Root Strength & Tree Anchorage

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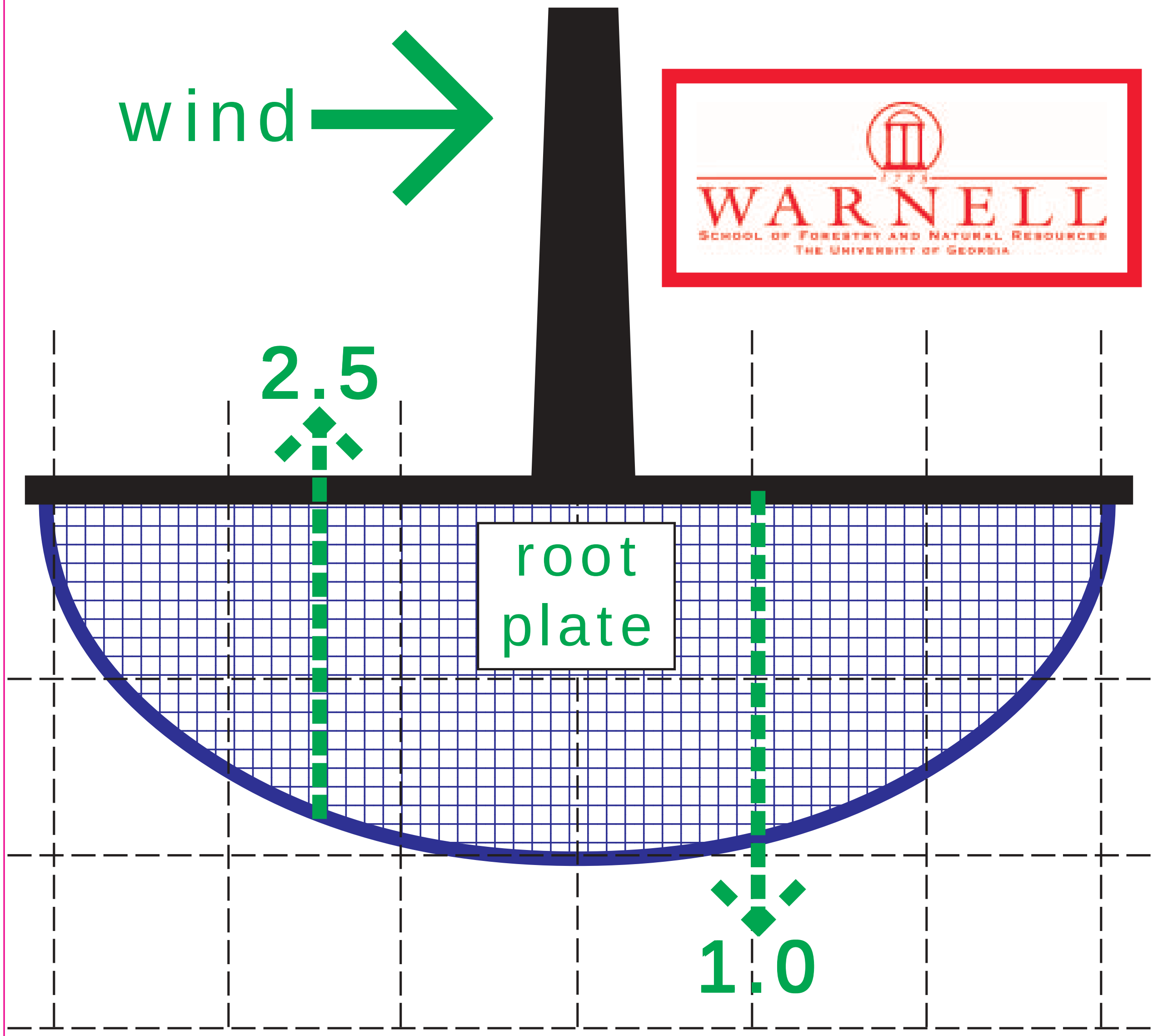

Warnell School Outreach Monograph WSFNR10-19* May 2010

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 product is a synthesis and integration of current, peer-reviewed research, field proven guides, and educational concepts regarding how tree root strength and geometry impact whole tree biomechanics. This product is for awareness building and educational 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 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 assessment.

Scientific Citation:
Coder, Kim D. 2010. **Root Strength & Tree Anchorage.** University of Georgia Warnell School of Forestry & Natural Resources monograph publication WSFNR10-19*. Pp.88.

Root Strength & Tree Anchorage

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There has been a proliferation of tree anchorage research in the last decade. Most of the research published in the best peer-reviewed, scientific journals have focused on forest stands, steep slopes, and single tree failure risks. Much of this research has been published outside the usual arboriculture literature and may not be accessible to tree health care providers. The tree research groups from the European Union (France, United Kingdom, and Italy in particular), Japan, China, Canada, and New Zealand have led the way in understandings regarding root strength and tree anchorage.

This paper reviews, synthesizes, and integrates a number of these new research findings for tree health care providers. The purpose of this paper is to try and understand how trees stand erect, and how they overturn or uproot, as proposed by a number of researchers. Because researchers do not always agree on specific values of different attributes in supporting a tree, continuous scientific reevaluation is key to discarding dogma and proposing new ways of assessing tree anchorage. The understandings generated by research are important components of tree risk assessment and field application of biomechanics.

Failure

All trees fail with time. The means of trees standing erect against wind and gravity loads (anchorage) involve a complex set of soil and structural interactions. Successful tree anchorage over time depends upon both the size of wind and gravity loads placed on a tree, and the tree / site structural resistance to these loads. Resistance to wind and gravity loading is distributed and shared throughout a tree and associated soil. Figure 1. Trees and sites have many structural components which must be protected from damage, and must be examined for failure risks, in order to provide for sustainable tree life.

Size Matters

Many individual tree and soil factors contribute in some way to tree anchorage. A number of key tree anchorage attributes have been identified and are directly linked to tree size. In its simplest form, anchorage success in a tree is proportional to stem diameter to roughly the third power (DBH^3). As tree stem diameter increases by 2X (two times), the energy required to cause uprooting increases by ~6.7X . (Lundstrom et.al. 2008; Stokes 1999; Stokes et.al. 2005). Figure 2; Figure 3.

Other tree size features related to tree anchorage include tree diameter--height relationships (i.e. generic stem taper or slenderness ratio) (Cucchi et.al. 2007; Lundstrom et.al. 2007) (Figure 4; Figure 5), and tree weight (Bergeron et.al. 2009) (Figure 6; Figure 7; Figure 8). In one case, tree weight accounted for 63% of the variation in tree anchorage, where the heavier a tree, the less likely is uprooting. (Nicoll et.al. 2008) Because trees are continually challenged and react to changing mechanical loads, bigger trees have had longer times to adjust to wind conditions while selectively adding growth, and are more difficult to uproot than smaller, younger trees. (Achim et.al. 2005; Elie & Ruel 2005).

Multiple Factors

Beyond basic tree size lies a complex set of anchorage factors. Table 1 lists various structural components found to be significant in tree anchorage. Table 1 was pulled from tree research over just the last decade . The table shows there are many aspects of tree growth and development which have been found to play a role in tree root strength and anchorage. To summarize the long list of components in Table 1, anchorage of trees depends primarily upon the following items: (see Figure 9)

1) soil must resist fracture (shear strength) and remain dryer than its plastic limit;
2) longest major 2-3 windward roots must resist pulling out of the ground and breaking in tension;
3) weight of tree on soil must be sufficiently great;
4) leeward roots must resist buckling / hinging in compression and snapping in shear; and,
5) stem base and large roots must provide a wide, stiff, supporting platform which resists splitting (delamination).

Root Attributes

Tree roots, and their soil interactions, must resist environmental forces to keep a tree upright. Trees have many roots of many sizes which all play some role in anchorage. It is important to develop an image of tree roots as their biological and structural functions are draped by soil and soil surface materials. What is a general image of tree roots?

Many / Small

For example, one spruce examined had a total of 82,500 roots. Of these roots, large roots (>1/5inch) were estimated to be 62% of all roots, while small roots (<1/5inch) 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. (Abe & Ziemer 1991) Another study estimated 96% of tree roots are less than 2/5 inch in diameter. (Abernethy & Rutherfurd 2001) In another study, 60% of all roots in three hardwood species were smaller than 1/5 inch in diameter. (Abdi et.al. 2010). In other words, most tree roots are small in diameter.

Dominant structural roots were found to provide more than 80% of the total root mass, concentrated in 3-10 of the largest roots. (Coutts et al. 1999) Figure 10. 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 11; Figure 12. The decreasing number and size of roots with soil depth, generate a declining total cross-sectional area of roots in a soil with depth. Figure 13. A greater number of larger roots are concentrated closer to the soil surface. (Abernethy & Rutherfurd, 2001; Danjon et al. 2008; Tosi 2007)

Shallow

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 14. Large diameter roots generated at the stem base taper quickly and may have eccentric, structurally optimized cross-sectional shapes. Figure 15. Tree roots are relatively shallow. In one study, ~30% of all roots in three tree species were in the top 4 inches of soil, and >50% of all roots were found in the top 12 inches of soil. (Abdi et.al. 2010)

Root Model

Resistance to tree anchorage failure is associated with structural components of root systems. Figure 16 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 increasing wind speeds; and, 3) non-structural, shallow, horizontal absorbing root fans. The root plate edge and drip line edge are delineated in the figure.

In summary, there are a few large diameter roots and a host of small roots, all positioned close to the soil surface. The shape, size, length, taper, and depth of tree roots are optimized to provide both anchorage and soil resource gathering and control. (Kalliokoski et.al. 2008)

Root Resistance

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 of wind pressure center in tree crown).

Tree roots must successfully resist 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 usually 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 area of tree crowns of various shapes toward the wind. Figure 17 provides Coder tree crown shape coefficients.

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 overturning is challenged by force placed on the crown through wind loading. Figure 18 shows the proportion of various stresses applied to a tree. Wind has roughly 10X the impact of a tree lean of 5°, 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, more stem and root taper, and greater root surface area. After establishment and effective site colonization, the relative change in tree resistance to overturning remains roughly the same until old age constraints begin to limit tree reactions to its wind environment. (Achim et.al. 2004) Figure 19.

As trees age, structural investment differences between stem and roots occur. Both root plate resistance and wind force applied (i.e. an uprooting resistance index) increase with tree age and size, suggesting uprooting 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 uprooting occurs. (Koizumi et.al. 2007; Stokes 1999) Shallower rooting young trees developed thicker stems, thicker lateral roots, and longer lateral roots as to increase tree anchorage (Korndorfer et.al. 2008). Figure 20 shows stem resistance to failure with age outpacing root resistance over time.

Failings

Uprooting resistance of trees depend 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 horizontal roots will tend to fail in tension. In deep soils, the entire 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 uprooting. (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 the 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 the 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.

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-sections 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 21. Root diameter growth assures stiffness and associated resistance to hinging or bending. Large trees maintain anchorage by increasing radial growth without changing number of roots. (Abdi et.al. 2010).

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

Root Strength

In considering tree anchorage and resistance of roots to failure, root tensile strength is 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)

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

Specific root tensile strength for a number of different tree species are given in Table 2. There is a trend for angiosperms to have an exponent value near "-1," and for gymnosperms to have an exponent value near "-0.75." There are many notable exceptions. (Bischetti et al. 2005)

Another calculation form used in estimating tree root tensile strength is: (Sun et.al. 2008)

root tensile strength (MPa) =
[4.0 X maximum force exerted in newtons] / [3.1416 X (root diameter in mm) ^{2})]

Note the tensile strength of a root declines as its root diameter increases. It is the small roots which provide great tensile strength for a given cross-sectional area.

Mighty Mite

Greater root tensile strength per cross-sectional area lies in smaller roots, while greater root stiffness lies with larger roots. Figure 22. As discussed earlier, most tree roots are small in diameter (i.e. estimated 96% of tree roots are less than 0.4 inch in diameter (Abernethy & Rutherfurd 2001)). The seeming conflict in perception of root strength differences among small and large root diameters come 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 related to root tensile strength.

Cellulose is highly resistant in tension but has low resistance to bending. Smaller roots, with proportionally more cellulose, are much more resistant to tensile forces than large roots per cross-sectional area. (Genet et al. 2005; Tosi 2007) The larger root diameter (with its associated larger cross-sectional area), the smaller tensile strength becomes per cross-sectional area. Large roots can resist great total tensile forces simply because of their size but their anchorage value lies with their resistance to bending and shear. (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 23. 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 24. (Abe & Ziemer 1991) Total root tensile strength for a tree can be estimated using a formula which includes adding together root number and cross-sectional area, and their pull out resistance. Total root strength is: (Greenwood 2006)

total root strength = sum of all individual roots =
[(number of roots per diameter) 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 the roots, and resistance to failure. Root branching angle does impact pullout force. Figure 25 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° between a primary lateral and a secondary lateral root. (Stokes et al. 1996)

Strong or Stiff?

Tree root systems are genetically optimized between stiffness and strength. Small diameter roots are flexible with a high tensile strength. Large diameter roots are stiff, resisting 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 strength into larger diameter roots. (Bischetti et al. 2005).   One study found root tensile strength to be an insignificant part of tree anchorage. (Dupuy et.al. 2007).

Soil Resistance

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)

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 composite and 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, roots will break when placed under critical loads. If root tensile strength is greater than fictional forces, 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)

Tension / Compression

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 generate 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 26. 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 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).

In further study, strain to windward and to leeward in small trees were examined separately for root top and bottom. Figure 27. 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) Mechanical stress differences in root tension and compression stress and strain initiates significant radial growth of roots, and contributes to eccentric secondary root growth within the first 2-3 feet of the stem base. (Ghani et.al. 2009)

Beam Up & Down

Strong anchorage near the tree base 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 focal 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 28.

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 was found to be significantly more important than root tensile strength for increasing soil shear resistance. (DeBaets et.al. 2008) Root area index is determined by measuring cross-sectional area of roots exposed on a flat vertical face of soil with a given surface area. Figure 29. 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 30. (Bischetti et al. 2005) Full range of root area ratio values vary 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 to the soil surface. The greater density of roots (high root area ratio) and the deeper into soil this density is maintained, 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 and oxygenation, as impacted by soil texture, bulk density, and physical soil constraints. Tree roots in a native soil are distributed following a gamma distribution curve. Figure 31. A gamma distribution has a maximum point near the soil surface and tails-off with soil depth depending upon soil constraints. See Figure 32. (Bischetti et al. 2005)

Roots can be found concentrated within a set radius from a tree stem . Figure 33 shows the expected radius for most roots, (>1mm or >1/25 inch diameter) away from a tree stem. With increasing tree diameter, rooting distance away expands proportionally less. (Roering et al. 2003). Figure 34 demonstrates how as rooting distance (radius) in feet increases, total root colonization area in square feet greatly increases. As trees grow larger, small increments of rooting distance 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

One important concept of tree anchorage which consolidates many aspects of tree structure is the "root plate." Tree root plates are one simple way to understand and work with tree anchorage in the field. A tree root plate is composed of large diameter roots generated at the base of a stem. These large roots taper quickly away from the stem base. A point is reached along a large root where the structural dominance of root stiffness in supporting a tree shifts to dominance of root and soil tensile strength supporting a tree. This point of functional change in large roots represents the edge of a root plate. A tree root plate is a stiff, shallow, horizontal disk-shaped rooting area, and associated soil mass, under and near the stem base.

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.

Oval Plates

Estimating root plate size and shape are critical to tree anchorage and tree risk management. There are several ways to describe root plate size and shape. One way is as an ellipse, when viewed looking down on a tree and soil surface from above. Figure 35. In this case, the ratio of short axis to long axis is about 0.85 across the direction of the wind. Root plate size is used to estimate tree anchorage. (Koizumi et.al. 2007)

$$\text{relative tree anchorage} = [\,(\text{windward root plate distance from stem})^2 \;\; X \;\; (\text{root plate long axis})\,] \;/\; 3.$$

Critical components of the Koizumi root plate and its resistance to failure include the windward side of the root plate and total root plate size. In this formula, simple soil surface estimates of root plate dimensions help define tree anchorage, with great emphasis on windward roots. (Koizumi et.al. 2007)

The Achim root plate is oval in shape when viewed from above. Dimensions for leeward radius, windward radius, and lateral radius (perpendicular to the wind direction) are calculated in Figure 36 for a range of tree diameters. An example of this type of root plate is given in Figure 37 for a 12 inch diameter tree.

Round Plates

Other root plate models are circular shaped when viewed from above from above, and either a shallow cone shape (Peltola 2006) (Figure 38), or half an ellipse shape when viewed from the side. (Lundstrom et.al. 2007) (Figure 39). The Lundstrom root plate model uses a three unit proportional measure for defining a root plate. The root plate horizontal radius along the soil surface away from a stem base is three units, the leeward hinge point distance is one unit, and the depth is two units. Figure 40.

Calculating Size

Many authors have determined tree size is directly related to tree anchorage as associated with root plate size. Root plate size in the field can be estimated by using a multiplier of tree stem diameter. The Koizumi root plate ellipse long axis can be determined by multiplying tree stem diameter in inches times 0.92 to yield the long axis in feet, and times 0.78 to yield the short axis in feet. Figure 41. These root plate dimensions can then be used to estimate tree anchorage:

$$\text{relative tree anchorage} = [\,(DBH_{in} \;\; X \;\; 0.39)^2 \;\; X \;\; (DBH_{in} \;\; X \;\; 0.92)\,] \;/\; 3.$$

For example, a 9.5 inch diameter tree would have a Koizumi 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). The relative tree anchorage value of 120.0 can be used to compare different trees, or growth changes in the same tree over time. (modified from Koizumi et.al. 2007)

Other Models

Many other root plate models and field calculation methods exist. For example, one field method (i.e. Coder Root Plate Model) used for years on construction sites multiplies tree diameter in inches times 0.9 for a standard root plate diameter (in feet), and times 0.15 for the position away from a stem base in feet (a radius) of the leeward hinge or bending point across a 90° arc. Figure 42 shows this estimated circular root plate form and the hinge point location opposite wind direction.

The Danjon root plate area model is non-circular is shape. Critical parts include a leeward hinge diameter arc and a windward wedge-shaped area filled with a number of long major roots. The Danjon root plate area hinge point away from a stem in feet is determined by multiplying the diameter of a tree in inches times 0.367. The windward portion of the structural root area should contain at least 2-3 long major roots. (Danjon et.al. 2005) Figure 43.

Combo

One way to consider tree root plate size is to combine simple research models and field applications to provide a composite view. Figure 44 uses components of selected models above to show a complex shaped root plate area. The general circular root plate, hinge point to leeward, and area with 2-3 longest major roots to windward are shown. A second composite root plate form is shown in Figure 45. This form eliminates root plate areas not associated with direction wind response. These root plate shapes can be used to protect and assess tree anchorage.

Composite root plate forms are drawn based upon the dominant wind direction. Figure 46. Most open grown trees are challenged by wind loads from all directions. Loss or damage of roots on one side of a root plate may partially determine failure direction depending upon how far root damage was from the stem base. Clearly no root plate model will fit the highly variable conditions existing in tree root system development. Wind dominant direction (or lack thereof), wind dynamic changes, and the amount and form of tree loading will all generate great variation in root plate development which are not summarized in standard simple models. A root plate, however determined, represents a tree anchorage area and should be avoided for activities like site development, soil disturbance, paving, and compaction.

Plate Depth

Root plate depth is limited by aerobic soil values. (Peltola 2006) Many ways can be used to determine root plate depth. Figure 47. One way used in the field (i.e. Coder Root Plate Model) is to multiply tree diameter in inches times 0.3 for a root plate depth in feet within an unconstrained, aerated rooting volume. A second way of defining root plate depth is 1/3 maximum rooting depth. (Danjon et.al. 2005) Depending upon aerobic soil depth and other soil attributes, the value of determining root plate depth in estimating tree anchorage is debatable. One study of tree failures found root plate depth was not a significant factor of anchorage. (Koizumi et.al. 2007) In another study, root depth alone was found to be detrimental to tree growth, compared with lateral root spread. (Korndorfer et.al. 2008).

Wide Or Deep?

In most studies, both root plate diameter increases (Figure 48) and depth increases (Figure 49) improve tree anchorage. Of these two root plate dimensions (diameter and depth), root plate diameter expansion more effectively increases tree anchorage than increasing depth. (Moore 2000) An example of root plate diameter increases improving anchorage is shown by trees on sites with serious rooting depth limitations. In this case, a very shallow root plate is generated with roots reinforced farther out from the stem, creating a larger diameter root plate and a longer hinge distance from the stem. (Coutts et.al. 1999). Figure 50.

Research continues examining the role of tree root depth in anchorage. Some research shows more near-surface roots and greater root plate diameter are more important to tree anchorage, rather than depth. (Fourcaud et.al. 2008; Kamimura & Shiraishi 2007) Other research shows effective tree anchorage is due to increasing maximum rooting depth, lateral root number, stem taper, and depth of rooting volume. (Khuder et.al. 2007) Over time, better root plate definitions by soil type and site constraint will become available.

Stiffness

Successful tree anchorage comes from an intact and 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). (Coutts et.al. 1999; Tobin et.al. 2007) For example, gaining a 1 foot diameter on a 10 feet diameter root plate (+10% diameter increase) represents a +46% increase in root plate stiffness. Table 3.

Different parts of a root plate carry different portions of anchorage responsibility. Proportionally, windward roots (50%), root plate mass (40%), and leeward root hinge and soil resistance (10%) support tree anchorage (Danjon et.al. 2005; Peltola 2006). Windward roots are responsible for bearing 2.5X (two-and-one-half times) greater tree anchorage resistance than leeward roots. Figure 51. Leeward roots are bent and pressed into supporting soil while windward roots are pulled up and out of the soil in tree anchorage failures. (Stokes 1999; Watson 2000)

Symmetry

Root plate symmetry is also critical for anchorage especially for open-grown trees. Root plates providing effective anchorage usually contain no more than 60% of component roots along the axis of dominant winds. Leeward roots tend to be larger in diameter at the surface than windward roots, and have sinkers growing downward. Windward roots tend to be longer and more branched at a greater distance. (Tobin et.al. 2007) Trees continue to reinforce roots for anchorage under wind loads. In one study, leeward roots within the root plate were reinforced in diameter +21% more than other roots. Beyond the root plate, windward roots were reinforced +30% more than other roots, increasing root length (+28%) and root number (+32%). (Danjon et.al. 2005)

Soils

As wind load is applied to a tree top, forces are transferred to the root plate, individual roots, and soil. Roots can stretch between 10-20% before breaking while soil can stretch (pulled in tension) less than 2% before breaking. The result is soil breaks first and pulls away from roots. As larger roots flex up and down, (i.e. normal root plate wobble), soil separates from root surfaces around the stem base. This loss of root-soil contact continues out along major roots as more wind load is applied. (Tobin et.al. 2007) Anchorage failures differed by soil type with 92% of up-rooting failures occurred in sand and 11% in clay soils. (Moore 2000) Simple root plate models do not usually include adjustments for soil types.

Tree root plate stability is impacted by soil type. In sandy soils, root plates tend to fail on the windward side because of soil weakness and roots pulling out of the soil. Tree anchorage in sandy soils depends upon rooting depth, intact windward roots (Dupuy et.al. 2005b), and stiffness of leeward roots. (Fourcaud et.al. 2008). In clays, root plate failure occurred along a symmetrical slip / shear zone around the perimeter of the root plate. (Dupuy et.al. 2007) In clay soils, tree anchorage depends upon large diameter roots both to windward and leeward close to the stem base (Dupuy et.al. 2005b), and 2-3 long major windward roots. (Fourcaud et.al. 2008) In clay soils, there is more total resistance to tree anchorage failure than in sandy soils.

Shape

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 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)

Five Views of Tree Anchorage & Root Plates

The composite positive value of root plate anchorage is represented by three components listed in order of importance: windward roots growing beyond the root plate edge; root plate mass; and, leeward roots as the hinge / bend point is moved farther from the stem base. (Elie & Ruel 2005).

1) 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. The amount of wind load and length of the lever arm turning a tree out of the ground negatively impacts anchorage.

2) A more simple 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.

3) 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).

   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 against the mechanical load.

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

5) In another study, root plate volume was found to be proportional to anchorage, but not the entire volume. In this case, not all the root plate participated in tree anchorage. Only about 70% of the root plate volume contributes to tree stability. The root plate volume contributing to anchorage was: (Lundstrom et.al. 2008)

   root plate volume contributing to anchorage =
   [root plate diameter parallel to wind X root plate diameter perpendicular to wind X
   root plate depth] X $0.7^{0.334}$.

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 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 is a valuable concept in understanding and educating people about tree anchorage, but not all researchers agree.

Using root plate models to measure, estimate and describe tree anchorage have limitations because root architecture is highly complex and guided in development by interactions of genetic and environmental constraints. Root architecture remains more important to tree anchorage than simple root plate dimensions. (Dupuy et.al. 2005a; Fourcaud et.al. 2008; Khuder et.al. 2007; Moore 2000; Peltola 2006) The specific root system layout 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 an idealized root plate diameter value. (Fourcaud et al. 2008).

The root plate is a composite structure, (a theoretical construct?), providing anchorage resistance under average conditions. Given all the limitations, root plate concepts still can provide value in working with tree anchorage.

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. This latter type of failure is subject to root system architecture issues, not stem base and root plate stiffness concerns.

Anchorage of trees depends upon the characteristics of the 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.

Areas of Concern

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 root depth in angiosperms = 14% shallower and root depth range of angiosperms = 75% the depth range of gymnosperms in same soil). (Roering et al. 2003)

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)

Which Side of the Wind?

Compressive and bending root strength to leeward are important to understand. Figure 52 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)

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)

Upside of Slopes

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) In two hardwood species, downslopes had roots deeper while upslopes tended to have more roots. Figure 53.

In another study, the amount of slope significantly changed rooting attributes and associated anchorage. The contribution of roots to tree anchorage on the upslope side of trees increased with slope percent. The number of lateral roots were less on higher degrees of slope, while root diameter, root tensile strength, and length were greater.

Figure 54. A tree anchorage failure curve was developed and shows two key points as more force is applied to the stem. The first point is a failure of the downslope roots, and the second somewhat later point is the failure of the upslope roots. (Sun et.al. 2008). Figure 55.

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 when there was increased root branching in the larger (>4.7 inches) diameter roots and when greater total root length was 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) diameter roots, greater branch root length in small diameter roots, and greater total root length in small diameter roots. To summarize, 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 56 shows three different root forms and the relative anchorage effectiveness of each. (Dupuy et.al. 2005) In this research model, 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.

Tap Roots!

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 57. 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)

Overall, 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) Increasing the rooting depth component increased anchorage resistance to failure by about 12%. (Nicoll et al. 2006) Alternatively, one study showed deep rooting proved detrimental as rooting depth increased with constrained lateral rooting. (Korndorfer et.al. 2008). Figure 58.

Massive

Total tree mass and stem mass both 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)

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

Use of tree height multiplied by tree diameter squared is easily measured and does not have the error of stem weight estimations. (Cucchi et al. 2004) Surprisingly, 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 shallow structural roots on thinner soils. Trees also allocate more biomass to roots with increasing live crown ratios. (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 rapid tapering and root branching close to the stem base can lead to structural problems. If one root of 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. Figure 59. (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)

Beyond the root plate area, root tensile strength becomes more critical to anchorage. (Fourcaud et al. 2008) Tree anchorage strength then 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 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 60 provides a composite examination of the components of root resistance to over-turning as the 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 laterally loaded. The resistance to hinging by leeward roots increases up to 2.5^o inclination, 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) One significant error in pulling test is where (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)

Another concern in many studies is 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.

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) 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.

Ending Point

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 a near-soil surface 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. Tree anchorage factors are so varied and diverse because trees use many features and craft many solutions to stay erect. Tree health care providers can but estimate in a tree-literate and sustainable manner tree anchorage and root strength.

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Table 1: Factors recently identified by researchers to be positively correlated with anchoring trees in soil and to resisting up-rooting.

Root Attributes:	
large root bases resist delamination	(Mattheck & Breloer 1994)
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	(Abdi et.al. 2010; Dupuy et al. 2005a/b; Elie & Ruel 2005; Korndorfer et.al. 2008; Stokes et al. 2005)
root length	(Bischetti et al.2005; Dupuy et.al. 2005; Khuder et.al. 2007; Korndorfer et.al. 2008; Stofka & Kodrik 2008; Stokes et al.2005)
root depth	(Dupuy et.al. 2005; Elie & Ruel 2005; Ghani et.al. 2009; Khuder et al. 2007; Nicoll et al. 2006)
root number	(Dupuy et.al. 2005; Khuder et al. 2007)
root size	(Dupuy et.al. 2005; Khuder et.al. 2007)
root / soil friction	(Dupuy et al. 2007; Peltola 2006; Watson & Marden 2004)
root surface area	(Bischetti et al. 2005)
root taper	(Kalliokoski et.al. 2008)
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	(Achim & Nicoll 2009; Anderson et al. 1989; Coutts et al. 1999; Ghani et.al. 2009; 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; Lundstrom et.al. 2008)
windward root plate radius	(Koizumi et al. 2007)
Soil Attributes:	
soil cohesion	(Dupuy et al. 2005; Dupuy et.al. 2007; Khuder et.al. 2007; Watson & Marden 2004)
soil density	(Bischetti et al. 2005; Dupuy et.al. 2005; Khuder et.al. 2007)
soil depth	(Bischetti et al. 2005)
soil strength	(Peltola 2006; Tobin et al. 2007)
Stem Attributes:	
stem diameter	(Achim & Nicoll 2009; Ghani et.al. 2009; Korndorfer et.al. 2008; Lundstrom et al. 2007; Lundstrom et.al. 2008; Stokes 1999)
stem mass	(Achim et al. 2004; Bergeron et.al. 2009; Elie & Ruel 2005; Nicoll et al. 2008)
stem taper	(Dupuy et.al. 2005; 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	(Ghani et.al. 2009)
tree height / tree diameter	(Bergeron et.al. 2009; Moore 2000)
tree mass	(Achim et al. 2004; Kato & Nakatani 2008)
tree + root plate mass	(Coutts et al. 1999)

Table 2: Example formula for estimating tree root tensile strength by species. Note root diameter (D) measures are in millimeters.

species	root tensile strength	citation
spruce	$28\ D^{-0.7}$	(Bischetti et al. 2005)
general trees	$29\ D^{-0.52}$	(Danjon et al. 2008)
willow	$31\ D^{-1}$	(Bischetti et al. 2005)
salt-tree	$32\ D^{-0.89}$	(DeBaets et al. 2008)
European mt. ash	$35\ D^{-1}$	(Bischetti et al. 2005)
alder	$35\ D^{-0.75}$	(Bischetti et al. 2005)
larch	$34\ D^{-0.75}$	(Bischetti et al. 2005)
beech	$42\ D^{-1}$	(Bischetti et al. 2005)
eucalyptus	$50\ D^{-0.75}$	(Abernethy & Rutherfurd 2001)
hazel	$60\ D^{-0.75}$	(Bischetti et al. 2005)

Table 3: Relative stiffness or rigidity (D^4 basis) of tree root plates of different diameters. (Coutts et al. 1999; Tobin 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.

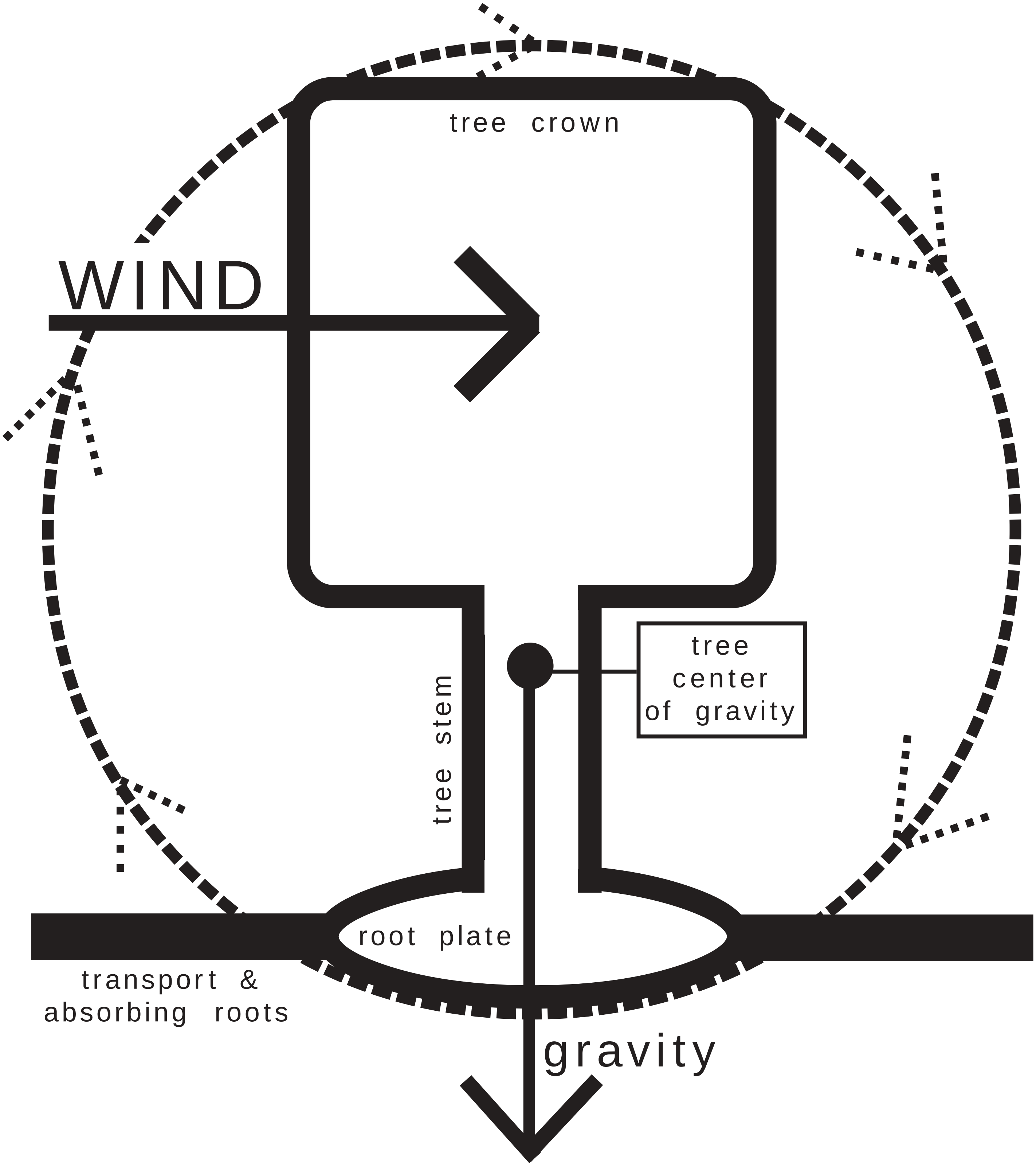


Figure 1: Simplified view of wind loading and gravity acting to rotate a tree out of a soil as a combined load wheel.

