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Tree Strength & Resistance To Damage Under Ice Storm Loads

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Ice storms generate large structural loads on trees due to accumulated ice weight, ice load duration (how long ice is on a tree), and wind loads during ice accumulation. Major ice storms generate severe tree damage. Across Eastern North America, a number of research papers have examined remains of trees and forests after major ice storms. These studies provide a number of key observations on tree structure, health, and mortality. From Southeastern Canada to the deep South of the United States, major ice storms periodically occur. Tree damage resulting from major ice storms can be divided into eight (8) general causes, locations, and damage categories. These attribute categories leading to or causing tree damage from ice storms include: Figure 1.

1) ice storm loads;
2) tree site & location;
3) general tree form;
4) stem attributes;
5) crown or canopy attributes;
6) branch growth form, and attachment;
7) root / soil attributes; and,
8) tree species strength and resistance to ice loads.

Among these eight general categories of attributes playing a role in tree damage or mortality in ice storms, 45 recent research studies have identified 56 individual specific features of an ice storm, tree site, and/or tree structure which lead to severe tree damage.

Species Susceptibility

Of all the literature surveyed, many studies provided insight into how trees were badly damaged by ice storms, as well as some sense of susceptibility of tree species to ice damage. Figure 2 provides a list of tree species cited by multiple studies as being susceptible or at high risk of damage by ice storms. Note any single citations of a tree species susceptibility were not included. This figure presents tree species scientific name, common name, composite susceptibility value, and the number of scientific citations used in determining damage susceptibility value.

The composite score value for susceptibility is derived from averaging a 1 - 3 range of tree species susceptibility, where one (1) is the most resistant and three (3) the least resistant to ice storm damage. A simple average of all cited rankings is presented under the susceptibility column. Note some tree species are well represented across Eastern North America ice storm areas and some species have only a few susceptibility citations.

Less Susceptible

Figure 3 shows trees species cited as being a moderate risk from ice storm damage. As in the previous figure, tree species names and susceptibility to ice damage are given, as well as the number of studies used in determining the average score. Single citations of a species susceptibility were not included. This list provides tree species considered intermediate between highly susceptible / high risk, and low susceptibility / low risk for ice storm damage.

Figure 4 lists tree species cited as low risk / low susceptibility for ice storm damage. These species are most resistant to ice load damage across multiple studies in Eastern North America. The susceptibility values are an averaged rating between one (1) and three (3), with one (1) being resistant to ice damage, and three (3) being susceptible to damage.

Species of Note

To summarize the previous three figures, tree species most often cited as resistant, or least susceptible to damage, are hickory (*Carya* spp.), ginkgo (*Ginkgo biloba*), black walnut (*Juglans nigra*), sweetgum (*Liquidambar styraciflua*), ironwood (*Ostrya virginiana*), and swamp white oak (*Quercus bicolor*). Tree species most often cited as susceptible or at greatest risk of ice storm damage are boxelder (*Acer negundo*), striped maple (*Acer pensylvanicum*), pitch pine (*Pinus rigida*), Virginia pine (*Pinus virginiana*), cottonwood and aspen species (*Populus* spp.), pin cherry (*Prunus pensylvanica*), black cherry (*Prunus serotina*), willows (*Salix* spp.), and Siberian elm (*Ulmus pumila*). Figure 5.

Strength Value

One of the major categories of tree and site attributes associated with ice storm damage is tree species greenwood strength and load resistance (number 8 on the list of catagories above). Fifteen studies suggested tree greenwood strength plays some role in resisting damage. Bragg et.al. 2003; Brommit et.al. 2004; Bruederle & Stearns 1985; Hauer et.al. 1993; Irland 2000; Kraemer & Nyland 2010; Lafon 2006; Lemon 1961; Prouix & Greene 2001; Rhoads et.al. 2002; Seischab et.al. 1993; Sisinni et.al. 1995; Takahashi et.al. 2007; Vowels 2012; Warrillow & Mou 1999.

Authors cite tree species strength ranging from having a major role in resisting ice storm damage to an insignificant role. Tree species strength values in resisting ice storm loads continue to be a common attribute cited in scientific and popular press as an observation, but its actual significance continues to be debated. In a number of cases, tree species greenwood strength is dismissed as having no impact on tree species susceptibility to ice storm damage.

Greenwood Not Wood

Tree strength and load resistance as used here involves living or greenwood resistance to ice and associated wind loads. The measurable values representing strength and load resistance are dominantly wood density (specific gravity), modulus of rupture (MOR), modulus of elasticity (MOE), fiber strength, and various combinations of measures. Here living or greenwood strength and load resistance values will be examined for any relationship to tree species susceptibility to ice storm damage discussed above.

Greenwood Density

Wood density would seem to be a good starting point in determining which tree species are strong or weak under ice storm loads. In other words, does wood density determine susceptibility to ice storm damage? Wood density is composed of two components: A) wood structure (solids and spaces); and, B) wood moisture content. In a single living tree, and across many different species, average moisture contents differ widely. The large variability of moisture present in greenwood makes a simple measure of wood density prone to errors.

To approach living tree species strength and load resistance values based upon greenwood density, greenwood specific gravity is a good measure to use. Specific gravity is a ratio between density of wood and density of water (measured at 40°F where water is densest). A greenwood sample volume is measured and then ovendried to determine sample weight. This ovendry weight and green volume will provide wood structure density. Comparing this wood density to the density of water yields a specific gravity value. The greater the specific gravity value, the greater wood density. Specific gravity is the standard reference value used for wood density, and usually ranges from ~0.30 to ~0.80. Green et.al. 2007; Simpson & TenWolde 2007.

Specific Gravity

Figure 6 presents an average greenwood specific gravity by tree species for select temperate Angiosperms. The list is divided into low specific gravity species (0.30 - 0.45), medium specific gravity species (0.46 - 0.59), high specific gravity species (0.60 - 0.70), and one species at greater than 0.70. Figure 7 lists select greenwood specific gravity values for temperate Gymnosperms. This figure divides these tree species between low specific gravity and medium / intermediate specific gravity (i.e. dividing line = 0.445).

Figure 8 provides a summary of select temperate tree species greenwood specific gravity values. Most species (30 tree species) are in the middle category between 0.45 and 0.59 specific gravity. The high specific gravity species group (17 species) has a greenwood specific gravity of greater than 0.60. Sixteen (16) tree species have low specific gravity of less than 0.44. The significance of determining specific gravity values for select temperate zone trees is to find a correlation between greenwood density and resistance to ice storm damage. Does greater density of living or greenwood confer more strength in resisting ice storm loads?

To accomplish a comparison of tree species' greenwood strength and resistance to ice storm loads, tree species susceptibility to ice storm damage reviewed earlier can be compared with specific gravity values. Figure 9 shows trees species susceptibility values (1 - 3 scale with 1 being most resistant to damage, low risk of damage, or strong) compared with greenwood specific gravity values. Note the graphical data area (i.e. shaded area) is primarily horizontal. Highly susceptible trees and highly resistant trees share similar or the same specific gravity. Specific gravity is not an effective means for differentiating ice storm damage susceptible species from less susceptible species.

Trends & Relationships

Figure 10 provides background for viewing ice storm damage susceptibility compared with greenwood strength characters. Note susceptibility value one (1) represents a tree species considered at low risk of damage, strong, and resistant to ice storm loads. If various greenwood strength values occupy a horizontal area graphically, then no discrimination can be made between tree species based upon a greenwood strength property and an ice storm damage susceptibility rating. If there is a strong trend between ice storm damage susceptibility values and greenwood strength values, a relationship is suggested and may mean the given strength / resistance value has a direct impact on ice storm damage susceptibility.

