemer 1991)

Total root strength for a tree can be estimated using a formula which includes adding together the number and cross-sectional area of roots and their pull out resistance. Total tree root strength is: (Greenwood 2006)

total tree root strength = sum of all individual roots =
[(number of roots) X 3.1416 X
(root diameter) X (pull out resistance)].

Tree anchorage failure from roots pulling out of soil is primarily determined by rooting depth and root length. Both rooting depth and length maximize root / soil friction, mass of soil held above roots, and resistance to failure. Figure 22 demonstrates how larger angles of lateral root branches decrease the amount of force needed for pulling roots out of soil. The optimum branching angle zone of strongest anchorage occurs up to 20^{o} between a primary lateral and a secondary lateral root. (Stokes et al. 1996)

Strong or Stiff?

Tree root systems are genetically optimized for both stiffness and strength. Small diameter roots are flexible with a high tensile strength. Large diameter roots are stiff and resist shear and bending. Small roots act to generate a strong friction zone between soil and root. Large roots act as unbending anchors. This combination of root sizes allows trees to stand. (Bischetti et al. 2005)

Tree roots fail in response to forces placed on tree crowns by either stretching, slipping, or breaking. Cell wall content differences in roots, and cross-sectional area increases with growth, combine to have large diameter roots pulled from the soil and small diameter roots broken with application of force. (Tosi 2007) On average, upland hardwoods tend to have roots with high tensile strength in the smallest diameters. Bottomland hardwoods and conifers tend to have less tensile strength in smaller roots but hold that relative strength into larger diameter roots. (Bischetti et al. 2005)

Friction

Another way of examining tree anchorage is by determining root / soil cohesion. As root tensile strength, root diameter, and root density in the soil increases, total root / soil cohesion increases. The force needed to pull apart this root-soil connection is: (Schmidt et al. 2001)

force applied =
3.1416 X (root diameter) X (root length) X
(root & soil strength in friction and cohesion).

The last factor in this formula is difficult to estimate for tree roots. Generally soils with finer textures and water contents exceeding their plastic limits would allow wholesale root slippage. (Schmidt et al. 2001)

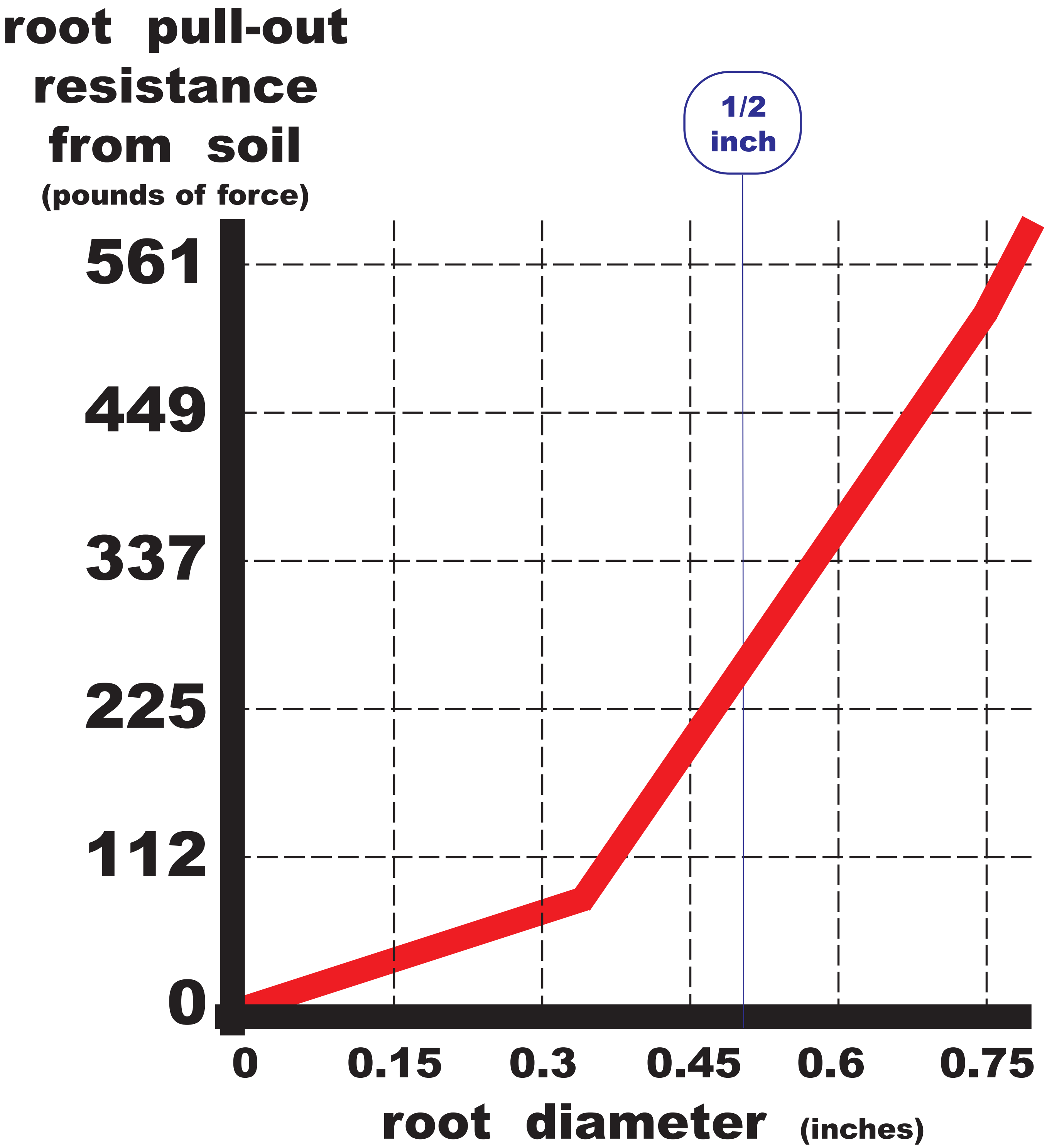

Figure 20: Tree root pull-out resistance in pounds of force by root diameter.
(from Norris 2005)

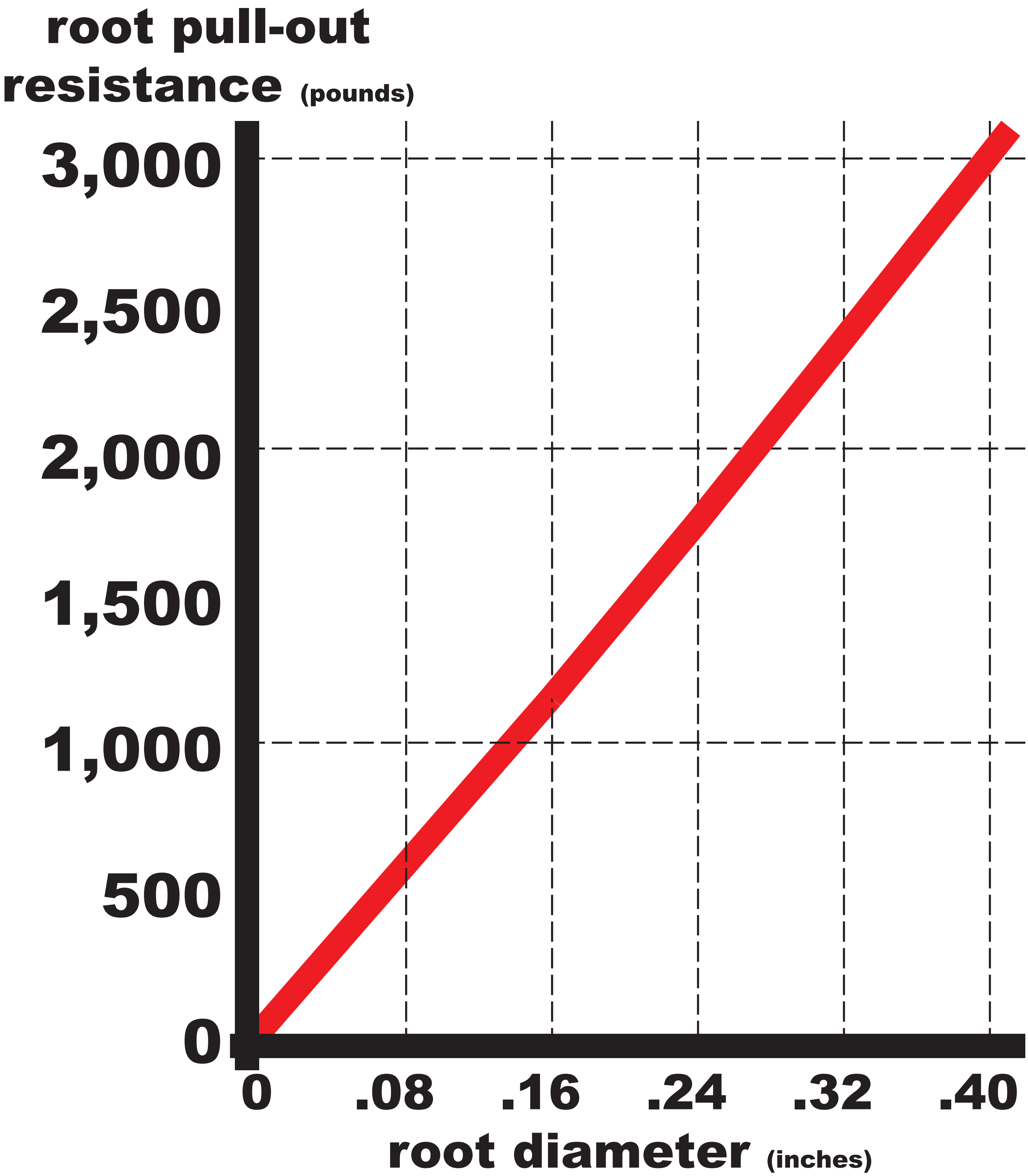

Figure 21: Root pull-out resistance (in pounds of force) for conifer roots of a given diameter in inches. (Abe & Ziemer 1991).

pull-out resistance in pounds force = 278.7 X (root diameter)$^{1.03}$

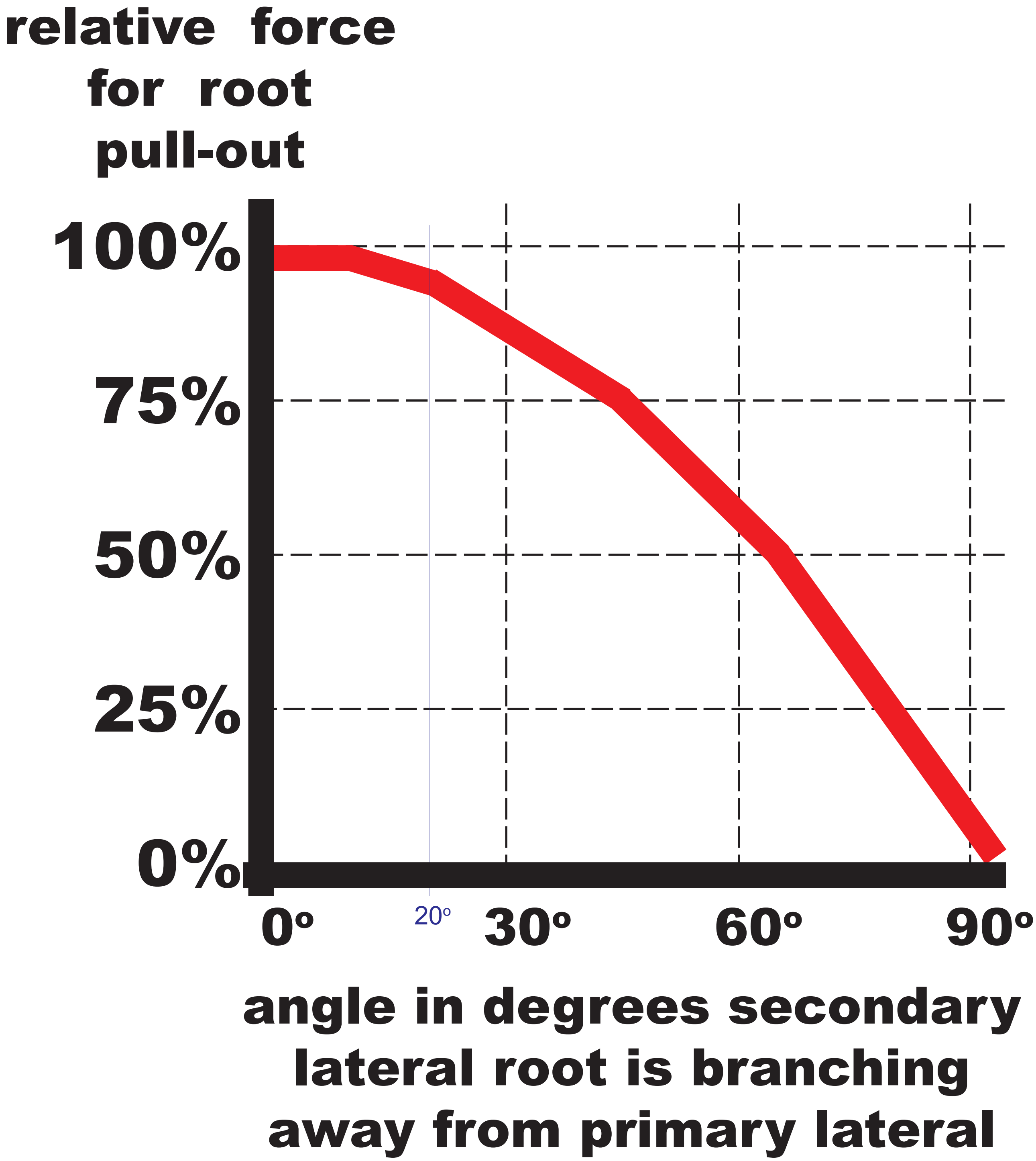

Figure 22: Examination of how much force is neded to pull out roots as impacted by branching angle of lateral roots. (from Stokes et al. 1996)

In the most simple terms, tree roots add soil strength through cohesive forces. Root-soil cohesion in a soil can be estimated by: (Bischetti et al. 2005)

root-soil cohesion =
1.1 X (average tensile strength of root per cross-sectional area) X (root area ratio %).

In other words, the greater root strength and the more roots distributed through a soil, the stronger root / soil combinations, and so the better tree anchorage.

Slip Sliding Away

Anchorage is a function of root tensile strength, interface friction which is proportional to root length, and the distribution of roots or rooting density. If friction exceeds root tensile strength, then roots will break when placed under critical loads. If root tensile strength is greater than fictional forces, then roots slip and pull out when placed under critical loads. Whether a root will slip depends upon root length, root branching patterns, and rooting tortuosity. (Abernethy & Rutherfurd 2001)

Even dead tree roots provide resistance to anchorage failure. After conifer trees were cut or killed in-place, dead trees lost about 65 psi of tensile strength per month on average. (O'Loughlin & Ziemer 1982) (Watson & Marden 2004)

Asymmetrical

Roots can grow in an eccentric manner depending upon how far from the stem base they are and the types of forces applied. Close to a stem base, roots in sandy soil tend to grow more tissue on the underside. Lateral roots farther out grew more tissue on the topside of larger roots. The reversal point from more growth on bottom to top occurred within about 10 inches of the stem base for small trees. (Fourcaud et al. 2008)

Stokes (1999) looked at small tree root systems, some younger and some older. Figure 23. In these root systems, younger tree roots tended to be subject to more tension strain out to about 12 inches on the windward side and compression strain out to about half that distance on leeward side roots. Leeward side root strain from compression was significantly greater close to the stem than tension strain to windward. In older small tree root systems, root tension strain to windward stretched out to beyond 22 inches from the stem, while leeward roots under compression strain were found out to 16 inches, switching to tension strain to leeward after 20 inches. In older trees, the relative strain values at the stem in both tension and compression were roughly equal. (Stokes 1999).

Top To Bottom

When strain to windward and to leeward in small trees were examined separately for root top and bottom, several unique features were revealed. Figure 24. To windward, upper root surfaces were under tension strain and lower surfaces were under compression strain. To leeward, upper root surfaces were under significant compression strain, quickly shifting to tension strain after about 12 inches. Leeward side lower root surfaces were under tension strain from 6-12 inches from the stem. (Stokes 1999) The differences in root tension and compression stress and strain lead to asymmetrical growth adjustments by the tree. There is no data available for large mature trees.

