Trees & Storm Wind Loads

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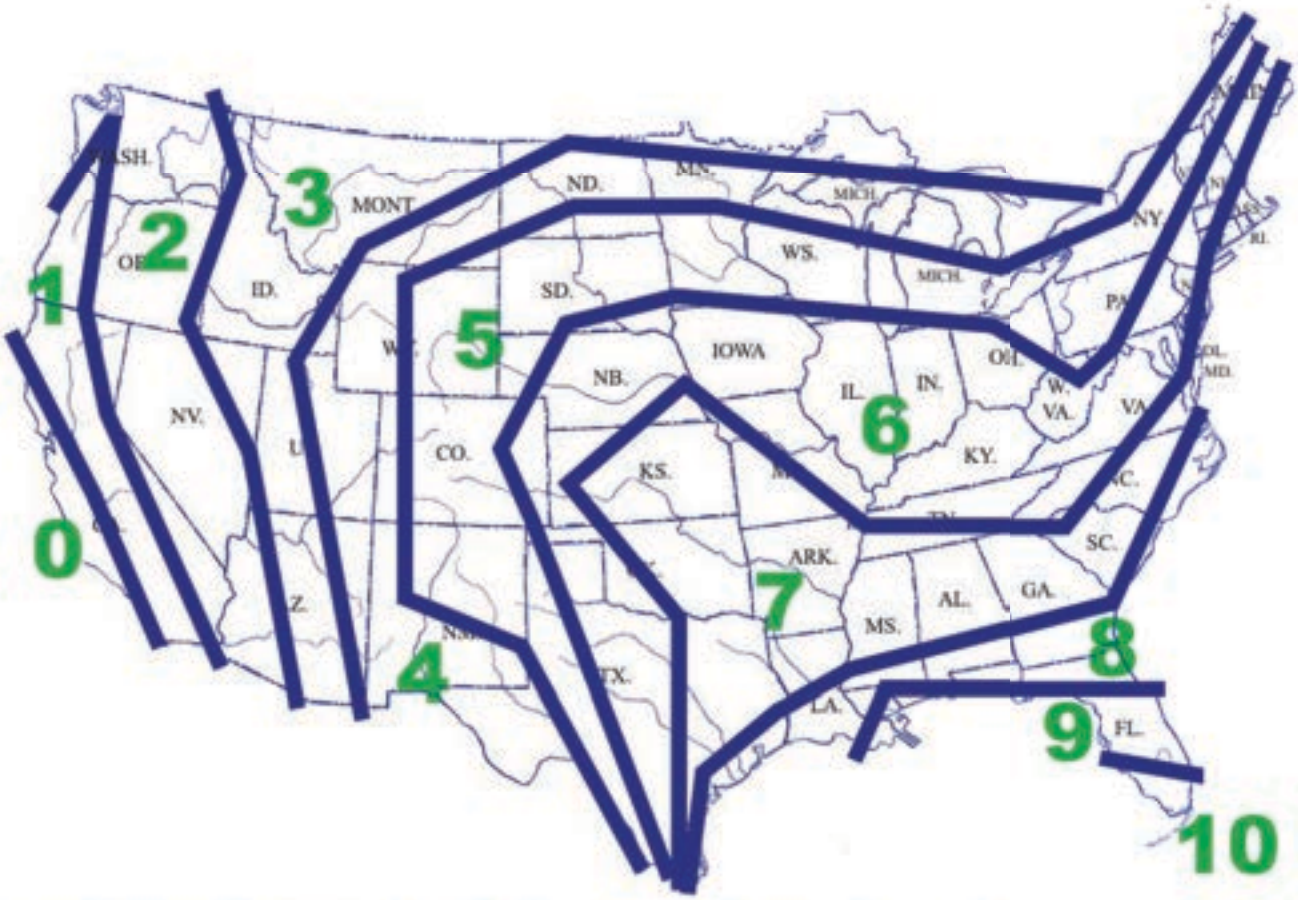

Coder Storm Intensity Map of composite potential risks for tree damage.

This publication is an educational product designed for helping tree professionals appreciate and understand basic aspects of tree mechanical loading during storms. This educational product is a synthesis and integration of weather data and educational concepts regarding how storms wind loads impact trees. This product is for awareness building and educational development.

At the time it was finished, this publication contained information regarding storm wind loads on trees thought by the author to provide the best means for considering fundamental tree health care issues surrounding tree biomechanics. 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 structure and mechanics 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 assessments.

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Trees & Storm Wind Loads

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Trees must withstand wind to survive. Wind and gravity both impact trees in storms, but the dominant load is from wind. Storm winds push on tree crowns and stems causing root plates to wobble, and all tree parts to twist and bend leading to either tree part or supporting soil failure. Trees sense structural stress and attempt to minimize failures through adaptive growth. Trees modify their structure over time as they are challenged by wind. Trees are biologically designed to sustain average wind loads. What are the mechanical loads applied by storms to trees?

Sailing Along

A tree has a large sail area (leaves and twigs) held upright high into air by a tapered mast (stem). The stem is held aloft by a thick horizontal mat of large structural roots at the stem base which forms a root plate. Rapidly tapering roots growing away from the stem base provide a tree with a structural framework and an absorbing surface. The center of gravity (effective weight center) of a tree is usually somewhere in the middle of a stem above the root plate and below the crown base. Gravity is pulling down on the tree all over, but has a total effect focused at the center of gravity. Wind is pushing the tree around its center of gravity.

The weight of a tree is pulled down onto the soil surface. As long as its center of gravity remains positioned above its supporting base, the stem is usually stiff enough to keep a tree upright. If the center of gravity for a tree is not positioned over its supporting base, gravity may topple a tree if the tensile and compressive strength of the stem and root base is compromised or inadequate. Storm winds can push the center of gravity in the stem out from over its supporting base. The combined result is wind moving a tree laterally and gravity pulling a tree downward, providing a rotation force acting to roll a tree out of the ground -- a load wheel. Figure 1.

Gravity

Trees seldom fail under their own weight -- external loads stress and strain a tree until failure. Gravity loads trees in tandem with wind to initiate these failures, but wind loads greatly exceed gravity loads in most situations. Wind is an acute mechanical variable for which trees must constantly adjust growth processes. Gravity is a chronic stress and strain with which trees must cope. Adding mass to a tree in the form of growth (size, extent, and reach), or in applied water, ice or snow loads, can magnify gravity's impact on a tree, causing fiber creep (permanent tissue changes) and failures. But, it is storm winds which push tree structures to their limits.

Impact Trinity

In order to more clearly understand storm initiated failures in trees, wind loads must be fully appreciated. Wind has three primary components which impact trees:

1) velocity or speed (mile per hour or feet per second);
2) acceleration (velocity changes over time or velocity squared); and,
3) throw weight (mass of air and its contents).

Wind speed is a simple concept easily measured and applied against a tree. It is not solely wind speed which pushes trees to catastrophic failures.

Dynamic Pressure

Wind acceleration is a dynamic load variable which is not easily measured. How fast wind speeds change through acceleration and deceleration place constantly changing loads on trees. The duration of time between minimum and peak velocity (gusts), and then peak velocity and minimum velocity (calms) greatly impact trees. Is the changing wind load applied over one second or one hour? A load gently applied over time can be more easily dealt with in a tree than a hammer blow of wind applied suddenly. Rapid changes in wind velocity impact trees proportionally to wind velocity squared.

Wind at increasingly greater velocity does not exist in a perfect linear, laminar, and continuous flow. Storm winds are not equivalent to wind tunnel winds. Not only are storm winds gusting in large wave forms, wind can show many smaller periodic patterns which constantly and quickly load and unload trees. Wind is a complex of pulsing and rotating pressure waves with multiple periods. Sometimes these wave peaks or pulses of wind combine to generate extraordinary gusts, other times the calms between the different wave patterns combine to generate relatively still periods.

Another component of wind impacting trees is the mass of the wind stream, sometimes called the throw weight of the wind. Wind propelling rain, ice, snow, soil, or debris is heavier (has more mass) than atmospheric gas components. For the same wind velocity, the more materials in the windstream, the more impact this wind will have on a tree. There is a weight class difference among storm winds which all impact trees differently. In addition to twisting and bending loads applied by "heavier" winds, tissue scouring from wind bourne debrie can greatly damage trees.

Drag

Once the dynamic nature of wind is appreciated, tree resistance or drag can be considered. Drag is caused by air hitting and moving past a standing tree. Drag represents the resistance or friction of a tree to wind. Force on a tree is generated due to the velocity of wind and air density striking and moving past tree surfaces. Because a tree is not a solid unmoving object, but a flexible, bending, porous object, only a part of the total wind force is applied to the tree (a portion represented by a drag coefficient). The faster wind velocity (V), the greater the pressure placed onto a tree (V^2), but the smaller drag coefficients can become to some minimum point.

Trees reconfigure stem, branches, twigs, and foliage under increasing wind loads by falling back against the wind or streamlining, including changes in stem and branch flexing / twisting, twig and foliage folding / rolling, generating a smaller frontal area, and effectively increasing crown porosity. The frontal area of a tree can be reduced by more than 50% as wind velocity increases. Because of tree reconfigurating in wind, drag coefficients change (decrease) with increasing wind velocity. There is great variability in tree drag coefficients across the research literature (range = 1.35 - 0.10). Here a drag coefficient of 1.0 is used to simplify understandings of storm wind loads.

Wind Hammer

Wind loads on trees can be summarized as a constant pressure, additional pulsing of short wind bursts, a rolling shock wave of high pressure occasionally applied, an overall acceleration and deceleration around an average value, and a variable weight windstream. Trees in storms are hammered with a dynamic combination of blows. Note the average wind velocity values and gust peaks measured for media meteorology information do not adequately represent the full dynamic nature of storm winds on trees.

For example, it is both gusts and calms which impact trees. Trees bend and twist back against the force of wind and rebound in calm periods between gusts. Winds load and unload trees in different ways, over various time frames, and on different tree parts. Dynamic storm winds are more difficult to

successfully resist over time than a simple straight wind. The periodicity of tree swaying, coupled with the frequency of wind pressure peaks, can generate tremendous synergies of load and resistance in trees.

Storming

As small scale winds differ over time, large scale meteorologic events differ in the amount and intensity of energy applied to trees and landscapes. The six major forms of storms considered when examining tree impacts are thunderstorms, hurricanes, glazing (ice) events, tornadoes, derechos (horizontal rolling squall lines with clusters of downbursts), and snow events. Lightning is an additional tree damaging feature of storms. Every storm event has a different size, power, duration, and residual impact. Different areas of a landscape receives different combinations of storm wind energy not predictable based solely upon typography, aspect, openness, or history.

T-Storms

Thunderstorms can be found across the continent. Thunderstorms generate updrafts in the atmosphere, large columns of falling rain and air, and ground level winds. The straight line winds in a thunderstorm can be caused by downbursts of various sizes: microbursts (<1 mile diameter & 160 mph winds); macrobursts (>2.5 miles diameter & 130 mph winds); and, derechos (band of downburst clusters >240 miles long & >100 mph winds).

Figure 2 is a map of the average number of thunderstorm days in the continental United States. Hot, humid air running into colder air masses tend to generate storms with massive air flows. Note the Southeastern and Central United States have many events per year which could potentially overload and damage trees. Florida leads the nation with thunderstorm days. Figure 3 provides an estimate of the average number of storms each year with winds greater than 50 mph.

Beaufort Scale

Wind in thunderstorms are usually reported in average miles per hour and peak gust speeds. Historically, winds from thunderstorms were classified by a 0-12 numerical force scale. These classes comprised the Beaufort Wind Scale developed for mariners. Beaufort Wind Scale force numbers are tied to a miles per hour wind velocity range and a simple descriptive title. Figure 4 provides the Beaufort Wind Scale force number, wind speed range in miles per hour, a mid-point wind pressure value in pounds per square feet, and wind force classification description. Figure 5 provides potential tree impacts from Beaufort wind scale forces.