Other Measured Attributes

A tree species average greenwood strength and resistance to bending and deformation, can be estimated by several other measured values other than greenwood density / specific gravity. Figure 11. Other measures cited as related to tree species resisting ice storm loads are:

1. Modulus of rupture (MOR) is a measure representing the maximum load capacity in bending. MOR is an accepted criteria for greenwood strength and resistance to bending loads. Because MOR is considered a primary measure of greenwood strength, a comparison to ice storm damage susceptibility could be useful.

Figure 12 presents greenwood modulus of rupture (MOR) for select temperate tree species compared to each species' ice storm damage susceptibility value. Note MOR for black locust and white-cedar are outside the main body of measurements. The shaded space shown does have a significant trend. Unfortunately, the range of high MOR species with low susceptibility to ice storm damage almost completely overlaps the range of low MOR species with high ice storm damage susceptibility. In other words, MOR does not effectively separate ice storm damage susceptibility among various tree species.

2. Modulus of elasticity (MOE) is a measure of the maximum load which can be applied, and when removed, is completely recoverable by a sample. Any greater load than MOE would cause a plastic deformation or failure. MOE has been cited as related to ice storm damage susceptibility, especially for long duration ice loads. Figure 13 presents ice storm damage susceptibility for select temperate tree species and MOE. As with previous MOR, note black locust and white-cedar are significant outliers. There seems to be a trend relating MOE and ice storm damage susceptibility, but the overlap in values between the highly resistant to ice damage with larger MOE, and the highly susceptible to ice damage with smaller MOE, is great. MOE does not differentiate tree species susceptibility to ice storm damage well.

3. Compression stress perpendicular to the wood grain is a measure of the smallest load which causes failure across the grain. This value represents deformation of greenwood fibers until failure, and can be considered one measure of greenwood strength and resistance to loading.

4. Shear strength parallel to the greenwood grain is a measure of the largest load which resists internal slippage of greenwood fibers along the grain. This value represents a load up to a shear fault within greenwood, and can be considered one measure of greenwood strength and resistance to loading.

Figure 14 provides a select list of temperate tree species by common name and values for these common deformation and strength measures listed above. Green et.al. 2007. Note Angiosperms and Gymnosperms are separated in this list. Also note the different units of measure used to determine each value.

Indexing

As previous figures have demonstrated, there are not strong relationships between greenwood strength measures and susceptibility to ice storm damage. Combining various strength and resistance measures might further accentuate differences and more effectively discriminate among ice storm damage susceptibility classes. Figure 15 provides three multiple variable index values.

Modulus Index

One combined index is a Modulus Index (MI) which uses values of modulus of rupture (MOR) and modulus of elasticity (MOE). MI values are listed in Figure 16 for Angiosperms and Figure 17 for Gymnosperms. MI truncates both measurement unit values and then combines them into a single value between 30 and 100. MI is calculated by the following formula:

$$\text{Modulus Index} = \text{MI} = \{ [(\text{MOR}_{\text{kPa}} / 1{,}000) + (\text{MOE}_{\text{Mpa}} / 100)] / 225 \} \times 100.$$

Figure 18 shows the range of MI across different ice storm damage resistance or susceptibility levels. Figure 19 shows there is a trend toward larger MI values and less susceptibility of tree species to ice damage. Unfortunately, there remains two significant outliers, and an overlap of values between smaller MI with higher resistance to ice storms damage, and larger MI with higher susceptibility to ice storm damage. MI is not an effective means to differentiate between tree species greenwood strength and resistance to bending, and ice storm damage susceptibility.

Fiber Strength Index

Another composite index is a Fiber Strength Index (FSI) which combines values of fiber compression stress and fiber shear strength. FSI values are shown in Figure 20 for Angiosperms and Figure 21 for Gymnosperms. FSI combines the two fiber strength values into one index number ranging from 15 to 60. FSI is calculated by the following formula:

$$\text{Fiber Strength Index} = \text{FSI} = \{ [(\text{compression}_{\text{kPa}} / 100) + (\text{shear}_{\text{kPa}} / 100)] / 300 \} \times 100.$$

Figure 22 shows the range of FSI across different tree species susceptibility to ice storm damage levels. Figure 23 shows the index susceptibility space (i.e. shaded area). Unfortunately, highly ice storm damage resistant species are not well differentiated from the intermediate susceptibility species. In addition, there is significant overlap between tree species with larger FSI which are highly resistant to ice storm damage, and smaller FSI which are highly susceptible to ice storm damage. FSI is not an effective means to differentiate between tree species greenwood strength and resistance to bending, and ice storm damage susceptibility.

Coder Ice Index

A third composite index is the Coder Ice Index (CII) which combines specific gravity, MOR, MOE, compression strength and shear strength into one value. CII for select tree species are listed in Figure 24 for Angiosperms and Figure 25 for Gymnosperms. CII values range from 15 to 155. CII is calculated by the following formula:

$$\text{Coder Ice Index} = \text{CII} = \{ [[(MOR_{kPa} / 1{,}000) + (MOE_{Mpa} / 100) + (\text{compression}_{kPa} / 100) + (\text{shear}_{kPa} / 100)] \times \text{specific gravity}] / 250 \} \times 100.$$

Figure 26 shows the range of CII across different tree species susceptibility to ice storm damage levels. Figure 27 presents the ice storm damage / tree susceptibility space (i.e. shaded area). Unfortunately, the index space is without significant trends and is not an effective means to differentiate between tree species greenwood strength and resistance to bending, and ice storm damage susceptibility. In this case, more variables of greenwood strength and resistance did not generate a stronger relationship.

General Properties

In agreement with a number of authors, and as seen in the previous figures, simple and compound greenwood strength and resistance values do not effectively represent susceptibility of tree species to ice storm damage. An alternative simple means of determining tree species susceptibility to ice storm damage is shown in Figure 28, where bending resistance, stiffness, and splitting attributes are categorized and used to estimate tree species strength and resistance. Some of these species greenwood properties line-up with species susceptibility values.

Conclusions

Tree species greenwood strength and resistance to bending and deformation is easy to measure and can be found in references. The relationship between tree species greenwood strength and tree species susceptibility to ice storm damage is weak. These relationships support the studies where greenwood stregth was found to have no or little relation to ice storm damage susceptibility.

Ice storm damage in a tree species, as it is related to tree strength and resistance values, is probably less than 20% of observed damage variability, and is more likely less than 7%. This lack of a strong relationship between tree species strength and resistance, and ice storm damage susceptibility, substantiates the Wessoly biomechanics ratio for tree failure and damage, which is 80% of damage variability is due to loading (forces applied) issues and only 20% is due to holding (structural resistance) issues. Tree species greenwood strength measures alone are not effective is determining ice storm damage susceptibility.

Citation:

Coder, Kim D. 2022. Tree strength & resistance to damage under ice storm loads. Warnell School of Forestry & Natural Resources, University of Georgia, Outreach Publication WSFNR-22-54C. Pp.38.

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1) ICE STORM LOADS

4 major variables — 19 citations

2) TREE SITE POSITION & LOCATION

6 major variables — 23 citations

3) GENERAL TREE FORM

8 major variables — 23 citations

4) STEM ATTRIBUTES

6 major variables — 15 citations

5) CROWN ATTRIBUTES

10 major variables — 23 citations

6) BRANCH ATTRIBUTES & ATTACHMENT

12 major variables — 19 citations

7) ROOT / SOIL ATTRIBUTES

3 major variables — 7 citations

8) TREE SPECIES STRENGTH

7 major variables — 19 citations

Figure 1: Attribute catagories associated with ice storm damage to trees and forests. Number 8 above is explored at depth in this publication.

