Lightning Damage Process & Risk Assessment in Trees

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Lightning and trees share a mythological connection centered around the forces of nature. Lightning strikes, thunder rolls, and trees stand (or fall) over many years. Tree damage from severe lightning strikes can be massive and terminal. Even small damage volumes in a tree are susceptible to attack by secondary pests, like bark beetles, leading to tree death. Dehydration, tissue disruption, heating, and bark loss can all lead to critical tree problems. This paper reviews tree lightning damage and its assessment from the standpoint of a tree health specialist.

Charge Exchanges

For lightning strikes between cloud and ground, the most critical tree interaction is the enhancement of the electrical field on the ground. A traditional construct of this field enhancement process following along the ground below storms has been termed *ground streamers*. Ground streamers are generated off the top of tall structures, like trees, by the standing wave of charge potential on the ground which peaks just before and just after the center of a storm. The ground streamers provide a charge exchange conduit which can connect with *cloud leaders* about 5-6 times the tree height above a tree. (Rokov & Uman 2003)

When the ground and cloud electric potential fields connect, charge exchanges occur at 1/3 the speed of light, spewing light and instantaneously heating the air. This lightning strike is composed of a number of individual high voltage / high amperage exchanges averaging three to four strokes per strike. The duration of a flash of lightning, including periods between individual strokes, is usually around one-half second. Because of rapid changes in air resistance, wind movement of ionized air, and the present location of the strongest ground streamer, various strokes within one lightning strike may not follow the same pathway.

Ground points exchanging charges in one lightning strike can be separated by as much as a mile, but are usually closely grouped. One tree can be struck by all the strokes in one lightning strike. At times, several trees in a row show damage from different strokes following different paths within one lightning strike. The same tree can be struck many times by lightning over many years. (Uman 1971,1987)

Physical Force

The electric charge exchanged in a lightning strike is highly variable. Average values for a strike are 100 million volts and 35,000 amps. The size of the lightning strike core ranges from 1/5 to 1/2 inch in diameter surrounded with an ionized, glowing envelope of air 4-6 inches in diameter, and a bright light corona of 1-5 feet in diameter. Temperature at the core of a strike can be greater than 50,000^{o}F. (Uman 1971; Few 1995; MacGorman. & Rust 1998) Figure 1. The near instantaneous heating of the air in the lightning core to such extreme temperatures initiates a supersonic shockwave (~10X the speed of sound).

The force of this strong shock wave is applied perpendicular to, and over the top of, tree tissues. This explosive force can be greater than 40 atmospheres of pressure over distances of less than 1/5 inch. Figure 2.

Rapid air expansion quickly slows and generates an acoustic wave heard as thunder after about 2 inches. Figure 3. (Few 1995; MacGorman & Rust 1998). Other direct impacts of lightning on a tree include heat developed from resistive heating in tissues and associated tissue disruption from micro steam explosions. The strong shock wave in the air represents about 10 times more tree damaging energy than tissue heating and steam expansion.

When the charge exchange pathway is opened, energy is dissipated across the ground surface and downward into the ground. The soil surface and tree roots channel large voltages. The grounding process is comprised of soil water and atmosphere components chemically capturing energy and quickly diluting charge intensity. Lightning energy is converted to heat, temporarily held by various atoms, or permanently associated with higher energy chemical bonds in the soil.

Tree Lightning Strikes

Storm clouds with the right internal conditions can generate large electric field potentials. When and where the cloud leaders and ground streamers connect to generate lightning is impossible to predict. The strength of ground streamers (ground field enhancement) can be estimated based upon the height and position of different objects on the ground. Tree lightning damage risk assessments concentrate on ground streamer strength.

Examining probabilities of any one tree falling along a lightning strike path requires a set of assumptions, most derived from research on free-standing communication towers. A simple tree lightning strike probability formula used here is from Bazelyan & Raizer, 2000. (Coder 2001c). The basis of a tree being struck by lightning depends upon historic lightning strike density in the area, height of a tree, and the presence of any surrounding tall objects close to a tree.

Figure 4 provides the historic number of lightning strikes per square mile per year expected for any area in the Southeastern United States—a lightning strike density map. Lightning strike density maps are available for most areas on Earth. Table 1 lists the number of years between lightning strikes on a single tree of a given height above its surroundings under a specific lightning strike density, as given in Figure 4. The formula used to determine strike probabilities in Table 1 is:

$$\text{Number of Years Between Lightning Strikes} = \frac{1}{(\text{N mile}^2 \text{ per year}) \text{ X } (3.142) \text{ X } [(((\text{HT feet}) \text{ X } (3)) / (5{,}280))^2]}$$

N mile^2 per year = Number of lightning strikes per square mile per year from Figure 4.
HT feet = Tree height in feet above its surroundings.

Note Table 1 values in years have been rounded or truncated to provide a whole number. The annual probability of a tree being struck by lightning is given by the following formula, the inverse (1/X) of the number of years between lightning strikes as given in Table 1:

Annual Probability of a Lightning Strike =

$$(\text{N mile}^2 \text{ per year}) \times (3.142) \times [(((\text{HT feet}) \times (3)) / (5{,}280))^2]$$

N mile^2 per year = Number of lightning strikes per square mile per year from Figure 4.
HT feet = Tree height in feet above its surroundings.

For example from Table 1, if Figure 4 shows the number of ground strikes per square mile per year as 15, and tree height above its surroundings as 60 feet, then the estimated number of years between strikes to a tree would be 18 years. The inverse of 18 is the annual probability of a lightning strike on the tree, or 0.056 (5.6% per year).

Remember strike probabilities in Table 1 are based upon an estimate of lightning attraction by ground field enhancement effects and a highly summarized map of historic lightning ground strike data. Table 1 is intended to help tree professionals understand lightning strike probabilities on trees of various heights above their surroundings. These probabilities are a rough estimate of dynamic natural events. Use of this information can assist tree health care professionals decide if lightning protection systems would be appropriate and cost-effective for a tree in a given position in the landscape. (Coder 2001c)

Grounding

When lightning strikes a tree, the grounding volume needed beneath the tree in the soil is proportional to the energy of the strike. The voltage surge in the soil around the tree base can be large, and can be significant a long distance from the tree (>500 feet). Energy dissipated in the grounding process can cause serious tree root damage.

To calculate the voltage at any place along the ground surface away from a tree lightning strike, the following formula can be used: (Bazelyan & Raizer, 2000)

Voltage Change Along the Ground =

$$[(\text{kAmp} \times \text{SRst}) / (6.283)] \times [(1 / D) - (1 / (D + 1)]^2$$

kAmp = current of lightning strike
SRst = soil resistance in ohms
D = radial distance to tree of closest ground contact

Soils and site attributes, especially moisture contents, are highly variable and constantly changing beneath a tree. Given the great variability in lightning strike grounding beneath a tree, no calculated value can accurately represent an individual strike. Using the formula above, tree professionals can better understand the magnitude of lightning energy as it interacts with the tree roots and soil. Table 2 & Table 3 were generated by using the formula above, and provide an estimate of voltage values which could be encountered near a tree lightning strike. (Coder 2001 a)

Table 2 shows the voltage passing between two ground contacts separated by one foot (30,000amp lightning strike and 25 ohms soil resistance). For example from Table 2, the voltage across ground contacts one foot apart at the soil surface, 50 feet from the tree lightning strike, would be approximately 2,000 volts. At 500 feet from the tree lightning strike, the voltage across ground contacts one foot apart at the soil surface would be 240 volts.

In human terms, a person standing with one side toward a tree lightning strike and with feet one foot apart would feel an induced current flow through their legs of 240 volts if they were 500 feet away. This would cause the person to collapse on the ground. In tree terms, the energy moving through the rooting area of a tree is large. Trees are damaged through interactions of root grafting, fine absorbing root distribution, and root contact points with other materials in the soil. Lightning energy is dissipated along many soil paths.

Table 3 provides approximate voltage passing between two ground contacts at some distance (in feet) along a radial line from a tree lightning strike (30,000 amps) and separated by one foot (1 ft.) for a number of different soil resistance values (ohms). Soil resistance values vary with a number of physical and chemical features of the soil including organic matter content, soil texture, and water content. For example from Table 3, at 10 feet away from the tree lightning strike and with a soil resistance value of 200 ohms, ground contacts one feet apart would differ by 87,000 volts. Especially close to the tree, the energy moving through the rooting area of a tree is immense. As soil resistance climbs, the energy surge through the soil reaches out to much greater distances. (Coder 2001a)

Damage Process

Trees are damaged by several events during a lightning strike. (Uman 1971,1987; Taylor 1977; Coder 2001b) A direct strike can electrically disrupt the most vigorous areas of a tree. Heat generated from the strike (resistance heating), and the shock wave impacts the wood and bark, can disrupt intercellular connections. The explosive shock wave radiating from the lightning core pounds against the tree stem, loosening bark and slabs of wood. Large sections of bark can be ripped away all over the tree. Bark damage from lightning allows rapid water loss. Trees quickly react to damage but have few tools to stop water loss along large longitudinal injuries. A lightning damaged tree is also an open invitation to many pests, like bark beetles.

Unseen damage from disrupted cell connections lead to localized tissue death and compartmentalization from twig to root. Roots of the tree can sustain massive damage, especially in soils with large electrical resistances. Root bark can be blown out of the ground. Lightning-caused root damage is one of the hardest type of mechanical disruption to diagnosis in trees. Groups of trees have died due to one lightning strike because of massive root damage.

Depending upon the state of the tree (active/dormant) and time of year (summer/winter), extensive damage can occur from a lightning strike. Because of the variability in lightning strike current, stroke number, residual current, polarity, and grounding conditions, each tree and each site will be affected differently by each lightning strike. Tree damage mirrors the strength of the charge exchange and the structural components of the tree. (Coder 2001b)

Most trees along the lightning discharge path are not killed. More than 20% of trees along a lightning path carry no visible external signs of past strikes. Trees presenting no visible sign of lightning damage can still be prone to decline and weakness which present inadequate defenses to pest attacks. Most people recognize tree lightning strikes by the long bark or wood strips, or bark sheets, removed from a tree. (Taylor 1977)

Observations

Over the years many professional observers and researchers have examined lightning struck trees (notably A. Taylor, 1977). Some of these key observations are critical in developing a better understanding of the tree damage process. Observers found most scars follow the longitudinal axis of the xylem grain. Because xylem grain orientation develops due to unequal loading across the crown (torque/twist), and many trees do not have perfectly balanced crowns, unequal wind forces tend to lead to xylem grain which spirals down the stem. Lightning scars tend to follow longitudinal pattern of xylem elements, whether straight or spiral grained. Electrical movement along the grain offers the least initial resistance within the tree.

