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Anatomy of Branch Attachment Strength

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Branches were an early development in trees which led to many new issues and solutions within tree health and structure. Branch connections and their reinforcement became key to tree survival and success. Branch connection points to supporting stems, or branch connection points to supporting branches, are called a confluence. A confluence is where resources coming from many leaves and many roots meet. Visualizing how branches are attached to stems, and how they begin to fail, can assist tree health care providers manage crown form, adjust pruning techniques, and identify failure risks.

Branch Connections

Branch development and maintenance requires continual investments in structural components to hold food production tissues, provide water, and generate living storage areas. Solutions for holding branches onto trees is generally conserved across all wood-generating tree forms of angiosperms and gymnosperms. Branch generation and maintenance presents a complex set of structural problems.

A branch attachment point is a node. A node is a weak point or defect along a stem or branch, and a location where mechanical stress is concentrated. (Jungniki et al. 2009; Kane & Clouston 2008; Kane 2014) In one study, all stem failures found occurred at lateral branch nodes along a main trunk. (Kane & Clouston 2008) But, branch failure can serve to protect the whole tree from failure. Excessive sway, and failure under bending and torsion, can allow a branch to be lost while the tree continues to live. For example, branch failures were approximately six times (6X) greater than whole tree failures in large storms. (Koeser et al. 2020) Branches are designed to fail first.

Nodes & Internodes

Trees grow in sections or modules with straight structural fiber runs (termed internodes), separated by fiber disruption areas called nodes. Figure 1. Nodes are where tissues supporting organs such as leaves, buds, twigs and branches are generated. Along tree branches and stems, everywhere a node occurs, the connecting structure is weakened and made less resistant to failure. Nodes act like springs along stem and branch lengths, allowing for more flexibility and less stiffness. The gap in tissues generated along an internode by a node changes fiber orientation, cell types, and cell wall content, all of which can generate both structural weakness and flexibility. (Gardiner et al. 2016) These changes in direction of vascular connections allow branches to be extended and supported, while stem tissues separate for branch emergence and then close around the branch base and continue on as before. (Coder 2021b)

As tree and branch diameters increase, branch geometry changes by increasing average branch diameter, extending length, adding diameter and length to secondary branches, and increasing taper. (Coder 2021d) The result allows heavier loads to be applied to greater branch surface areas and volumes with less flexibility. (Kane & Finn 2014) There are problems with increasing branch size. Codominant branches, which are cited as being >66% to >75% of stem diameter, represent a significant structural defect accounting for roughly 36% of all trunk failures. (Kane & Clouston 2008) Large branches and codominant branches induce significant failures in open-grown trees because their junctions with the stem represent significantly weaker structural zones. (Kane 2014)

Nodes Within Internodes

Branch emergence from a main stem or higher order branch depends upon primary tissues generating a growing point and secondary meristems generating periderm, phloem, and xylem tissues. The structural components required to resist wind and gravity loads for effective branch anchorage is a combination of stem and branch tissues. The branch emergence node is an area of both stem tissue disruption and stem/branch tissue integration and confluence. Figure 2. The biology of resource delivery, food transport, and associated growth regulator signals all flow through a branch node area. The structural components of a branch node must support and maintain the skeletal framework upon which biological tissues function.

Stems and branches are defined by their biological and structural functions. Internode strength is generated and adjusted by the vascular cambium responding to wind and gravity load changes. Resisting failure demands continued sense and respond changes in tissue stiffness, toughness, and flexibility as growth increments are added. Internode tissues are interrupted or disrupted by nodes which support buds, leaves, twigs and branches. Nodal structures must provide resource transport into and out of attached organs, as well as provide for continuity of transport along the supporting internode. Figure 3. Resource supply and structural support functions are optimized for current load resistance, and for minimizing food costs required to both create and maintain structures as well as their resistance to failure.

Disruption Geometry

Branch node tissues are generated or modified to allow for branch emergence and attachment. Branch nodes disrupt the supporting internode tissues. This internode disruption is essential for branch support and function, but generates a weakness within the internode section from where a branch emerges and is attached. Figure 4. Node areas are weak points along internode pathways. The extent of stem disruption due to branch attachment can suggest failure resistance of a stem/branch confluence area or branch node.

Branch node disruption of stem internode tissues can be characterized in many ways, including aspects of transport, tissue density, live tissue content, fiber orientation, and relative differences in size of interacting components. Internode disruption measures can estimate proportional branch disruption of a stem where it is attached. Various stem and branch shapes, branch angles, growth rates, and original formation of a branch will all modify internode disruption values. Figure 5. The greater percent of a stem disrupted by a branch at the branch node, the greater potential branch attachment weakness and its less resistance to failure.

Branch Emergence & Support

Branch junctions are weaker, less stiff and more flexible in support, than surrounding supporting tissues. (Gardiner et al. 2016) One study found branch joint anchorage rotation at the connecting node was highly significant (75% of variability) in branch failures, as was branch slenderness (67% of variability in failures). (Vojackova et al. 2019) The greater number of nodes along a stem or branch, the more negative mechanical properties generated. (Gardiner et al. 2016) One interesting tree response in supplementing nodal weakness is found in pines where reinforcement of branch junctions with resin impregnation helps make the junction area more rigid. (Loehle 2016) Branches are designed to be variably stiff and flexible along their length, and disposable at their base or supporting node.

Turbulence

Confluence junctions combine stem and branch xylem and phloem transport flows, producing resource concentration and causing changes in tissue development. (Novitskaya et al. 2016) All food and associated growth regulator flows from throughout a tree crown are consolidated and generally move down the stem. Figure 6. As flow of these materials from a branch joins the supporting stem, food and growth regulator flow across a confluence area generate unique tissue changes which structurally and biologically support a branch while enhancing branch node transport and defense. Figure 7. The densest concentration of thick-walled parenchyma cells and structural fibers are in the axils of confluences, along stem flange sides, and at fork unions, where food streams are concentrated. Figure 8. (Novitskaya et al. 2016)

Flange Area

A primary tissue holding a branch onto a tree is the stem flange area (stem collar). A stem flange is similar in purpose to a pipe flange used in building construction and plumbing, supporting material aligned in a direction away from the primary axis. Figure 9. (Coder 2019a) Tissues in stem flanges surrounding a branch base are generated and adjusted for load changes and self-pruning, especially in the confluence axil area. Figure 10. Without load challenges, branch flange area strength will atrophy. (James et al. 2017; Slater & Ennos 2016) Once loads below a node decline, stem tissues will revert to straight-line forms (internode). (Novitskaya et al. 2016) Stem flange areas should be carefully conserved and never cut or injured, regardless of their visible length outward along a branch. (Dujesiefken & Liese 2015)

Tissue Connections

The flexibility and rotational movement of a branch at its anchorage point influences rotation of the whole branch. (Vojackova et al. 2019) Stem flange tissues have a large proportion of reinforced ray cells making wood stronger in a radial direction. (van Casteren et al. 2012) Xylem vascular bundles are generated moving from the stem into tissues at the branch base allowing for a strong but flexible attachment area. (Hesse et al. 2016) These xylem layers provide strength as they are reoriented into a branch, with a surrounding matrix of reinforced parenchyma cells enabling tissue flexibility. (Hesse et al. 2016) Figure 11.