For example, a "force 8" wind is called a "fresh gale" and has a velocity between 39 and 46 miles per hour, breaking twigs on some trees. A force 12 wind is 73 miles per hour or greater, which begins the hurricane classifications. Note the wind pressure values represent a drag coefficient of 1.0.

Hurricanes

Figure 6 is a map of historic hurricane landfalls in the Eastern United States over the last 50 years. Any land form which juts out into the Atlantic Ocean is prone to being slammed by a hurricane being driven north and east by prevailing winds. Most of the coast bordering the Gulf of Mexico has seen many hurricane landfalls. Florida which borders both the Atlantic and Gulf is ideally positioned to take hits from many hurricanes.

How often hurricane level storms make landfall in any one area of the coast is important to risk management of trees and community forests. A statistical estimate of how many years are expected between major hurricanes is shown in Figure 7. Places like the Georgia bite, and the DelMar peninsula and North can receive hurricane winds, but at greater times between landfalls.

Figure 8 shows the distribution of hurricanes from a 100 year period grouped across the months of the year. September is the peak month and September 10 is the peak day on average. Hurricanes in June and December have occurred. The cumulative impacts of hurricane events on maritime forest trees is to limit height, and modify crown and stem shape, generating a "flagged" tree canopy form.

Saffir-Simpson Scale

As wind velocity climbs past 73 miles per hour, a different wind classification system is used instead of the Beaufort scale. The hurricane "category" value is spouted by the public and in the simplest weather forecasts. This classification system is the Saffir-Simpson Hurricane Scale. Figure 9 provides a summary of the Saffir-Simpson Hurricane Scale with category number, wind speed in miles per hour, midpoint velocity range wind pressure value in pounds per square feet, and potential tree impacts. Note the wind pressure value represents a drag coefficient of 1.0. This hurricane scale has a noticeably uneven level of increasing wind velocity classes topping out at greater than 155 miles per hour in a category 5 hurricane.

The hurricane categories also contain ocean storm surge heights in feet. Storm surge and hurricane wind speeds are not strongly coupled, as many land, sea, and tide conditions modify water volumes and heights. Figure 10.

For example, a category 3 hurricane would have top sustained winds of 111-130 miles per hour and push ashore a storm surge of water 9 to 12 feet in height. A category 3 hurricane would be expected to strip leaves from trees and topple trees with large sail areas. Trees with full frontal exposure to category 3 winds would be expected to fail.

Surging

Trees are impacted by hurricane storm surges. A storm surge is usually composed of near ocean level salinity water pushed ashore. Knowing the height of a surge and topography of the area can help predict present and future tree problems from soil salt. Storm surges also can lead to plastic and liquid soil limits being reached in finer soils, and within finer soil layers in coarse soils. Water logging of soils can greatly reduce soil strength and root resistance to slipping under wind loads. On the other hand, as trees are flooded, and flood waters rise, the weight of the water over the root plate can off-set (by stabilizing the tree) some of the soil strength loss.

Inland from beach areas are places lower in the landscape than their surroundings, or places protected by levees and berms. As storm surges rise, the chance of inundation increases and the difficulty in removing accumulated brackish water can increase. In low-lying areas protected by levees, levee height would have to be taller than any storm surge, plus additional height to prevent overtopping and erosion of the levee.

Inland Winds

One poorly understood and planned for aspect of a hurricane landfall is how far from the coast wind damage can occur as remnants of the storm moves inland. Hurricanes can spawn other types of storms (like tornadoes) and other types of winds (isolated thunderstorm events), but the primary hurricane winds generated over the ocean decline as land is crossed. The declining wind speeds do not drop instantaneously. Figure 11 shows how many miles inland maximum hurricane winds could be felt and at what velocity for a category 3 storm.

The time between landfall and maximum wind impact on any tree will depend upon the ground speed of the storm as it moves inland and the distance inland of a tree. Figure 12 shows the distance inland from the coast where a category 3 hurricane landfall would still generate 60 mph sustained winds as it moved inland. Of course, higher category storms would deliver faster wind speeds farther inland.

Tornadoes

Tornadoes can be a component of many types of storms. This intense, high velocity, rotating storm event plagues trees. The top momentary wind speeds can be tremendous. Direction of the heaviest winds change with passage of the storm. Trees near the direct track of a tornado must withstand the bending loads applied by winds as well as twisting (torque). In addition, tornadoes are often accompanied by heavy rains, damaging hail, and intense lightning activity, all of which impact trees.

Tornado events are on the rise in the United States. Figure 13 provides a trend line for increasing tornado events over the last 55 years. Note since 1950, tornado events have increased roughly seven-hundred percent (7X). Figure 14 is a map developed from storm data from the last 45 years showing the average number of tornadoes per year for the continental United States. The map categories are broad, but demonstrate a concentration of storms in the legendary "tornado alley" of the Great Plains.

Old Tornadoes

Tornadoes in the United States used to be (up till 2/1/2007) categorized using the Fujita Tornado Scale. Figure 15 provides the historic "F" category number, wind velocity range, midpoint velocity range wind pressure value, and generic tornado description. Figure 16 provides potential tree impacts of tornado scale forces. Note the wind pressure value represents a drag coefficient of 1.0. Fujita Tornado Scale categories always begin with the letter "F" to assure there is no confusion with hurricane category numbers. This scale was originally designed for nuclear explosions shock waves.

For example, a F3 tornado would have wind speeds of 158-206 miles per hour, wind pressure at 182 miles per hour of 87 pounds per square feet, and is called a severe tornado. Trees and forests near the storm-track are expected to be flattened and twisted apart. Because of the narrow band of the most intense winds within a tornado, many trees survive near-misses by tornadoes.

Note the Fujita Tornado Scale ranges from a F0 gale tornado with winds ranging from 40-72 miles per hour to a F6 inconceivable tornado with winds ranging from 319-379 miles per hour. A F6 tornado has not been identified in North America. F2 to F5 tornadoes snap stems, strip branches, and uproot trees close to the storm track. Overall storm damage to trees often seems less in tornadoes than in other less violent but more widespread storms because the devastation is along a narrow band which can be reached from either side by clean-up and removal equipment. Wind pressures generated in tornadoes are clearly the most extreme of any storm type.

Enhanced Tornadoes

Recently a new tornado scale has been developed emphasizing the resulting damage, not necessarily the maximum wind gust speed. The new scale is called the Enhanced Fujita (EF) scale. Figure 17 provides a comparison of the tradition Fujita scale and the new EF scale for tornado events. Note the EF scale stops measuring wind gust velocity at 200 mph, and at an Enhanced Fujita scale number of EF-5.

Figure 18 graphically shows the difference between the old F and the new EF scales. Figure 19 provides gust speeds, wind pressure, and tornado descriptors. Figure 20 provides tree impacts for EF scale forces. Note the wind pressure values represent a drag coefficient of 1.0. The EF scale for tornado events now includes some specific tree damage information. Figure 21 provides general damage ratings for hardwoods and softwood trees under the EF scale.

Remember actual wind speed values can vary widely for the same storm event and same gust depending upon the technique used to measure wind velocity and the statistical means used to describe wind velocity. A wind speed value could represent a maximum gust or a variety of average speeds. Common measures include fastest mile, greatest 3-second gust, or averaging over 5 or 10 minute intervals.

Euro-Tornado

The Fujita and Enhanced Fujita Scales for tornadoes were designed for special uses in the energetic storms of North America. It does not easily coincide with other wind scales. Another tornado scale is used elsewhere in the world which categorizes tornadoes with less intensity and wind velocity. This tornado wind scale is the Meaden Tornado T-Scale. This scale was designed to fit well with and compliment the Beaufort Wind Scale. Figure 22 provides the category "T" number, wind velocity range in miles per hour, midpoint velocity range wind pressure value in pounds per square feet, and generic tornado description. Figure 23 provides potential tree impacts from Meaden Tornado Scale forces. Note the wind pressure values represent a drag coefficient of 1.0.

Glazing Ice

Ice storms can impact most of the United States. Figure 24 shows the average number of days in a year with freezing precipitation. Figure 25 shows ice accumulation (in radial inches) for a 50-year ice storm across the United States. Generally, the farther north, the greater the chances of glazing events impacting trees, on average. Figure 26 provides wind gusts associated with a 50-year ice storms across the United States. The combination of ice and wind conspire to damge trees worse than each alone. It is in more southern parts of the nation where chance ice storms, especially with strong winds, greatly load and damage trees.

Ice accumulation on trees can amount to 20X - 50X the dry weight of branches and twigs. Ice glazing makes branches and twigs stiff, increasing resistance (drag) to the wind and prevents crown reconfiguration, leading to structural failures. Glazing events also cause severe wood creep, an irreversible decline and drooping of tissues. Wind loads on ice covered trees can greatly multiply any branch weight and stiffness (lack of reconfiguration -- increased drag) loads. Figure 27 shows an ice damage severity index (range 0-5, with 5 being severe) for combined ice and wind loads. Small ice loads with large wind loads, or large ice loads with little wind, can be equally damaging to trees.

Deluge

The force of wind upon tree crowns can be immense. Trees remaining upright and stable depend upon the integrity of many mechanical components of a tree and site. One site component sometimes overlooked in storms is soil strength. Storms apply wind loads to trees which distribute loads through their stems and into their base woven into soil. Storms can also apply large amount of water onto a site along with wind.

Figure 28 shows a generalized map for the maximum rainfall in inches falling in one 24 hour period across the United States. If the water content of a soil exceeds the plastic or liquid limit of a soil, the soil will not behave as a solid matrix holding tree roots, but as either a slowly deforming plastic material or a rapidly flowing liquid. Figure 29 shows the plastic and liquid limits of soils with various amounts of fine textured materials. Rainfall amounts modifying soil strength can lead to to tree failures especially when combined with wind loads.

Storm Intensity Zones

In trying to summarize storm winds and associated damage to trees, the Coder Storm Intensity Map was developed for the continental United States. This map was created using cluster analysis of average historic data for thunderstorms, hurricanes, tornadoes, lightning ground strike frequency, ice glazing events, snow fall accumulation values, and general wind speed values. Figure 30 is a map of storm intensity as it relates to potential tree damage. The range of storm intensity impacting trees are categorized into zones from 0 to 10. Note these zones include both wind and gravity related tree struc-

tural impacts. The most intense area of potential tree damage from storms is in zone 10, the southern tip of Florida.

The value of the Coder Storm Intensity map is in appreciating areas which share common storm intensity and associated risks of tree damage. For example, most of Georgia is in the same zone as most of Kansas, the heart of tornado alley. The storm types may be different but the total yearly impact potential on trees from storms is roughly the same.

Gusting

In all of the meteorological scales presented here, wind speed in miles per hour is a common means of demonstrating storm strength and potential for tree damage. Unfortunately, for most people listening to media reports of storm conditions, both wind speeds and associated tree impacts can be underestimated. The traditional way of presenting wind speeds to a general audience has been a ground measurement in miles per hour taken at an airport or in an open field averaged over some time period (usually every 10 minutes to one hour). This average wind speed is helpful in appreciating the intensity of any storm.

Remember it is gusts and calms which are critical to understanding wind loads and associated risks of tree damage. An average wind speed of X could have gusts of 1.5X to 2X hidden within the wind speed value. For example, an average wind speed may hover around 50 miles per hour for a period of time in the middle of a storm. It is entirely possible for maximum wind speeds to have reached 75 to 100 miles per hour in short duration gusts.

