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Trees, Sites & Ice Storms: Attributes Leading to Tree Damage, Failure, & Mortality

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Ice storm events happen periodically 2 - 25 years apart in most of the Eastern portion of North America. Figure 1 shows the distribution of ice storms by month, with the peak coming in February and March when warm fronts are moving over cold surface temperatures. Even places in the deep South are not immune to occasional icing events.

In some locations, major ice storms (>$1 million damages) generate catastrophic tree damage every 4 to 100 years apart. Figure 2 demonstrates differences in damage classes for one major ice storm in two locations along its path – Maine and Quebec. Major ice storm impacts on trees have been carefully studied for almost 100 years. This publication will look at more recent studies for what makes trees susceptible to damage and failures.

Damage Components

The three primary interacting components of ice storm damage to trees include: A) ice storm attributes; B) tree attributes; and, C) site attributes. From one ice storm to the next, legacy of past management and damage, current conditions, and short and medium term responses by a tree generate highly variable and complex interactions. This variability produces seemingly contradictory information in different studies regarding why and how trees were damaged or failed.

To review attributes causing (directly or indirectly) tree damage or failure in ice storms, recent studies from Eastern North America were combed for specific storm, tree, and site characteristics found to have led to major tree damage. Estimating tree damage requires definitions and catagories for field use. Figure 3 shows damage classes, severity ratings, or damage catogories used by various studies to define or delineate ice storm damage to trees. Note most use a four position scale for damage observation and 25% increments for branch and crown loss.

Storm - Tree - Site

In reviewing ice storm caused damage in trees, it is possible to formulate some tree health care and management applications in preparation for the next major ice storm. Damage from ice storms could be summarized into four interrelated event items:

1) ice storm loads on trees;
2) tree / site position and location;
3) tree architecture and form; and,
4) tree stem or trunk attributes.

Figure 4 presents primary components as well as the number of individual variables and research citations included in each. General components from each study cited have a number of specific individual terms which have been observed to cause tree damage in ice storms. Note some single citations actually represent multiple studies. Figure 5 shows papers citing multiple studies and whether these multiple studies were included here.

The type of tree damage in ice storms, and proportion of damage types present, can be appreciated within the next two figures from one study. Figure 6 shows proportional damage to bole and canopy, as well as tree mortality, sustained in one major ice storm. Figure 7 presents another view of proportional damage type and mortality in trees.

Outline:
Attributes Leading To Tree Damage

ICE STORM LOADS

TREE POSITION & SITE LOCATION

TREE FORM & ARCHITECTURE

STEMS / TRUNKS / BOLES

Conclusions

ICE STORM LOADS

ICE THICKNESS / WEIGHT – Within major ice storms, storm characteristics vary greatly by location and over time. Ice loads placed on trees to resist can be immense. A major damage component to trees usually considered first is the amount of ice accumulated. Ice thickness and associated weight accumulated by tree structure, can account for many times tree greenwood weight. Ice accumulation is closely involved with meteorological events of precipitation, surface / tree temperature, and atmospheric characters which allow water supercooling. Bragg & Shelton 2010; Bruederle & Stearns 1985; Hauer et.al. 2011; Kraemer & Nyland 2010; Prouix & Greene 2001; Rhoades & Stipes 2007; Seischab et.al. 1993; Sisinni et.al. 1995; Smolnik et.al. 2006; Weeks et.al. 2009.

For example, Figure 8 shows ice accumulation and percent of stems with greater than 75% crown loss for an ice storm. The 50% point of severely damaged trees occurs roughly at 70mm (2.75 inch) of ice accumulation. Figure 9 presents the probability of tree mortality with increasing ice accumulation. Expectation of tree mortality is 10% with ice accumulations of ~47mm (~1.85 inches), and is predicted to reach 100% of trees dead with an ice accumulation of 100mm (3.9 inches).

Figure 10 shows the percent of trees damaged with increasing ice accumulation. In this study, the point where half of all trees are damage occurs around 36mm (1.4 inches) of ice. Figure 11 presents another way of considering tree damage. This figure shows the amount of downed tree debris expected as ice accumulation increases.

Figure 12 shows ice thickness and amount of tree damage and mortality. Figure 13 also presents the level of tree mortaility with ice accumulation. As ice accumulation exceeds 0.5 inches, mortality significantly increases. Figure 14 follows ice damaged trees five years after a major ice storm to examine mortality given the type of damage a tree sustained. Note root tipping during a major ice storm led to large mortality levels within five years.

ELEVATED WIND LOADS – As trees accumulate ice, some ice storms generate additional loads on trees through elevated wind velocity, measured either as average wind speed or as peak gusts. A tree loaded with huge amounts of ice, and with branches and twigs stiff from ice, allows any wind load to be accentuated. Higher velocity winds can match and exceed structural loads caused by ice alone.

The wind loading environment of an ice storm can range from no wind and vertical freezing rain fall, to large lateral loads with strong gusts and heavy ice accumulation. Figure 15 presents the proportion of tree damaging agents between ice accumulation and ice storm associated wind. Note the combination if ice accumulation and significant wind has a synergistic impact on trees. Bragg & Shelton 2010; Bruederle & Stearns 1985; Hauer et.al. 2011; Irland 2000; Kraemer & Nyland 2010; Lafon 2004b; Lafon et.al. 1999; Prouix & Greene 2001; Rebertus et.al. 1997; Rhoads et.al. 2002; Seischab et.al. 1993; Sisinni et.al. 1995; Smith 2000; Smolnik et.al. 2006; Weeks et.al. 2009.

ICE LOAD DURATION – One interesting component of ice storm damage is ice duration on tree surfaces. Topography, follow-on weather conditions minimizing sunlight, and stalled weather systems can lead to any ice accumulated remaining on a tree for longer periods of time. Some ice accumulations may be gone within hours, other accumulations my hang on trees for days. Ice duration brings more strength and resistance to bending or failure, tree architecture, and site characteristics for resisting mechanical stress and strain into a tree load equation. Longer duration ice causes greatly increased damage. Bragg et.al. 2003; Kraemer & Nyland 2010; Rhoades & Stipes 2007; Takahashi et.al. 2007; Vowels 2012.

ICE STORM RETURN RATE – A component of ice loading on trees over their lifespan is the periodicity of ice storms on a site. The more a tree is challenged by light icing and associated light wind events, the greater chance damaged, poorly connected, or dead materials will be cleaned from a tree. This natural cleaning of the crown minimizes canopy surface area for future ice accumulation and wind loading. For major ice storm events, tree structural components may be loaded beyond native safety factors and catastrophically fail. The smaller the number of years between major ice storms, the more stress and strain structural components are under, and any faults generated can be multiplied in the next major ice storm. Kraemer & Nyland 2010.

TREE POSITION & SITE LOCATION

GENERAL TOPOGRAPHY – In many studies, topography is cited as being among the causal agents for tree damage due to impacts on ice and wind loading, ice duration, and ice storm periodicity. Many studies do not specifically list topographic features except as elevation, slope, slope position, and aspect. Elevation in particular has been found to have a direct impact on trees. The higher elevation in mountainous terrain, the worse tree damage in ice storms. Landscapes provide complex and chaotic variability in ice loading and tree resistance. Bragg et.al. 2003; Bruederle & Stearns 1985; Lafon et.al. 1999; Prouix & Greene 2001; Rebertus et.al. 1997; Rhoads et.al. 2002; Seischab et.al. 1993; Sisinni et.al. 1995; Smith 2000; Takahashi et.al. 2007; Vowels 2012; Warrillow & Mou 1999.

Elevation does increase exposure to ice and wind, but damage remains highly variable. For example, Figure 16 demonstrates how elevation increases ice accumulation. In this figure, up to 700 meters (2,250 feet) of elevation increase showed ice accumulation amounts greatly increased. Figure 17 presents a nearly opposite observation along a topographical mediated moisture gradient (dry ridge tops to mesic bottoms) where tree ice damage significantly increases (>5X) under more moist growing conditions. Soil features and tree height strongly interact with topography.

TOPOGRAPHIC POSITION – In predicting ice storm severity, cold air damming, cold air drainage, and lower slopes have been cited as involved with tree damage. Both formation of ice storm events and duration of ice on trees can be associated with some topographic positions. A given tree site may be loaded repeatedly from ice for long periods, while neighboring sites may not sustain the same ice loads as often due to topographic position. Lafon 2004a; Rebertus et.al. 1997; Takahashi et.al. 2007; Vowels 2012.

STEEP SLOPES – Consistently, trees growing on steep slopes are cited as being damaged or toppled by ice storms. The amount of slope steepness is difficult to place a degree or percent value on because other soil factors and rooting attributes are also impacted by steep slopes. As slope increases, soils become thinner and the root impervious soil zone below the ecologically active zone is closer to the surface. With diminished rooting volume to help remain upright, trees can be damaged or toppled by less ice and wind loading. Figure 18 shows tree damage probability as slope increases. Increasing slope tends to decrease canopy damage but increase severe trunk damage. Bragg et.al. 2003; Bruederle & Stearns 1985; Lafon 2004a; Lafon 2004b; Kraemer & Nyland 2010; Mou & Warrillow 2000; Prouix & Greene 2001; Rebertus et.al. 1997; Rhoades 1999; Rhoads et.al. 2002; Seischab et.al. 1993; Sisinni et.al. 1995; Vowels 2012; Warrillow & Mou 1999.

EDGE TREES – Many studies observe edge trees more susceptible to damage than stand interior or protected trees. There are differences among studies due to tree locations and tree age. Trees newly exposed at the edge of roadcuts, right-of ways, or harvest cuts can be quite prone to damage. Long established trees both on the edge and interior share similar potential damage, except where an edge tree has a significantly lopsided canopy. Generally, edge trees are more easily damaged in ice storms than interior forest trees. Beaudet et.al. 2007; Bragg et.al. 2003; Hauer et.al. 1993; Jacobs 2000; Mickovski et.al. 2005; Prouix & Greene 2001; Rebertus et.al. 1997; Seischab et.al. 1993; Smith 2000. In a contrasting view, some interior stand trees with vines, emergent or dominant canopy position, and other characters sustain great tree damage from ice storms. Jacobs 2000.

Figure 19 presents average canopy loss for sugar maple (*Acer saccharum*) in stand interior and edge positions with increasing ice accumulation. Note as ice accumulation increases, trees within stands sustain more canopy loss. Figure 20 presents average canopy loss for red maple (*Acer rubrum*) in a stand interior and edge position with increasing ice accumulation. Note in this species, the edge position trees sustained much more damage as ice increases. There are many difference between these two species and the sites they prefer. Stating one position or the other alone (i.e. either edge or interior grown), is not the sole attribute defining tree ice damage.

EXPOSURE TO WIND & ICE – Slopes and ridgetops where wind and ice accumulation is most direct can have significant damage, even under smaller ice accumulations. Windward positions, and exposed slopes, allow more tree loading and so, more tree damage. Figure 21 presents tree canopy damage from windward to leeward exposure. Note windward exposed trees had greater ice damage. Bragg et.al. 2003; Bruederle & Stearns 1985; DeSteven et.al. 1991; Kraemer & Nyland 2010; Millward & Kraft 2004; Lafon 2004b; Lafon et.al. 1999; Rebertus et.al. 1997; Rhoades 1999.