HIGH RISK

scientific name	common name	susceptibility	citations
Acer negundo	boxelder	3.0	2
Acer pensylvanicum	striped maple	3.0	2
Betula papyrifera	paper birch	2.5	4
Betula populifolia	gray birch	2.5	2
Celtis occidentalis	hackberry	2.7	3
Fraxinus pennsylvanica	green ash	2.3	6
Gleditsia triacanthos	honeylocust	2.5	4
Pinus resinosa	red pine	2.7	3
Pinus rigida	pitch pine	3.0	3
Pinus virginiana	Virginia pine	3.0	3
Populus grandidentata	bigtooth aspen	3.0	2
Populus spp.	aspen/cottonwood	3.0	4
Populus tremuloides	quaking aspen	2.7	3
Prunus pensylvanica	fire cherry	3.0	2
Prunus serotina	black cherry	2.8	13
Pyrus calleryana	callery pear	2.7	3
Quercus velutina	black oak	2.3	8
Robinia pseudoacacia	black locust	2.7	3
Salix ssp.	willow species	3.0	3
Sassafras albidum	sassafras	2.3	3
Tilia americana	basswood	2.6	12
Ulmus americana	American elm	2.7	7
Ulmus pumila	Siberian elm	3.0	2
Ulmus rubra	slippery elm	2.5	2

Figure 2: List of tree species cited as susceptible to ice storm damage. Species cited by only one study were not included.
(susceptibility range = 1 - 3, with 1 being resistant and 3 being susceptibile to ice storm damage)

MODERATE RISK

scientific name	common name	susceptibility	citations
Acer platanoides	Norway maple	2.0	3
Acer rubrum	red maple	2.1	18
Acer saccharinum	silver maple	2.2	6
Acer saccharum	sugar maple	2.1	16
Betula alleghaniensis	yellow birch	1.9	8
Carya cordiformis	bitternut hickory	1.8	4
Cornus florida	dogwood	1.8	4
Fagus grandifolia	American beech	1.9	14
Fraxinus americana	white ash	1.8	13
Malus spp.	crabapple species	2.0	2
Nyssa sylvatica	blackgum	1.7	3
Oxydendrum arboreum	sourwood	2.0	3
Pinus strobus	Eastern white pine	2.0	7
Platanus occidentalis	sycamore	1.8	4
Populus deltoides	Eastern cottonwood	2.0	3
Quercus coccinea	scarlet oak	2.0	2
Quercus palustris	pin oak	2.0	3
Quercus rubra	Northern red oak	2.1	17
Salix nigra	black willow	2.0	2
Thuja occidentalis	Northern white-cedar	2.0	2
Tilia cordata	little-leafed linden	1.7	3
Ulmus spp.	elm species	2.2	5

Figure 3: List of tree species cited with intermediate susceptibility to ice storm damage. Species cited only once were not included. (susceptibility range = 1 - 3, with 1 being resistant and 3 being susceptibile to ice storm damage)

LOW RISK

scientific name	common name	susceptibility	citations
Betula lenta	sweet birch	1.5	2
Carpinus caroliniana	American hornbeam	1.3	6
Carya glabra	pignut hickory	1.5	2
Carya ovata	shagbark hickory	1.0	3
Carya spp.	hickory species	1.0	3
Fraxinus spp.	ash species	1.5	2
Ginkgo biloba	ginkgo	1.0	2
Juglans nigra	black walnut	1.0	4
Liquidambar styraciflua	sweetgum	1.0	2
Liriodendron tulipifera	yellow-poplar	1.6	7
Ostrya virginiana	Eastern hophornbeam	1.1	8
Quercus alba	white oak	1.3	15
Quercus bicolor	swamp white oak	1.0	2
Quercus macrocarpa	bur oak	1.5	2
Quercus montana	chestnut oak	1.5	4
Tsuga canadensis	Eastern hemlock	1.5	13

Figure 4: List of tree species cited as resistant or low susceptibility to ice storm damage. Species cited only once were not included.
(susceptibility range = 1 - 3, with 1 being resistant and 3 being susceptibile to ice storm damage)

MOST RESISTANT:

Carya spp.

Ginkgo biloba

Juglans nigra

Liquidambar styraciflua

Ostrya virginiana

Quercus bicolor

MOST SUSCEPTIBLE:

Acer negundo

Acer pensylvanicum

Pinus rigida

Pinus virginiana

Populus spp.

Prunus pensylvanica

Prunus serotina

Salix ssp.

Ulmus pumila

Figure 5: Most resistant and most susceptible tree species cited in ice storms across Eastern North America.

species	specific gravity	species	specific gravity
basswood	0.32	black oak	0.56
quaking aspen	0.35	Northern red oak	0.56
bigtooth aspen	0.36	water oak	0.56
black willow	0.36	willow oak	0.56
Eastern cottonwood	0.37	chestnut oak	0.57
yellow-poplar	0.40	overcup	0.57
silver maple	0.44	pin oak	0.58
Southern magnolia	0.46	honeylocust	0.60
sweetgum	0.46	bitternut hickory	0.60
sycamore	0.46	pecan	0.60
black gum	0.46	sweet birch	0.60
American elm	0.46	scarlet oak	0.60
black cherry	0.47	post oak	0.60
red elm	0.48	swamp chestnut	0.60
paper birch	0.48	white oak	0.60
hackberry	0.49	post oak	0.60
red maple	0.49	swamp chestnut	0.60
black walnut	0.51	white oak	0.60
Southern red oak	0.52	swamp white oak	0.64
green ash	0.53	mockernut hickory	0.64
white ash	0.55	shagbark hickory	0.64
yellow birch	0.55	pignut hickory	0.66
beech	0.56	black locust	0.66
sugar maple	0.56		
		live oak	0.80

Figure 6: Live or greenwood specific gravity for select temperate Angiosperm trees. (Green et.al. 2007)

species	specific gravity
Northern white-cedar	0.29
balsam fir	0.33
Eastern white pine	0.34
red spruce	0.37
Eastern hemlock	0.38
jack pine	0.40
red pine	0.41
baldcypress	0.42
Eastern redcedar	0.44
Virginia pine	0.45
loblolly pine	0.47
pitch pine	0.47
shortleaf pine	0.47
longleaf pine	0.54
slash pine	0.54

Figure 7: Live or greenwood specific gravity for select temperate Gymnosperm trees. (Green et.al. 2007)

Specific Gravity

number of species	specific gravity value	class
17	> .60	H
30	.45 -- .59	M
16	< .44	L

Figure 8: Live or greenwood specific gravity values and classes for select temperate tree species.
(H = high; M = medium; L = low)

