UNIVERSITY OF GEORGIA
Warnell School of Forestry & Natural Resources

Publication WSFNR-22-65A

November 2022

Standing Against The Wind: Introduction To Tree Structural Mechanics

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This publication is a brief introduction to a variety of tree biomechanical and failure mechanisms. Key to understanding how trees stand and fall is in appreciating tree life. Note, this publication will concentrate almost exclusively upon above-ground tree structure. Tree root anchorage and strength, and associated soil strength issues, are covered elsewhere. (Coder 2021f)

Trees are living creatures dealing with an environment full of constraints. Many of these constraints involve shortages of essential resources, most crucially light and water. Other constraints deal with social interactions and interference (competition / allelopathy) with other living things. To be successful in life, trees are always optimizing their biology for surviving, thriving, and reproducing. One critical component of a tree's biological success and sustainability is generating a viable structure to display, contain, and support its biology while interacting with its environment.

Skin Over Core

Tree structure is composed of individual parts and components coupled together so each is stiff, flexible, and disposable – all at the same time. The bulk of solid tree mass, both above and below ground, is a composite material known as wood. Wood is renewed and regenerated every new growing season as a sheath of tissue generated over top of last year's tree. Wood tissues responsible for water and element transport (when cells are dead), are generated and modified through a tree responding to its biological sensors reacting to new environmental conditions and constraints. Figure 1.

Tree structure is generated to facilitate placing both light gathering and water gathering equipment at some distance from the tree base. This presents a mechanical issue for perennial woody structures with significant height and extent to resist gravity and wind, as well as for woody structures grown out into a porous matrix of mineral and organic materials for anchorage. Successfully holding this new season's biologically active skin over a mostly dead structural skeleton is an iterative process of sense and respond. Tree genetics, honed over more than 420 million years of terrestrial evolution, generates and sustains structures with built-in safety factors to resist average and most peak loads against gravity and wind.

Tree Loads

Mechanical loads on trees are applied through both constant downward (gravity), and periodic lateral (wind) force applications and release. A mechanical load regime is a mix of static and dynamic forces. Gravity is a static load, while wind is a mix of static and dynamic loads. Static loads occur over long durations and are usually directional. Dynamic loads have very short durations and change in both magnitude and direction. (Niklas & Spatz 2012).

Trees seldom fail under their own mass unless fractures, injuries, and growth faults are present. Lateral loads from wind create (by far) the greatest impacts on trees, sometimes accentuated by unique weather conditions like ice or precipitation. Gravity focused impacts on trees include wood creep (plastic flow with gravity causing decline in position), leans, plastic or liquid soil flow processes, asymmetrical crown mass distribution, and shear extent and reach of branches.

Wind Loads

To appreciate trees resisting wind loads, some basic appreciation of applied wind forces on a tree is needed. There are three primary wind scales used in the United States. Beauford wind scale provides a set of force numbers between 0 (calm - 0-1 mph) and 12 (hurricane - 72-83 mph), divided into descriptors of air, breeze, gale, storm, and hurricane. The Saffir-Simpson hurricane wind scale provides categories between 1 and 5 for hurricanes from 74 to >156 miles per hour, with categories 3-5 (111 - >156 mph) considered major hurricanes. The Enhanced Fujita tornado scale provides a set of six storm categories between EF0 (65-85 mph) and EF5 (>200 mph) for tornado winds. For every wind scale category or force number, and its associated miles per hour range, there is a calculated applied force on the frontal area or sail of a tree. (Coder 2021a; Coder 2021e)

Figure 2 compares wind velocity in miles per hour to partial force applied to a tree in pounds per square foot of frontal area facing the wind. For example, a category 3 hurricane pushing winds of 120 mph would apply a maximum force on a tree of roughly 38 pounds for every square foot of frontal surface area of sail facing the wind. The cumulative impact of this load, its release, and sway can lead to catastrophic damage. Because of a tree's plastic and brittle reorientation / reconfiguration, and drag coefficient changes with increasing wind velocity, trees will usually not be subject to maximum listed loads, but will still have relatively large forces applied.

Calculation

The pounds of wind pressure applied to a tree advances roughly proportionally to the square of wind velocity ($\sim V^2$). One calculation for this accelerating force applied to a tree is: (Coder 2021e)

wind pressure applied to tree in pounds per square foot of frontal area toward wind =
0.013 X (wind speed in miles per hour X 0.45)^2 .

Note a drag coefficient of one (1.0) is used for simplicity.

Another way of considering wind loads and potential damage, Figure 3 presents for hurricane wind speeds (V), the relative wind force (V^2) and the damage potential multiplier (V^8) used by federal agencies in assessing damage to man-made and natural structures. In trees, it is important to consider the entire sail area (in square feet) of canopy (leaves, twigs and branches), and stem attached and integrated into a root base and soil matrix, resisting large wind applied loads.

Drivers Of Change

In order to resist large forces applied by wind and gravity, tree structures are generated and sustained by four biomechanical processes and growth forms. Each process helps maintain tree stability against gravity and wind loads. Figure 4.

1. The first structural component minimizes wind breakage and twist. Trees accomplish resistance to failure by generating more diameter growth and developing taper. Wood strength and stiffness, and diameter cubed (D^3) are proportionally generated to hold against applied loads. Tree aspects which interfere or degrade resisting loads include: increasing drag coefficients of stem and crown primarily through tree frontal area; increasing center of load height above the ground; and, amount of asymmetry in crown shape. (Fournier et.al. 2013; Thibaut 2019). Increased wind speed, sail area, height, and lateral and vertical asymmetry lead to failure unless structures can be effectively adjusted by stiffness and diameter increases. Figure 5.

2. The second structural component maintains tree self-support while minimizing self-buckling or bending under self-loading. Trees accomplish this by increasing wood stiffness and diameter ($D^{1/2}$). Tree aspects interfering with or degrading resistance against self-loading include height increases, and increasing stem and crown biomass. (Fournier et.al. 2013; Thibaut 2019). Increased height and crown mass lead to failure unless structure can be adjusted by stiffness and diameter increases.

3. The third structural component is a reaction to restore any displacement, such as a lean, in order to regain a competitive position for height growth and light foraging. Actively sustaining upright position is completed with tropic motion. Trees use asymmetric growth forces (i.e. motion) and changes in flexibility (MOE) radially along the axis of structural parts. This process is termed tropic motion velocity (MV) and is the rate of curvature near stem, branch, branchlet, and twig bases due to radial growth changes and wood maturation strain differences across the diameter. (Fournier et.al. 2013; Thibaut 2019). Displacement away from vertical or away from normal longitudinal pathways change both structural stress and strain, as well as competitiveness for light. Structure is adjusted by upward curving developed from unequal growth forces applied across basal diameters.

4. The fourth and final structural component is active posture control to sustain an upright position, controlled by two sensor systems. Trees manipulate their structural forms using gravity sensitivity to change positions near tissue bases, and an associated counter (proprioceptive) sensitivity from tissue terminals to limit curvature. Both processes actively compensate for increased self-loading. (Fournier et.al. 2013; Thibaut 2019). Tree posture control depends upon height or length, and diameter ($D^{1/2}$). Changes in aspect relative to gravity initiates curvatures against or opposite gravity. Curvatures initiate anti-curvature processes to assure tissue growth does not continue on past an upright position. Figure 6.

Dual Passive & Active

Tree wood structural systems have been considered passive in providing for water supply and mechanical support (the first two biomechanical processes and forms listed above), but there are two other active roles. Trees can quickly generate additive growth in specific locations and can produce a "muscle" or "motor" function by generating force along the exterior sapwood edge. Figure 7. Trees continue to balance or optimize all four biomechanical processes and forms. The first two processes balance structural safety traits against wind loading and self-buckling failures, and the second two processes actively balance motor traits (i.e. tropic motion and posture control) to sustain an upright / vertical position. (Gardiner et.al. 2016; Thibaut 2019).