Most (80%) lightning scars on trees are shallow and continuous between a point at least 80% of the tree height above the ground to within several feet of the tree base, unless the lightning path jumped (side-flashed) to another object. Of the trees with lightning scars, about 10% have more than one scar. In approximately 9% of lightning struck trees, various portions of the tree crown are killed or blown out. In 1% of tree lightning strikes, large areas of the above ground portion of the tree were severely deconstructed and torn apart. A trend was observed of different lightning damage forms occurring in trees with different annual increment structures. Ring-porus *and thick-barked* trees tended toward narrow injuries and diffuse porus *and thin-barked* trees tended toward ragged, wide spread damage. (Taylor 1977)

The cause of tree structural damage is derived primarily from a short distance, short duration, intense, strong shock wave radiating from the lightning core. Additional structural damage is caused by green tissues being superheated and steam venting. The latter is a significant cause of root damage. An interesting observation from tree lightning strikes was the presence of a thin, narrow line of collapsed phloem tissue remaining attached to the center of the strike wound even under unbroken bark. (Taylor 1977) This "line" of tissue is generated by pressure-caused adhesion from an external explosive force directed inward. (Coder 2001b)

Tree Strike Path

Tree tissues all have highly variable resistances to energy movement. Unfortunately, tissue resistance is only important in the first few moments (1-4 micro-seconds) of a charge exchange until the massive current blasts through. These first few moments of pathway development set the stage for leading the damage path. In the outer twigs and branches of a tree, which have a high percent of sapwood and thin bark, the charge path tends to move internally. As current load quickly builds, the internal pathway cannot sustain current and a “flash over” to the surface begins.

The flash-over point is usually around 80% of the tree height. Branches and twigs above this point in the tree, if along the charge exchange path, will have massive electrical disruption of cells, heating, burning, and structural disruption which can lead to severe damage and death. Branch and twig death around the outside of a crown (stag-heading) is a direct result of internal current flow. Alternatively, the lightning exchange path can occur over the exterior of the crown leaving only a few leaves injured. (Taylor 1977)

It is important to understand that moisture on the bark surface does not modify the charge exchange path. Precipitation and tree surface moisture changes have little effect on the electrical resistance of tree surfaces. The charge exchange path develops along the internal grain pattern of the tree, not along the rain-wetted bark surfaces. The bark surface has a high resistance to electrical movement compared with internal living tissue.

Leaf surfaces and buds have extremely high electrical resistances. See Figure 5. The small scale measures of tissue resistance include a perimeter of leaves which can have as much as a 25,000 ohm resistance. As tree tissues are measured farther down the tree, the large resistances of the crown edge quickly diminish. On average, tree electrical resistance is reduced at least 15 ohms for every foot of large branch and stem pathway descended toward the ground after passing the twigs and leaves.

The least electrically resistant of tree tissues are phloem and cambial xylem-initial cells just below the bark. As the current quickly builds, the electrical pathway reaches capacity and a surface flash-over occurs through to the bark surface. Because the initial pathway is imbedded within the xylem initials and phloem, the charge exchange path follows the grain of the xylem.

As surface flash-over builds, any cellular spaces near the xylem initials and phloem cells are subjected to great forces of heating and cellular disruption. The surface flash-over is still connected through the bark to the under-bark portion of the charge exchange. The surface flash-over generates a shock wave from atmospheric heating that pounds against the bark surface. This shock wave is a focused compression on the bark and into the wood, followed by a tension wave rebounding from the tree center and moving around its perimeter. Resistive heating forces and any steam venting in the internal tissues are pushed to either side beneath the focused shock wave center.

Mythology suggested resistance heated water being turned to steam was the primary force in damaging trees. In living tree tissues the water contents are large. Super heating water instantaneously (<5 micro-seconds) does cause a narrow line of steam expansion in the intercellular spaces and moist tissues. The surrounding water jacket in tissues rapidly dissipates any heat load. The energy of steam explosions and super heated air in open intercellular spaces does not generate enough force to present the damage seen in lightning struck trees. If damage from this source does occur, it is very narrowly confined with tree tissues. Large circumferential damage of bark, and the extent and pattern of the debris field after a lightning strike is difficult to explain if steam expansion alone was the mechanical damaging agent.

The shock wave generated along the thin core of the charge exchange path produces hundreds of pounds of force per square inch over a short distance (1/5 inch). The range of energy expended can be greater than 600 pounds of force per square inch, or 40 atmospheres of pressure. Not all of this force is focused on the tree, but a significant portion impacts the tree branches and stem. The reflection (rebound) of this compression wave is a tension wave which tears tissues apart.

The explosive shock wave generates a physical deformation wave on the stem surface which first compresses and then pulls upon the bark, potentially shearing off bark connections from the rest of the tree. Old-knotty heartwood cores, cavities, longitudinal faults, and well-developed compartment lines can lead to internalization of current flow and associated shock-wave. Internally this can represent an additional explosive force.

The most visible result of this strong shock wave is the splitting of the bark and wood along annual increments and ray cells directly beneath the charge exchange path caused by an energetic rebound of woody materials in reaction to the shock wave. The shock wave shears-off cellular connections, pulls fibers apart, and loosens bark-phloem, phloem-cambial, cambial-xylem, and xylem growth increment connections. Multiple strokes in a single lightning strike can generate multiple shock waves. (Taylor 1977)

The strong shock waves bounce off the inside of the tree, move through the tree, and move around the circumference of the tree. Because of the high moisture content inside the tree, the shock wave can be thought of as similar to a person slapping a watermelon and feeling the reverberations within. The time pulse for this shock wave is extremely short given its intensity.

Damage Pattern

A lightning strike and associated damage to a tree usually follow a specific pattern. Figure 6. This pattern can be divided into three main sections and eight sub-sections. First, the current front begins to build in the phloem and xylem cambium-initials, with some tissue heating and disruption of intercellular connections. Second, most of the current flow breaks out to the bark surface (termed a surface flash-over). Third, an intense explosive pressure wave is generated from the lightning core focused on a narrow portion of the bark and wood, pounding against the branches and stem. Fourth, the high intensity shockwave first compresses the bark and wood toward the center of the tree with a circumference surface compression wave moving around the tree. Fifth, the tree tissues are then subjected to tension forces as the shockwave rebounds in the tree.

The sixth step of the damage pattern is due to the shockwave impacts—cells and tissues begins to separate and lose contact. Wood and bark split. Tissue interconnections are shattered, leading to internal and external injuries. Seventh, the compression and tension portions of the shockwave in the tree lead to annual ring separations, breakage along old compartment lines, loosening of bark and wood pieces, and the propelling of loose tissue pieces away from the tree. A lightning strike debris filed is generated. Eighth, mechanical stress and strain are focused on existing structural faults, injury modified wood, open spaces, gaps, cavities, drill holes, imbedded metal objects, and insect galleries. The stress and strain of the shockwave concentrates force along the edges of faults leading to additional fiber separations. The tree is torn apart along natural compartmentalization boundaries and opened to the environment. Figure 6.

Tree Differences

Key historic observations of lightning damage to a variety of trees included recognition of a difference between thin and thick-barked trees, ring and diffuse porus trees, and the associated stem architecture-based extent of tree damage. Due to internal tree structure and the current level needed to attain flash-over, some tree attributes lead to different types of damage. (Taylor 1977)

Figure 7 shows the strength of different tree structural types under compression and in tension. The ability to sustain stress and strain from both impact and rebound from the lightning core shockwave is partially based upon living wood strength. Different species of trees can handle different internal forces better than others. Most ring porus trees can handle quite large pressures in both compression and in tension. Many diffuse porus trees are more easily damaged by shockwave initiated forces. Conifers handle compressive forces well, but not tension forces.

Bark has been cited as mirroring damage types. Thin-barked trees tend to have damage which is shallow and wide, while thick-barked trees tend to have damage that is relatively deep and narrow. Thin-barked trees, and trees with diffuse porous xylem architecture, usually sustain little deep damage from lightning strikes. Thin barked trees with smooth, flat bark quickly allow surface flash-over and present little deep damage in stem tissues. Because of the shock wave radiating around the stem, large patches or sheets of bark can be loosened or pushed-off. Figure 8. (Rakov & Uman 2003; Uman 1971; Taylor 1977)

In thick-barked trees, and trees with ring porous xylem architecture, the damage can be deep into the sapwood with narrow portions of bark and wood being pushed off the tree. Thick barked species more commonly show lightning damage than thin barked species and tend to have one or two narrow spiraling lines of damage. The center line of these narrow injuries can be a thin compressed line of phloem tissues, or a radial crack moving into the wood. The radial crack can range in depth of less than one growth increment to more than four growth increments. The width of these injuries can range from 3-10 inches wide. Figure 9. (Taylor 1977)

Bark and several layers of xylem (slabs) can be blown off from the injury. Figure 10. The thickness of the wood loss depends upon the depth of the radial crack. Many times the pieces (slabs) pushed off the tree will be approximately one-half the width of the whole injury. In other words, the wood and bark slabs loosened or blown off the tree will be of various longitudinal lengths with the horizontal widths comprised of two halves. In some instances, the radial crack is present and a ring separation has occurred in the sapwood, but the wood was not blown away from the tree. (Taylor 1977)

Bark on roots, stems, and twigs of the same tree are different from one another due to weathering, compression, thickness, and age. New thin bark on juvenile twigs can be on the same tree which has coarse, thick, corky bark on the mature stem. Historic field observations of damage types related to bark type integrate many types and levels of observations into a single trait. It is clear that many tree features influence portions of the ground streamer strength (field enhancement) and charge exchange path.

Strike Symptoms

Twigs and branches where the current moves internally until surface flash over (approximately the top 20% of tree height), can be disrupted and damaged enough to lead to decline or death. This stagheading or partial crown mortality is a common symptom of a lightning strike. Stem openings, cavities, or open insect galleries can concentrate forces which tear tissues apart. Root damage and death are much more difficult to diagnosis. Branches may wilt and decline because of root damage. Roots killed in the grounding process can lead to later wind-throw because of loss of soil contact.

Pests are a secondary problem attacking through physical injuries and attracted by volatile materials released to the air from the wound site and from the debris field. A good example is pine. It is estimated that 31% of all pine beetle spots in the Southeastern United States are due to a lightning strike at a center tree. A lightning strike to a pine can throw a debris shower up to 150 feet, exposing the tree to attack and scattering wood, bark, and resin particles across a site. This lightning debris field is a large biological attractant area for many pests. Because of internal gaps and fiber separations, pine pitching (resin exudate production) is reduced. Internal changes within the tree to prepare defensive materials reduces supplies of growth materials.

Many trees are not visibly damaged by a lightning strike. It is difficult to ascertain if a tree has been struck if no injury is seen. Better sensing and measurement systems are required. Years after a lightning strike, a “lightning ring” may be seen as a defensive boundary among the xylem growth increments. These increment rings are similar to false rings generated by drought, pests, and floods except for the defensive chemicals deposited throughout the cell walls. A shock wave from the lightning strike initiates a standard compartmentalization defense in and around the broken tissue connections and separated tissues layers. The cambium and ray cells set compartment lines around the electric current flow pathways. Dead and damaged cells at the site of the injury are sealed off.