The shape of a confluence area is optimized through increased cambial activity expanding the flange to hold a branch as needed in order to avoid local stress concentrations (Muller et al. 2006) Raised mounds on either side of a confluence are new tissues produced in response to branch attachment area movement, which helps reinforce the flange area. These ridges or mounds of tissue on either side of a branch confluence represent a reaction to stress/strain challenges, especially from lateral wind loads. (Slater 2021)

Axil Wood

At the top center of a stem flange is the axil area of a branch confluence. Figure 12. Modified axillary tissues in the stem flange are structurally different than surrounding tissues. Axillary tissues which are under load challenges, and well supplied with food, are denser and stronger than surrounding internode stem wood. Axillary wood density in a confluence is 13-54% greater than stem wood density. (Meadows & Slater 2020; Slater 2021; Slater & Ennos 2015)

Axil wood tissues have: 12% lower moisture content (Meadows & Slater 2020); 66% less water conducting vessels (Novitskaya et al. 2016; Slater & Ennos 2015); 58% more active parenchyma cells (Novitskaya et al. 2016); and, greater cell wall thickness than surrounding stem tissues. (Slater & Ennos 2015) Axillary wood strength is 200% - 500% stronger than surrounding stem tissues. (James et al. 2017; Tothill & Slater 2019)

Resisting Loads

The axil area of a branch confluence (or a fork union) has dense interlocking, interweaved, and tortuous grain patterns which provide mechanical support and stop longitudinal fiber cracking. (James et al. 2017; Mattheck et al. 2015; Meadows & Slater 2020; Pfisterer 2003; Slater & Ennos 2015; Slater & Ennos 2016; Slater & Harbinson 2010; Tothill & Slater 2019) The whorled, interlocked, or zig-zag grain patterns found in the axil area of a stem / branch confluence provide more than twice the tensile and compression strength of adjacent stem wood. (Slater & Ennos 2015) In forks, axillary tissues are significantly denser along each side (+28%) and at the apex (+31%) of the union compared with surrounding stem tissues. (Slater & Ennos 2016) However, anything preventing branch movement or load challenges, result in a failure to form interlocking axillary wood. (James et al. 2017)

Each new growth increment in a stem and branch is generated as a response to new load challenges, which builds flange and axillary wood resistance to failure. Interlocking wood grain patterns support phloem's unimpeded flow across a confluence, but cause xylem water conduction to be significantly reduced. (Slater & Ennos 2015) Where axillary wood is missing or periderm (bark) is included within a stem flange, branch connections are significantly weaker. (Tothill & Slater 2019) In fork unions, a U-Shaped confluence is stronger than a V-shaped confluence due to more effective interlocking of axillary tissues. (Kane et al. 2008)

Bark Union

A branch bark ridge or periderm union visible on the surface above a confluence appears to curve around, downward, and away from a branch base, elongating every year. This external sign of tissue changes which have been generated beneath, is initiated at the topmost position (axil) of the stem-branch confluence. As both stem and branch grow in diameter, new tissues are generated across the center of the confluence top with older tissues sloughed off to the side, diverging farther every year. The visible periderm union overlies where stem and branch tissues were reorientated into a standing wave. (Coder 2019a) The periderm union is not a dividing line between stem and branch tissues, but a sign of an interlocking and intermeshed tissue area which is shifted to either side of the confluence axil as both branch and stem grow in diameter. (Mattheck et al. 2015)

If a stem flange is visible at a confluence, dominance is maintained by the stem (stem control). If no clear stem flange is present at a confluence, then the fast growth of a branch is dominating the interaction with its stem (branch control). (Mattheck et al. 2015) This branch dominance or codominance generates poor structural interconnections with the stem, usually beginning as branch diameter reaches 66% to 75% of the diameter of the stem where it is attached. This branch - stem size difference is known as a branch ratio (i.e. branch ratio = BR = branch base diameter / stem diameter at branch location).

Connections & Faults

Branch base attachment within a confluence can be a location where branches fail under load. Stem tissues stabilize a branch flange area with large surface area interactions, and intermeshed and overlaping growth increments, both increasing branch failure resistance. (Jungniki et al. 2009) Alternating patterns of interlocking stem and branch tissues around and below a branch are critical in providing stability for the attachment. (Jungniki et al. 2009) Branches are affixed to a stem by both a small but strong axillary tissue zone on the confluence top, and by a relatively long branch trace (branch tail) below a branch which is incorporated into stem tissues. (Muller et al. 2006; Shigo 1983) Branch tissues in the trace below a confluence help hold a branch erect and onto a stem. (Mattheck et al. 2015) Figure 13.

Branch Traces

Branches are affixed to a stem by a small but strong axillary tissue zone on the confluence top, and with a relatively large branch trace below a branch along the stem. (Muller et al. 2006; Shigo 1983) The branch tissues (branch trace) below a branch help hold a branch erect and onto the stem. (Mattheck et al. 2015) The branch trace resists branch lifts from wind gusts and help interlock internode and node tissues. Immediately below a branch across the branch trace area, stem tissues do not always quickly meet and reform together, sometimes showing a recess or loose union below a branch. (Shigo 1983; Coder 2021b) The branch trace area is integrated into the stem internode tissues below a branch and becomes inditinguishable from internode tissues.

Confluence Changes

The stem flange surrounds a branch base with tissues of increased density and cell wall fiber angles making the wood tougher. In contrast, wood tissues in a branch base as it approaches a stem flange area has a relative low density and microfibril angle which allows deformity and flexibility. (Gardiner et al. 2016) The confluence area has a mix of locations with differing wood density. This combination of differing wood density locations help prevent: clean fractures and crack progression at and around attachment points; tearing of tissues below a branch; and, a large fracture surface. (Jungniki et al. 2009) The branch attachment pattern of both high and low density wood also protects the stem from failure by minimizing load transfer from branch to stem while holding a branch in-place. (Jungniki et al. 2009) Figure 14.

Failings

In order to appreciate branch attachment success, branch failure should be examined. How do branches fail? Branch failure is a common event in trees. In one study of branch failures during a major storm, branch failures were caused by: 5.4% included periderm (bark) unions; 9.7 % lion's tailed foliage concentration; 9.8% codominant branches; 11.6% branch cavities; 18% dead branches; 25.8% overextended branches; and, 33.3% branch decay. (Koeser et al. 2020) In another study, branch failures were caused by: branch or branch union decay (3%); codominant branches (10%); lack of pruning care & lion's tailing (10%); branch base periderm inclusions, cracks, and sharp bends (23%); and, simply excessive wind / snow / ice loads (54%). (van Haaften et al. 2021) Branches and their attachment areas fail for a variety of reasons.

With all discussions of branch failures, it should be remembered for a majority of tree branches which fail under strong wind loads, most are not defective. (Kane & Finn 2014) Most branches fail in bending or shear, with only 22% of failures, in one case, associated with defects. (Kane & Finn 2014) For example, branch failure causes associated with defects included weak confluences (80%), decay (12%), or a combination (4%). On the other hand, branches not failing had significant defects of weak confluences (78%), decay (13%), and a combination (4%). (Kane & Finn 2014) These values suggest branches fail when overloaded, regardless of defects. (Coder 2019b)

Conclusions

Visualizing how branches are attached to stems, and how they begin to fail, can assist tree health care providers manage crown form, adjust pruning techniques, and identify failure risks. Figure 15. The strength of branch attachment areas can be compromised by many things. Structural areas of a stem flange must be protected and conserved. Visual assessments using branch attachment strength attributes can be performed to estimate branch success and failure.