Adjustments To Change

Above-ground components of trees must provide: progressively larger and taller support of the canopy through manufacturing of structure; resistance to external forces – primarily gravity and wind; control and restoration of posture across the structure; and, a network of strong and functional hydraulic conduits. (Thibaut 2019). Trees reorient their crowns toward light (phototropism), grow upwards (gravitropism), and reduce branch curvature and reorientation due to phototropism and gravitropism, termed autotropism. The balance between tropisms and structural responses, generate the tree crown shapes seen. (Duchemin et.al. 2018)

Trees react to wind loads through changing growth patterns (thigmomorphogenesis), and through active posture and equilibrium control through correction motors. Trees are constantly sensing and correcting aspect changes, and over the long-term, performing acclimation of supporting structures to immediate past and current load conditions. (Gardiner et.al. 2016; Moulia et.al. 2006). Trees actively sense normal load challenges in their current environment. Figure 8 shows three simple structural components of a tree model which interact with each other and wind challenges, and must be optimized by a tree for continued growth and effective shedding.

Wind Loading & Response

Trees are tuned to their mechanical environment. Trees are more than "fixed poles or aerial antennas." (Moulia et.al. 2006) As trees age, frontal area, crown mass, lever arm length, and drag continue to increase. Tree growth and aging cause increases in applied wind loads and vibrations due to turbulence. (Gardiner et.al. 2016) The biomechanical features of a tree change across its lifetime as it ages, grows, and gains total mass (both living and dead). (Jelonek et.al. 2019) Appreciating tree size rather than species, is key to understanding long-term stability. (Cannon et.al. 2015) Figure 9 summarizes trees being loaded and resisting those loads.

Trees balance five components of life: light for photosynthesis; water transport; expanding reach and extent through growth; reproduction; and, mechanical support under dynamic and static loads across their lifetime. (Gardiner et.al. 2016) Trees respond to mechanical loads by either growing or shedding. (James et.al. 2006) Tree growth occurs in progressive layers around their periphery, each layer adjusted for current stress / strain levels. Every new layer in a tree has two internal mechanical loads applied: maturation stress adjustments during wood formation; and, modified resistance to increased self-weighting. (Almeras et.al. 2018)

With no wind, trees are loaded under their own weight, exacerbated by asymmetrical crown components and leans. Trees avoid buckling under their own weight effectively while maintaining light collection for photosynthesis through maintaining a stable posture. (Gardiner et.al. 2016) But, wind lateral load impacts are a fact of life for trees and almost always greatly exceed gravity load impacts.

It's A Drag

Drag forces define the wind load environment on trees. Wind flows through and around a tree resulting in displacement of crown and bending of stem. (Angelou et.al. 2019) Open grown trees have wind loads applied from above the canopy and from subcanopy jets beneath, as well as from all directions. (Gardiner et.al. 2016) Trees need to be both flexible (lower MOE) and rigid (increased diameter) at the same time to resist static (self-weighted) and dynamic (wind) forces. (Gardiner et.al. 2016) Trees tend to be flexible when small, young and juvenile, becoming more rigid when large, old, and mature. (Telewski & Moore 2016) Trees adjust to wind by elastic reconfiguration, streamlining, and fracture (tissue loss) to reduce drag. (Gardiner et.al. 2016)

For survival, trees must be able to withstand and adjust to chronic (average) winds plus gusts, over their life. (Gardiner et.al. 2016) Wind is not steady, not applied in a straight-line, rapidly fluctuating, and highly turbulent. There is major wind turbulence just behind and immediately downwind from a standing tree. (Gardiner et.al. 2016) Tree branch tips are in almost constant motion with winds above 5 mph, continuously moving and changing orientation. (Thibaut 2019)

Only The Strongest

Wind pushes on, deflects or deforms tree parts. In response, trees use a number of means to reduce wind loading and drag impacts. Wind causes: reorientation of leaves, twigs, and branches; a general reconfiguration of crown shape; and, shedding of leaves, twigs, and branches – all which reduce drag. (Gardiner et.al. 2016) Trees reallocate growth materials internally in response to wind. Under wind loads, trees are better rooted, have greater stem taper, larger branches, shorter height, and generate more flexure wood. (Gardiner et.al. 2016) Figure 10.

Trees sense and respond to local wind loads and release. But not all wind causes a response. Only the strongest winds are sensed by trees. (Bonnesoeur et.al. 2016) Daily wind speed peaks are not sensed and are filtered out within a tree's response system. Tree growth changes occur under more rare intense seasonal storms between 25 mph (once a week) to 49 mph (once a year). (Bonnesoeur et.al. 2016) Trees sense and respond to wind through living cells being strained (micro-faults) which generates a mechanical response in the cambium. (Gardiner et.al. 2016) Strains of 0.15% above normal strain regimes in cell walls initiate tree responses for radial growth changes. (Bonnesoeur et.al. 2016)

More Extreme

With a changing and more variable wind environment, more extreme wind events are expected over time. Even if chronic wind (average winds) remain the same or decrease, extreme events are expected to increase. (Gardiner et.al. 2016) Under extreme wind events, trees have two major forms of failures: uprooting and soil instability; and, stem breakage. (Thibaut 2019) Figure 11.

In one study of hurricane tree damage, the most common damage types reported were for uprooted and broken trees, followed by leaning trees. Figure 12. Tree damage was most prevalent in the 58 – 74 mph sustained wind zones. (Hiesl & Rodriguez 2019) Another study of hurricane tree damage found large overstory trees uprooted with subcanopy and understory trees crushed by falling trees and debris. (Jones-Held et.al. 2019) Figure 13 shows general wind-generated damage forms in trees. Optimizing tree form internally against hurricane force winds requires flexible materials, stiff bases, large tapers, and generation of small frontal areas. (Paz et.al. 2018)

Reconfiguration

Trees streamline or reorient tissues downwind due to wind loads. (Manickathan et.al. 2018) Under greater wind loads, tissues reach the limit of their ability to reconfigure and then break. Because of tree structural variance in diameter, length, and number of nodes, crowns reorient and then break in predetermined ways (weak zones / abscission zones) preserving tree life. Branches are more likely to break before stems, and leaves / twigs more likely to break before branches. (Gardiner et.al. 2016)

The periphery of a tree crown receives the most loading and suffers the greatest brittle reconfiguration (breakage). Wind load energy applied to the smallest components (if not broken) are shed back into the wind stream as vortexes. (Gardiner et.al. 2016) Stem and branch breakage risks increase with past damage, faults and decay (from old pruning and periderm damage), included periderm inclusion faults, and mechanical damage from touching and being struck by other components. (Gardiner et.al. 2016) Figure 14 provides an index of tree crown reconfiguration under wind loads, and under wind loads with ice coverage (i.e. ice storms). Note trees reach 100% plastic reconfiguration (non-breakage) in wind around 55 - 65 mph, or ~8 - 10 pounds of force per square foot of tree area. (Coder 2021e)

Growth Changes

Trees reallocate growth resources and change structure under wind loads. Most large wind-induced bending loads are sensed and countered by changes to outer parts of a stem cross-section. (Almeras et.al. 2018) These changes can be quite swift. In one study, trees challenged by wind loads generated 4.7% more stem strength within one season. (Bonnesoeur et.al. 2016) Tree size attributes of height, diameter, volume, growth rate, and frontal area all interact with wood characters, load resistance, and structural shape features. (Fournier et.al. 2013) The reallocation of resources to resist wind loads mean total tree biomass remains roughly the same under wind loads, but root / shoot ratios become greater. (Gardiner et.al. 2016)

Wind resistance in trees is sensed by tissue flexing and strain, and generates changes including increased stem and branch taper, more spiral grain (under asymmetrical loads), larger branches, and reduced wood stiffness at the periphery. (Telewski & Moore 2016) Wind forces trees to have less height growth, more root biomass, and greater diameter growth. (Telewski & Moore 2016; Wu et.al. 2016) Tree failure under wind loads has been found to be less likely with increased stem and branch taper, greater base rigidity or stiffness, less crown mass, lower crown center of mass, and shifting increased stiffness toward the stem top. (Dargahi et.al. 2019) All of these changes occur as trees age.