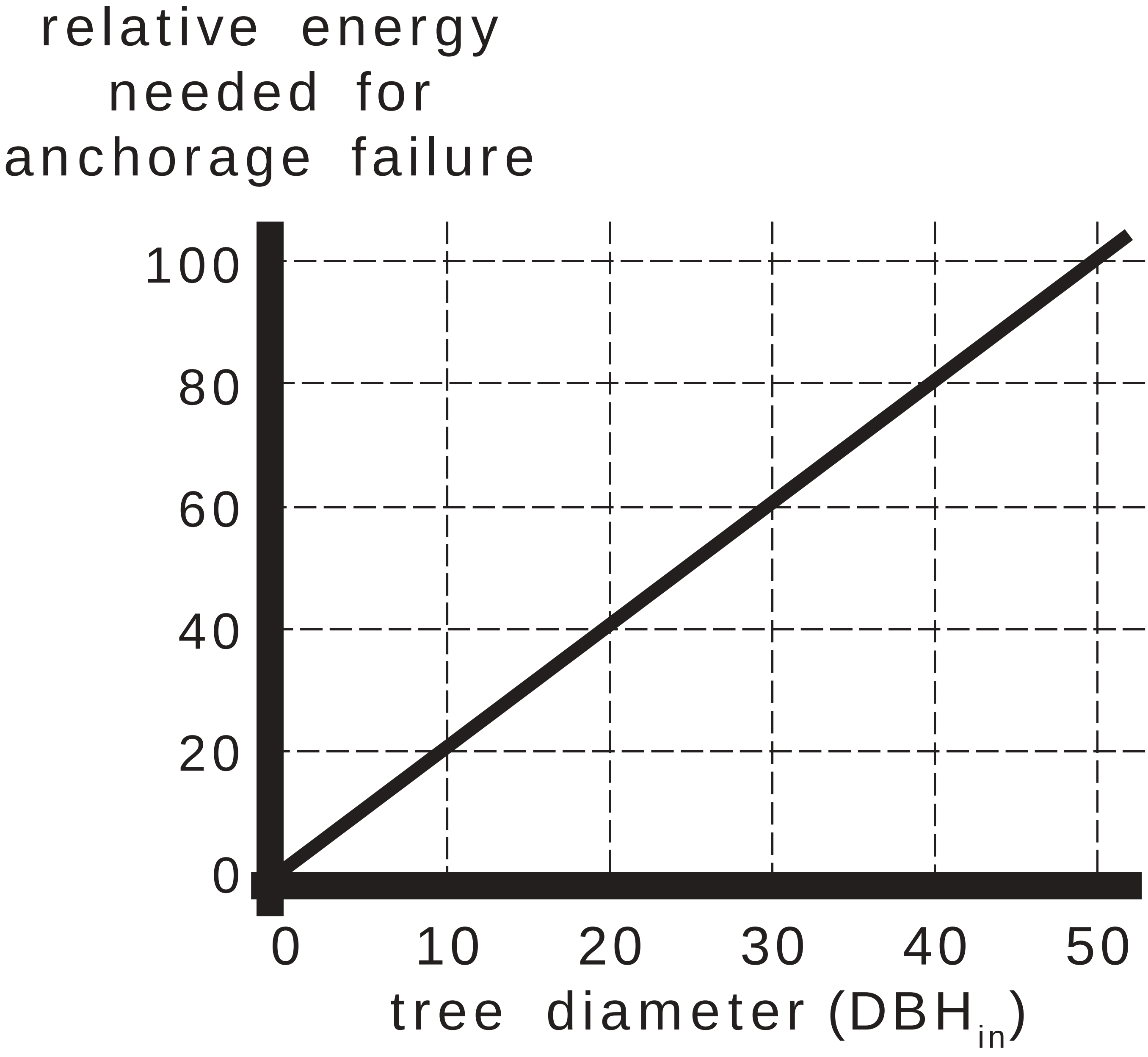


Figure 2: Relative amount of energy needed to over-turn or up-root a tree of a given diameter in inches. (derived from Stokes 1999)

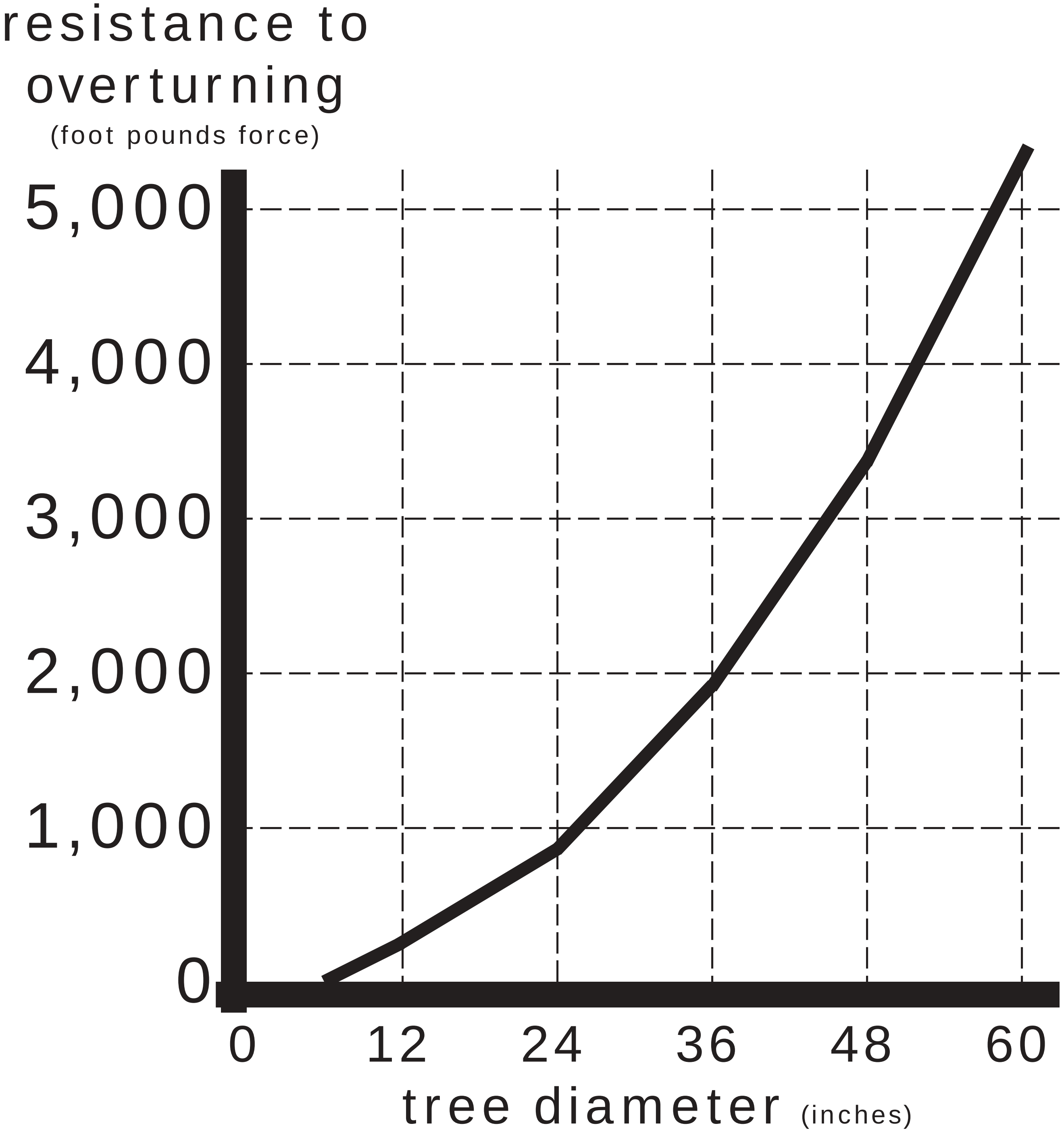


Figure 3: Impact of stem diameter in inches on tree resistance to over-turning in foot pounds of force. (Lundstrom et al. 2007)

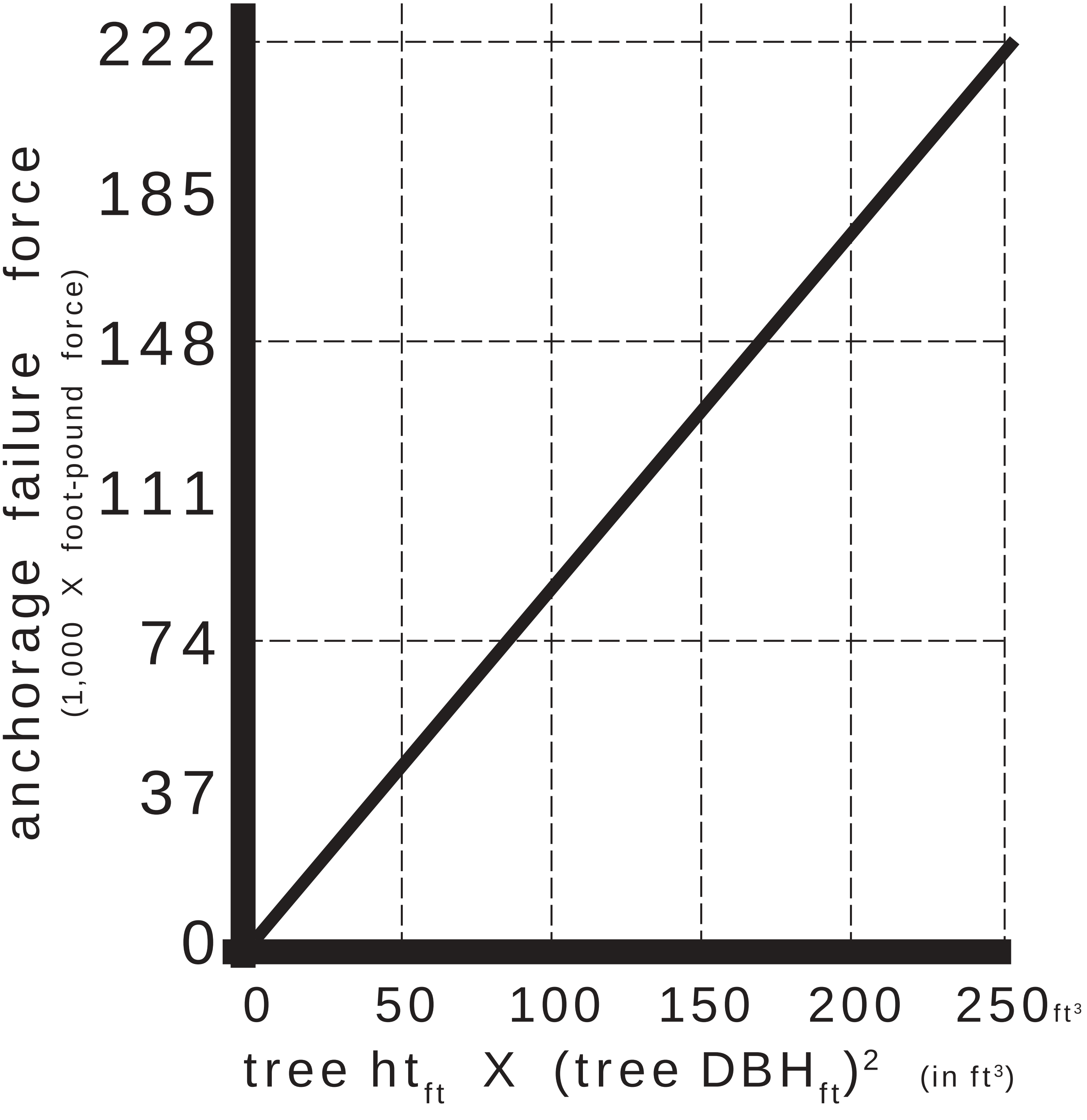


Figure 4: Critical turning force required as stem form changes. Stem form is measured as: (tree height in feet) X (tree diameter in feet)^2 = graph axis value in cubic feet. (from Cucchi et al. 2004)

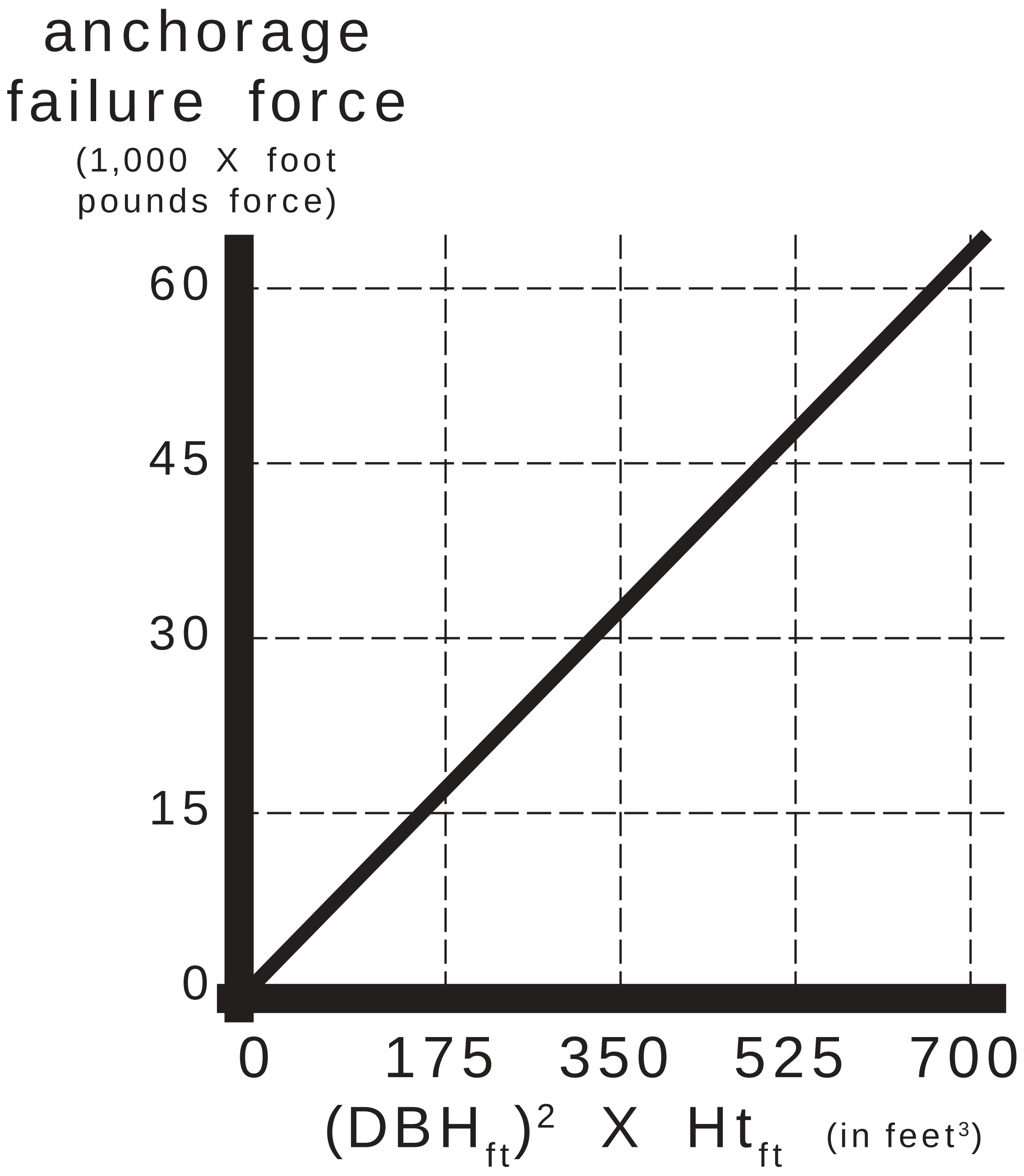


Figure 5: Anchorage strength of conifers in thousands of foot pounds of torque with increasing tree size, as measured by stem diameter in feet squared multiplied by stem height in feet.
(from Lundstrom, et al. 2007)

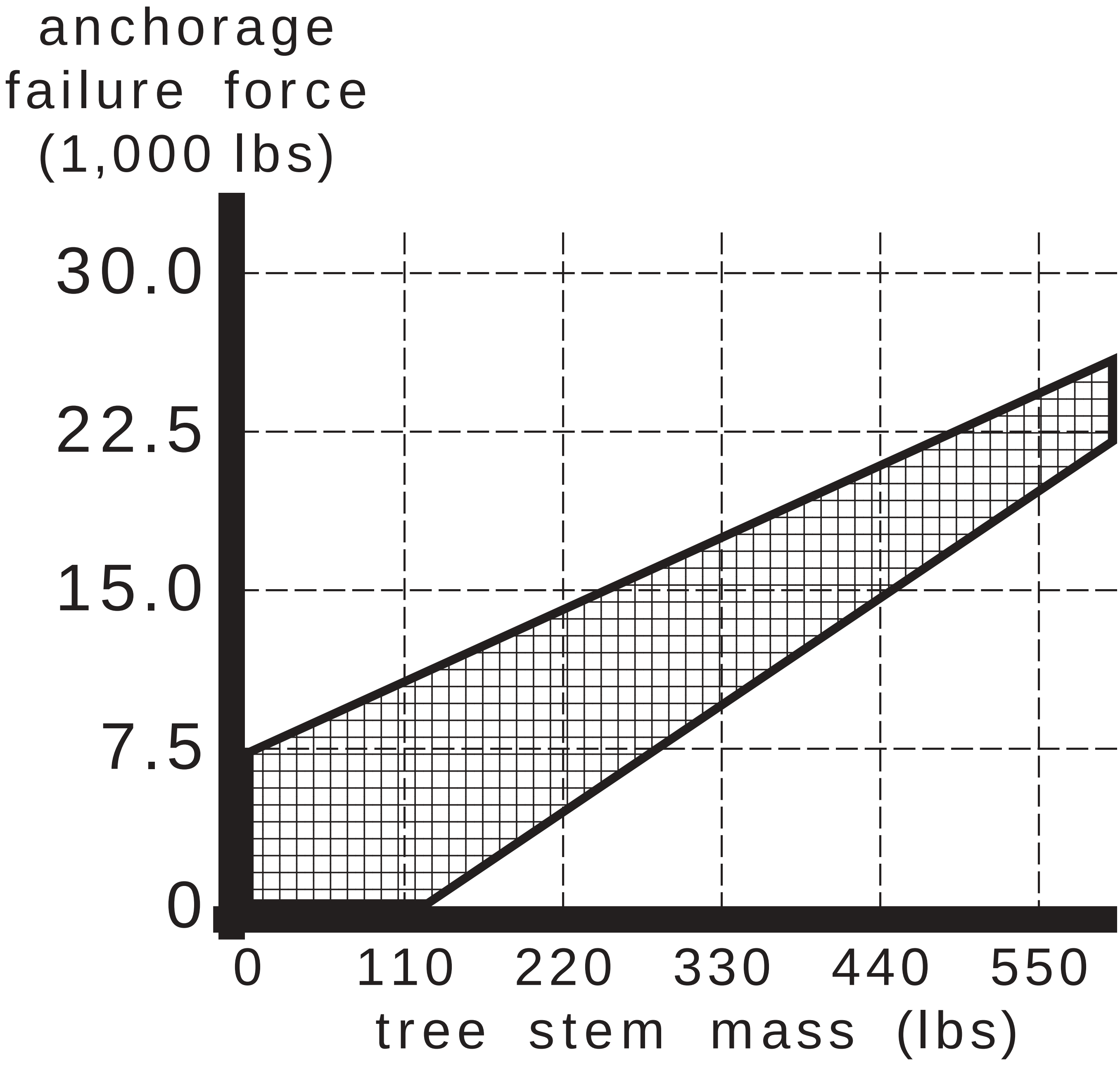


Figure 6: Range of critical turning force in 1,000 pounds for given tree stem mass in pounds. Combined data from three studies for two spruces, one fir, and two pines. (derived from Elie & Ruel 2005)

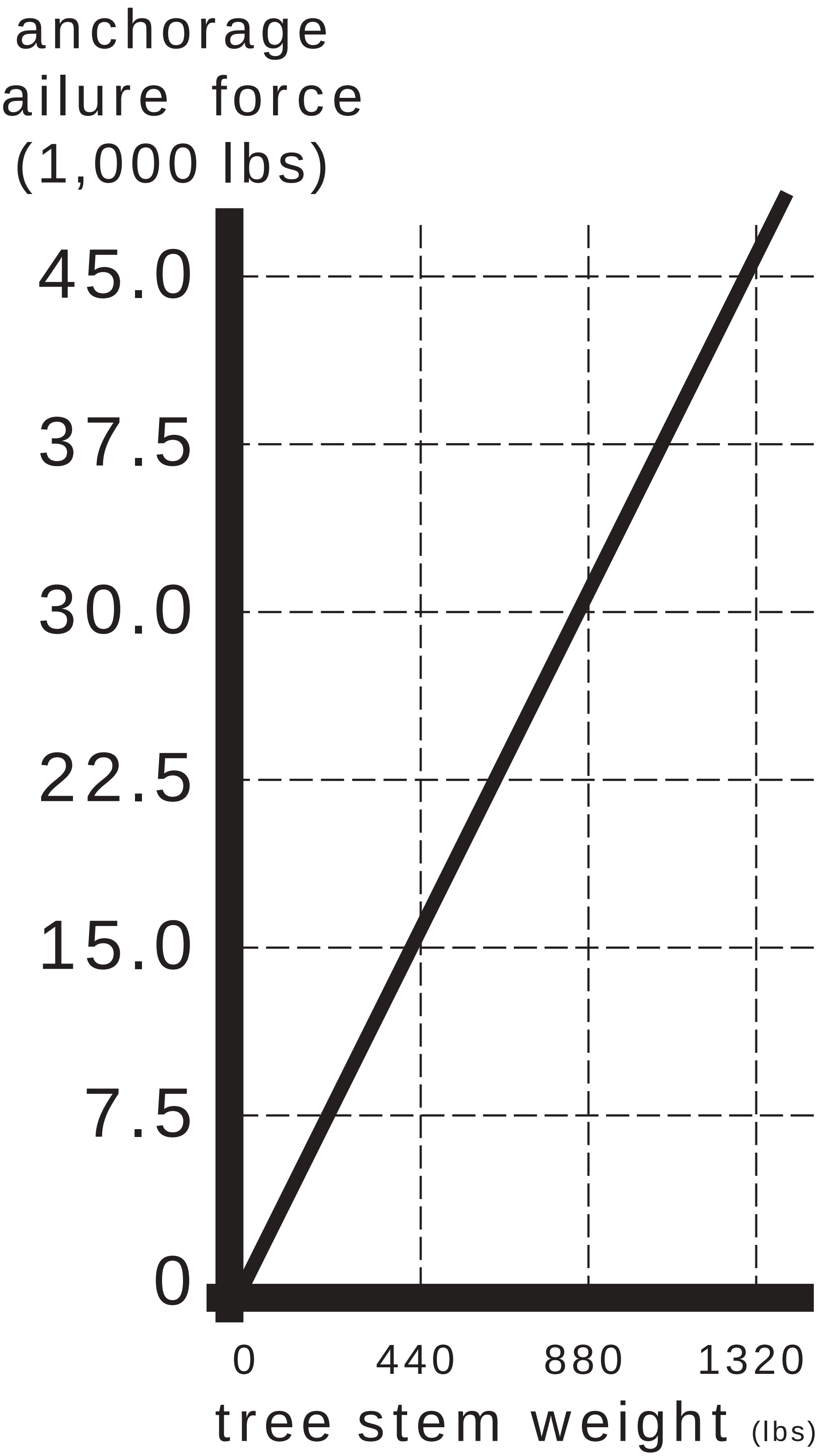


Figure 7: Critical turning force in 1,000 of pounds needed for a given stem weight in pounds. For spruce and fir on different sites. (modified from Achim et al. 2005)

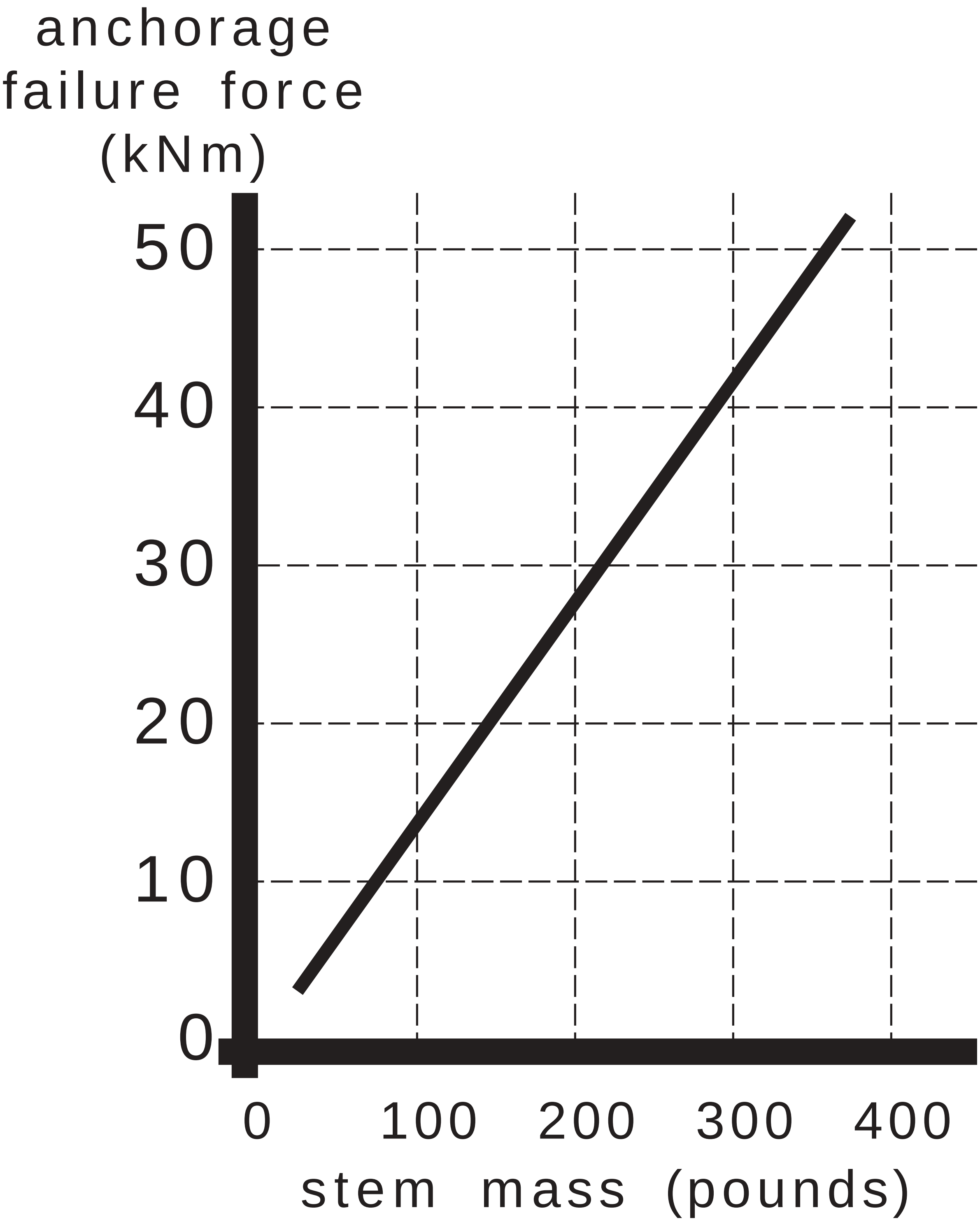


Figure 8: Anchorage failure force compared with stem mass for 107 winched trees.

(Bergeron et.al. 2009).

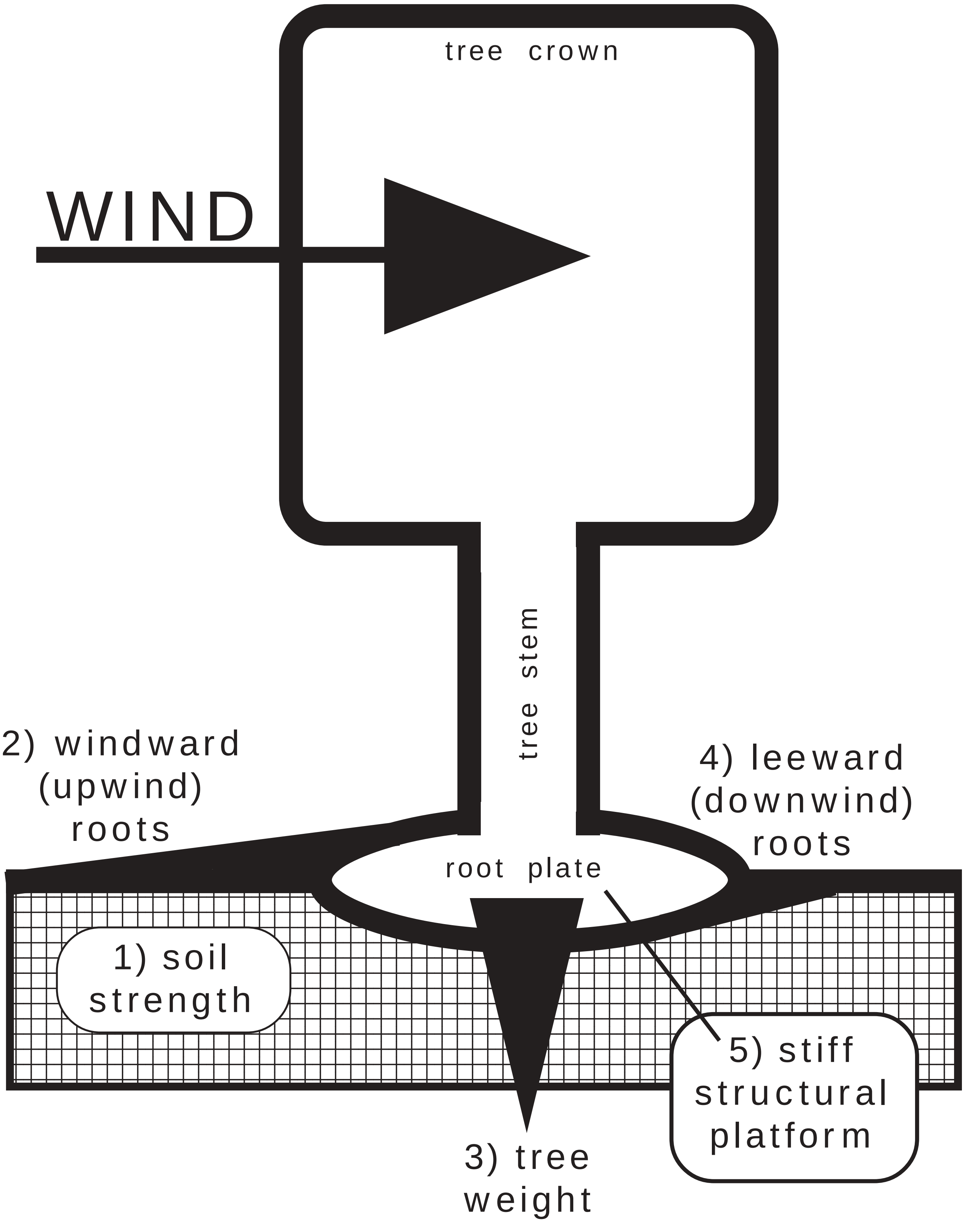


Figure 9: Five primary tree anchorage components.