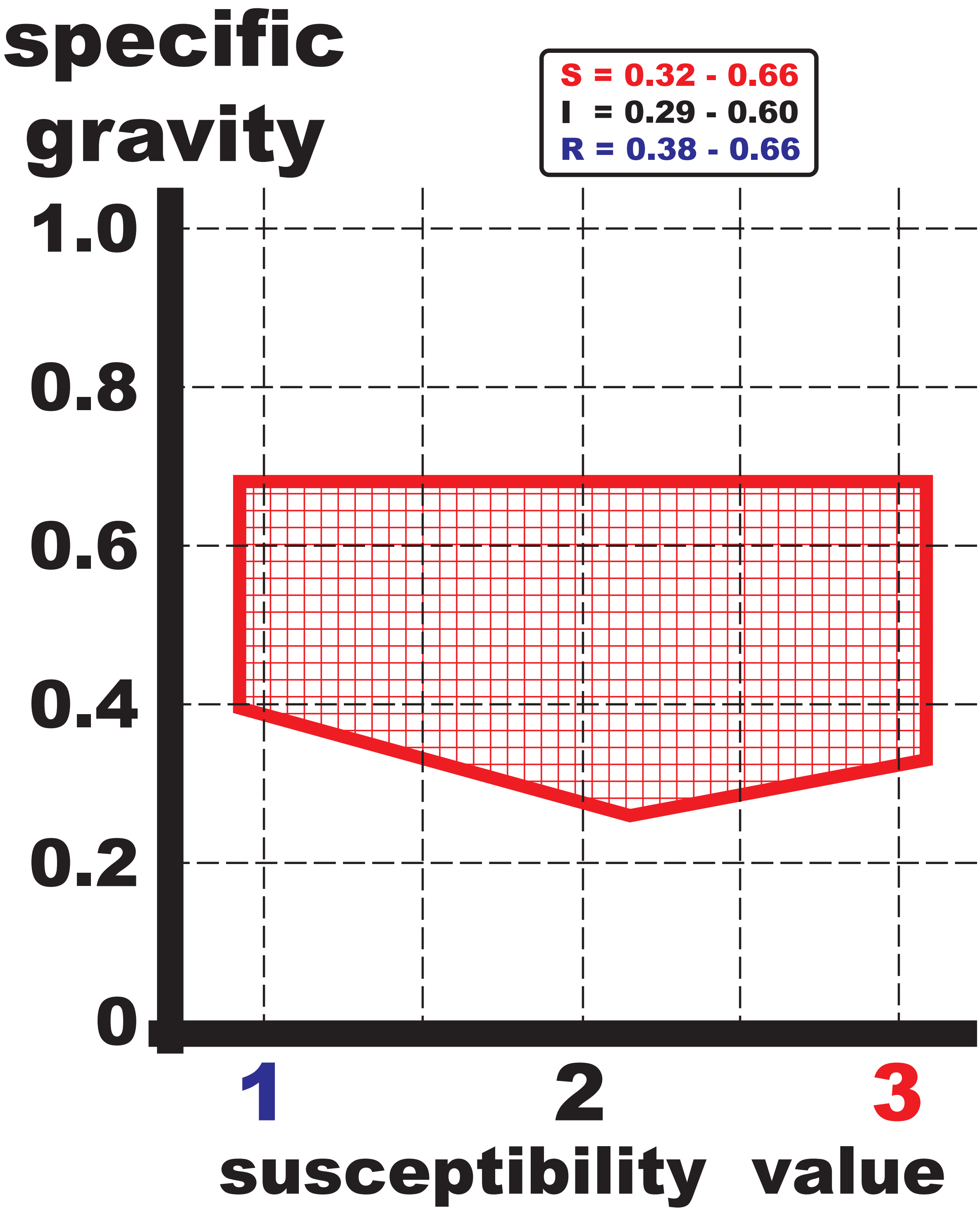

Figure 9: Tree species susceptibility to ice storm damage using greenwood specific gravity.
(1 = low risk or strong (R); 3 = high risk or weak (S))

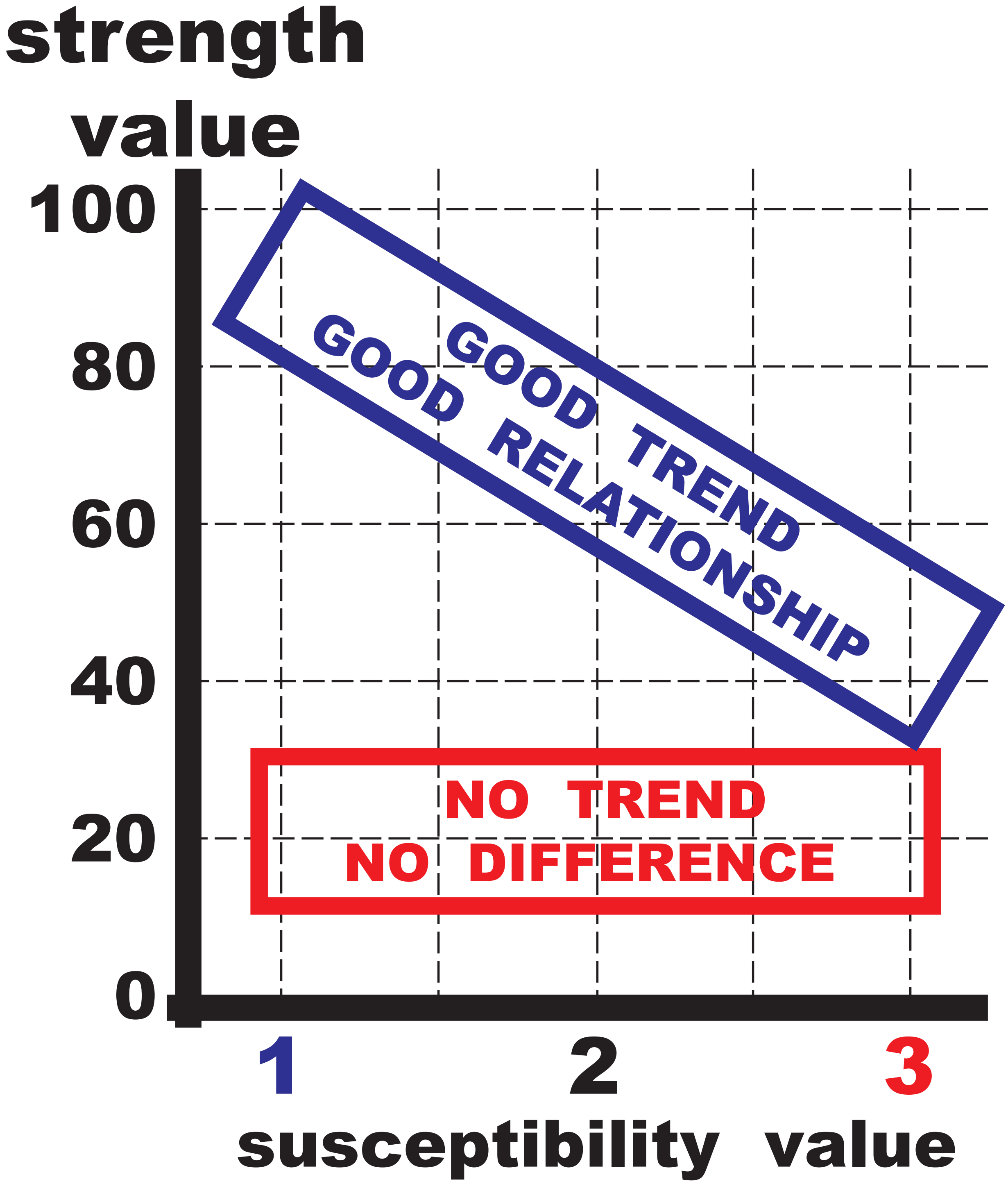

Figure 10: Example of tree species susceptiblity to ice storm damage versus strong and weak trends in greenwood strength values.
(1 = low risk or strong; 3 = high risk or weak)

MOR = Modulus of Rupture

Maximum load capacity in bending.
Accepted criteria for strength.

MOE = Modulus of Elasticity

Maximum load which is completely recoverable.
Higher loads cause plastic deformation or failure.

Compression Stress

(perpendicular to grain)
Load to failure across grain.

Shear Strength

(parallel to grain)
Load to internal slipping along grain.