Narrow spiral injuries seen at the stem surface are not usually girdling. Because of crown dynamics in the wind, and tree attempts to adjust for torque (twist), the fiber orientation (grain) in the stem may be at some angle to the longitudinal axis of the stem. This spiral grain can be followed by the charge exchange pathway initially, leaving a spiral injury. Many vascular connections are still intact and function normally. If less than 25% of the circumference is damaged, around the cross-section of the stem, defensive capabilities and resource transport means should remain viable in the tree. (Taylor 1977)

The symptoms of a lightning strike on a tree begin with a disruption and reduction in the water movement capacity of the tree. In addition, resin flow is greatly reduced in species with standing resin systems. Chemical defensive compounds are rapidly generated and/or moved requiring significant reallocation of growth materials. Permanent leaf wilting on a single major branch is usually the first noticeable symptom of a lightning strike if the tree was not clearly blown apart or killed. Another form of damage is a recoverable foliage wilting that comes and goes over several months, sometimes leading to eventual twig death. This process of sense and correction within the tree provides bark-resident pathogens avenues to effectively attack. The least noticeable symptom is a slow decline of a branch or tree over 1-3 years with various pest and site constraints limiting new growth processes. (Taylor 1977)

Fire!

Approximately 12,000 fires per year are lightning initiated in the United States. Ignition is usually at the base of a tree where other fine fuels are available. A constant current during a lightning strike between individual strokes can be between 100-400 amps. This constant current provides enough energy input and contact duration for the sustained heating needed for ignition. Approximately 20% of all lightning strikes have this constant current. A majority of lightning strikes on trees do not cause sustainable ignition as the shock wave blows fuels and heated surfaces apart. Many charred fine particles can be found in lightning strike debris fields, but are not usually sites of ignition for other fuels. (Taylor 1977)

Groups of Trees

Regardless of how we focus and concentrate our field and analytical views onto a single tree with a single strike, lightning-initiated damage and death of groups of trees also demand attention. Orchards, especially in high resistance soil areas, have been decimated by single strikes. In most group strikes, only one or two trees in the center may show visible above-ground injuries. Root damage from grounding impacts is the causal agent of death. (Taylor 1977)

Therapeutics

Preparation, risk reduction, and installing conductance systems in trees before a lightning strike is the best way to minimize damages. Once injured, time is of critical importance. The faster treatments are commenced, the better the biological results. Starting treatment processes within 8-24 hours, especially if little drying of tissues has occurred, can provide a window of treatment for watering, preventing water loss, and using pressure to reattach tissues. After 16-36 hours, compartmentalization processes have been initiated and reinvigoration actions to the whole tree will be more appropriate.

Due to site, tree, and injury differences, no specific treatment procedure can be defined. General best management practices (BMPs) should include the following considerations. If the tree will survive, consider if a tree lightning protection system is warranted. Next, water must be a critical consideration. Institute a specially targeted and zoned watering/irrigation program for at least one and one-half growing seasons, if drainage can be assured. Install crown misting and wind protection for one full growing season in areas with low humidities and areas sustaining large advected heat loads.

For loosened bark and wood, consider use of a pressure belt. Use of belts and surface pressure to pull/push slightly displaced tissues back into near original position for six weeks. Cover the area with a temporary covering. Apply white plastic sheeting over injuries to minimize water loss for four weeks. Pruning paints can be used to hide the wound but do little to assist in recovery. Remove clearly dead and seriously damaged branches. Do not over-prune. Delay green-wood pruning until tree allocation priorities are clear. Remove and clean up shattered tissues. Do not scribe or cut into living tissue.

Apply preventative pesticides to open surfaces, if needed. Be sure pesticides and their carriers do not damage new parenchyma cells generated on xylem surfaces. Delay any nitrogen fertilization one season. Protect soil surface and soil health across the tree's rooting system area including use of light mulch and small amounts of composted organic matter.

Lightning Strike Risk Assessment

A critical component of tree risk management is assessing whether a lightning protection system is needed. There are a number of tree and site attributes which can change risk values for trees being struck by lightning. Assessed risk values primarily concern historic lightning strike density and various aspects of ground streamer strength (ground field enhancement). (Coder 2001d)

Ground streamer strength is based upon many factors which can be increased to a point where any cloud leaders in the area will connect and exchange charges. Topographic position and height above surrounding objects or structures play crucial roles in determining where lightning will strike. Isolated, tall trees would have the potential for strong ground streamer strength and serve as a conduit of charge exchange exceeding simple random probabilities. Trees along the path of potential lightning strikes, where risk is based upon ground streamer strength factors, should be evaluated.

A quick risk analysis process is presented here. (Coder 2001d). It is based upon an educational summary of lightning risk factors in trees and should not be used as a single source in determining lightning protection requirements for trees. This risk assessment uses a number of lightning strike risk factors (i.e. ground streamer strength factors) associated with trees. Tree height, relative height of the tree within its surroundings, location on the land, closeness of neighboring trees and structures, and historic number of ground strikes per square mile per year are all incorporated. The result is a simple assessment for determining if a lightning protection system is warranted. It does not (can not) include tree values or benefit/cost analysis. This assessment can be used as a training guide for determining the potential lightning strike probabilities on trees. (based upon Robert E. Cripe's work, personal communications)

To use this assessment aid, you will need several pieces of information about the tree and site. An accurate tree height and neighboring structure height are essential. Use a clinometer, hand altimeter, or height stick with a 100 feet tape to record height measures.

Figure 11 represents risk factor #1, where the tree is located topographically in the landscape. Determine where on the landscape the tree is growing. Higher locations, compared with lower neighborhood surroundings are more likely to have strong ground streamer strengths. Large scale, landscape level positions which accentuate a tree’s effective height and ground streamer strength carry higher risks. Pick the risk percentage closest to the assessed tree's topographic location. For example, trees on hilltops will usually have stronger ground streamer strength than trees in valley bottoms. A risk percentage for the topographic position of the tree should be determined.

Figure 12 represents risk factor #2, the relative height of the tree crown compared with surrounding tree crowns. Classic crown class descriptions are used to determine if the assessed tree is taller (an emergent crown class) than its surrounding tree neighbors. The more the tree crown rises above neighboring trees, the stronger its ground streamer strength. Select the risk percentage closest to the assessed tree's crown class.

Figure 13 represents risk factor #3, tree crown openness or the view aspect of the tree toward open areas. Determine how open the tree crown is from the sides compared with other surrounding trees. Trees open to water, fields, large open spaces, or facing areas with vegetation significantly shorter in height, will leave the sides of their crowns open and more likely to produce strong ground streamers. Single trees standing alone are open on all sides and tend to have the strongest ground streamer strength. As neighboring trees close in on different sides, the openness risk factor declines. A risk percentage for the degree of tree openness should be determined.

Figure 14 represents risk factor #4, the relative height of other structures in the neighborhood. A direct measure of the single tallest structure or tree in the neighborhood is compared to the assessed tree. The neighborhood distance of a tree on the ground is a radius three times the assessed tree height (3 X tree height) away from the assessed tree. Within this neighborhood distance, calculate the relative height difference for the single tallest structure or tree. The taller the tree is in its neighborhood, the stronger its ground streamer strength. A risk percentage for how tall the assessed tree is compared to the tallest structure in the neighborhood should be determined.

Figure 15 represents risk factor #5, the proximity of human or property targets. When lightning strikes a tree, collateral damage can result. The closer and taller the assessed tree is to targets, the strong ground streamer of the tree may lead to other assets in the area being harmed. The risk of a tree lightning strike impacting structures, electronics, animals and humans in the vicinity is a major concern. A risk assessment must determine the spacial relationship between trees and these targets. The closer and taller the assessed tree is compared to a target, the stronger the ground streamer potential, and the more likely target damage and injuries (possibly death) will occur if lightning strikes. Structures surrounded by, or overhung with, tree branches should have their own lightning protection system. A risk percentage for targets close to the assessed tree should be determined.

Once the first five risk factors have been determined, the percentage numbers (not decimal percents) should be added together. The total sum should be divided by 500. The result is a decimal value called a Composite Risk Factor, since it combines and averages the first five risk factors together.

Figure 16 represents risk factor #6, the annual lightning strike probability. Different places across globe have different numbers of lightning strikes per square mile per year. The map displayed in Figure 16 represents the number of lightning strikes per square mile per year for the Southeastern United States. This map provides the lightning strike number used in the calculation for Risk Factor #6. The other value needed is the height of the tree. These two values are placed in the following formula:

Annual Lightning Strike Probability =

$$\text{lightning strike number from Figure 16 map} \ \times \ 3.142 \ \times \ [((\text{tree height in feet}) \ \times \ 3) \ / \ 5{,}280]^2$$

Figure 16 helps generate the Annual Lightning Strike Probability value representing a risk value for a single tree standing alone in a flat landscape with nothing taller in its neighborhood. An Annual Lightning Strike Probability risk factor should be determined.

The Composite Risk Factor (determined from Risk Factors #1 - #5) should be multiplied by the Annual Lightning Strike Probability (Risk Factor #6). The result is the Total Tree Lightning Strike Risk Value. Figure 17. If the Total Tree Lightning Strike Risk Value is greater than 0.05, then there is greater than a 1 in 20 chance a tree may be struck by lightning each year. This is considered a severe risk of tree damage. If the Total Tree Lightning Strike Risk Value is 0.01, a 1 in 100 chance exists a tree may be struck by lightning each year. This is considered a low risk.

Unfortunately this risk assessment does not include expected tree life-span, or historic or cultural values of the tree. A tree expected to live another 300 years, and culturally valuable, would have a much greater risk, and much higher remorse factor if lost, than this assessment tool would determine. A formal Tree Lightning Risk Assessment Worksheet example similar to Figure 17 is available immediately after this figure.

Conclusions

We cannot stop lightning from striking and damaging trees. Tree health care professionals can develop risk management systems that cost-effectively minimize tree damage, reduce collateral damage around the tree, and effectively conduct electrical charges between cloud and ground. Damage from lightning strikes to trees is a unique set of injuries stemming from tremendous physical forces. Although treatments are comparably minor in the face of lightning’s power, trees can be helped to survive and thrive through our actions.