Tree Responses

Trees are a mix of passive and active responses to wind and gravity loads. The heartwood and most of the sapwood is dead, rigid, and represents a passive structural skeleton. (Thibaut 2019) Gravitropism and phototropisms are used to seek light resources through local curving (i.e. light sensed reorienting) along stems and branches. (Fournier et.al. 2013) Open grown trees do not have light competition as a key issue, and they tend to develop larger crowns and branches with less height growth to resist greater wind exposure. (MacFarlane & Kane 2017)

Removal of tree branches and foliage, or changes in neighboring trees or structures around a tree, changes wind loading and causes a reallocation of growth allowing trees to acclimate to new circumstances. (Gardiner et.al. 2016) Trees in groups tend to show less wind damage and better survival than isolated trees. Reduced tree failure risks come from removal of over-mature and damaged trees, an active pruning program, and rooting space improvements (increases in aeration, drainage, compaction mitigation, and horizontal rooting volume). (Gardiner et.al. 2016)

Flexness & Stiffability

Tree response to applied loads are composed of two contrasting changes: more flexibility (elastic resilience) to resist greater wind loads focused primarily in the top two-thirds of a tree stem; and, more stiffness to avoid displacement and fracture focused primarily in the bottom two-thirds of the tree stem. Figure 15. Trees develop increased resistance to breakage, but also develop lower stiffness and greater capacity for reconfiguration and bending without fracture, under wind loads. (Gardiner et.al. 2016; Wu et.al. 2016)

Wind challenges cause trees to be stiffer overall, but reaction wood and flexure wood generated has less proportional stiffness. The result is more resistance to wind overall, but greater capacity for reconfiguration and bending without damage. (James et.al. 2017) This trend to decrease modulus of elasticity (MOE), which increases flexibility and minimizes breakage, coupled with a reduction of length to diameter (increased taper) of stem and branches, both help resist bending, increase plastic reconfiguration, and maintain a specific orientation. (Niklas & Spatz 2012)

Adjusting To Failure

Trees break where they are weakest, and where stress and strain is concentrated, usually occurring at the same point. Trees do not break if the modulus of rupture (MOR) at each point is greater than the mechanical stress at each point. The elastic restoration forces in the stem, branches and root, along with the mass of the stem/root/soil system, can resist significant wind and gravity loads and not fail. (Gardiner et.al. 2016) The key internal process of hardening trees against strong wind loads is called thigmomorphogenesis. (Bonnesoeur et.al. 2016)

Wood Fractures

Tree materials consist of stiff fibers in a plastic matrix, which combines stiffness and toughness. The advantage of composite materials like wood in trees is cracks will not propagate effectively even under load. In addition, notch stress sites focused on wounds, faults, nodes, and growth deformities are actively strengthened by additional growth of wood material. When loads in bending, tension, or torsion become too great, fractures or cracks do occur, both radially into the wood and longitudinally along the length of tissues, but are slowed in their propagation by the composite nature of wood. (Niklas & Spatz 2012) Figure 16.

A crack on the tension side is usually initiated at a fault or discontinuity. It propagates radially only a short way inward then changes direction to run longitudinally. Radial cracking is most likely to be stopped at the latewood / earlywood interface. With fractures, bending energy in adjoining parts is reduced, which slows or ends longitudinal cracking. Continued tension from curvature at the site will then cause new radial cracks, continuing the fracture process as long as the bending load is applied. As cracks propagate, geometry of the part changes and becomes more prone to further cracking. (Niklas & Spatz 2012)

Getting Old

As trees age and get larger, there is a greater chance for growth defects and compartment lines to form fracture zones. Internal flaws in fiber orientation, knots, old injuries and decay all greatly impact mechanics of trees. Even small cracks are potentially dangerous and can be centers of serious damage. Notch stresses in tree stems and branches, or places where concentration of stress and strain around tree faults are focused, are actively countered by tree growth processes to fortify structure and minimize further failure. (Niklas & Spatz 2012). Seams, ridges, bulges, and other types of responsive / adaptive growth are visible signs of a tree countering weak points.

CONCLUSIONS

Trees exist in a mechanical load environment within which they must defend their position to live by bolstering and continually reinforcing their structure, or by reorienting structures to a reduced stress / strain position. The environment challenges a tree with many biological and structural constraints, and a tree responds using energy and resources to successfully colonize, control, and defend resource-containing ecologically viable space. Tree structure must continue to develop in response to environmental loads in order for trees to be successful.

Citation:

Coder, Kim D. 2022. Standing Against The Wind: Introduction To Tree Structural Mechanics. University of Georgia, Warnell School of Forestry & Natural Resources Outreach Publication WSFNR22-65A. Pp.26.

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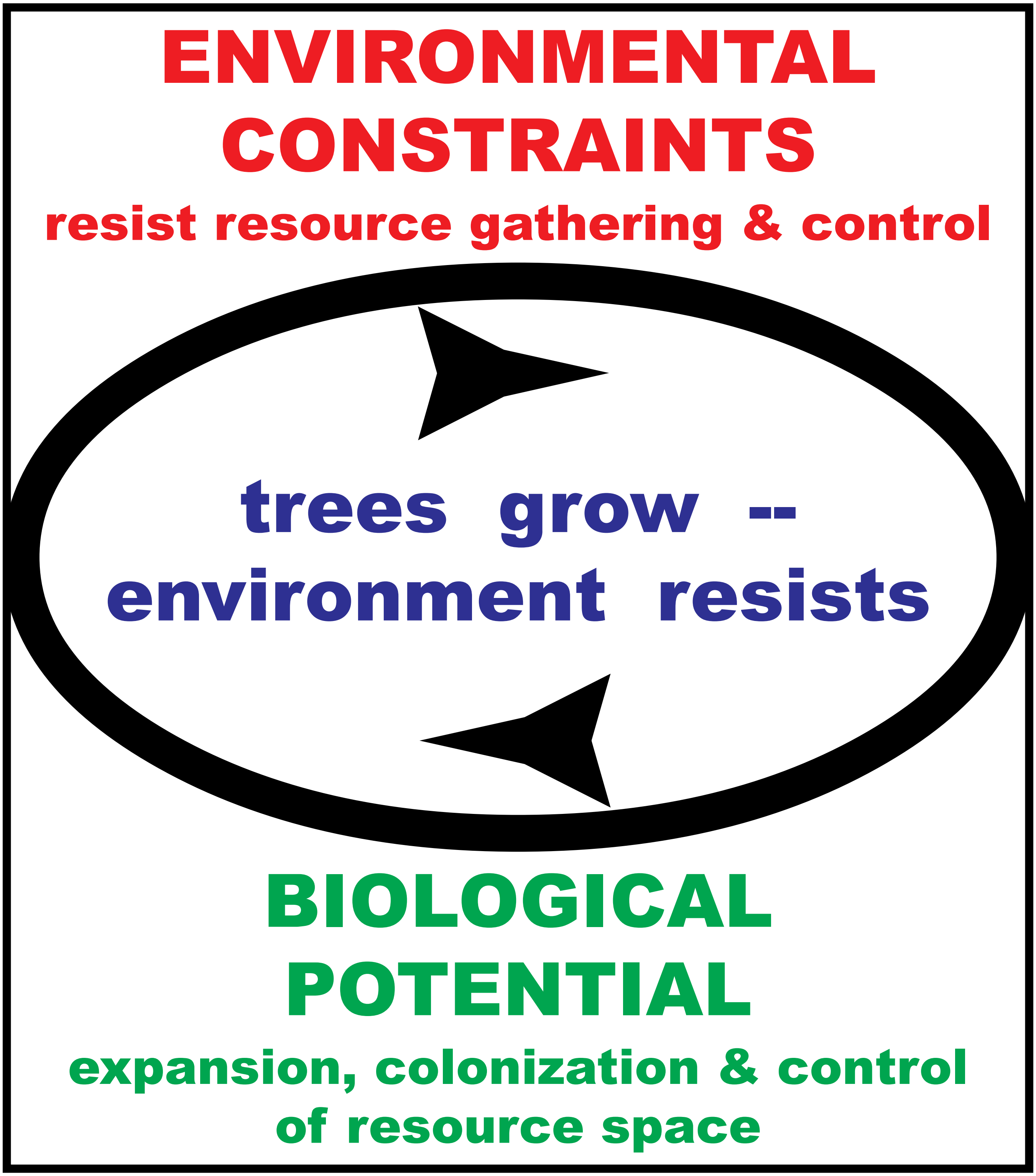

Figure 1: Tree life circle balanced over the long run among thriving, surviving and declining.