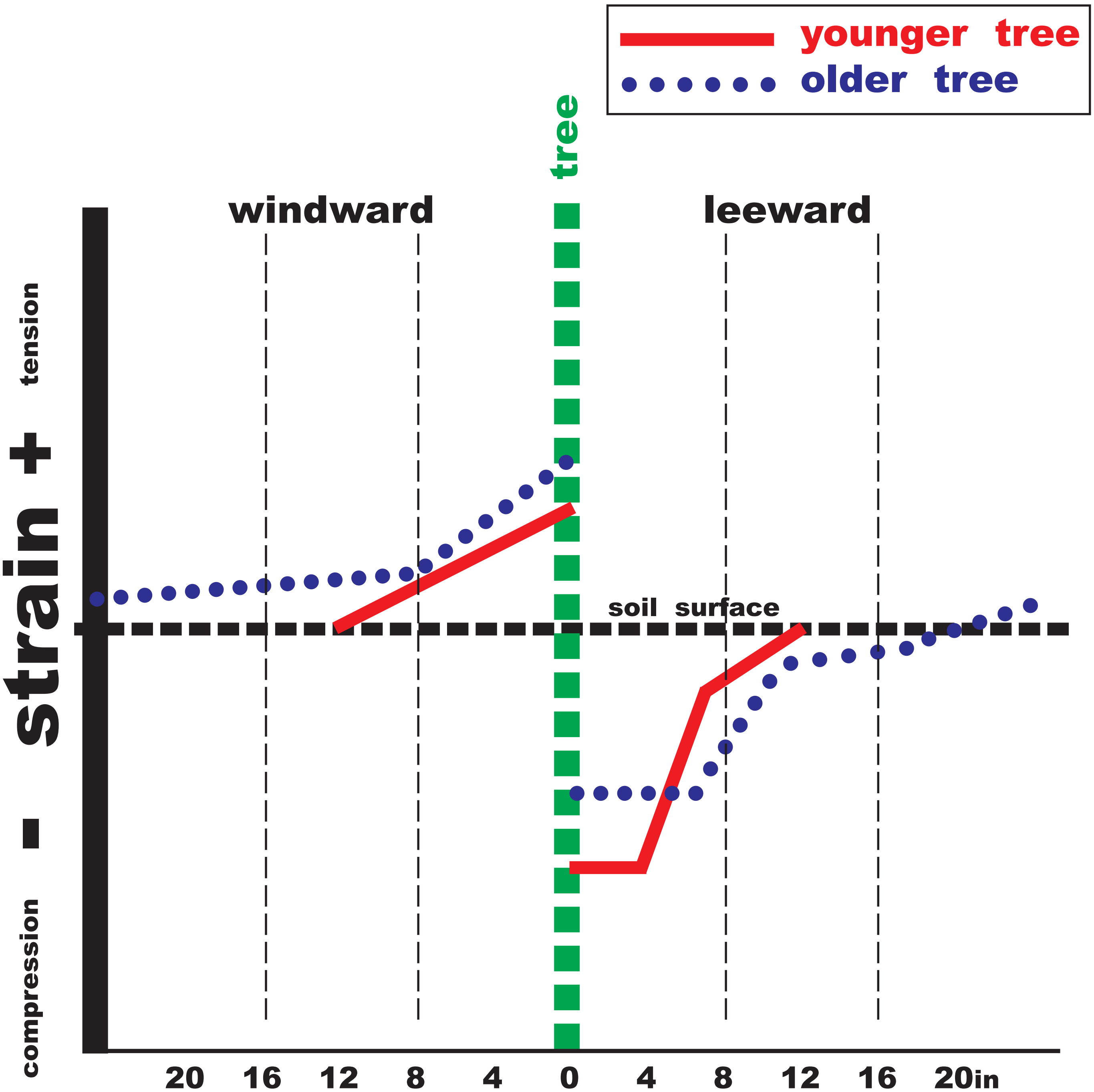

Figure 23: Tension and compression strain on the windward and leeward side of small trees (denoted as younger trees and older trees). Hinge point on leeward sides of younger trees are ~4 inches away from stem base, and ~6.3 inches away from stem base on older trees.
(derived from Stokes 1999)

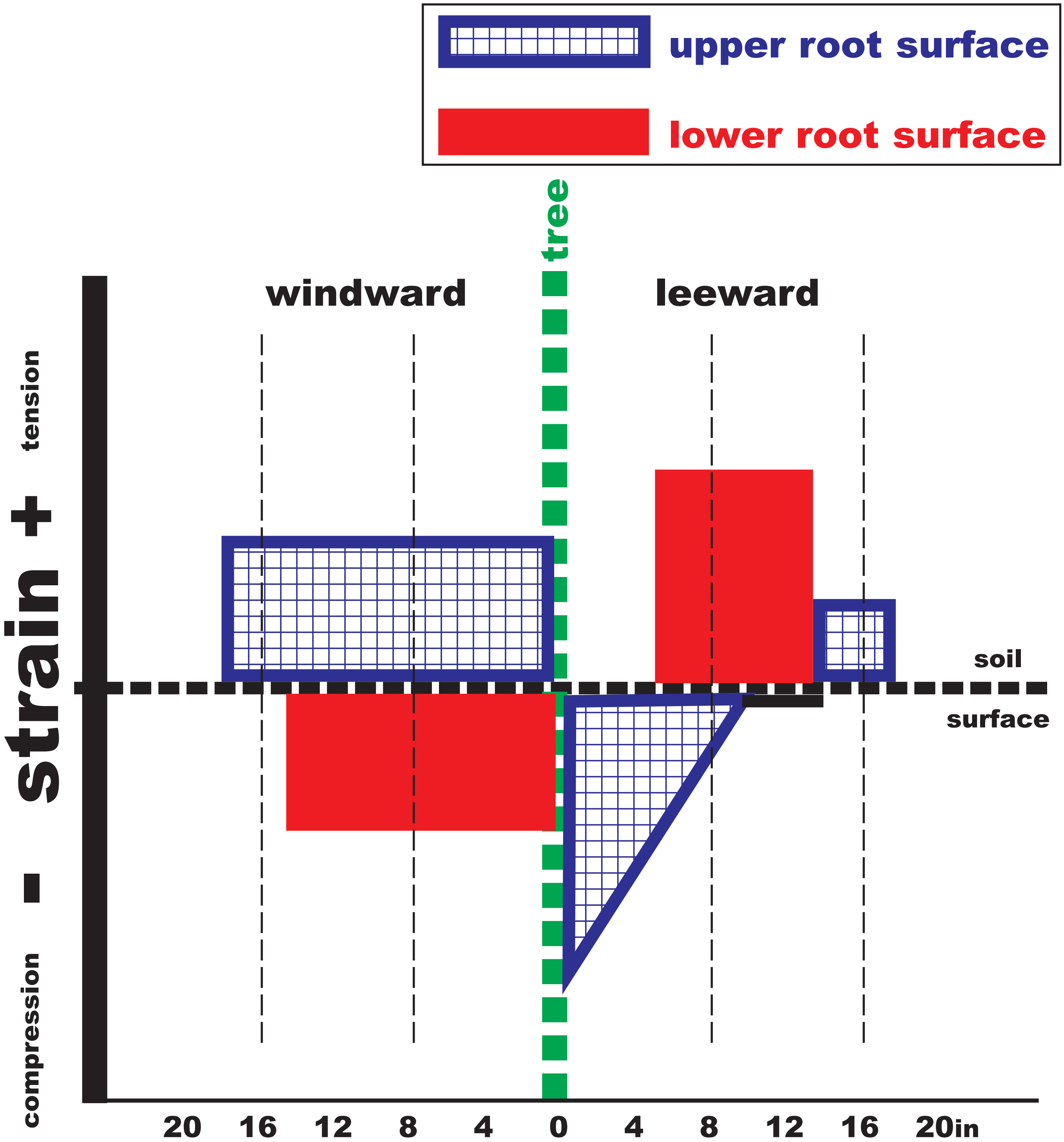

Figure 24: Tension and compression strain on upper and lower surfaces of windward and leeward tree roots in small trees.
(derived from Stokes 1999)

Beam Up & Down

Strong tree anchorage utilizes four different cross-sectional shapes of large roots: circular, oval, T-beam, and I-beam. On shallow soil sites and in young trees, T-beam shaped roots tend to develop close to the stem base on the leeward side. I-beam shaped roots tend to develop on the windward side approximately 2.5X (two-and-one-half times) farther out from the stem base than the T-beam shaped root area on the leeward side. Both of these root shapes move the focus point of bending / hinging farther out and away from the stem over the root plate. (Nicoll & Ray 1996; Chiatante et al. 2003; Stokes 1999)

For example, the I-beam shape of roots increase stiffness by roughly 300 times over circular shaped roots with equal cross-sectional areas. (Nicoll et.al. 2006) Trees on steep slopes tend to develop oval or I-beam shaped roots to maintain anchorage. (DiIorio et al. 2005) Deeper soils allow good anchorage without beam shaped roots and root cross-sections approach circular shapes. (Nicoll & Ray 1996) Figure 25.

The stem base, and major roots close to the stem base, can also develop exaggerated buttresses to stiffen and support a tree. In gymnosperms, larger buttresses occur on the leeward side of a tree and tend to form T-beam shapes to minimize bending and hold compressive forces. In angiosperms, larger buttresses are on the windward side and tend to form a flattened, plank-like shape capable of resisting tensile forces. (Nicoll & Ray 1996)

Root Density & Distribution

Root area ratio or root area index is a measure of rooting density in a soil. (Bischetti et al. 2005) Root area ratio is significantly more important than root tensile strength for increasing soil shear resistance. (DeBaets et.al. 2008) Root area index is based upon cross-sectional area of roots exposed on a flat vertical face of soil with a given surface area. Figure 26. In well drained soils, the peak root area ratio is found somewhere between 8-10 inches of depth and ranged from 0.35 to 0.55%. Figure 27. (Bischetti et al. 2005) Full range of values is from 0.001% to 1%. (Danjon et al. 2008)

Root area ratio increases with tree age, approaching a maximum between 20-40 years of age. Over time more roots can be identified less than 1/12 inch in diameter and nearer the soil surface. The greater density of roots (high root area ratio) and the deeper into soil this density holds, the more resistance to anchorage failure. In shallow, fine textured, or poorly drained soils, roots are concentrated at a much shallower depth. (Bischetti et al. 2005)

Location

Like root density, root distribution in a soil depends upon soil drainage, oxygenation, and carbon dioxide loss as impacted by soil texture, bulk density, and physical soil constraints. Tree roots in a native soil are distributed following a gamma distribution curve. A gamma distribution has a maximum point near the soil surface and tails-off with soil depth depending upon soil constraints. Figure 28. (Bischetti et al. 2005)

Roots can be found concentrated within a set radius from a tree stem. Figure 29 shows the expected radius for most roots, (>1mm or >1/25 inch diameter) away from a tree stem. With increasing

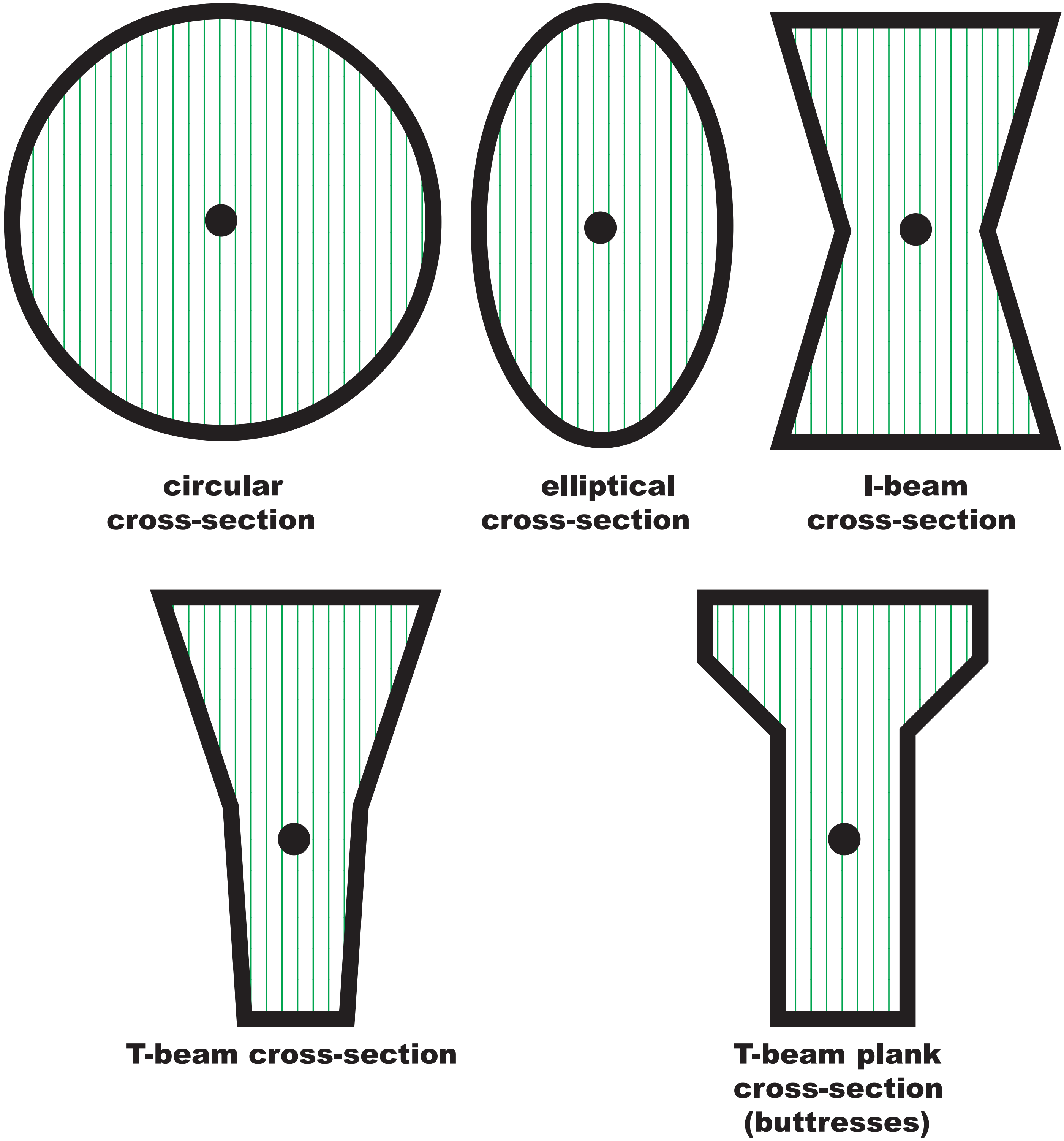

Figure 25: Idealized shapes of root cross-sections as tree growth responds to assymetrical mechanical stress across upper and lower surfaces. Dot represents root center.

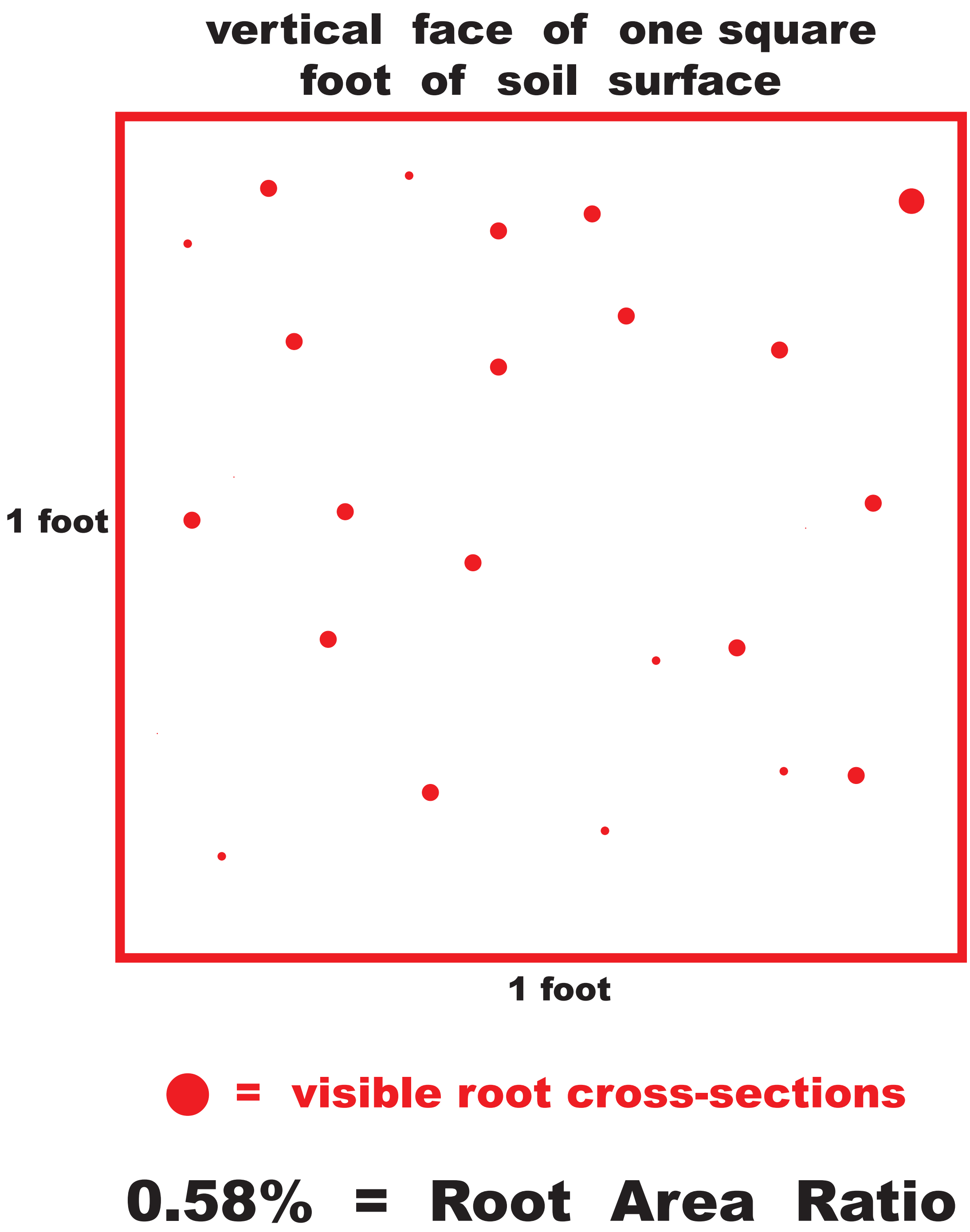

Figure 26: Demonstration of how Root Area Ratio or Root Area Index determinations are made. Root Area Ratio is the percent of root cross-sectional area represented on a vertical exposed face of soil for a specified area.