Figure 11: Four primary measures of greenwood strength (i.e. resistance to bending, deformation, and failure).
(Green et.al. 2007)

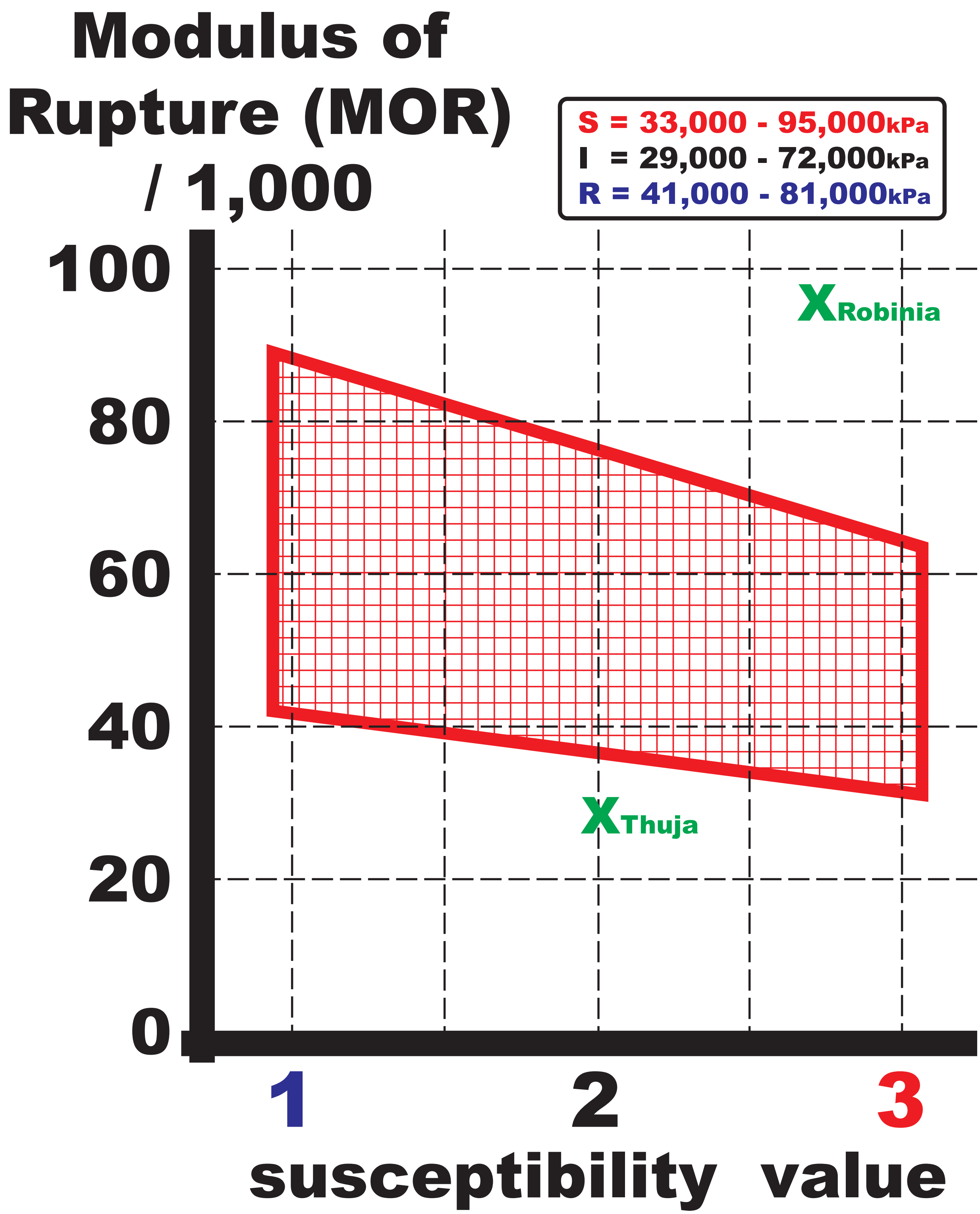

Figure 12: Tree species susceptiblity to ice storm damage using Modulus of Rupture (MOR_{kPa}) divided by 1,000.
(1 = low risk or strong (R); 3 = high risk or weak (S))

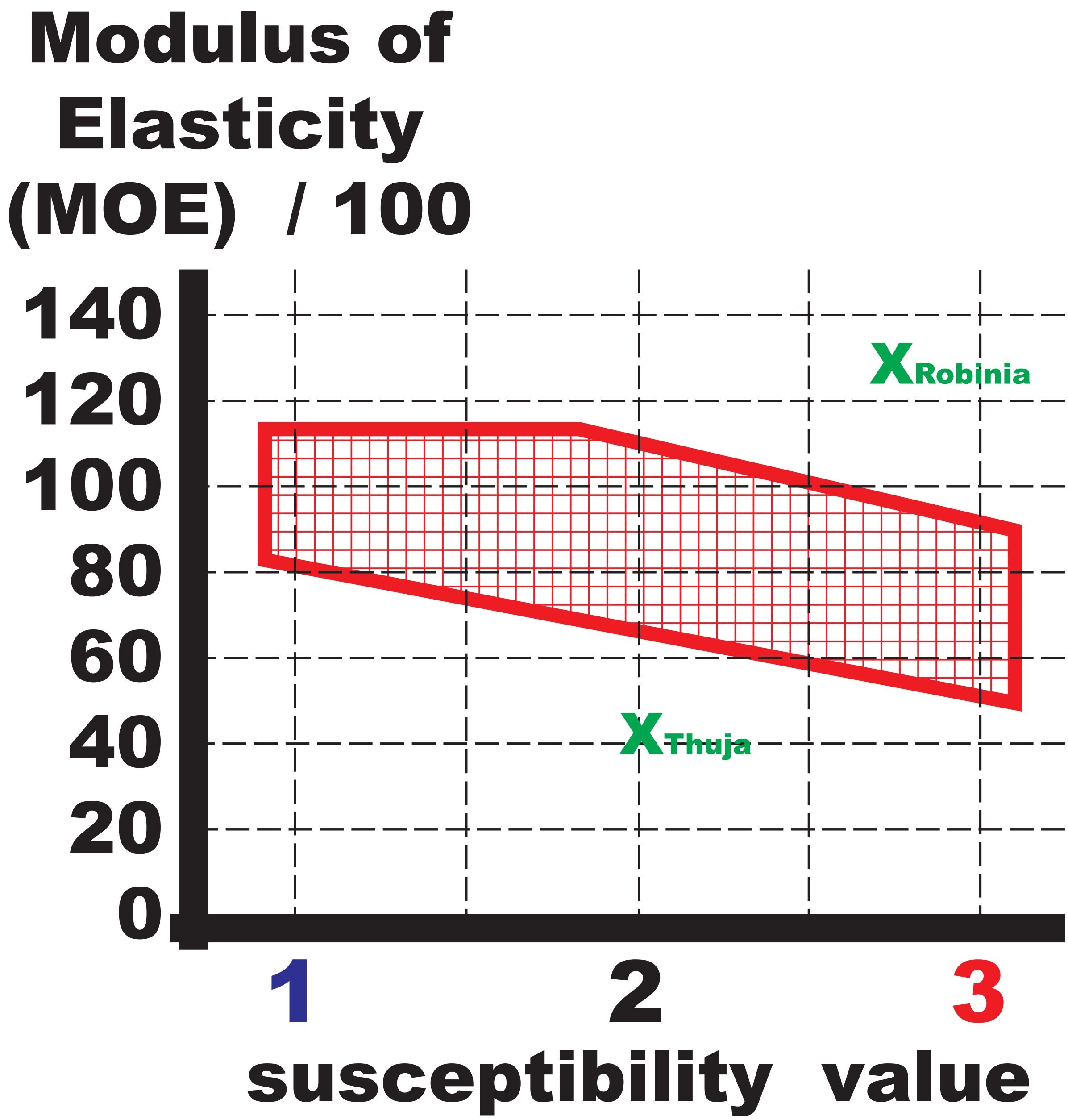

Figure 13: Tree species susceptility to ice storm damage using Modulus of Elasticity (MOE_{MPa}) divided by 100.
(1 = low risk or strong (R); 3 = high risk or weak (S))

species	MOR (kPa)	MOE (Mpa)	compression (kPa)	shear (kPa)
Angiosperms --				
green ash	66,000	9,700	5,000	8,700
white ash	66,000	9,900	4,600	9,300
bigtooth aspen	37,000	7,700	1,400	5,000
quaking aspen	35,000	5,900	1,200	4,600
basswood	34,000	7,200	1,200	4,100
beech	59,000	9,500	3,700	8,900
paper birch	44,000	8,100	1,900	5,800
sweet birch	65,000	11,400	3,200	8,000
yellow birch	57,000	10,300	3,000	7,700
black cherry	55,000	9,000	2,500	7,800
Eastern cottonwood	37,000	7,000	1,400	4,700
American elm	50,000	7,700	2,500	6,900
red elm	55,000	8,500	2,900	7,700
hackberry	45,000	6,600	2,800	7,400
bitternut hickory	71,000	9,700	5,500	8,500
pecan	68,000	9,400	5,400	10,200
mockernut hickory	77,000	10,800	5,600	8,800
pignut hickory	81,000	11.400	6,300	9,400
shagbark hickory	76,000	10,800	5,800	10,500