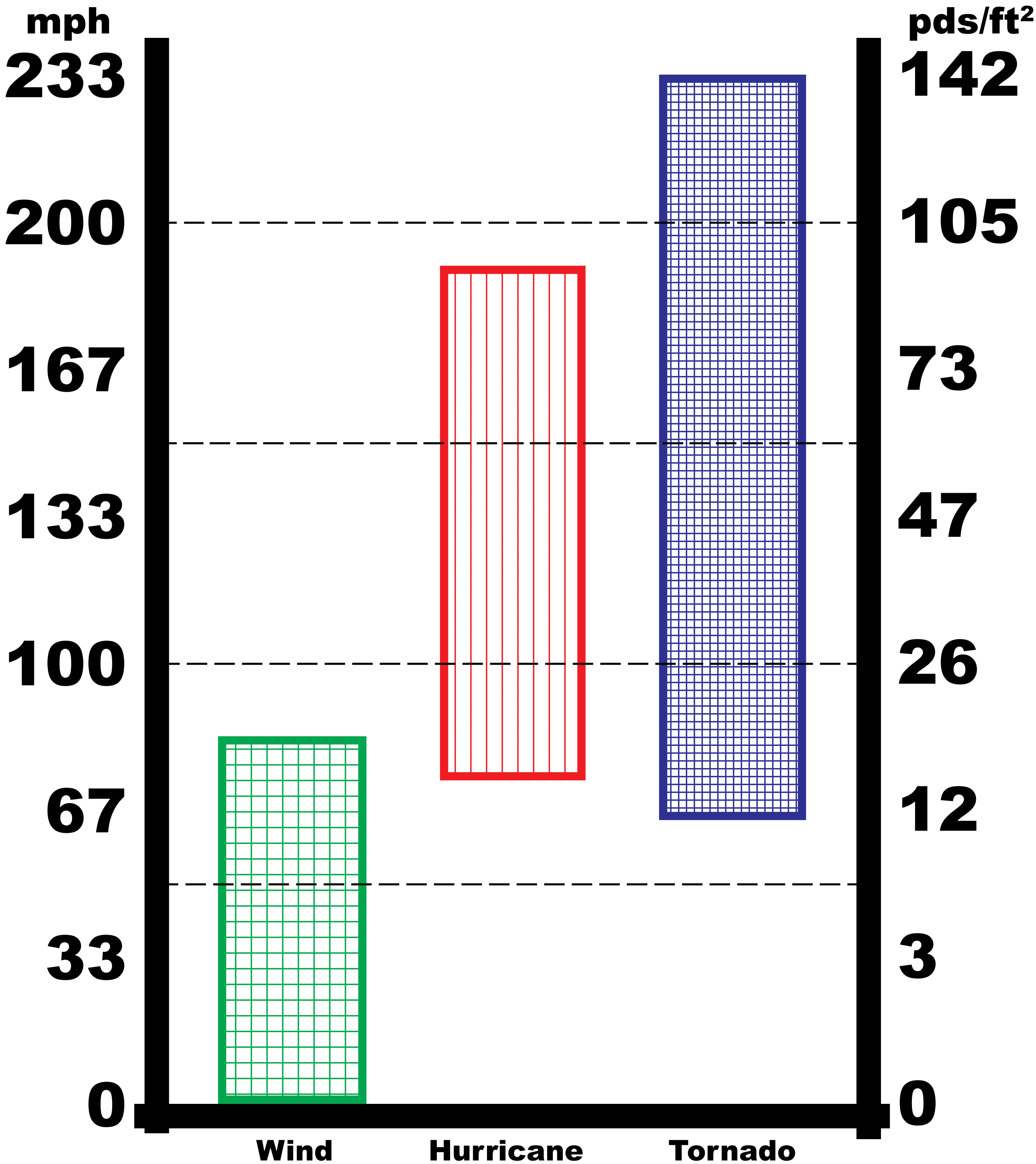

Figure 2: Comparing wind scale speeds in miles per hour with wind pressures applied to trees in pounds per square foot of frontal area. (Coder 2021a; Coder 2021e)

hurricane category	wind speed (mph)	relative wind force	damage potential multiplier
1	75	1.0X	1.0X
	80	1.1X	1.6X
	85	1.3X	2.9X
	90	1.4X	4.3X
	95	1.6X	6.6X
2	100	1.8X	10X
	105	2.0X	15X
	110	2.2X	21X
3	115	2.4X	30X
	120	2.6X	43X
	125	2.8X	60X
4	130	3.0X	82X
	135	3.2X	110X
	140	3.5X	147X
	145	3.7X	195X
	150	4.0X	256X
	155	4.3X	333X
5	160	4.6X	429X
	165	4.8X	549X
	170	5.1X	697X
	175	5.4X	879X
	180	5.8X	1,101X

Figure 3: The relative increase in wind load force (kinetic energy = x^2), and its potential damage (x^8) as wind velocity increases from a 75 mph base line. (NWS -- NOAA)

-SKELETAL-

1. avoid breaking

(resist bend & twist)

2. self supporting

(resist buckling)

-POSTURE-

3. regain position

(tropisms)

4. maintain position

(posture)

Figure 4: Tree biomechanical components for resisting and responding to structural loads and changes in orientation.