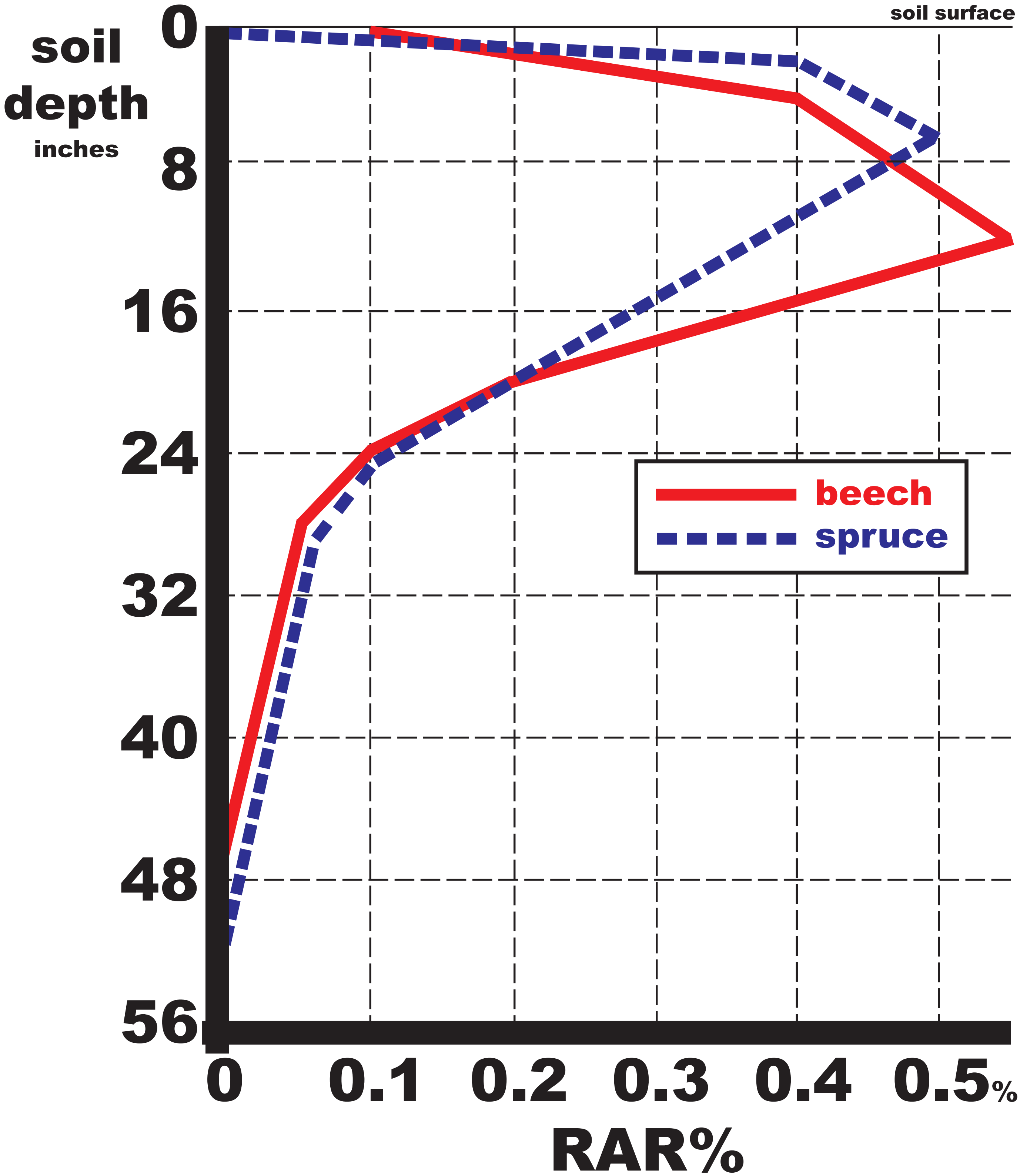

Figure 27: Represenative Root Area Ratio (RAR) percents for beech and spruce as soil depth increases.

(selected examples from Bischetti et al. 2005)

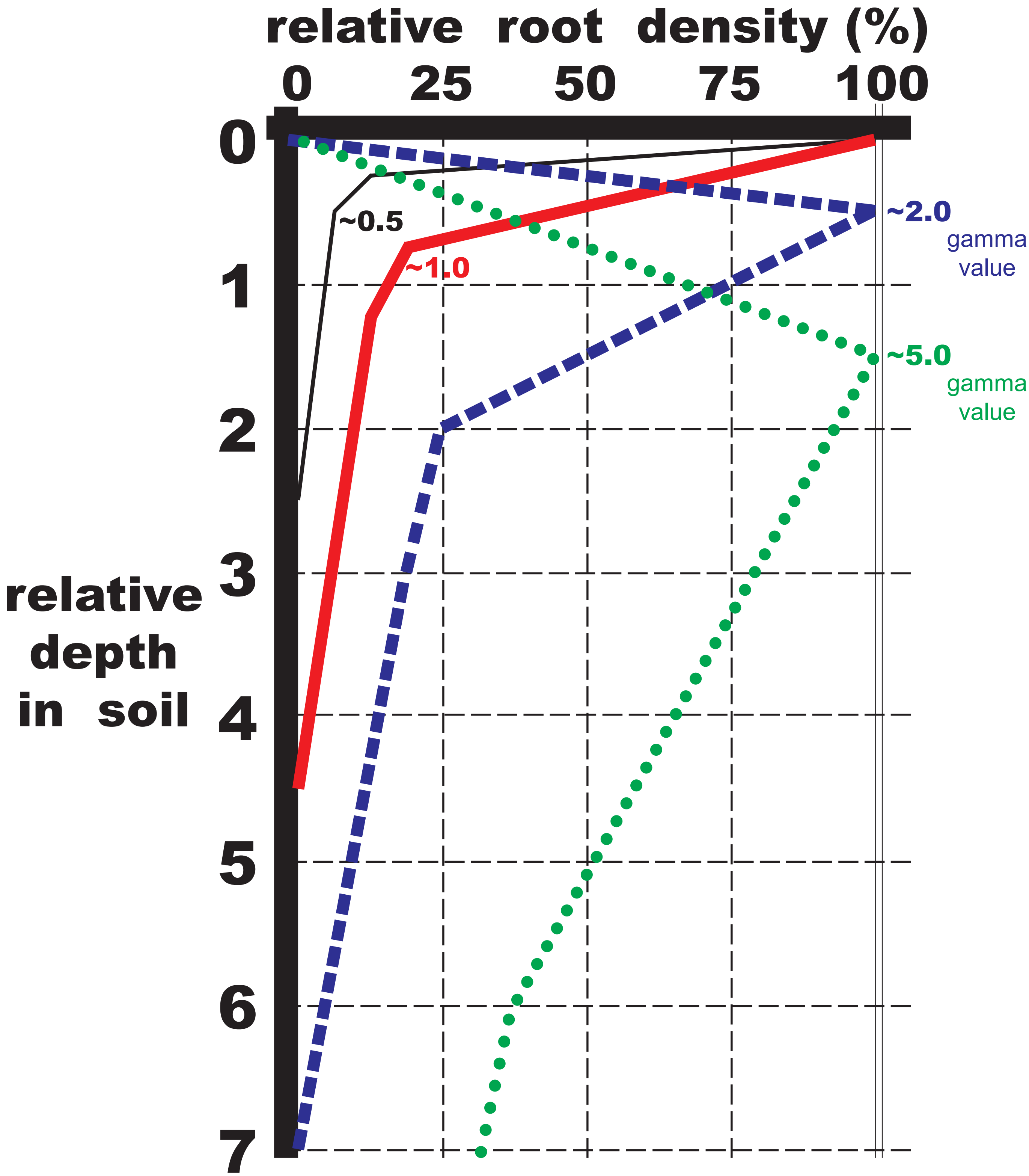

Figure 28: Relative tree root density with increasing soil depth following a gamma distribution curve. The larger the gamma value, the more well-drained the soil. (O_2 at depth must be minimally >5%). (expanded from Bischetti et al. 2005)

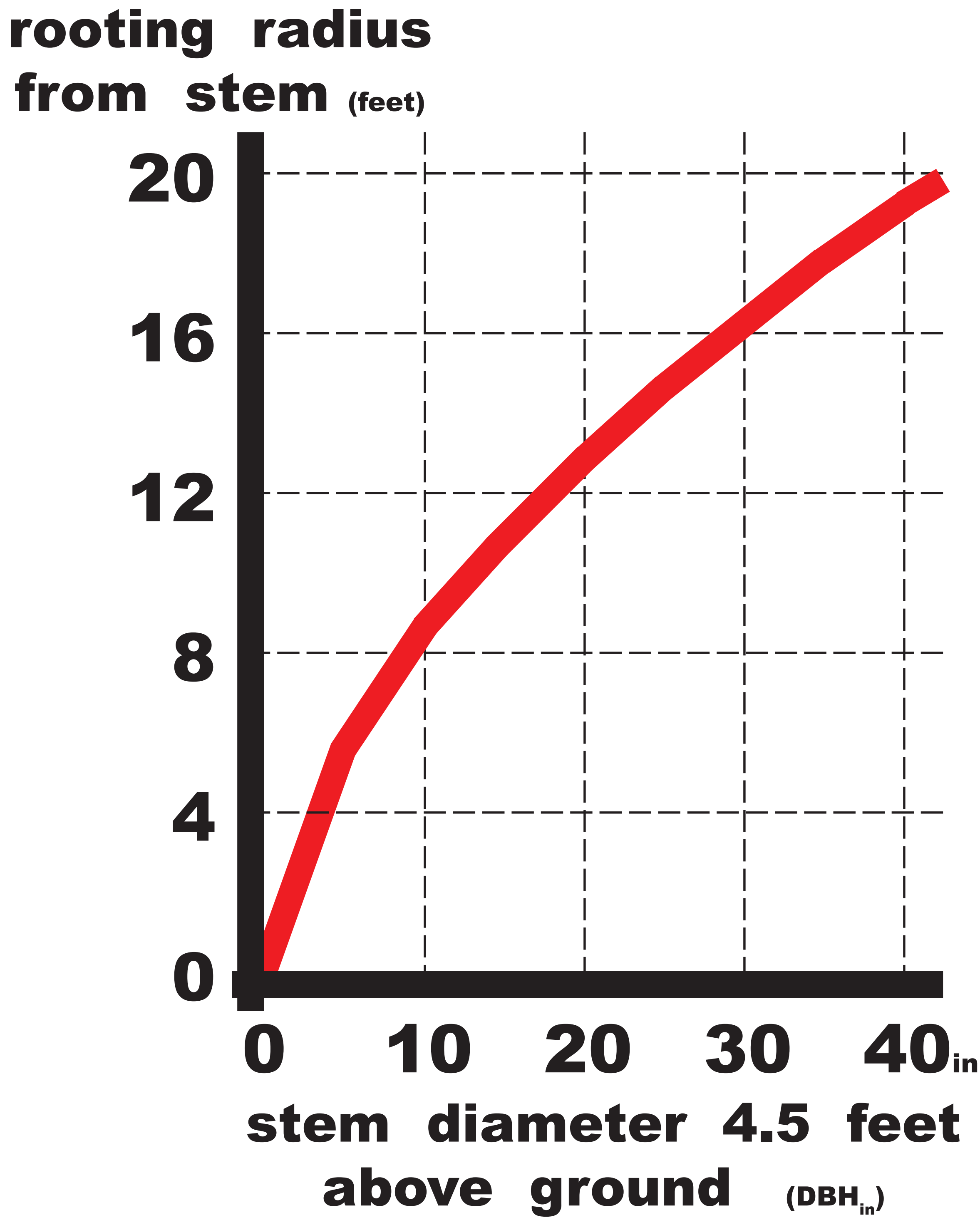

Figure 29: Radial distance away from tree stem where roots greater than 1mm are expected. (Roering et al. 2003)
root radius from stem in feet = $19.057 \times (0.0254 \times DBH_{in})^{0.59}$.

tree diameter, rooting distance away from a tree expands proportionally less. (Roering et al. 2003). Figure 30 demonstrates how as rooting distance (radius) in feet increases and total root colonization area in square feet greatly increases. As trees grow larger, small increments of rooting distance sdded translate into proportionally greater rooting area. For example, a one foot radial increase in rooting distance away from the stem base of a 10 inch diameter tree generates a 44% increase in rooting area.

Root Plate

Trees develop stiff, shallow, quickly tapering roots around their stem base. These large roots and associated soil form a compound, horizontal, disk-like structure on and in soil referred to as a "root plate." A root plate can be the same as, or a great deal larger in diameter than a "zone of rapid taper" (ZRT), depending upon the author. A ZRT usually is associated with defining the distance away from a stem of leeward root hinging or bending. Since root plate and ZRT are not synonymous in the literature, only the term "root plate" will be used here.