Figure 14: Live or greenwood resistance to deformation and strength measures by species. (Green et.al. 2007)

species	MOR (kPa)	MOE (Mpa)	compression (kPa)	shear (kPa)
honeylocust	70,000	8,900	7,900	11,400
black locust	95,000	12,800	8,000	12,100
Southern magnolia	47,000	7,700	3,200	7,200
red maple	53,000	9,600	2,800	7,900
silver maple	40,000	6,500	2,600	7,200
sugar maple	65,000	10,700	4,400	10,100
black oak	57,000	8,100	4,900	8,400
Northern red oak	57,000	9,300	4,200	8,300
pin oak	57,000	9,100	5,000	8,900
scarlet oak	72,000	10,200	5,700	9,700
Southern red oak	48,000	7,900	3,800	6,400
water oak	61,000	10,700	4,300	8,500
willow oak	51,000	8,900	4,200	8,100
chestnut oak	55,000	9,400	3,700	8,300
live oak	82,000	10,900	14,100	15,200
overcup	55,000	7,900	3,700	9,100
post oak	56,000	7,500	5,900	8.800
swamp chestnut oak	59,000	9,300	3,900	8,700
swamp white oak	68,000	11,000	5,200	9,000
white oak	57,000	8.600	4,600	8,600
sweetgum	49,000	8,300	2.600	6.800
sycamore	45,000	7.300	2,500	6,900
black gum	48,000	7,100	3,300	7.600
black walnut	66,000	9,800	3,400	8,400
black willow	33,000	5,400	1,200	4.700
yellow-poplar	41,000	8,400	1,900	5,400

Figure 14: Live or greenwood resistance to deformation and strength measures by species. (continued)
(Green et.al. 2007)

species	MOR (kPa)	MOE (Mpa)	compression (kPa)	shear (kPa)
Gymnosperms --				
baldcypress	46,000	8,100	2,800	5,600
Eastern redcedar	48,000	4,500	4,800	7,000
Northern white-cedar	29,000	4,400	1,600	4,300
balsam fir	38,000	8,600	1,300	4,600
Eastern hemlock	44,000	7,400	2,500	5,900
Eastern white pine	34,000	6,800	1,500	4,700
jack pine	41,000	7,400	2,100	5,200
loblolly pine	50,000	9,700	2,700	5,900
longleaf pine	59,000	11,000	3,300	7,200
pitch pine	47,000	8,300	2,500	5,900
red pine	40,000	8,800	1,800	4,800
shortleaf pine	51,000	9,600	2,400	6,300
slash pine	60,000	10,500	3,700	6,600
Virginia pine	50,000	8,400	2,700	6,100
red spruce	41,000	9,200	1,800	5,200

Figure 14: Live or greenwood resistance to deformation and strength measures by species. (continued)
(Green et.al., 2007)

Modulus Index = MI =

$$[\,[\,(\,MOR_{kPa} / 1{,}000\,) + (\,MOE_{MPa} / 100\,)\,] / 225\,] \times 100.$$

Fiber Strength Index = FSI =

$$[\,(\,compression_{kPa} / 100\,) + (\,shear_{kPa} / 100\,)\,] / 300\,] \times 100.$$

Coder Ice Index = CII =

$$\{\,[\,[\,(\,MOR_{kPa} / 1{,}000\,) + (\,MOE_{MPa} / 100\,) + (\,compression_{kPa} / 100\,) + (\,shear_{kPa} / 100\,)\,] \times \text{specific gravity}\,] / 250\,\} \times 100.$$

Figure 15: Formula for greenwood strength and resistance to bending and deformation indexes (composite variables).

species	Modulus Index (MI)	species	Modulus Index (MI)
black willow	39	pin oak	66
quaking aspen	42	red maple	66
basswood	47	chestnut oak	66
silver maple	47	Northern red oak	67
Eastern cottonwood	48	swamp chestnut	68
hackberry	49	beech	68
bigtooth aspen	51	yellow birch	71
sycamore	52	honeylocust	71
black gum	53	green ash	72
		pecan	72
Southern magnolia	55	white ash	73
paper birch	56	black walnut	73
American elm	56	bitternut hickory	75
Southern red oak	56	water oak	75
yellow-poplar	56	sugar maple	76
post oak	58	scarlet oak	77
sweetgum	59	swamp white oak	79
overcup	60		
black oak	61	sweet birch	80
willow oak	62	mockernut hickory	82
red elm	62	pignut hickory	87
white oak	64	shagbark hickory	82
black cherry	64	live oak	85
		black locust	99

Figure 16: Live or greenwood resistance to deformation / bending from ice loading using the Modulus Index (MI), sorted from least to greatest for select temperate Angiosperm trees.

species	Modulus Index (MI)
Northern white-cedar	32
Eastern redcedar	41
Eastern white pine	45
jack pine	51
Eastern hemlock	52
balsam fir	55
baldcypress	56
red pine	57
pitch pine	58
red spruce	59
Virginia pine	60
shortleaf pine	65
loblolly pine	65
slash pine	73
longleaf pine	75

Figure 17: Live or greenwood resistance to deformation / bending from ice loading using the Modulus Index (MI), sorted from least to greatest for select temperate Gymnosperm trees.

Modulus Index (MI)

number of species	MI value	resistance class
Angiosperms --		
6	> 80	H
30	55 -- 80	M
9	< 55	L
Gymnosperms --		
2	> 70	H
10	50 -- 70	M
3	< 50	L

Figure 18: Live or greenwood resistance to deformation / bending from ice loading, using the Modulus Index (MI) to develop tree species resistance classes for ice storm damage.
(H = high resistance; M = moderate resistance; L = low resistance)