Citation:

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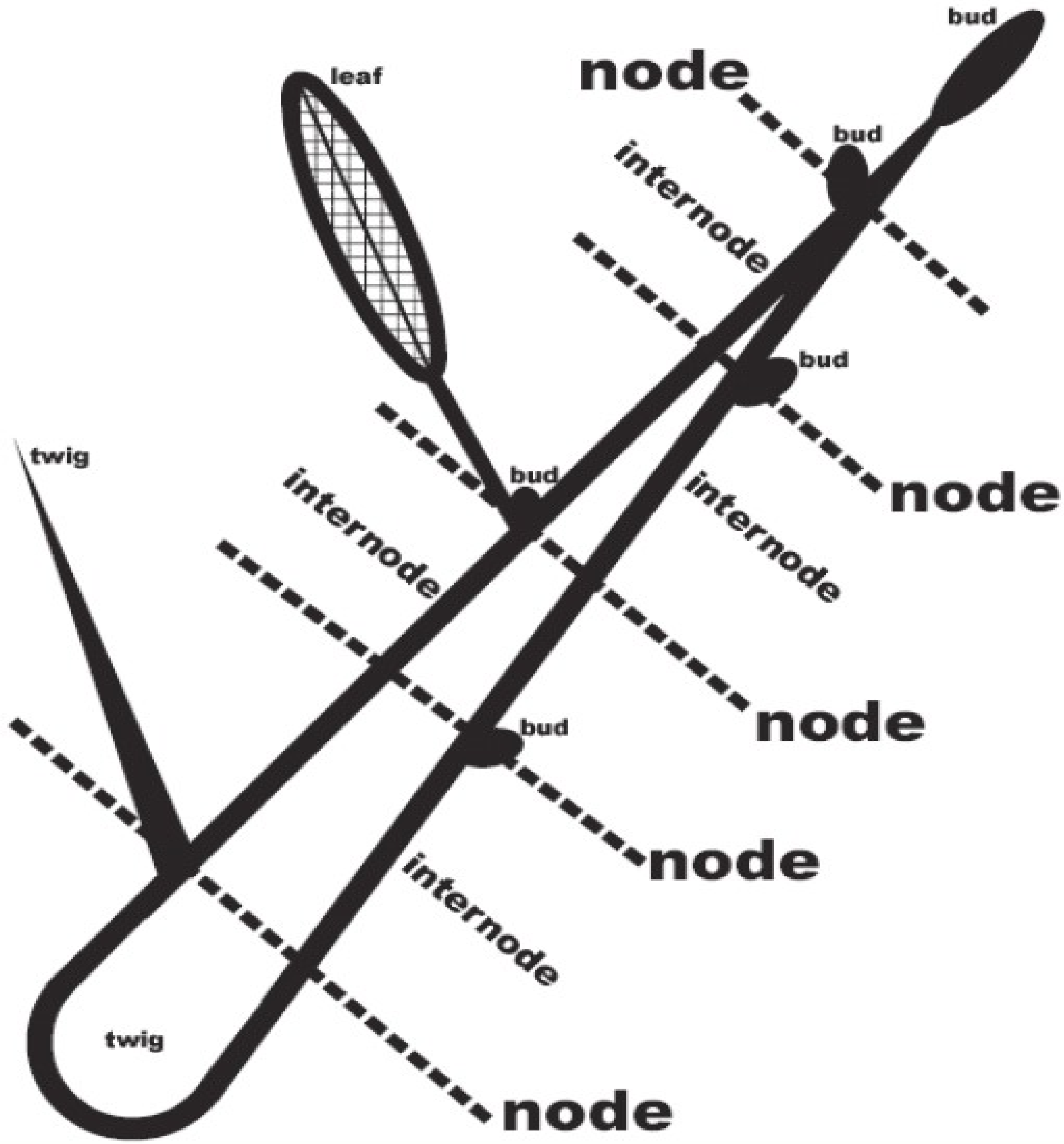

Figure 1: Internodes with nodes generated between as twigs and branches grow, demonstrate the modular or segmented nature of trees. Branches emerge from branch nodal areas disrupting stem internode lengths.

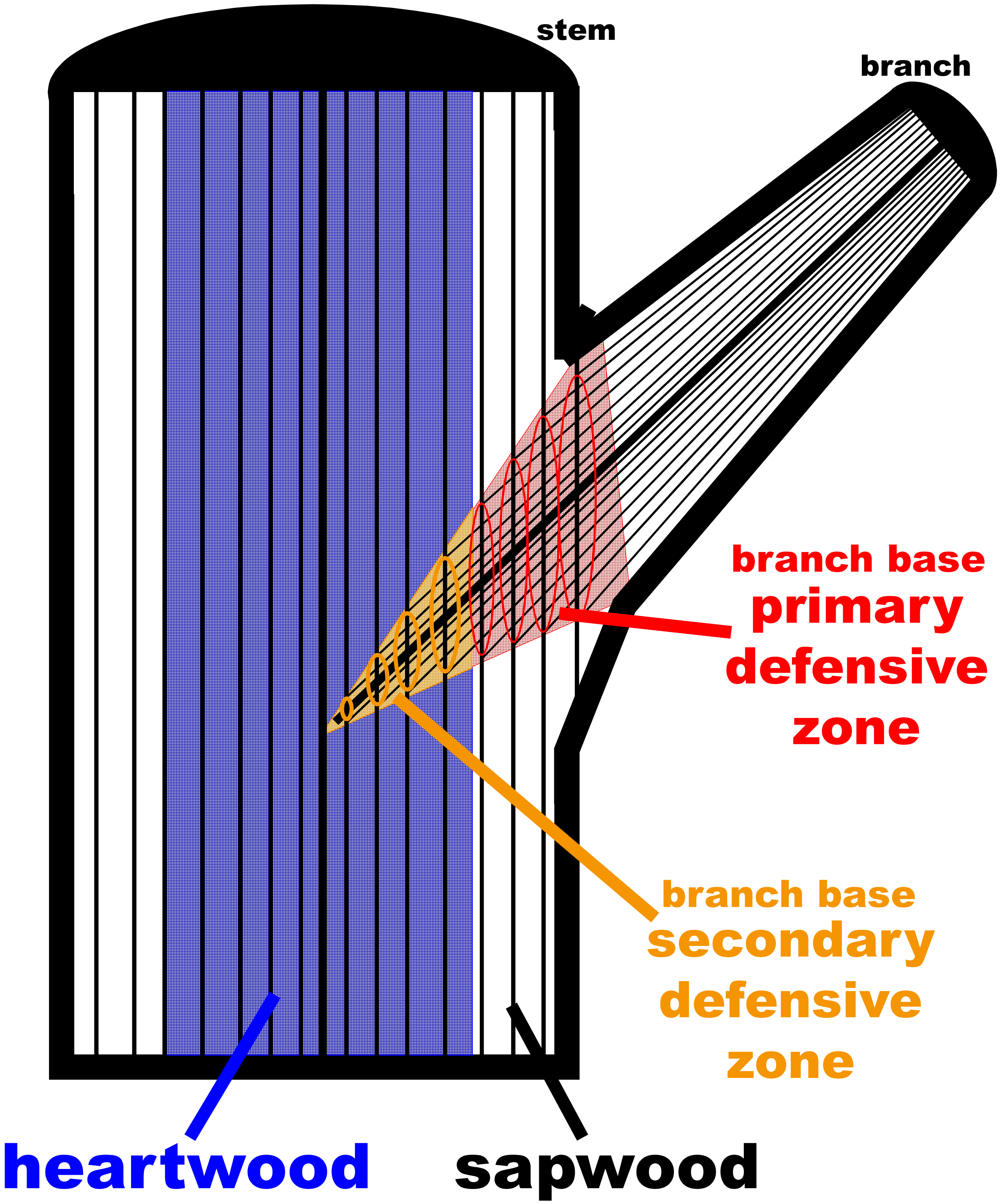

Figure 2: Stem / branch confluence area (a node) with branch base tissues within and surrounded by disrupted stem internode tissues.