ASPECT – The direction a slope faces has been shown to play a role in tree damage from ice storms. Slope aspect can have two compounding attributes: A) facing the ice storm for ice accumulation and wind loading; and, B) preventing fast melting of ice accumulation (longer ice duration). Northeast and East aspects have been cited as providing more tree damage than other slope directions. Bragg et.al. 2003; Bruederle & Stearns 1985; Hauer et.al. 1993; Rebertus et.al. 1997; Seischab et.al. 1993; Smith 2000; Vowels 2012; Warrillow & Mou 1999.

TREE FORM & ARCHITECTURE

POOR FORM – A nebulous description of a tree which has sustained damage from ice is the term "poor form." There are many features of a tree which allows resistance or failure under ice and associated wind loads. The concept of poor tree form or poor architecture is not well defined in most studies, but is cited numerous times as leading to ice damage. In some studies, authors continue on to better define and delineate poor form in an ice storm damage context. Boerner et.al. 1988; Bragg et.al. 2003; Brommit et.al. 2004; Bruederle & Stearns 1985; Hauer et.al. 1993; Rhoads et.al. 2002; Sisinni et.al. 1995.

TREE SIZE – One key measurable characteristic of a tree is its size. Tree size usually represents canopy volume, reach and extent, as well as branch and stem diameters / girth. For many studies, the larger a tree, the greater damage from ice storms. Large size carries large ice accumulation surface areas for the amount of greenwood tissue present and its inherent mechanical properties. This tree attribute is still quite general in its application to ice storm damage. Boerner et.al. 1988; Kraemer & Nyland 2010; Lafon 2004a; Prouix & Greene 2001; Rebertus et.al. 1997; Rhoads et.al. 2002; Ryall & Smith 2005; Takahashi et.al. 2007; Vowels 2012; Zipperer et.al. 2004.

TREE AGE – Tree age, like tree size, is a measurable character of a tree. Because many times tree size and age increase together, although at continuously varying rates, the older a tree becomes, the more likely it is to sustain ice damage. Increasing age and ice damage is a complex variable because as trees age, more wind storms, soil movement, decay, pests, and human injury can occur. In some sense, ice storms clean the crown of unsound and damaged branches and twigs. Bragg et.al. 2003; Brommit et.al. 2004; Bruederle & Stearns 1985; Lafon & Speer 2002; Rhoads et.al. 2002; Sisinni et.al. 1995; Smith 2000.

TREE HEIGHT – The physical size of a tree, specifically height, can lead to ice storm damage. Both tree height above its neighboring trees, and total tree height, places a tree further into a wind loading and ice accumulation zone above ground. The taller a tree, the greater ice storm damage sustained.

Figure 22 shows height impacts as overstory trees and understory tree damage. Of the 22% overstory trees damaged in this study, 91% were considered severly damaged and 57% were uprooted. Only 8% of understory trees were damaged with 29% of these severely damaged. Figure 23 presents overstory tree species and relative damage. The overstory pine (*Pinus*) species were damaged more severely than overstory oak (*Quercus*) species. Amateis & Burkhart 1996; Boerner et.al. 1988; Kraemer & Nyland 2010.

Another aspect of increasing tree height is where (and how far away) debris will fall. Figure 24 suggests a debris radius field around a tree when canopy damage occurs (not whole tree failure and toppling). Most debris falls or becomes entangled within 20% of tree height away from a tree. Note this is based upon power structures data. Mulherin 1996

CENTER OF MASS – When the center of a tree's mass moves off-center or beyond its base or root plate, gravity compounds ice and wind forces leading to catastrophic failure. The center of tree mass can be estimated using several regional or species specific formula. Generally, tree center of mass is usually near 35% – 40% of tree height along its main axis. As ice accumulates and wind loads increase, significant change in center of mass can occur due to root / soil failures, stem bending, branch loss, increasing canopy asymmetry, and other structural load changes. Prouix & Greene 2001.

VINES – A interesting load component magnified by ice storms is the present of vines on / in a tree. Vines can greatly increase surface area for ice accumulation but provide little structural support resisting ice and wind loads. The greater number of vine stems and surface area added to a tree, the more likely ice storm damage will occur. Some forests depend upon vine-caused failures to open small canopy gaps. Ice storms may be a mechanism for sudden gap formation. Bragg et.al. 2003; Kraemer & Nyland 2010; Lafon et.al. 1999; Seischab et.al. 1993; Smith 2000.

TREE LIFE-FORM – There has been many observations regarding differences between evergreen conifers and deciduous broadleaf trees to ice damage. Roughly 2/3s of ice storm studies designate evergreens as more susceptible to damage. Figure 25 provides a percent of severely damaged tree species divided between needle-leaved and broad-leaved. Broad-leaved tree species in this study sustained ~38% less damage than needle-leaved tree species. Boerner et.al. 1988; Brommit et.al. 2004; Hauer et.al. 1993; Irland 2000; Rhoades & Stipes 2007; Smith 2000; Travis & Meentemeyer 1991; Warrillow & Mou 1999; Whitney & Johnson 1984.

About 1/3 of studies observed broadleaf trees as more susceptible to ice damage compared with evergreens. Hauer et.al. 1993; Irland 2000; Jacobs 2000; Millward & Kraft 2004. The increased surface area of evergreens during ice storm season has been suggested as a causal agent for damage, but other tree and site variables, as well as storm attributes, are more dominant in leading to damage than simple life-form strategy.

INTERMEDIATE SIZE TREES – One observation concerns forest tree damage by size class. Large and small size classes are damaged and have some recovery potential. Pole size stands seem to be caught in an intermediate phase of developing mechanical resistance to loads. Pole size stands tend to sustain more damage and more mortality in ice storms than other size classes. Hook et.al. 2011; Vowels 2012.

EXOTICS & NON-NATIVES – An interesting observation suggested differences in exotic / non-native tree susceptibility to ice damage. A number of species of non-native trees, as found in urban forests, tend to sustain significantly more ice damage than native trees. Irland 2000.

STEMS / TRUNKS / BOLES

STEM DIAMETER – For most studies, tree diameter increases symbolize a larger crown, more surface area, and taller form, and so, increasing ice damage. As trees increase in girth, over all size increases and presents more opportunity for ice and wind loading, and associated damage. Figure 26 presents the probability of tree ice damage based upon tree diameter. Amateis & Burkhart 1996; Boerner et.al. 1988; Rebertus et.al. 1997; Rhoades & Stipes 2007; Seischab et.al. 1993; Sisinni et.al. 1995. Two studies did find smaller diameters led to more ice damage, although collateral damage from overstory falling debris damaging mid- and lower story trees can be a significant part of any ice storm. Lafon 2004a; Ryall & Smith 2005.

Stem diameter is a complex variable. Figure 27 shows decreasing probability of stem damage from ice loads with increasing diameter. Figure 28 shows the percent of trees damaged by a major ice storm based upon diameter. The type of damage is presented, with large trees having large amounts of canopy damage and small diameter trees having a mix of damage types. Figure 29 presents a summary list of tree diameters and expected ice storm damage. The middle diameters had catastrophic failures. Figure 30 shows the severity of damage from ice by tree size class. The largest size class (>24 inch dbh) sustained the highest level of ice damage in this study. Stem diameter alone is not an effective way of determining ice storm damage due to many other interactions between diameter and loads.

BASAL AREA OF STAND – Basal area is a measure of site / stand density or stocking. As basal area increased, most studies found ice storm damage increased. Most studies suggested the less tapered growth form of trees in high basal area stands led to more ice damage. Boerner et.al. 1988; Bragg et.al. 2003; Ryall & Smith 2005. One study suggested at the low end of basal area, trees are prone to ice damage as they are not fully open grown and well tapered, but are still more forest-like and ill-formed for minimizing ice storm damage. Smith 2000.

STEM LEAN – Leaning trees can have their resistance to mechanical stress and strain compromised by center of gravity and crown assymmetry changes. The more lean (in degrees or percent) of a stem, the greater chance of ice storm damage. Figure 31 presents how ice associated bending or lean can be recovered / corrected over five (5) years. Note after 45^o of lean is reached in initial ice storm damage, little recovery occurs. Small leans of less than 20^o can be recovered well. Boerner et.al. 1988; Lafon 2004a; Rhoads et.al. 2002.

STEM FORM FACTOR – Lack of strong tree stem taper, or more slenderness over its length, was found to allow more ice storm damage. Especially with lateral wind loads under ice loads, lack of taper led to greater ice load damage. Bragg et.al. 2003; Mickovski et.al. 2005; Vowels 2012.

THINNING STANDS – An interesting observation regarding silvicultural treatments was cited in two studies. Stands of trees in a forest setting which were unthinned tended to have greater ice storm damage. Mickovski et.al. 2005; Ryall & Smith 2005. On the other hand, stands of trees immediately after heavy thinning showed more ice storm damage than unthinned stands. Irland 2000; Kraemer & Nyland 2010. Thinning may help reduce ice damage if the treatment is light to intermediate in application, but can allow more damage immediately after a heavy thinning, until trees structurally adjust to their new mechanical load environment.

MULTIPLE STEM FORMS – Trees growing in a clump or multiple stem group, as opposed to a single stem, sustained more ice damage. The resistance of multiple stem trees is reduced from ice loads by how stem and root plate portions for each individual stem interacts each other and with ice and wind loads. Seischab et.al. 1993.

Conclusions

Trees can bear tremendous ice and wind loads. Components of ice storms, tree archetecture and structure, and site issues can conspire to generate unusual or rare loading patterns for which a tree may not have been challenged in the past and is ill-prepared to resist. It is critical tree health care providers and community foresters understand the diversity of impacts to tree structure from various types and forms of ice storm loads upon trees.