Plate Size

There are several ways to describe or define a root plate. One way to define a root plate is as an ellipse when viewed looking down on a tree and soil surface. Figure 31. In this case, the ratio of short axis to long is about 0.85. The root plate long axis can be determined by multiplying the stem diameter in inches times 0.92 to yield the long axis in feet. For example, a 9.5 inch tree would have a root plate with dimensions of 8.7 feet perpendicular to the wind direction (long axis of the ellipse) and 7.4 feet parallel to the wind direction (short axis of the ellipse). (Koizumi et al. 2007)

These root plate dimensions can then be used to estimate differences in resistance to over-turning: (Koizumi et al. 2007; modified from Koizumi et al. 2007)

$$\textbf{root plate resistance to over turning} = \left[(\textbf{root plate radius to windward})^2 \times (\textbf{root plate diameter}) \right] / 3.$$

or

$$\left[(\textbf{tree DBH}_{in} \times 0.39)^2 \times (\textbf{tree DBH}_{in} \times 0.92) \right] / 3.$$

Specific components of root plates cited here as having key roles in resistance to up-rooting include two counteracting forces: A) increasing dimensions of the windward side of a root plate resisting up-turning; and, B) increasing upturning force applied to entire root plate initiating up-turning. In these formula, simple surface measures of root plate dimensions or stem diameter help define anchorage, with emphasis on windward roots. Note this study examined root plates with depths of ~24 inches, but root plate depth was not found to be a significant factor for anchorage. (Koizumi et al. 2007)

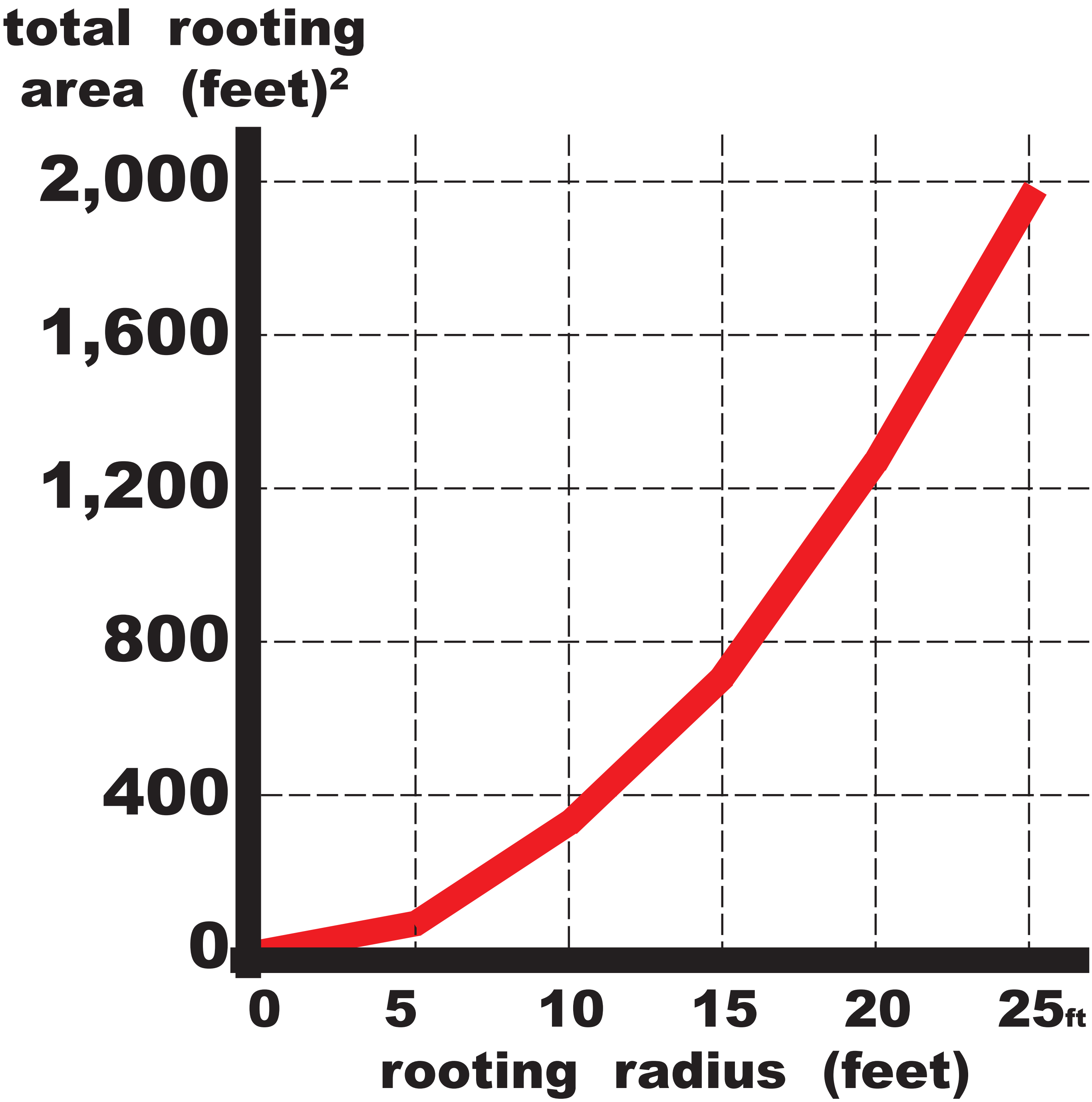

Figure 30: Comparision of how increasing rooting radius away from a stem base in feet can greatly increase total root colonization area in square feet.

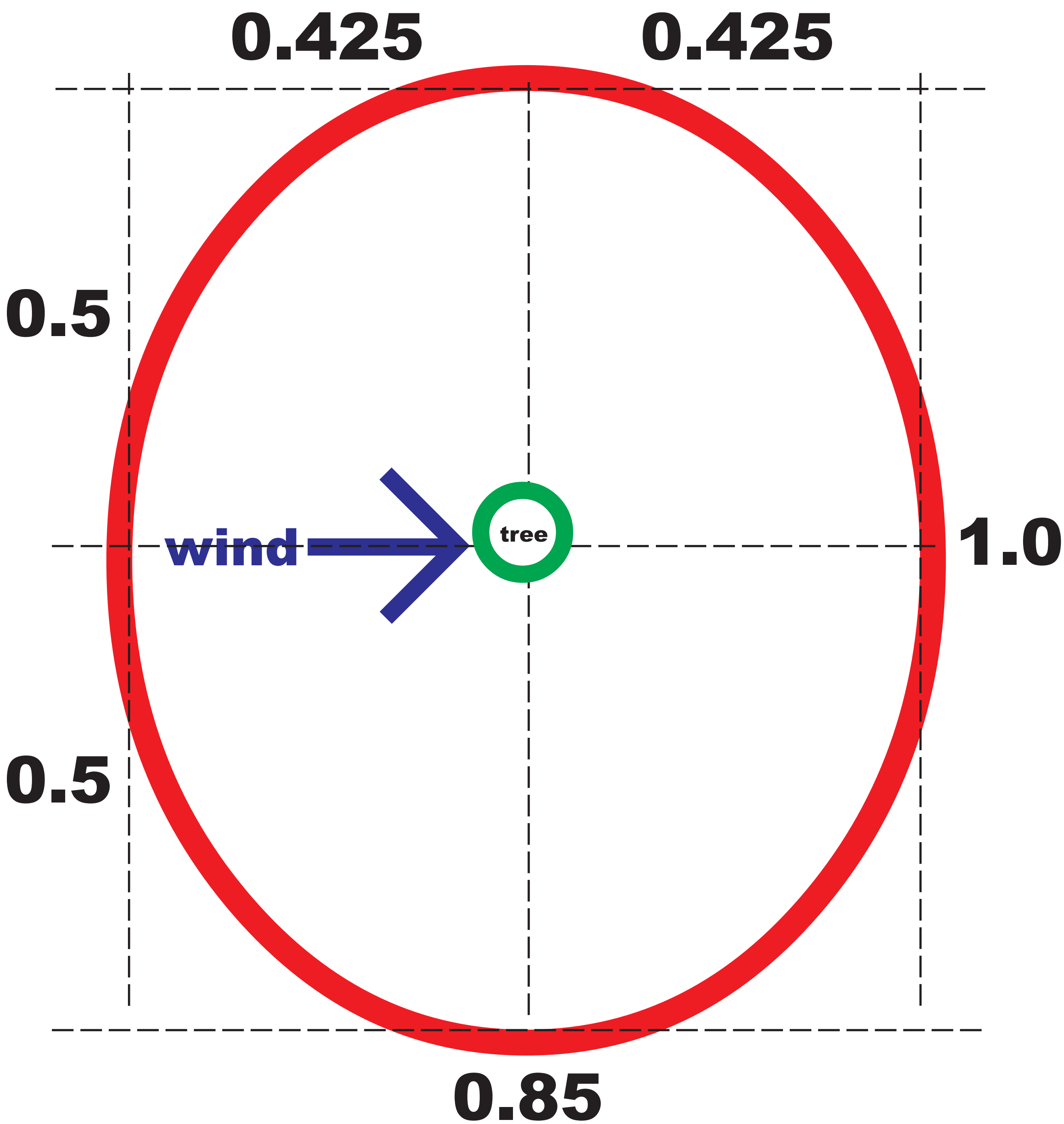

Figure 31: Proportions of a tree root plate viewed from above, delineated with an ellipse having a long axis of 1.0 and a short axis of 0.85.
(from Koizumi et al. 2007)

Plate Measures

Other ways to define root plates are circular shaped delineations at the soil surface proportional to tree diameter. An easy root plate definition method is to use stem diameter (DBH_{in}) times some value. Figure 32. The Coder structural root plate formula multiplies tree diameter in inches times 1.2 for the extent of windward roots holding in tension into the wind (in feet), 0.9 for the standard structural root plate diameter (in feet), or 0.3 for the position away from a stem base of the leeward hinge or bending point opposite from the wind (in feet). In contrast, another way to define a root plate diameter in feet is by taking the diameter of a tree in inches times 0.367. (Danjon et al. 2005) Many other calculations exist. Clearly no calculation will fit the highly variable conditions existing in tree root system development.

A side view (depth view) of a root plate in cross-section has been defined as a shallow cone under a stem base. Figure 33. The depth is limited by aerobic soil values. (Peltola 2006) Another way of defining a side cross-section of a root plate is as a half ellipse shape with a proportion ratio of roughly 3 units horizontal radius to 2 units depth from the stem base. Figure 34. The normal hinge or bending point is considered to be 1 unit away from the stem base on the leeward side. (Lundstrom et al. 2007) An additional definition of root plate depth is 1/3 maximum rooting depth. (Danjon et al. 2005) The Coder structural root plate formula multiplies tree diameter in inches times 0.6 for a root plate depth in feet within an unconstrained rooting volume.

Stiffness

Successful tree anchorage comes from a stiff root plate. The stiffness or rigidity of a root plate is proportional to root plate diameter to the 4th power (root plate diameter^4). (Tobin et al. 2007; Coutts et al. 1999) Figure 35. For example, a 1 foot increase in diameter of a 10 feet diameter root plate (+10% diameter increase) represents a +46% increase in root plate stiffness.

Root plate symmetry, in addition to stiffness, is also critical to anchorage. Root plates providing effective anchorage display no more than 60% of the roots along the axis of dominant winds. Leeward roots tend to be larger in diameter at the surface and have sinkers growing downward. Windward roots tend to be longer and more distally branched. (Tobin et al. 2007)

In one study, leeward roots in the root plate were reinforced +21% more than other roots, generating a greater volume of roots due primarily to greater diameter growth. Beyond the root plate, windward roots were reinforced +30% more than other roots generating a greater volume of roots. To windward, both root length (+28%) and root number (+32%) were increased. (Danjon et al. 2005)

Soil Changes

Tree root plate stability is impacted by soil type. Comparing sand and clay soils, with everything else being equal, tree anchorage in sandy soils depended predominantly upon rooting depth and conservation of windward roots. (Dupuy et al. 2005b) In sandy soils, plate stiffness shared by many roots defines resistance to failure, especially stiffness of leeward roots. (Fourcaud et al. 2008) In clay soils, tree anchorage depended predominately upon larger root diameters and conservation of both windward and leeward roots close to the stem base. (Dupuy et al. 2005b) In clay soils, plate resistance to failure can be defined by the 2-3 longest roots, not by root biomass. (Fourcaud et al. 2008)

Modification or constraint of roots, and root plate shape and size, will impact anchorage and the potential bending or hinge point. (Fourcaud et al. 2008) The bending / hinge point on a root plate is significantly farther away from the tree in sandy soil compared with clay. (Dupuy et al. 2005b) In

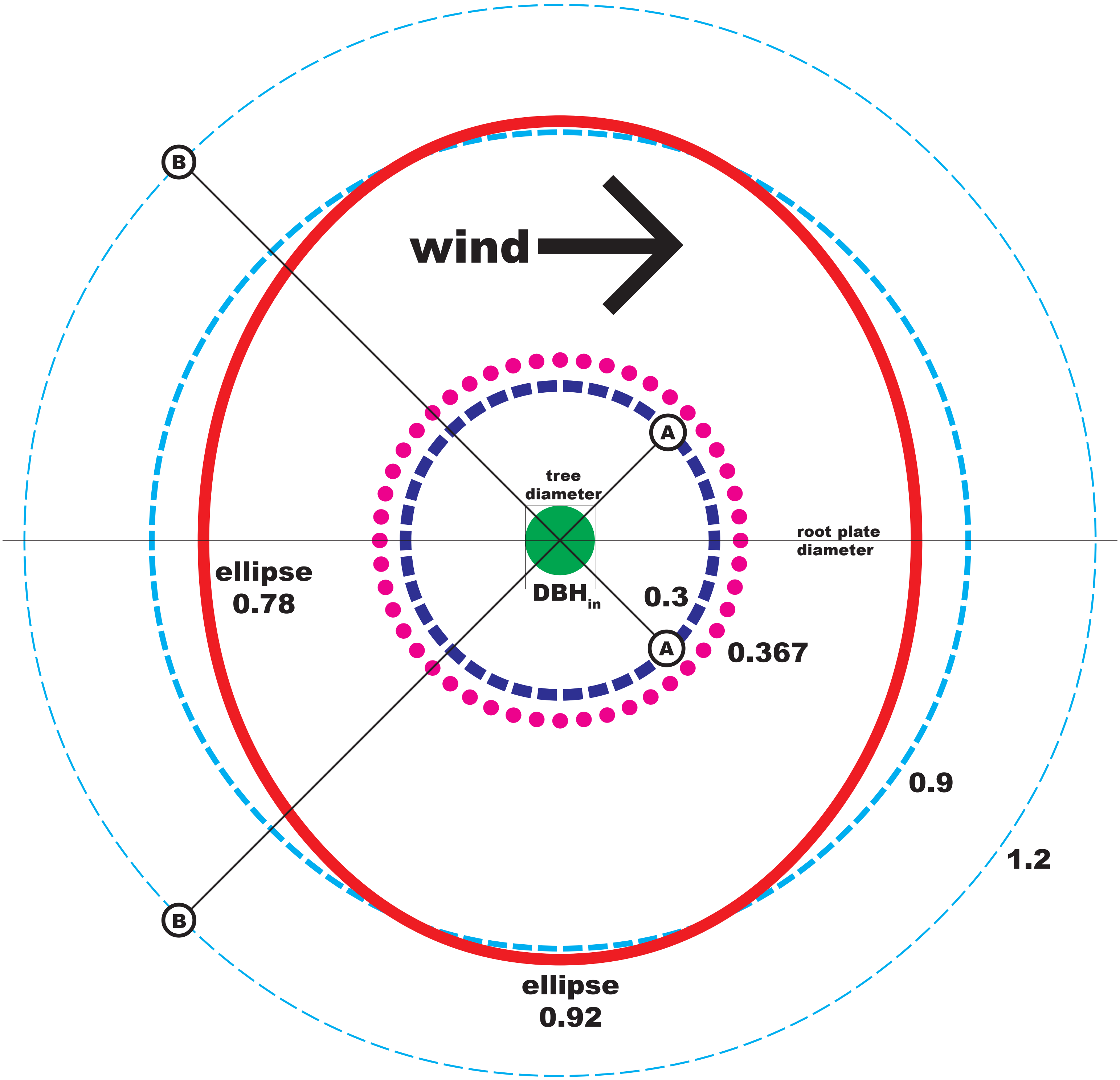

Figure 32: Aerial view of different root plate dimensions surrounding a tree of a set diameter (DBH$_{in}$).

The decimal values are the multiplier of tree diameter inches yielding diameter of root plate in feet. Coder root plate = 0.9; Danjon zone of rapid taper = 0.367; Koizumi root plate ellipse = 0.78 short axis with wind / 0.92 long axis perpendicular to wind. Coder hinge point (90^{o} to leeward code A) = 0.3. Coder windward root zone (90^{o} to windward code B) = 1.2.