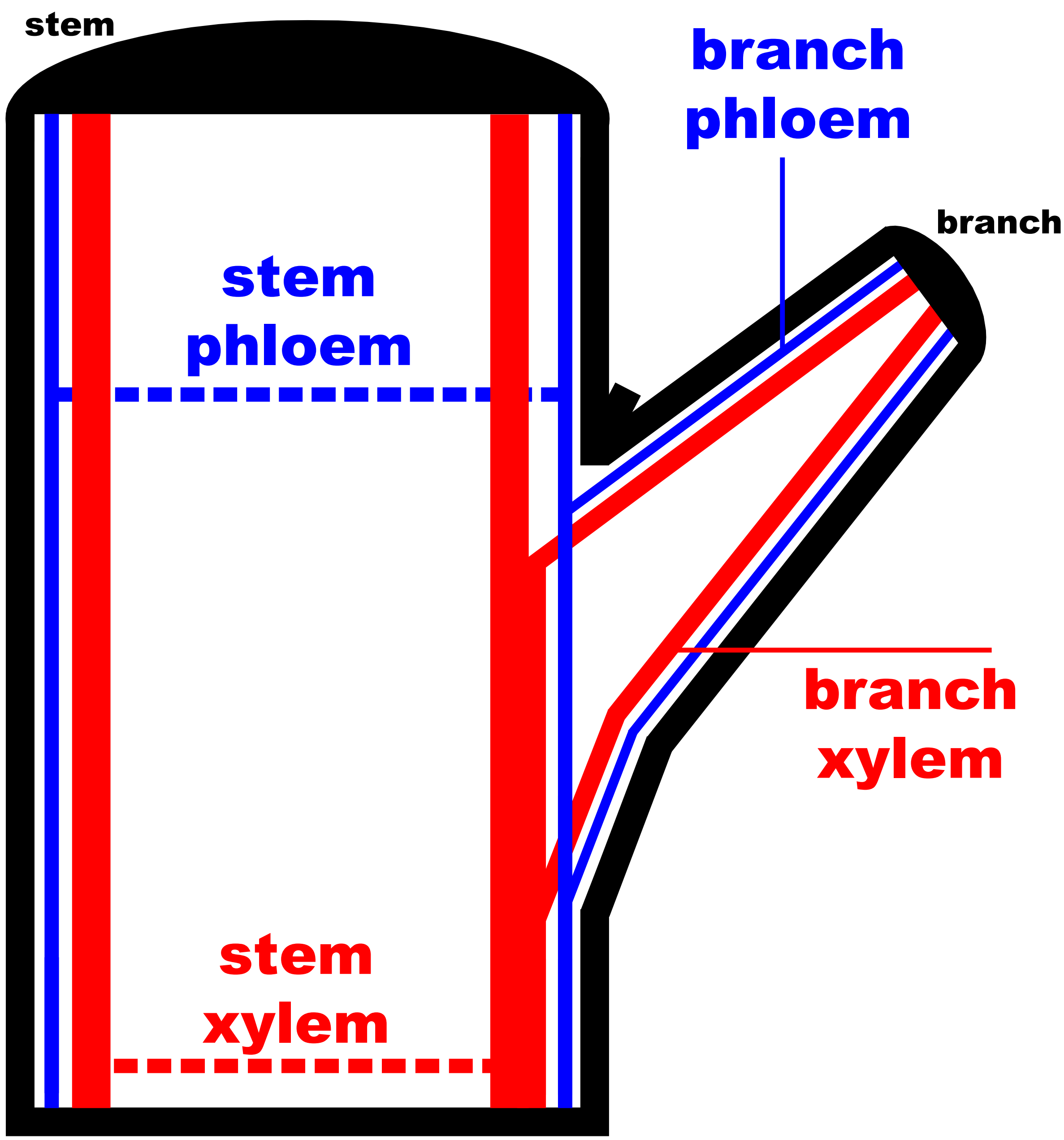

Figure 3: Stem and branch phloem continuity beneath the periderm over all exterior living surfaces of a tree. Branch xylem below the stem / branch connection point generates a structural branch tissue trace. Branch phloem pathways do not turn upward and transport of food materials in phloem beyond the branch base is only downward.

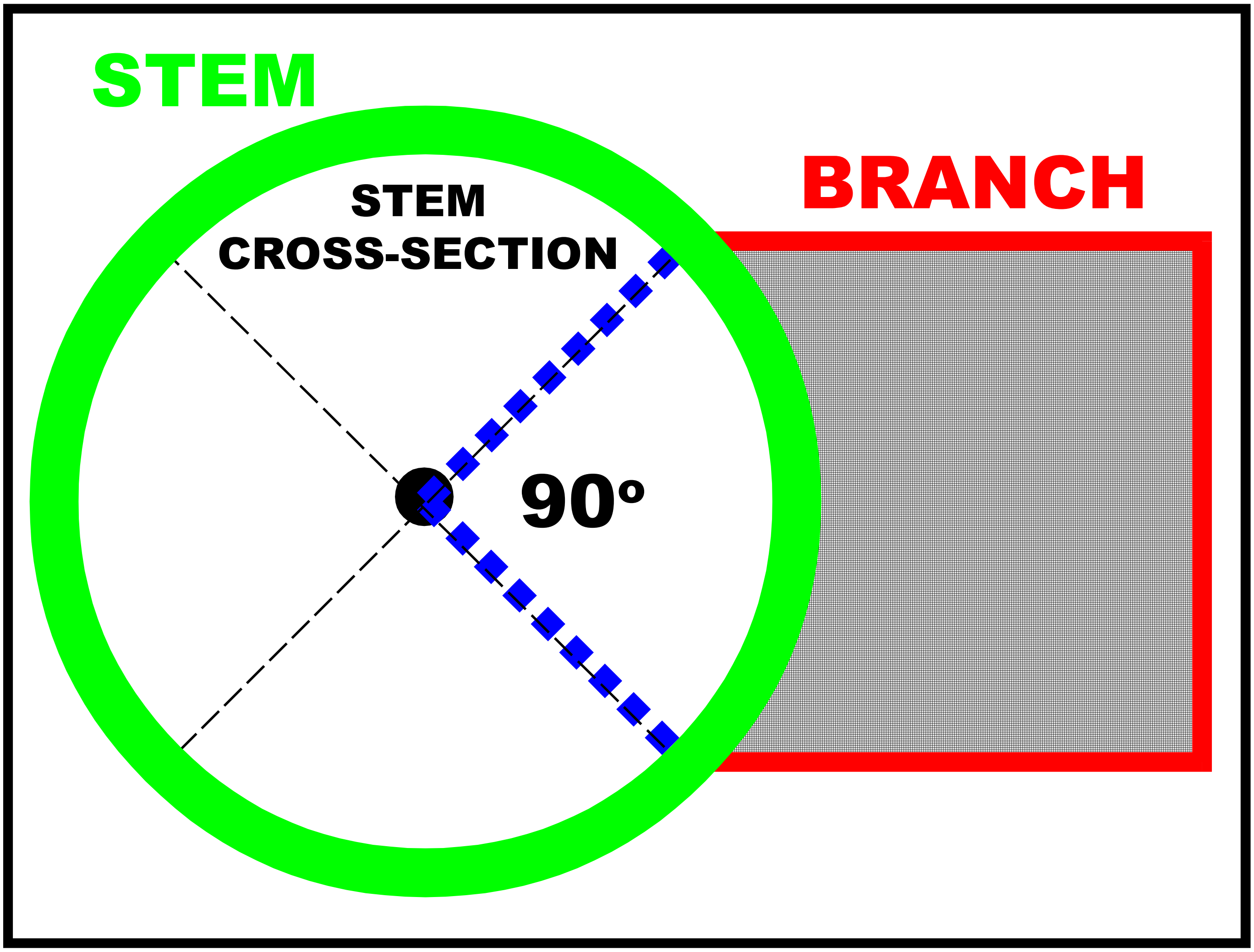

Figure 4: A two-dimensional geometric model of internode disruption of stem circumference by a branch union (node).
In this example, the stem circumference impacted by branch connection is 25% of the circumference (across a 90° angle with a branch ratio of 0.71).

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BRANCH RATIO	PERCENT STEM AREA DISRUPTED BY BRANCH
0.1	0.03%
0.2	0.2%
0.3	0.7%
0.33	0.8%
0.4	1.5%
0.5	3.0%
0.6	5.5%
0.66	7.5%
0.7	9.0%
0.8	14%
0.9	23%
1.0	50%

Figure 5: Percent of total stem cross-sectional area disrupted by a branch connection (branch node) based upon branch ratio. (branch ratio = branch diameter / stem diameter)

Figure 6: All photosynthetic tissues are generating food (sucrose -- CHO) and growth regulators which flow primarily downward (toward the base) in a tree.