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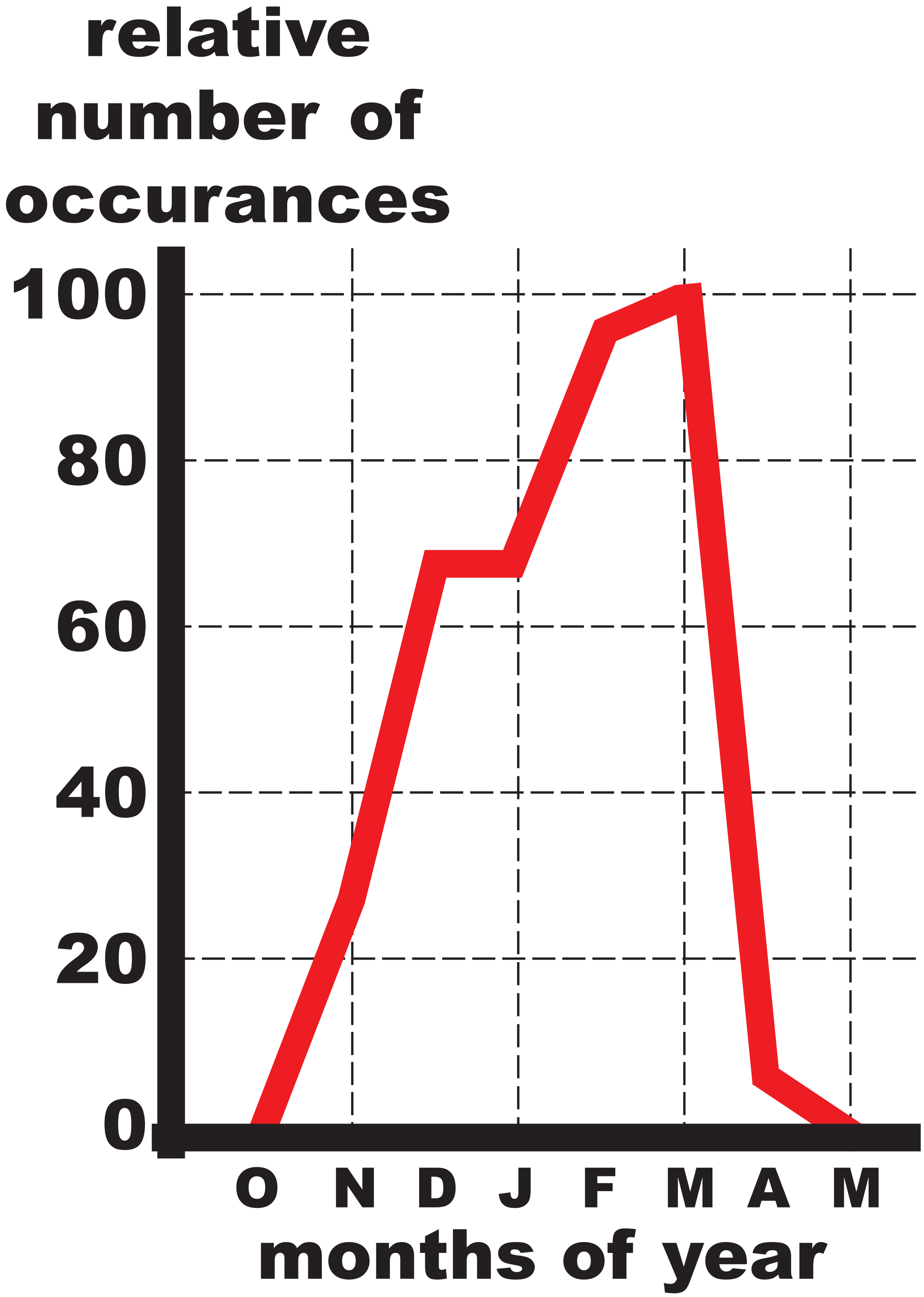

Figure 1: Ice storm damage by month. (Mulherin 1996)

NE North America
Ice Storm - 2 Locations

damage classes	M%	Q%
none / trace / slight	47	34
light / moderate	22	30
moderate / severe	29	32
heavy / very severe	2	4

M = Maine; Q = Quebec

Figure 2: Variation in damage classes within same major ice storm seperated by a short distance. (Irland 2000)

DAMAGE CATAGORIES

Bragg & Shelton 2010
insignificant
minor
moderate
major
critical
lethal

Wonkka et.al. 2013
none / little - <5% crown loss
little 5-25% crown loss
moderate 25-50% crown loss
bad >50% crown loss
severe total crown loss

Duguay et.al. 2001
undamaged / <5% branches
little impact 5-25% branches
moderate 25-50% branches
bad >50% branches
severe 100% canopy loss / broken bole

Ryall & Smith 2005
no visible damage
<25% crown damage
25-50% crown damage
50-75% crown damage
stem breakage / loss

Wonkka et.al. 2013
bent bole
leaning bole
snapped bole
uprooted bole

Rebertus et.al. 1997
no damage
light damage
moderate damage
heavy damage

Wonkka et.al. 2013
no crown loss
1-49% light crown loss
50-79% heavy crown loss
80-100% severe crown loss

Smolnik et.al. 2006
0-4% crown loss - very light
5-33% crown loss - light
34-66% crown loss - moderate
>67% crown loss - severe

Wonkka et.al. 2013
none
<25% light crown loss
25-75% moderate crown loss
>75% severe crown loss

Vowels 2012
none
light
moderate
severe

Irland 2000
none / trace
light
moderate
heavy

Whitney & Johnson 1984
none / little
permanently bent
>50% crown loss
fallen

Shortle et.al. 2003
<50% crown loss
50-75% crown loss
>75% crown loss

Warrillow & Mou 1999
undamaged / <25% crown loss
25-75% crown loss
>75% crown loss

Tremblay et.al. 2005
low susceptibility to damage
intermediate
highly susceptible to damage

Figure 3: Example number of, and descriptions of, descrete ice damage catagories used in ice storm studies cited here. (average catagories used = 4)

1) ICE STORM LOADS

4 variables 19 citations

2) TREE SITE POSITION & LOCATION

6 variables 23 citations

3) GENERAL TREE FORM

9 variables 27 citations

4) STEM ATTRIBUTES

6 variables 15 citations

Figure 4: Summary of all attributes cited in research studies as leading to tree ice damage.

Multiple / Duplicate Citations

Boerner et.al. 1988

reviewed 5 studies
3 studies cited here
2 not used due to age & coverage

Tremblay et.al. 2005

reviewed 11 studies
5 studies cited here
6 not used due to age, language, & coverage

Seischab et.al. 1993

reviewed 9 studies
3 studies cited here
6 not used due to age

Warrillow & Mou 1999

reviewed 7 studies
4 studies cited here
3 not used due to age

Figure 5: List of studies used in this publication which reviewed multiple / duplicate studies on trees and ice storm damage.

damage form	relative damage percent
uprooted bole	10
snapped bole	14
leaning / bent bole	22
major canopy loss	30
moderate canopy loss	16
none / little canopy loss	8
tree mortality	25

Figure 6: General tree damage forms from major ice storms in the Appalachians. (modified from Wonkka et.al. 2013)

TREE DAMAGE

damage form	relative damage percent
fallen	9
>50% crown loss	30
permanently bent	22
none / little damage	39
tree mortality	27

Figure 7: General tree damage from major ice storms in Virginia. (modified from Wonkka et.al. 2013 & derived from Whitney & Johnson 1984)

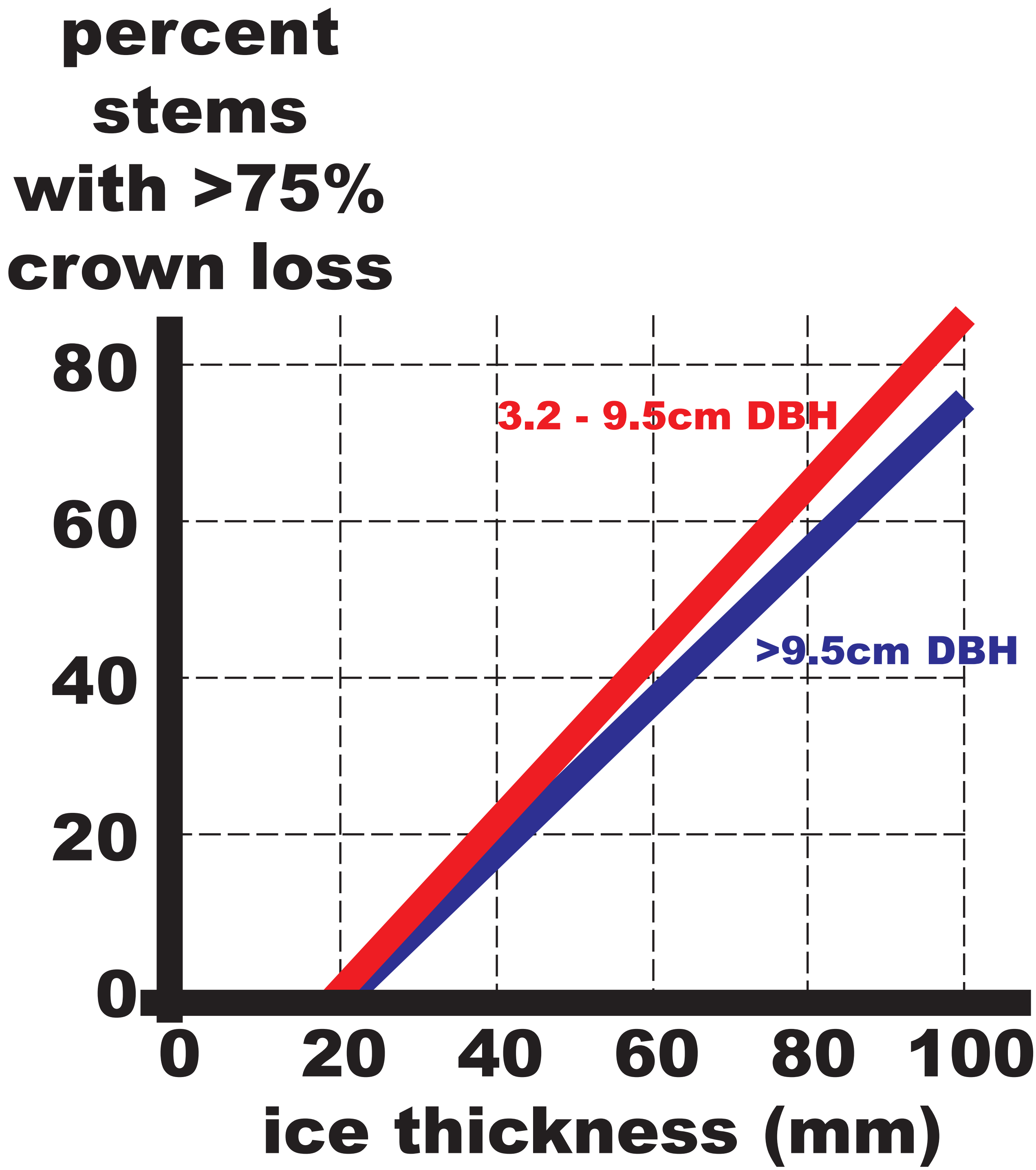

Figure 8: Percent of interior forest tree stems, in two different size classes, with greater than 75% crown loss by ice thickness. (Prouix & Greene 2001)