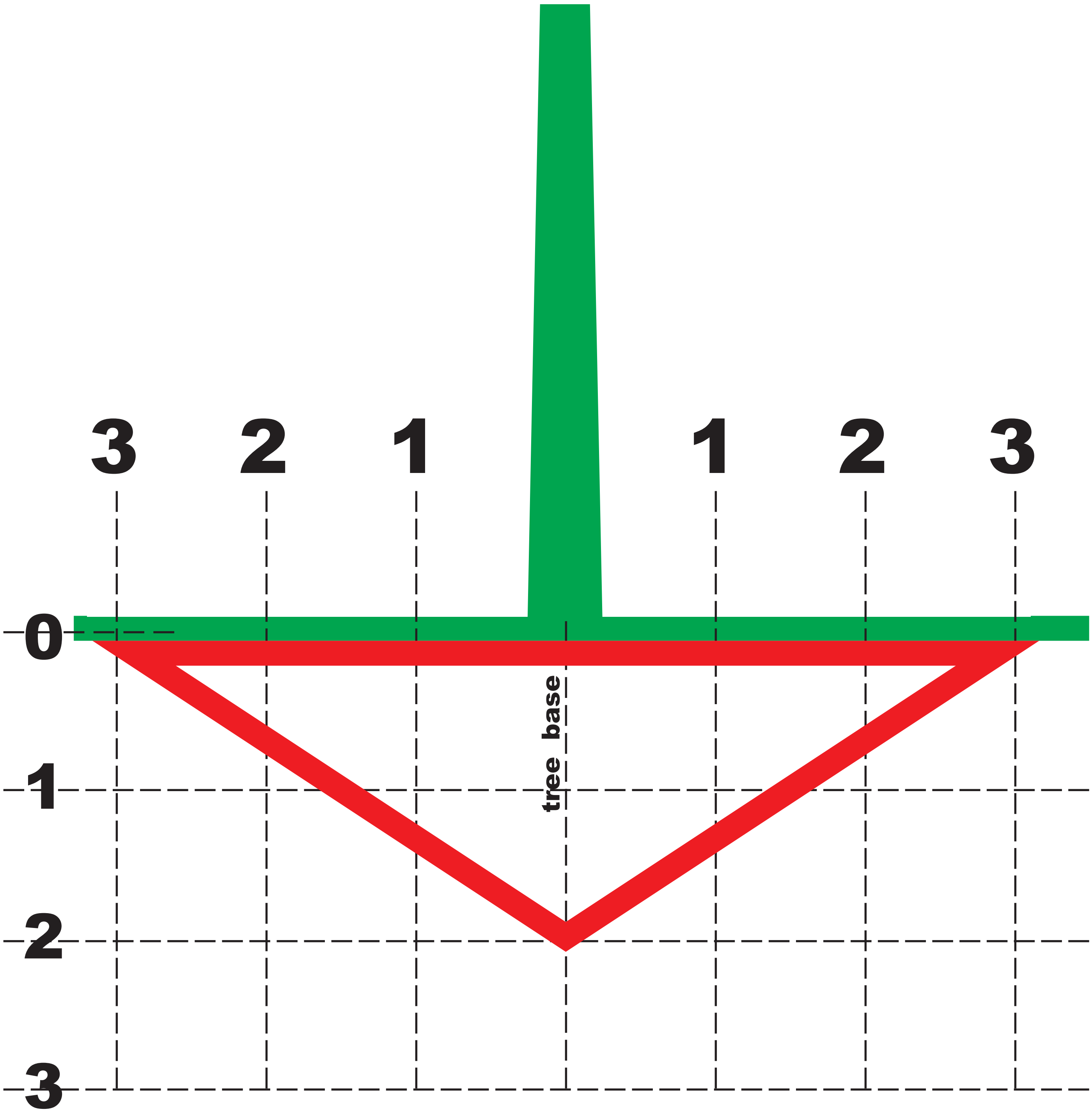

Figure 33: Side view of a tree root plate cross-sectional area representing a conical shape. Shown on a site with no soil depth limitations. (from Peltola 2006)

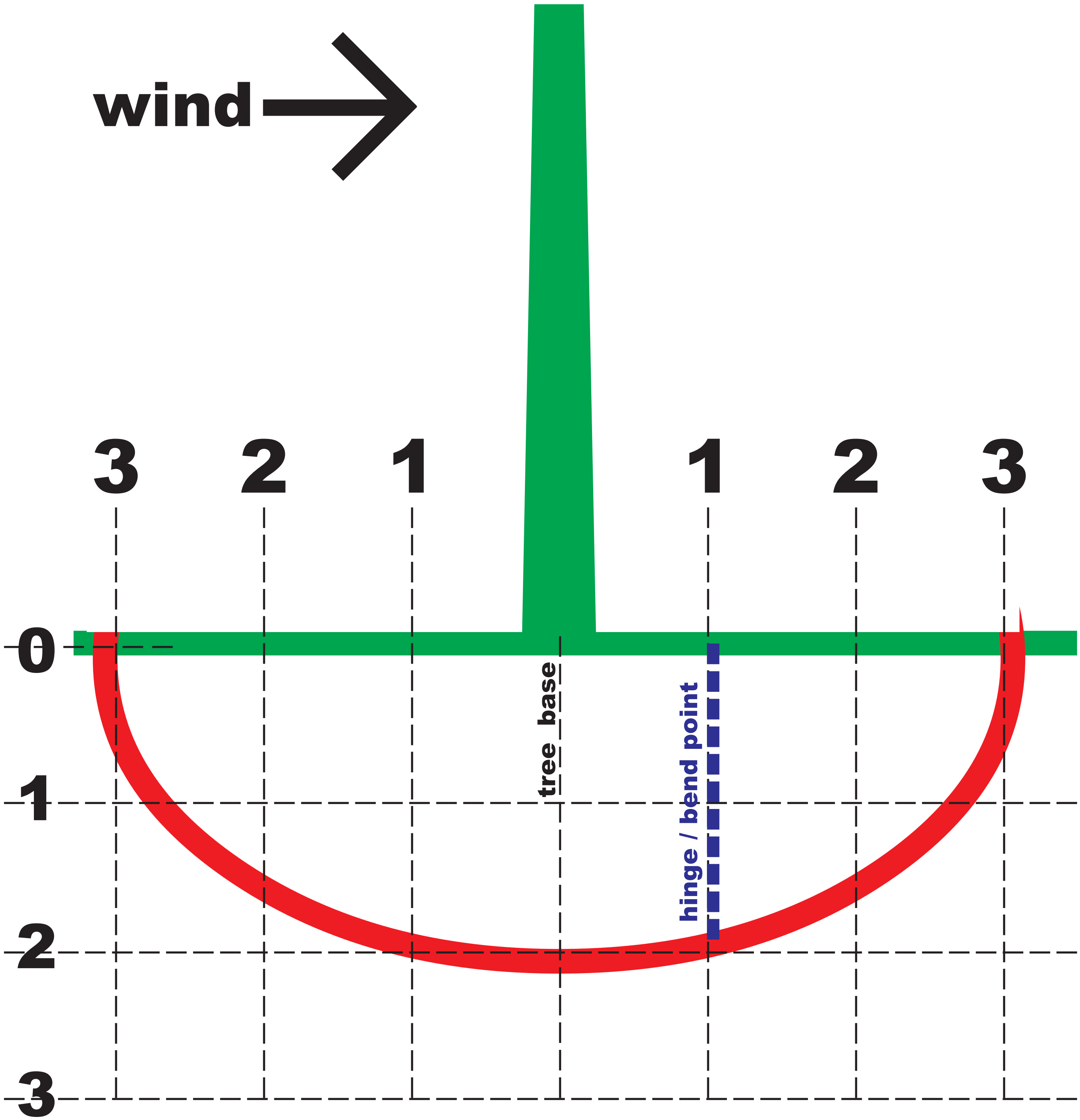

Figure 34: Side view representation of a tree root plate cross-sectional area represented as a half ellipse shape. Shown on a site with no soil depth limitations. Inserted is a heavy dotted line representing the leeward side root hinge point. (from Lundstrom et al. 2007)

root plate diameter (feet)	relative plate stiffness	change in relative stiffness	percent change
5	625		
		9,375	1,500%
10	10,000		
		40,625	406%
15	50,625		
		109,375	216%
20	160,000		
		230,625	144%
25	390,625		
		419,375	107%
30	810,000		
		690,625	85%
35	1,500,625		
		1,059,375	71%
40	2,560,000		

A 1 ft increase in diameter of a 10 ft diameter root plate (10% diameter increase) represents a 46% increase in stiffness.

Figure 35: Relative stiffness or rigidity (D^4 basis) of tree root plates of different diameters. (Coutts et al. 1999; Tobin et al. 2007)

shallow root plates, as the hinge distance is moved out away from the stem base by a factor of 2, root plate resistance to failure in increased by a factor of 2. (Coutts et al. 1999) Figure 36 shows a side view of a root plate cross-section where soil constraints limit plate depth.

Resistance

The composite value of root plate anchorage is represented by windward roots growing beyond its edge. Of secondary value is root plate mass. Tertiary value is placed in leeward roots as the hinge / bend point is moved farther from the stem base and anchorage becomes greater. (Elie & Ruel 2005) A tree root plate anchorage formula used to understand resistance to failure, containing wind loading factors is: (Coutts et al 1999)

tree anchorage resistance =
[(tree and root plate mass) X (root plate radius)] /
[(wind load) X (height to crown center of wind load force)].

Here combined tree and root plate mass, and root plate radius are positively related to increasing anchorage while the amount of wind load and length of the lever arm turning a tree out of the ground negatively impact anchorage.

A simplified formula of root plate load and hold factors is: (Anderson et al. 1989)

up-rooting resistance =
(6.28 X (root plate radius)^2) / (3 X wind load).

In this examination only root plate radius (i.e. holding factor) and wind load on the tree top (i.e. loading factor) were significant. Because of the root plate factor being a square, a 20% increase in root plate diameter yields a ~60% reduction in shear forces.

Wide Or Deep?

The impact of root plate width on tree anchorage failure is shown in Figure 37. Note as root plate width increases so does tree resistance to failure. The impact of root plate depth on tree anchorage failure is shown in Figure 38. Note as root plate depth increases, so does tree resistance to failure. (Moore 2000) Of these two plate dimensions (width and depth), root plate width expansion can quickly increase tree anchorage more effectively than increasing depth.

In one study, 91% of the variability in uprooting was concentrated in just three measures: stem volume, tree height to diameter ratio, and root plate width. (Moore 2000)

ln (root plate resistance to failure) =
10.86 + (0.83 X ln(stem volume)) +
(-.006 X (tree height / tree diameter)) +
(0.278 X root plate width).

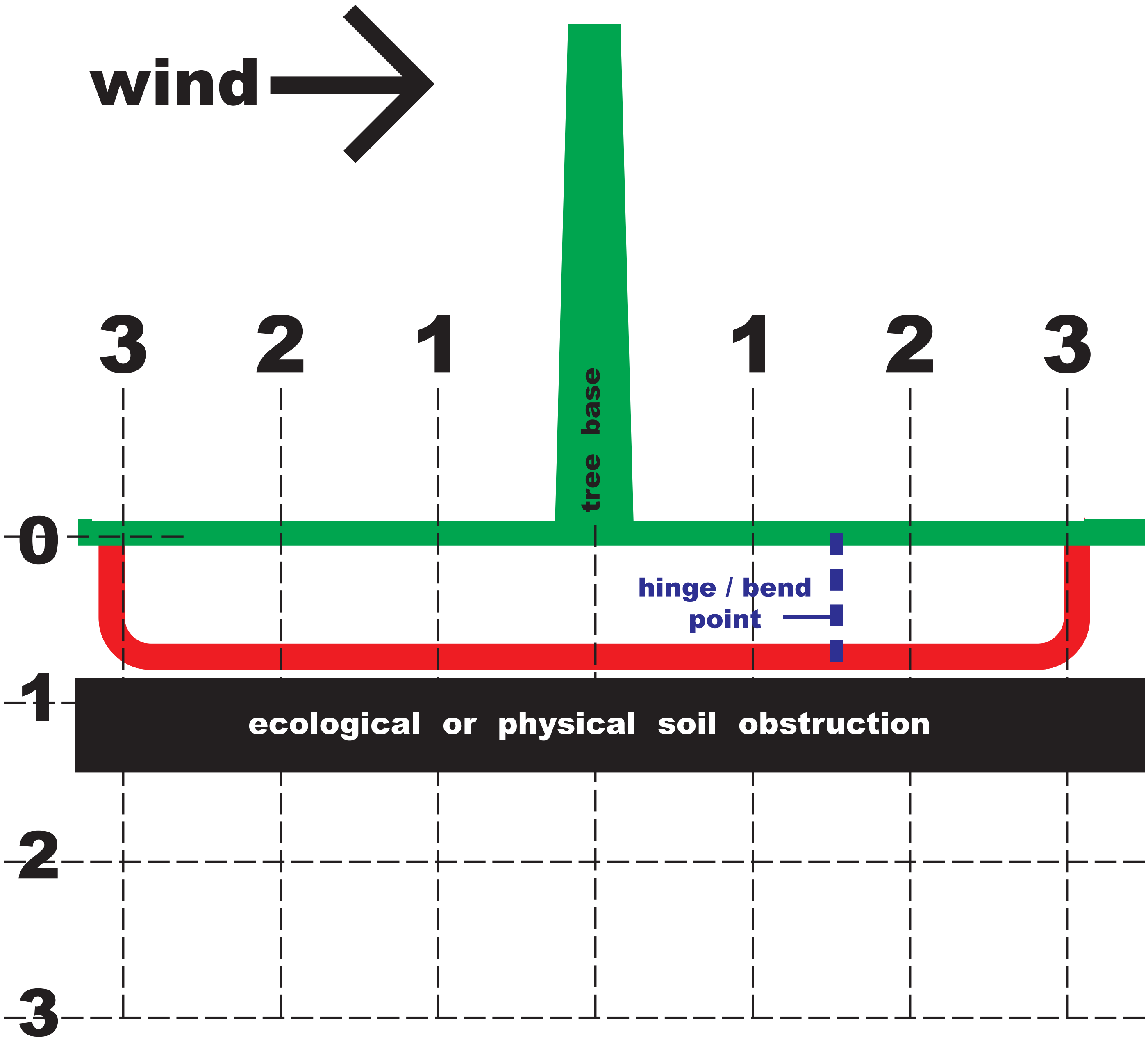

Figure 36: Side view representation of a tree root plate cross-sectional area in a depth-limited rooting space constrained by soil oxygenation, limited carbon dioxide loss, drainage, or obstruction. Inserted is a heavy dotted line representing the leeward side root hinge point. (derived from Lundstrom et al. 2007)

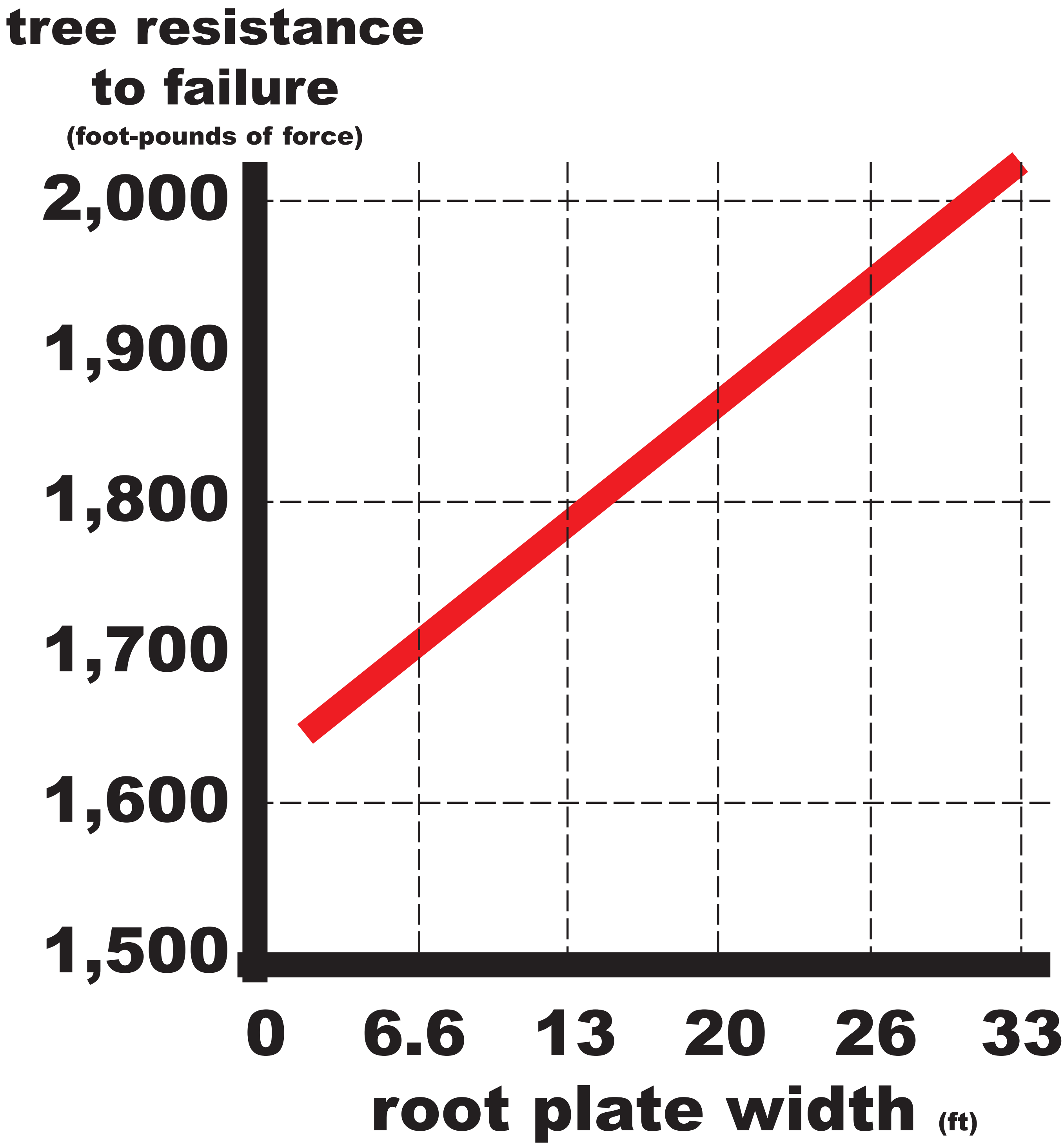

Figure 37: Impact of root plate width in feet on tree resistance to failure in foot pounds of force.
(Moore 2000)