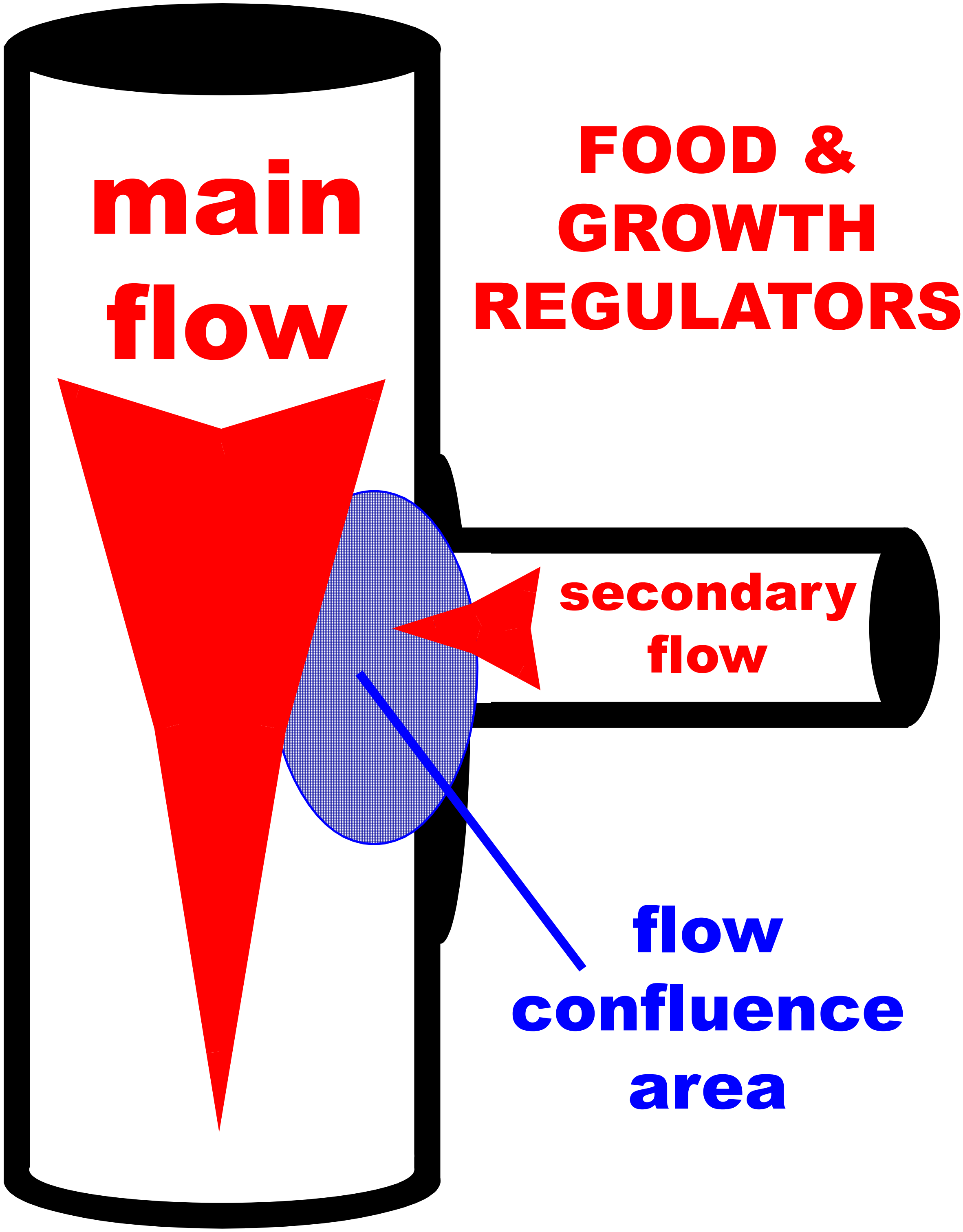

Figure 7: Stem / branch confluence area where food and growth regulator pathways converge and stimulate tissue generation.
(Branch Ratio = BR = 0.44; Branch Angle = BA = 90°)

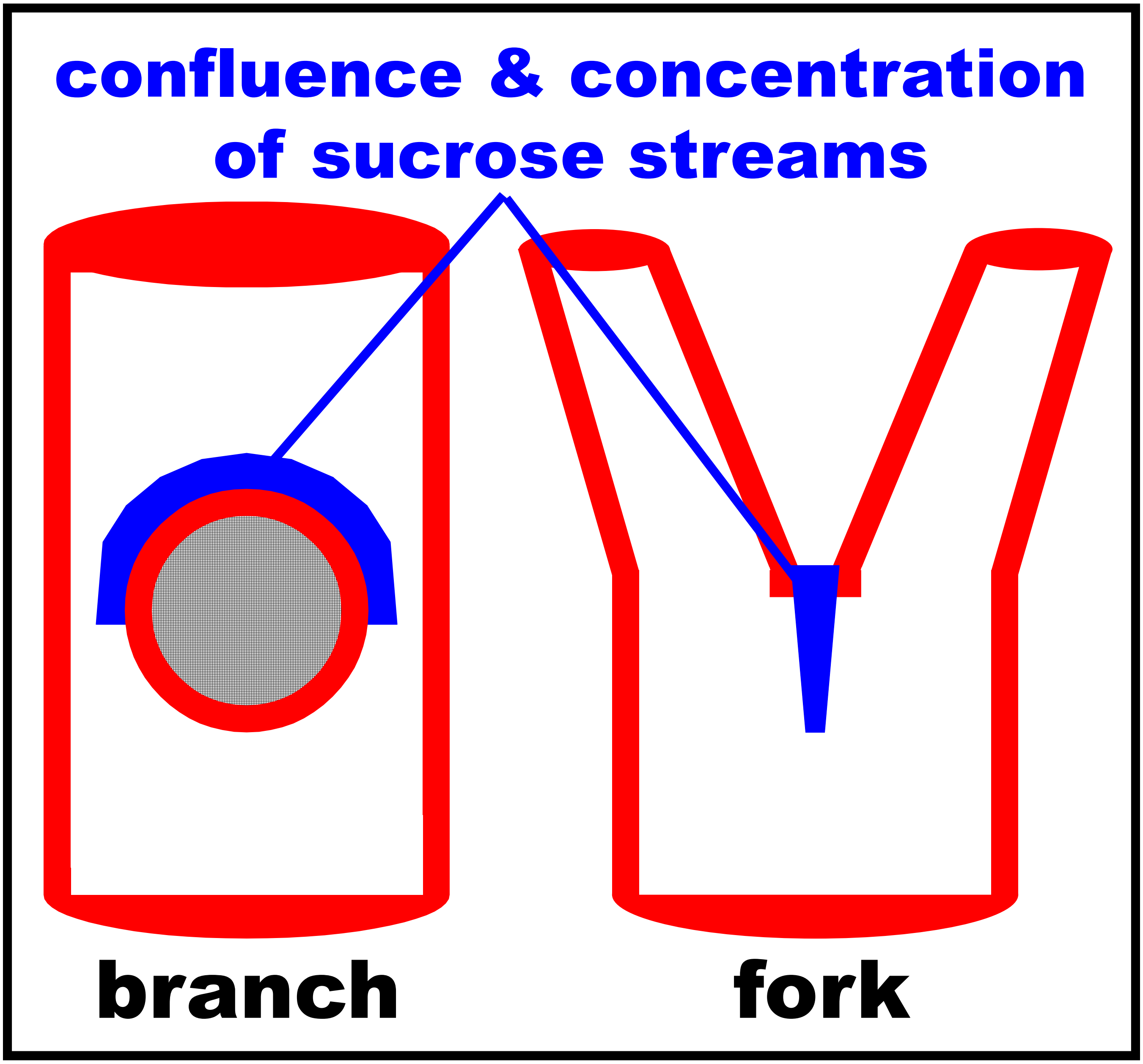

Figure 8: Flow confluence area and concentration of sucrose (food) and growth regulator streams from phloem transport for both a branch / stem attachment area and a fork.
(Novitskaya et.al. 2016)