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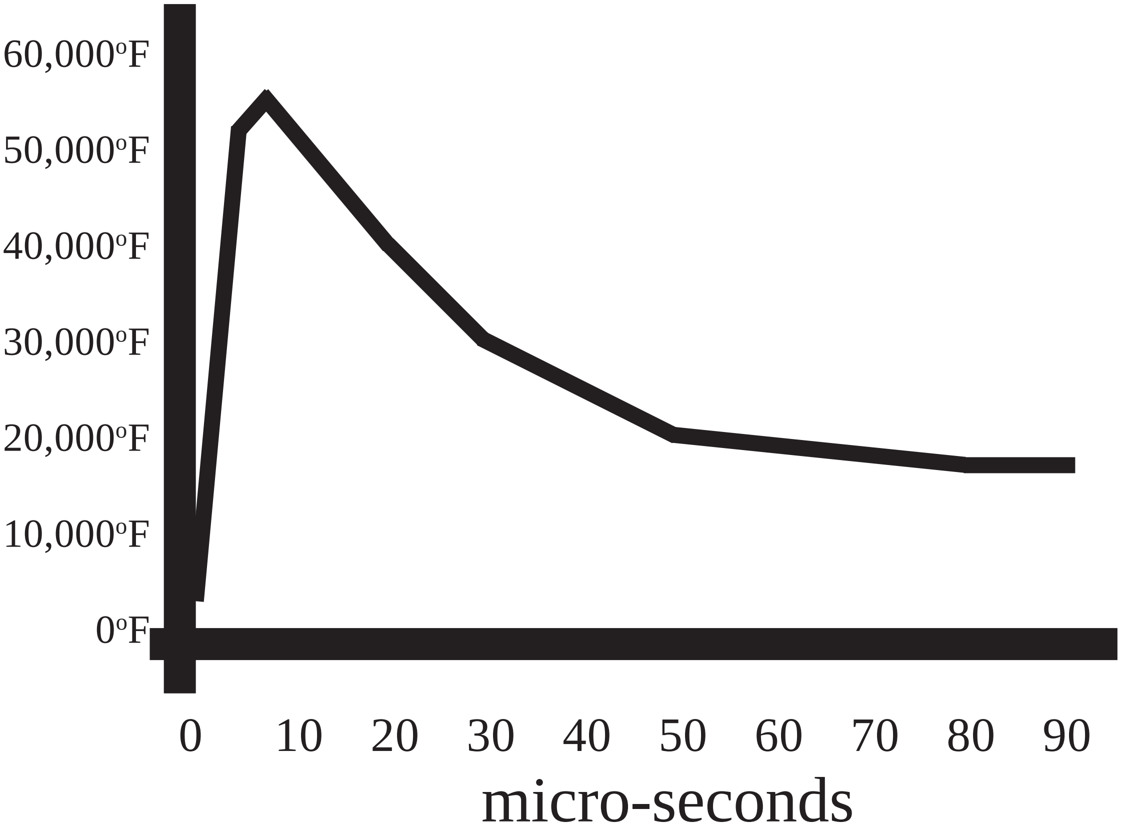
Figure 1: Lightning core temperature in degrees Fahrenheit (°F) over time in micro-seconds (millionths of a second).

(Few 1995; MacGorman. & Rust 1998; Uman 1971,1987)



(1 micro-second = 0.000,001 second)

Figure 2: Shock wave pressures, decaying into an acustic wave over time and space, spreading away from a lightning core. (derived from Few 1995; MacGorman. & Rust 1998)

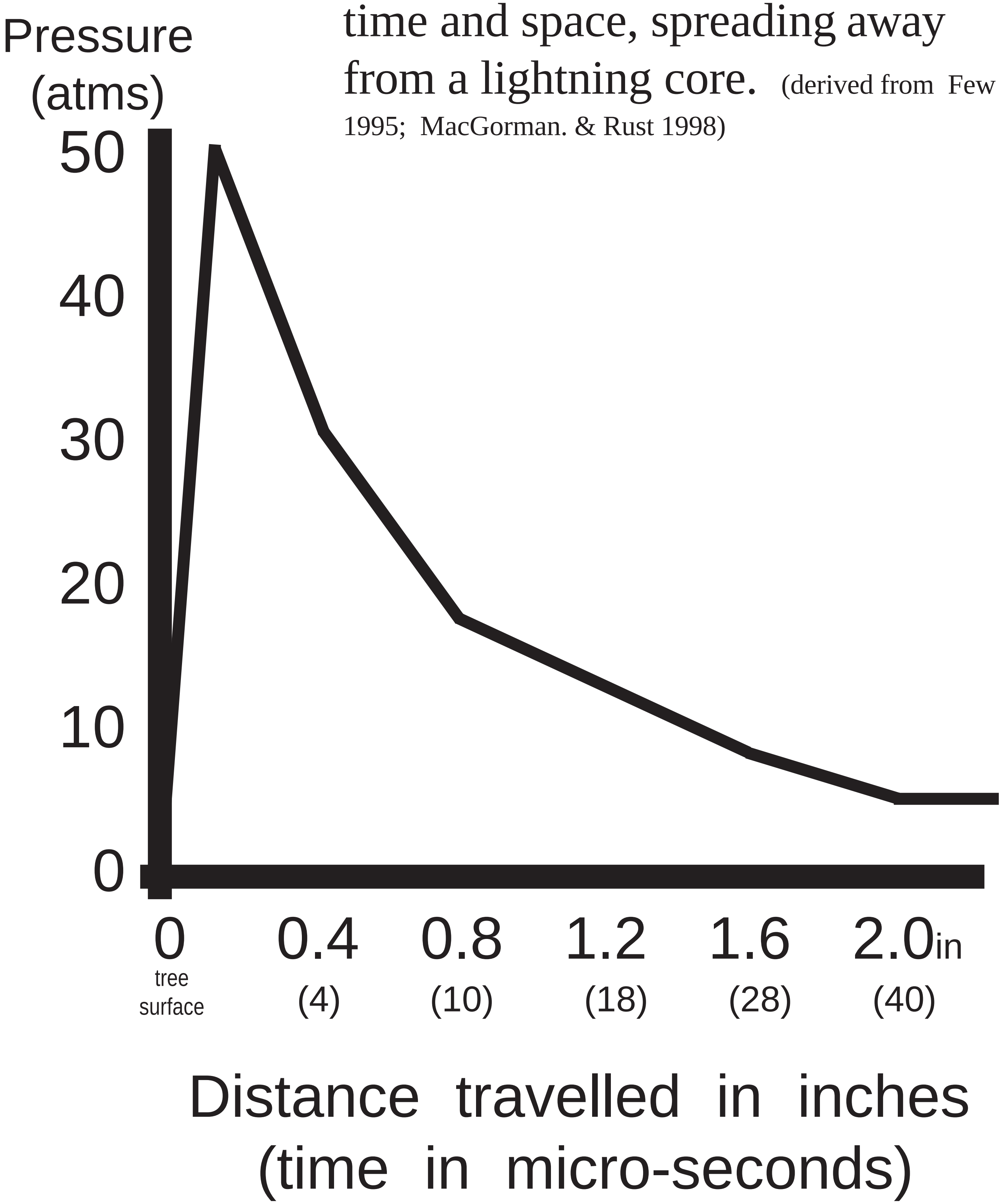
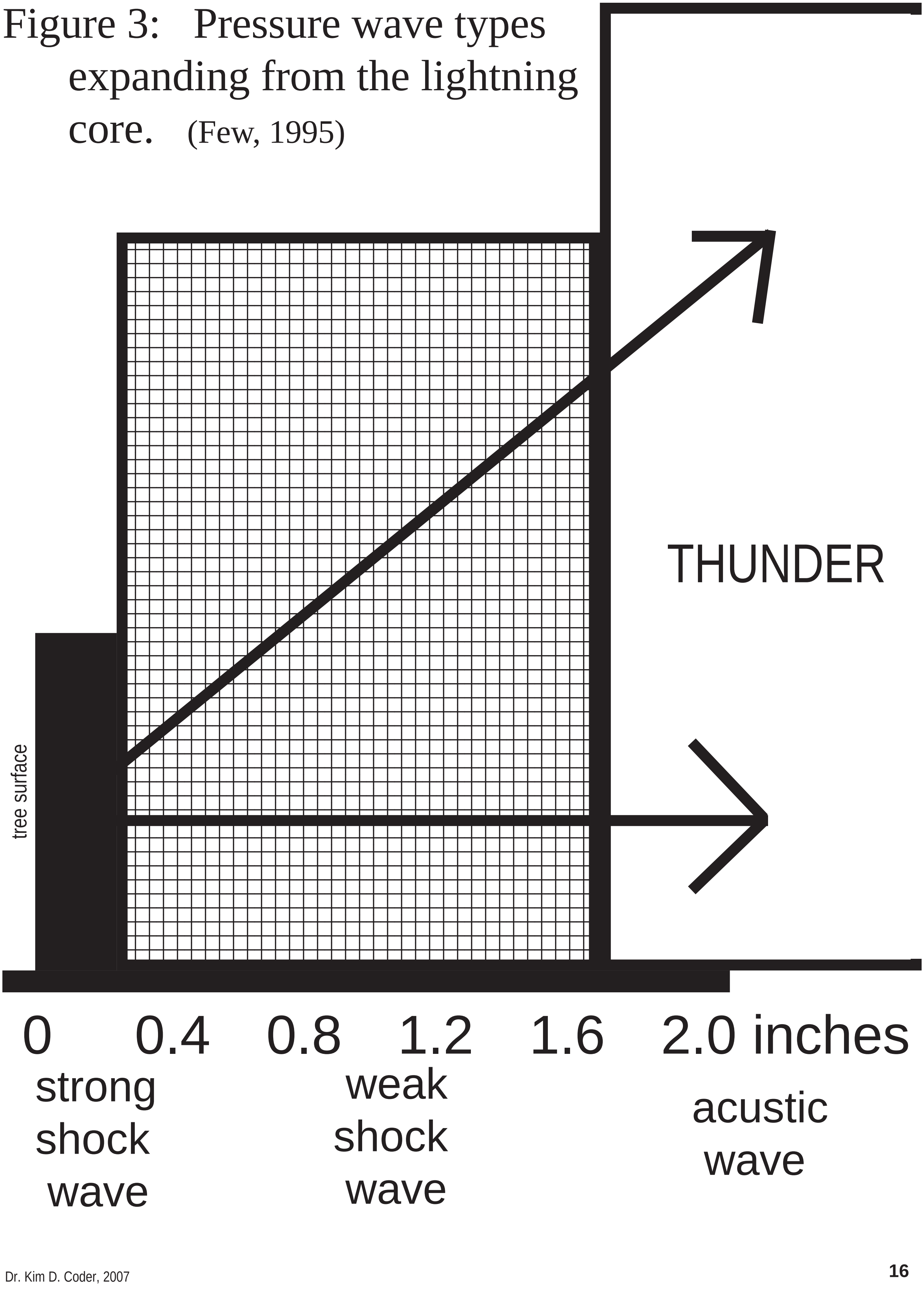


Figure 3: Pressure wave types expanding from the lightning core. (Few, 1995)