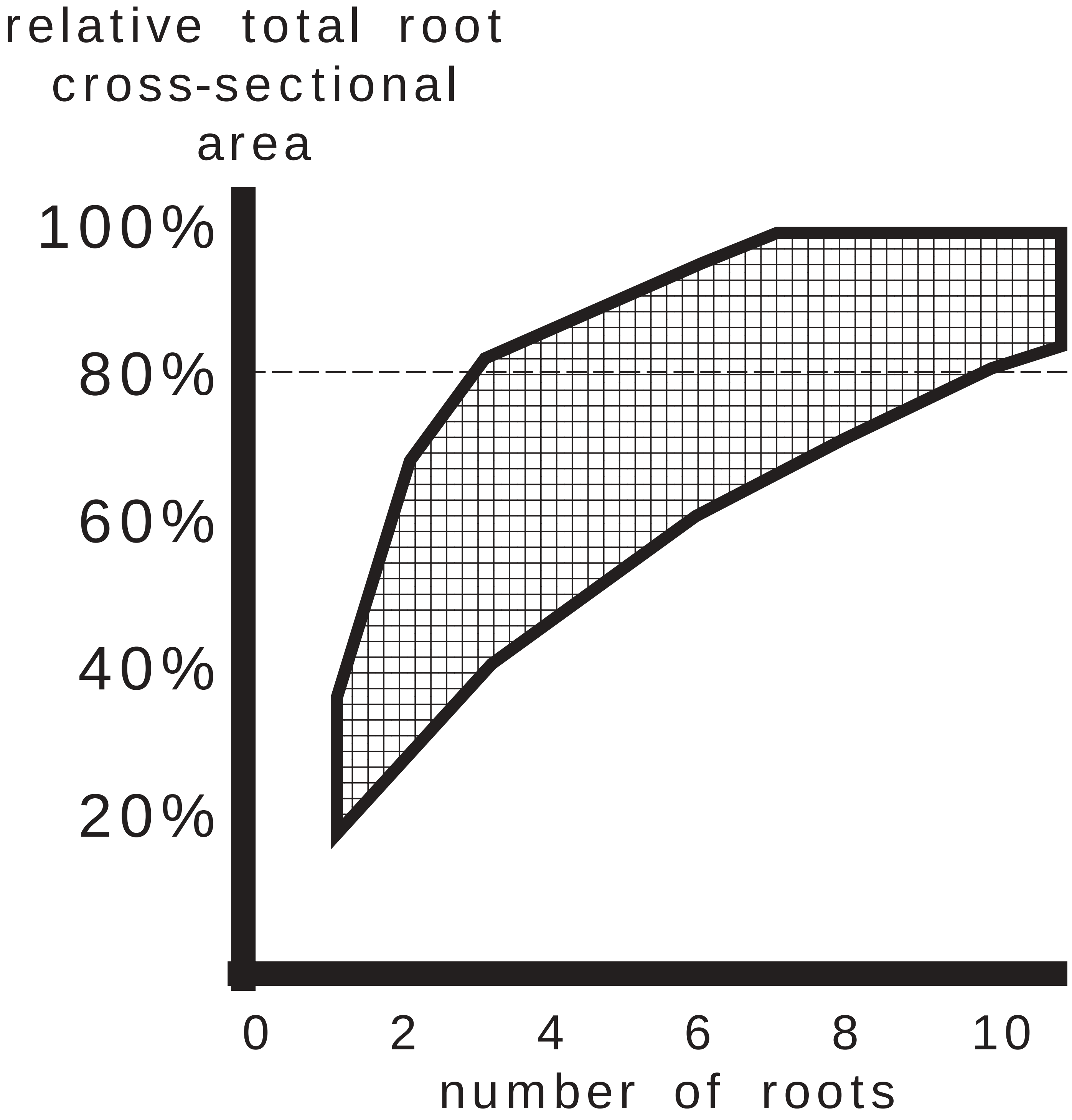


Figure 10: Range for total root cross-sectional area contained in the largest roots of *Picea sitchensis.* Number of roots = 2, means the combined cross-sectional area of the first and second largest diameter roots. (after Coutts et al. 1999)

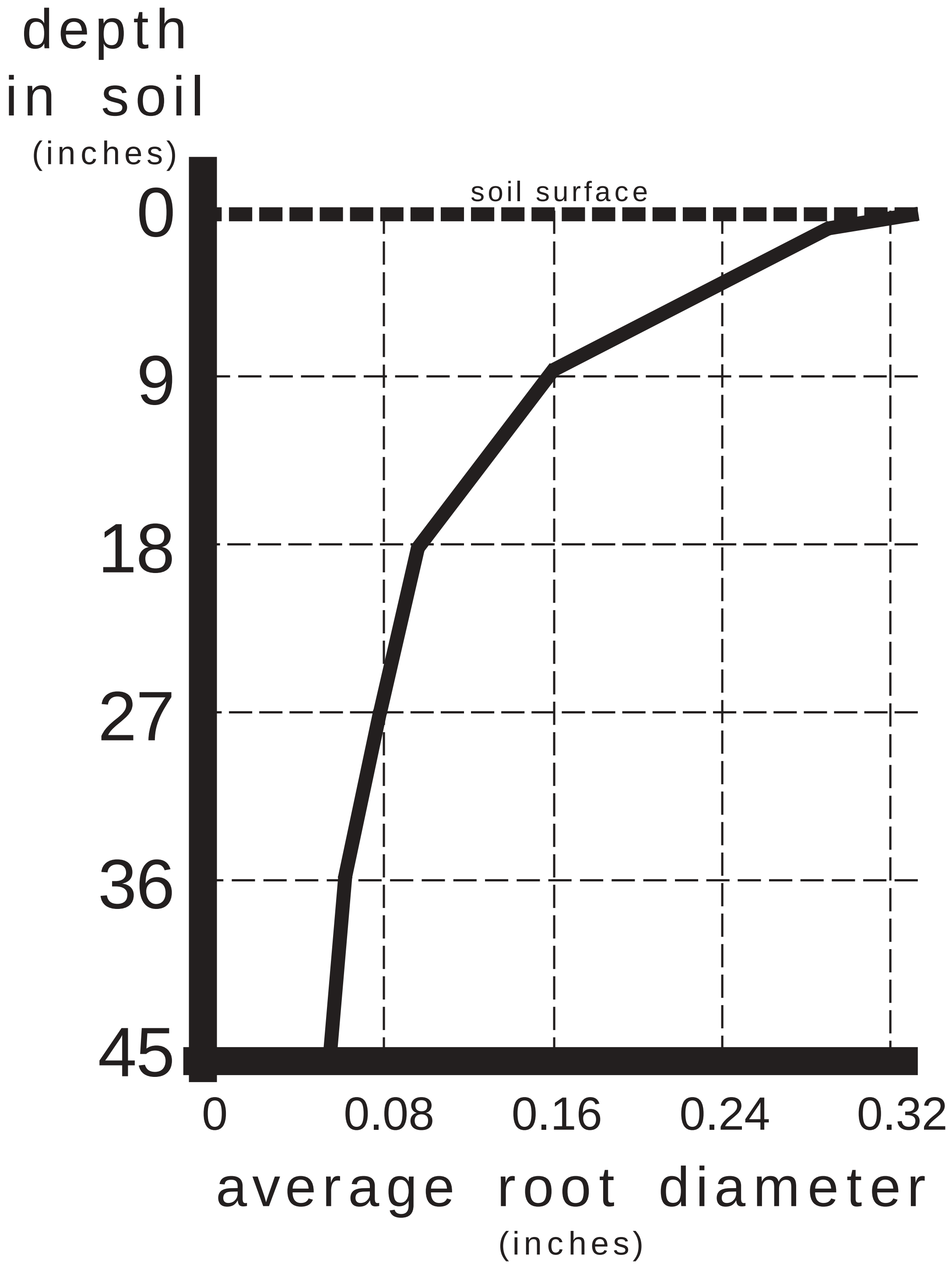


Figure 11: Average tree root diameter in inches with increasing depth in soil.
(from Tosi 2007)

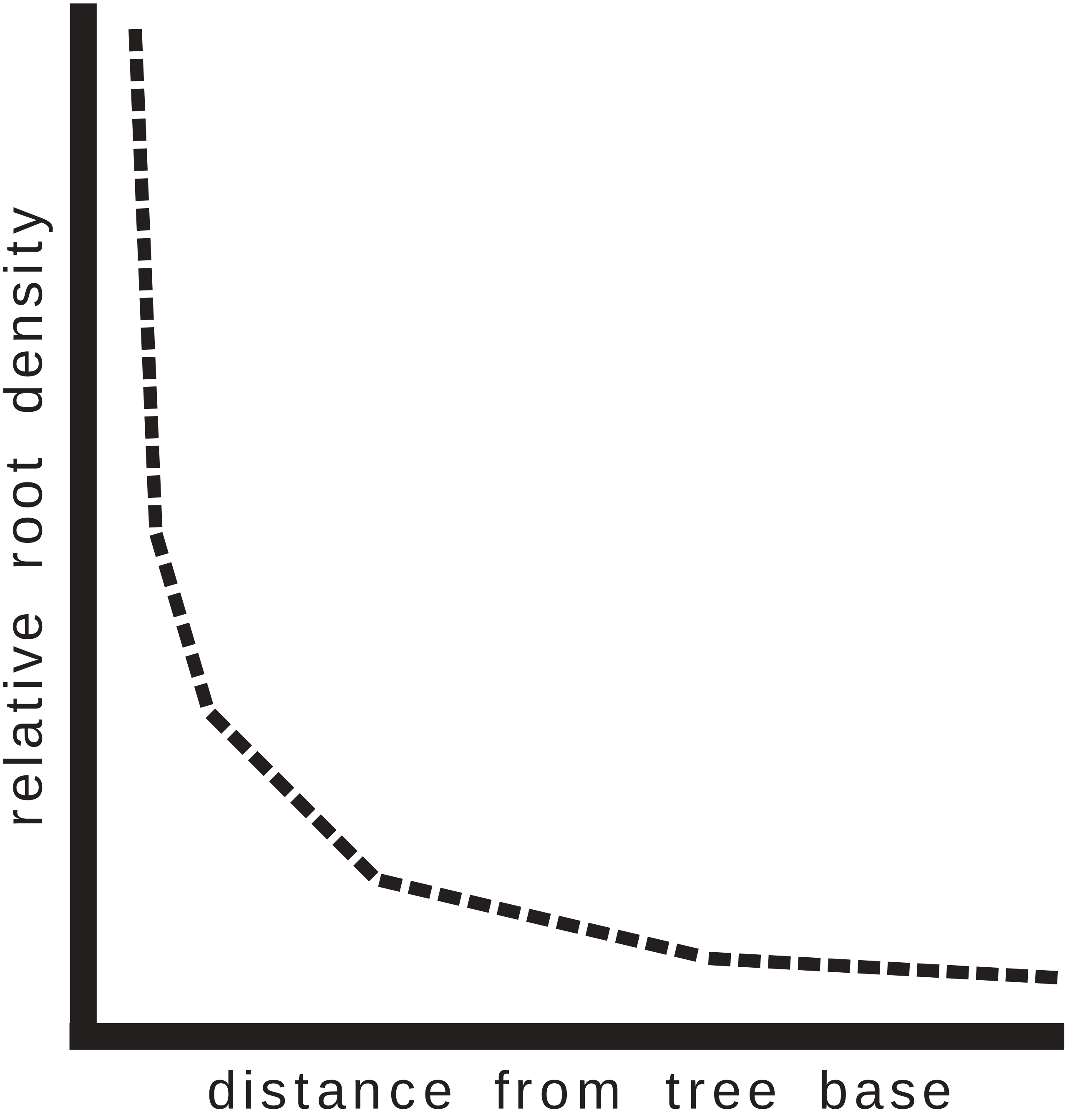


Figure 12: Relative root density with increasing distance from tree base. (derived from Abernethy & Rutherfurd 2001)

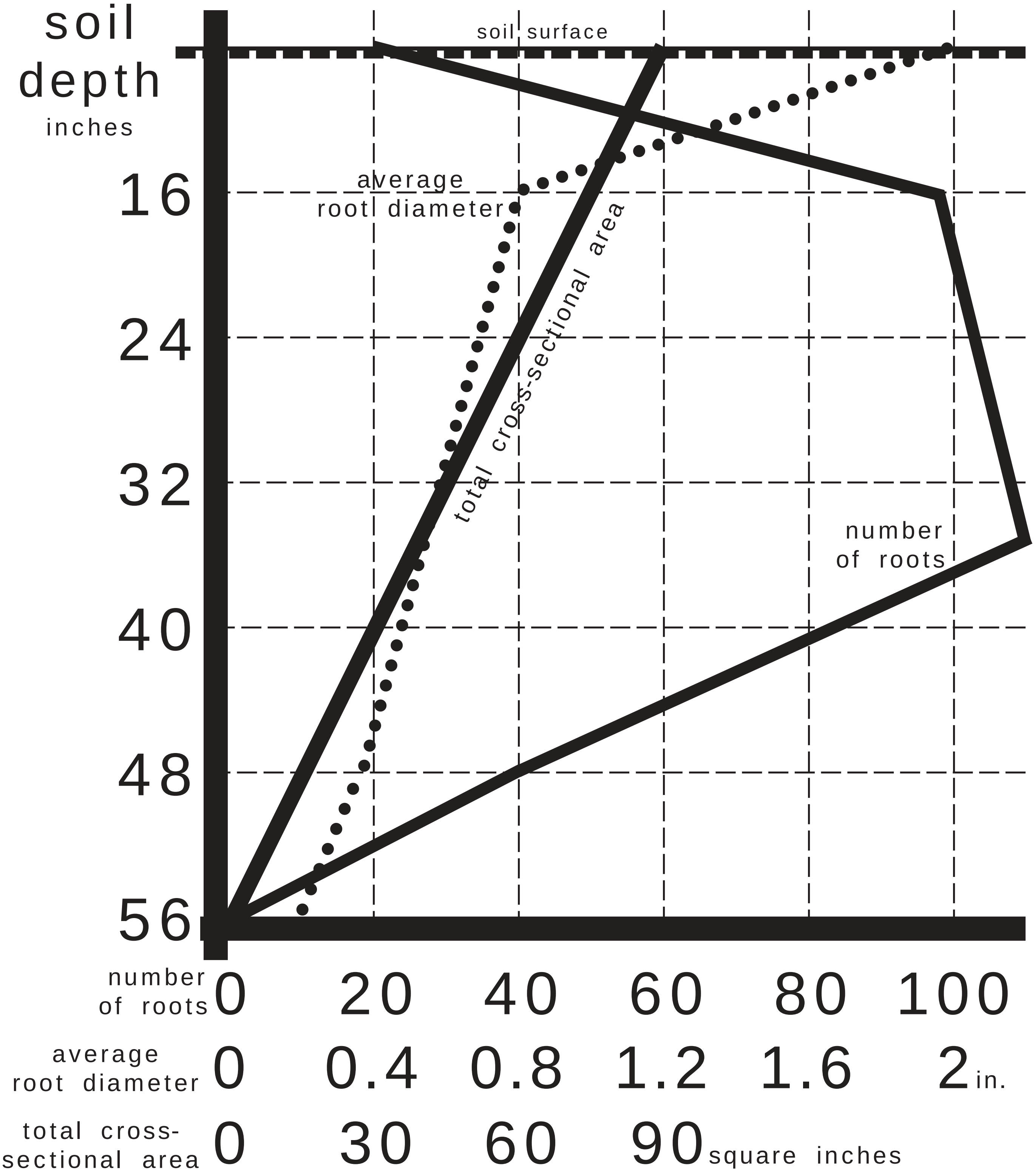


Figure 13: Tree root distribution in a well-drained, sloped soil showing number of roots, average root diameter in inches, and total cross-sectional area of roots in square inches. (from Danjon et al. 2008)

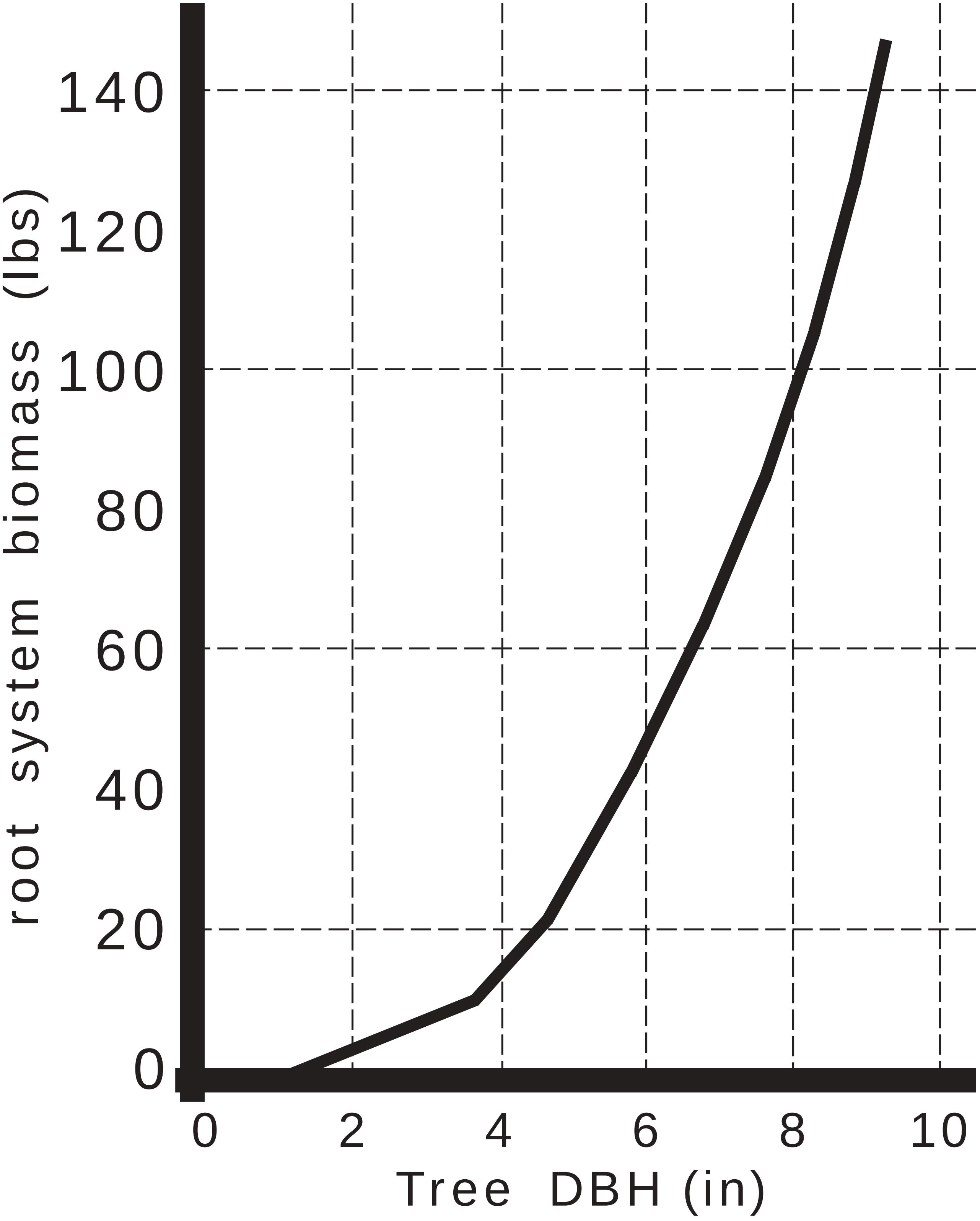


Figure 14: Root system biomass for *Pinus sylvestris* excluding fine roots. Composite data from five different studies. (modified from Tobin et al. 2007)

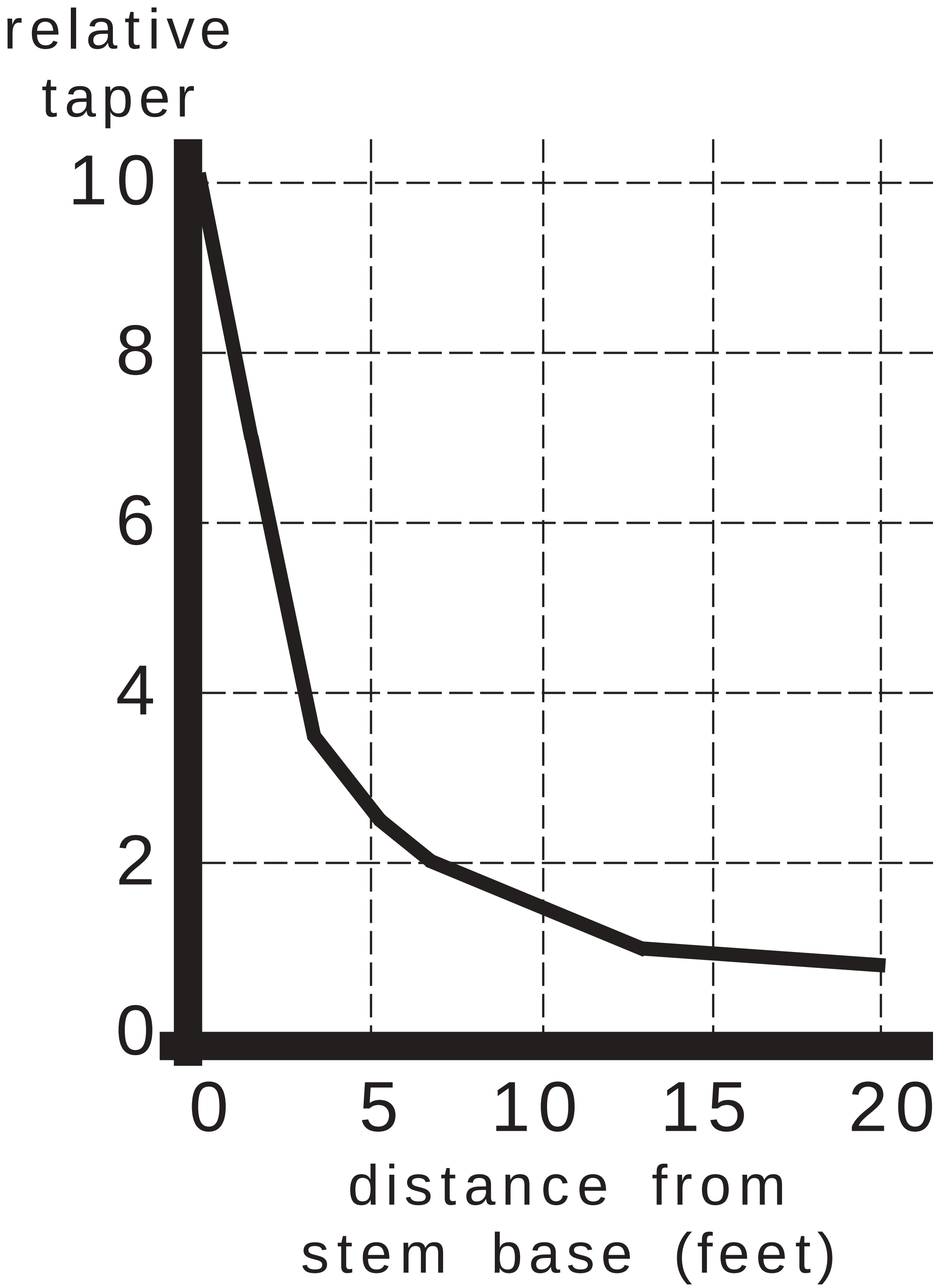


Figure 15: Relative taper curve for the main lateral roots of three mature tree species.

(Kalliokoski et.al. 2008)

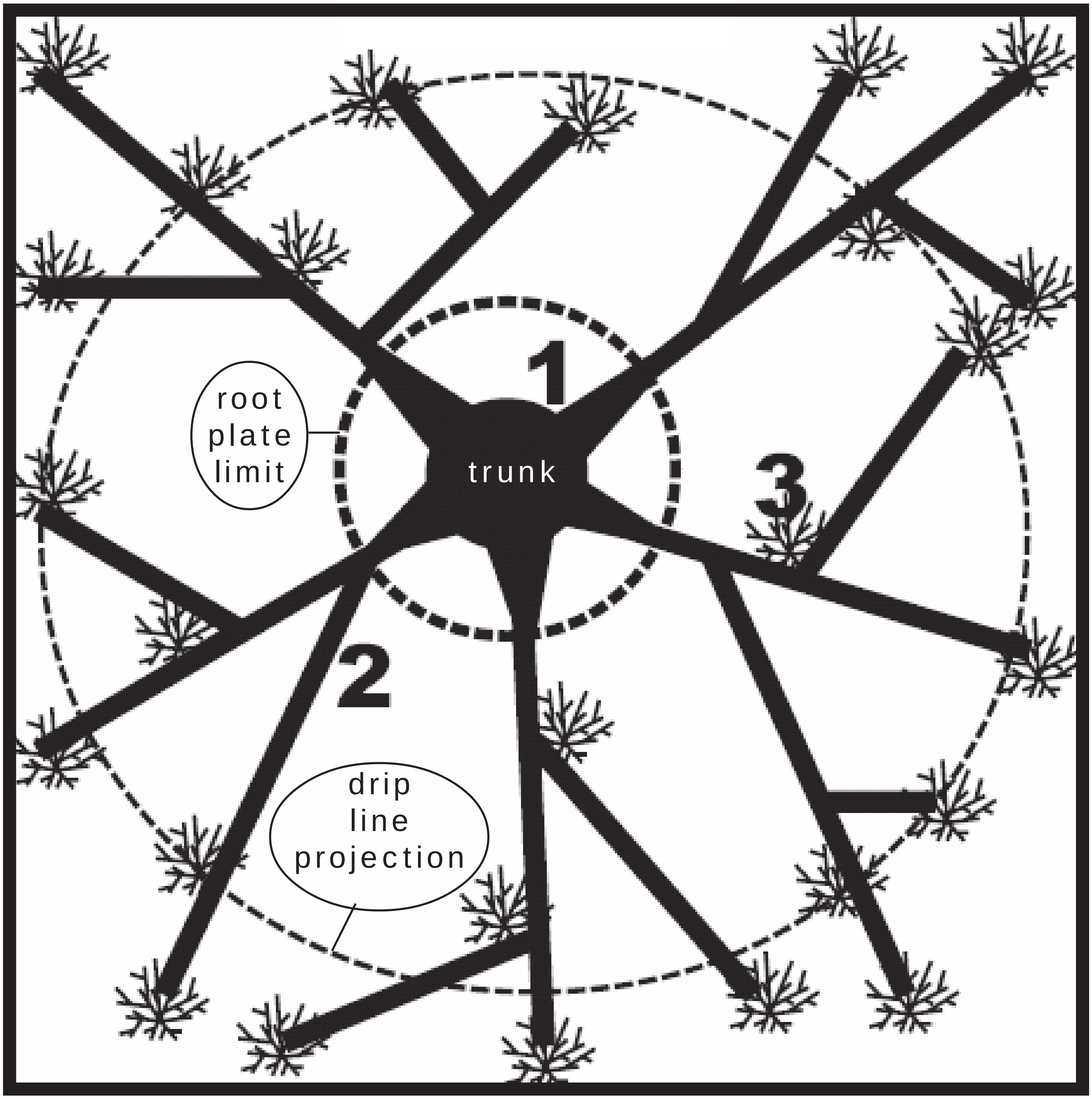
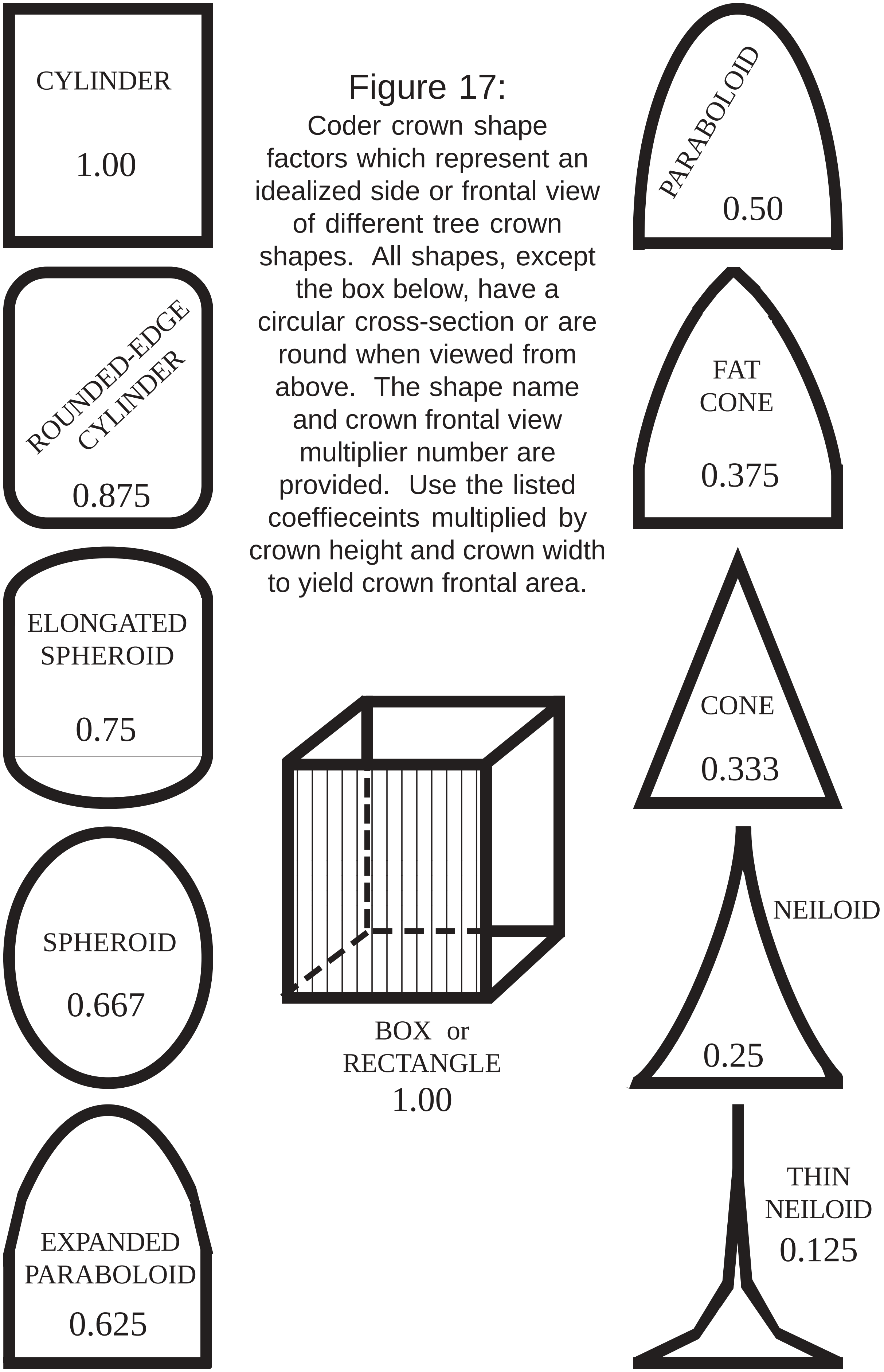


Figure 16: Stylized view from above of three different tree root zones (not to scale and not representing root sizes, number, and density): 1) structural roots and root plate; 2) woody transport roots; and, 3) ephemeral horizontal absorbing root fans. The dotted line representing crown projection on the soil (drip line) contains ~65% of roots found on average sites.

Figure 17:
Coder 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. The shape name and crown frontal view multiplier number are provided. Use the listed coeffieceints multiplied by crown height and crown width to yield crown frontal area.