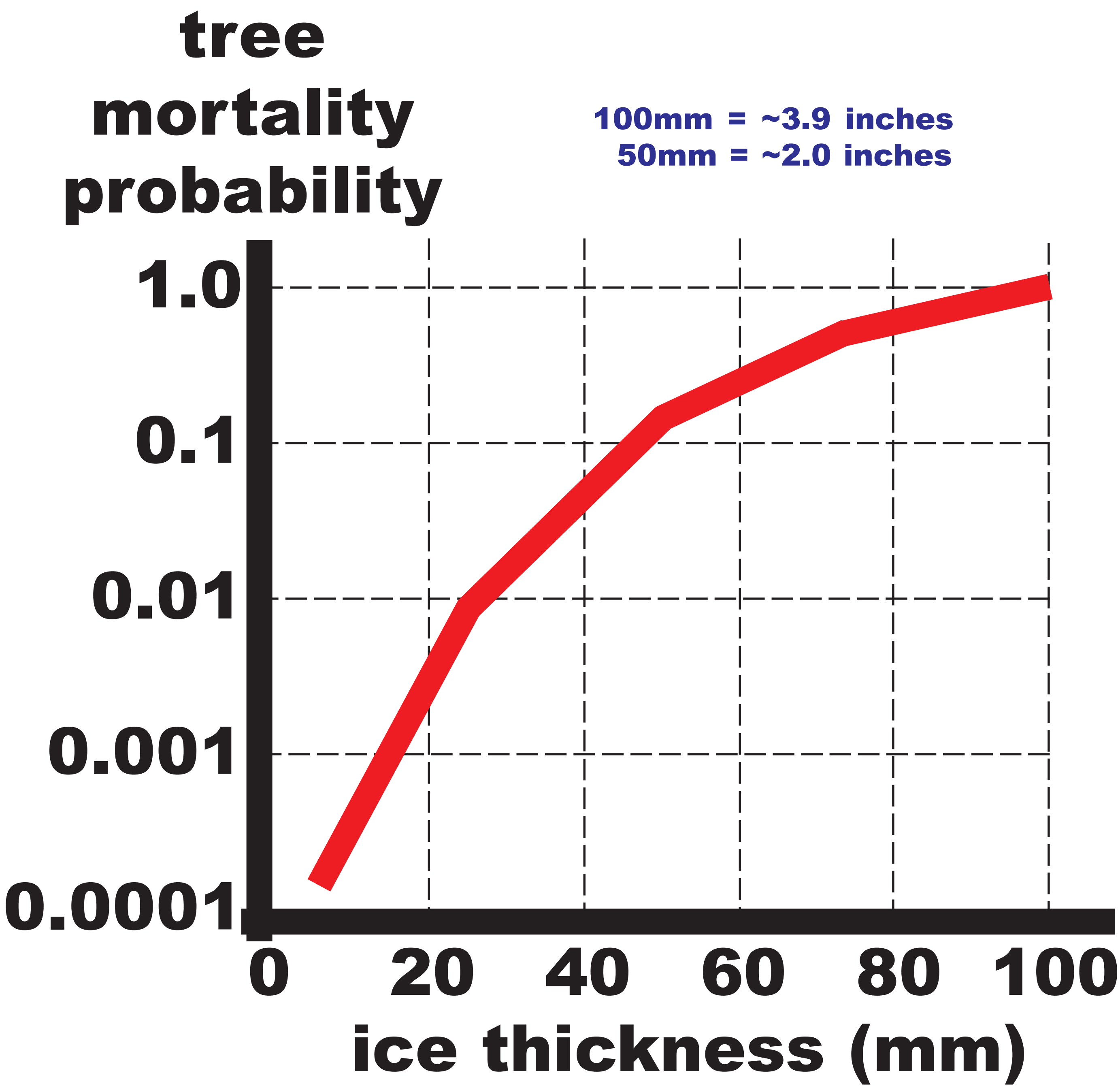

Figure 9: Probability of tree mortality by ice thickness (mm). (Prouix & Greene 2001)

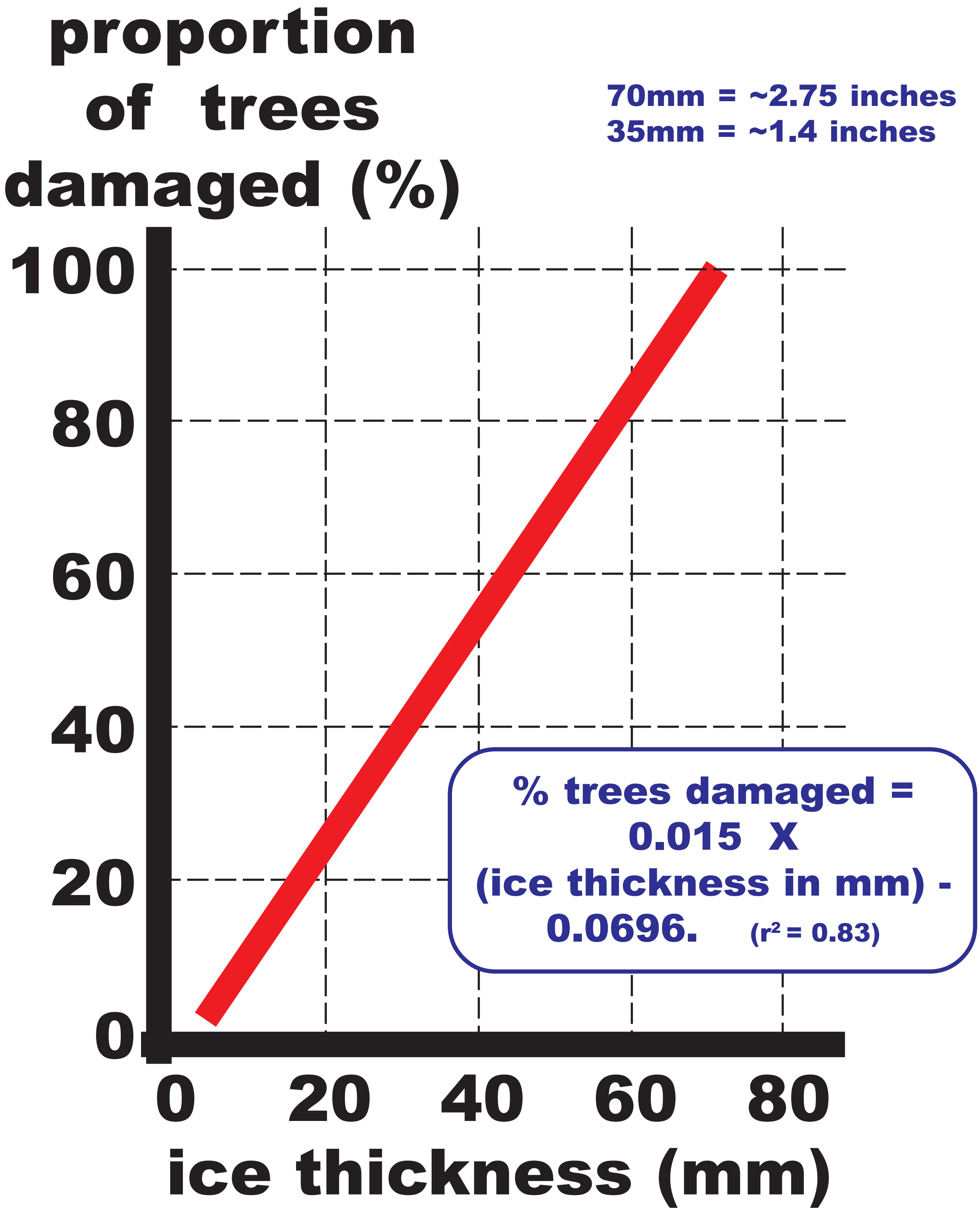

Figure 10: Percent of trees damaged based upon ice thickness (mm) on branch. (Lafon 2004a)

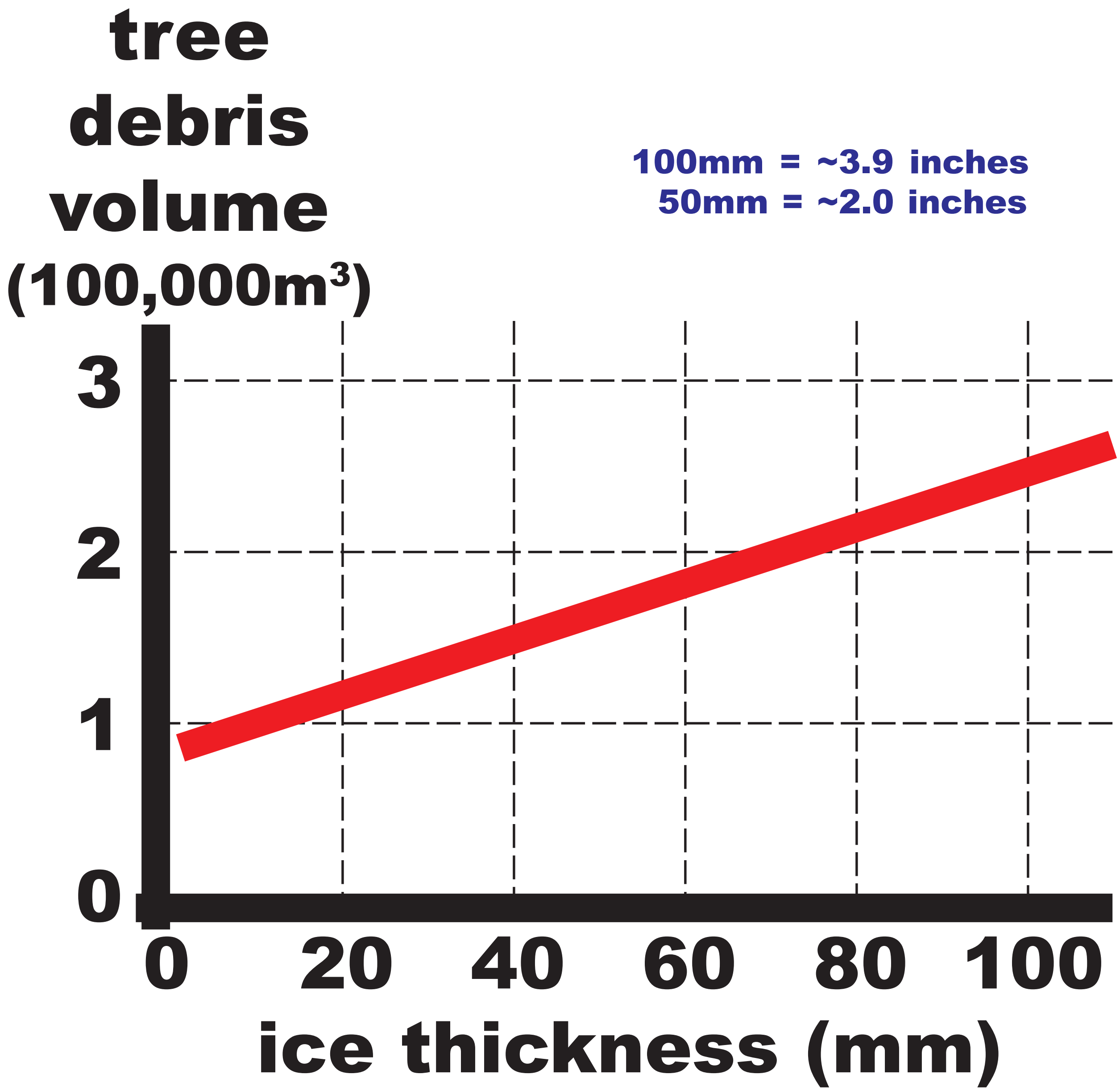

Figure 11: The amount of debris expected in cubic meters for an average community (average community size = land area, street length, & population) by ice accumulation in mm. (Hauer et.al. 2011)

ice thickness = amount of damage
0.5 inch ice = >75% canopy loss in larger trees **0.2 inch ice = >75% canopy loss in smaller trees**
2.0 inches ice = 21% tree mortality **3.5 inches ice = 68% tree mortality**

Figure 12: Ice thickness, tree damage, and tree mortality.
(Prouix & Greene 2001)

Most Ice Storms

< 0.28 inch ice

=

little mortality

Rare Ice Storms

0.47 - 1.38 inch ice

=

most mortality

Figure 13: Ice accumulation and tree mortality within 5 years of ice storm. (Prouix & Greene 2001)

MORTALITY

damage type	tree mortality after 5 years
crown loss	14%
stem bent	22%
roots tipped	85%
no visible damage	2%
TOTAL OF ALL TREES	19%