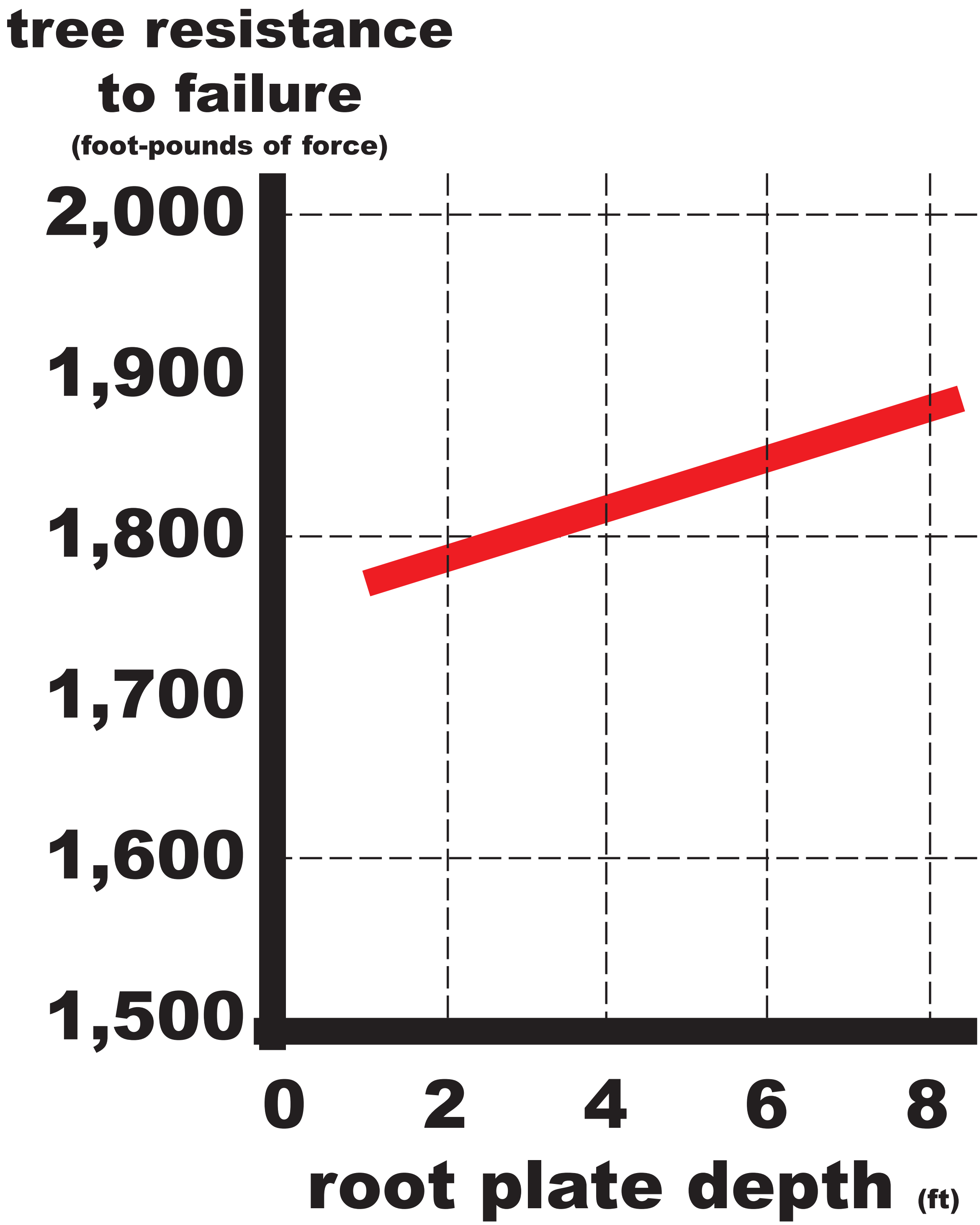

Figure 38: Impact of root plate depth in feet on tree resistance to failure in foot pounds of force. (Moore 2000)

In this case, two of the factors are wind load components from the tree top while one factor, root plate width, is involved with resisting or holding the mechanical load.

Plate Summary

Root plate anchorage has been shown by various studies to depend upon root plate weight, root plate depth, root plate diameter, and soil strength. In addition, strength of windward roots, strength of leeward root resisting hinging, and root - soil interface under and at the edge of the root plate base are critical to tree anchorage. (Peltola 2006) A root plate can be a valuable concept in understanding and educating people about tree anchorage. Not all researchers agree.

Using root plate models for anchorage is a reasonable and easy way to measure, estimate and describe tree anchorage. Unfortunately, root architecture is highly complex and guided in development by genetic and soil constraint interactions. Root architecture is more important to tree anchorage than simple root plate dimensions. The root plate is a composite structure, (some say only a theoretical construct), providing anchorage resistance under average conditions. The specific root system lay-out is always under modification, as is the stem base, by changing wind load conditions. (Moore 2000) The longest few roots (2-3 largest roots) have the greatest anchorage impact, not a model diameter value. (Fourcaud et al. 2008)

Anchorage

When examining tree anchorage failures it is important to differentiate between: A) *up-rooting* – the lifting of an intact root plate; and, B) *root failure* – trees pushed down without stem breakage. These two anchorage failures can appear similar but have different causes. (Moore 2000) "Up-rooting" is caused by separation of the root plate from the soil by wind loading and lifting of the crown until gravity pulls the tree down. This is a rotational load wheel type of failure. "Root failure" is an assortment of different root breakage, bending, and twisting events leading to tree toppling. Root failure is subject to root system architecture issues, not stem base and root plate stiffness concerns.

Anchorage of trees depends upon the characteristics of tissues produced in response to mechanical loading, and to their placement around the exterior of tree parts. (Niklas 1999) It is root architecture, including soil volume occupied and root density at depth, which are key to anchorage rather than simple root plate size. (Peltola 2006) It is mass, strength, stiffness, and geometry of root placement which controls effective anchorage.

Hold Position

As wind load is applied to a tree top, those lateral forces are transferred to the root plate and individual roots. Roots can stretch between 10-20% while soil can stretch (pulled in tension) only about 2% before breaking. The result is soil breaks away from roots under tension, compression, and bending loads. As the larger roots flex up and down, (i.e. root plate wobbles), soil separates from root surfaces from under the stem base. This loss of contact continues out along major roots as more wind load is applied. (Tobin et al. 2007)

There are many species and individual differences in root anchorage. Tensile strength remains roughly the same for most tree species. Species and individuals can develop root systems which differ greatly in resistance to failure including variations in rooting depth, density, and size distribution. Rooting depth, and distribution with depth, vary generally by tree type, with angiosperms tending to be slightly more shallow (average depth = 14% shallower; overall depth range = 75% of the depth range of gymnosperms in the same soil). (Roering et al. 2003)

Sides

Anchorage is concentrated in two general locations around a tree base: 1) close to the stem base on the leeward side and focused on several large diameter roots; and, 2) farther away from the stem base on the windward side in many, smaller, large surface area, near-surface roots. (Danjon et.al. 2005) Windward roots have forces applied which are concentrated approximately 1.5X (one and one-half times) farther away from the stem base than leeward roots. (Stokes 1999)

In examining maximum wind force applied to both tree sides (windward and leeward), about 2.5X more force is concentrated on windward roots compared with leeward roots. On average, windward roots have 2.5X (two-and-one-half times) greater failure resistance than leeward roots. Leeward roots are pressed into supporting soil. Windward roots are pulled up and out of the soil. (Watson 2000) Figure 39.

Compressive and bending root strength to leeward are important to understand. Figure 40 shows the compression strength in roots as they grow farther from the stem base. Compression strength increases for a short distance from the stem base before declining with length. Root compressive strength was found to be roughly the same for angiosperms and gymnosperms, but bending strength was found to be much greater in angiosperms. (Stokes & Mattheck 1996)

Investing In Hold

Anchorage responsibility between windward and leeward roots differ greatly. Trees placed in wind tunnels developed a greater number of large roots on both the windward and leeward side, with greater cross-sectional area added to the windward side. Greater branching, elongation growth, and diameter growth generally occurred on the windward side. In contrast for conditions mimicking shallow soils, the greatest cross-sectional area was added on the leeward side. (Stokes et al. 2005)

Root anchorage develops in unique ways on steep slopes. Trees in one study showed uprooting resistance (as measured in toppling velocity in miles per hour) in an upslope direction was 15% greater than for a downslope direction. The upslope portion of the root plate was thicker and more rigid, causing the hinge or bending point to be pushed farther out from the stem base and farther upslope. (Nicoll et al. 2005) Trees on steep slopes develop fewer but larger lateral roots as the root plate mass is shifted more to the upslope side. (DiIorio et al. 2005)

Comparing Failures

One means of understanding tree anchorage failure is by exhuming and examining both trees which have failed and trees in the same area which did not fail under the same wind load event. In one examination, anchorage failed in trees with increased root branching in the larger (>4.7 inches) diameter roots and with greater total root length concentrated in larger diameter roots. Anchorage did not fail in trees with greater root plate width, greater root plate depth, greater root branching in small (<2.4 inches)

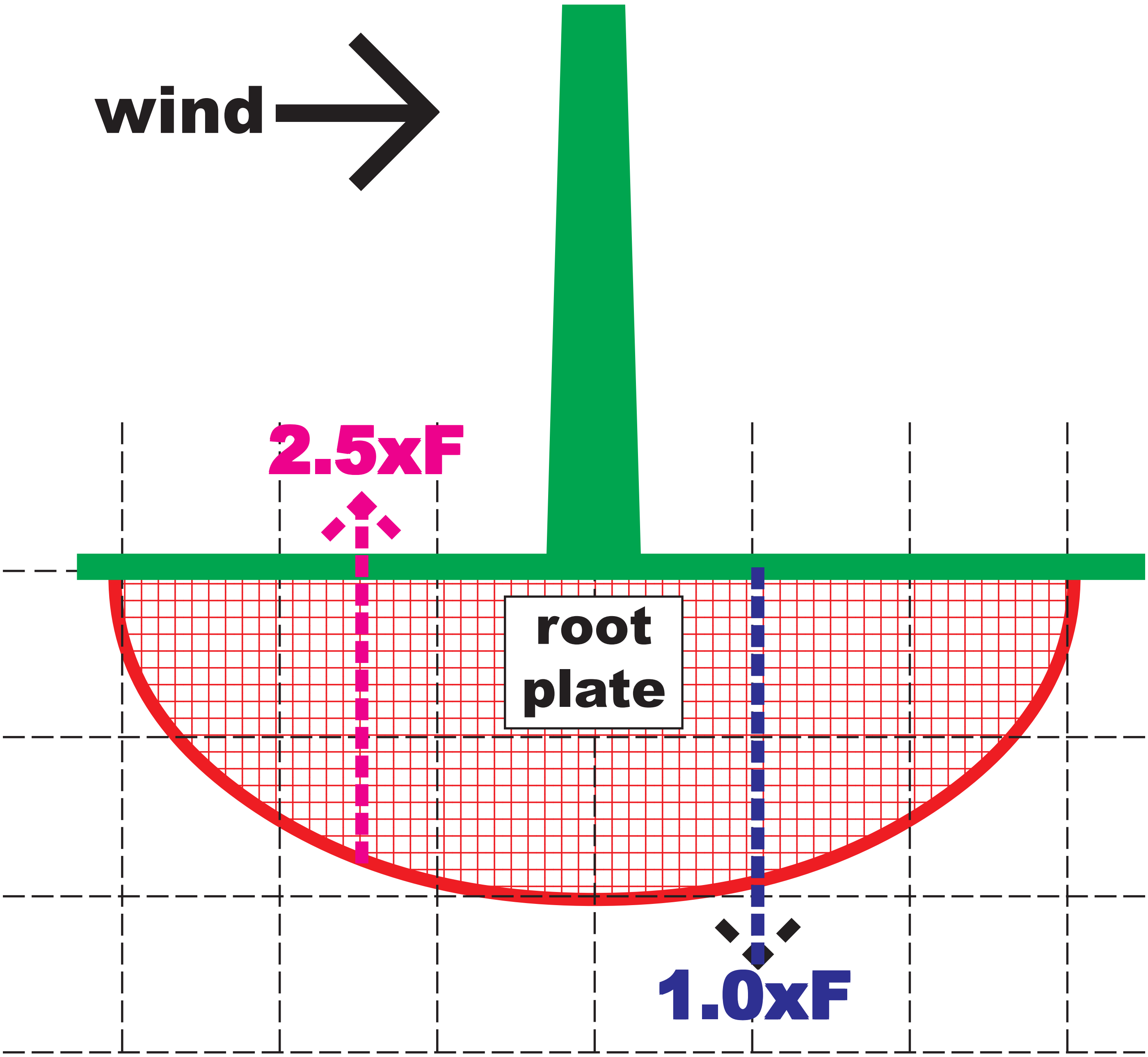

Figure 39: Cross-section of a tree root plate showing force concentration centers. Windward roots resist 2.5X (2.5xF) more force than leeward roots (1.0xF). Windward forces centered 1.5X farther from stem base than leeward. (derived from Stokes 1999; Watson 2000)

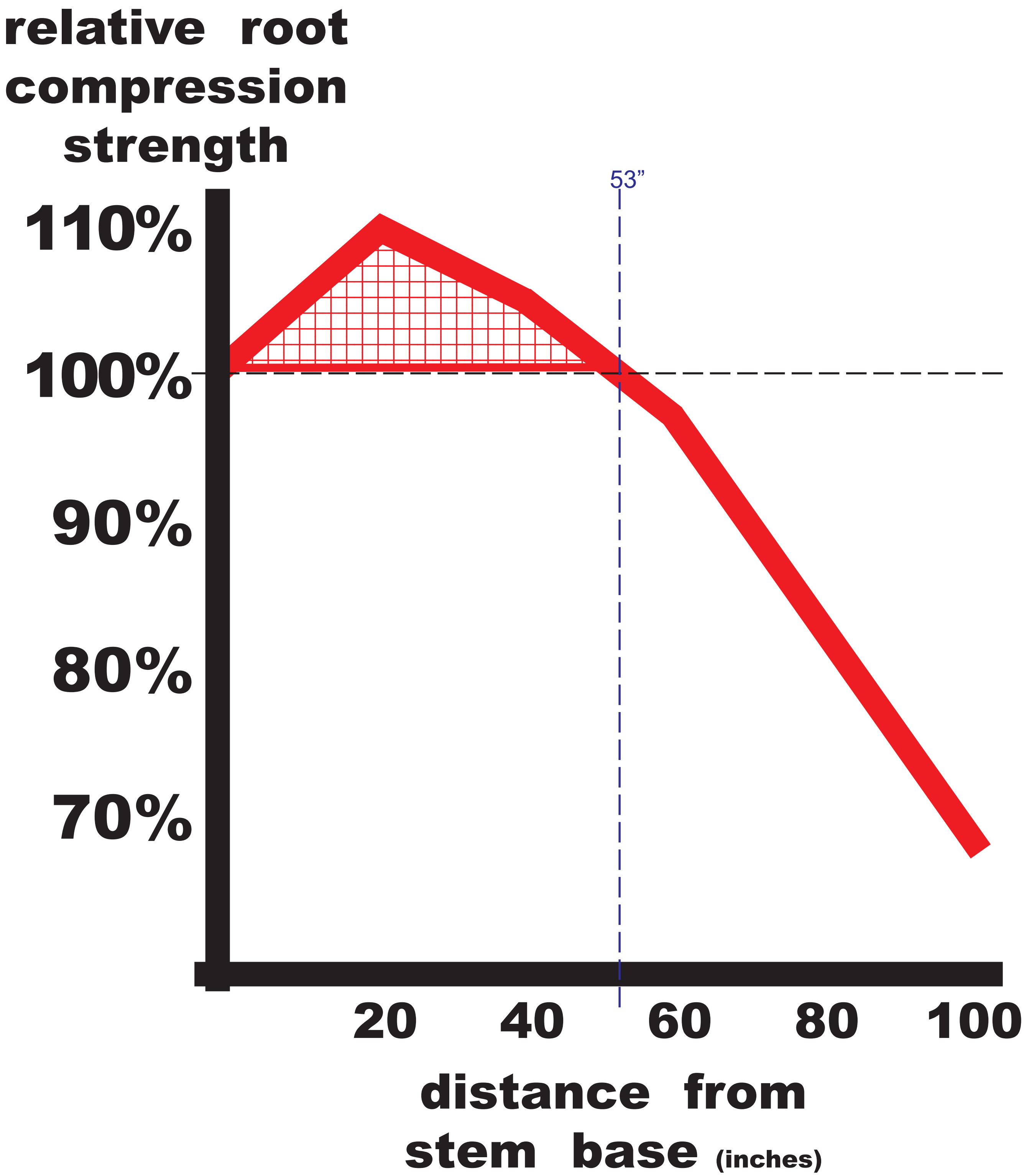

Figure 40: Relative tree root compression strength changes along root length away from stem base.
(after Stokes & Mattheck 1996)

diameter roots, greater branch root length in small diameter roots, and greater total root length in small diameter roots. A few large diameter and long roots can not provide effective resistance to failure. It is in the proliferation of smaller roots in consolidation of the root plate which provides anchorage success. (Stufka & Kodrik 2008)

Another way of examining root anchorage is by calculating anchorage difference with changing root architecture. Figure 41 shows three different root forms and the relative anchorage effectiveness of each. (Dupuy et.al. 2005) A dichotomous forking form of roots had much greater anchorage efficiency than either straight, non-branching roots, or roots with laterals growing perpendicular to the parent root.