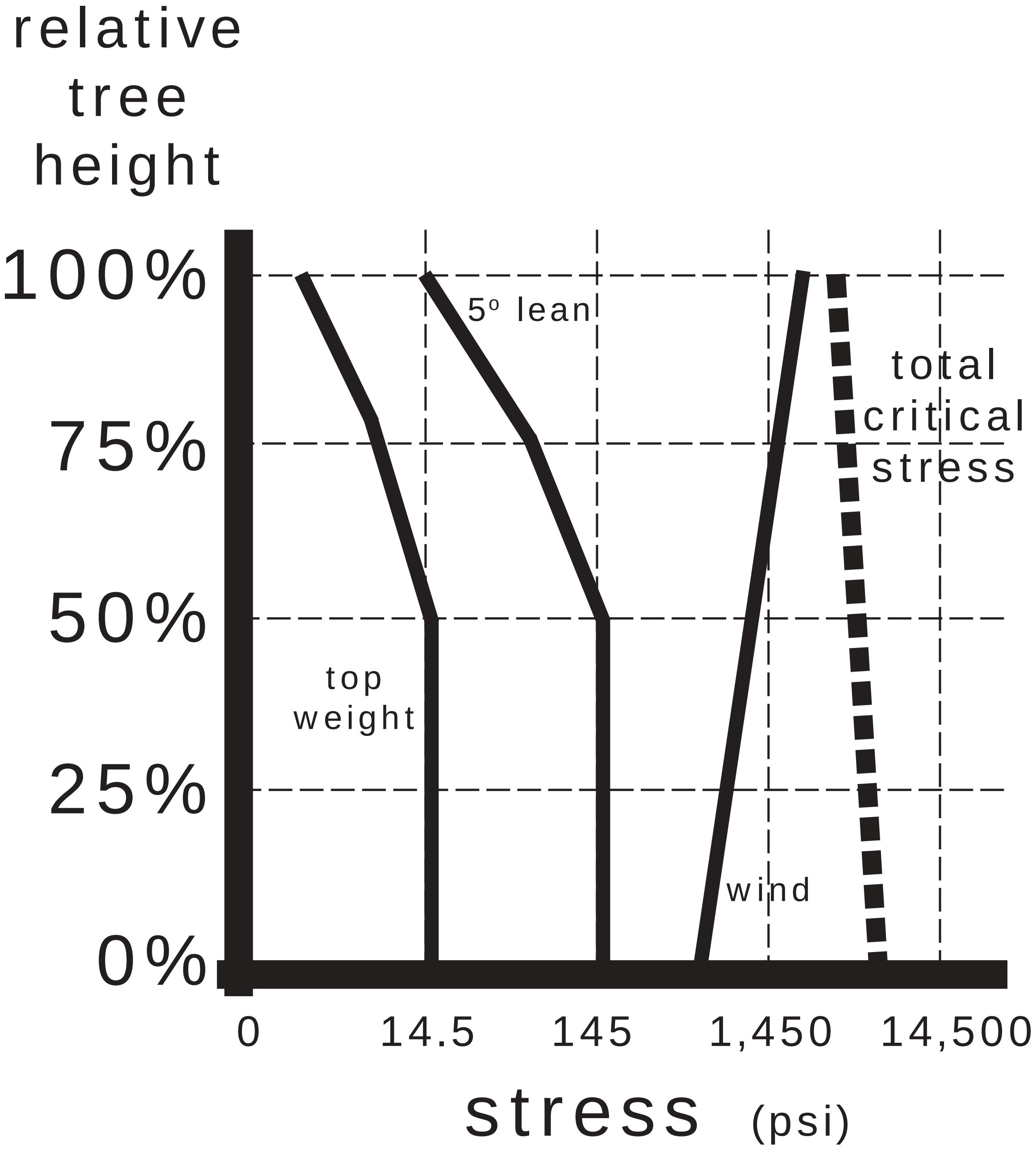


Figure 18: Proportion of total critical stress in pounds of force per square inch across three structural components with increasing relative tree height. Note the log scale for stress.
(derived from Spatz & Bruechert 2000)

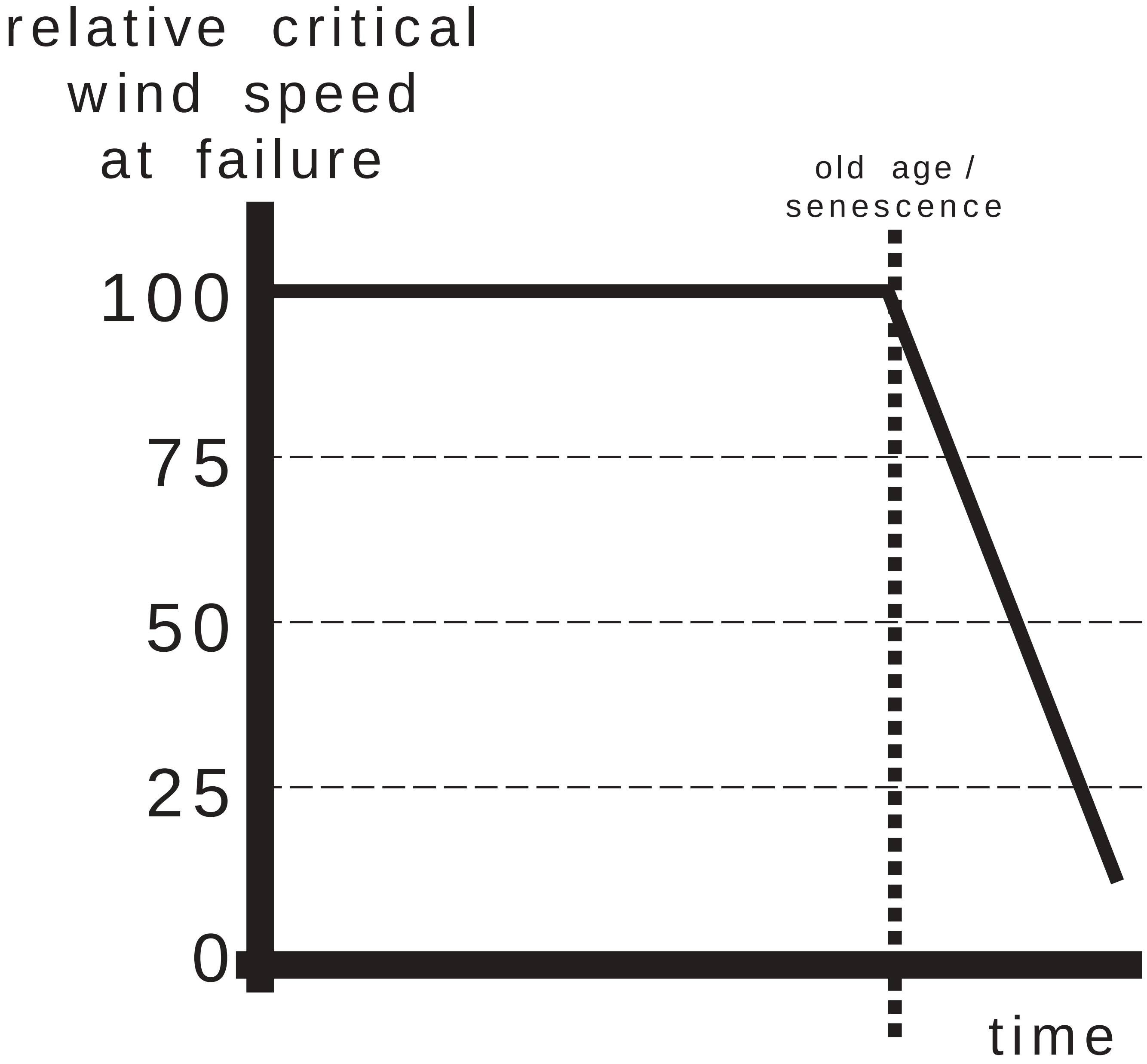


Figure 19: Relative changes in tree resistance to anchorage failure with time at peak wind speeds.
(Achim et al. 2004)

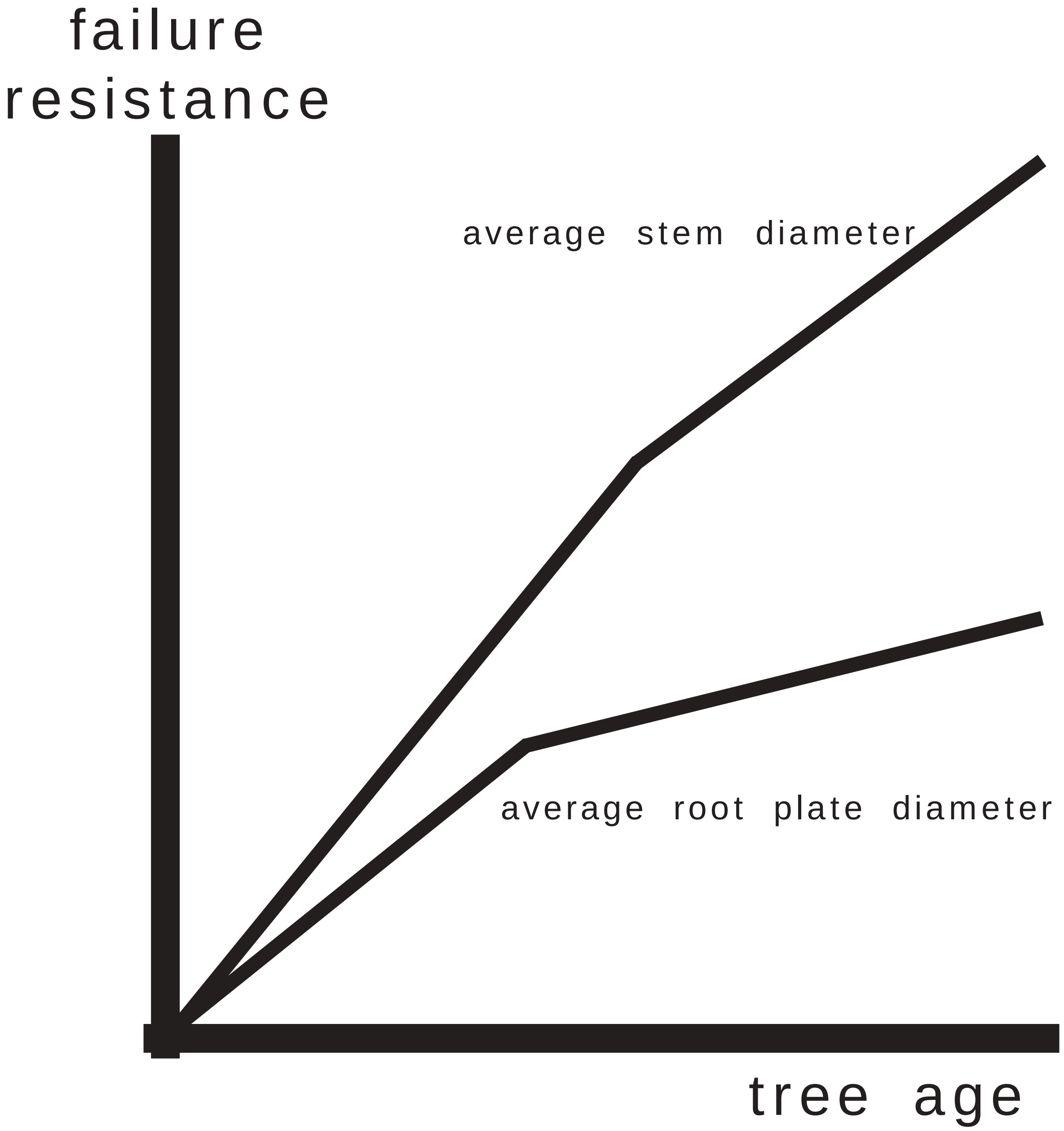


Figure 20: Change in root plate and stem resistance to failure as trees age. (after Koizumi et al. 2007)

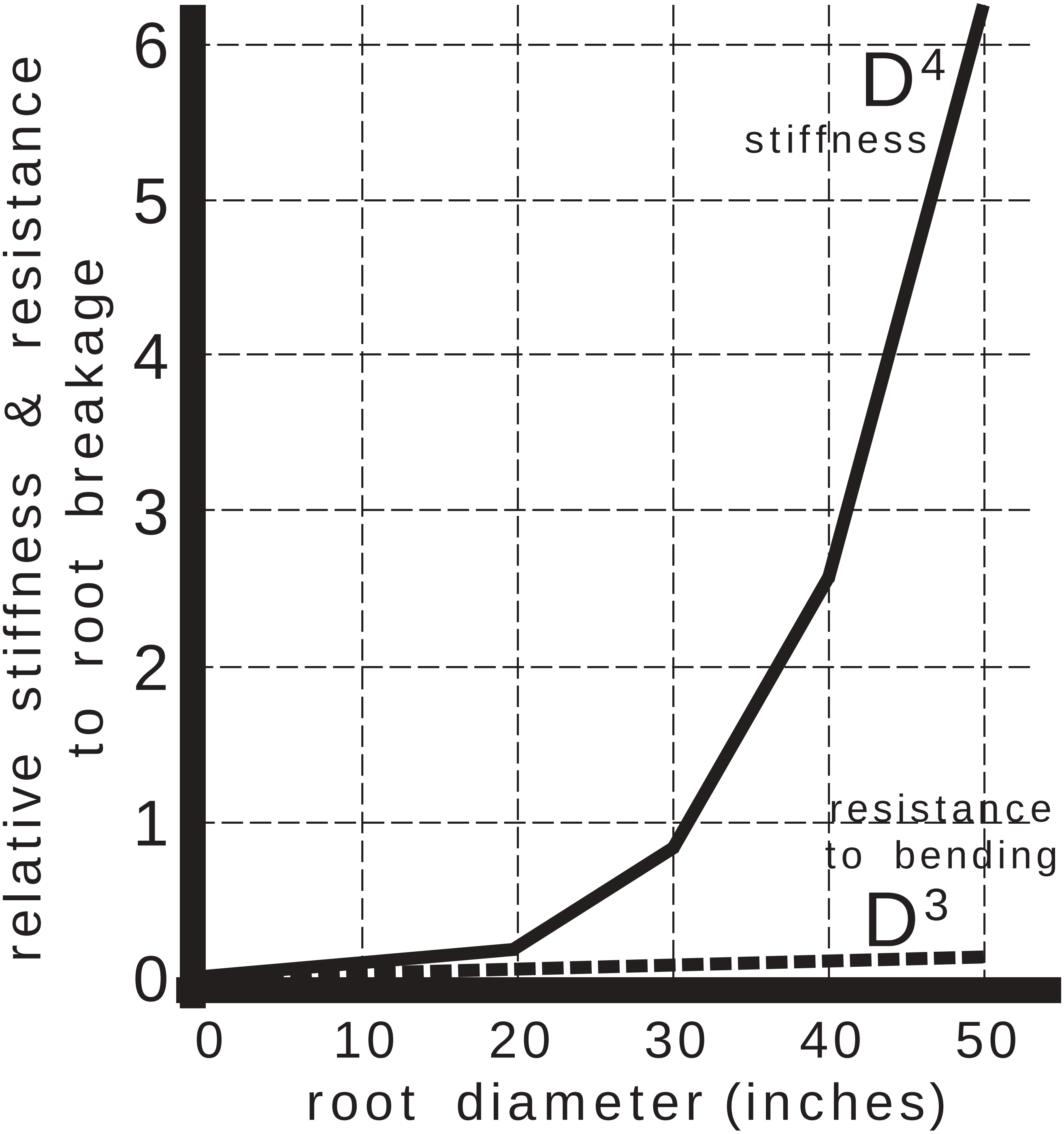


Figure 21: Comparison of roots with a circular cross-section and various diameters (D) for relative stiffness (solid line D^4) and resistance to breaking (dotted line D^3). (Danjon et al. 2005)

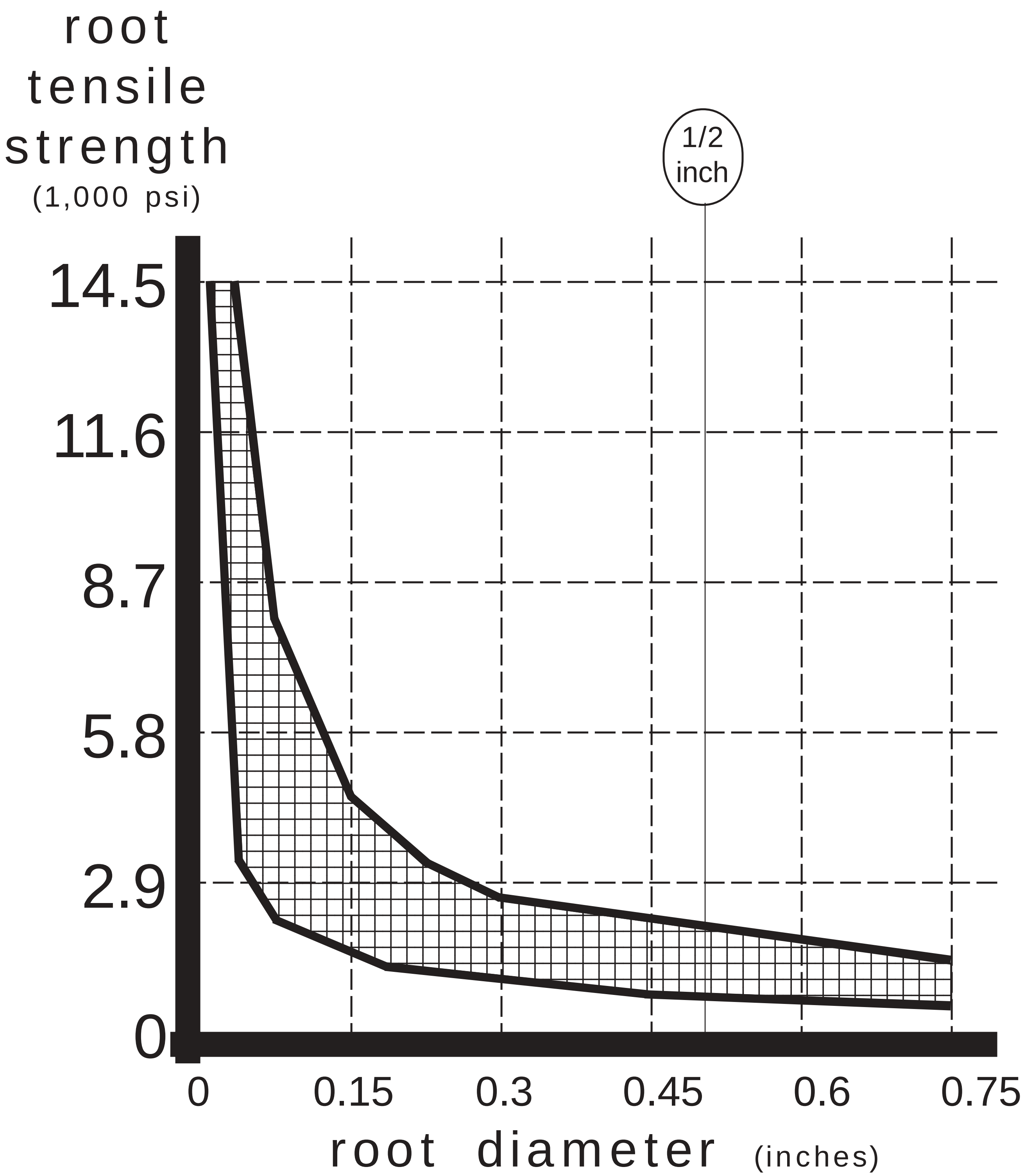


Figure 22: Range of root tensile strength from several studies on trees based upon root diameter. Root tensile strength is species dependent but most species follow similar trend lines and curve shapes.

(Derived primarily from Abernethy & Rutherfurd 2001; Bischetti et al. 2005; & Tosi 2007.)

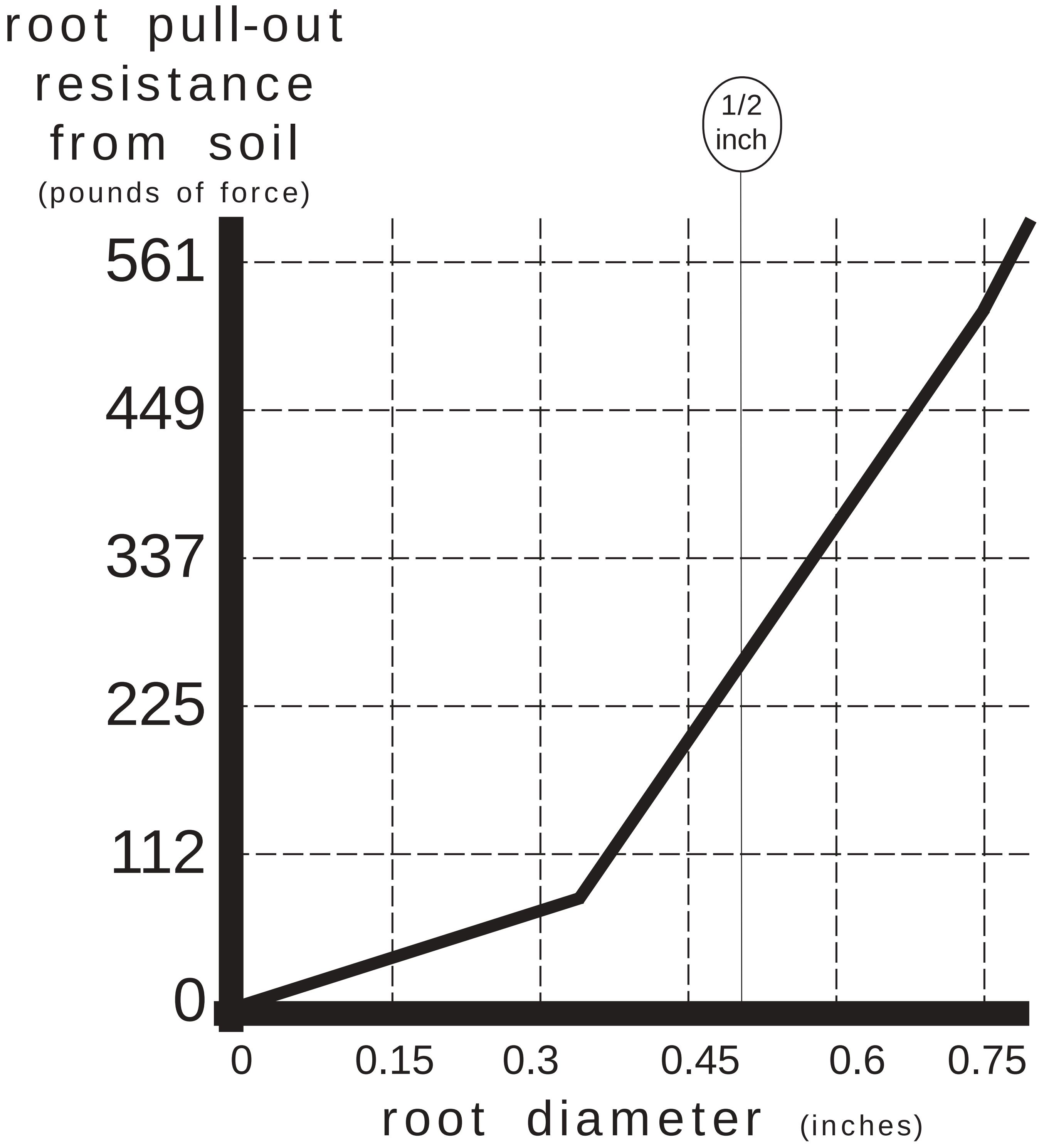


Figure 23: Tree root pull-out resistance in pounds of force by root diameter.

(from Norris 2005)

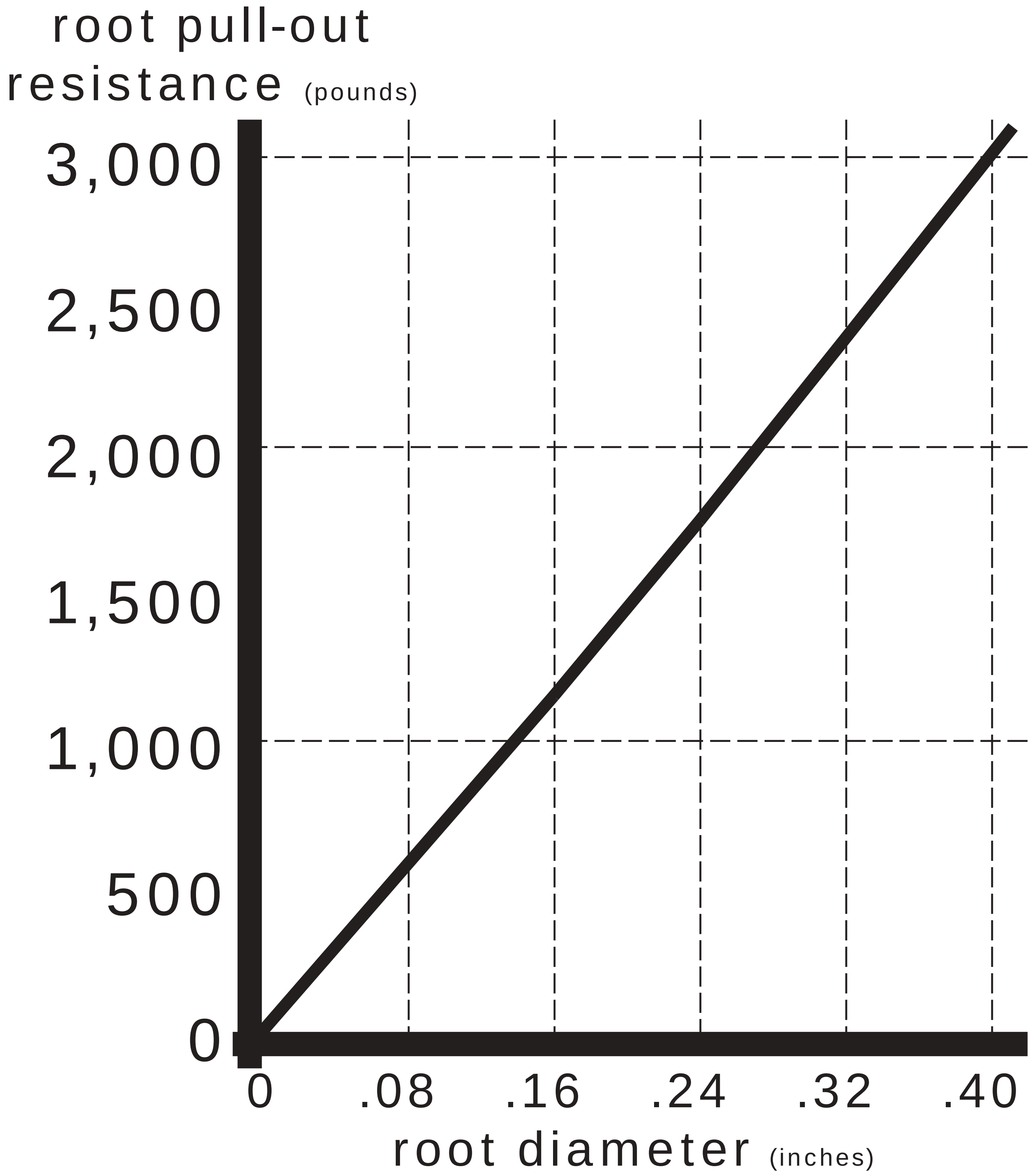


Figure 24: The pull-out resistance (in pounds of force) for conifer roots of a given diameter in inches.

(Abe & Ziemer 1991).

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

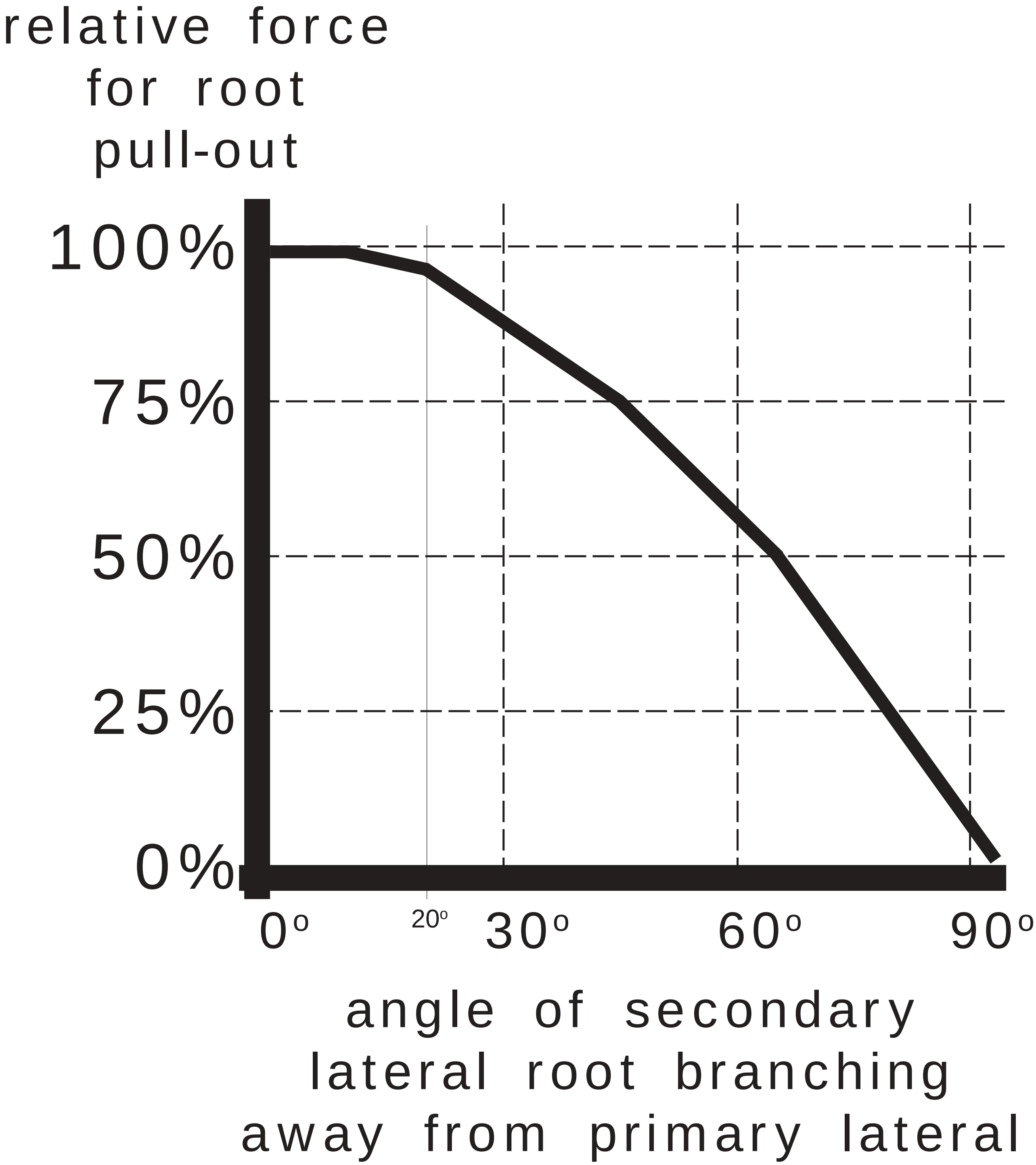


Figure 25: Examination of how much force is neded to pull out roots as impacted by branching angle (in degrees) of lateral roots. (from Stokes et al. 1996)

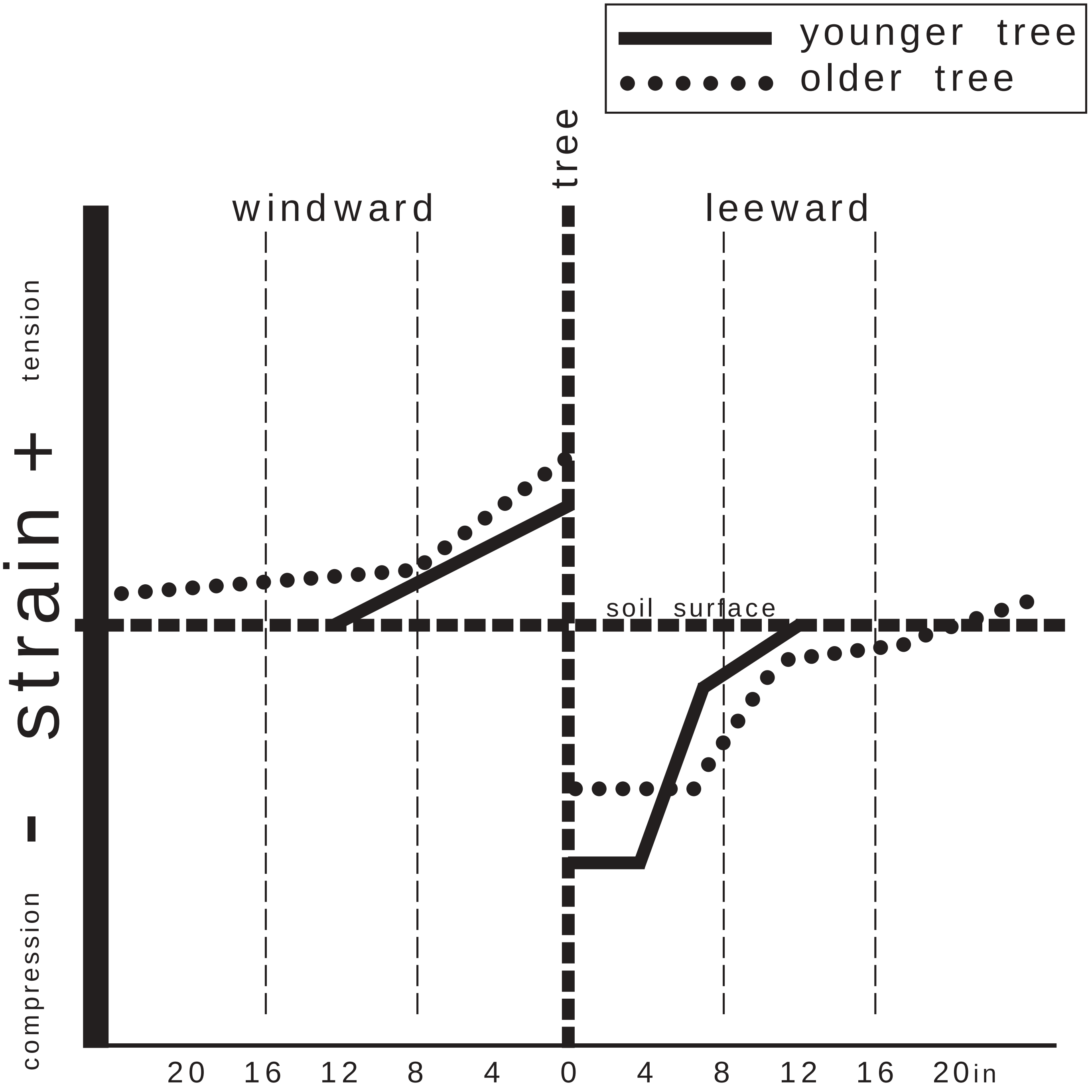


Figure 26: Tension and compression strain on the windward and leeward side of small trees (denoted as younger trees and older trees). Hinge point on leeward sides of younger trees are ~4 inches away from stem base, and ~6.3 inches away from stem base on older trees. (derived from Stokes 1999)