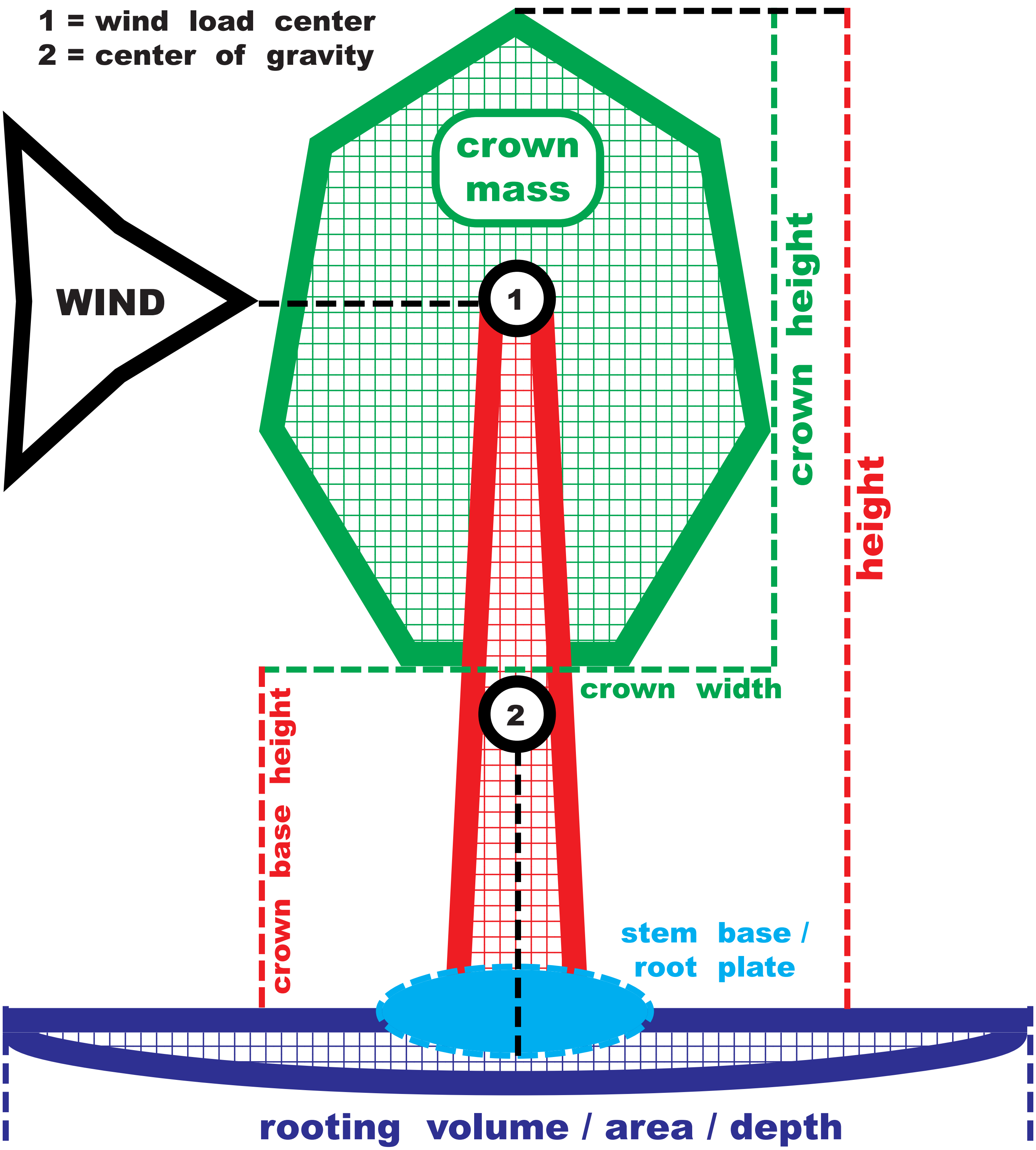

Figure 5: Tree structural model and critical biomechanical measures.
(derived from Jelonek et al. 2019)

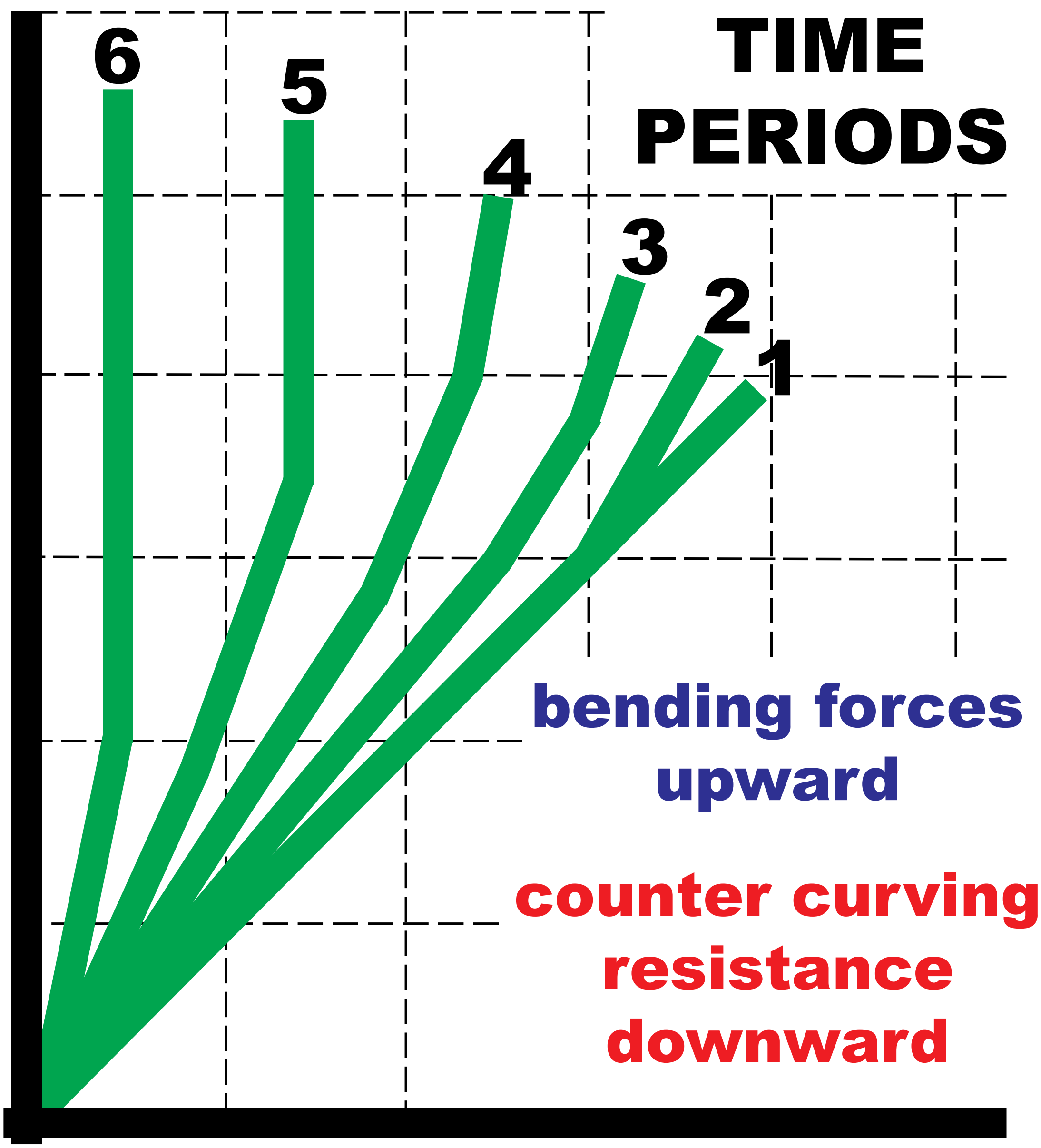

Figure 6: Active tree shoot straightening over 100 days (~16 day increments) without overshooting vertical (from a 45^{o} initial bend in shoot).
(after Moulia et al. 2006)