Force Not Speed

Storm wind loads on trees are not well represented by wind velocity values. Wind impacts on trees are directly related to the force or pressure wind applies to tree parts. The pressure of the wind applied to a tree can be estimated by multiplying the square of wind speed times one-half the density of air moved. The pressure of wind on trees is usually calculated at some standard temperature (like 68°F) at sea level. A simplified formula for quick estimates of wind pressure is given below:

$$\textbf{wind pressure in pounds per square foot} = (0.013) \times (\textbf{wind speed in mph} \times (0.45))^2.$$

Figure 31 presents the comparison between wind velocity in miles per hour and wind pressure in pounds per square foot created using the simplified formula above. Wind pressure values have been added to storm wind classification scales to help tree professionals appreciate the magnitude of force applied to trees. Note that as wind speed doubles, the wind pressure against a tree per square foot of frontal area would not simply double, but quadruple. Please remember the wind pressure values represent a drag coefficient of 1.0.

For example, if wind velocity is 20 miles per hour, the wind pressure applied to the front aspect area of a tree is 1.1 pounds per square feet (drag coefficient = 1.0). If storm wind velocity then accelerates and levels off at 40 miles per hour, the wind pressure is 4.2 pounds per square feet (drag coefficient = 1.0). A small increase in wind velocity can have great impacts on wind pressure applied to a tree. Figure 32 provides a graphical view of the greatly increasing wind force generated with increasing wind velocity.

Wind Speeds

From the many proceeding wind and storm scales, a single wind speed scale was derived for trees. The Coder Wind Scale of load factors on trees in given in Figure 33. Conversions of Coder Wind

Scale values to maximum wind gust speeds in mile per hour and to the associated wind load force applied to a tree are provided. The two dotted lines represent a maximum crown reconfiguration threshold (T1), and an exhaustion of average tree safety factors threshold (T2).

Tree Damage

Summarizing and simplifying all proceeding storm wind scales and load values produced and reviewed here, several features can be identified. Figure 34. The Coder Tree Wind Damage Assessment is intended to help tree health care professions focus on tree damage potential not storm severity. Presented in the assessment are wind velocity in miles per hour, wind pressure as applied to trees in pounds per square foot (drag coefficient = 1.0), and potential tree damage. Remember this assessment is only a guide and tree loss can occur at any wind speed, or under calm conditions, for many reasons other than wind loading. In addition, wind pressure on trees coated with ice can double or triple the stress and strain developed.

Because wind speed does not represent the actual wind force applied to a tree, wind pressure values should always be used. Wind pressure values here are in pounds per square feet of the tree's front aspect to windward with a drag coefficient of 1.0. Wind pressure values help remind professionals about the tremendous increase in forces applied to trees as wind speeds climb. Always use wind speed in miles per hour when addressing a lay audience since this is a common and relatable value. Wind pressure values should be prepared and used for profession tree health care managers and tree risk assessments as these values show the true extent of loading and resistance in trees.

Structural Thresholds

There are two critical storm load thresholds in trees, T1 and T2. The first limiting threshold (T1) is reached when wind speeds approach and exceed 56 miles per hour (~8 pounds of wind pressure per square feet). T1 is where the drag reconfiguration in a tree has been reached and cannot significantly be reduced any further without tissue loss (i.e. front impact of the wind on a tree has been minimized). Up to this threshold level, leaves are blown back against the wind, then rolled creating less drag or resistance. With increasing wind velocity, peripheral twigs and branches are reconfigured in the crown as they fall back and are bent against the wind. Finally, all crown reconfiguration through reduction of wind resistance occurs. Any more reduction in wind resistance will mean breaking of twigs and branches.

The second constraining storm load threshold (T2) is reached in a tree around 96 miles per hour (~24 pounds of wind pressure per square feet) when the mechanical safety factors of tree structure have been reached for most trees challenged by wind under "average" or normal situations. At this threshold, major damage is being initiated and resistance success by trees against increasing wind pressure is only through shear luck of position, buffering of wind loading by surroundings, or having been challenged by these wind forces over many seasons.

Falling Back

Figure 35 is the Coder Index of Tree Crown Reconfiguration used to quantify stages in how tree crowns fall back against the wind. With increasing wind pressure, more crown tissues are pushed back by the wind, until complete elastic flexure (tissue will return to original position when calm) is reached. After this point, inelastic flexure (permanent tissue creep from mechanical overload) and tissue breakage processes are initiated. For example, an index value of CIII is derived from two pounds of wind pressure per square feet being applied to various components across a tree crown. The tree crown is reconfigured by wind resulting in a period of near linear drag increases until T1 is exceeded. Figure 36 shows wind and ice loads quickly cause 100% crown reconfiguration to be reached in a tree at roughly one-half the

wind velocity as a tree under wind loads with no ice. The result is a tree under increasing wind and ice loads reaching maxiumum crown reconfiguration quickly and accelerating drag.

Conclusions

Trees are amazing for their successful growth and longevity under conditions of severe structural loading from storms. We will continue to be surprised and inspired by trees surviving storms which stripped human structures from the soil surface. Storm wind loads on trees must be accounted for in assessing tree structure and appreciating risks. It is wind load, not tree resistance, which must play a greater role in our observations and understandings of trees standing against the wind.

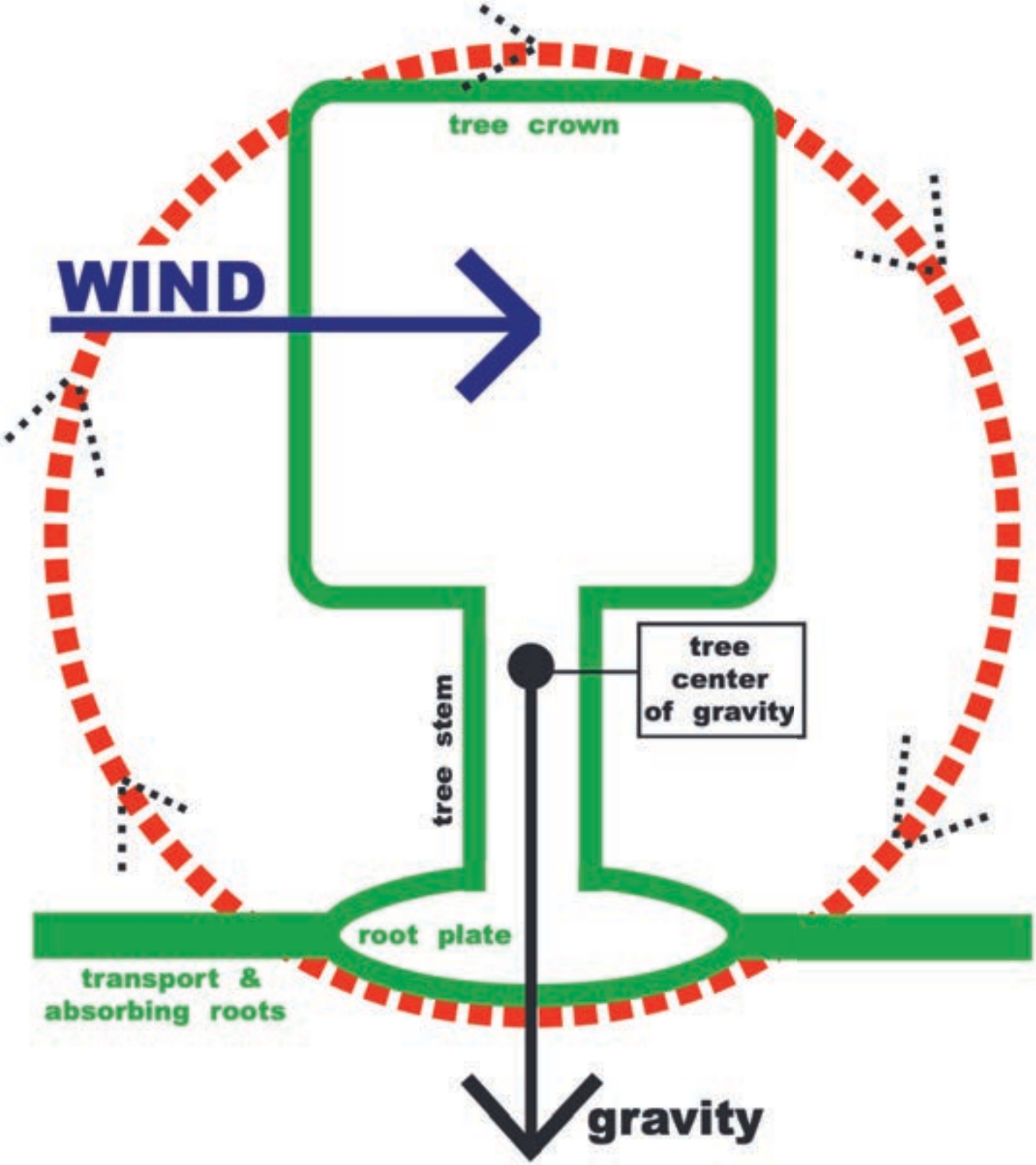

Figure 1: Storm wind forces, and to a lesser degree gravity, act to rotate a tree out of the soil as a combined load wheel.

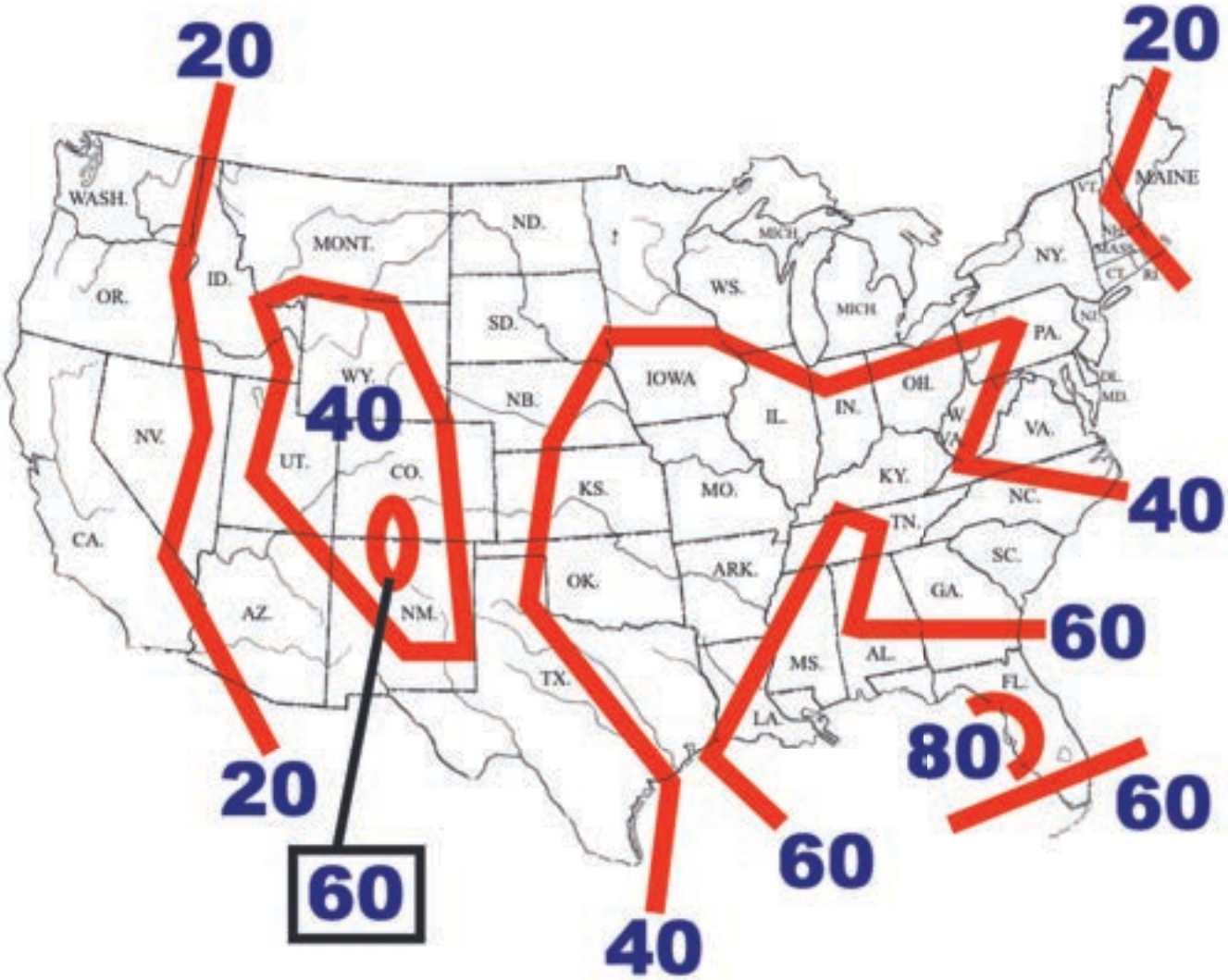

Figure 2: Average number of days with thunderstorm events per year.