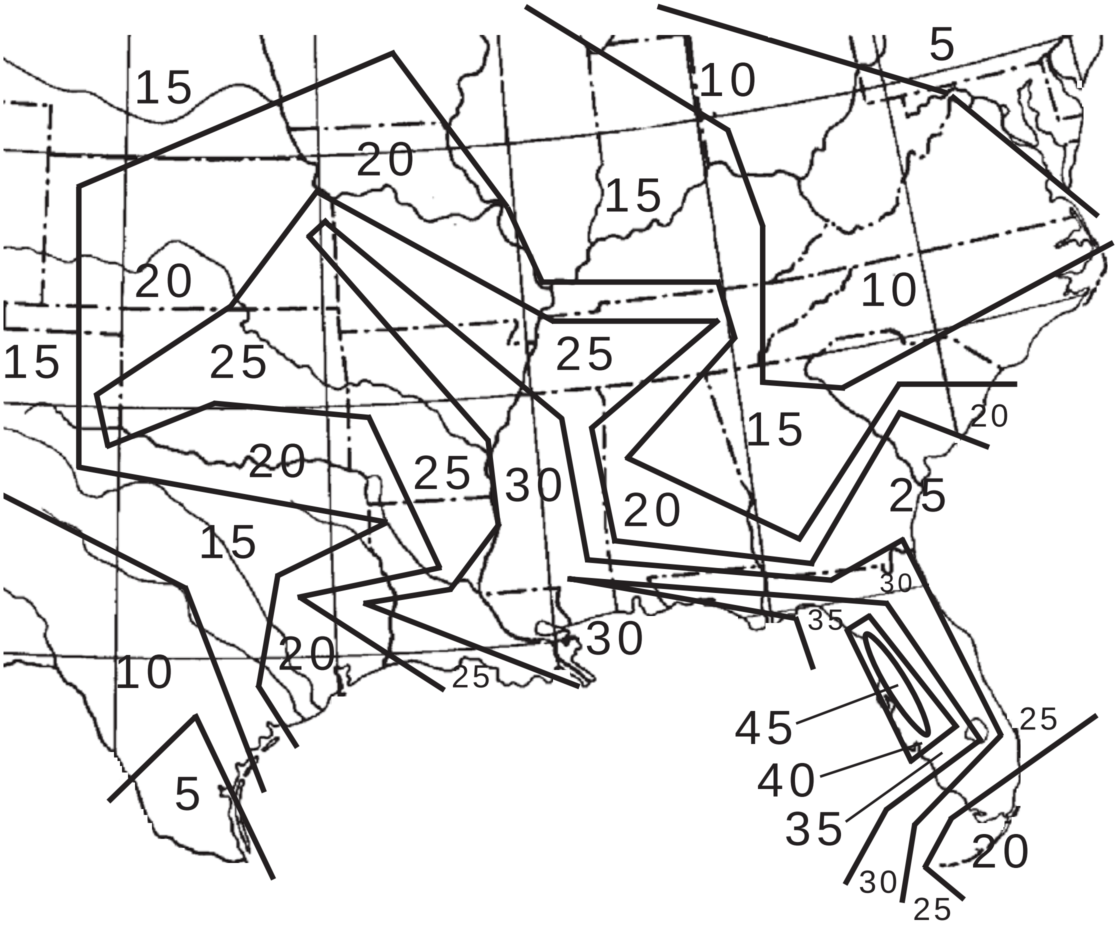


Figure 4: Average historic number of lightning strikes (ground strikes) per square mile per year for the Southeastern United States.

Table 1: Estimated number of years between a single lightning strike (ground strike) impacting a tree of a given height (in feet) standing by itself (i.e. no trees or structures within three tree heights in any direction), or for a tree of a given height above its surroundings, on a land area with a specified historic ground strike count per square mile per year as shown in Figure 4.
(Bazelyan & Raizer 2000)

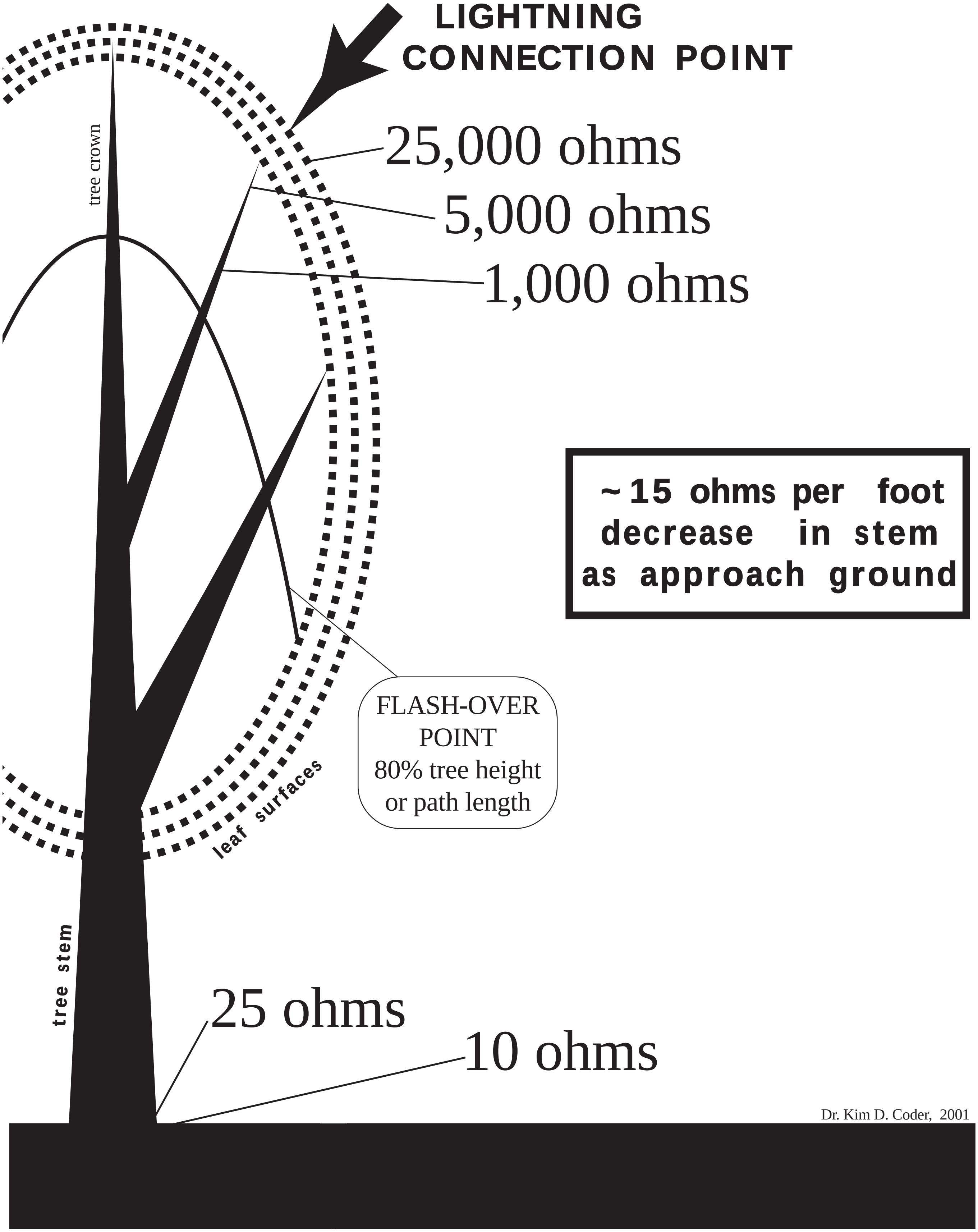
Tree Height (feet)	Number of Ground Strikes per square mile per year (from Figure 6)												
	1	2	5	10	15	20	25	30	35	40	45	50	55
5	10,000	10,000	8,000	4,000	2,500	2,000	1,500	1,300	1,100	1,000	900	800	700
10	10,000	5,000	2,000	1,000	650	500	394	328	281	246	219	197	179
15	4,000	2,000	900	438	292	219	175	146	125	109	97	87	79
20	2,500	1,200	500	246	164	123	98	82	70	61	54	49	44
25	1,500	800	315	157	105	78	63	52	45	39	35	31	28
30	1,000	550	219	109	73	54	43	36	31	27	24	21	19
35	800	402	160	80	53	40	32	26	22	20	17	16	14
40	600	308	123	61	41	30	24	20	17	15	13	12	11
45	500	243	97	48	32	24	19	16	13	12	10	9	8
50	394	197	78	39	26	19	15	13	11	9	8	7	7
55	325	162	65	32	21	16	13	10	9	8	7	6	5
60	273	136	54	27	18	13	10	9	7	6	6	5	4
65	233	116	46	23	15	11	9	7	6	5	5	4	4
70	201	100	40	20	13	10	8	6	5	5	4	4	3
75	175	87	35	17	11	8	7	5	5	4	3	3	3
80	154	77	30	15	10	7	6	5	4	3	3	3	2
85	136	68	27	13	9	6	5	4	3	3	3	2	2
90	121	60	24	12	8	6	4	4	3	3	2	2	2
95	109	54	21	10	7	5	4	3	3	2	2	2	1
100	98	49	19	9	6	4	3	3	2	2	2	1	1
110	81	40	16	8	5	4	3	2	2	2	1	1	1
120	68	34	13	6	4	3	2	2	1	1	1	1	1
130	58	29	11	5	3	2	2	1	1	1	1	1	1
140	50	25	10	5	3	2	2	1	1	1	1	1	1

Table 2: Approximate voltage passing between two ground contacts separated along a radial line by one foot (1 ft.) at some distance (in feet) from a tree struck by lightning (30,000amp lightning strike & 25 ohms soil resistance).
(Bazelyan & Raizer 2000)

Closest radial distance from tree stem (feet)	Approximate voltage across ground contacts separated by 1 ft. radially (volts)	Closest radial distance from tree stem (feet)	Approximate voltage across ground contacts separated by 1 ft. radially (volts)
1 ft.	89,000 volts	130 ft.	900 volts
2	46,000	140	850
3	32,000	150	800
4	25,000	160	750
5	20,000	170	700
6	17,000	180	650
7	15,000	190	625
8	13,000	200	500
9	12,000	250	475
10	10,000	300	395
15	7,000	350	340
20	5,000	400	300
25	4,000	450	265
30	3,000	500	240
35	3,000	550	215
40	2,000	600	200
45	2,000	650	185
50	2,000	700	170
60	1,000	750	160
70	1,000	800	150
80	1,000	900	132
90	1,000	1,000	120
100	1,000		
110	1,000		
120	1,000		

Table 3: Approximate voltage (in kilovolts (kV)) passing between two ground contacts at some distance (in feet) along a radial line from a tree lightning strike (30,000amps) and seperated by one foot (1 ft.) across various soil resistance measures (ohms). (Bazelyan & Raizer 2000)

closest radial distance from tree stem (feet)	soil electrical resistance measures (ohms)													
	25	50	75	100	125	150	175	200	225	250	275	300	350	400
1 ft.	89kV	179	268	358	447	537	626	716	805	895	984	1074	1253	1432
2	46	92	139	185	232	278	324	371	417	464	510	557	649	742
3	32	64	96	129	161	193	226	258	290	323	355	387	452	517
4	25	50	75	100	125	150	175	200	225	250	275	300	350	401
5	20	41	61	82	102	123	143	164	185	205	226	246	287	328
6	17	34	52	69	87	104	122	139	157	174	192	209	244	279
7	15	30	45	60	75	91	106	121	136	151	167	182	212	242
8	13	26	40	53	67	80	94	107	121	134	147	161	188	215
9	12	24	36	48	60	72	84	96	108	120	132	144	168	193
10	10	21	32	43	54	65	76	87	98	109	120	131	153	175
15	7	14	22	29	37	44	52	59	67	74	82	89	104	119
20	5	11	17	22	28	34	39	45	51	56	62	68	79	91
25	4	9	13	18	22	27	32	36	41	45	50	55	64	73
30	3	7	11	15	19	23	26	30	34	38	42	46	53	61
35	3	6	9	13	16	19	23	26	29	33	36	39	46	53
40	2	5	8	11	14	17	20	23	26	29	32	34	40	46
45	2	5	7	10	12	15	18	20	23	25	28	31	36	41
50	2	4	7	9	11	14	16	18	21	23	25	28	32	37



Dr. Kim D. Coder, 2001

Figure 5: Model-based tree resistance value estimates from leaf surface to the ground. (Defandorf 1956)

Figure 6: Typical tree lightning strike path pattern development.

steps -- observations

I LIGHTNING

1. TRICKLE
An initial trickle of current rolls along the phloem and xylem cambium-initials and rapidly builds in strength causing tissue heating and disruption of intercellular connections.