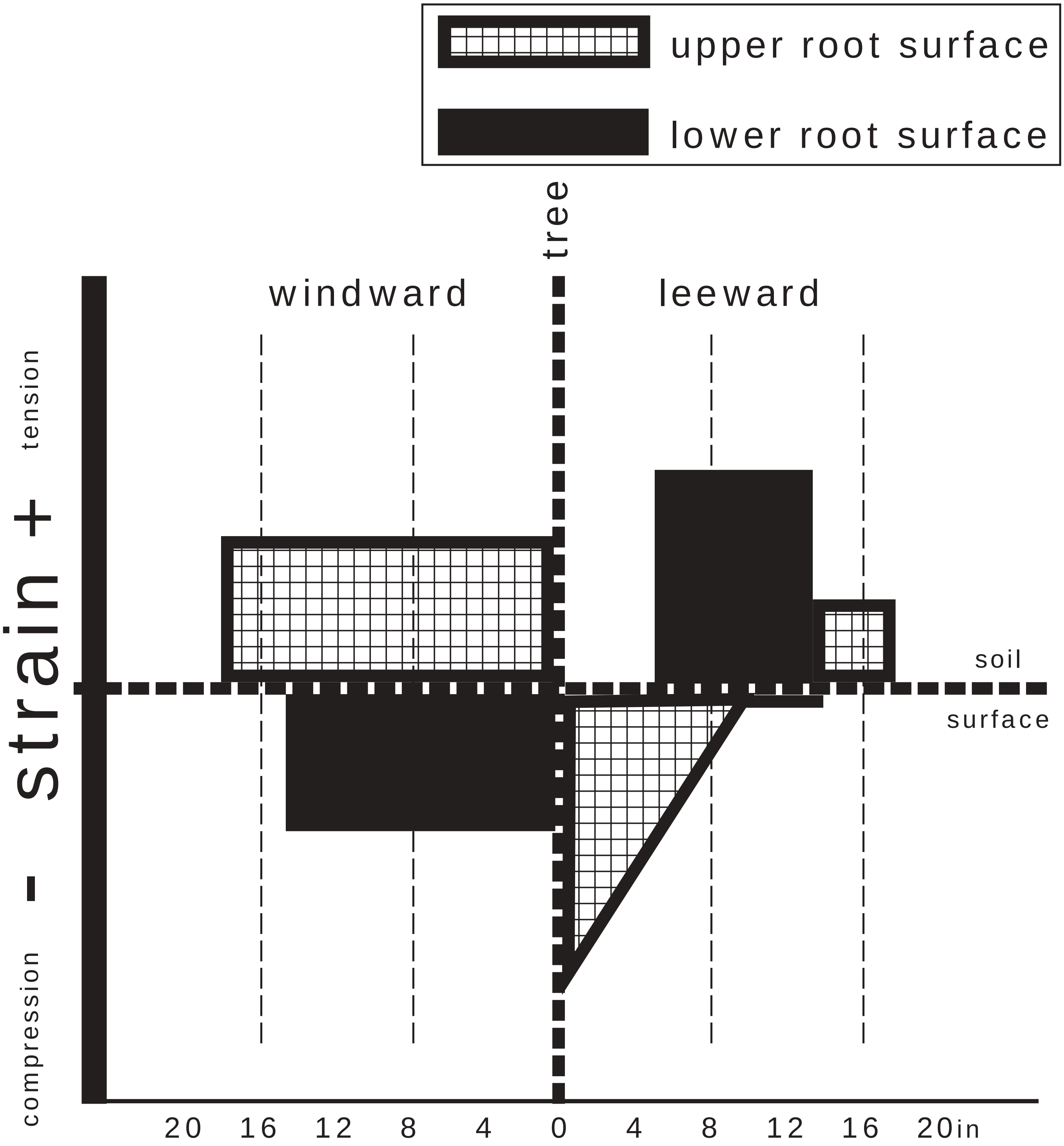
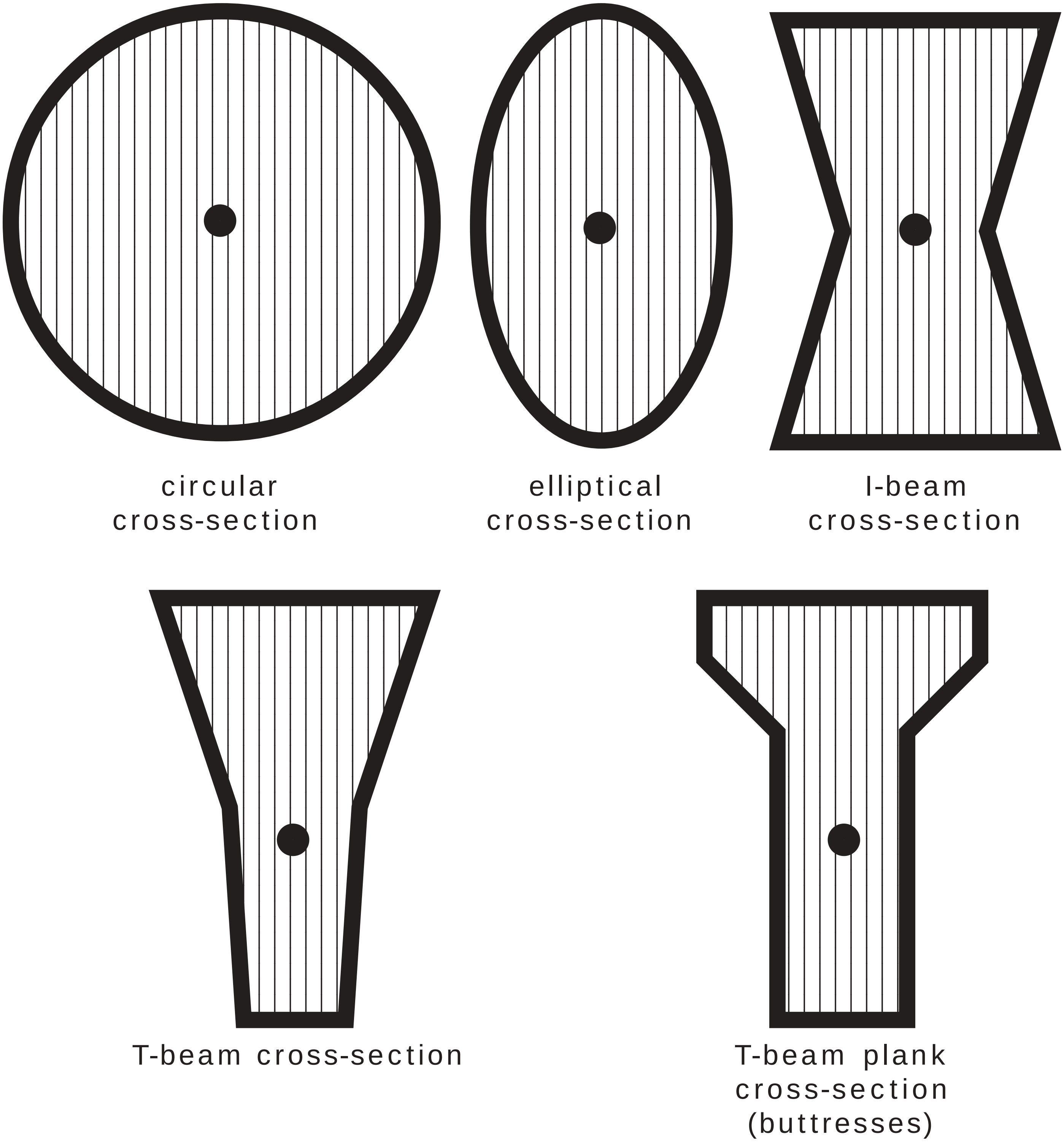


Figure 27: Tension and compression strain on upper and lower surfaces of windward and leeward tree roots in small trees.
(derived from Stokes 1999)



circular cross-section

elliptical cross-section

I-beam cross-section

T-beam cross-section

T-beam plank cross-section (buttresses)

Figure 28: Idealized shapes of root cross-sections as tree growth responds to assymetrical mechanical stress across upper and lower surfaces. Dot represents root center.

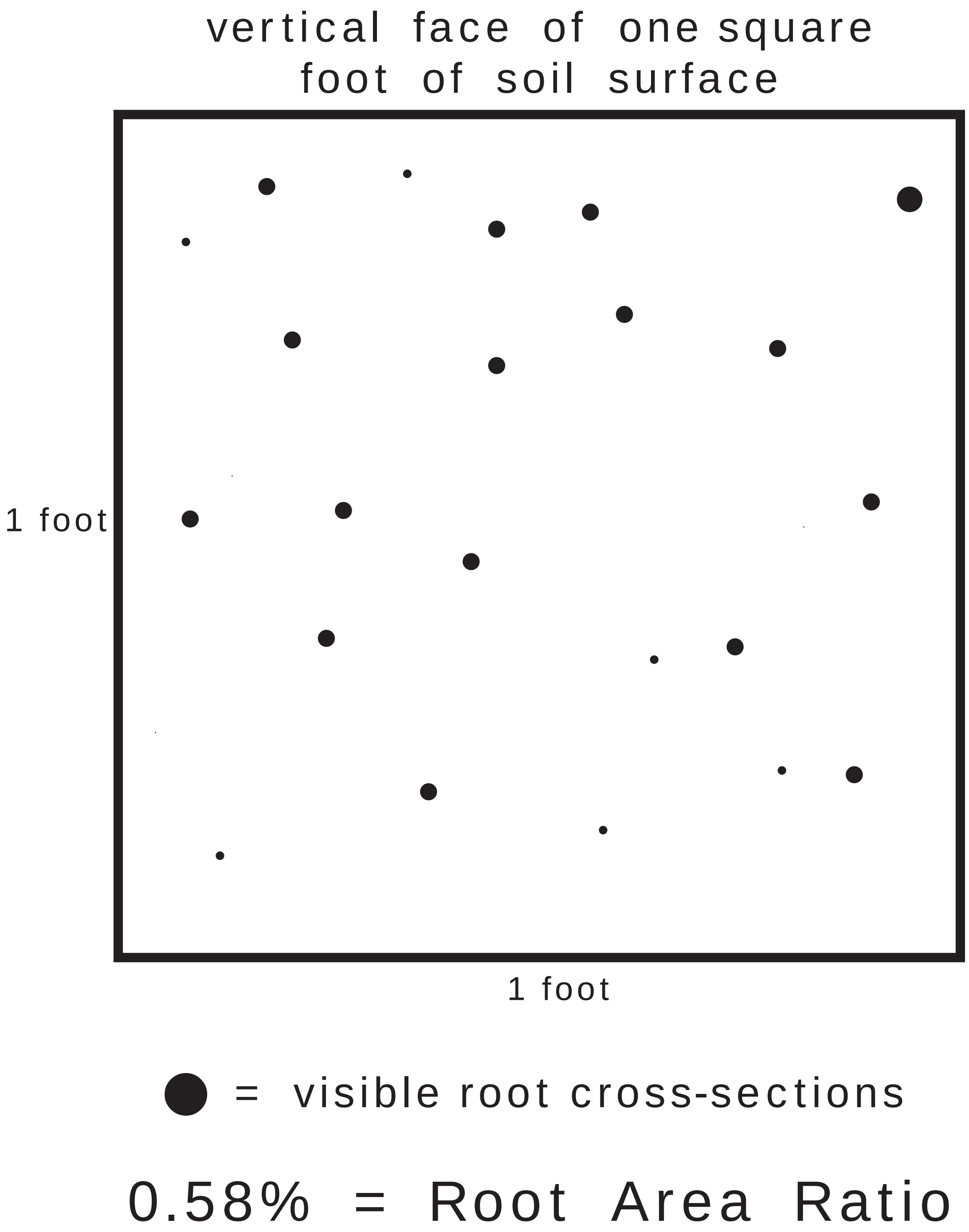


Figure 29: Demonstration of how Root Area Ratio or Root Area Index determinations are made. Root Area Ratio is the percent of root cross-sectional area represented on a vertical exposed face of soil for a specified area.

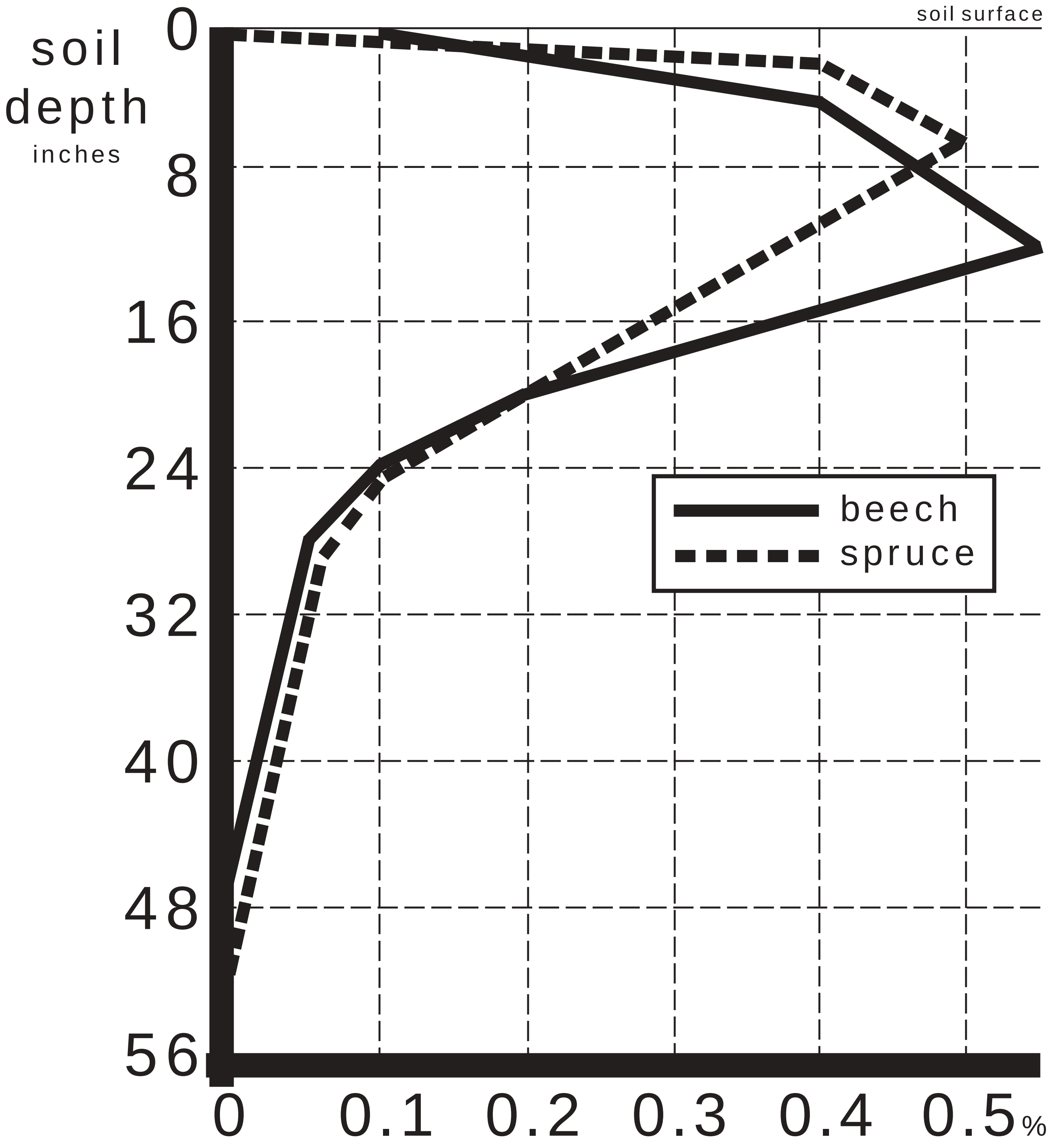


Figure 30: Represenative Root Area Ratio (RAR) percents for beech and spruce as soil depth increases.

(selected examples from Bischetti et al. 2005)

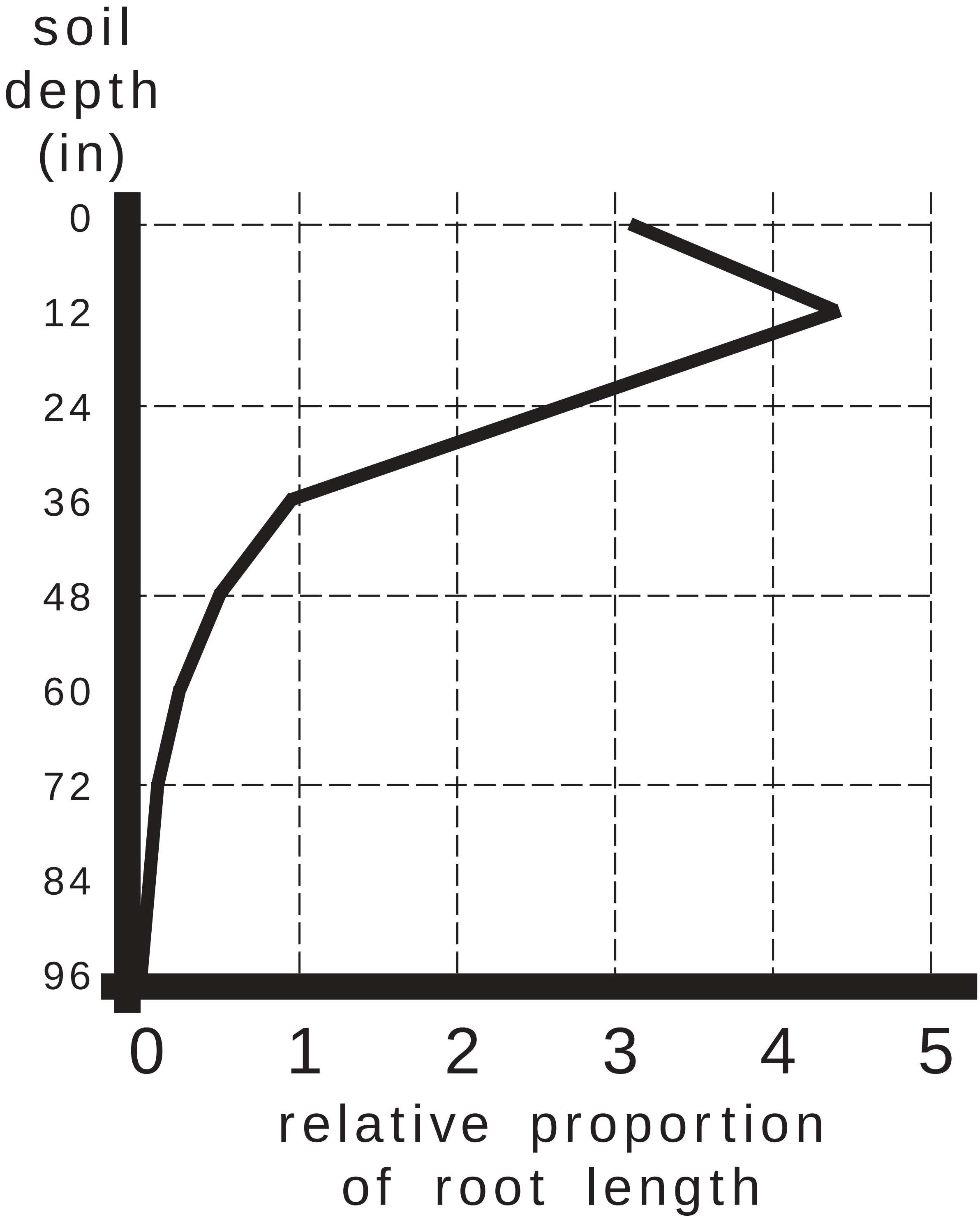


Figure 31: Distribution of roots at various soil depths for three tree species. (Kalliokoski et.al. 2008)

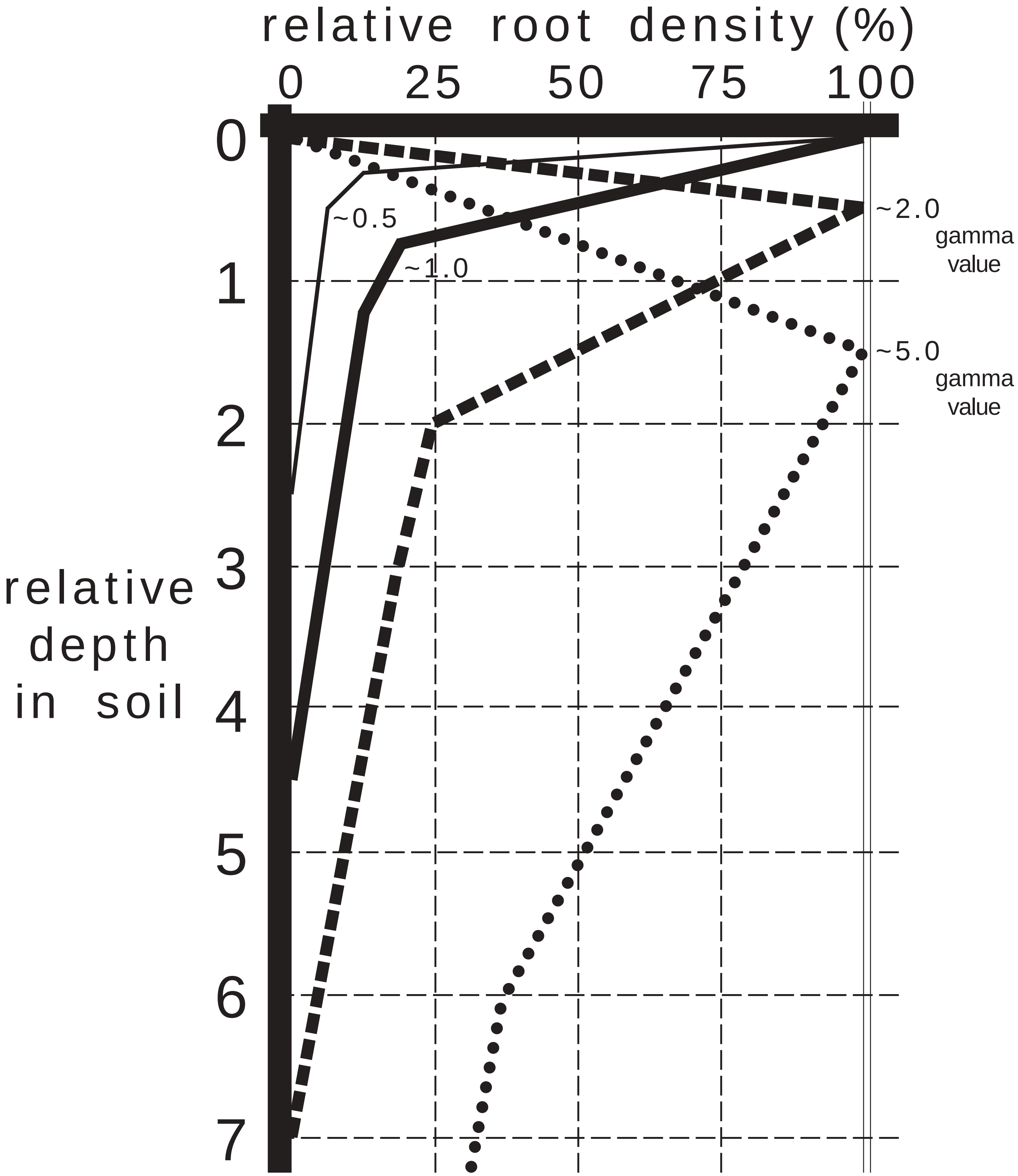


Figure 32: Relative tree root density with increasing soil depth following a gamma distribution curve. The larger the gamma value, the more well-drained the soil. (O_2 at depth must be minimally >5%).
(expanded from Bischetti et al. 2005)

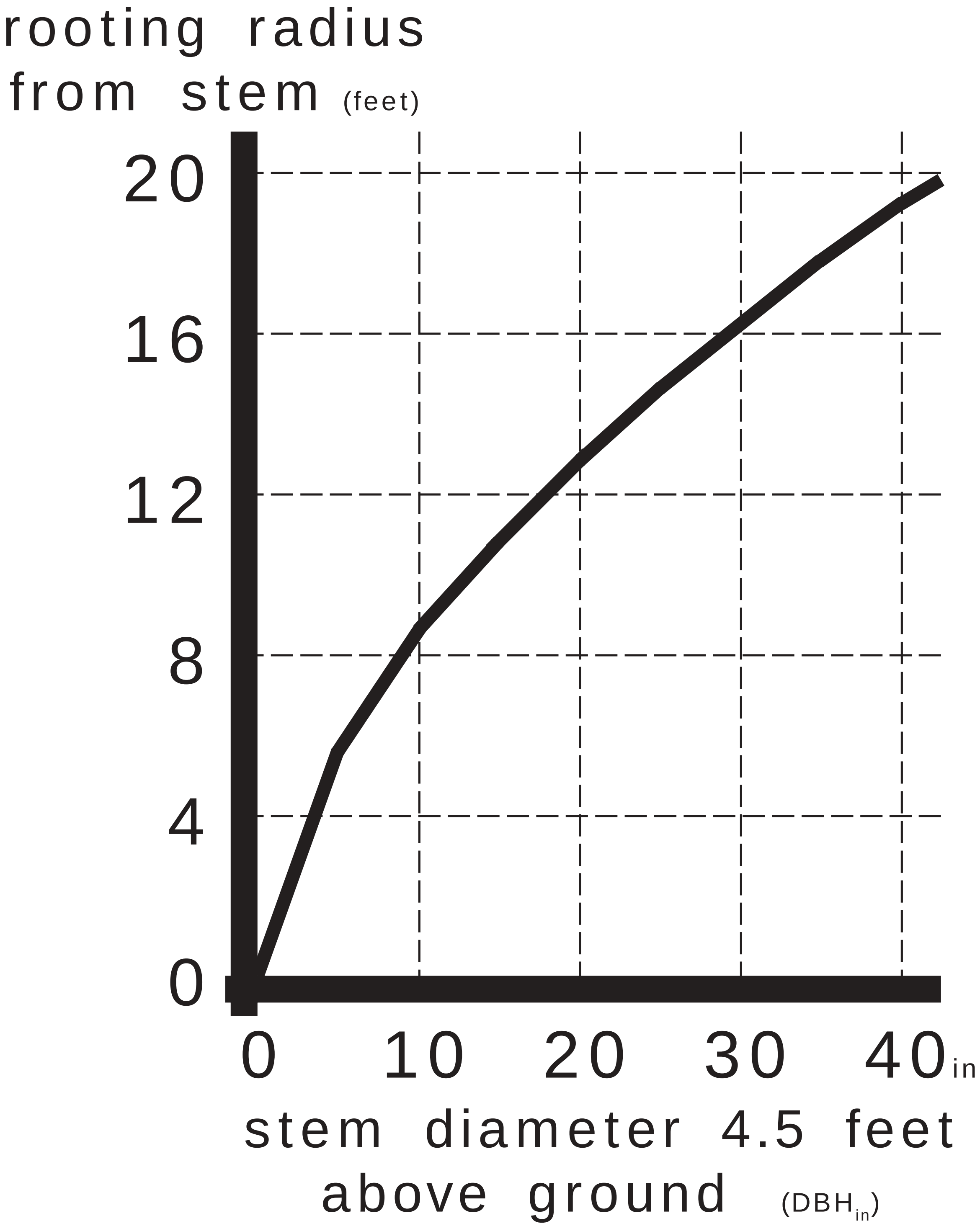


Figure 33: Radial distance away from tree stem where roots greater than 1mm are expected. (Roering et al. 2003)

root radius from stem in feet = $19.057 \times (0.0254 \times DBH_{in})^{0.59}$.

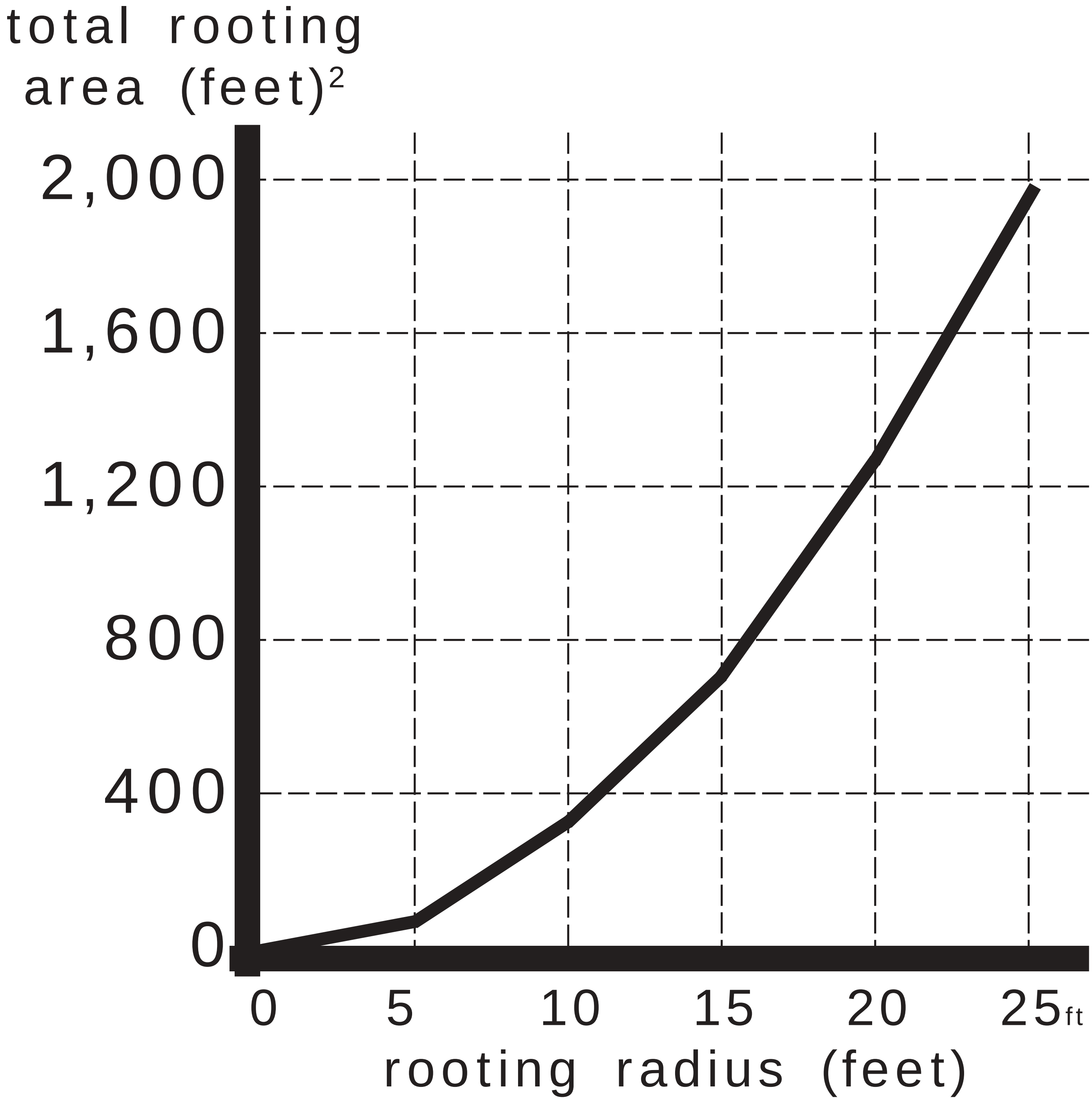


Figure 34: Comparision of how increasing rooting radius away from the stem base in feet can greatly increase total root colonization area in square feet.