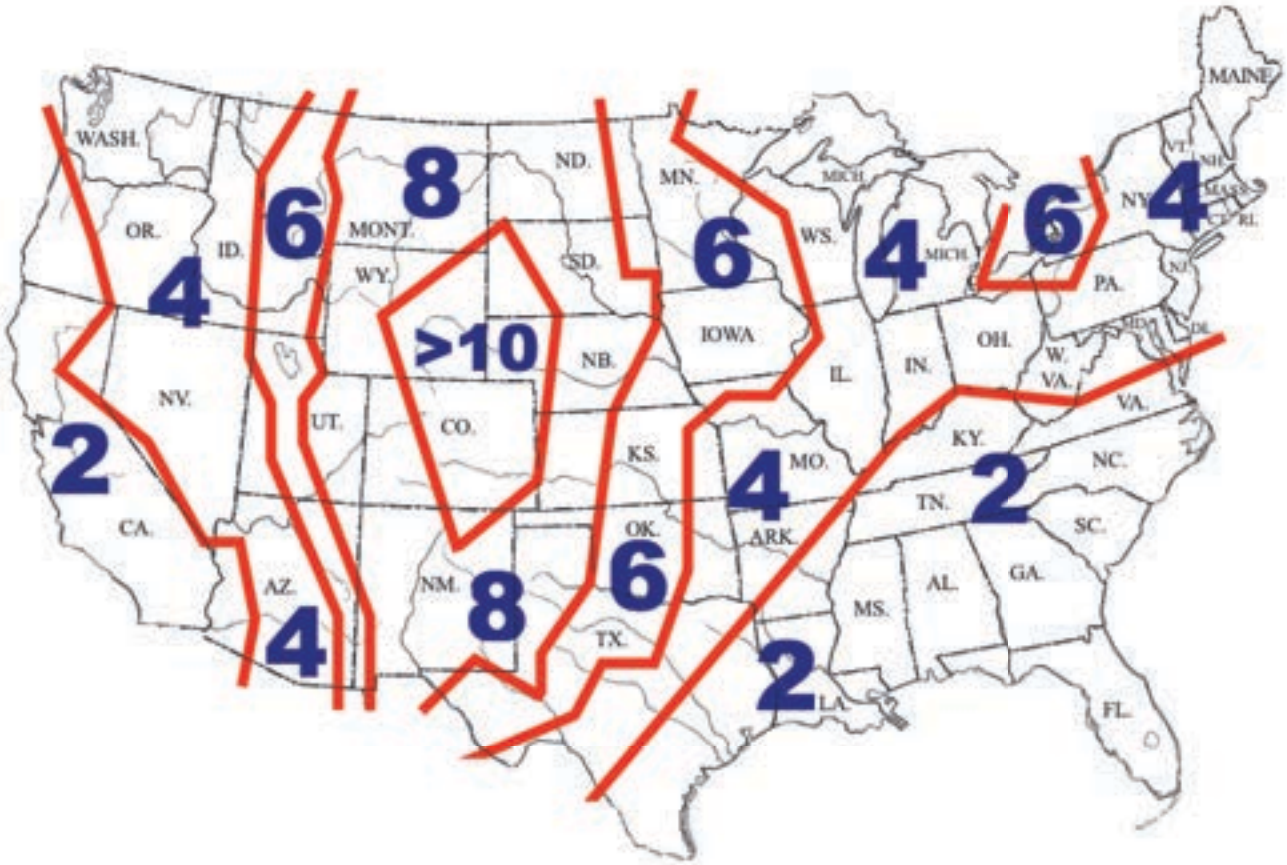

Figure 3: Estmated average number of wind events each year with winds greater than 50 miles per hour. (NOAA data)

force number	wind speed mph	mid-point wind pressure* lbs/ft²	wind force description
0	< 1	< 0.003	calm
1	1-3	0.01	light air
2	4-7	0.08	light breeze
3	8-12	0.26	gentle breeze
4	13-18	0.63	moderate breeze
5	19-24	1.2	fresh breeze
6	25-31	2.1	strong breeze
7	32-38	3.2	moderate gale
8	39-46	4.8	fresh gale
9	47-54	6.7	strong gale
10	55-63	9.2	whole gale
11	64-72	12	violent storm
12	> 73	>14	hurricane

(* column is not part of wind scale but added by author)

Figure 4: Beaufort Wind Scale.

force number	wind speed mph	mid-point wind pressure* lbs/ft²	tree impacts
0	< 1	< 0.003	
1	1-3	0.01	
2	4-7	0.08	leaves rustle
3	8-12	0.26	small twigs move
4	13-18	0.63	large twigs move
5	19-24	1.2	small trees sway
6	25-31	2.1	large branches move
7	32-38	3.2	large trees sway
8	39-46	4.8	twigs break
9	47-54	6.7	small & medium / branch break
10	55-63	9.2	trees break or uproot
11	64-72	12	forests destroyed
12	> 73	> 14	massive tree loss

(* column is not part of wind scale but added by author)

Figure 5: Beaufort Wind Scale with tree impacts.

Figure 6: Historic hurricane landfalls over a 50 year period in the Eastern United States. (from NOAA data)

Figure 7: Estimated number of years between a catagory 3 hurricane landfall. (after NOAA data)

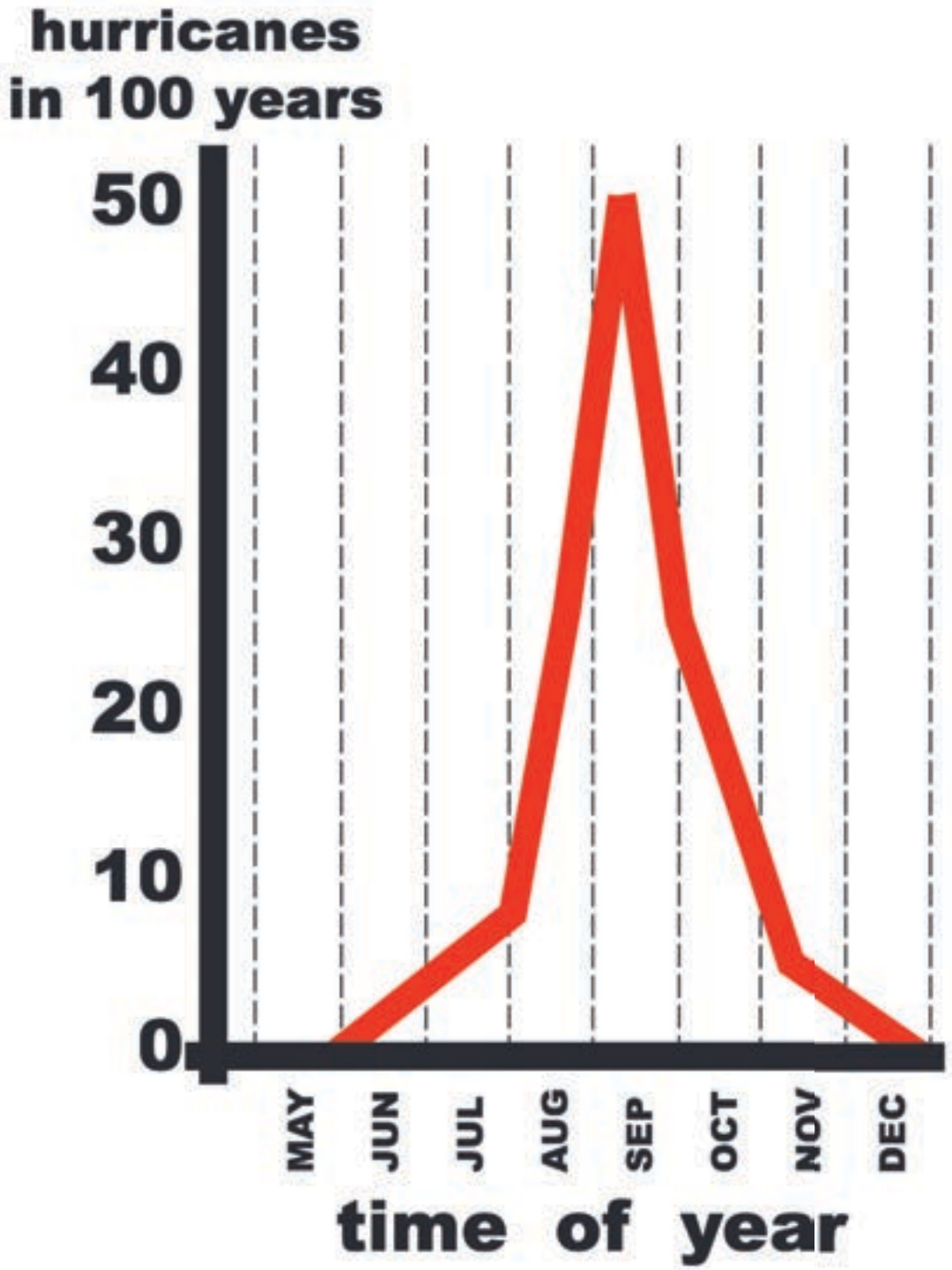

Figure 8: Estimated number of hurricanes in the United States over a 100 year period.
September 10 is peak. (from NOAA data)

storm category	wind speed mph	mid-point wind pressure* lbs/ft²	tree impacts
1	74-95	19	branch & tree failures
2	96-110	28	major tree failures
3	111-130	38	large tree failures – leaves gone
4	131-155	54	massive tree blow-downs
5	> 155	> 63	most trees down

(* column is not part of wind scale but added by author)

Figure 9: Saffir-Simpson Hurricane Scale with tree impacts.

storm category	wind speed mph	mid-point wind pressure* lbs/ft^2	storm surge feet
1	74-95	19	4-5
2	96-110	28	6-8
3	111-130	38	9-12
4	131-155	54	13-18
5	> 155	> 63	> 18

(* column is not part of wind scale but added by author)

Figure 10: Saffir-Simpson Hurricane Scale and associated ocean storm surge levels.