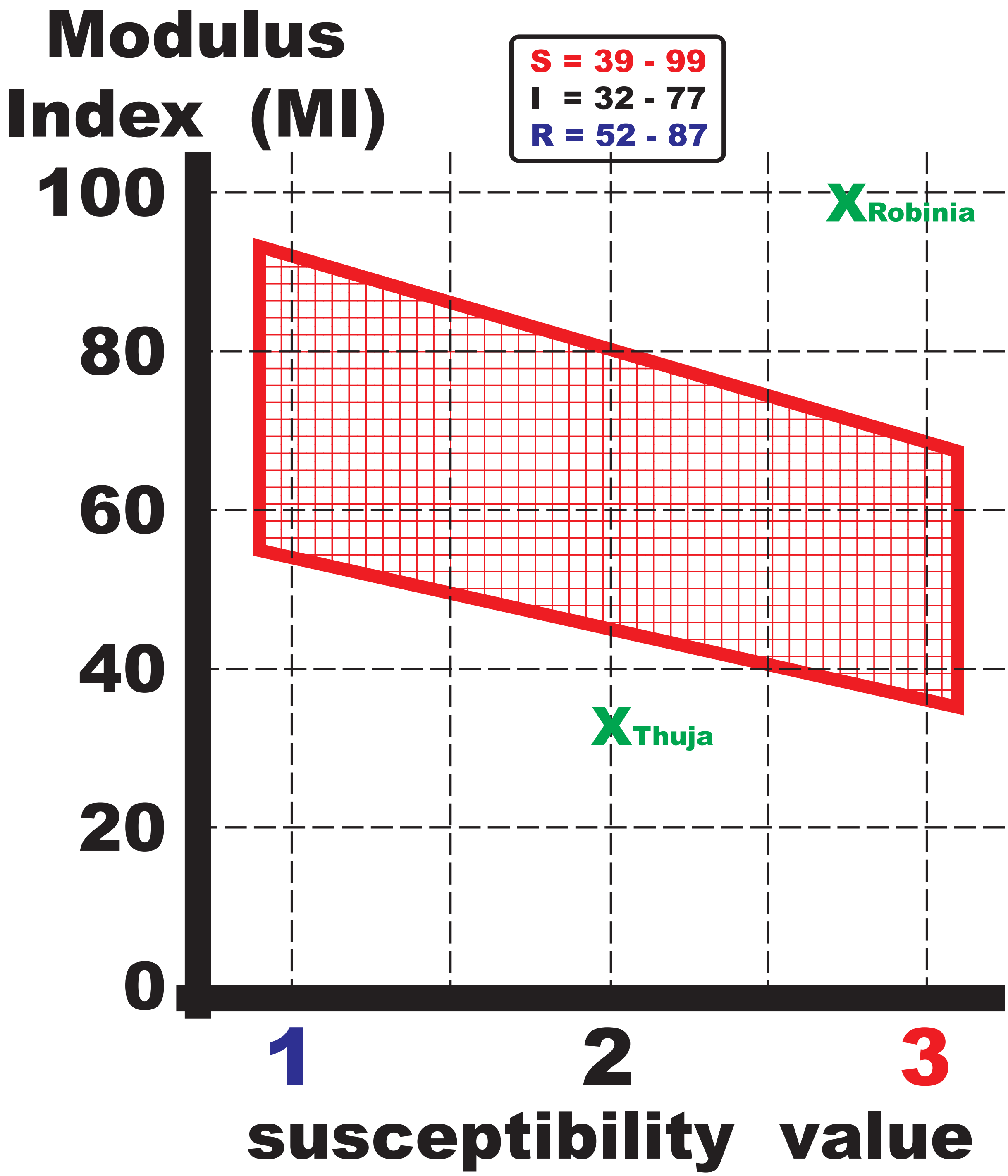

Figure 19: Tree species susceptibility to ice storm damage using Modulus Index (MI).
(1 = low risk or strong (R); 3 = high risk or weak (S))

species	Fiber Strength Index (FSI)	species	Fiber Strength Index (FSI)
basswood	18	Northern red oak	42
quaking aspen	19	beech	42
Eastern cottonwood	20	swamp chestnut	42
black willow	20	water oak	43
bigtooth aspen	21	overcup	43
yellow-poplar	24	white oak	44
paper birch	26	black oak	44
sweetgum	31	pin oak	46
sycamore	31	green ash	46
American elm	31	white ash	46
silver maple	33	bitternut hickory	47
Southern red oak	34	swamp white oak	47
hackberry	34	sugar maple	48
black cherry	34	mockernut hickory	48
Southern magnolia	35	post oak	49
red elm	35	scarlet oak	51
red maple	36	pecan	52
black gum	36	pignut hickory	52
yellow birch	36	shagbark hickory	54
sweet birch	37	honeylocust	64
black walnut	39	black locust	67
chestnut oak	40	live oak	98
willow oak	41		

Figure 20: Live or greenwood resistance to deformation / bending from ice loading using the Fiber Strength Index (FSI), sorted from least to greatest. (for select temperate Angiosperm trees).

species	Fiber Strength Index (FSI)
Northern white-cedar	20
balsam fir	20
Eastern white pine	21
red pine	22
red spruce	23
jack pine	24
Eastern hemlock	28
pitch pine	28
baldcypress	28
loblolly pine	29
shortleaf pine	29
Virginia pine	29
slash pine	34
longleaf pine	35
Eastern redcedar	39

Figure 21: Live or greenwood resistance to deformation / bending from ice loading using the Fiber Strength Index (FSI), sorted from least to greatest for select temperate Gymnosperm trees.

Fiber Strength Index (FSI)

number of species	FSI value	resistance class
Angiosperms --		
7	> 50	H
22	35 -- 50	M
16	< 35	L
Gymnosperms --		
0	---	H
9	> 25	M
6	< 25	L

Figure 22: Live or greenwood resistance to deformation / bending from ice loading, using the Fiber Strength Index (FSI) to develop tree species resistance classes for ice storm damage.
(H = high resistance; M = moderate resistance; L = low resistance)

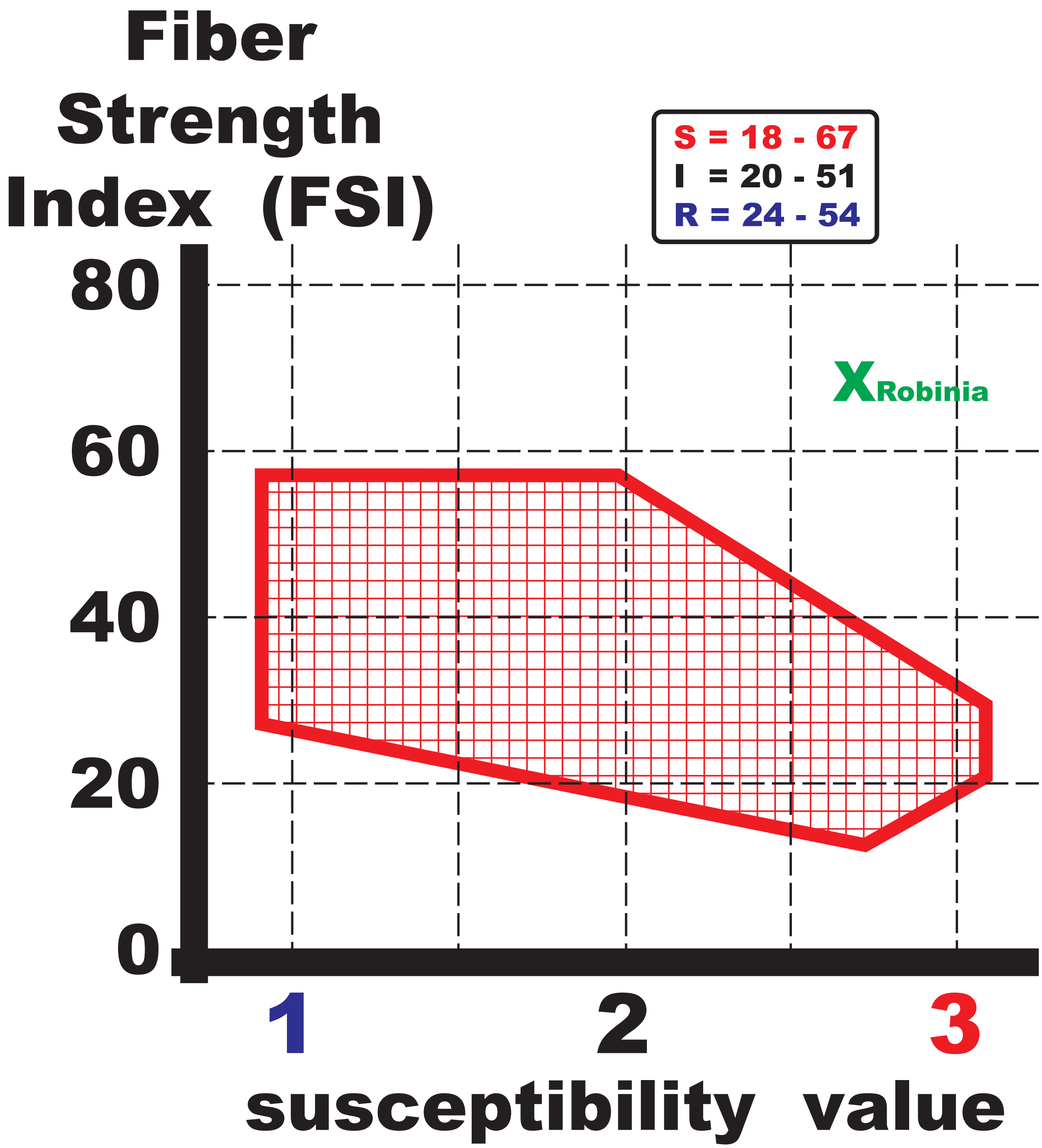

Figure 23: Tree species susceptibility to ice storm damage using Fiber Strength Index (FSI).
(1 = low risk or strong (R); 3 = high risk or weak (S))