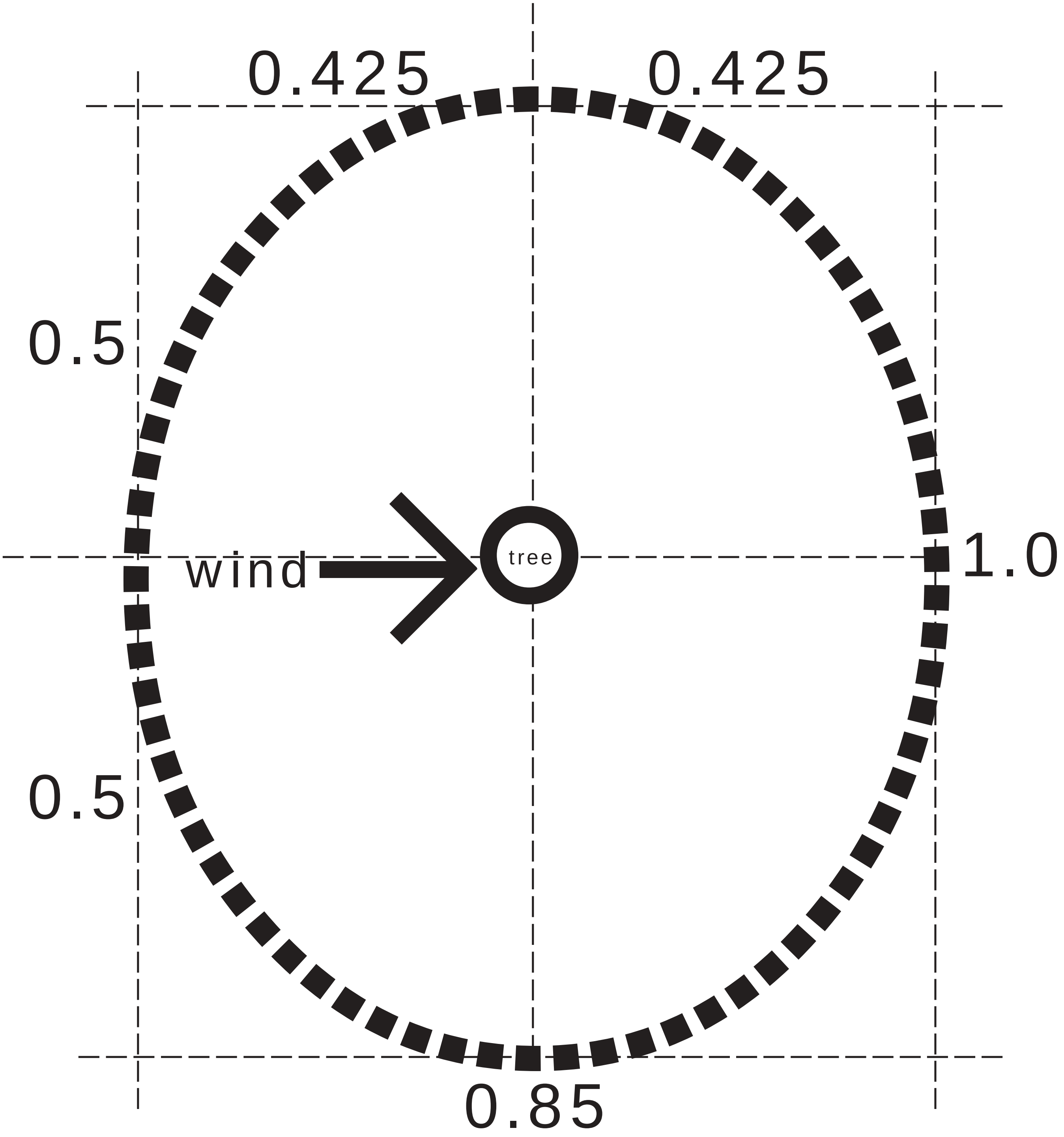


Figure 35: Proportions of an ellipical tree root plate viewed from above. Ellipse long axis = 1.0 and short axis = 0.85. (from Koizumi et al. 2007)

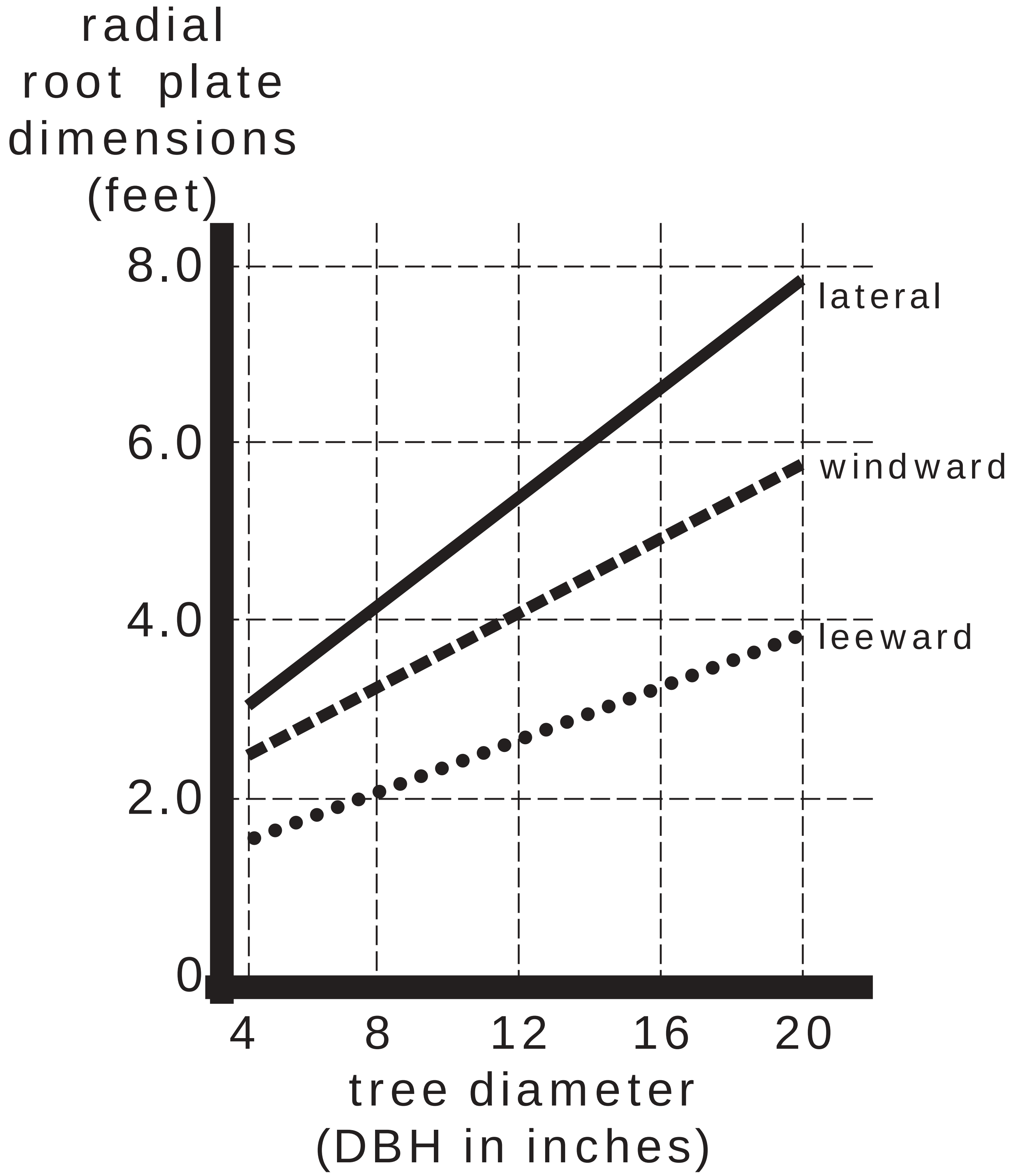


Figure 36: Root plate dimensions comparded with tree diameter at 4.5 feet above the ground. This is a composite graph for two soil types. (Achim & Nicoll 2009)

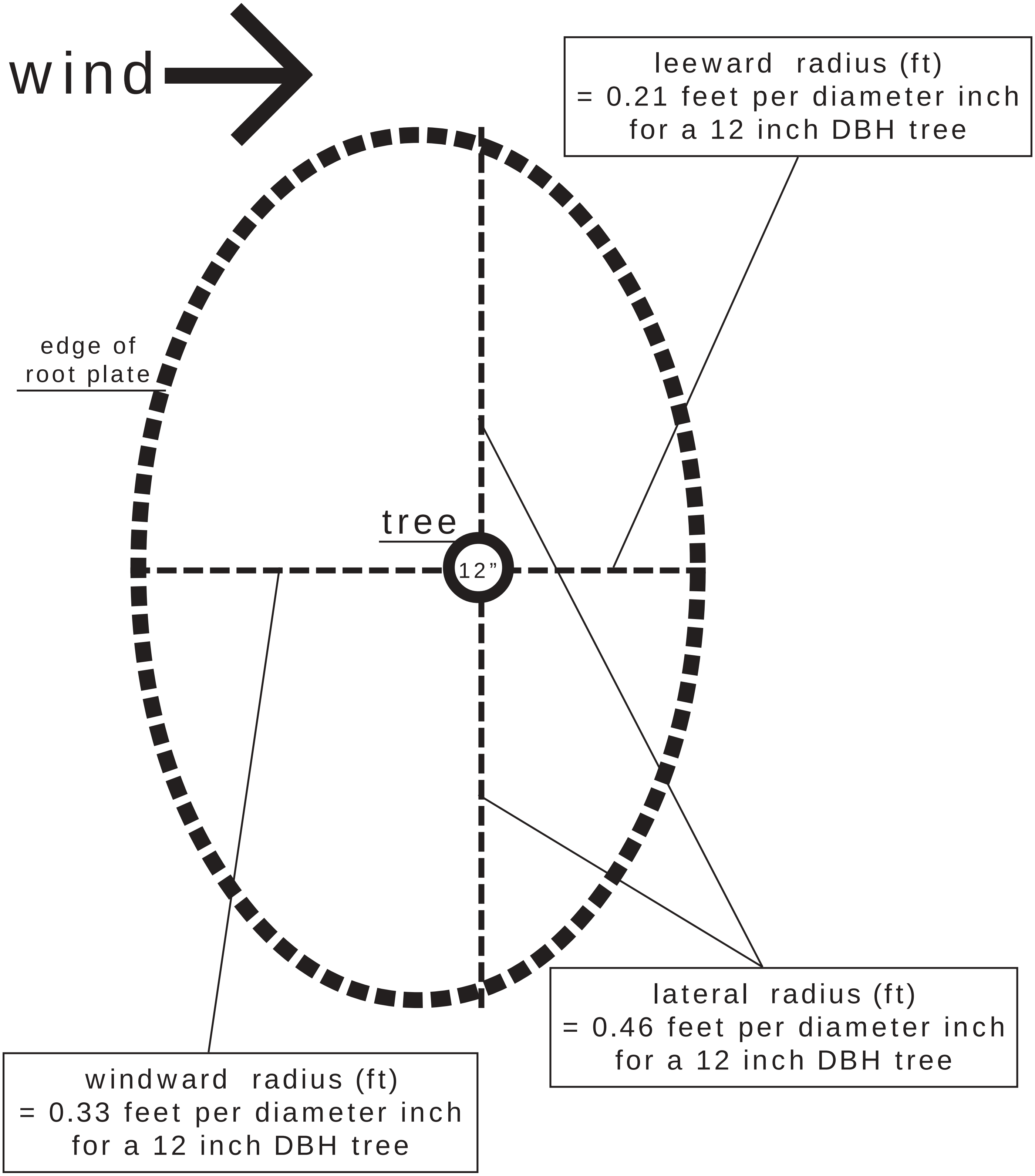


Figure 37: View from above of an oval root plate surrounding a 12 inch DBH tree. (Achim & Nicoll 2009)

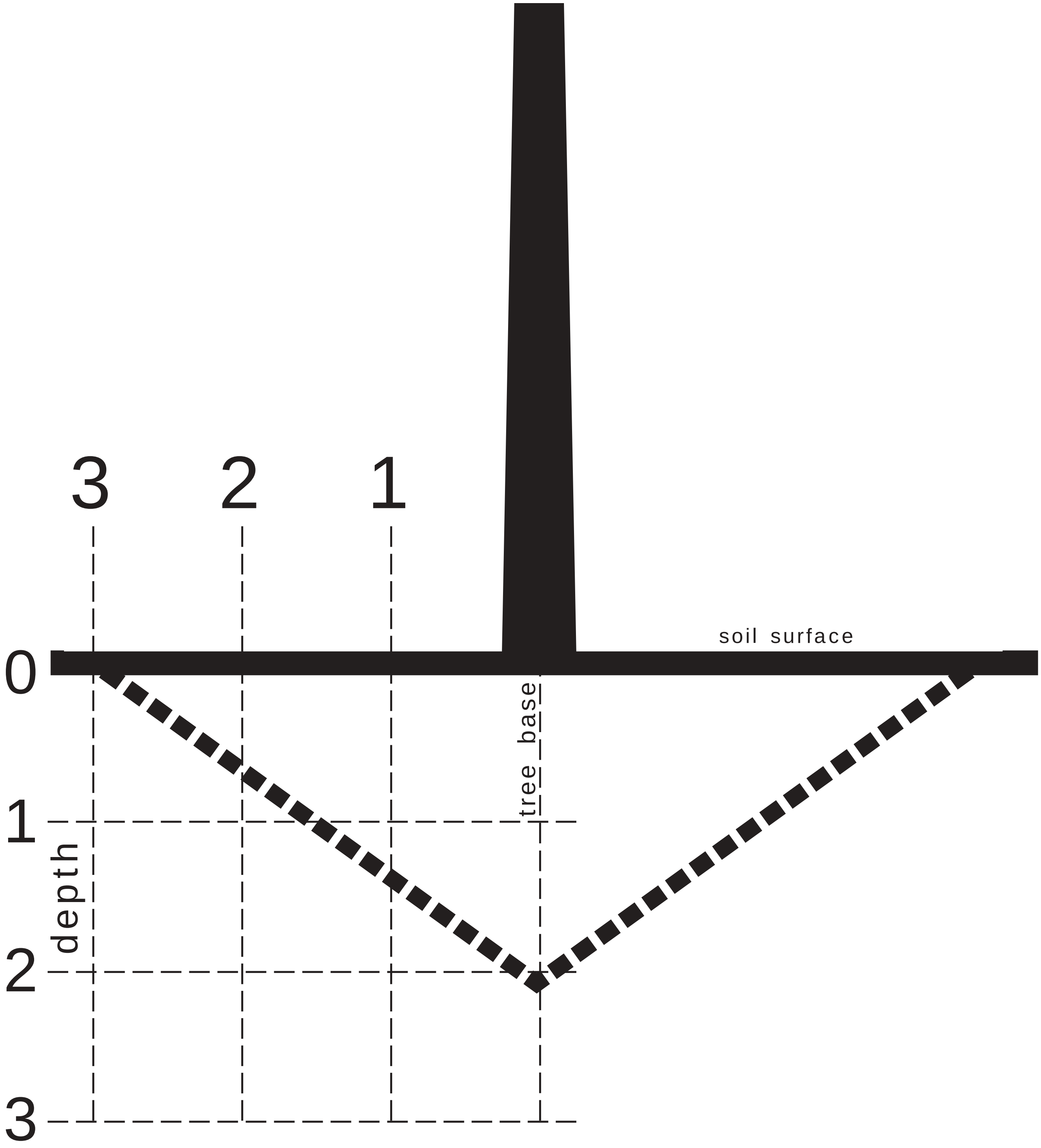


Figure 38: Two dimensional side view of a tree root plate cross-sectional area represented as a conical shape. Shown on a site with no soil depth limitations.

(from Peltola 2006)

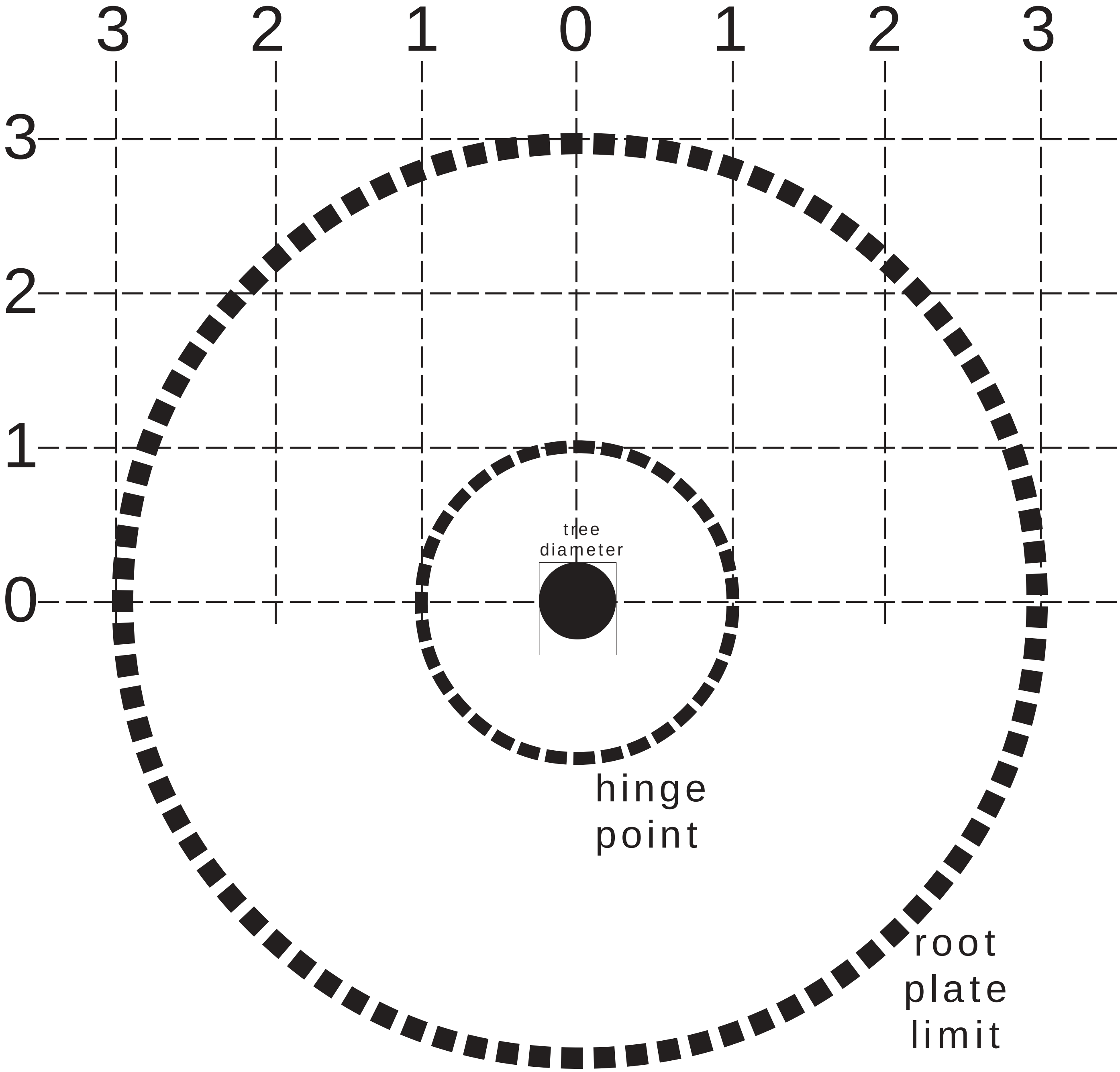


Figure 39: View from above of idealized circular root plate proportions surrounding a tree. The internal circular dotted line represents the expected hinge point. (from Lundstrom et al. 2007)

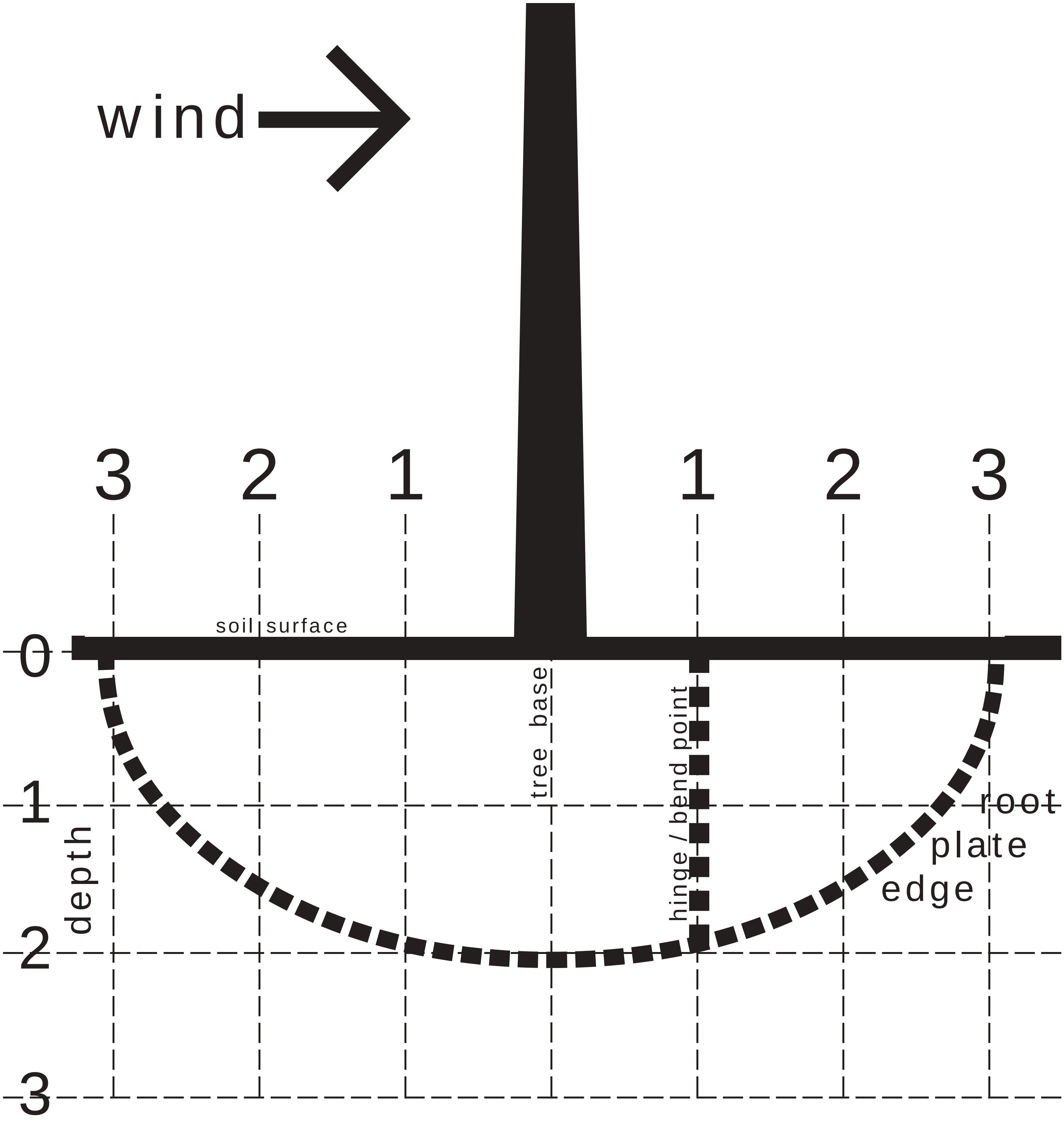


Figure 40: Two dimensional side view of idealized tree root plate proportions surrounding a tree. The cross-sectional area below the soil surface is represented as half an ellipse shape. Shown on a site with no soil depth limitations. (from Lundstrom et al. 2007)

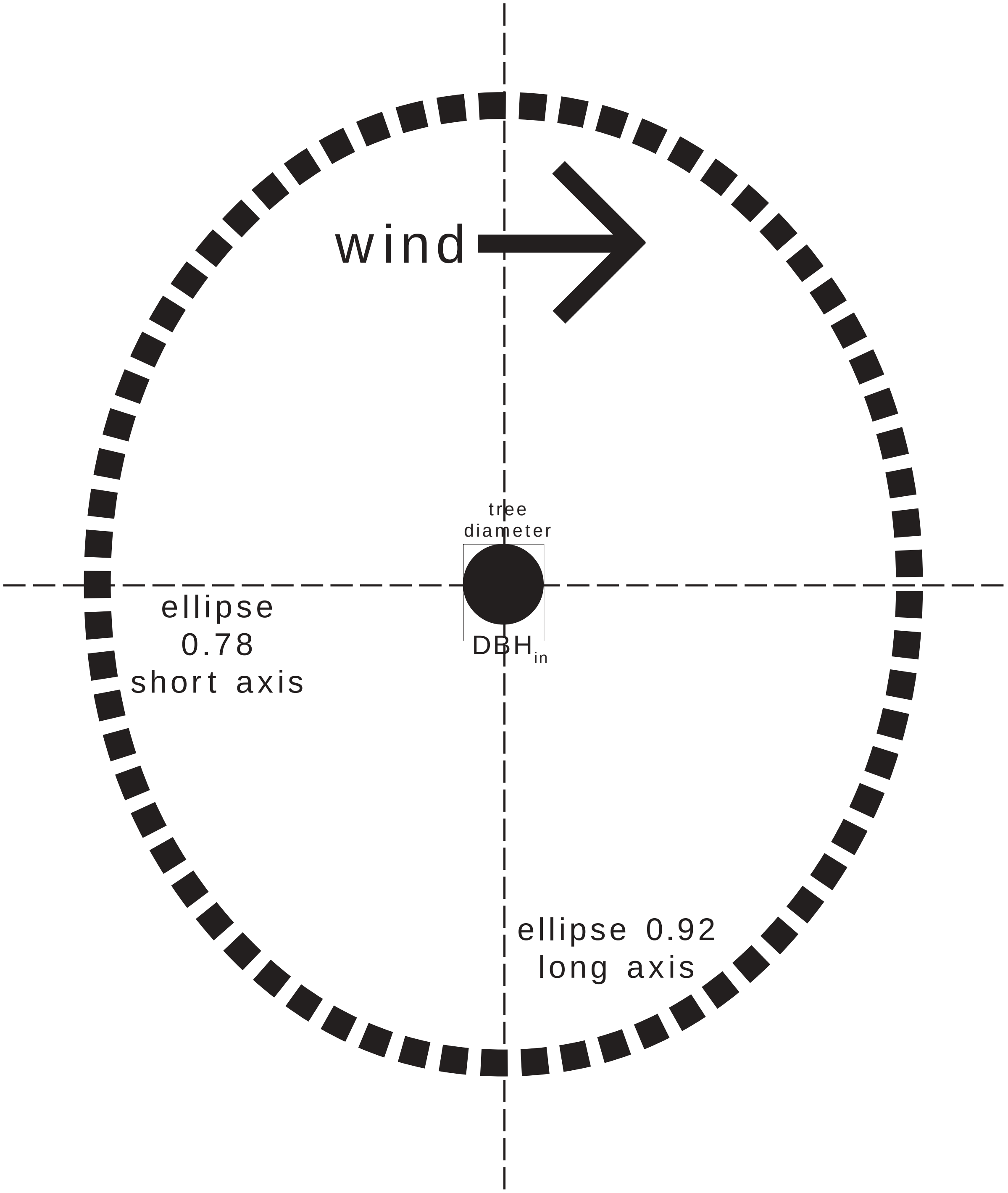


Figure 41: View from above of root plate dimensions surrounding a tree of a set diameter (DBH$_{in}$). The decimal values are multipliers for tree diameter in inches yielding the long and short axis of the root plate ellipse in feet. Koizumi (et al. 2007) root plate ellipse = 0.78 short axis with wind / 0.92 long axis perpendicular to wind.

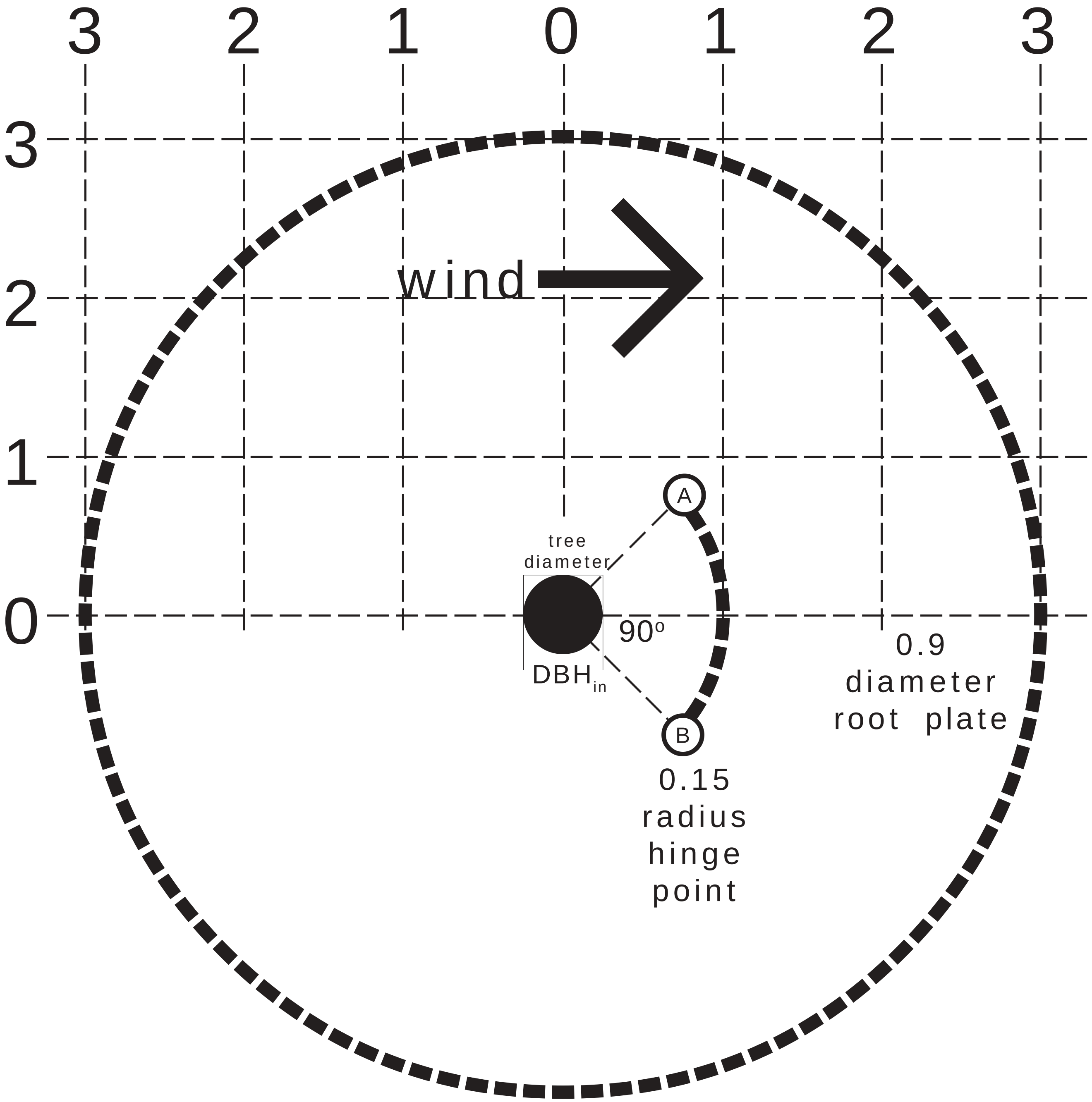


Figure 42: View from above of root plate dimensions surrounding a tree of a set diameter (DBH_{in}) as used in the field for identifying protection zones and for risk assessments (i.e. Coder Root Plate Model). The decimal values are the multipliers of tree diameter inches yielding diameter of root plate in feet or radial dimensions in feet.

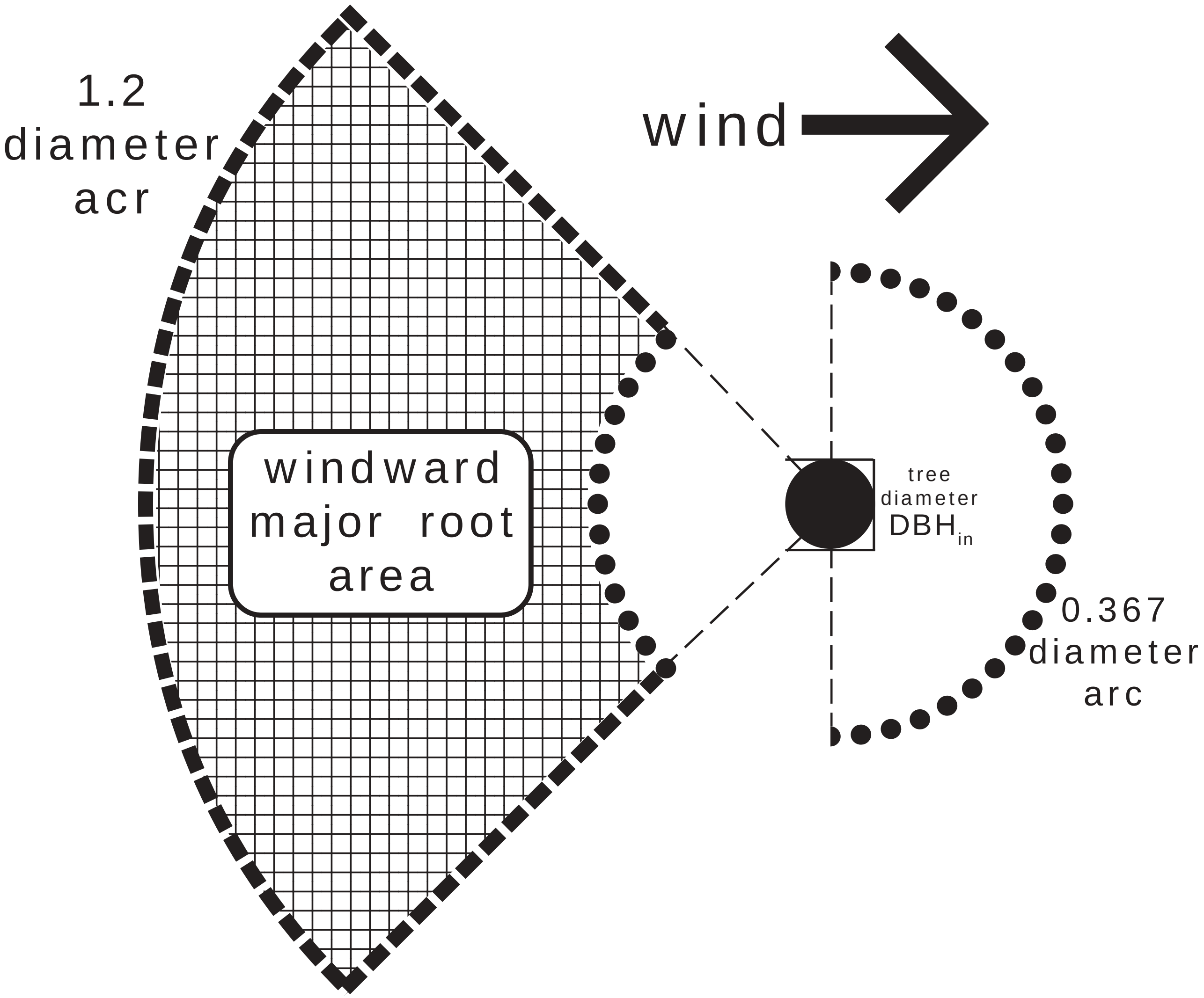


Figure 43: View from above of root plate dimensions surrounding a tree of a set diameter (DBH_{in}). The decimal values are multiplier of tree diameter inches yielding diameter of leeward hinge point in feet, and diameter of windward root area containing 2-3 major roots. Danjon (et. al. 2005)

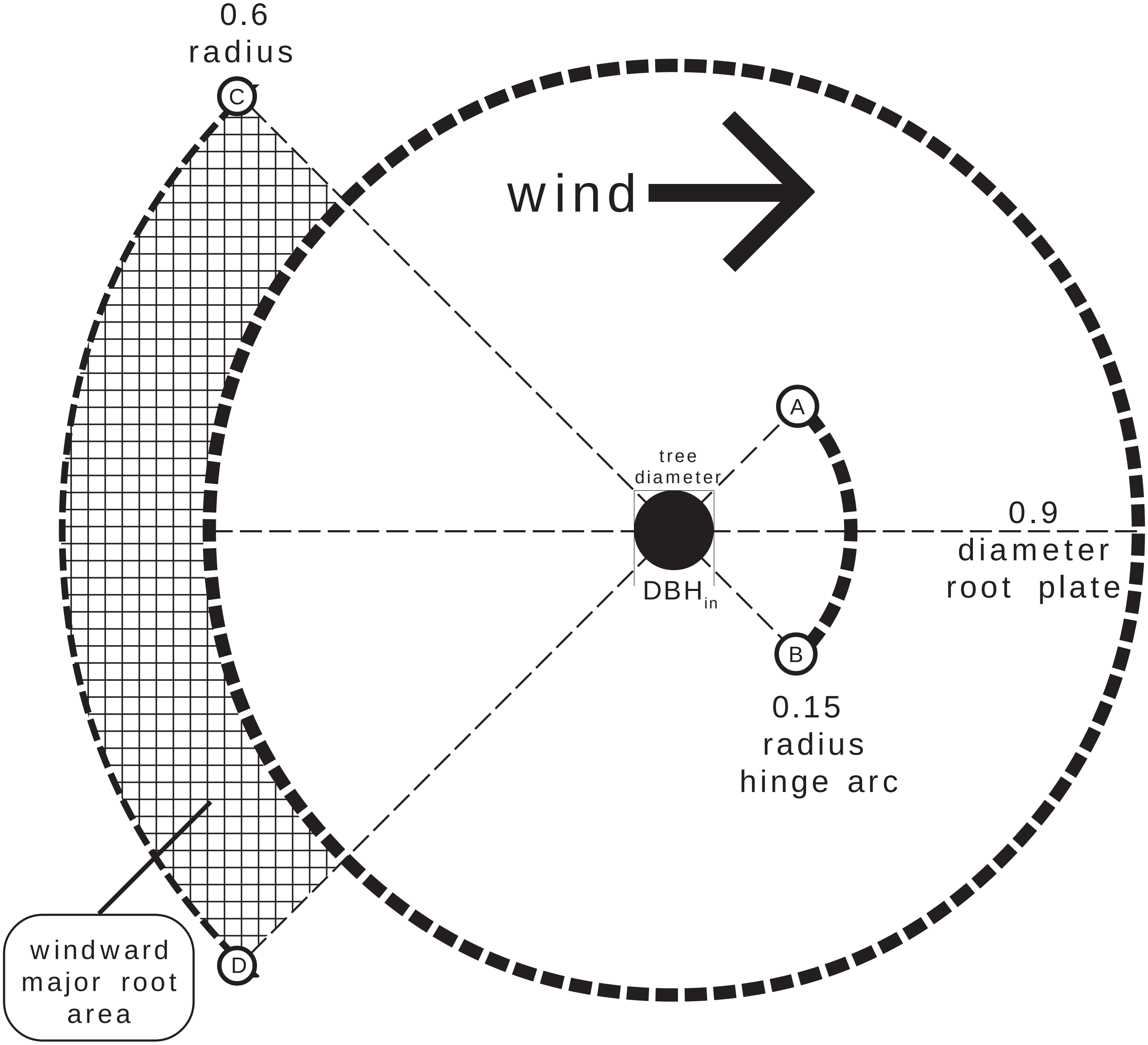


Figure 44: One composite root plate model using research and field application information. View from above of root plate dimensions surrounding a tree of a set diameter (DBH$_{in}$). The decimal values are multipliers of tree diameter inches yielding diameter of root plate in feet or radial dimensions in feet.