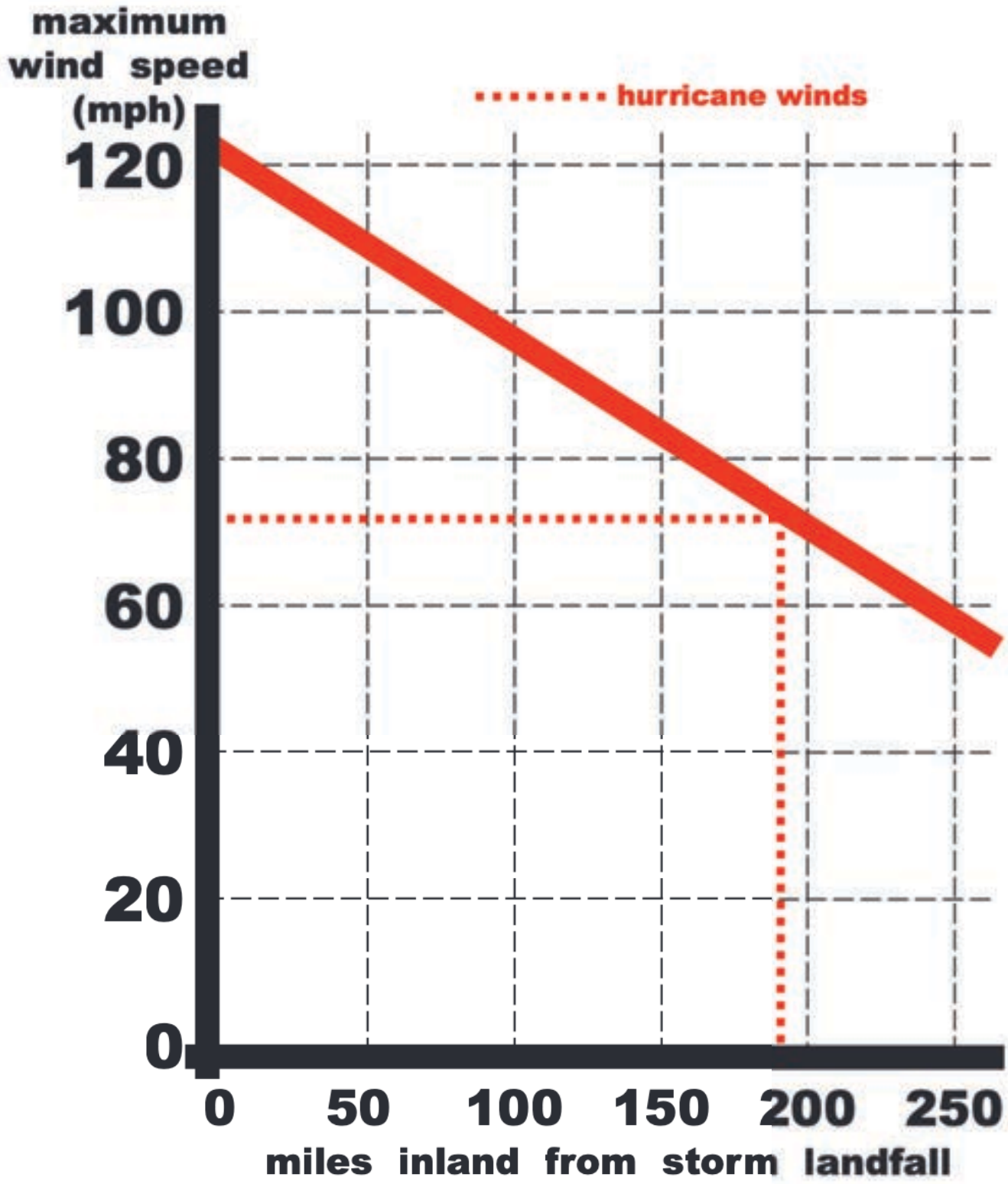

Figure11: Estimated maximum wind speed at various distances inland from a catagory 3 hurricane landfall.

(NOAA data)

Figure 12: Estimated sustained ~60 mph wind speed line for inland areas after a catagory 3 hurricane landfall. (after NOAA data)

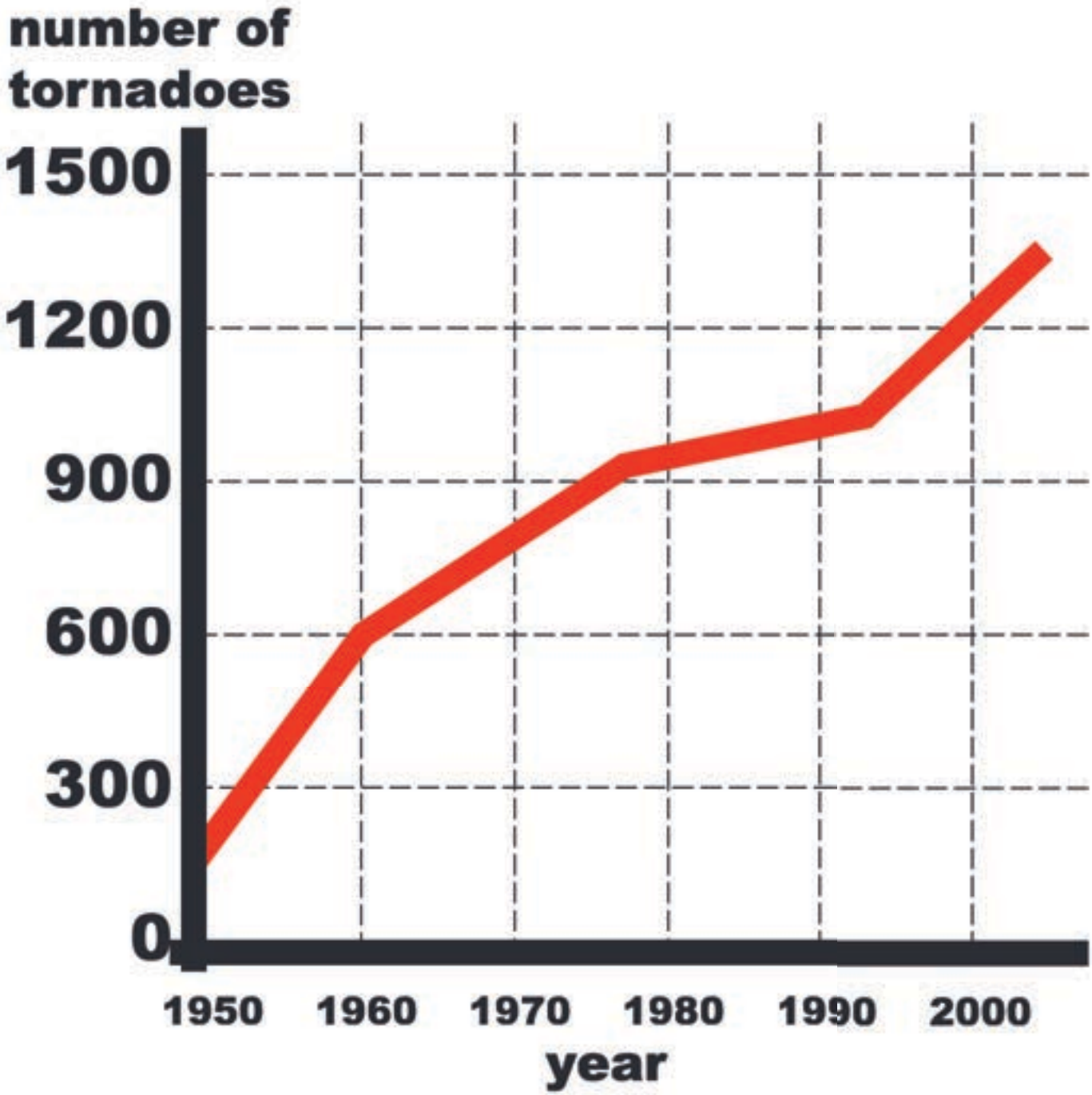

Figure 13: General trend line for tornado numbers. (NOAA data)

Figure 14: Average historic number of tornadoes per year.

category	wind speed range (mph)	mid-point wind pressure (lbs/ft²)*	tornado descriptor
F0	40-73	~8	gale tornado
F1	73-112	23	moderate
F2	113-157	48	significant
F3	158-206	87	severe
F4	207-260	144	devastating
F5	261-318	221	incredible
F6	319-379	321	inconceivable

(* column is not part of the wind scale but added by the author)

Figure 15: Fujita Tornado Scale. (used before 2/1/2007)

category	wind speed range (mph)	mid-point wind pressure (lbs/ft²)*	tree impacts
F0	40-73	~8	minimal damage – branch breakage
F1	73-112	23	moderate damage – trees uprooted
F2	113-157	48	major damage – large trees snapped & uprooted
F3	158-206	87	severe damage – forests flattened
F4	207-260	144	devastating damage – all trees destroyed
F5	261-318	221	incredible damage – tree parts debarked
F6	319-379	321	inconceivable damage – everything flattened

(* column is not part of the wind scale but added by the author)

Figure 16: Fujita Tornado Scale with tree impacts.
(used before 2/1/2007)

F number	gust mph	EF number	gust mph
0	45 - 78	0	65 - 85
1	79 - 117	1	86 - 110
2	118 - 161	2	111 - 135
3	162 - 209	3	136 - 165
4	210 - 261	4	166 - 200
5	262 - 317	5	>200 mph
6	318 - 380		

Figure 17: Comparison of historic Fujita tornado scale (F number) with new Enhanced Fujita tornado scale (EF number), and the speed of wind gusts in miles per hour sustained. (NOAA data)

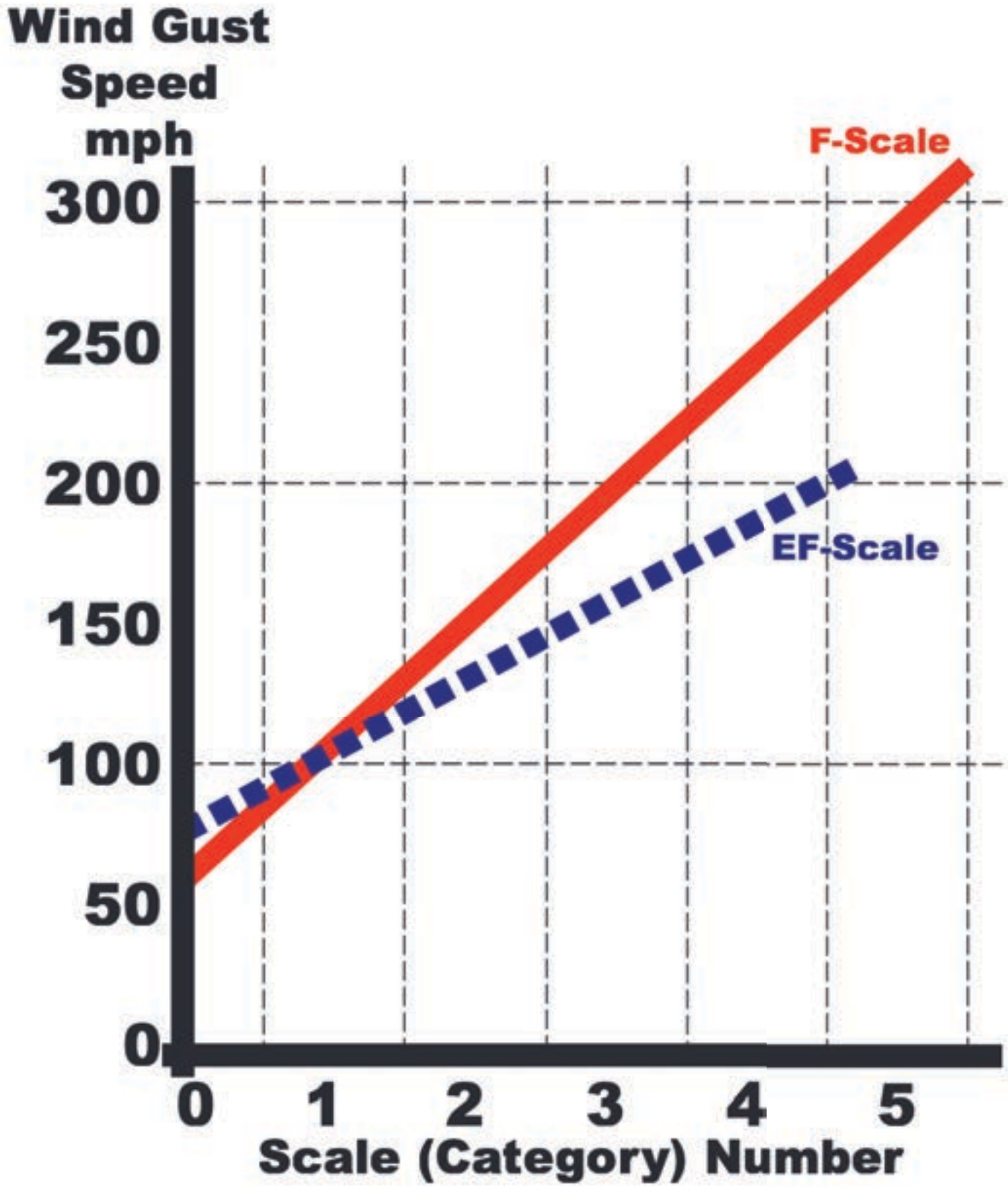

Figure 18: Comparison of F-Scale (solid line) and EF-Scale (dotted line) values. Note both scales are curves but are shown here as straight lines.

