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Stem Disruption Geometry of Tree Branch Attachment

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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. 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.

Branch Nodes Within Stem Internodes

Stems and branches are defined by their biological and structural functions. Internode strength is generated 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. Figure 1. Nodal structures must provide resource transport into and out of attached organs, as well as provide for continuity of transport along the supporting internode. Resource supply and structural support functions are optimized for current load resistance, and for minimizing food costs required to create and maintain structures and their resistance to failure.

Branch node tissues are generated or modified to allow for branch emergence and attachment. Branch nodes disrupt the supporting internode. 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 2. Node areas are weak points along internode pathways. Examining the extent of stem disruption due to branch attachment can help tree health care providers better appreciate failure resistance of a stem/branch confluence area. Several simple geometric based approximations of stem disruption by a branch attachment point can help visualize branch disruption of its supporting stem.

Disruption Geometry

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. Four simple geometric means of estimating proportional stem disruption by branch connections to be examinied here are:

1. Stem cross-sectional **circumference** disruption by branch attachment (two dimensional maximum);

2. Stem cross-sectional segment **area** disrupted by branch attachment (two dimensional maximum);

3. Stem segment **volume** disrupted by presence of branch base of a given size and shape (three dimensional maximum); and,

4. Stem **surface area** disruption by branch base attachment over a range of branch angles (two dimensional maximum).

All four disruption estimates suggest a proportion or level of impact each branch has upon the stem where it is connected. The first two measures estimate this year's branch impacts on this year's stem. The third measure examines branch base volumes from two different shapes of branch base, and presents a historic view of how branch disruption has occurred from a branch's beginning. The fourth measure examines interactions with stem disruption as branch angle decreases and its associated increase in stem surface area disrupted. Figure 3.

None of these measures of branch disruption of a stem equate to transport or structural constraints directly, but can help suggest indirect impacts for a branch of a given size existing at a point on a stem of a given size. These size differential values can be viewed as approximations of relative branch nodal weakness.

Stem Disruption Measure 1: The cross-sectional shape of a stem provides an exterior circumference measure. Where this circumference is breached by the diameter of a branch, a proportional disruption value can be estimated. This type of measure is a simple exterior view of a branch impact based upon percent of a stem's circumference compromised.

Figure 4 shows the branch width impacting stem circumference across some angle and percent, based upon branch size. The branch ratio (BR) is an easy measure for discussing the proportional size of a branch, based upon branch diameter divided by stem diameter. Figure 5. Regardless of absolute size of branch and stem, a proportion between diameters – branch ratio or "BR" – help gauge the disruption of a stem by the branch. Figure 6 provides the circumference impact angle on a stem for a given branch ratio.

In a two dimensional view of branch width impacting stem circumference, the larger branch diameter or branch ratio, the larger stem circumference disrupted. Figure 7. Figure 8 shows the percent of stem circumference disrupted by a specific branch ratio, and associated branch impact angle in degrees. Figure 9 provides the calculations used for this stem disruption assessment.

For example: If a tree stem is 20 inches in diameter (SD") and the branch is 14.1 inches in diameter (BD"), the branch ratio or aspect would be 0.707, and a calculated stem disruption angle would be 90^{o}. These values generate a stem circumference disruption percent for this branch connection as 25% of stem circumference. In other words, the branch connection is disrupting or taking up 25% of the stem circumference on a cross-sectional basis. This value is eight percentage points (+8%) greater than the maximum branch size suggested to be left on the tree (i.e. BR=0.5), and fourteen percentage points (+14%) greater than the optimum sized branch to be maintained on the stem at this location (i.e. BR=0.3). The branch in this example can be considered codominant due to it branch ratio.

Stem Disruption Measure 2: For a cross-section of a stem, its area can be easily determined, whether round or oval shaped. If this total area of stem cross-section can be impacted by a branch of a given diameter, some proportion of the stem's cross-section is dedicated to support the branch at that point. This is a cross-sectional surface area estimate using only branch diameter and stem cross-sectional surface area at a point where the branch diameter has fully met stem circumference. Branch disruption of the stem is considered an area of a circle line segment where diameter of a branch and its edges intersect stem circumference. Disruption is listed as a percent of stem cross-sectional area occupied by the branch base. Figure 10. Note this still represents an external view of stem surface disruption by a branch.