Figure 14: Tree mortality percent after 5 years for major damage forms under ice accumulation of 1.2 - 2.4 inches.
(Bragg & Shelton 2010)

TREE FAILURES IN ICE STORMS

cause	percent
ice	37%
wind	8%
wind & ice	55%

Figure 15: Causal mechanical loads leading to tree failures in ice storms divided among wind and ice loads.
(Mulherin 1996)

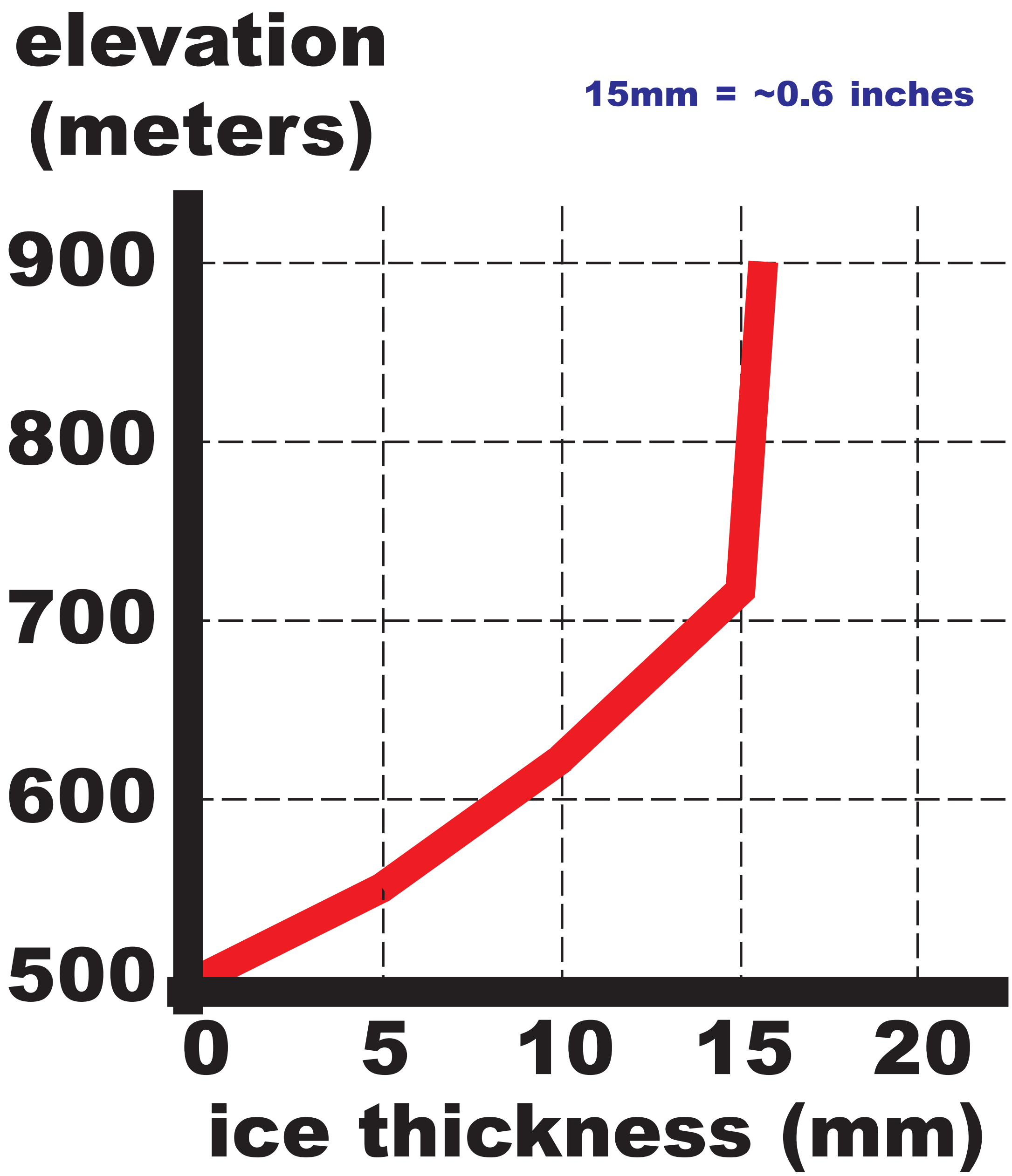

Figure 16: Amount of ice accumulation in mm with increasing elevation in meters. (Rhoads et.al. 2002)

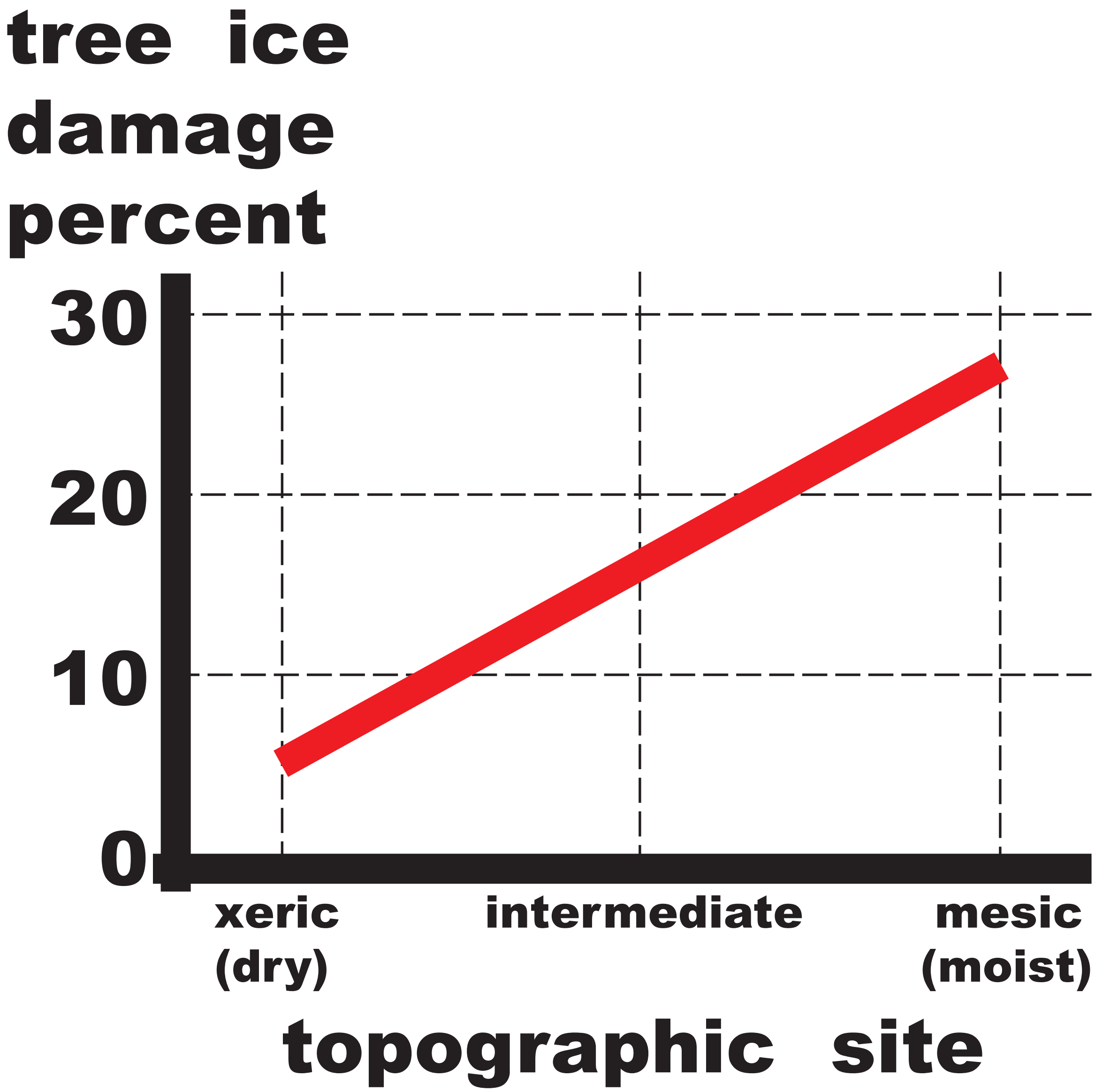

Figure 17: Ice accumulation damage on trees growing under different topographic mediated moisture conditions.
(Rebertus et.al. 1997)

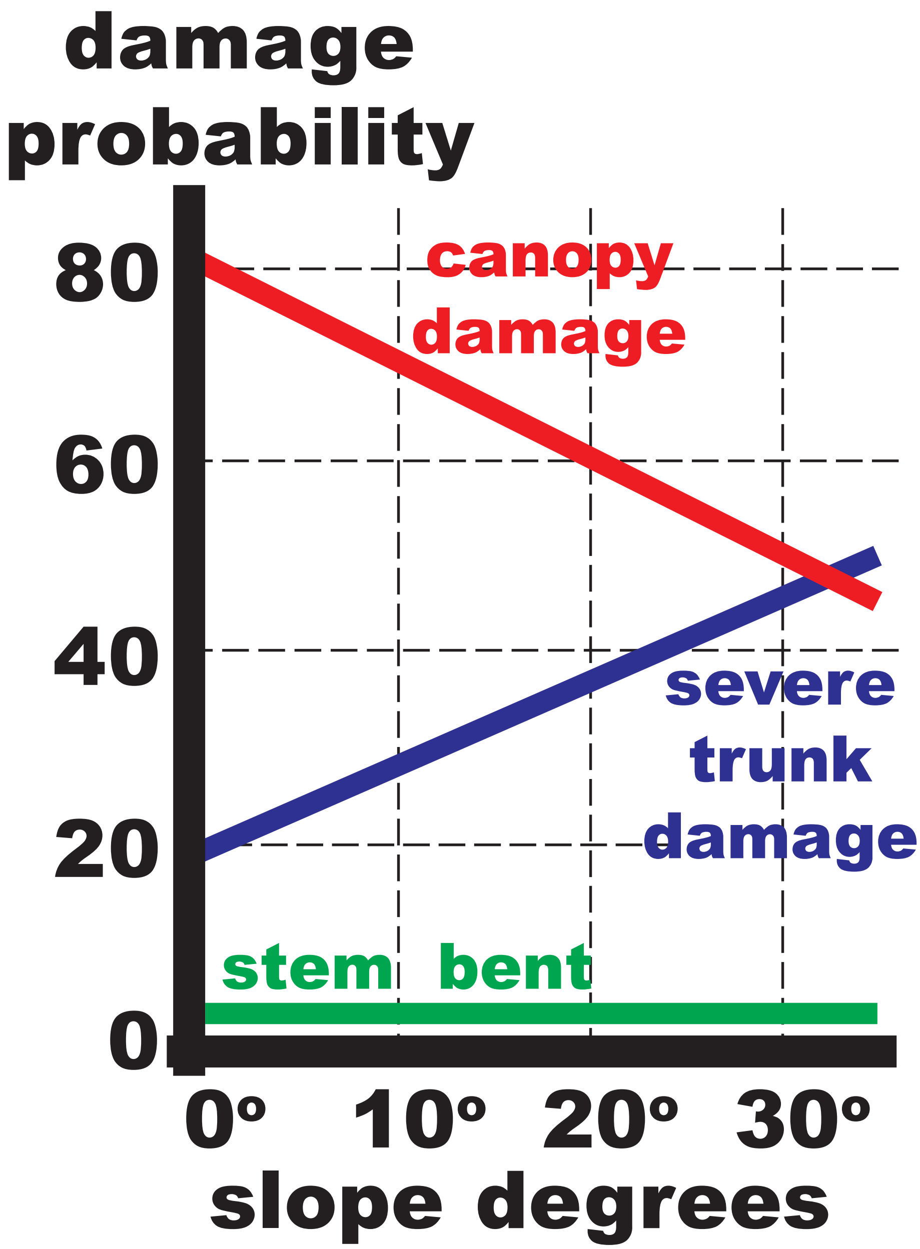

Figure 18: Tree damage probability in percent based upon slope in degrees. (Lafon 2004a)