2. FLASH-OVER
The capacity of the charge exchange pathway inside the tree is limited as current flow rapidly builds. Suddenly, a majority of the current flow breaks out onto the bark surface (termed a surface “flash-over”).

3. SHOCK WAVE
A pressure wave formed by an almost instantaneous heating of air at the center of the charge exchange path is usually focused along a narrow portion of the bark and wood.

II TREE

4. MASH
The large pressure wave first compresses the bark and wood toward the center of the tree with a surface compression wave moving around the tree.

5. STRETCH
Tissues are then subjected to an almost immediate tension force as the tree rebounds from the shock wave.

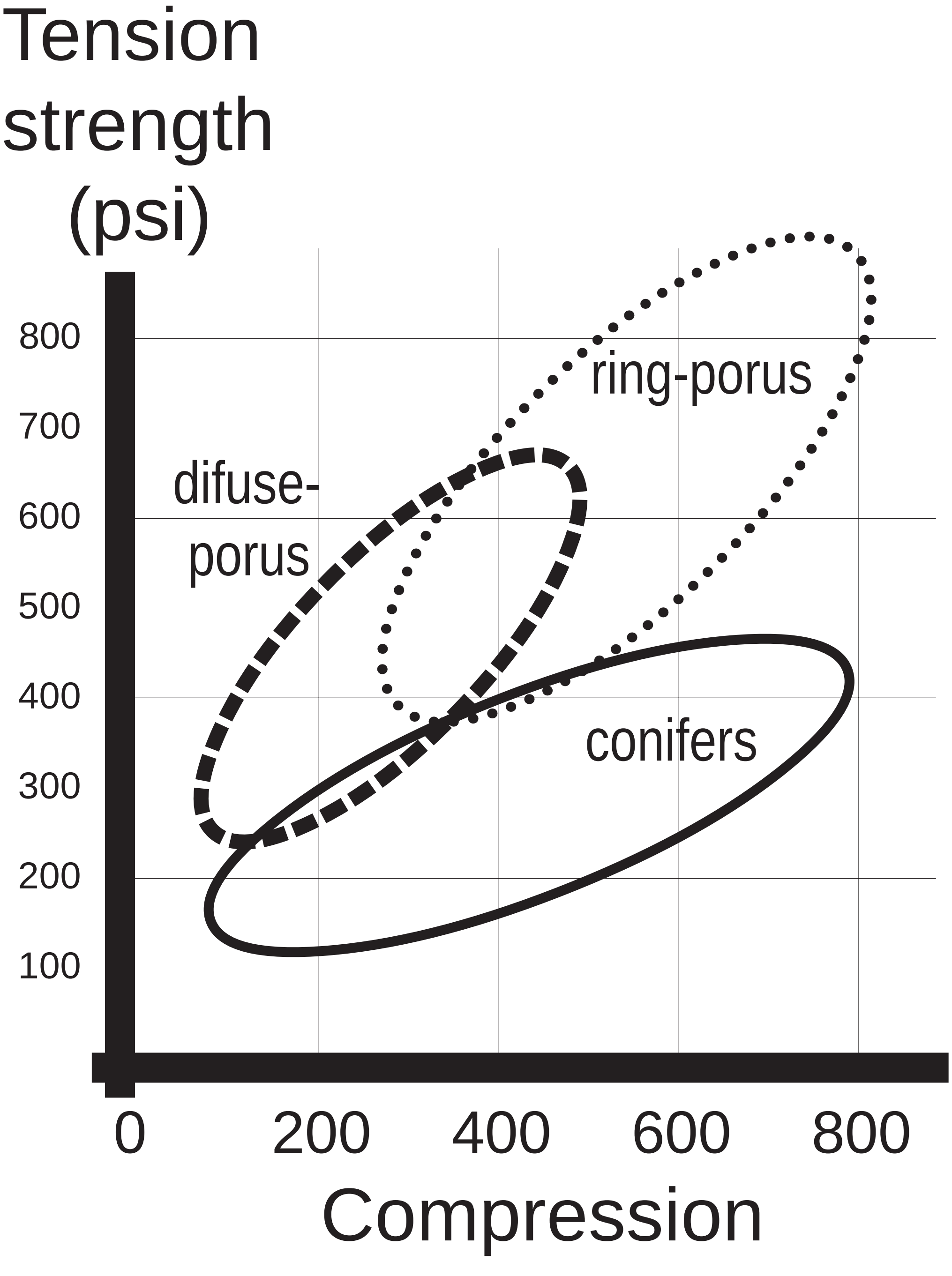
6. SPLIT
The wood and bark, alternativly compressed then stretched, splits. Tree tissues are deconstructed and interconnections are shattered, leading to internal and external injuries.

III INJURY

7. BREAKING
The compression and tension portions of the shock wave in a tree can lead to annual ring separations, breakage along old compartment lines, loosening of bark and wood pieces, and the propelling of loose tissue pieces away from the tree.

8. DAMAGE FOCUS
Structural faults, injury modified wood, open spaces, gaps, cavities, drill holes, imbedded metal objects, and insect galleries concentrate compression and tension forces along their edges leading to fiber separations. Trees tear apart along compartment boundaries.

Figure 7: The tension and compression strength perpendicular to the grain of living wood of various tree species. (Forest Products Laboratory 1987)



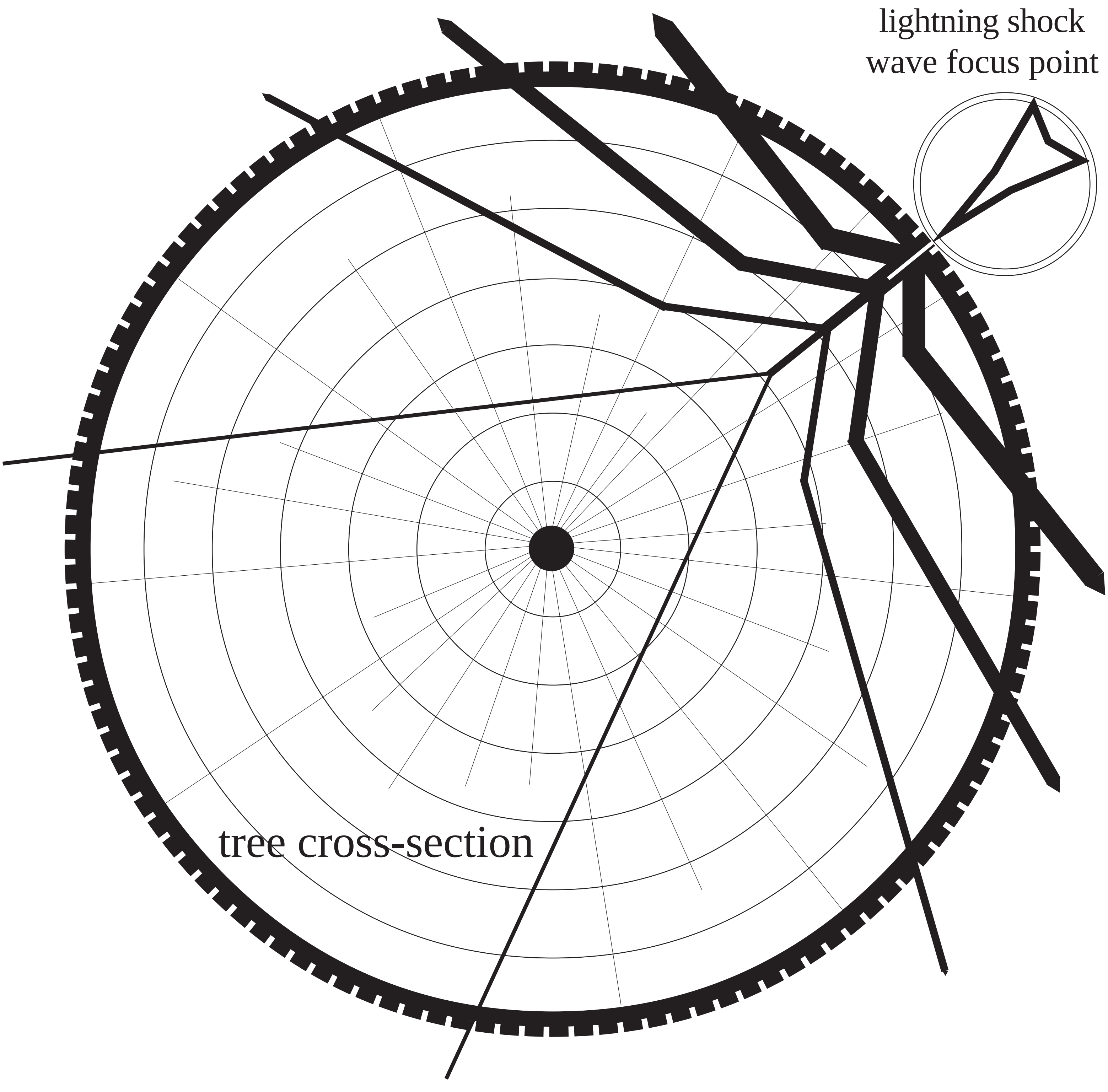


Figure 8: Lightning shock wave impact and rebound inside stem of diffuse-porous thin-barked species, or non-porous xylem species with no density differences within a single growth increment. Expected damage is shallow and spread around the circumference for some distance loosening bark plates and breaking intercellular connections. Great energy dispersion occurs through and around stem.