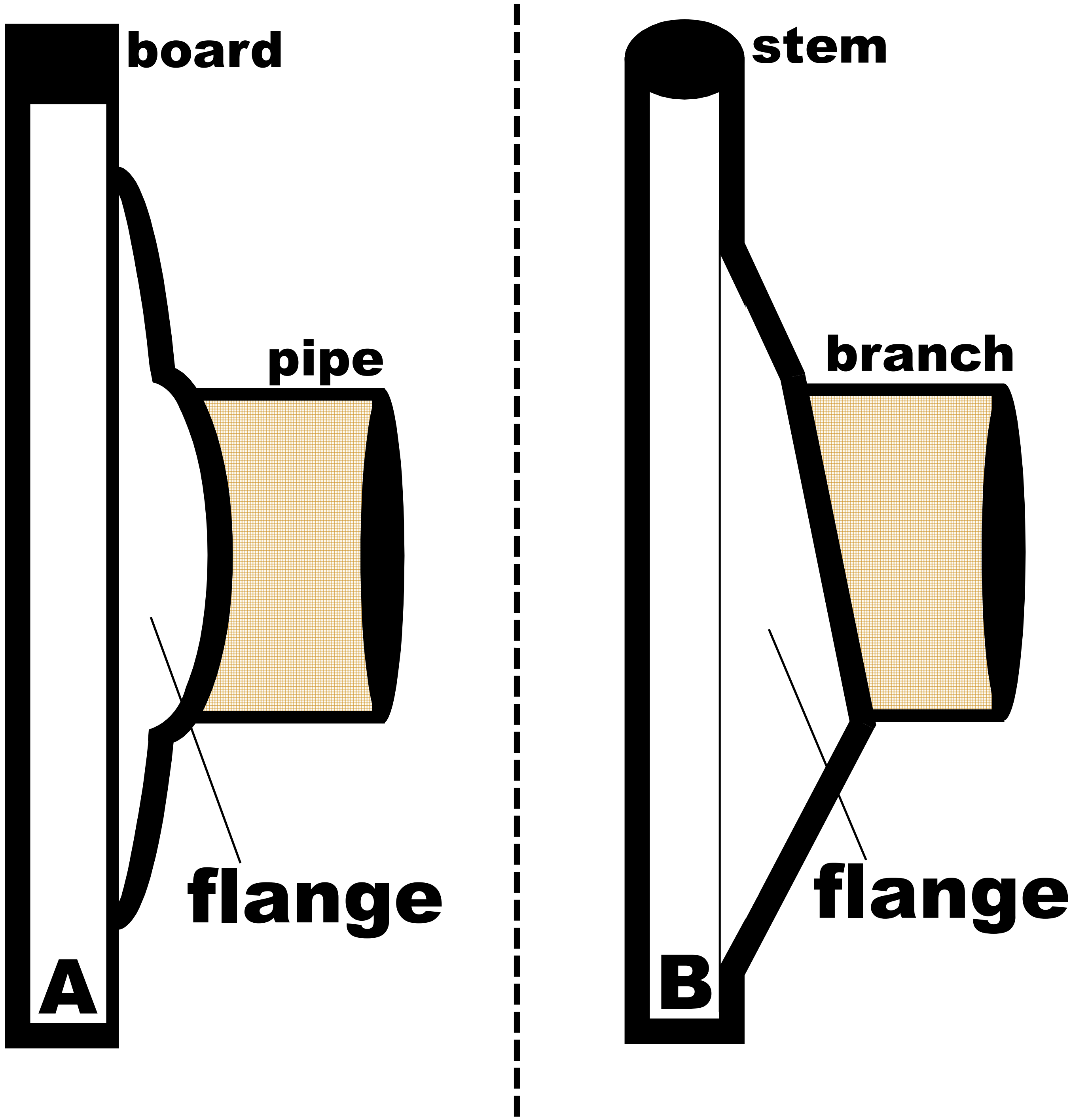

Figure 9: Descriptive model of a pipe held onto a board with a flange (A), and a branch held onto a stem with a combined tissue area acting as a flange (B).

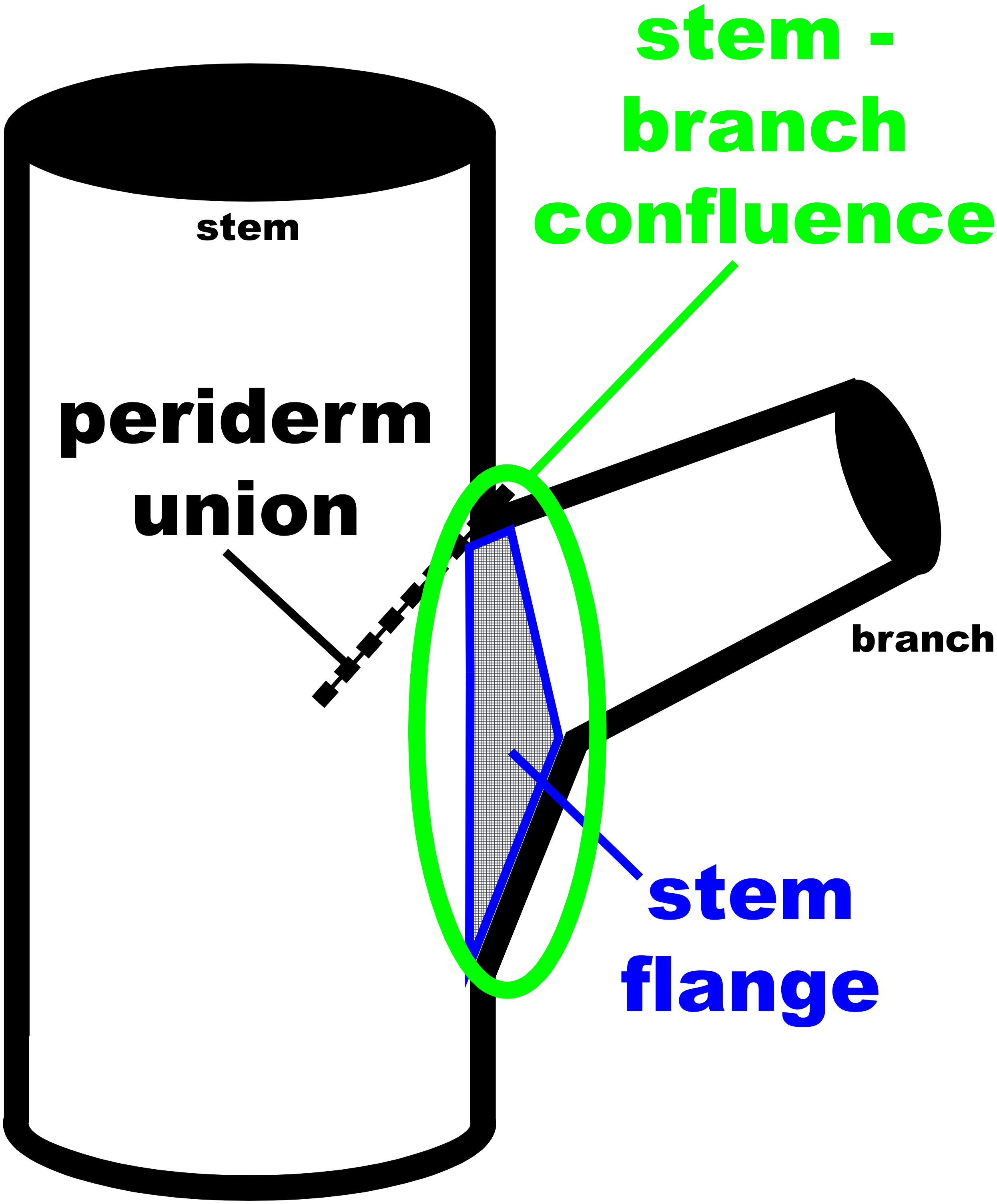

Figure 10: Stem / branch confluence area (branch node) with a periderm union and stem flange.
(BR = 0.48; BA = 70°)