category	wind speed range (mph)	mid-point wind pressure (lbs/ft²)*	tornado damge descriptor
EF0	65-85	15	light
EF1	86-110	25	moderate
EF2	111-135	40	considerable
EF3	136-165	60	severe
EF4	166-200	88	devastating
EF5	> 200	>105	incredible

(* column is not part of the wind scale but added by the author)

Figure 19: Enhanced Fujita Tornado Scale
(used after 2/1/2007) (NOAA data)

category	wind speed range (mph)	mid-point wind pressure (lbs/ft^2)*	tree impacts
EF0	65-85	15	branches break
EF1	86-110	25	trees uproot, trees snap
EF2	111-135	40	trees debarked - only branch stubs remain
EF3	136-165	60	trees destroyed
EF4	166-200	88	
EF5	> 200	>105	

(* column is not part of the wind scale but added by the author)

Figure 20: Enhanced Fujita Tornado Scale with tree impacts. (used after 2/1/2007) (NOAA data)

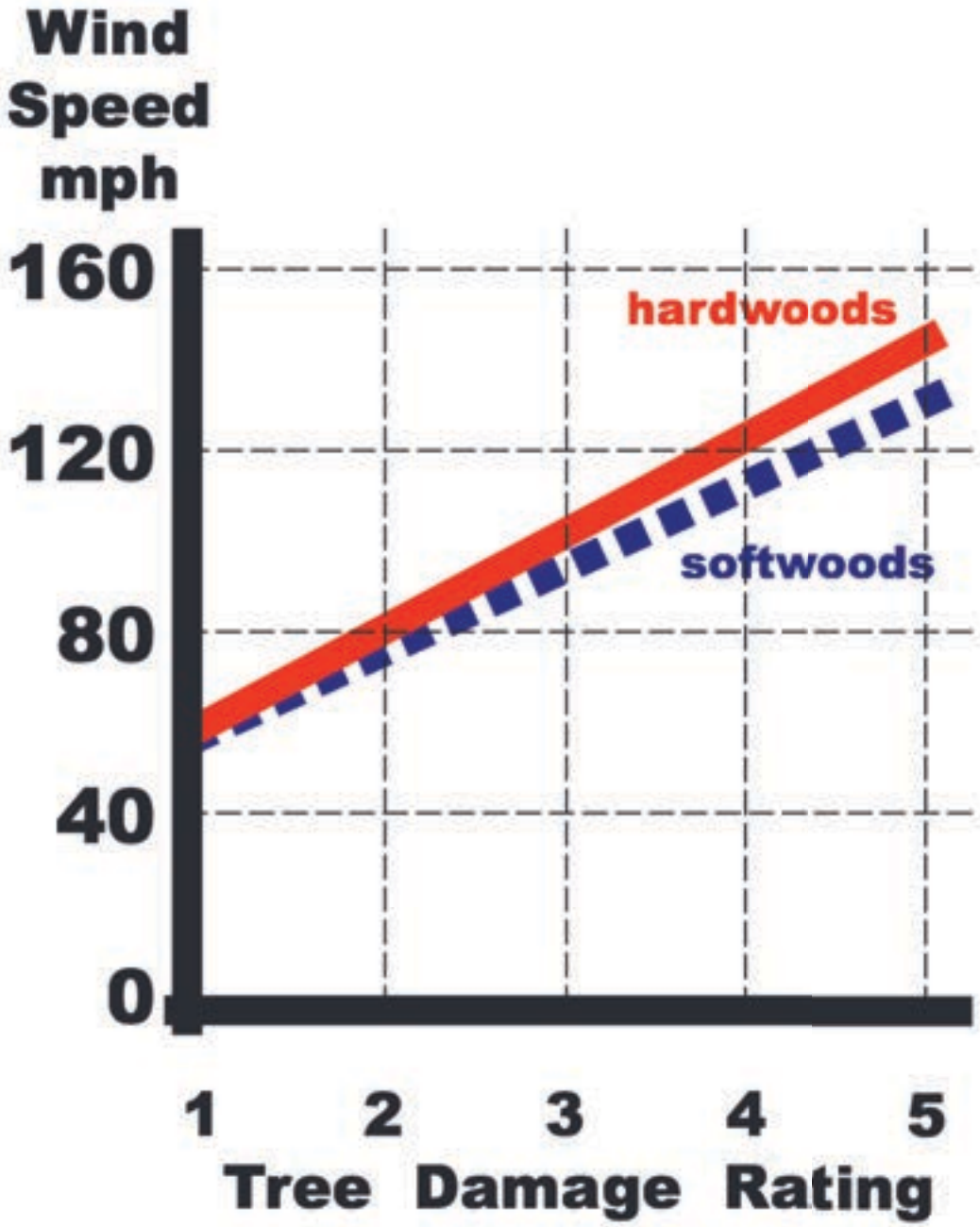

Figure 21: General damage ratings of the EF Scale, in linear form, by wind speed in miles per hour for hardwood (solid line) and softwood (dotted line) trees.

Tree damage rating descriptors: 1 = small limbs broken; 2 = large branches broken; 3 = uprooting; 4 = snapped trunks; 5 = debarked with only branch stubs remaining. (NOAA data)

category	wind speed range (mph)	mid-point wind pressure (lbs/ft^2)*	tornado descriptor
T0	39-54	7.7	light
T1	55-72	11	mild
T2	73-92	18	moderate
T3	93-114	28	strong
T4	115-136	42	severe
T5	137-160	58	intense
T6	161-186	79	moderately devastating
T7	187-212	105	strongly devastating
T8	213-240	135	severely devastating
T9	241-269	171	intensely devastating
T10	270-299	213	super

(* column is not part of the wind scale but added by author)

Figure 22: Meaden Tornado T-Scale.

category	wind speed range (mph)	mid-point wind pressure (lbs/ft²)*	tree impacts
T0	39-54	7.7	twig breakage
T1	55-72	11	slight damage
T2	73-92	18	branch twist & breakage / small trees uprooted
T3	93-114	28	some trees broken
T4	115-136	42	many trees uprooted or broken
T5	137-160	58	most trees uprooted or broken
T6	161-186	79	trees destroyed
T7	187-212	105	partial debarking
T8	213-240	135	trees flattened
T9	241-269	171	complete debarking
T10	270-299	213	all trees blown apart & toppled

(* column is not part of the wind scale but added by author)

Figure 23: Meaden Tornado T-Scale with tree impacts.

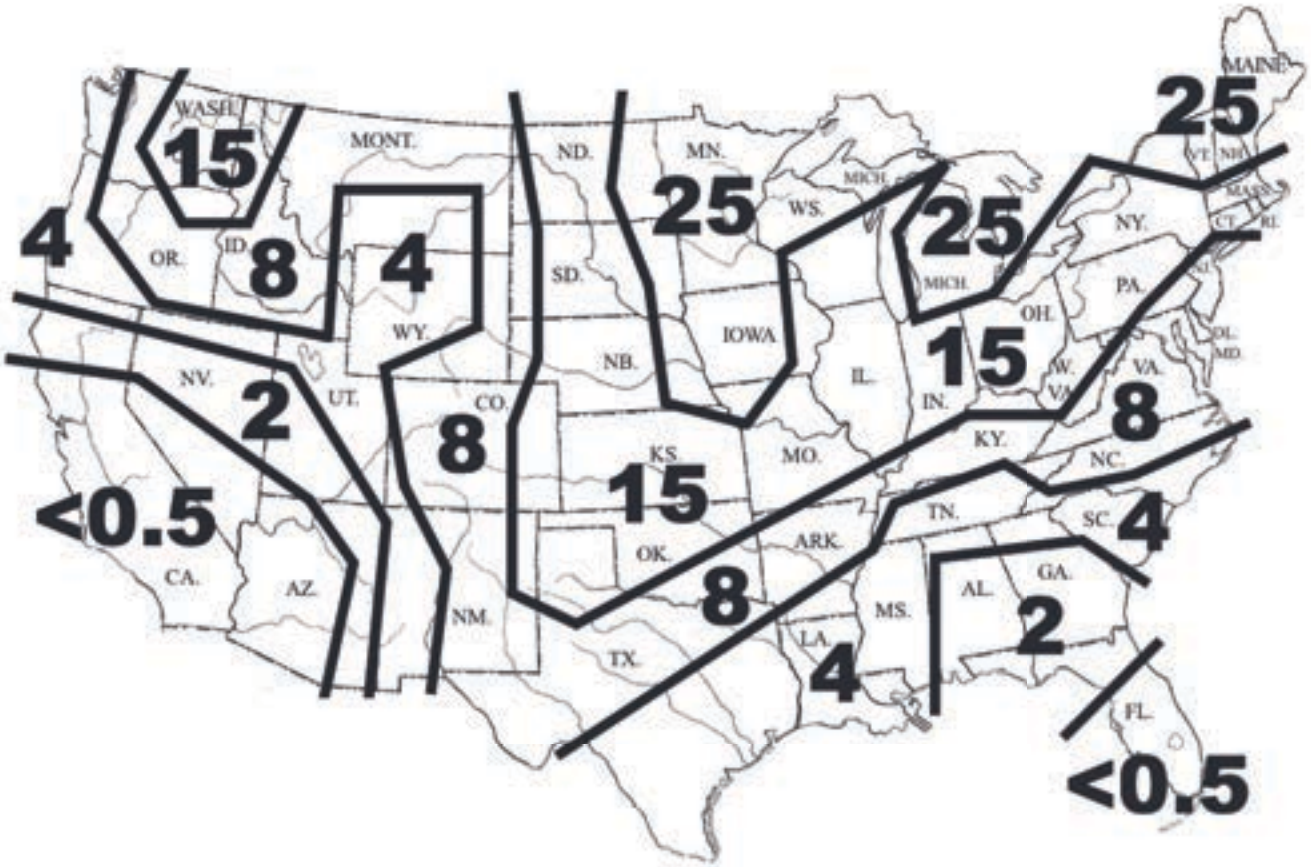

Figure 24: Estimated average number of days in a year with freezing precipitation. (NOAA data)