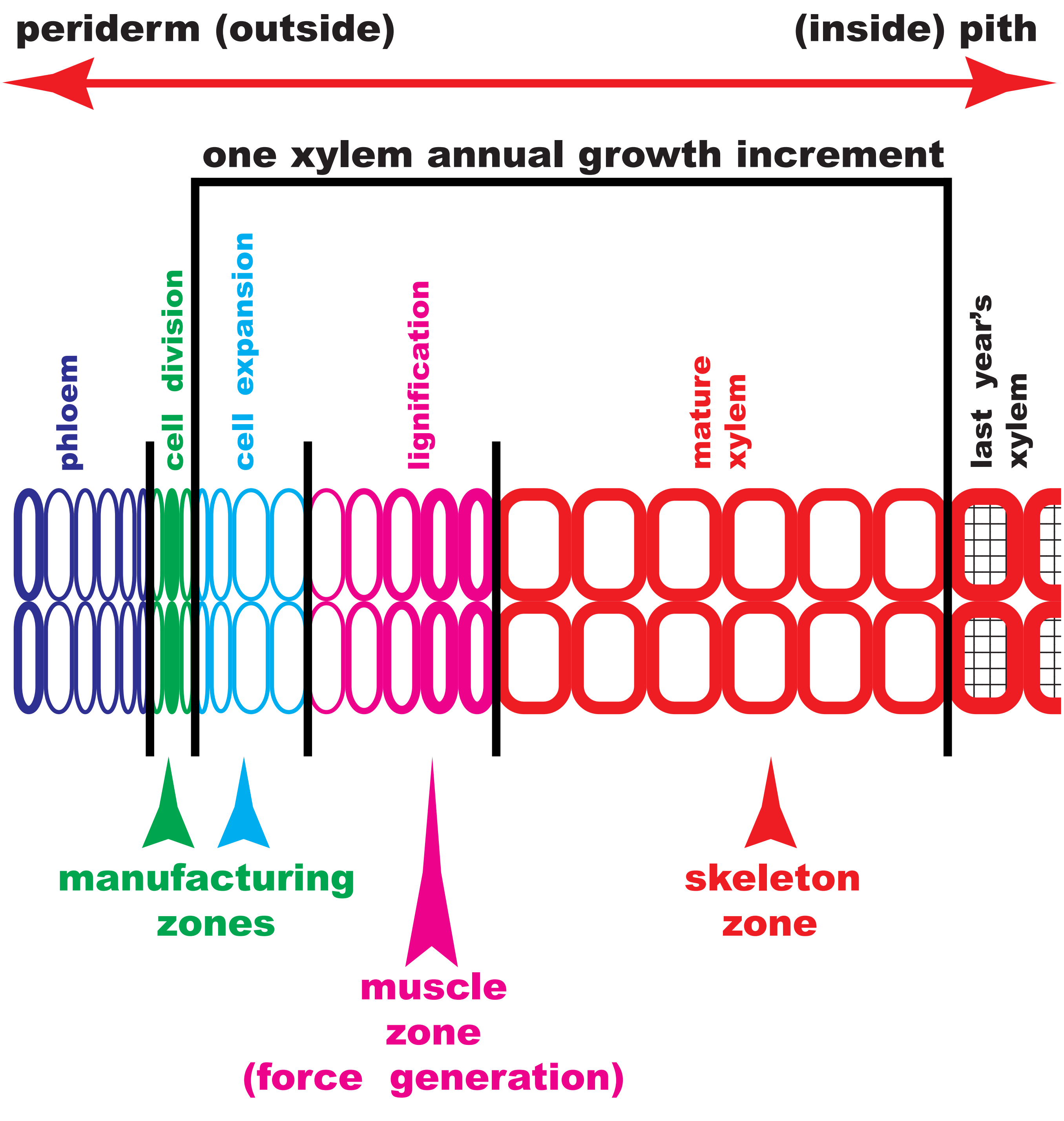

Figure 7: Functional secondary cell zones in the most outer increment of a tree cross-section generating mechanical force.
(after Thibaut 2019)

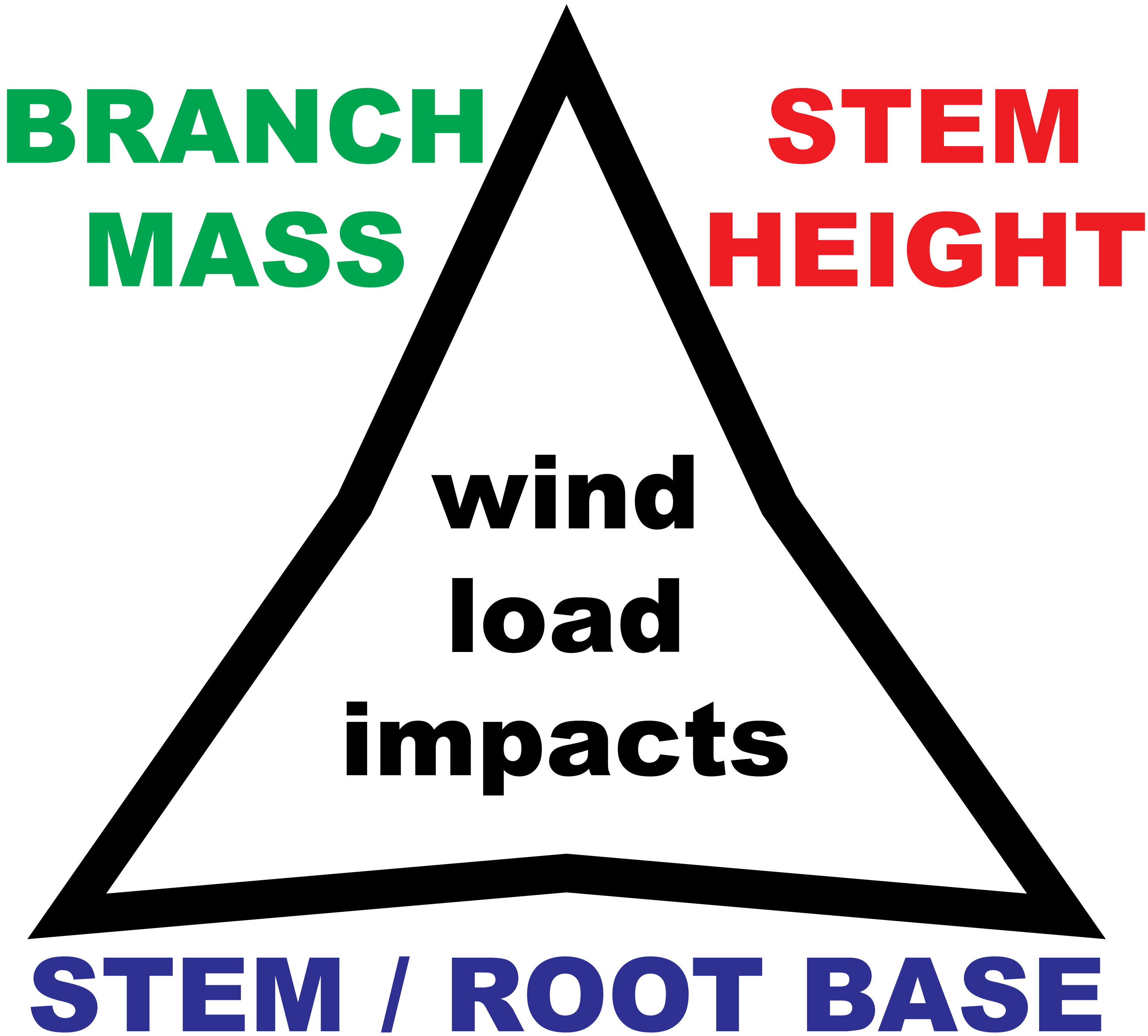

Figure 8: Three structural components of a tree model which interact with wind loads, and which are optimized by continued growth or shedding to maintain a tree upright.
(Coder 2021a; Coder 2021d)

FORCES APPLIED

wind
gravity
torque at base

APPLICATION FACTORS

wind speed
crown size, density, mass, asymmetry
stem mass, elasticity, displacement
tree height

RESISTING FORCES

branch damping
stem resistance
root-soil resistance

RESISTANCE FACTORS

wood strength
branch & stem natural sways
stem elasticity, diameter
root-soil weight, strength

Figure 9: List of load (forces applied) and hold (resistance) components in trees. (after Peltola 2006)

WIND LOADS

TREE INCREASES:

branch diameter
stem / branch flexibility
denser wood at perimeter
root / shoot ratio
coarse / fine root ratio
secondary growth -- diameter
eccentric growth --
root, stem, branch
tissue shedding -- leaf, branch
reconfiguration -- streamlining
sway damping
crown porosity (with larger wind loads)

TREE DECREASES:

height
crown porosity (under smaller wind loads)

Figure 10: Tree acclimation responses to increased wind loads. (Gardiner et al. 2019)

TREE DAMAGE

BREAKAGE (location)

stem buckling rare
compression side failure
1/3 to 1/2 tree height
heavy branch whorls / nodes
(breaking factors = diameter, MOR, knots, decay)

UPROOTING (location)

root plate rotation --
windward side lift
leeward side hinge down
root breakage close to stem
(uprooting factors = root architecture, taproot / rooting depth, root size windward, soil plastic limit)

Figure 11: Primary tree damage locations and forms caused by wind loading. (Coder 2021f; Gardiner et al. 2019)