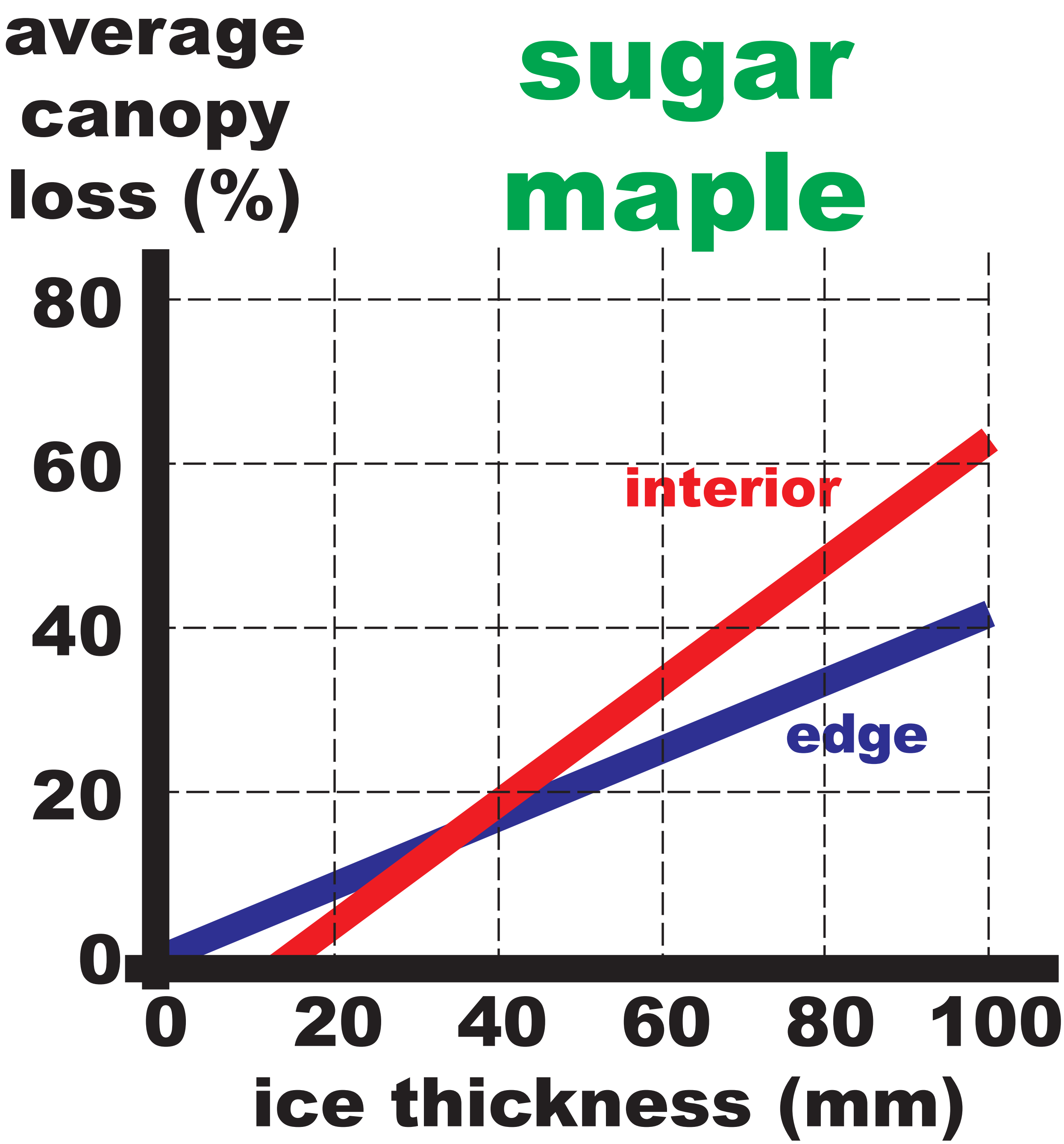

Figure 19: Forest edge and forest interior sugar maple (*Acer saccharum*) tree damage from ice accumulation.
(Prouix & Greene 2001))

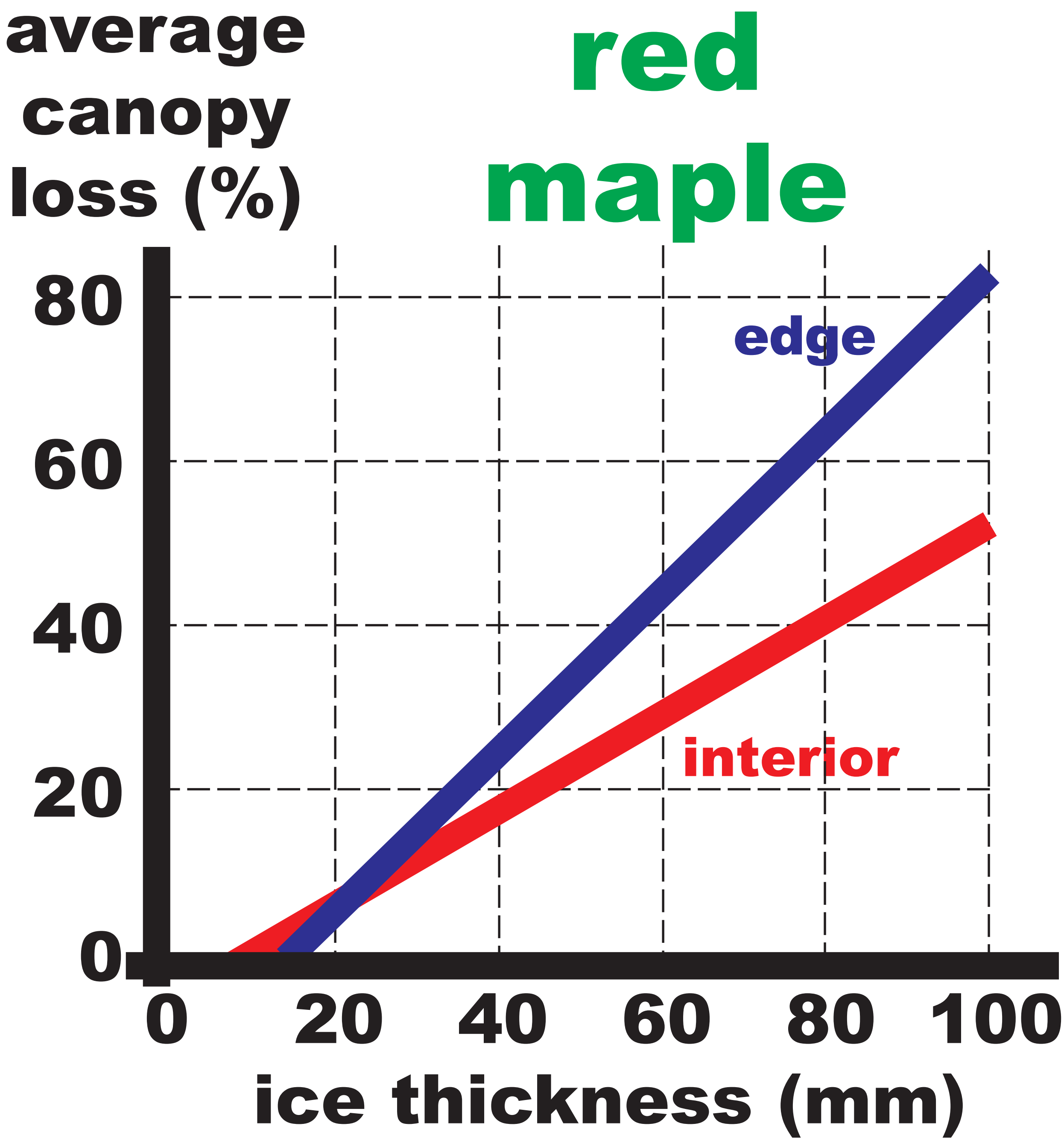

Figure 20: Forest edge and forest interior red maple (*Acer rubrum*) tree damage from ice accumulation.
(Prouix & Greene 2001)

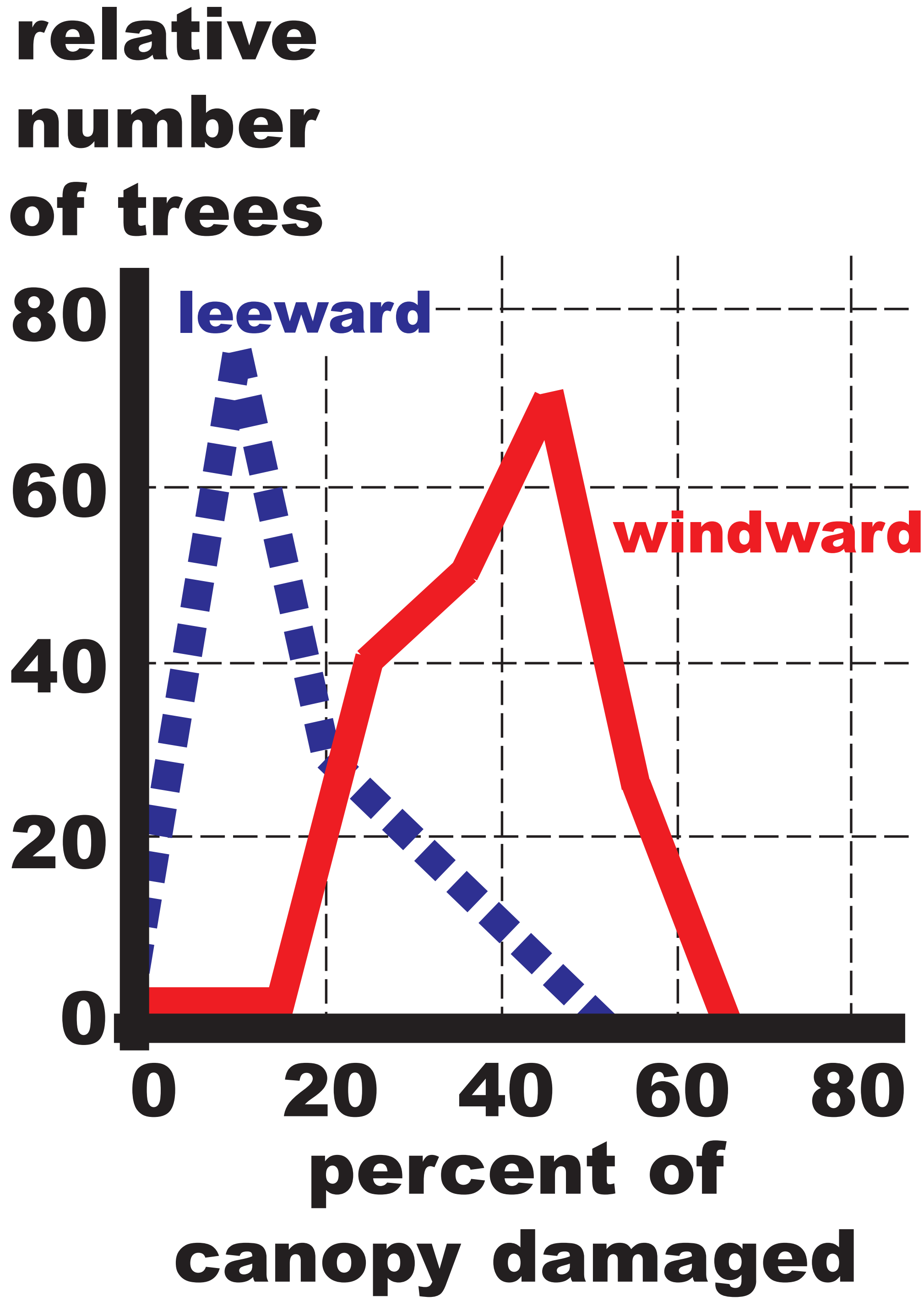

Figure 21: Tree canopy damage based upon position relative to windward or to leeward. (DeSteven et.al. 1991)