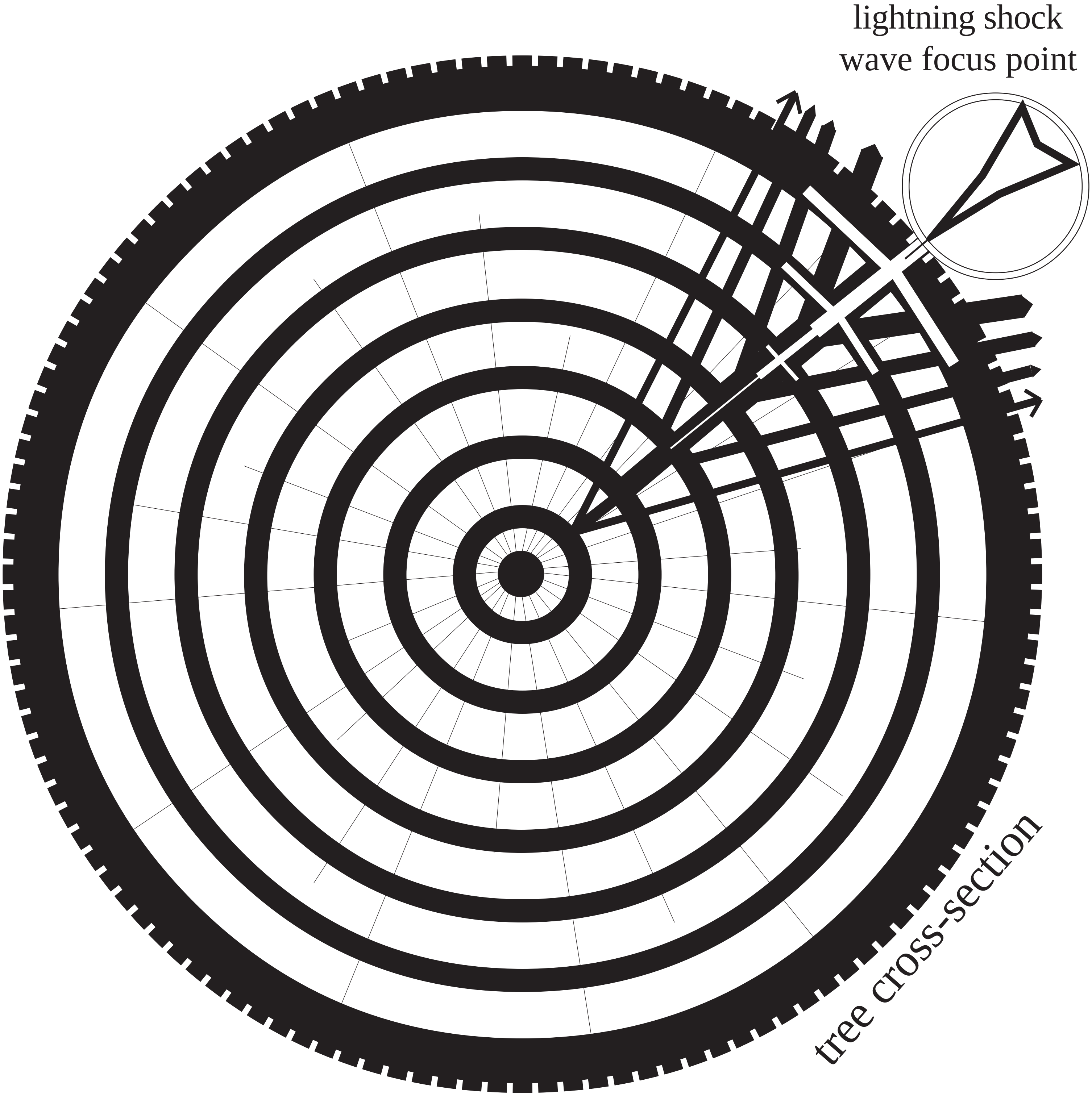


Figure 9: Lightning shock wave impact and rebound inside stem of ring-porous thick-barked species, or non-porous xylem species with large density differences within a single growth increment. Expected damage is deep with a narrow band of bark breakage, ray cracks, and localized bark and wood slab loosening. Energy concentration occurs deep in the stem and is narrowly focused.

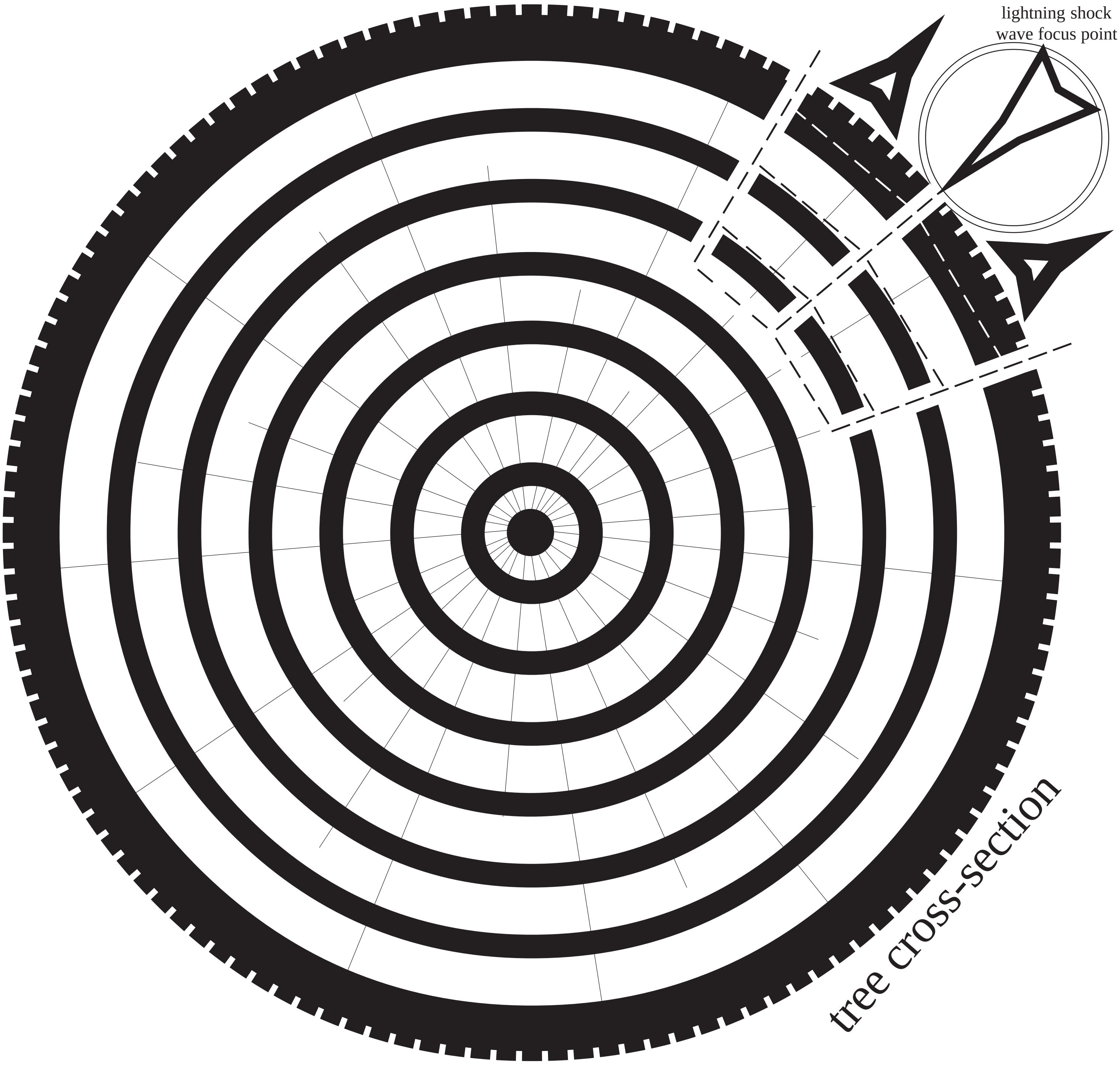


Figure 10: Lightning shock wave loosening and potentially removing bark and wood slabs in a stem of a ring-porous thick-barked species, or non-porous xylem species with large density differences within a single growth increment.

Figure 11: Risk Factor #1 — Topographic Location in the Landscape.

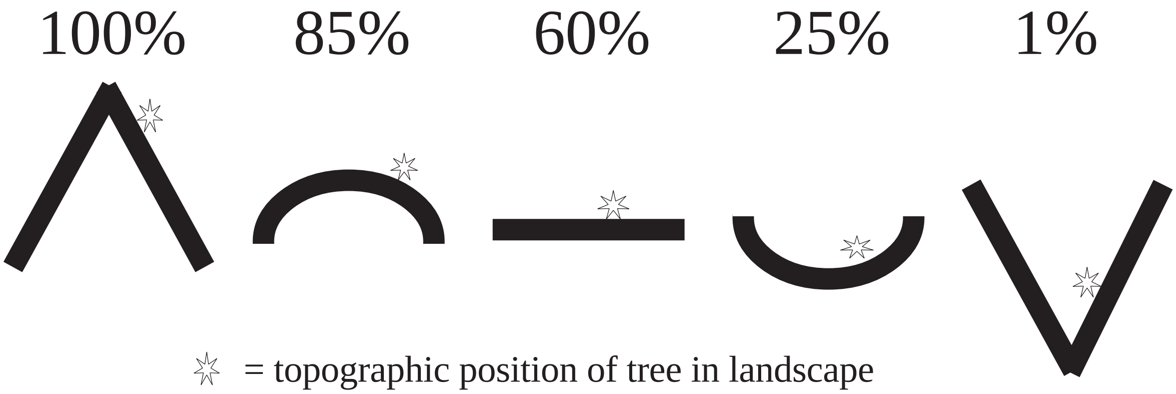


Figure 12: Risk Factor #2 — Relative Tree Height: Determine relative tree height compared with neighboring trees. Crown class concepts are applied. Here are shown the crowns of trees near each other and the names of crown classes (relative height values).

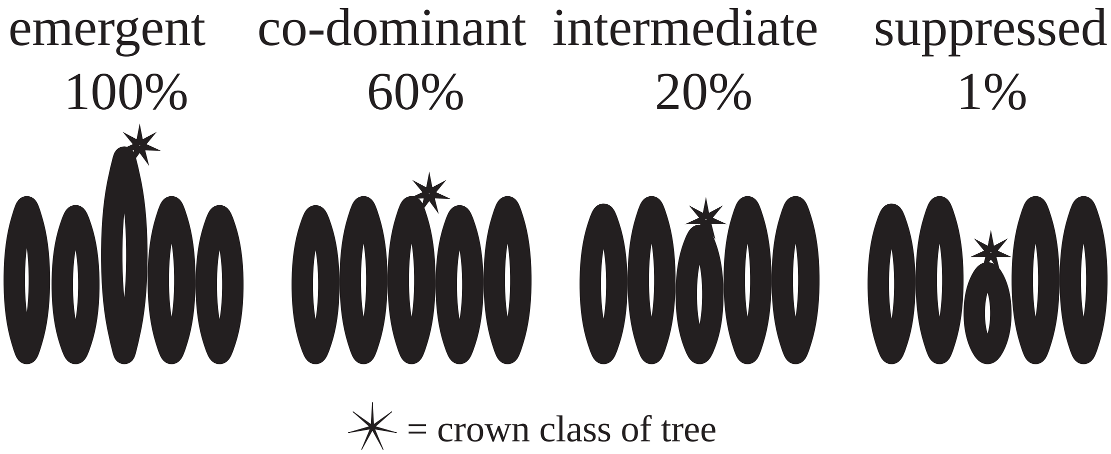


Figure 13: Risk Factor #3 — Tree Openness: Below are shown tree crowns from above representing the assessed tree (dark circle), neighboring trees, and the openness value of the assessed tree crown.The assessment risk percent is equal to the degrees of openness between 0^o & 360^o divided by 3.6. Pick the risk percentage closest to the assessed tree's crown openness.