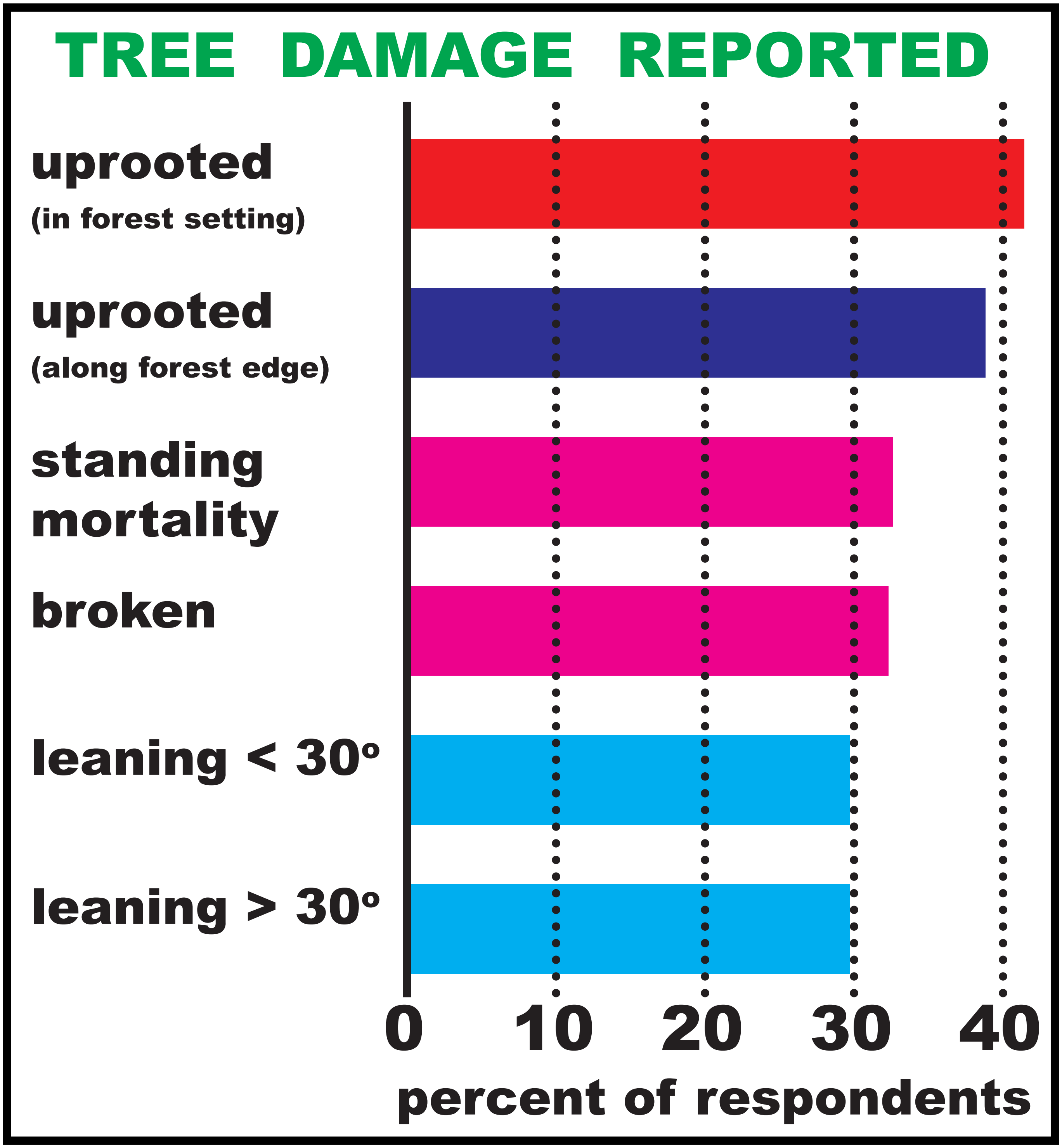

Figure 12: Survey representing high levels of different tree damage types after hurricane Matthew in South Carolina.
(Hiesl & Rodriguez 2019)

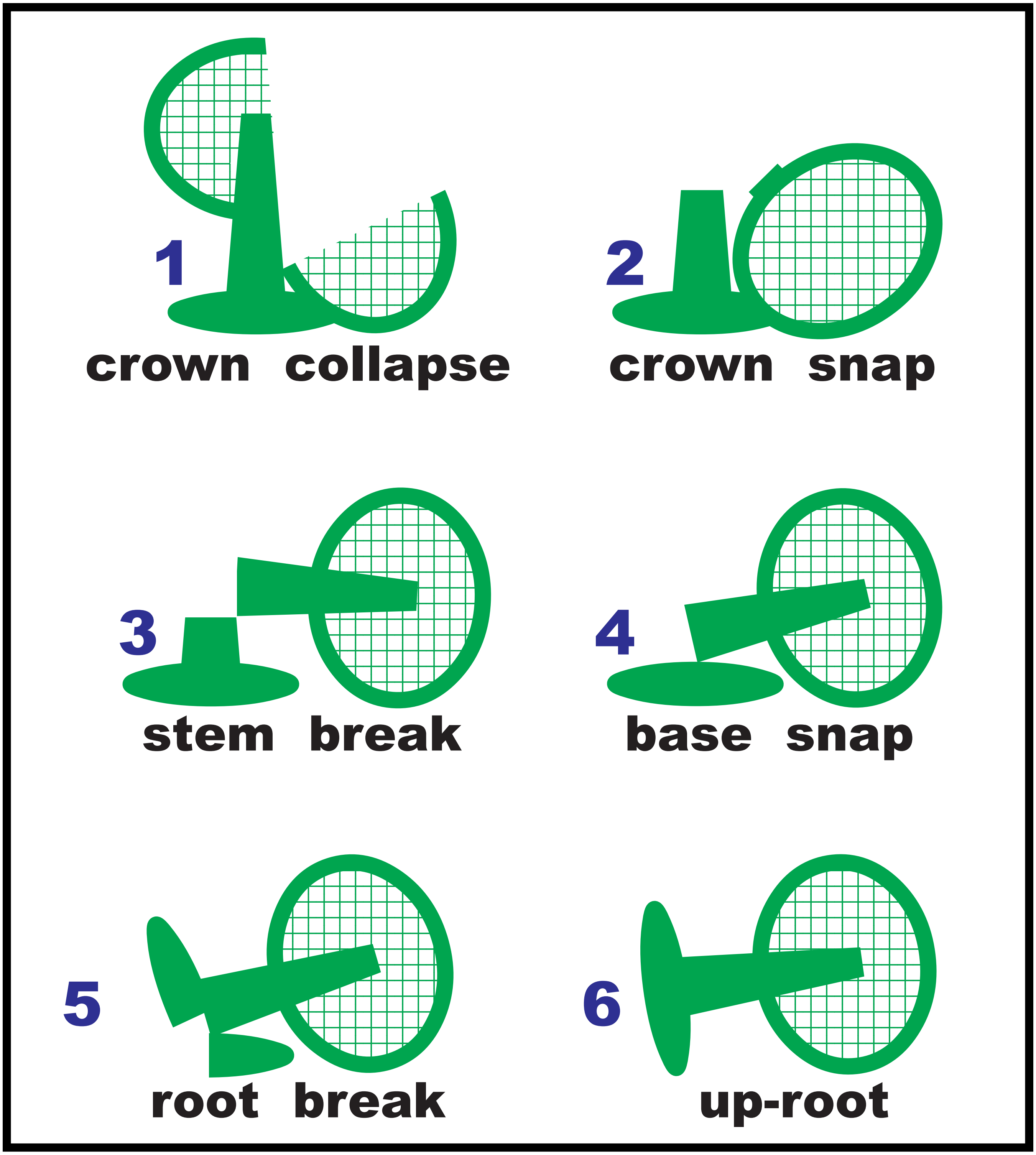

Figure 13: General wind damge forms and failure points in trees. (after Gardiner et al. 2019)

Index of Tree Crown Reconfiguration

index value	wind speed (mph)	wind pressure (lbs/ft2)	tree crown reconfiguration descriptor	tree crown reconfiguration value (%) wind	wind+ice
C0	0	0	gravity impacts only	0%	[10%]
CI	10	0.3	petiole & blade deforming, & twig sway	5%	[30%]
CII	19	1.0	leaves rolled back & large peripheral twigs sway	10%	[60%]
CIII	28	2.0	twigs pulled back & peripheral branches sway	25%	[100%]
CIV	37	3.6	branches pulled back & stem sway	45%	--
CV	46	5.6	twig breakage, stem pushed / held downwind	70%	--
CVI	55mph	8.0lbs/ft2	twig & branch breakage	100%	–

Figure 14: Index of tree crown reconfiguration or streamlining under wind loads, and under combined ice and wind loads. (Coder 2021b; Coder 2021e)