TREE DAMAGE

22% =
overstory trees
(91% severe / 2% light)
(57% uprooted)

8% =
understory trees
(29% severe / 63% light)

Figure 22: Tree damage in a Southern Appalachian forest from an ice storm. (derived from Rhoades 1999)

OVERSTORY TREES

overstory species	trees severely damaged percent
Pinus virginiana	100
Pinus strobus	67
Quercus alba	25
Quercus coccinea	22

Figure 23: Overstory tree species damaged in a Southern Appalachian ice storm. (derived from Rhoades 1999)

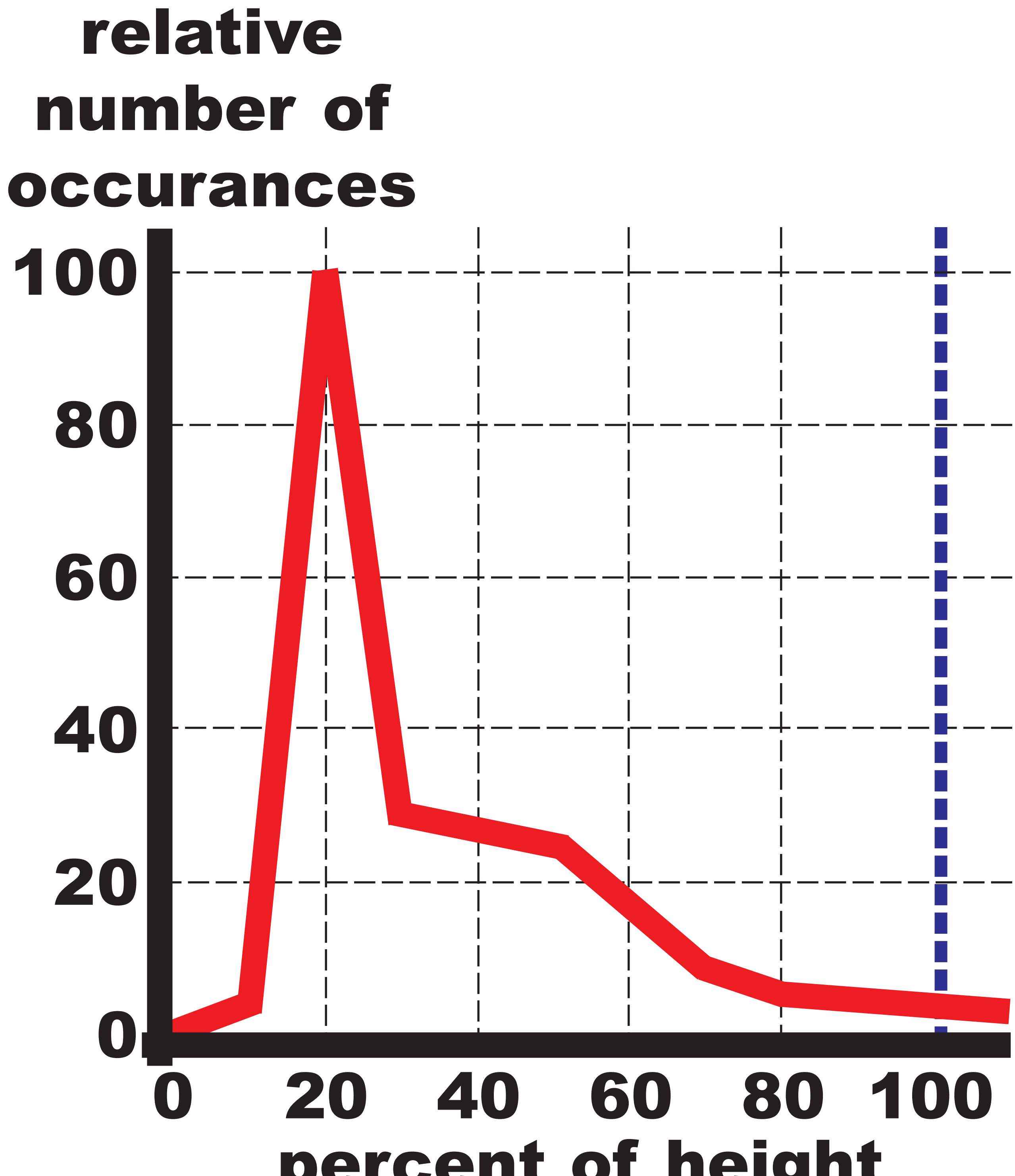

Figure 24: Debris radius of catastrophic failure in major ice storms as a percent of height.
(derived from power structure data -- Mulherin 1996)

Average Ice Damage Severity

needle-leaved trees

= ~24%

broad-leaved trees

= ~15%

broad-leaved trees severely damaged 38% less than needle-leaved trees

Figure 25: Average percent of needle-leaved and broad-leaved trees severely damaged by ice.
(derived from Boerner et.al. 1988)

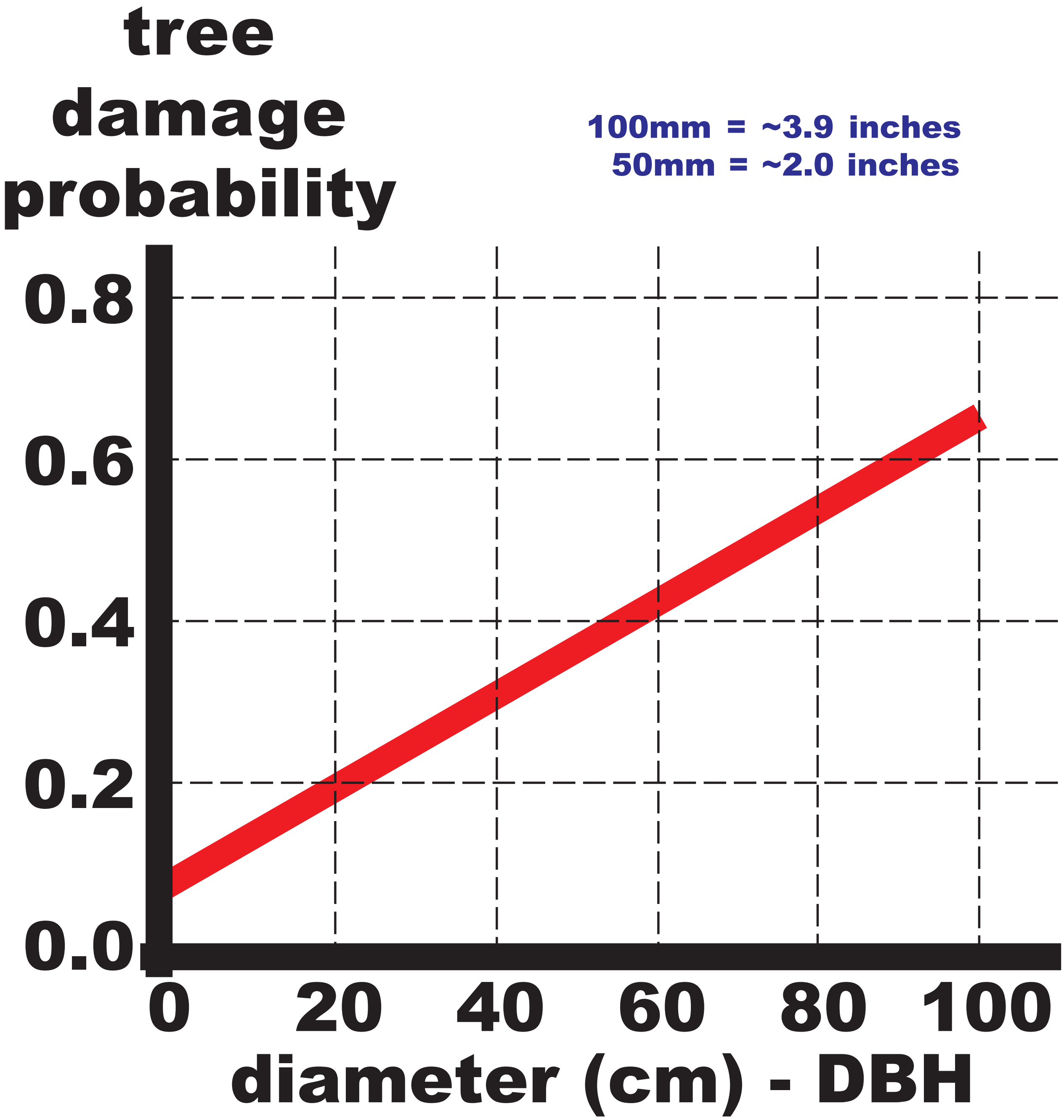

Figure 26: Probability of ice damage as a function of tree diameter (DBH cm) for all species studied.
(Rebertus et.al. 1997)