Soil Types

At the start of tree anchorage failure, soil resistance plays a role. As more force is added to a tree, soil strength is quickly exceeded. As soil fails, windward roots, root plate mass, and leeward root hinge resistance become critical. (Peltola 2006) One study prioritized resistance to failure as: 1) windward roots (50%); 2) root plate mass (40%); and, 3) leeward root hinging / bending and soil resistance (10%). (Danjon et al. 2005)

Examining interactions between soil characters and tree anchorage provides several insights. Sandy soils tend to fail on the windward side from soil failure and roots pulling out of the soil. In clay soils there is more total resistance to tree anchorage failure. In clays, up-rooting failure occurs along a symmetrical slip / shear zone around the perimeter of the root plate. (Dupuy et al. 2007) In another examination of soil type and anchorage interactions, 92% of up-rooting failures occurred in sand and 11% in clay soils. (Moore 2000) In all these evaluations, root tensile strength was not a significant component of anchorage failures. (Dupuy et al. 2007)

Taps

Smaller and lighter (i.e. younger) trees require relatively more anchorage volume than large heavy trees due to a lack of stem mass. (Kamimura & Shiraishi 2007) Tap roots are juvenile features of young trees and can have a limited structural role. Tap roots are important for structural support and in setting the geometry of developing lateral root systems. The taproot and windward sinker root architecture accounted for about 75% of anchorage support in smaller trees. (Moore 2000; Peltola 2006) On many sites, the tap root is limited by soil constraints and quickly becomes a minor part of anchorage. (Khuder et al. 2007) The near-surface windward roots take over the mechanical chores of the juvenile tap root over time. (Cucchi et al. 2004)

With age and increasing stem diameter, tap root anchorage values decline. Tap roots only play a significant mechanical role when they are longer downward than 1.1X to 1.4X the radial spread of lateral roots. Figure 42. Short tap roots play minor roles compared to laterals and root plates in anchorage. Tap roots and other deep roots do tend to have more mechanical impact in sandy soils, especially to leeward. If all leeward roots are shallow, there can be great anchorage value in a tap root. In clay soils, removal of tap root ends did not significantly impact anchorage as the laterals forming a stiff root plate were critical for tree anchorage. (Fourcaud et al. 2008) But, trees with deeper large roots were more resistance to failure. Heart root and sinker root forms mechanically replace taproots, making a tree more resistance to failure. (Elie & Ruel 2005) Rooting depth increases anchorage resistance to failure by about 12%. (Nicoll et al. 2006)

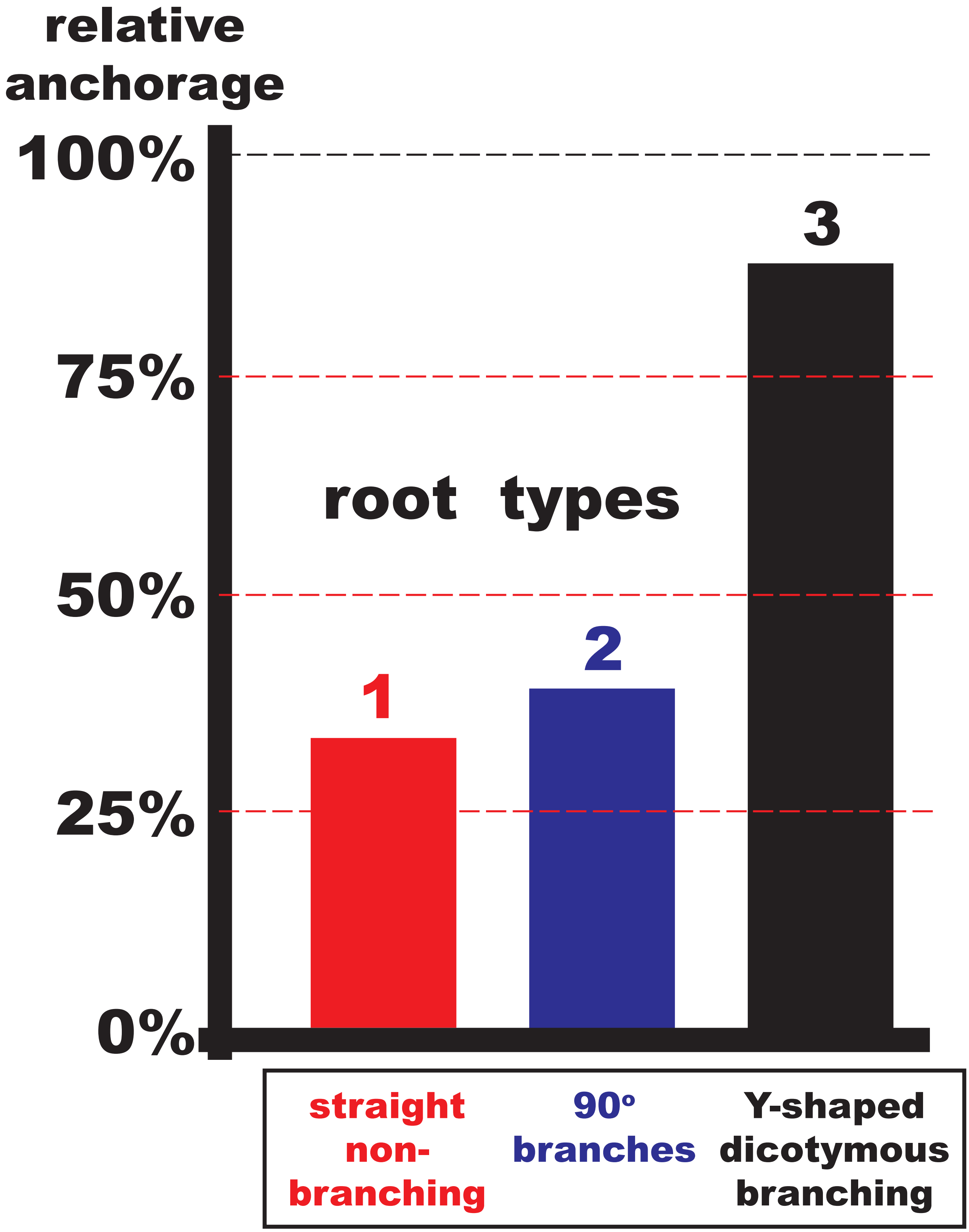

Figure 41: Relative tree root anchorage for three tested root types. (derived from Dupuy et al. 2005a & 2005b)

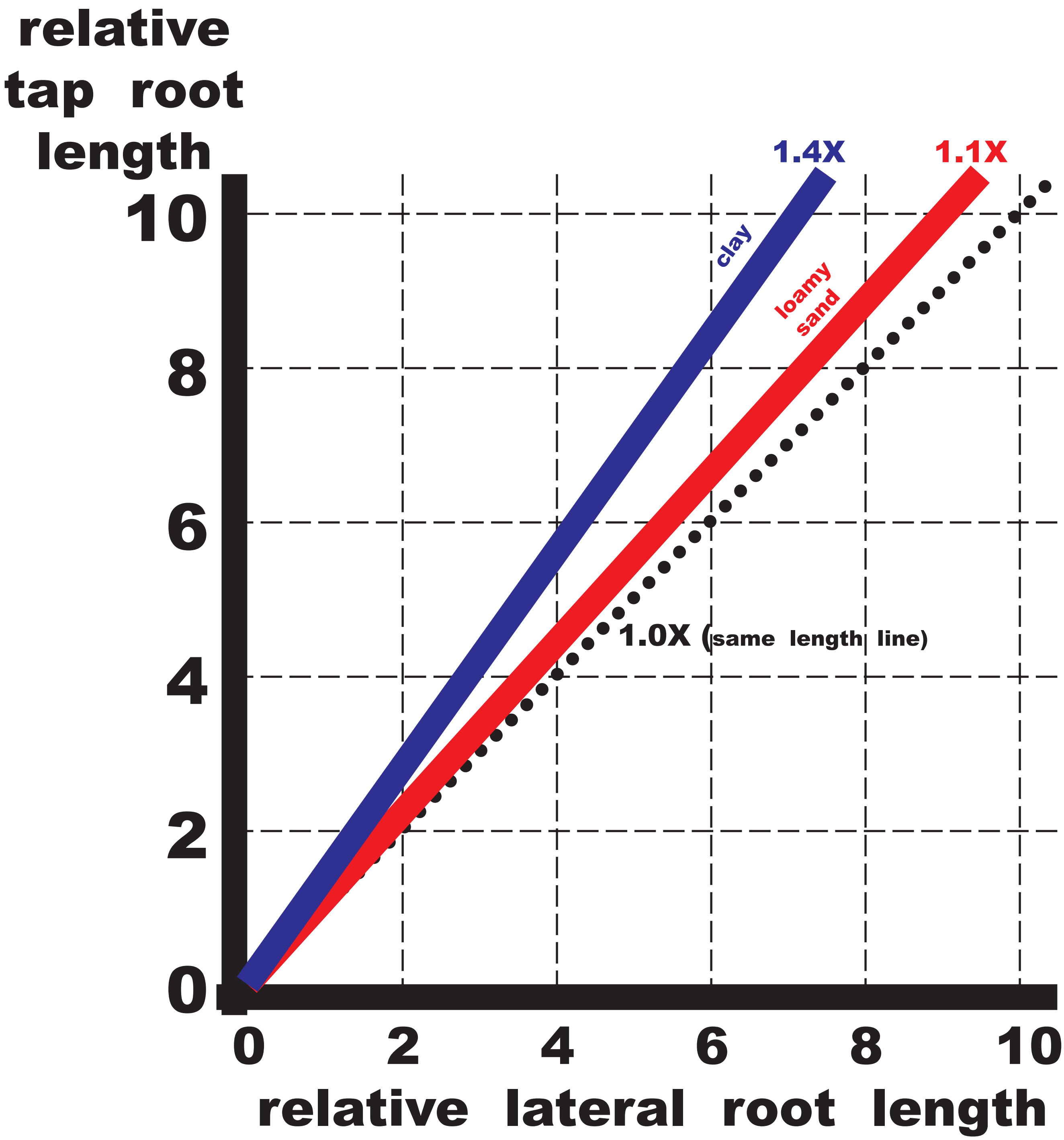

Figure 42: Point when tap root length becomes to significantly increase tree anchorage, as compared with structural lateral root length, for two different soil types. (Fourcaud et al. 2008)

Big Trunk

Anchorage success in trees has been found to be proportional to stem diameter to the third power (DBH^3). (Stokes 1999) Another anchorage model centered upon stem diameter is shown in Figure 43. Note as stem diameter increases, the tree anchorage resistance to over-turning greatly increases. (Lundstrom et al. 2007)

Both total tree mass and stem mass are significant factors related to anchorage. The greater tree mass, the more resistant to up-rooting failure. (Achim et al. 2004) As stem mass [i.e. tree height X (tree diameter)^2] increases, anchorage increases. (Elie & Ruel 2005; Lundstrom et al. 2007). One concept which consolidates tree size increase with resistance to failure is termed the *rotational stiffness* of a tree stem base. Rotational stiffness of the stem base can be calculated by the following formula: (Kato & Nakatani 2000)

$$\textbf{rotational stiffness of stem base} = 28.74 \times [\,(\text{tree diameter})^2 \times (\text{tree height})\,]^{-1.816}.$$

Use of tree height times tree diameter squared is easily measured and does not have the error of stem weight estimations. (Cucchi et al. 2004) Surprisingly though, stem base wood decay levels less than 45% did not significantly influence static load resistance of stem base stiffness. (Achim et al. 2004)

Small or Large?

Strong taper of the stem base for a given tree height, and development of structural roots with gently tapered forms, minimize up-rooting. The more wind loading challenges a tree, the stiffer and stronger the stem and root base become in order to resist failure under those wind conditions. (Nicoll et al. 2008) Trees allocate more biomass to structural roots on thinner soils, and with shallower roots. Trees with increasing live crown ratios also allocate more biomass to roots. (Tobin et al. 2007)

Trees with more large diameter roots have better anchorage because of their stiffness compared with trees with many small roots with the same cross-sectional area. Small roots, especially massed fibrous roots, do add additional anchorage to a tree because they entangle and hold much more soil volume than large roots. But root branching close to the stem base can lead to structural problems. If one root of diameter Z and stiffness X branches or forks into two roots with the same combined cross-sectional area, then stiffness or bending resistance of those roots are 0.25X of the root before branching. (Tobin et al. 2007; Coutts et al. 1999)

Pushing Resistance

Tree anchorage can be summarized as a combination of forces applied to a lever arm of a tree stem standing above, and overall resistance to those forces in the rooting area. Overall tree anchorage resistance to failure depends upon: the slip or shear surface location including depth and distance away from the stem base; tensile strength of windward roots; tensile strength of soil; compression and bending strength of leeward side roots close to the stem base; shape and weight of the root plate; and, the location of the bending / hinging zone. (Fourcaud et al. 2008; Tobin et al. 2007)

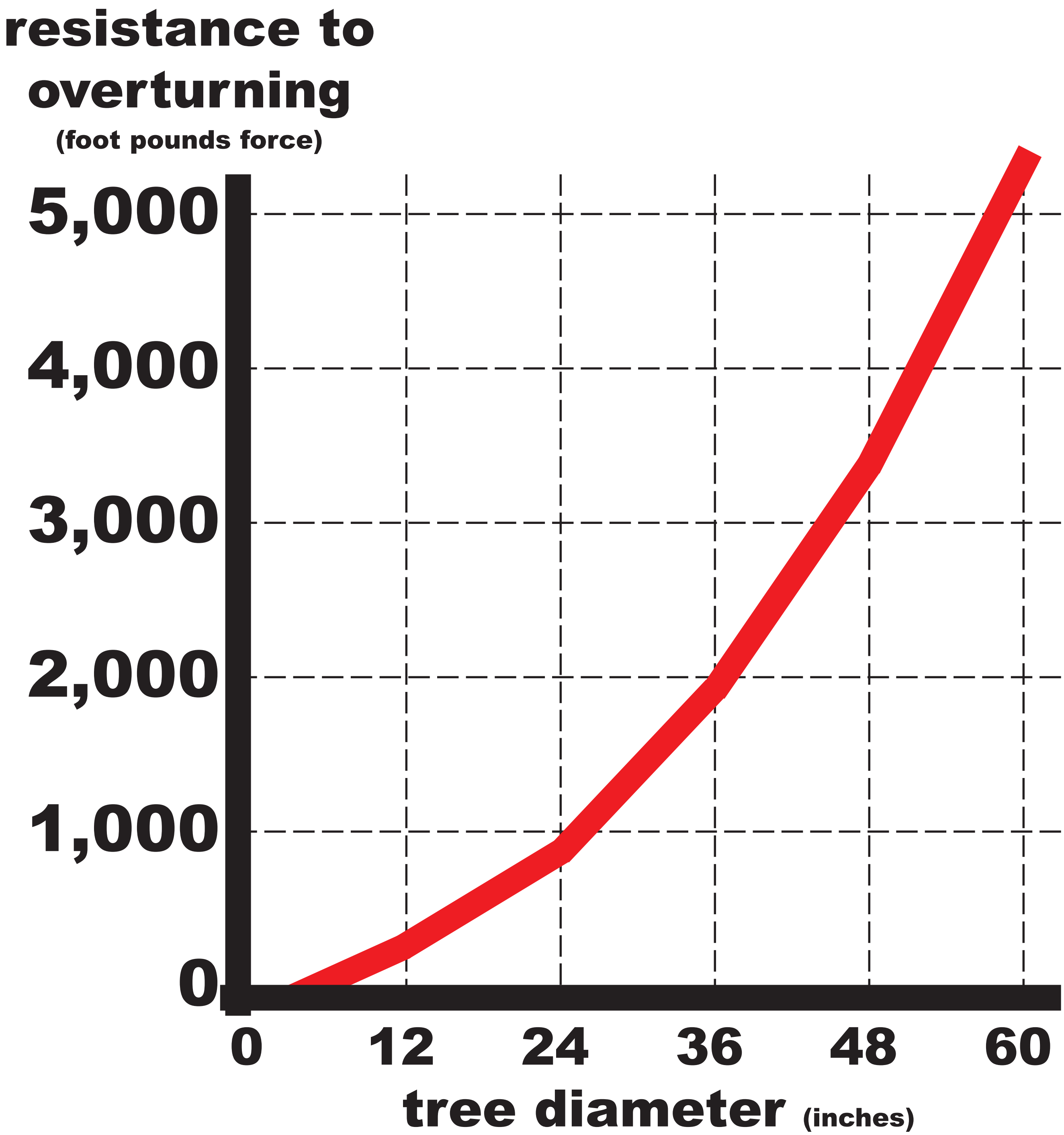

Figure 43: Impact of stem diameter in inches on tree resistance to over-turning in foot pounds of force.
(Lundstrom et al. 2007)

A proxy for tree anchorage is: (Fourcaud et al. 2008)

tree anchorage =
(root plate volume or mass) X
(leeward hinge distance from stem base).