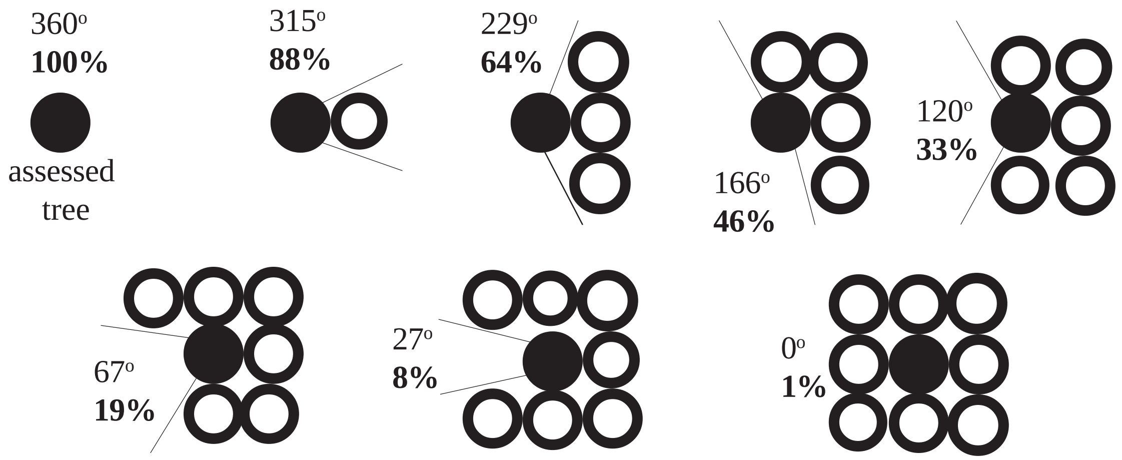
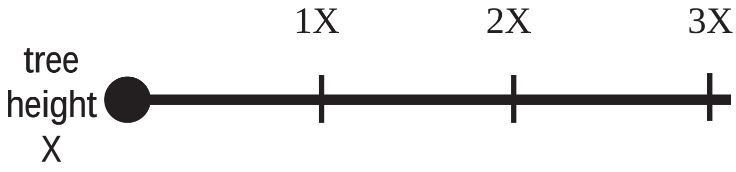
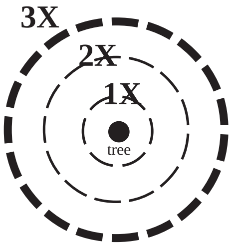


Figure 14: Risk Factor #4 — Relative Neighborhood Height Differences

Step #1: Calculate neighborhood distance (radius of three times the tree height on the ground away from assessed tree stem).





Step #2: Measure the single tallest tree or structure within the neighborhood of the assessed tree. The neighborhood is within a radius drawn around the assessed tree on the ground at a distance of five times (5X) the assessed tree height. Determine how many times taller the tallest tree or structure is compared to the assessed tree.

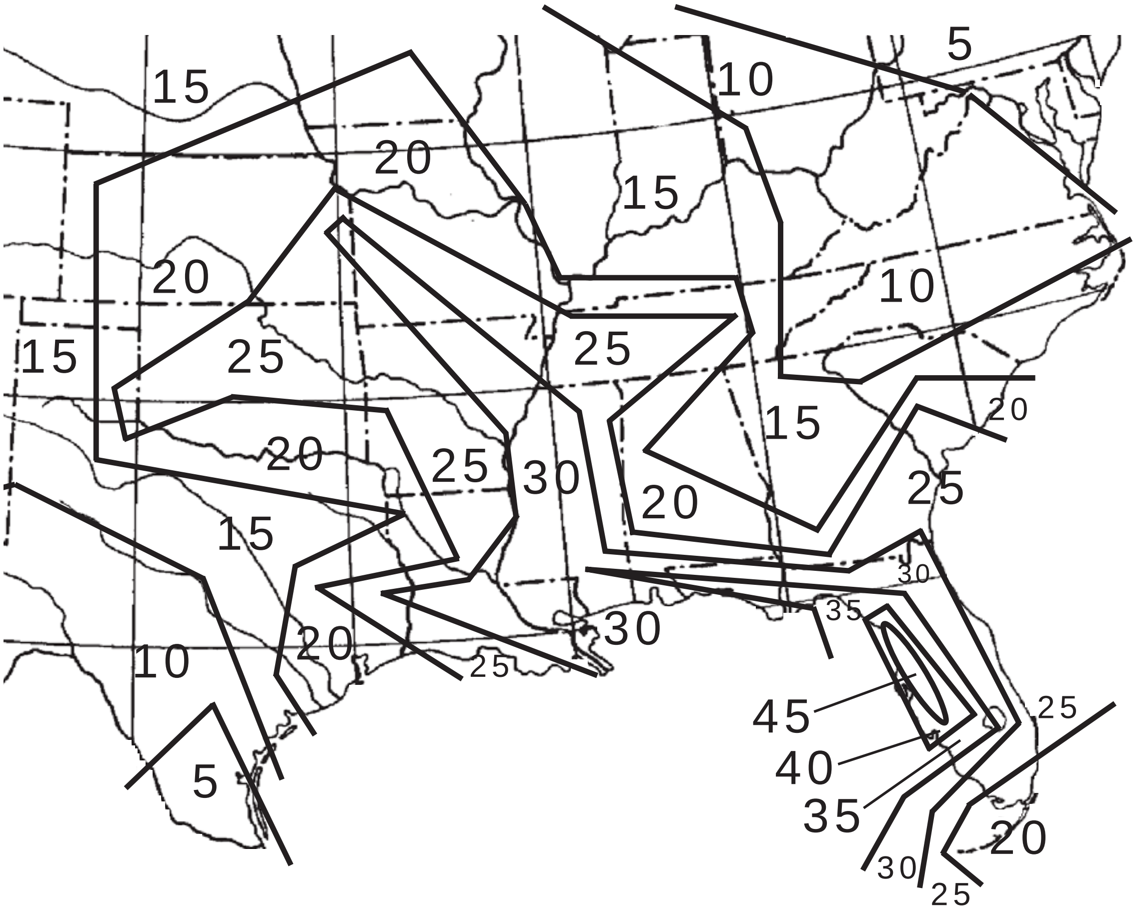
number of times taller than assessed tree	assessment value (%)
2.5 times taller	2%
2.0 times taller	10
1.5 times taller	25
1.25 times taller	55
same height	80
shorter	100

Figure 15: Risk Factor #5 — Tree Target Proximity: The distances listed here are based upon radial distances away from the base of the assessed tree stem at the ground surface.

tree position relative to target	assessed value (%)
tree as tall or taller, and touching	100%
overhanging (target beneath crown)	95
within 1/2 tree height	90
within 1 tree height	80
within 2 tree heights	60
within 3 tree heights	25
beyond 3 tree heights	1

Figure 16: Risk Factor #6 — Annual Lightning Strike Probability

Different places on Earth differ in thunderstorm and lightning events (duration, intensity, number, etc.). Trees in areas with many lightning strikes are more at risk than trees in areas where lightning strikes are rare. Please see the map below (lightning strike number) for the numerical value to insert into the probability formula for your area. The probability formula uses lightning strikes per square mile per year and tree height to determine the annual lightning strike probability.



Annual Lightning Strike Probabillity =
lightning strike number from map X 3.142 X
[((tree height in feet) X 3) /5,280]^2

Figure 17: Tree Lightning Risk Assessment

A) Record all assessed values for risk factors #1 through #5 below. The risk factor values will range from 1% -100%. Note: Use percent values in whole numbers not decimal percent values (i.e. 90% instead of 0.90).

RISK FACTOR #1: ____________% +

RISK FACTOR #2: ____________% +

RISK FACTOR #3: ____________% +

RISK FACTOR #4: ____________% +

RISK FACTOR #5: ____________% =

SUM RISK FACTORS #1-#5: ____________ / 500 =

COMPOSITE RISK FACTOR = ____________

B) Record risk factor #6, the annual lightning strike probability below.

RISK FACTOR #6 — ANNUAL STRIKE PROBABILITY = ____________

C) Multiply composite risk factor and annual strike probability together.

COMPOSITE RISK FACTOR X ANNUAL STRIKE PROBABILITY =
TOTAL TREE LIGHTNING STRIKE RISK VALUE

_____________ X ______________ = ______________

TOTAL TREE LIGHTNING STRIKE RISK VALUE	RISK DESCRIPTION
> 0.05	severe risk (installation recommended)
> 0.03	high risk
> 0.02	moderate risk (consider installation)
> 0.01	low risk
< 0.005	very low risk (installation not recommended)

Remember that risks are low, not zero, and lightning strikes can still occur.

TREE LIGHTNING RISK ASSESSMENT WORKSHEET

Dr. Kim D. Coder, Warnell School of Forestry & Natural Resources, University of Georgia, April, 2007

RISK FACTOR #1: TOPOGRAPHIC LOCATION IN LANDSCAPE = ____________%

RISK FACTOR #2: RELATIVE TREE HEIGHT = ____________ %

RISK FACTOR #3: TREE OPENNESS = ____________ %

RISK FACTOR #4:
RELATIVE NEIGHBORHOOD HEIGHT DIFFERENCES = ____________ %

RISK FACTOR #5: TREE TARGET PROXIMITY = ____________ %

ADD RISK FACTORS #1 - #5 TOGETHER TOTAL = ____________

DIVIDE TOTAL BY 500 = COMPOSITE RISK FACTOR =

RISK FACTOR #6: ANNUAL STRIKE PROBABILITY =

COMPOSITE RISK FACTOR X ANNUAL STRIKE PROBABILITY =
TOTAL TREE LIGHTNING RISK VALUE

______________ X _______________ =

COMPOSITE RISK FACTOR ANNUAL STRIKE PROBABILITY

TOTAL TREE LIGHTNING RISK VALUE

TOTAL TREE LIGHTNING RISK VALUE

> 0.05	**severe risk (installation recommended)**
> 0.03	**high risk**
> 0.02	**moderate risk (consider installation)**
> 0.01	**low risk**
< 0.005	**very low risk (installation not recommended)**

Remember risks are low, never zero, and lightning strikes can still occur.