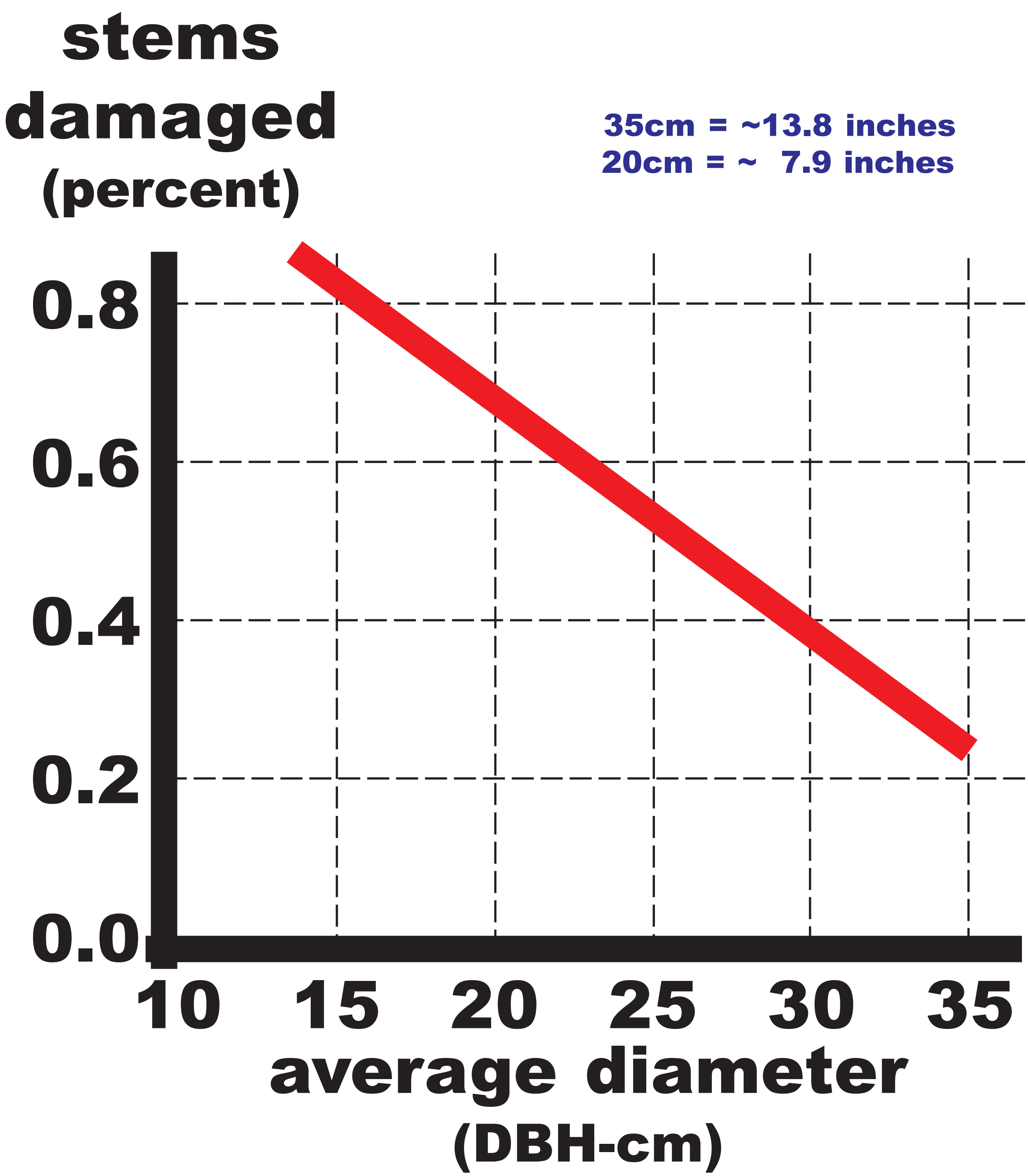

Figure 27: Percent stems damaged by ice loads based upon average diameter (DBH cm). (Ryall & Smith 2005)

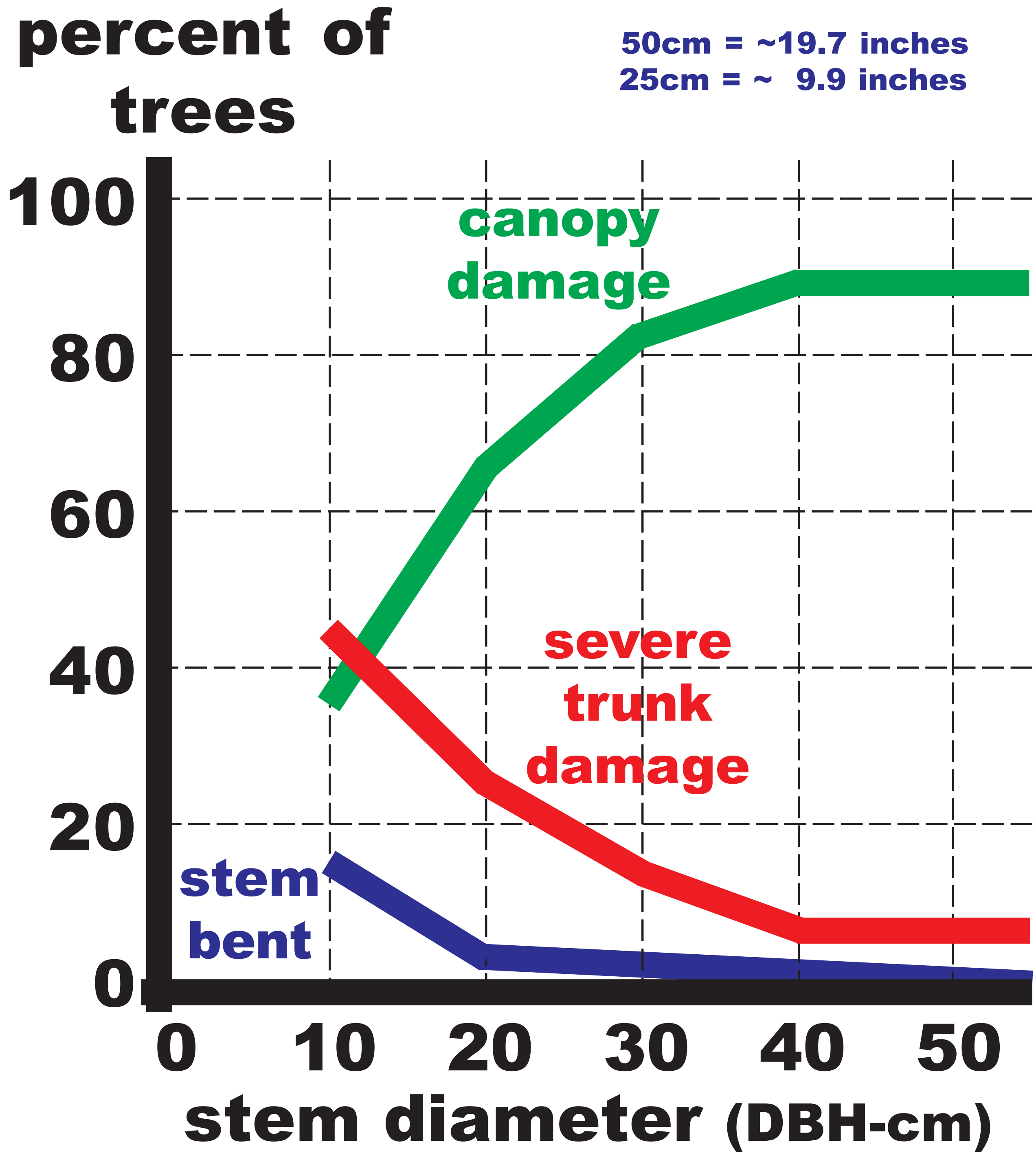

Figure 28: Percent of trees damaged by type of damage and diameter (cm). (Lafon 2004a)

tree size =
damage type
(bend, stem break, branch loss)

< 7 inches dbh =
bend

5.2 - 7.0 inches dbh =
stem break

> 7 inches dbh =
branch loss

Figure 29: Ice thickness and tree size-based damage impacts.
(Prouix & Greene 2001)

SEVERE ICE DAMAGE

tree size class	tree size (inches dbh)	percent severely damaged
small	< 12”	1.3%
medium	12” - 24”	6.5%
large	> 24”	17.1%

Figure 30: Severe ice storm damage to trees by tree size class in inches. (Rhoades & Stipes 2007)

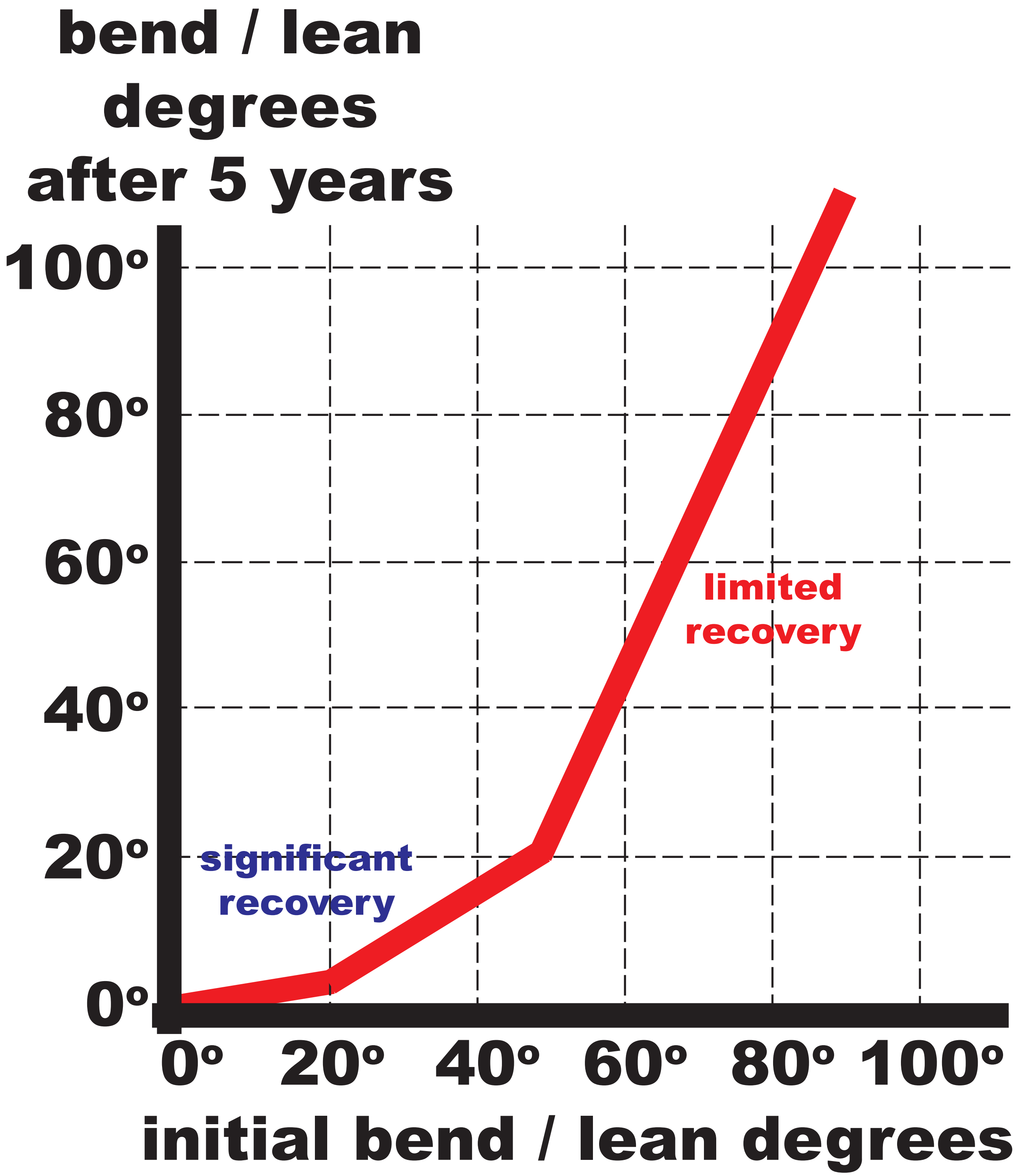

Figure 31: Recovery after five years from a stem bend or lean (not caused by root damage) initiated by a major ice storm. (Bragg & Shelton 2010)