Figure 11: Stem flange tissues in a stem / branch confluence (branch node). (periderm removed)

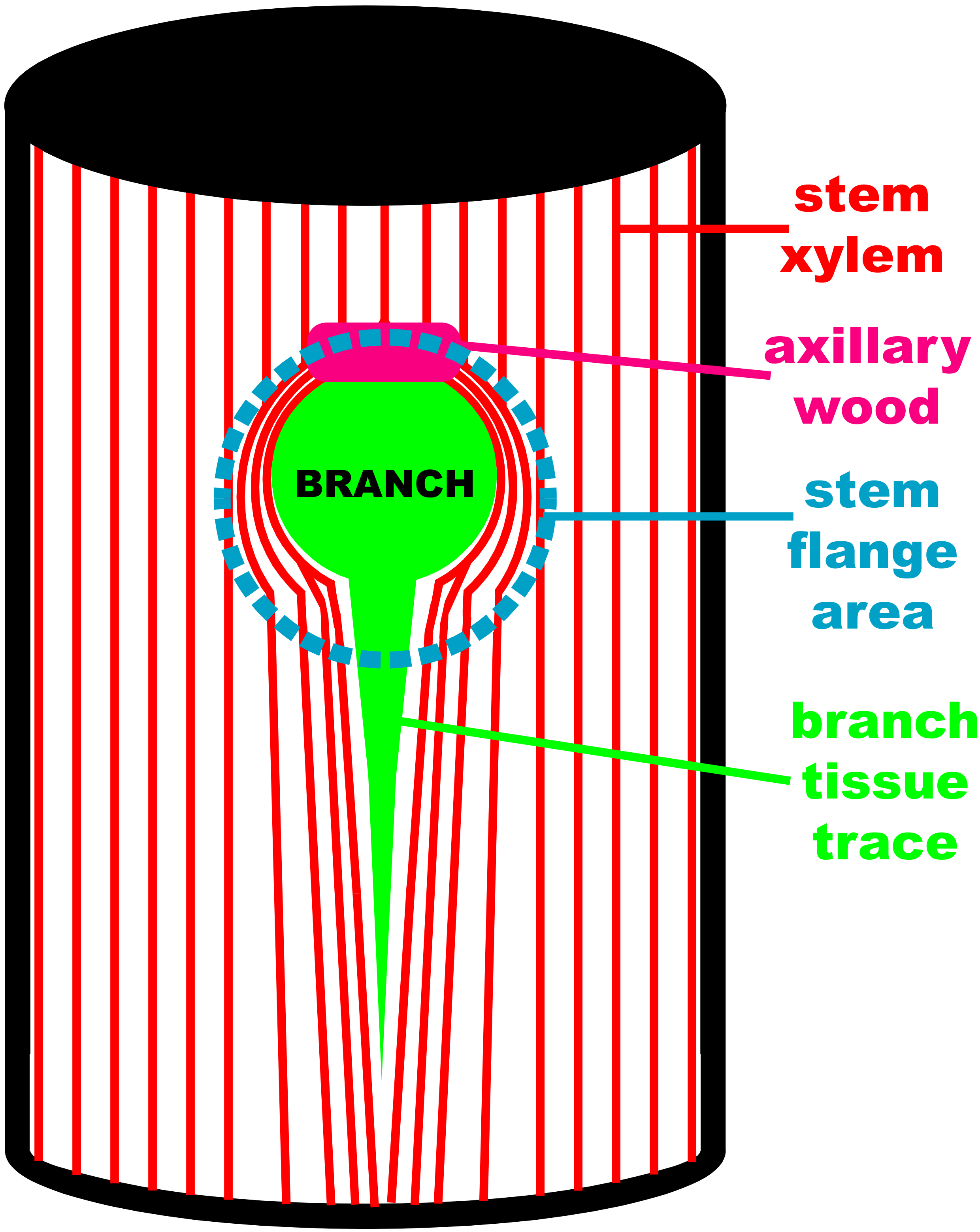

Figure 12: Trace of branch xylem below a branch, and dense axillary wood at top of confluence. (BR = 0.32)

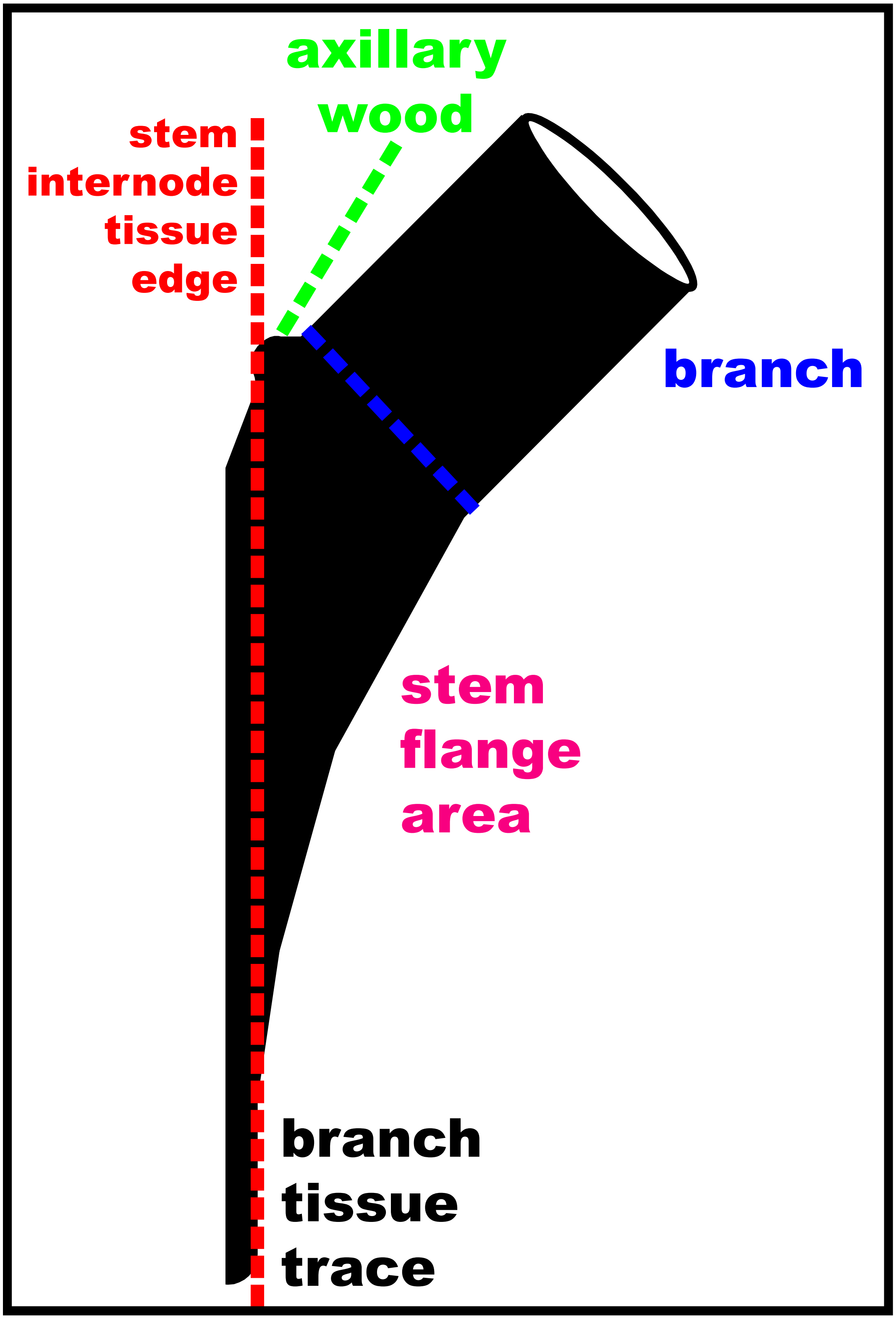

Figure 13: Side-view of current growth increment components of a branch confluence area generating structural resistance.
(BA = 45^{o})