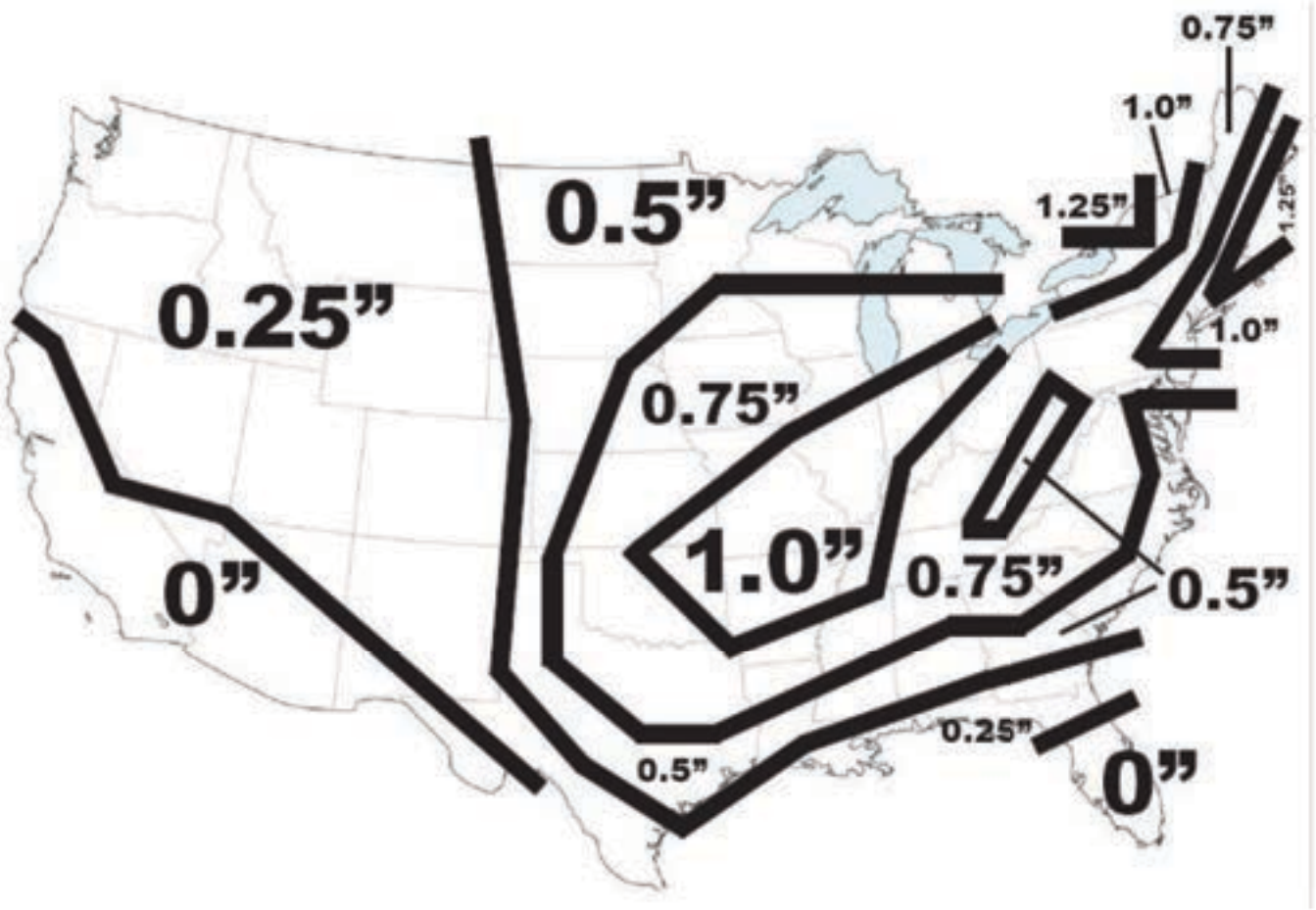

Figure 25: Ice storm ice accumulations (uniform radial thickness in inches) for a once in 50 year storm.
(derived from Jones et.al. 2002)

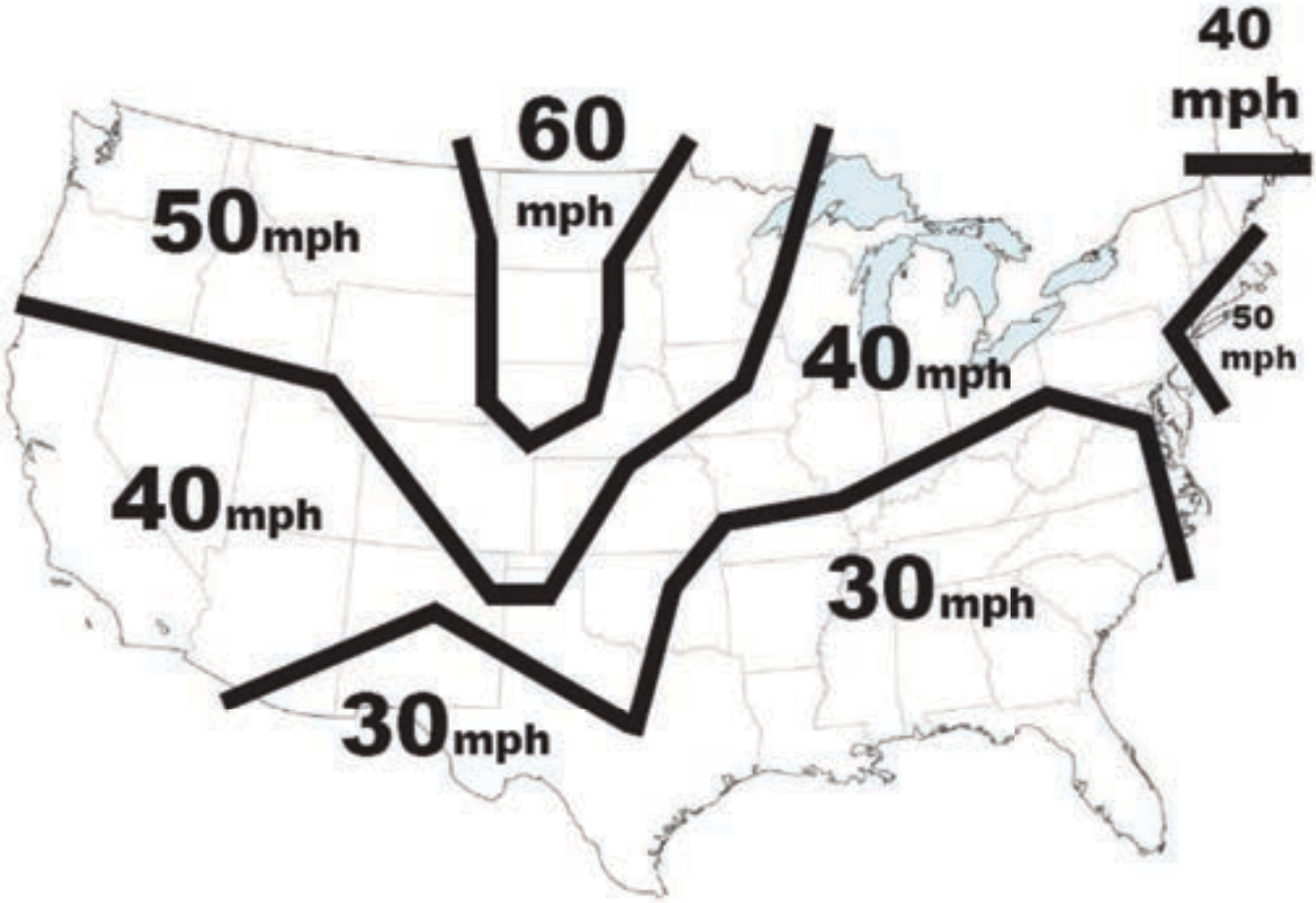

Figure 26: Ice storm wind gusts for a once in 50 year storm (3 second average velocity in mph).
(derived from Jones et.al. 2002)

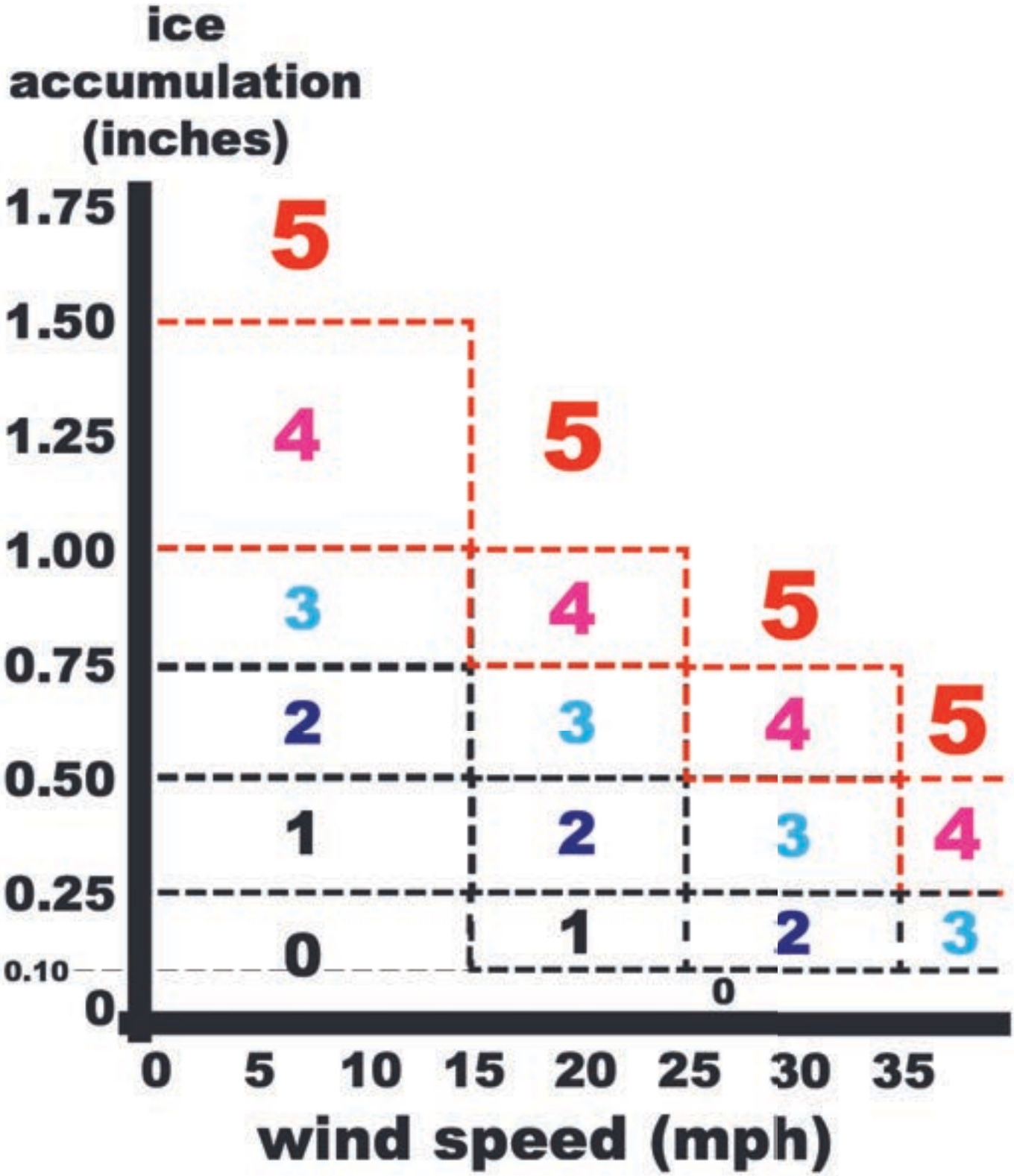

Figure 27: Ice damage severity catagories (SPIA Index) using ice accumulation (inches) and wind speed (mph).
(derived from NOAA 2009)

Figure 28: Maximum rainfall in inches by state for one 24 hour period.