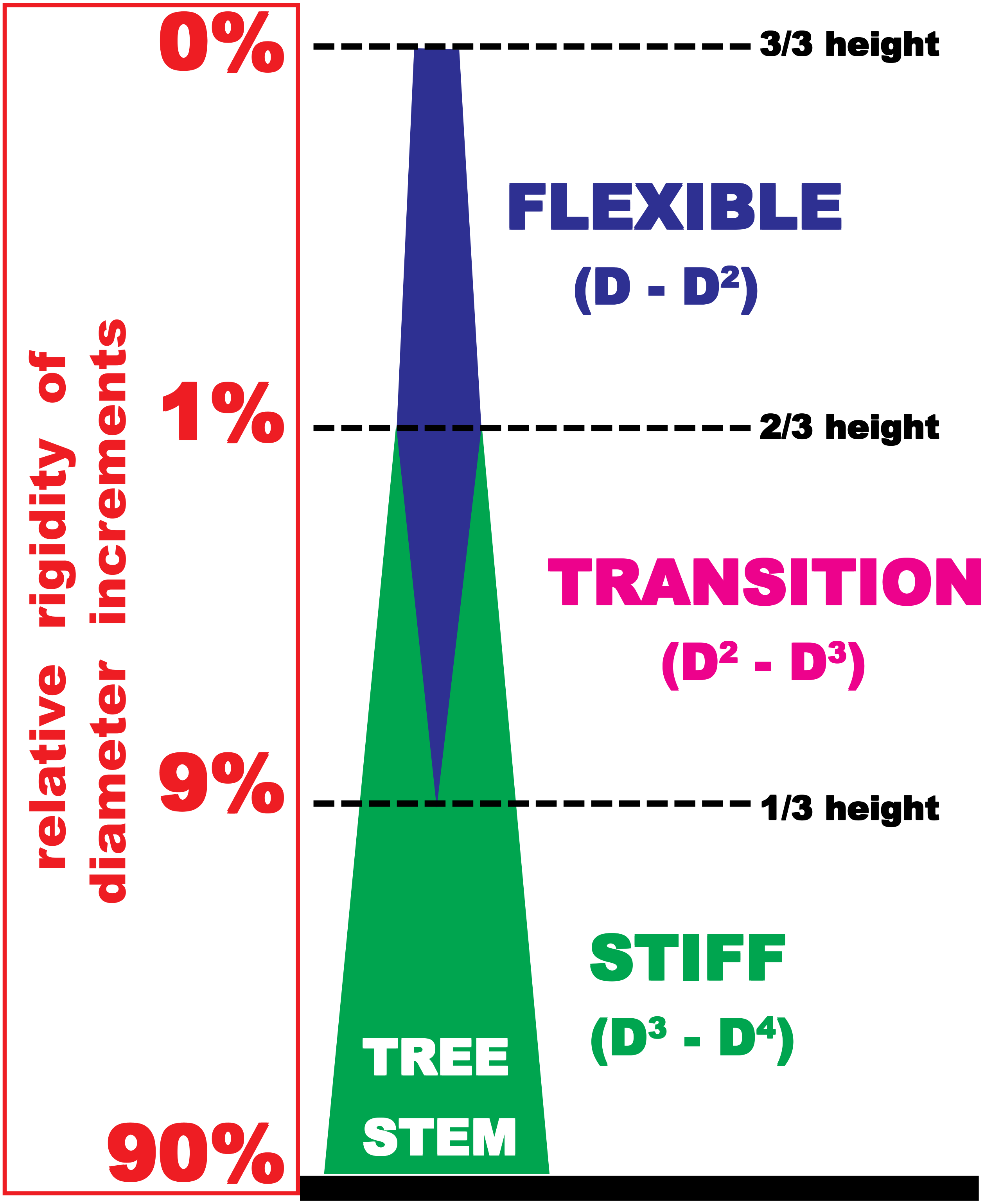

Figure 15: Tree stem stiffness and flexibility zones based upon calculated diameter increment values (D^X) and comparative rigidity of diameter increments at each location.
(Coder 2021a; Coder 2021c; Coder 2021d)

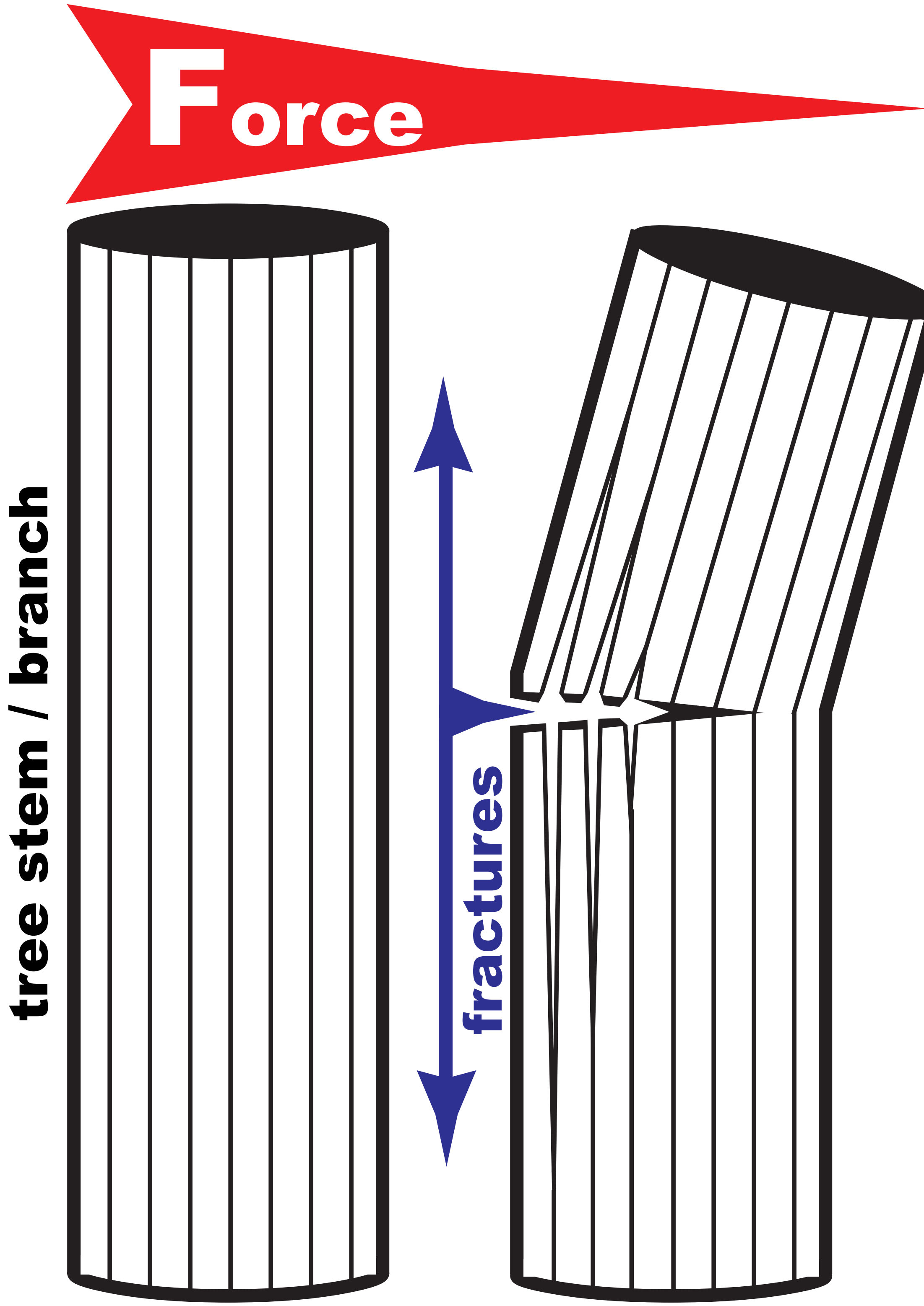

Figure 16: Tree wood fracture progression under wind loading in radial and longitudinal directions. Tree tissue composition keeps shifting fracture path from radial to longitudinal direction.