The larger both of these factors become, the surer is tree anchorage. Tree investment in larger diameter, stiffer surface lateral roots significantly increases anchorage. (Fourcaud et al. 2008)

Beyond the root plate area, root tensile strength becomes more critical to anchorage. (Fourcaud et al. 2008) Tree anchorage strength depends upon root tensile strength (~25%), frictional resistance (~26%), and soil bonding properties (~49%). Anchorage strength can be estimated by measuring pull-out force, soil/root friction, and soil cohesion. Turning forces will be focused upon, and roots fail near, the root plate edge. Note root tensile strength is significant, but in only one component of tree anchorage. (Watson & Marden 2004; Dupuy et al. 2007)

Component Values

Figure 44 provides a composite examination of components of root resistance to over-turning as a stem is pushed away from vertical up to four degrees (4^o). At the very beginning, soil tensile strength resists up-rooting but quickly declines in value. Root tensile strength coupled with root plate weight then become the dominant components in up-rooting resistance. It is interesting to note stem weight has a negative value once a tree is pushed which accelerates quickly. The resistance to hinging by leeward roots increases up to 2.5^o, after which they provide no resistance. (England et al. 2000)

Assessment Problems

In all studies of tree anchorage, some problems have been identified. Assessing static anchorage by pulling can lead to errors. Measuring and assessing static loads on trees are insufficient in determining tree mechanical loading and failures under real-world conditions. Trees fail under dynamic loads significantly smaller than static load tests suggest. (Niklas et al. 2006)

In most studies, wind is assumed to be applied in only one direction. Both the dynamic nature of a pulsing, swirling, and multi-vectored natural wind load is ignored, and the wind-challenged reactivity of an open grown tree is diminished. Most trees must optimize for average wind conditions in multiple, if not all, directions.

One significant error in pulling test is where (i.e. height in the tree) the pulling cable is attached. Pulling experiments should be attached at a position on a stem which is about 80% of tree height. If attached below this height, trees tend to break stems, while attachment above this mark tends to up-root trees. (Achim et al. 2004) In pulling tests for anchorage assessment, tree stems can usually be pulled to 5^o without root failure. Up-rooting usually will occur before 20^o is reached. (Lundstrom et al. 2007)

Opinions Differ!

There remains significant differences in valuing rooting depth and root plate depth for anchorage. Several researchers thought the most effective tree anchorage strategy is to invest in near-surface roots and more root plate width rather than depth. (Fourcaud et al. 2008; Kamimura & Shiraishi 2007)

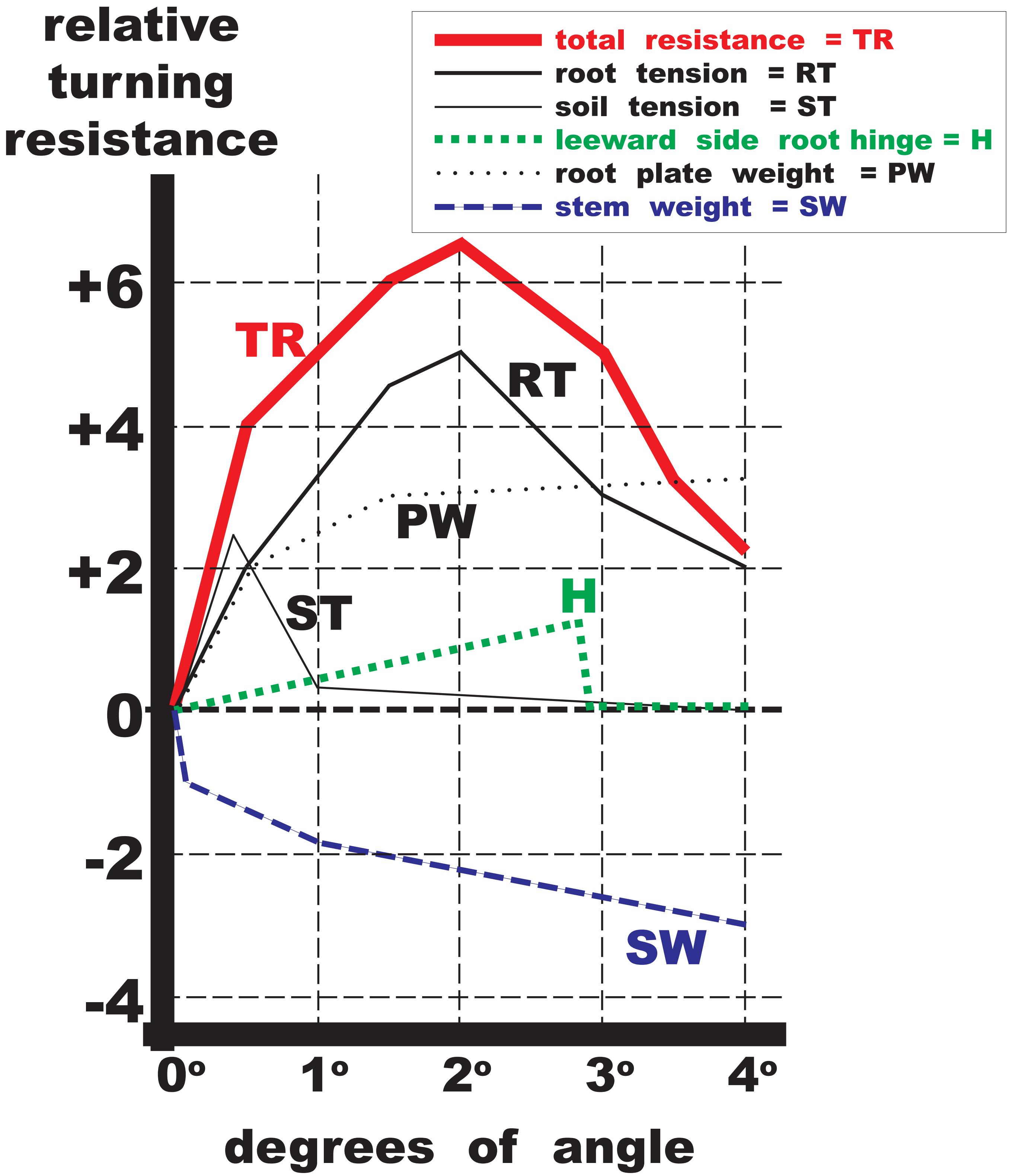

Figure 44: Model components of relative root resistance to turning by degrees of stem change.
(derived from England et al. 2000)

Another set of researchers stated tree anchorage is proportional to number of roots, volume of space occupied and size of roots in general, determined by maximum rooting depth, lateral root number, stem taper, and deep root volume. (Khuder et al. 2007) It is interesting both sides of the depth argument share a common researcher as author.

Summary

Many individual factors have been cited for contributing in major and minor ways to tree anchorage. In all these studies a number of common factors keep being recognized. Tree top geometry and wind load applied is a constant factor to considered. In its simplest form, anchorage success in trees is proportional to stem diameter to the third power (DBH^3). (Stokes 1999) Stem mass is the most important component (63% of the variation) in tree anchorage. The heavier the stem, the less likely is tree uprooting and over-turning. (Nicoll et al. 2008) Beyond tree size lies a complex set of anchorage factors.

More Complexity?

The formation of a stiff root plate provides anchorage through increasing root plate weight, root plate depth, root plate diameter, and soil strength. These factors can be summarized as the strength of windward roots, resistance of leeward root to hinging, and root-soil contact along the root plate base. (Peltola 2006) Figure 45 provides a view from above of a root plate / structural rooting area specific to wind loads from one direction and from several directions (i.e. more open grown), depending upon wind load probabilities on the site.

At the edges and beyond the root plate, tree anchorage becomes dependent upon root distribution or arrangement in soil. Roots hold trees in stable positions based upon interactions with soil density, rooting extent, root depth, number of roots, volume of space occupied, size of roots, maximum rooting depth, stem taper, and root surface area friction with soil. (Dupuy et al. 2005; Khuder et al. 2007)

Simple Reality?

To come back to a more understandable and simple form, approximately 70% of variability in tree up-rooting was found to be concentrated in just three factors: 1) number of root branches; 2) root volume area (combination of root number and rooting pattern); and, 3) root basal diameters (root size). As each increased, the less chance of up-rooting was presented. (Dupuy et al. 2005)

Multiple Factors

Figure 46 lists the various factors found to be significant in studies of root strength and tree anchorage. The following list summarizes tree anchorage information presented in the figure.

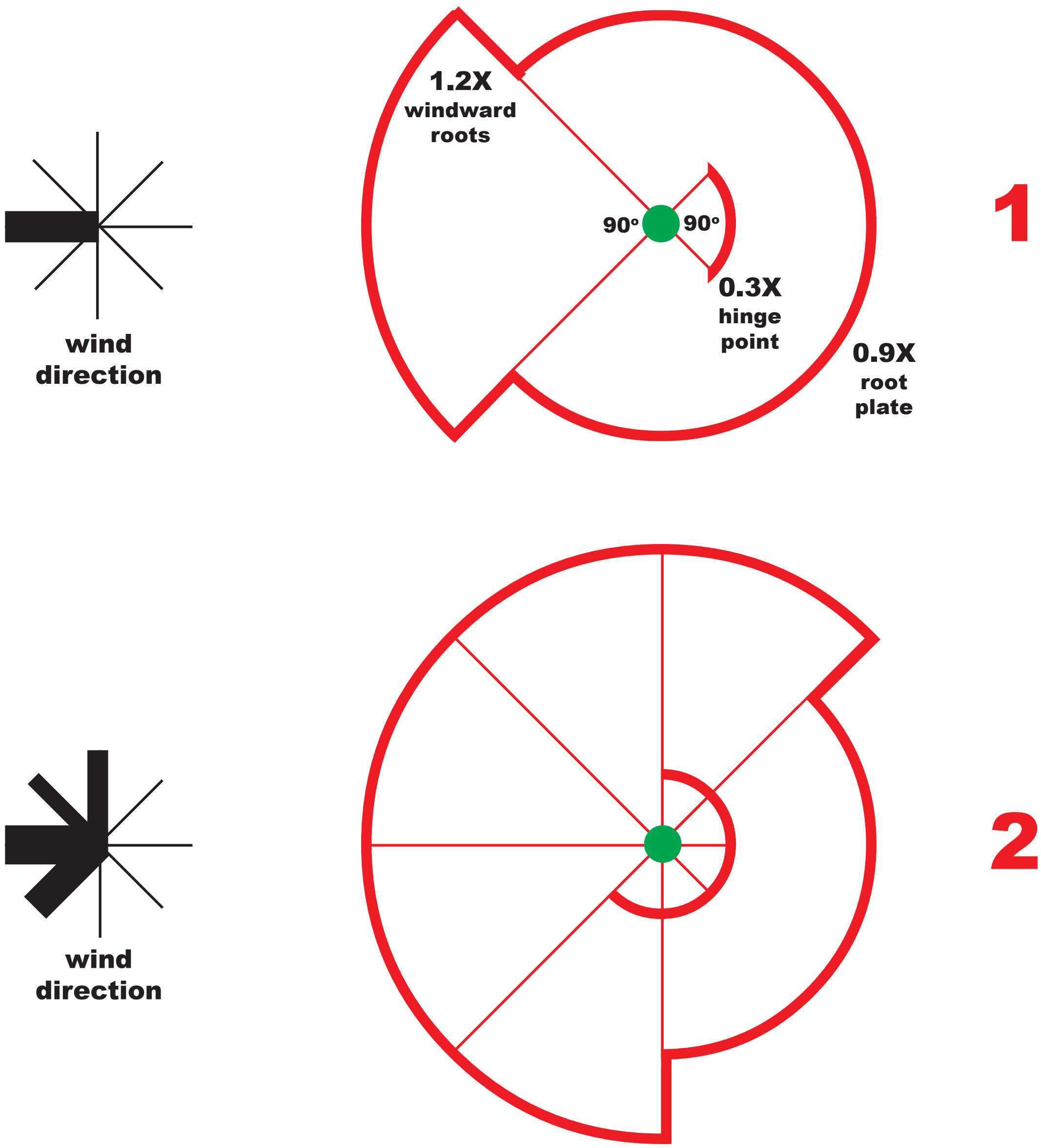

Figure 45: View from above of a: 1) single root plate development area formed with challenge from one wind direction only; and, 2) expanded root plate development area beneath an open-grown tree challenged by wind loads from the dominant directions given by the wind rose shown.

Root Attributes:

large root bases resist delamination	(Mattheck & Breloer 1994)
lateral root number	(Khuder et al. 2007)
leeward root resistance to hinging	(Peltola 2006; Tobin et al. 2007)
pull-out force	(Watson & Marden 2004)
root area ratio	(Bischetti et al. 2005)
root branch length	(Stofka & Kodrik 2008)
root branching	(Dupuy et al. 2005a/b; Stofka & Kodrik 2008; Stokes et al. 2005)
root diameter	(Dupuy et al. 2005a/b; Elie & Ruel 2005; Stokes et al. 2005)
root length	(Bischetti et al.2005; Stofka & Kodrik 2008; Stokes et al.2005)
root maximum depth	(Elie & Ruel 2005; Khuder et al. 2007; Nicoll et al. 2006)
root number	(Khuder et al. 2007)
root size	(Khuder et al. 2007)
root / soil friction	(Dupuy et al. 2007; Peltola 2006; Watson & Marden 2004)
root surface area	(Bischetti et al. 2005)
root tensile strength	(Bischetti et al. 2005; Dupuy et al. 2007; Watson & Marden 2004)
root volume total	(Dupuy et al. 2005a/b; Khuder et al. 2007)
root volume at depth	(Khuder et al. 2007)
windward root tensile strength	(Peltola 2006; Tobin et al. 2007)

Root Plate Attributes:

root plate depth	(Moore 2000; Peltola 2006; Stofka & Kodrik 2008)
root plate diameter	(Anderson et al. 1989; Coutts et al. 1999; Kamimura & Shiraishi 2007; Koizumi et al. 2007; Moore 2000; Peltola 2006; Stofka & Kodrik 2008)
root plate mass	(Peltola 2006; Tobin et al. 2007)
root plate stiffness	(Tobin et al. 2007)
root plate volume	(Fourcaud et al. 2008)
windward root plate radius	(Koizumi et al. 2007)

Soil Attributes:

soil cohesion	(Dupuy et al. 2007; Watson & Marden 2004)
soil density	(Bischetti et al. 2005)
soil depth	(Bischetti et al. 2005)
soil strength	(Peltola 2006; Tobin et al. 2007)

Stem Attributes:

stem diameter	(Lundstrom et al. 2007; Stokes 1999)
stem mass	(Achim et al. 2004; Elie & Ruel 2005; Nicoll et al. 2008)
stem taper	(Khuder et al. 2007; Nicoll et al.2008)
stem volume	(Moore 2000)
tree diameter squared X tree height	(Elie & Ruel 2005; Kato & Nakatani 2000; Lundstrom et al. 2007)
tree height / tree diameter	(Moore 2000)
tree mass	(Achim et al. 2004; Kato & Nakatani 2008)
tree + root plate mass	(Coutts et al. 1999)

Figure 46: Factors identified by various researchers to be positively correlated with anchoring trees in soil and to resisting up-rooting.

Anchorage of trees depends primarily upon the following seven items:

1) soil must resist fracture (shear strength);
2) windward roots must resist pulling out of the ground and breaking in tension;
3) weight of the tree pushing down into the soil must be sufficiently great;
4) leeward roots must resist buckling / hinging in compression and shear;
5) roots must be strong enough in cross-section to resist shearing;
6) large roots and stem base buttressing must resist delamination near soil surface; and,
7) soil must remain at less than the water content of its plastic / liquid limit.

END

Trees remaining tall and upright, while erecting large areas of photosynthetic arrays under highly variable wind and soil conditions, is amazing!
A tree is two creatures bound into one -- an above ground portion passively gathering resources and controlling space, and an underground portion actively interfering with and colonizing its surroundings. The ecological and biological optimization of these two portions, and their unique responsibilities is staggering to comprehend. The biomechanical optimization of these two portions of a tree within a highly variable and violent environment is difficult to fully appreciate.

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Warnell School of Forestry & Natural Resources

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