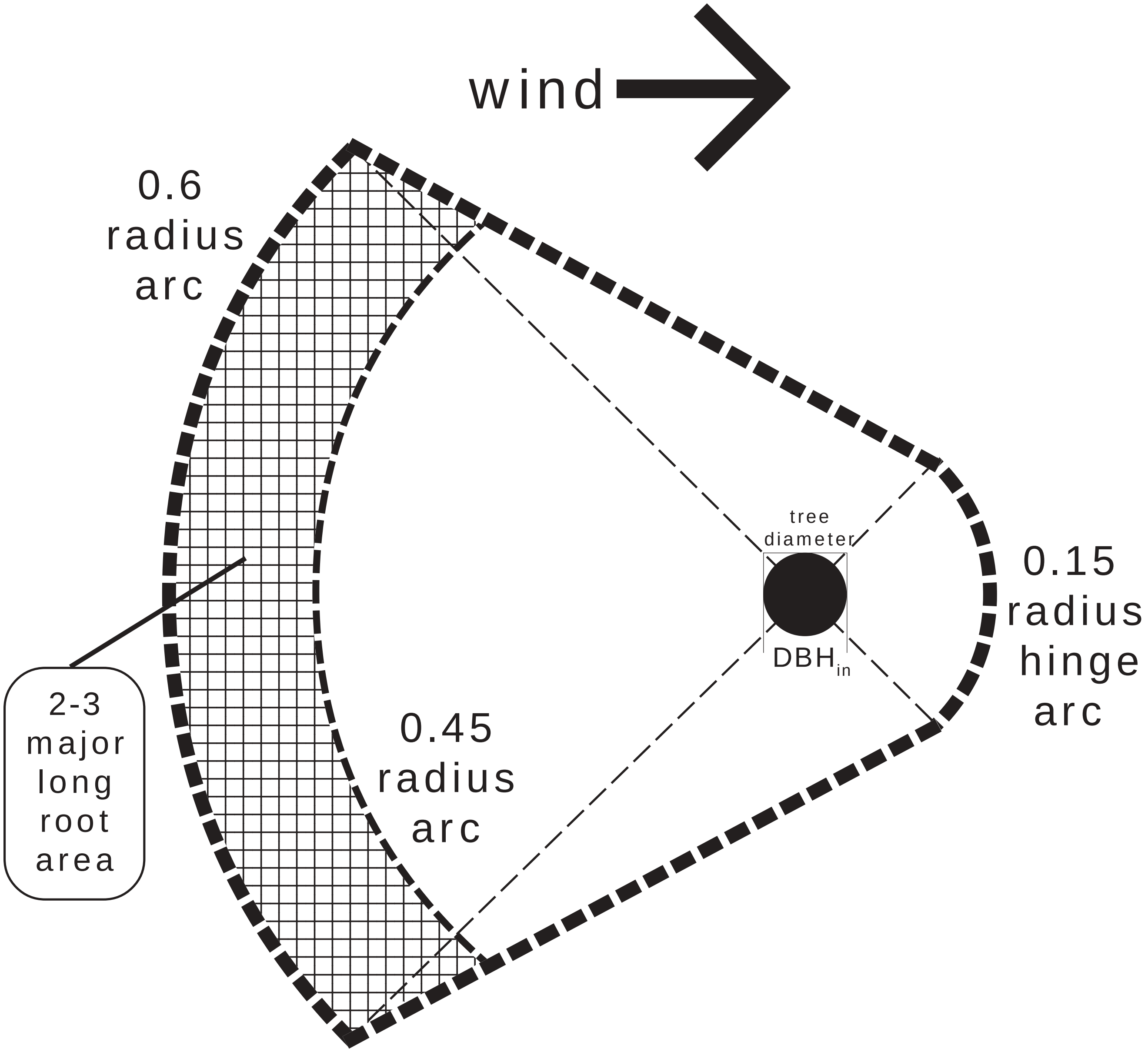


Figure 45: A second composite root plate model using research and field application information. View from above of root plate dimensions surrounding a tree of a set diameter (DBH_{in}). The decimal values are multipliers of tree diameter inches yielding diameter of root plate in feet or radial dimensions in feet. This model eliminates root plate area not associated with primary wind direction.

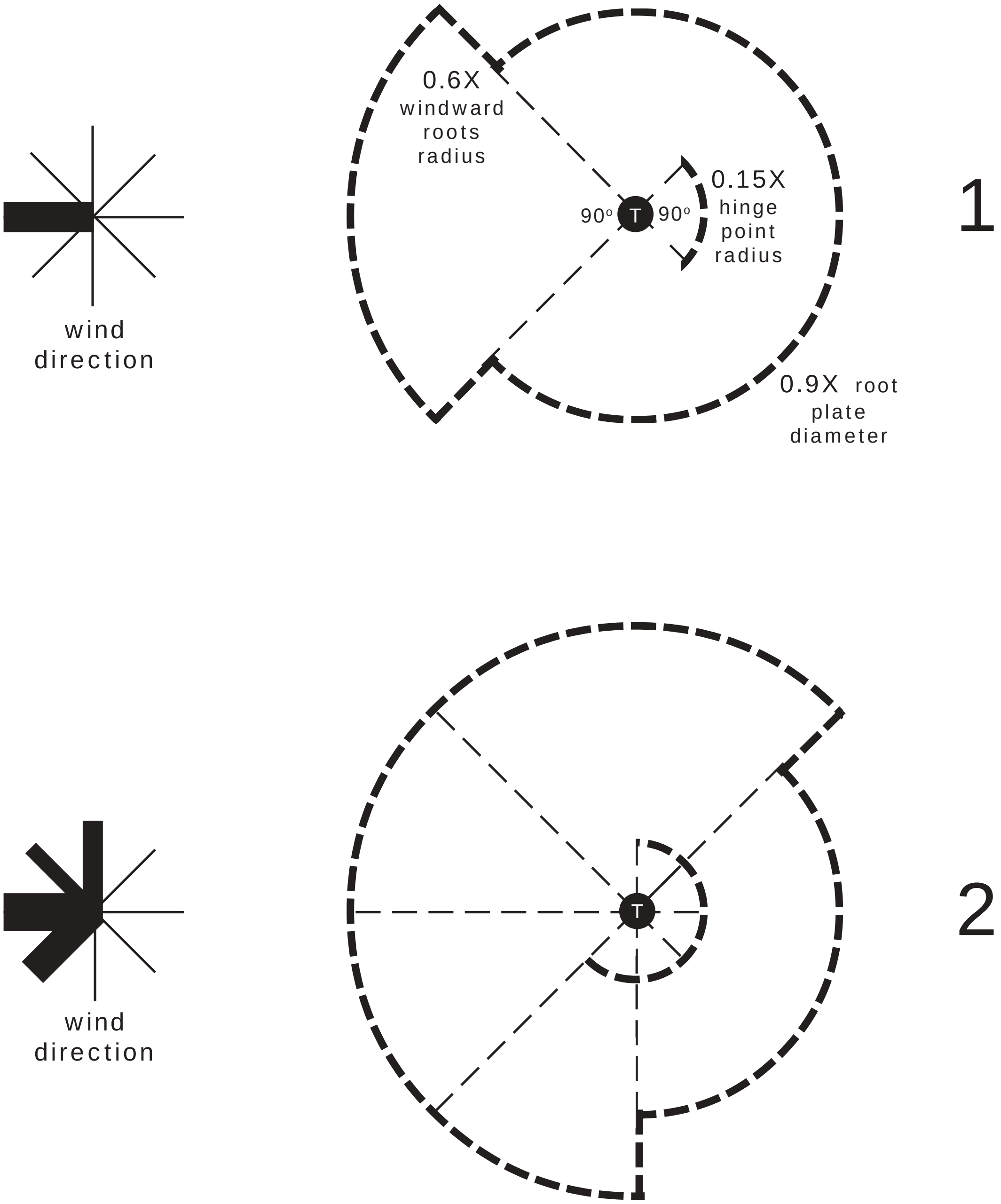


Figure 46: View from above of a: 1) single composite root plate development area formed with challenge from one wind direction only; and, 2) expanded composite root plate development area beneath a more open-grown tree challenged by wind loads from the dominant

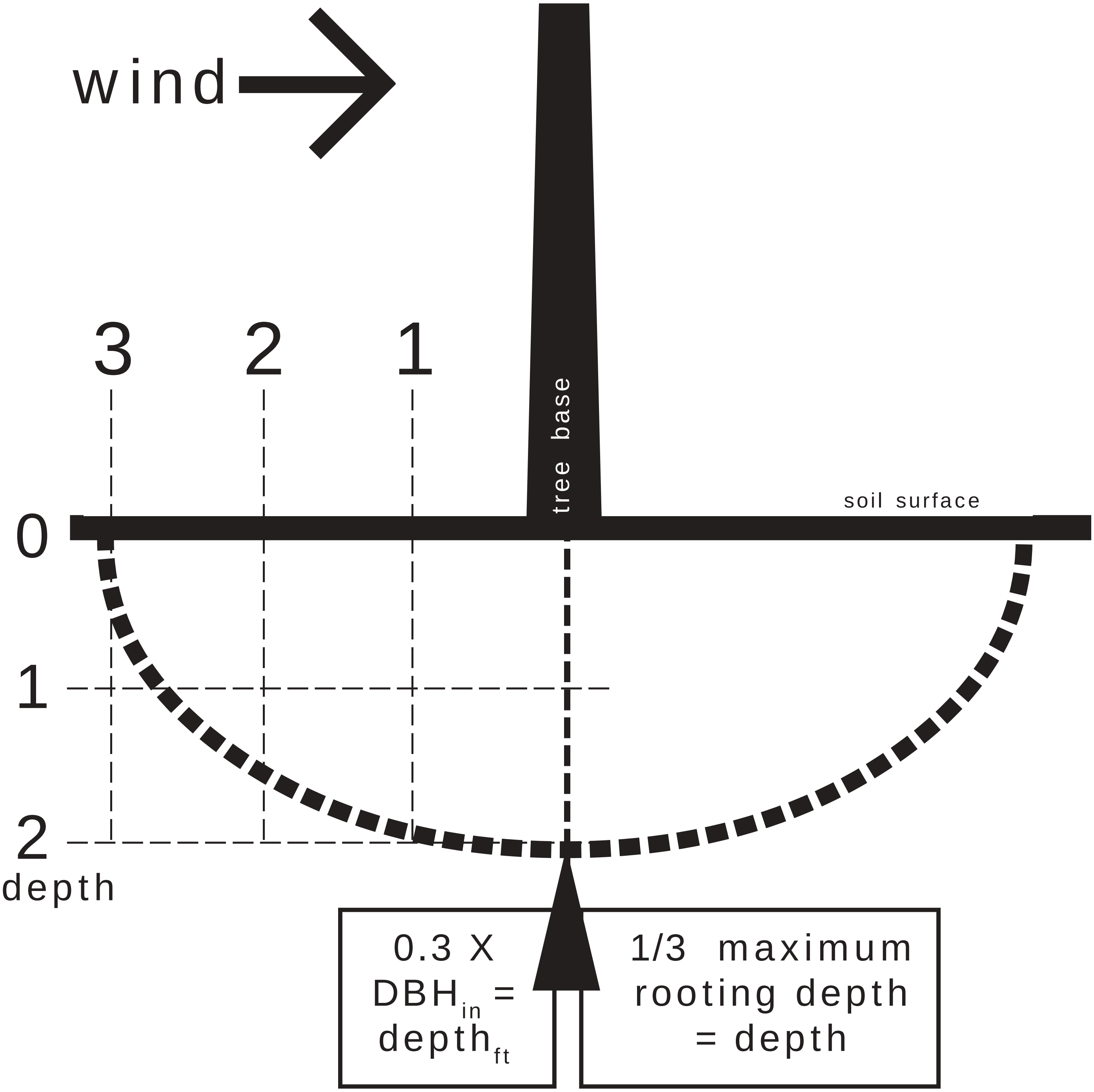


Figure 47: Two dimensional side view of a tree root plate cross-sectional area showing root plate depth and two means of determining root plate depth, one from research of Danjon et. al. 2005 and one from field measures (i.e. Coder Root Plate Model). Shown on a site with no soil depth limitations.

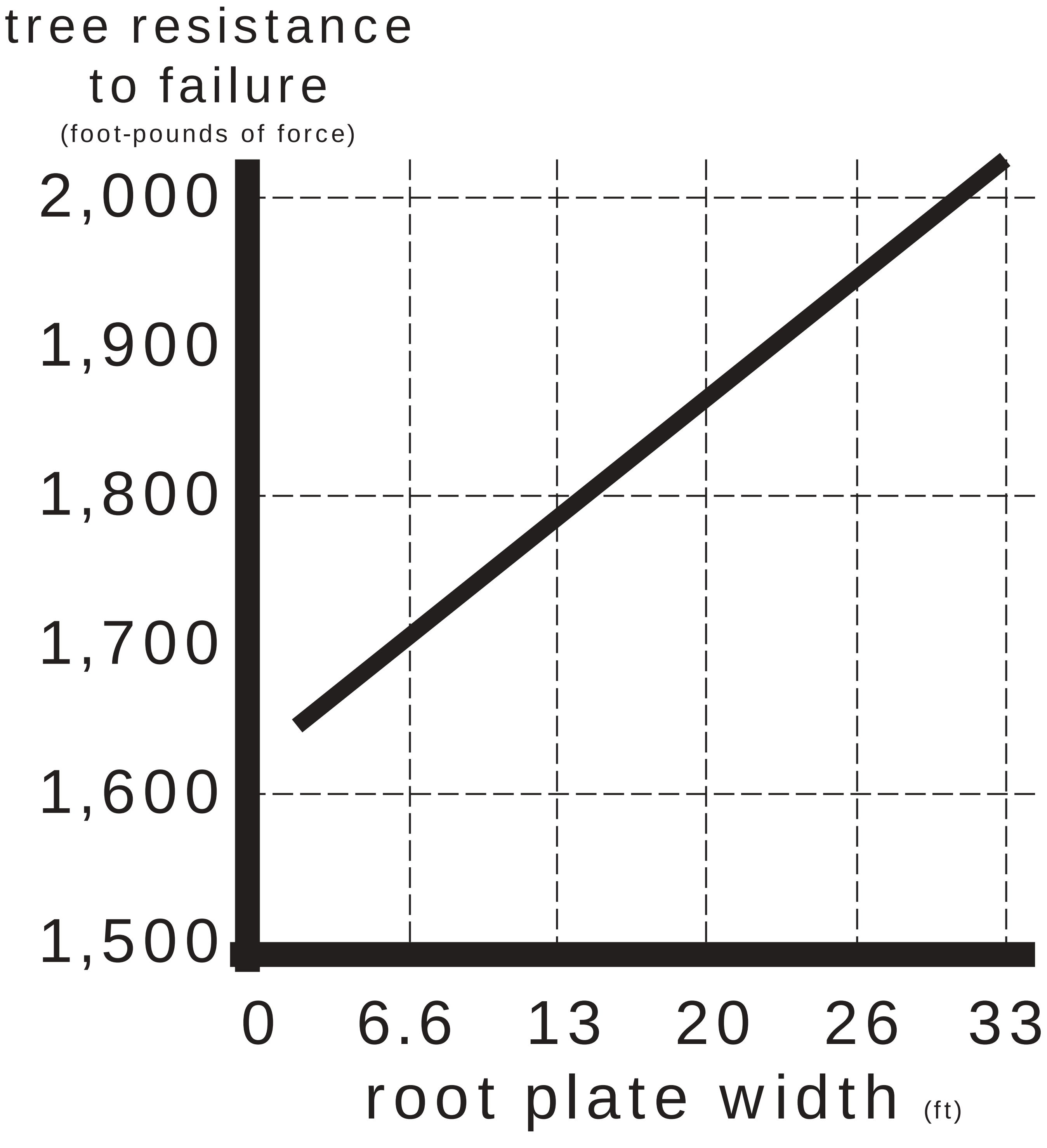


Figure 48: Impact of root plate width in feet on tree resistance to failure in foot pounds of force.
(Moore 2000)

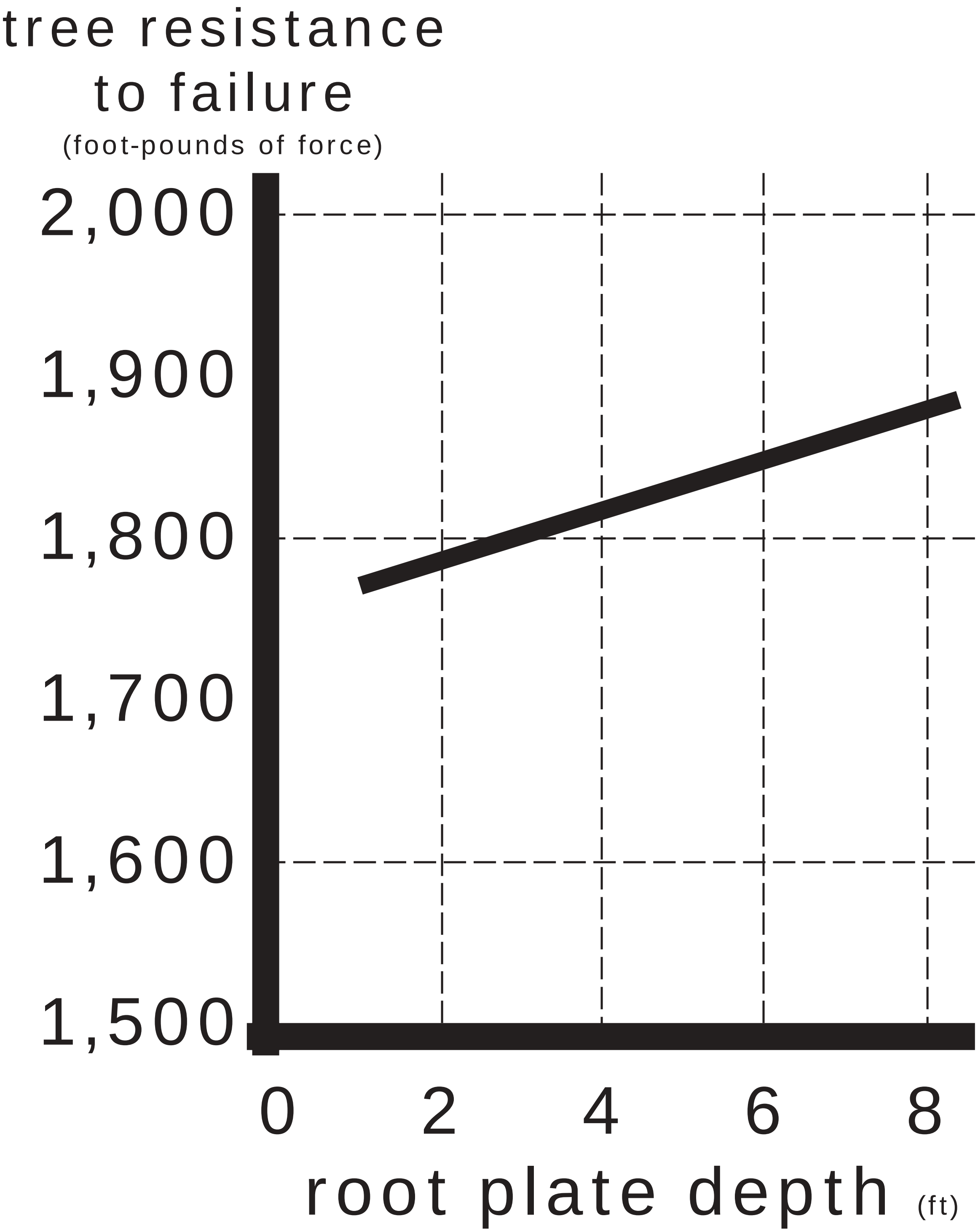


Figure 49: Impact of root plate depth in feet on tree resistance to failure in foot pounds of force. (Moore 2000)

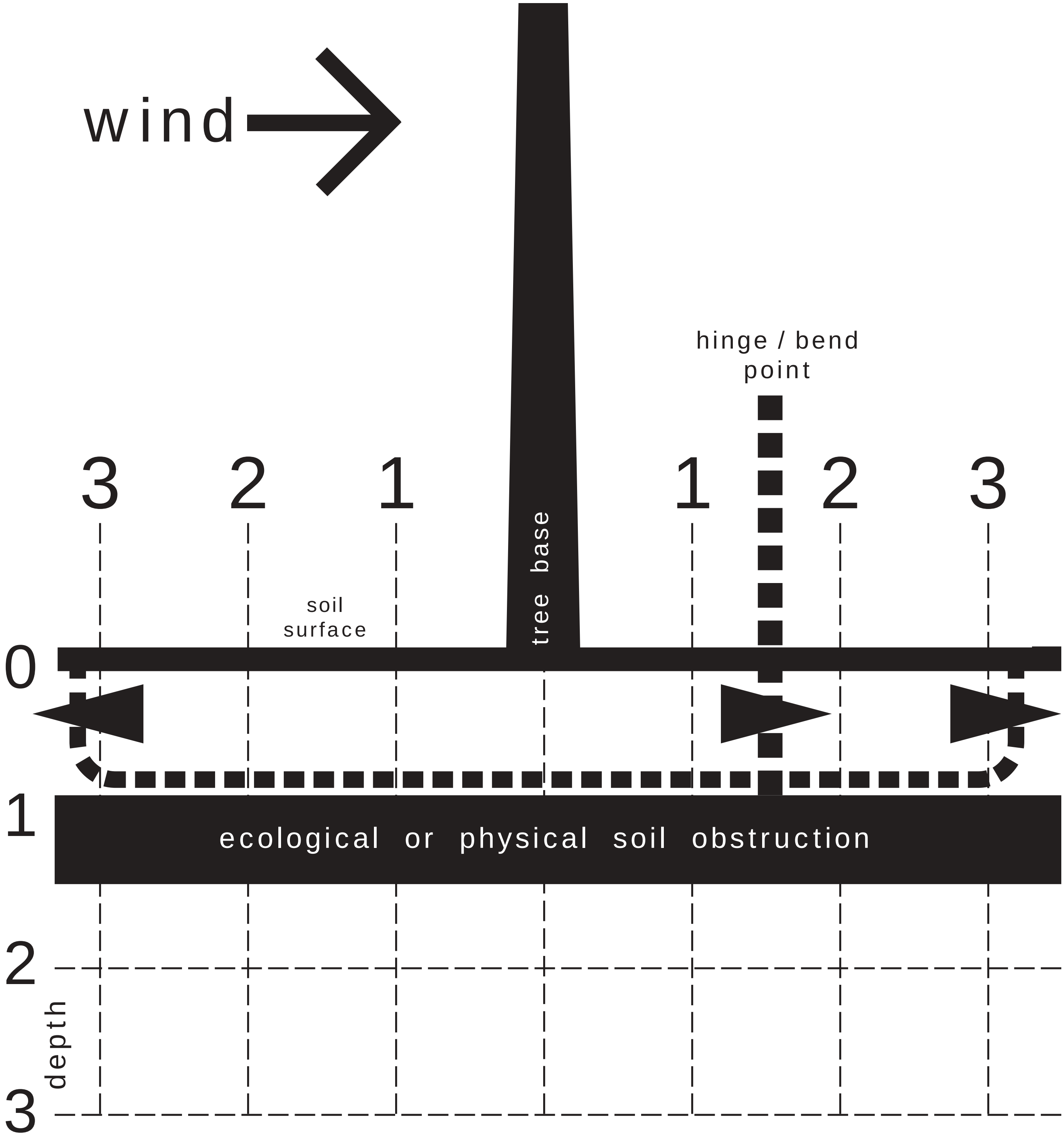


Figure 50: Two dimensional side view of a tree root plate cross-sectional area in a depth-limited rooting space constrained by soil oxygenation, drainage, or obstruction. Inserted is a heavy dotted line representing the leeward side root hinge point. (derived from Lundstrom et al. 2007)

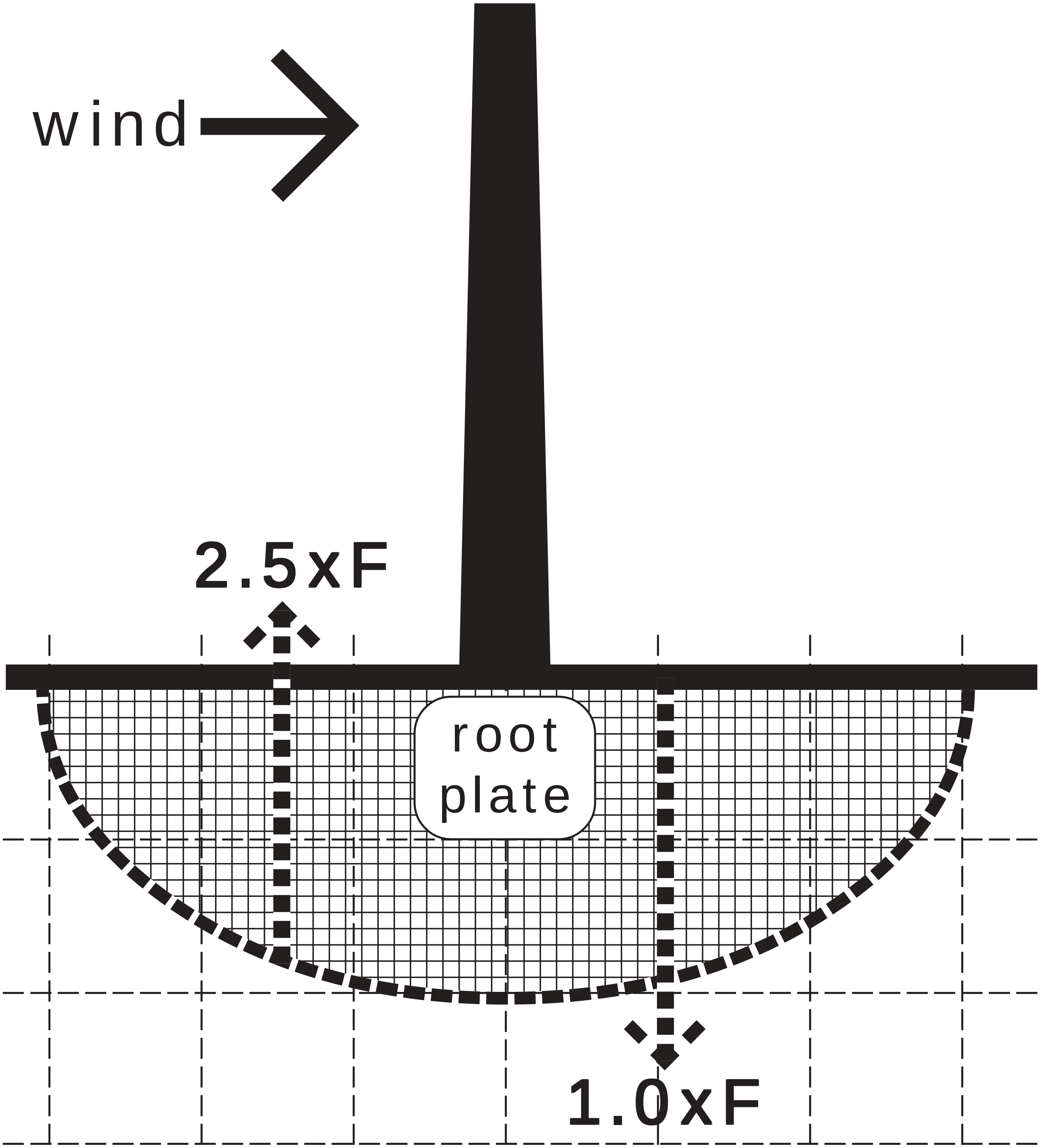


Figure 51: Cross-section of a tree root plate showing force concentration centers. Windward roots resist 2.5X (2.5xF) more force than leeward roots (1.0xF). Windward forces are centered 1.5X farther from stem base than leeward forces. (derived from Stokes 1999; Watson 2000)