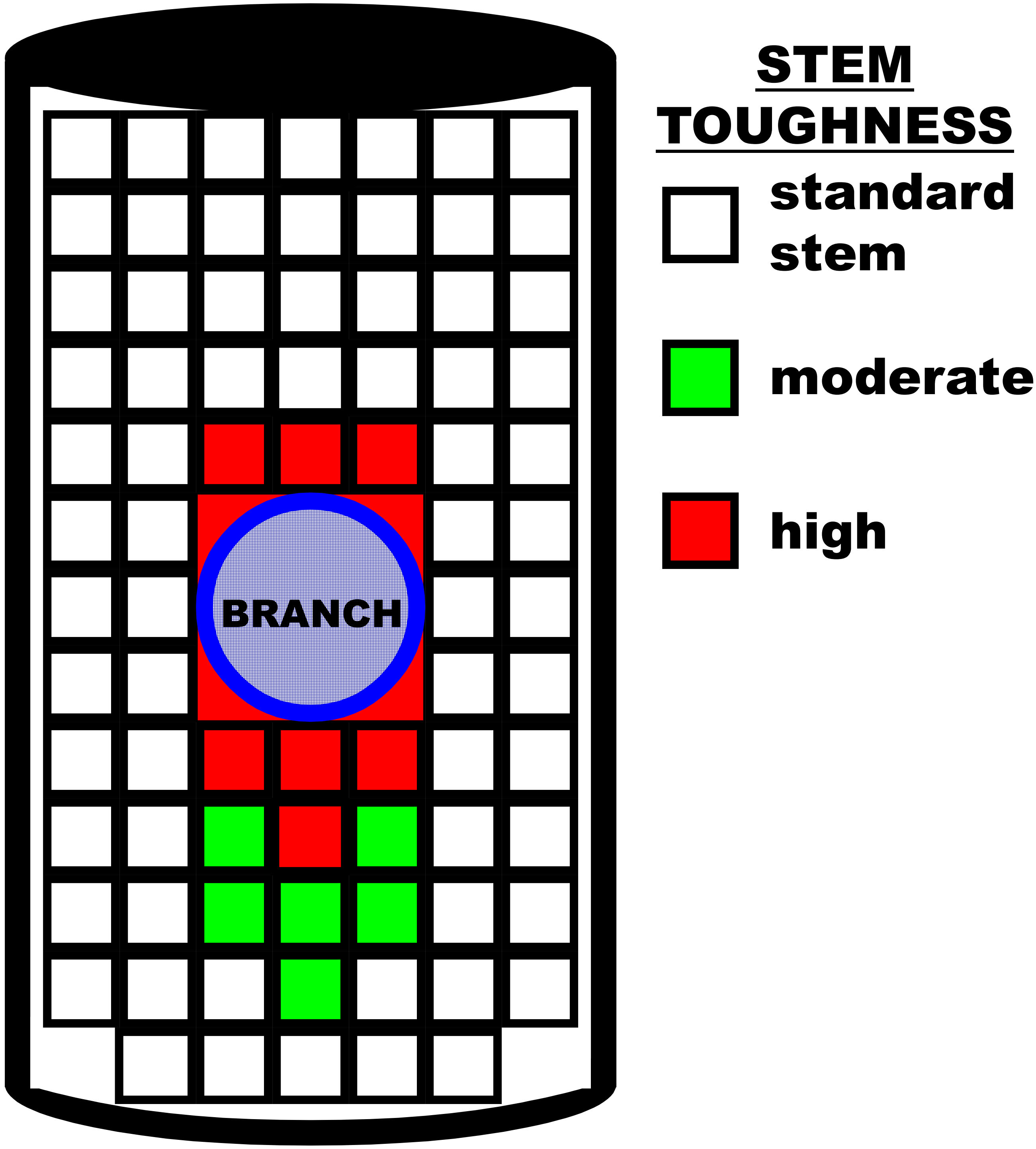

Figure 14: Toughness of stem flange and branch trace around a branch confluence.
BR = 0.38. (after Jungniki et.al. 2009)

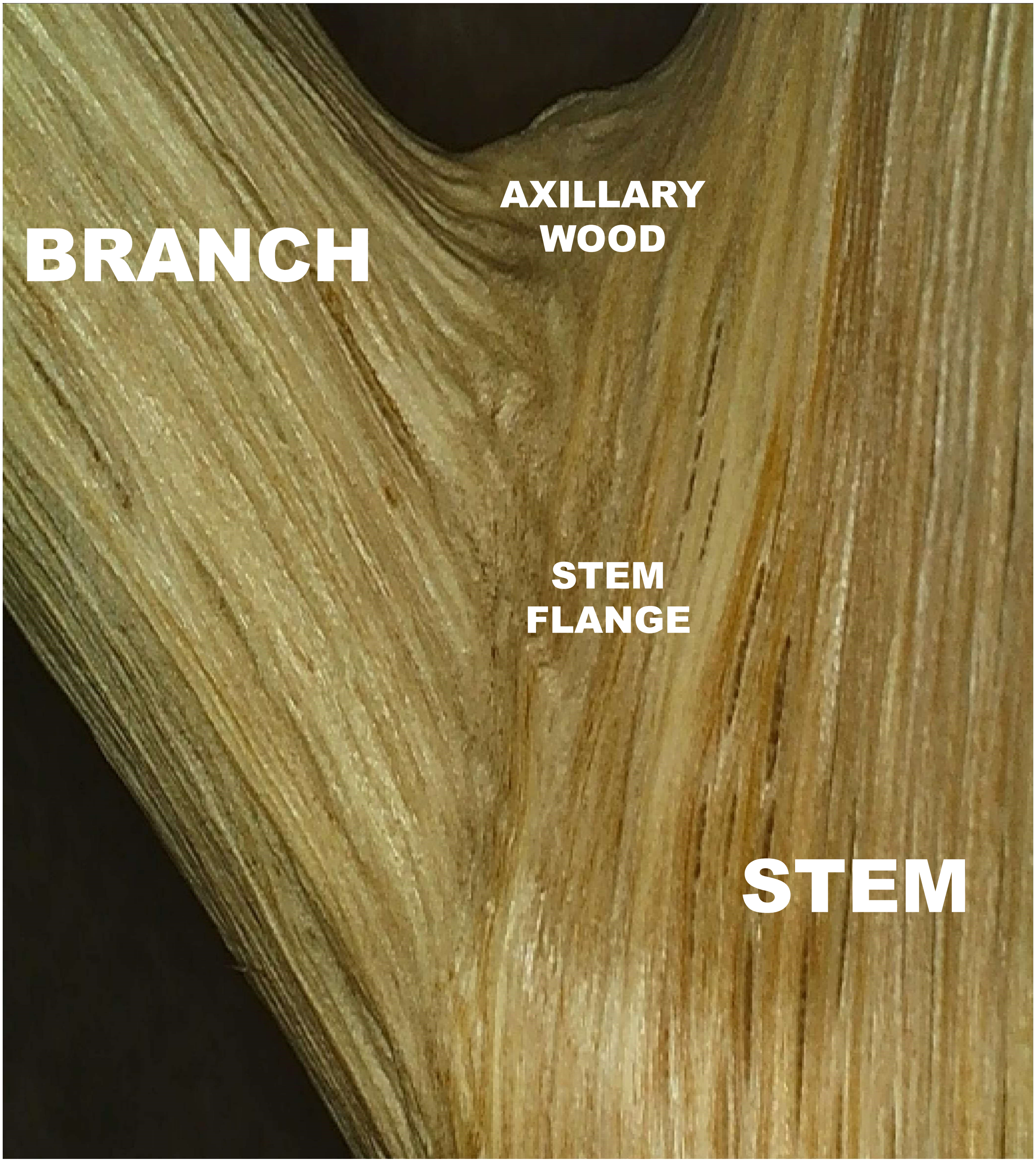

Figure 15: Interconnected and intermeshed tissues of the stem / branch confluence area.
(periderm removed)