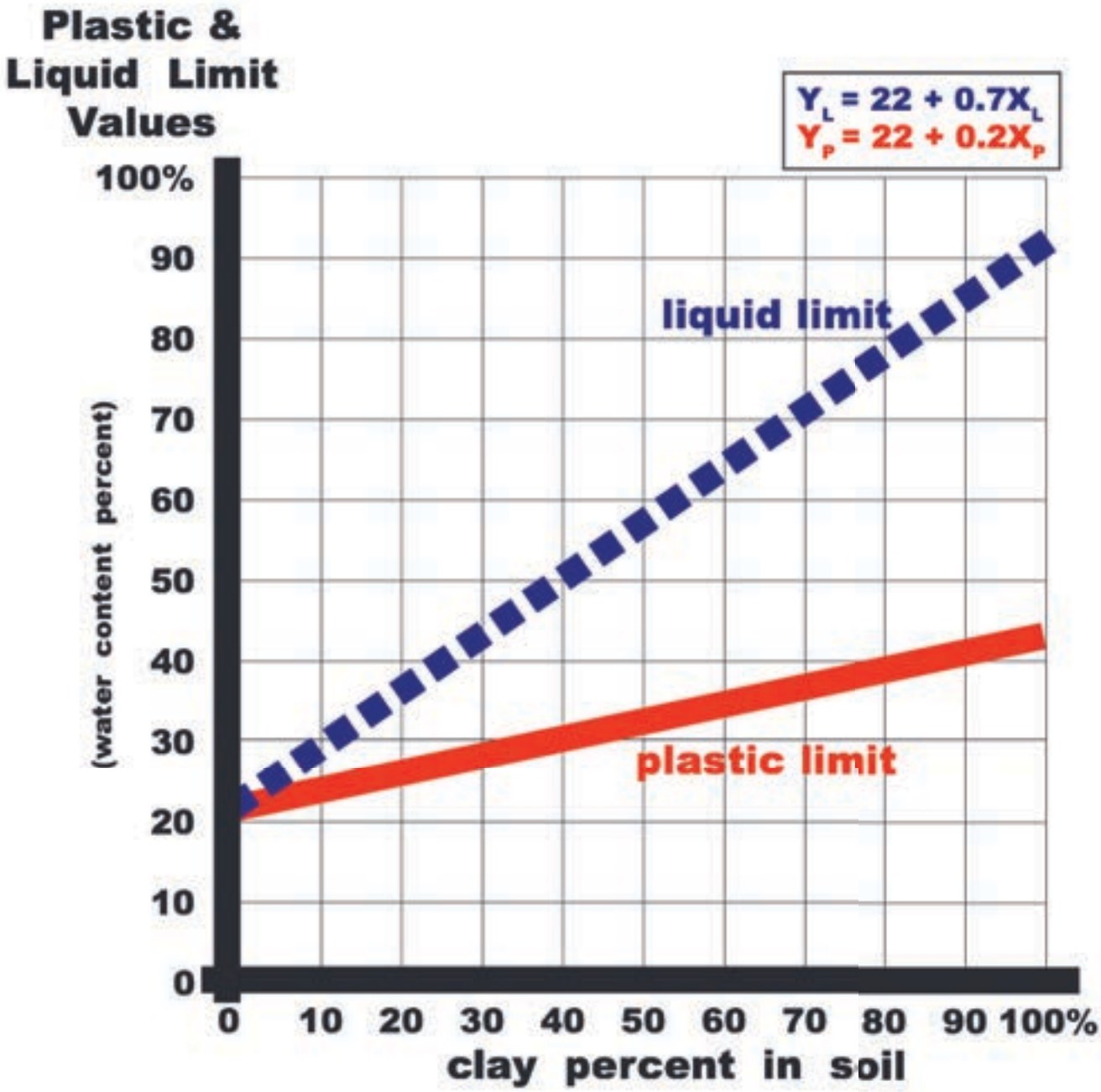

Figure 29: The plastic and liquid limits (water content percent) on soils with various clay contents.

Figure 30: Coder Storm Intensity Map of potential risks for tree damage. Zone 10 represents the greatest storm intensity area, leading to the greatest risk of tree damage.

wind velocity (mph)	pounds per square feet (lbs/ft^2)	wind velocity (mph)	pounds per square feet (lbs/ft^2)
5	0.1	80	17
10	0.3	85	19
15	0.6	90	21
20	1.1	95	24
25	1.7	100	26
30	2.4	110	32
35	3.2	120	38
40	4.2	130	45
45	5.3	140	52
50	6.6	150	59
55	8.0	175	81
60	9.5	200	105
65	11	225	133
70	13	250	165
75	15	275	199

wind pressure in pounds per square foot = (0.013) X (wind speed in mph X (0.45))^2

Figure 31: Estimated wind pressures in pounds per square feet (lbs/ft^2) calculated under standard conditions for various wind velocities in miles per hour (mph).

(drag coefficient = 1.0)

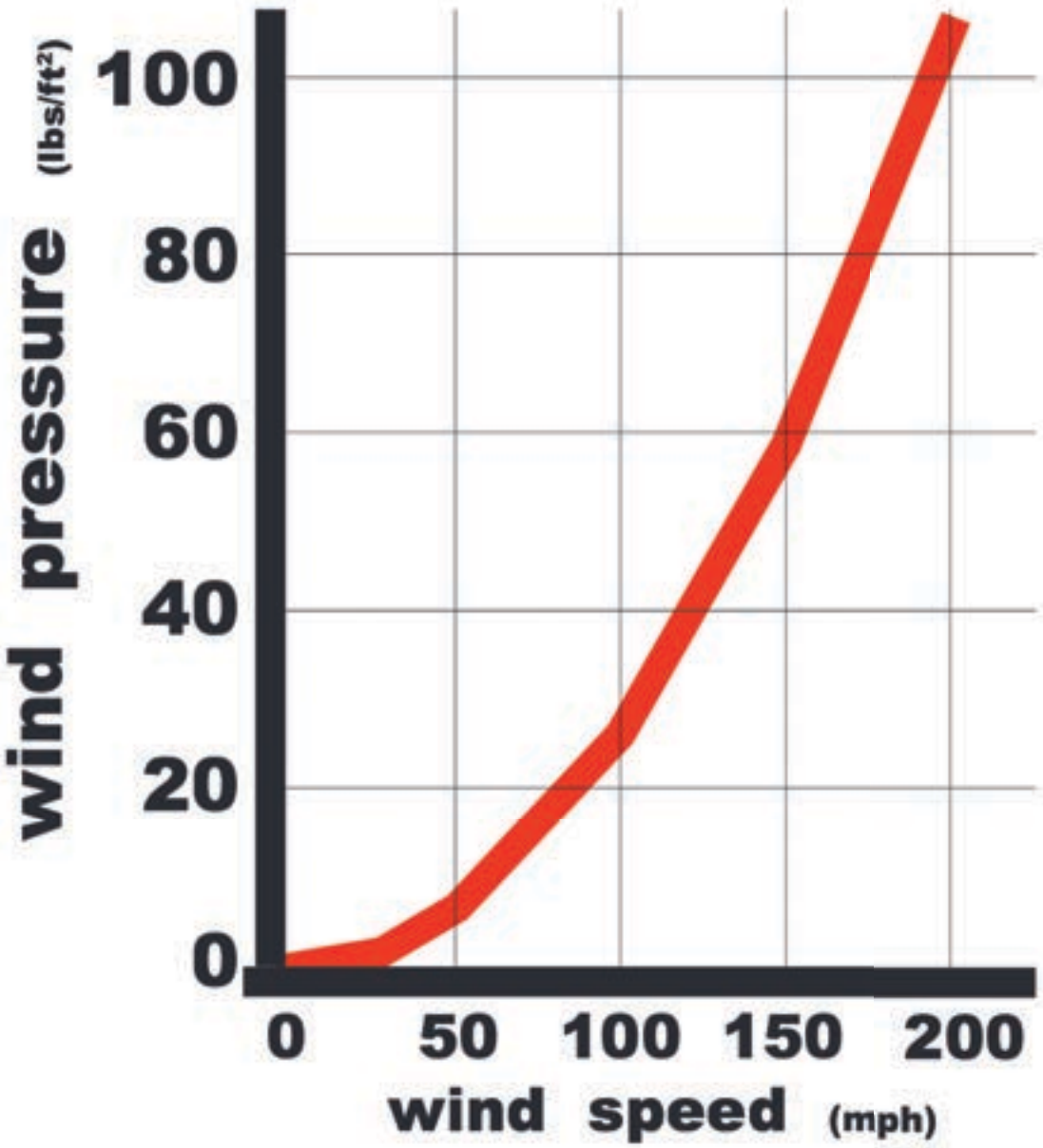

Figure 32: Estmated pressure of storm winds at different wind speeds applied to trees. (drag coefficient = 1.0)

wind pressure in pounds per square feet =
$(0.013) \times (\text{wind speed in miles per hour} \times (0.45))^2$

C-scale value		wind speed mph	wind force lbs/ft²
1		1.0 mph	--
2		5.7	0.09
3		15.6	0.64
4		32	2.7
5	T1	56	8.3
6		88	20.4
6.2	T2	~96	~24]
7		130	44.5
8		181	86
9		243	156
10		316	263 lbs/ft²

Figure 33: Coder Wind Scale (C-scale) of load factors on trees with associated wind speeds in miles per hour and wind loading force in pounds per square foot. (drag coefficient = 1.0)

(C-scale value)$^{2.5}$ = wind speed mph

((C-scale value)$^{2.5}$ X 0.45)^{2} X 0.013 = wind force lbs/ft²

wind speed (mph)	wind pressure (lbs/ft²)	tree damage descriptor
20	1.1	root / soil interface fractures initiated
40	4.2	major stem & crown sway – branch failures
	** T1 = end of crown drag reconfigurations = ~56mph (~8 lbs/ft²) **	
60	9.5	stem breakage – uprooting
90	21	major tree failures
	** T2 = tree safety factors consumed = ~96mph (~24 lbs/ft²) **	
125	41	catastrophic tree losses
>160	67	massive tree destruction

Figure 34: Coder Tree Wind Damage Assessment showing wind velocity in miles per hour, wind pressure in pounds per square foot (drag coefficient = 1.0), potential tree damage, and two wind load thresholds where tree resistance to loads change rapidly.

index value	wind speed (mph)	wind pressure (lbs/ft²)	tree crown reconfiguration descriptor	tree crown reconfiguration value (%)
C0	0	0	gravity impacts only	0 %
CI	10	0.3	petiole & blade deforming, & twig swaying	5 %
CII	19	1.0	leaves rolled back & large peripheral twigs sway	10 %
CIII	28	2.0	twigs pulled back & peripheral branches sway	25 %
CIV	37	3.6	branches pulled back & stem swaying	45 %
CV	46	5.6	twig breakage, stem pushed / held downwind	70 %
CVI	55mph	8.0lbs/ft²	twig & branch breakage (~ T1 threshold)	100 %

Figure 35: Coder Index of Tree Crown Reconfiguration giving index value symbol, wind speed in miles per hour, wind pressure in pounds per square feet, a tree crown reconfiguration description, and a tree crown reconfiguration percentage. (drag coefficient = 1.0)

index value	wind speed (mph)	wind pressure (lbs/ft²)	tree crown reconfiguration value (%) wind	wind + ice
C0	0	0	0	10
CI	10	0.3	5	30
CII	19	1.0	10	60
CIII	28	2.0	25	100
CIV	37	3.6	45	
CV	46	5.6	70	
CVI	55	8.0	100	

Figure 36: Coder Index of Tree Crown Reconfiguration under wind load (drag coefficient = 1.0), and under combined wind and ice loading. (Coder 2014)

Outreach

Warnell School of Forestry & Natural Resources

UNIVERSITY OF GEORGIA

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