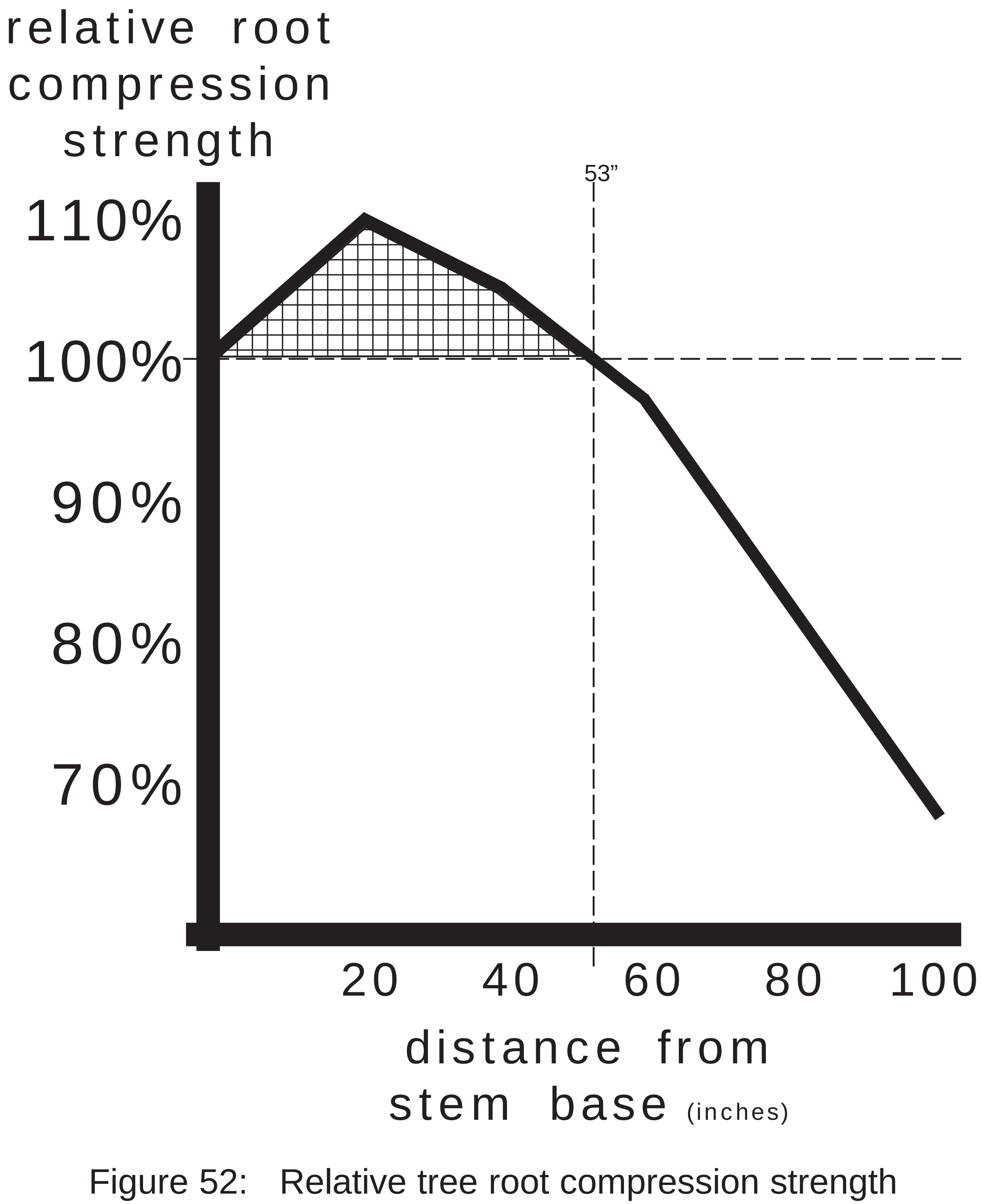


Figure 52: Relative tree root compression strength changes along root length away from stem base.
(after Stokes & Mattheck 1996)

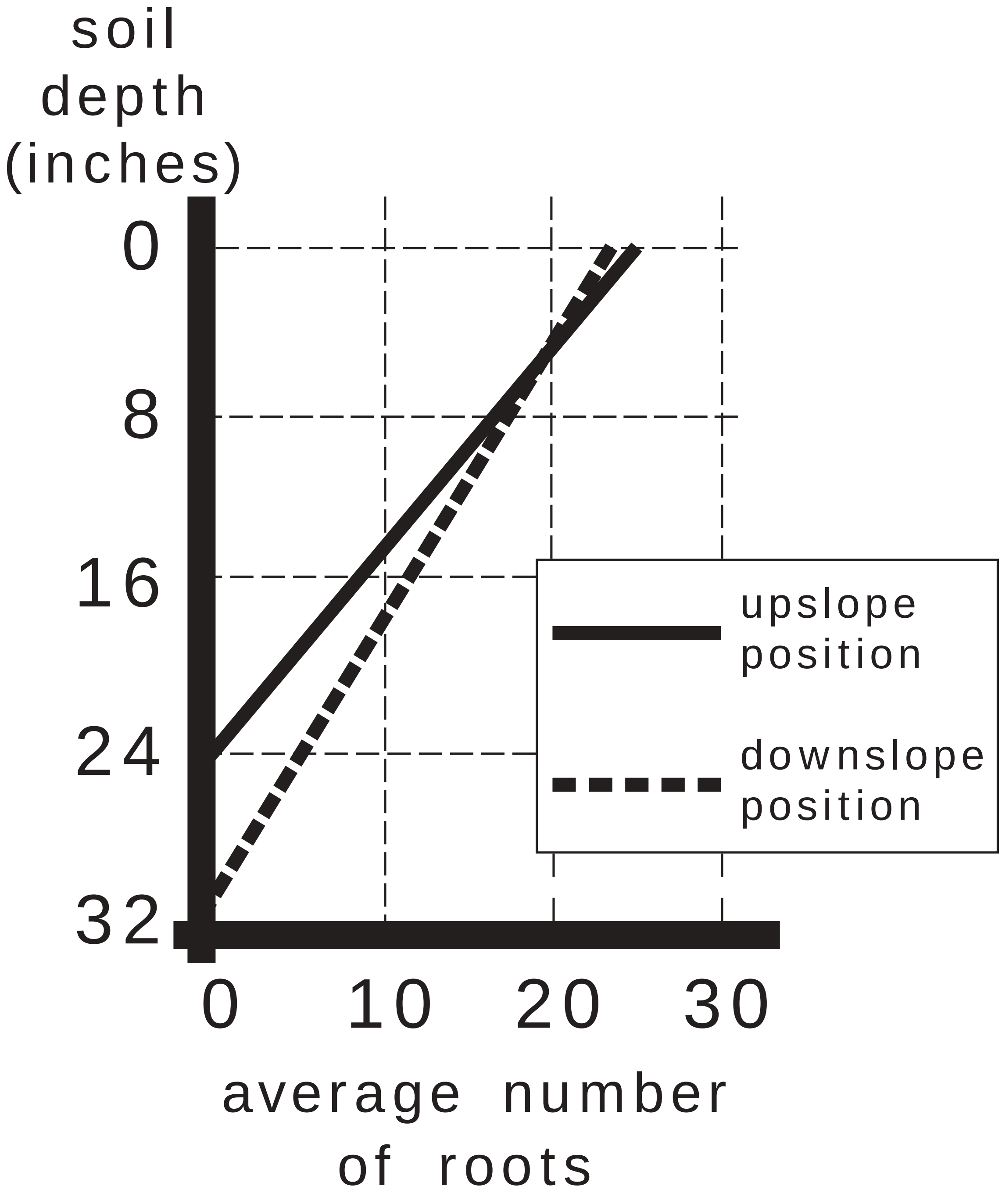


Figure 53: Idealized number of roots in downslope versus upslope positions for two hardwood species.

(derived from Abdi et.al. 2010).

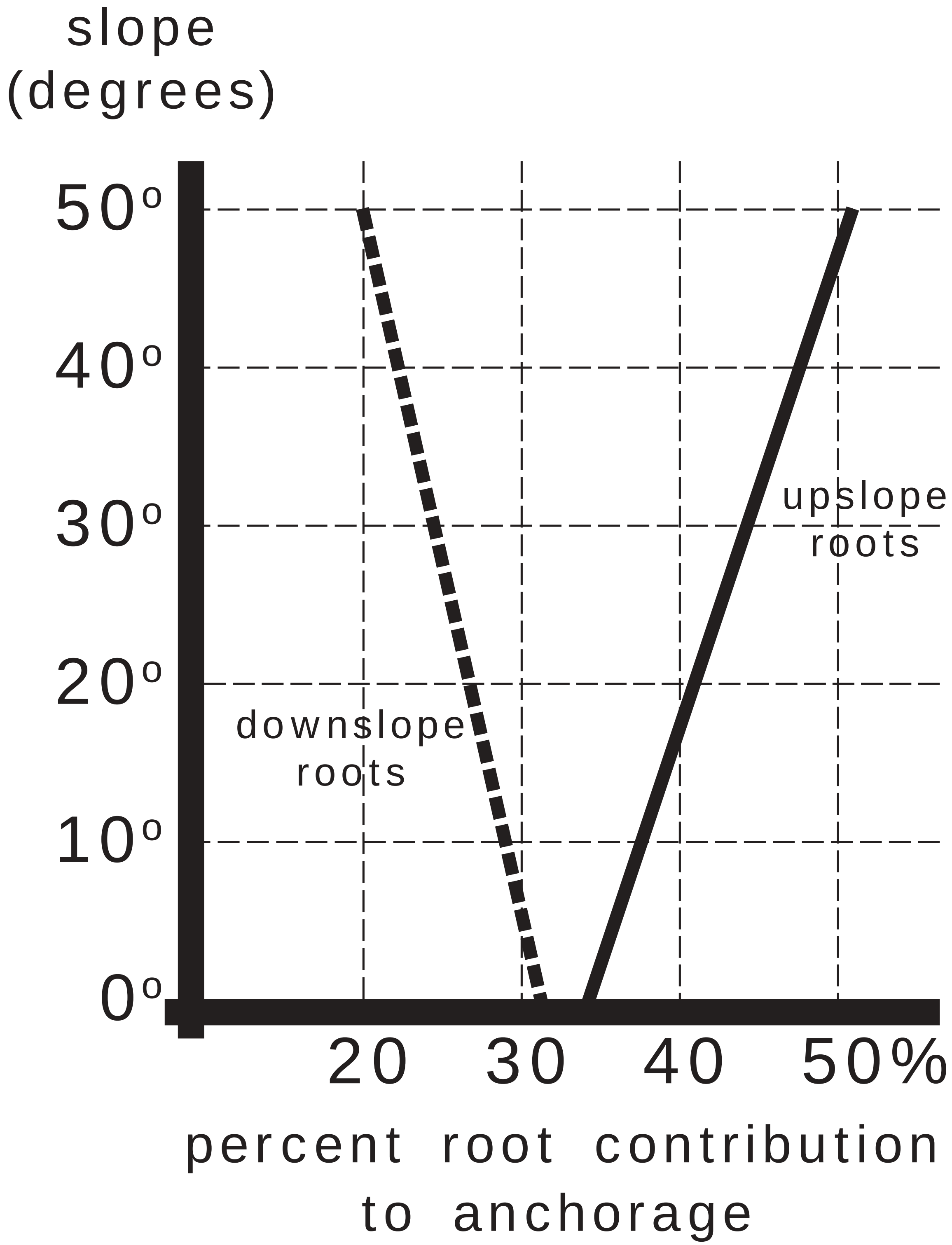


Figure 54: Comparison of upslope and downslope root contributions to whole tree anchorage with increasing slope. (Sun et.al. 2008)

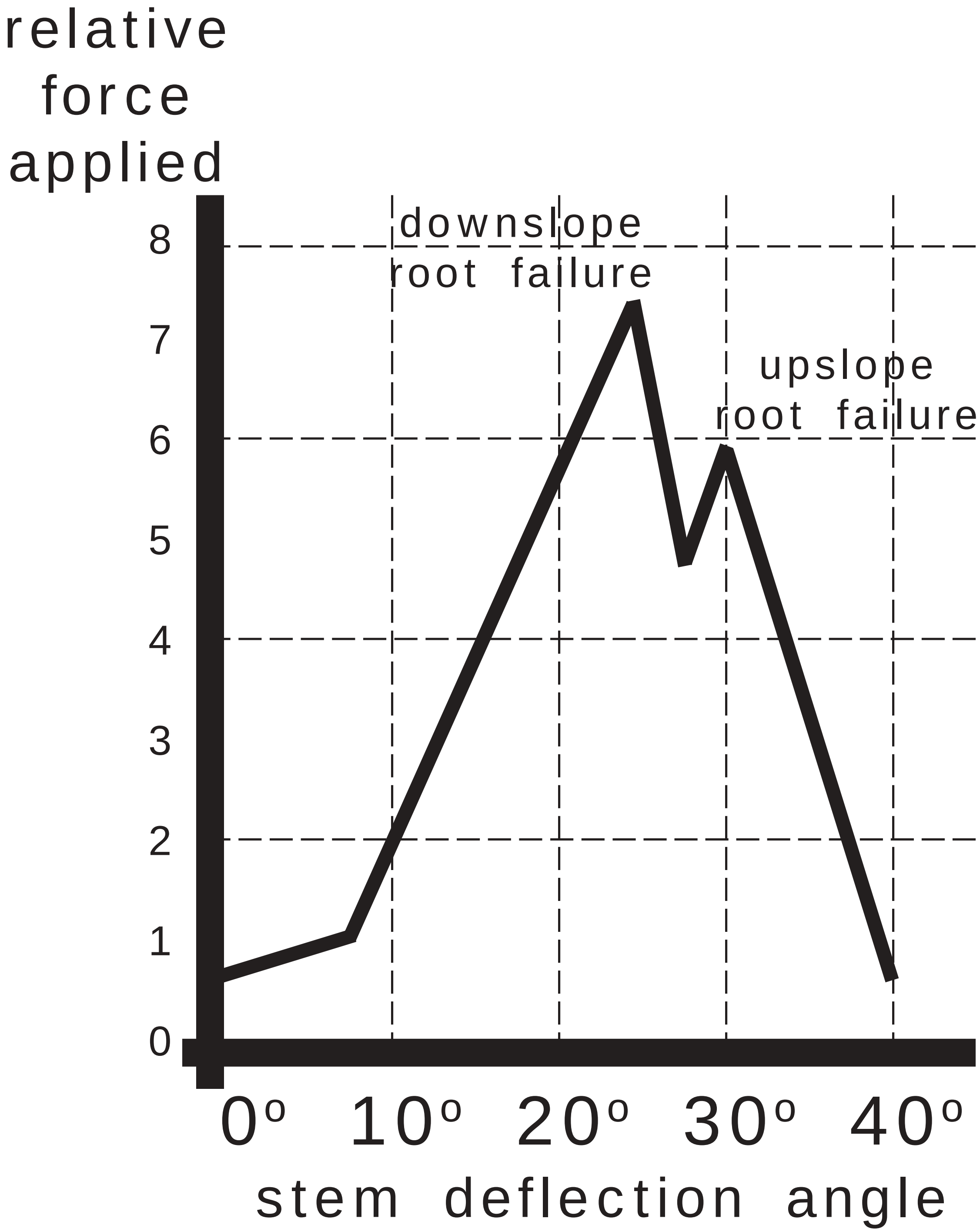


Figure 55: Idealized force to failure curve with increasing stem inclination angle. (Sun et.al. 2008)

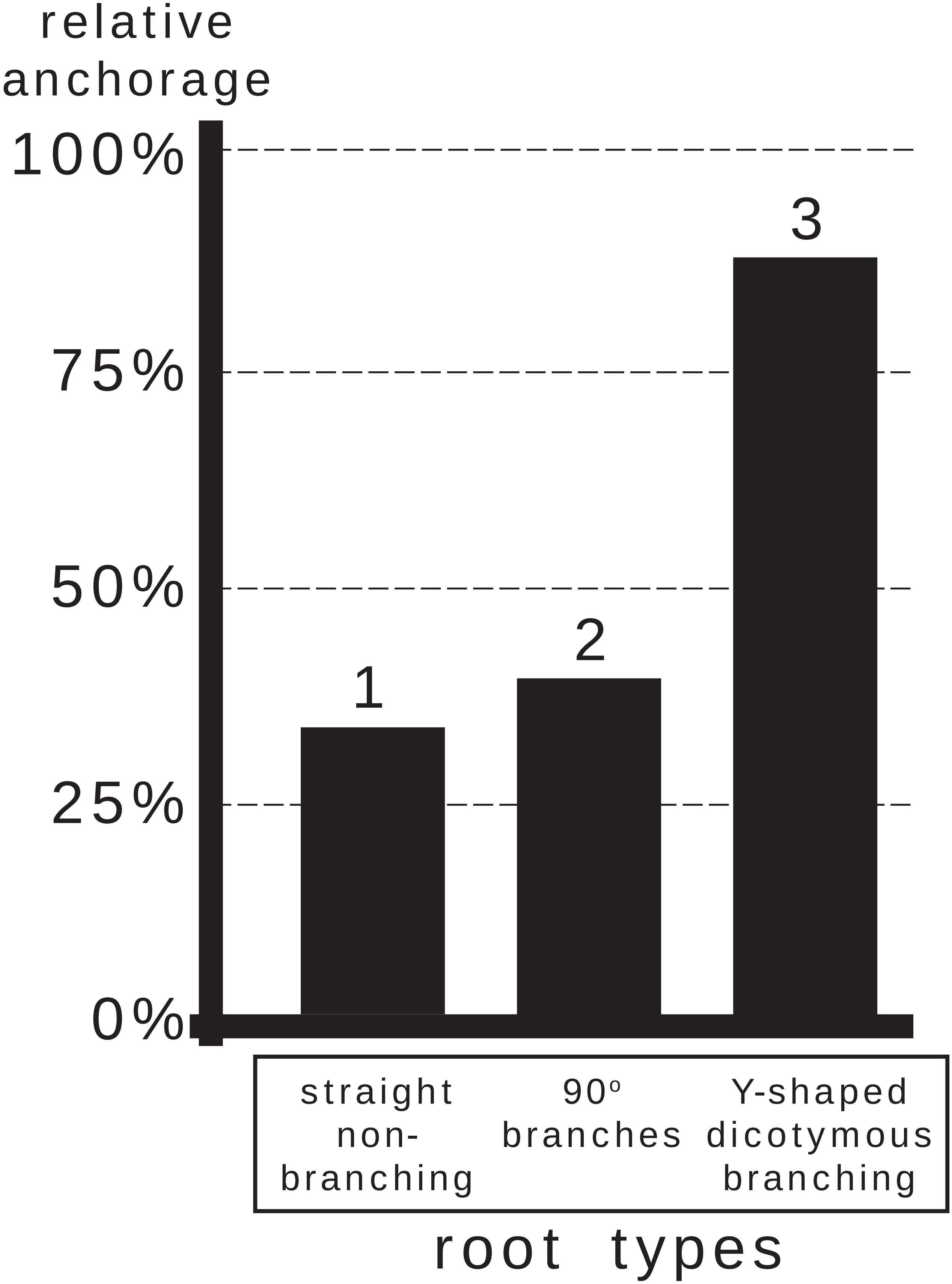


Figure 56: Relative tree root anchorage for three tested root types. (derived from Dupuy et al. 2005a & 2005b)

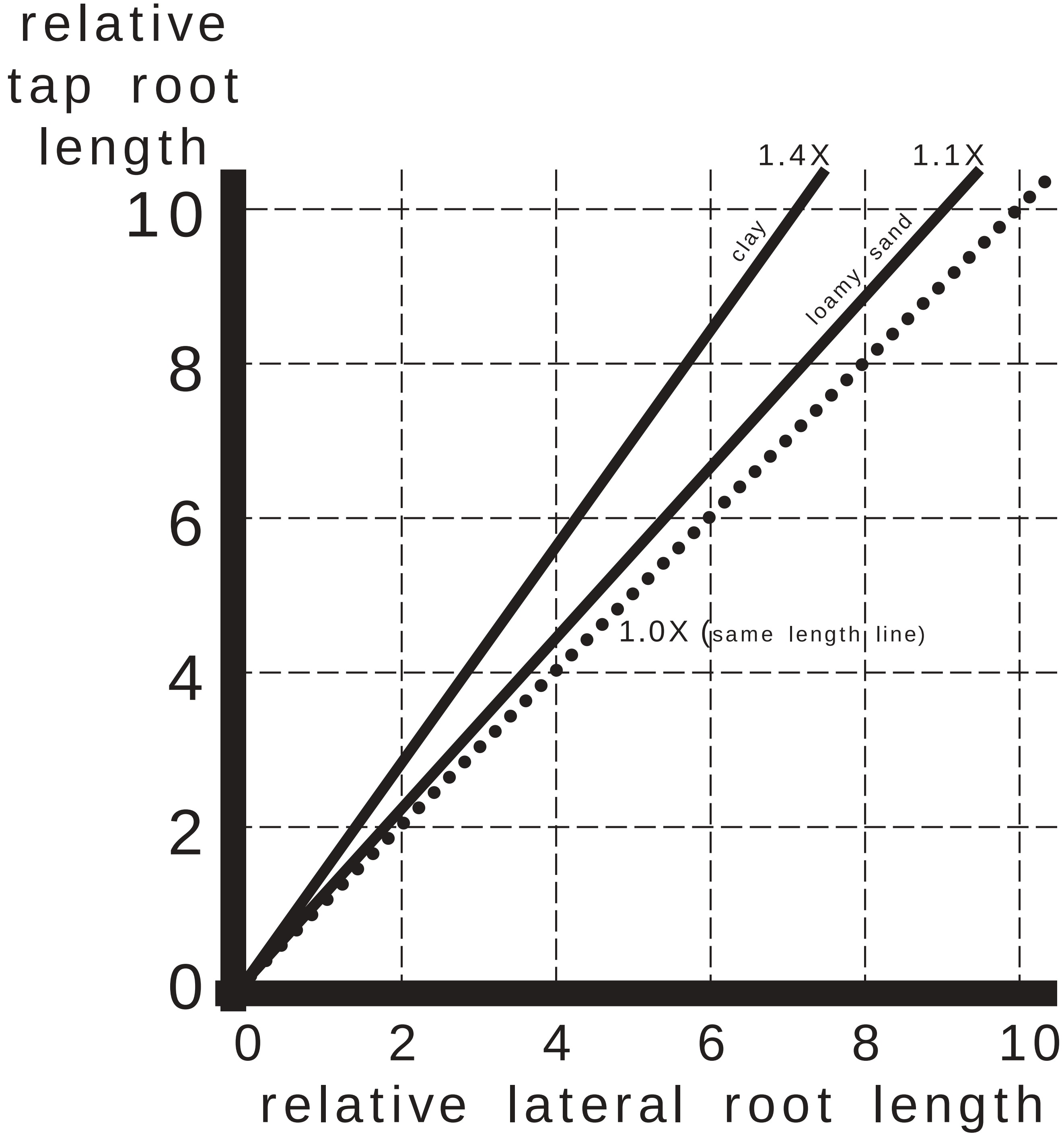


Figure 57: Point when tap root length becomes to significantly increase tree anchorage, as compared with structural lateral root length, for two different soil types. (Fourcaud et al. 2008)

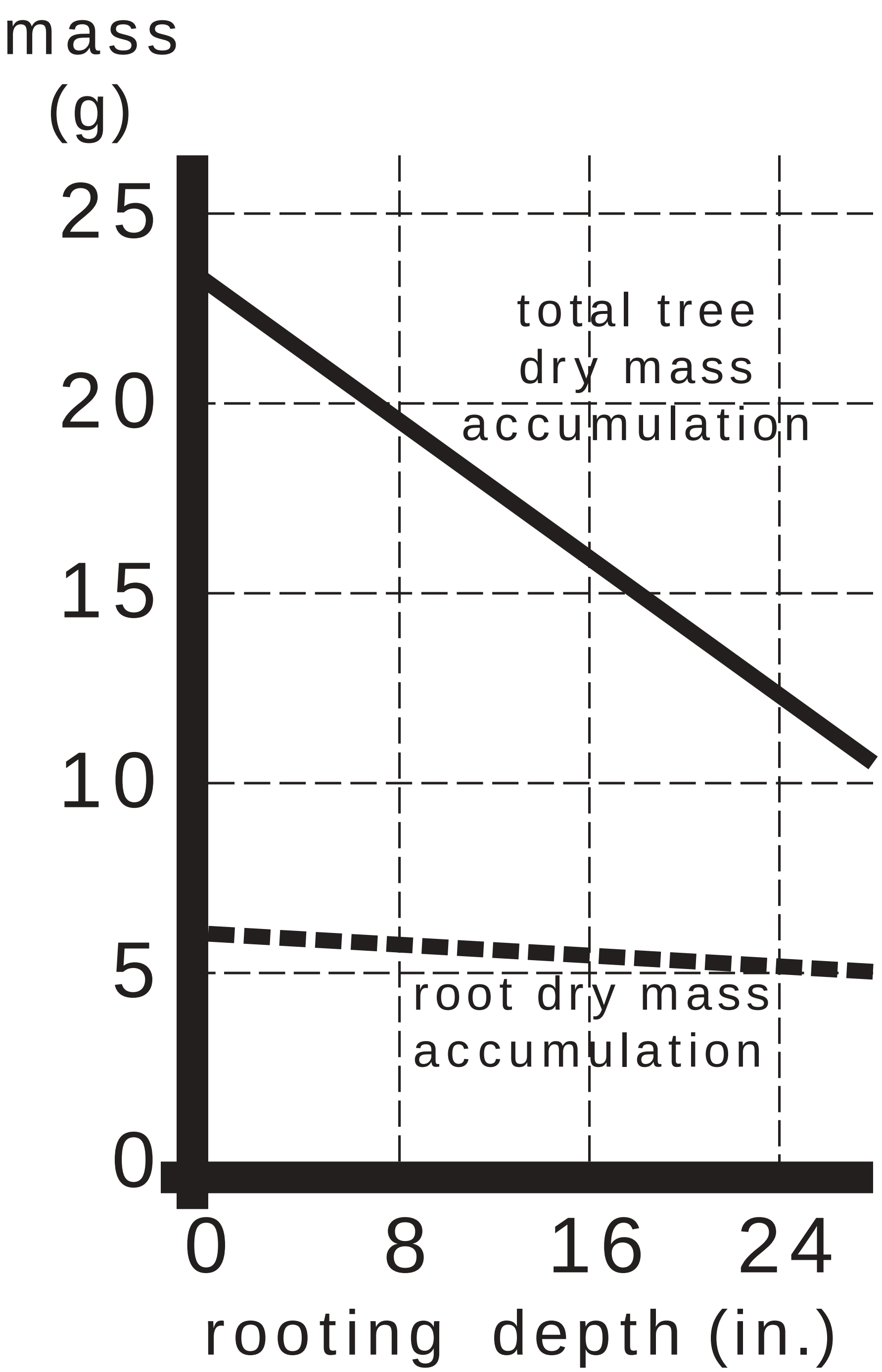


Figure 58: Accumulation of root and total tree dry mass across various rooting depths in young trees. (Korndorfer et.al. 2008).

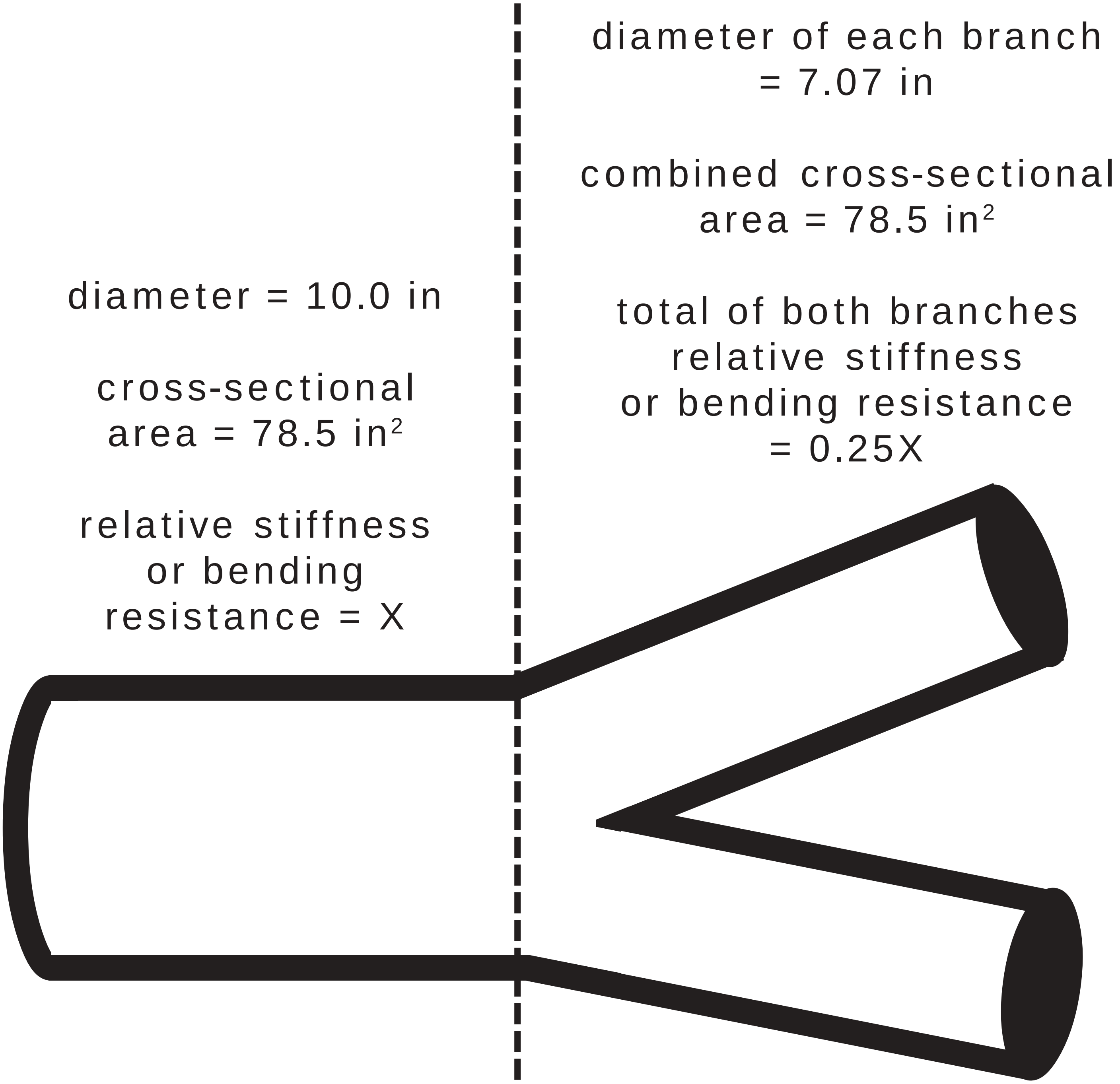


Figure 59: Example of how stiffness or bending resistance decreases greatly (-75%) along the length of a root at a branching point. The total cross-sectional area of the root remains the same before and after the branching point.

(Tobin et.al. 2007; Coutts et.al. 1999)

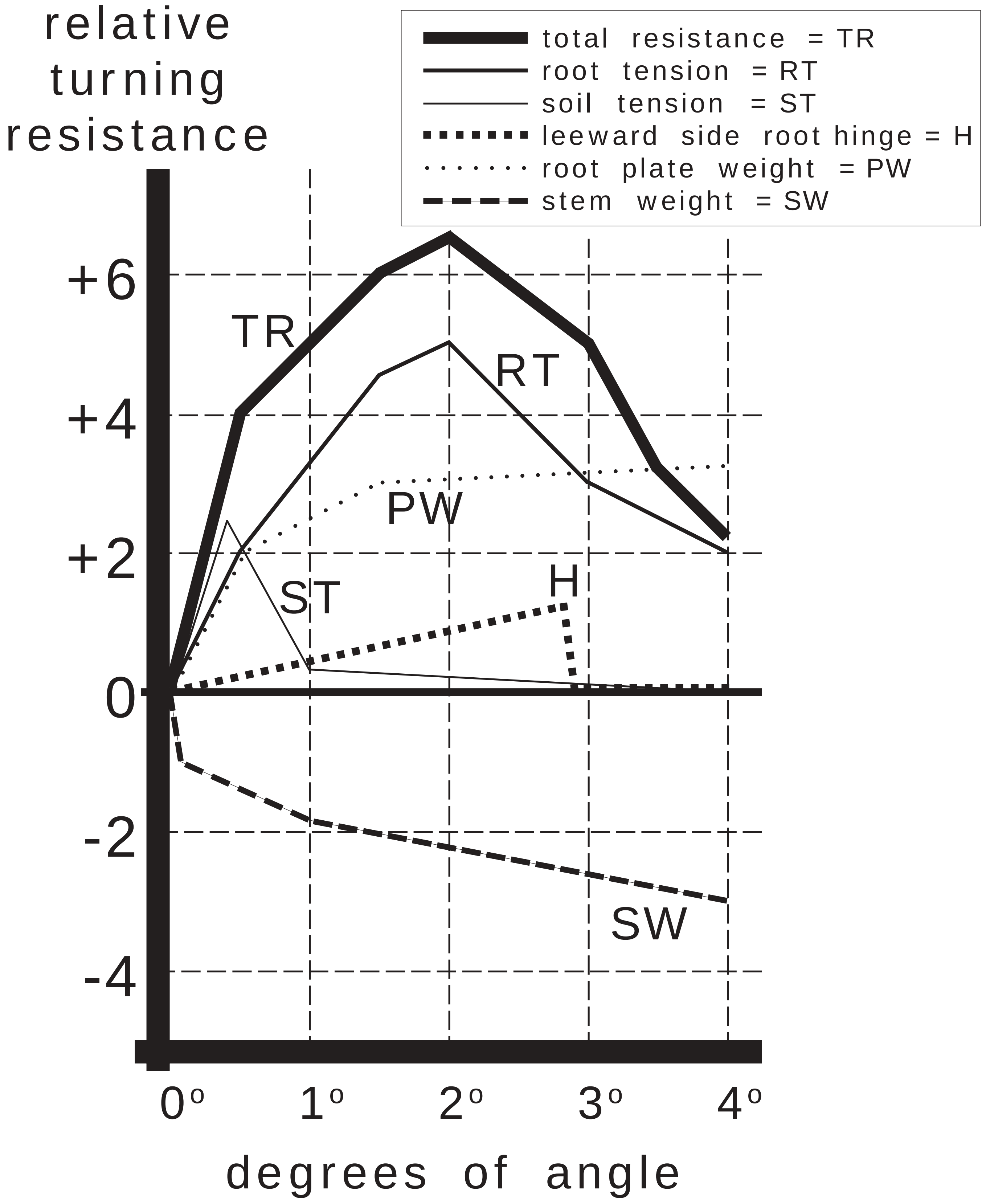


Figure 60: Model components of relative root resistance to turning by degrees of stem change.

(derived from England et al. 2000)