species	Coder Ice Index (CII)	species	Coder Ice Index (CII)
basswood	20	black oak	61
quaking aspen	21	chestnut oak	61
black willow	21	Northern red oak	62
Eastern cottonwood	25	beech	63
bigtooth aspen	26	green ash	64
yellow-poplar	32	white oak	66
silver maple	36	water oak	66
paper birch	39	pin oak	67
sycamore	39	post oak	67
American elm	41	swamp chestnut	67
hackberry	42	white ash	67
Southern magnolia	42	sweet birch	70
black gum	42	sugar maple	71
sweetgum	42	bitternut hickory	74
red elm	47	pecan	76
black cherry	47	scarlet oak	79
Southern red oak	48	swamp white oak	82
red maple	50	honeylocust	84
black walnut	58	mockernut hickory	84
willow oak	59	shagbark hickory	89
yellow birch	59	pignut hickory	93
overcup	60	black locust	112
		live oak	155

Figure 24: Live or greenwood resistance to deformation / bending from ice loading using Coder Ice Index (CII), sorted in order from least to greatest among select temperate Angiosperm trees.

species	Coder Ice Index (CII)
Northern white-cedar	15
Eastern white pine	22
balsam fir	24
jack pine	30
red spruce	30
Eastern hemlock	31
red pine	32
baldcypress	36
Eastern redcedar	37
Virginia pine	40
pitch pine	40
loblolly pine	44
shortleaf pine	44
slash pine	58
longleaf pine	59

Figure 25: Live or greenwood resistance to deformation / bending from ice loading using Coder Ice Index (CII), sorted in order from least to greatest among select temperate Gymnosperm trees.

Coder Ice Index

number of species	CII value	resistance class
Angiosperms --		
9	> 75	H
22	45 -- 74	M
14	< 44	L
Gymnosperms --		
2	> 55	H
6	36 -- 54	M
7	< 35	L

Figure 26: Live or greenwood resistance to deformation / bending from ice loading, using the Coder Ice Index (CII) to develop tree species resistance classes for ice storm damage.
(H = high resistance; M = moderate resistance; L = low resistance)

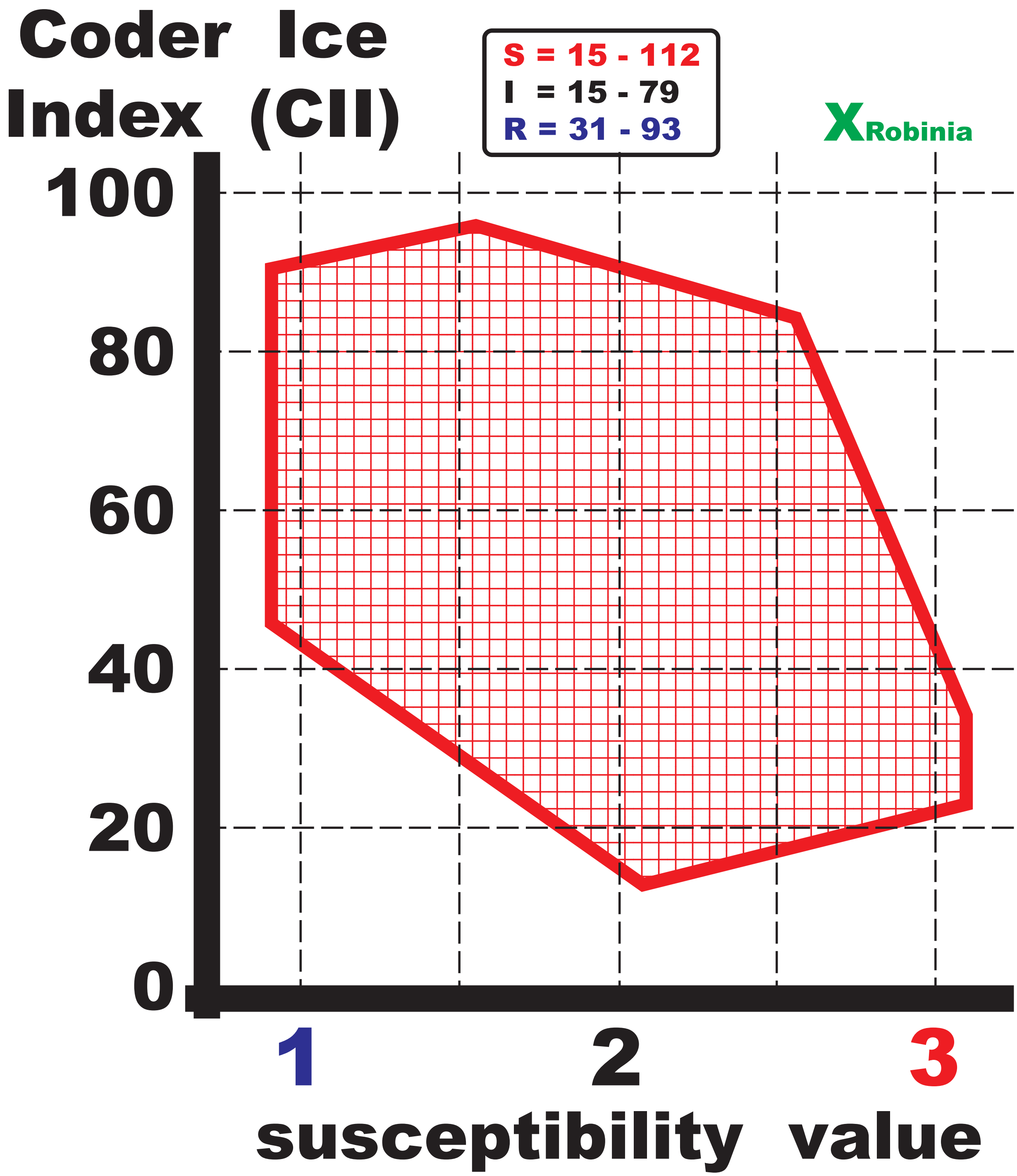

Figure 27: Tree species susceptibility to ice storm damage using the Coder Ice Index (CII).
(1 = low risk or strong (R); 3 = high risk or weak (S))

species	bending resistance	stiffness	splitting
Quercus coccinea	G/S	G/S	G/S
Quercus montana	G/S	G/S	G/S
Quercus velutina	G/S	M	G/S
Quercus alba	G/S	M	G/S
Oxydendrum arboreum	M	G/S	G/S
Acer rubrum	M	G/S	M
Pinus virginiana	M	M	P/W
Nyssa sylvatica	M	P/W	M
Tsuga canadensis	P/W	M	P/W
Pinus rigida	P/W	M	P/W
Liriodendron tulipifera	P/W	M	P/W
Aesculus flava	VP	P/W	P/W
Pinus strobus	VP	P/W	VP

VP = very poor; P/W = poor / weak; M = intermediate; G/S = good / strong.

Figure 28: Select wood strength property classes.
(derived from Warrillow & Mou 1999)