The measure of stem disruption begins with the same branch impact angle as before in Stem Disruption Measure 1. Figure 11. Figure 12 provides the amount of stem cross-sectional area in square inches which is disrupted by a branch with a given branch ratio. Figure 13 shows the percent of stem area disrupted by branch presence. Figure 14 is a list of calculations for determining Stem Disruption Measure 2.

For example: If a tree stem is 20 inches in diameter (SD") and the branch is 14.1 inches in diameter (BD"), the branch ratio would be 0.707, and the calculated stem disruption angle would be 90^o. These values generate a stem cross-sectional area disruption of approximately 28 square inches, or 9% of the total cross-sectional area of a stem at the point of branch union. In other words, the branch connection is disrupting or taking-up 28 square inches of two dimensional stem cross-sectional area in square inches. This value is six percentage points (+6%) greater than the maximum branch size suggested to remain on the tree (i.e. BR=0.5), and over eight percentage points (+8.2%) greater than the optimum sized branch to be maintained on the stem at this location (i.e. BR=0.3). The branch in this example can be considered codominant due to it branch ratio.

For the first two stem disruption measures (#1 & #2 above), a suggested optimal threshold to not exceed is a 13% Type 1 stem circumference based branch ratio (BR = 0.4), or a 1.5% Type 2 stem area based branch ratio (BR = 0.4). Figure 15. A codominant branch threshold should be present at ~23% Type 1 stem circumference based branch ratio (BR = 0.66), or a 7.5% Type 2 stem area based branch ratio (BR = 0.66).

Stem Disruption Measure 3: Because branch and stem interact across a branch node in a three dimensional volume, branch base volume disruption of stem volume can be estimated. The branch base currently and historically occupies volume within a stem as both have grown.

Because branch base growth rates could generate various sizes and shapes of internal base volumes within a stem, two example shape forms are used. One branch base shape representing a rapidly expanding volume over time could be a neoloid (shape factor 0.1964). A second branch base shape within the stem could be a cone (shape factor 0.262). Figure 16. The stem volume is the cross-sectional area of the stem multiplied by the diameter of the branch. Figure 17. This stem segment volume is partially disrupted or occupied by the presence of a branch base volume. Disruption is listed as a percent of volume occupied by a branch for one of two branch base shape factors.

Figure 18 demonstrates stem volume (in cubic inches) disrupted by a branch connection with a neoloid shaped base within the stem. Figure 19 shows stem volume (in cubic inches) disrupted by a branch connection with a cone shaped base within the stem. Figure 20 provides, across a range of branch ratios, percent of stem volume disrupted by a branch having either a neoloid shaped base volume, or a cone shaped base volume inside the stem segment. Figure 21 lists the calculations for determining stem volume disruption by a branch.

For example: If a tree stem is 20" in diameter (SD") and the branch is 14.1 inches in diameter (BD"), the branch ratio would be 0.707, and the calculated stem disruption angle would be 90^o. These values generate a stem segment volume disruption of approximately 384 cubic inches, or 8.7% of the total stem segment volume at the point of branch union for a neoloid shaped branch base. These values generate a stem segment volume disruption of approximately 510 cubic inches, or 11.7% of the total stem segment volume at the point of branch union for a cone shaped branch base.

In other words, the branch connection node is disrupting or taking-up 384 square inches (neoloid shape factor), or disrupting or taking-up 510 square inches (cone shape factor) of the three dimensional stem segment in cubic inches. These values are +2.5% (neoloid) and +3.3% (cone) greater than the maximum branch size suggested to remain on the tree (i.e. BR=0.5), and +4.9% (neoloid) and +6.6% (cone) greater than the optimum sized branch to be maintained on the stem at this location (i.e. BR=0.3). The branch in this example can be considered codominant due to it branch ratio.

Stem Disruption Measure 4: As branch angle decreases, or the angle between branch and stem becomes more narrow, the connection area of a branch onto a stem becomes elongated along the stem surface. This elliptical branch-print onto a stem disrupts a larger area of stem surface area as branch angles becomes smaller. Figure 22. In this measure, the branch base diameter short axis remains the same, but the long axis of a branch base becomes elongated. Figure 23 provides the framework for determining stem disruption surface area due to increasing branch angles. The stem surface area disrupted by the branch increases as branch angle decreases, shown in Figure 24. In comparision to a 90^{o} branch angle, and for every 10^{o} branch angle difference, stem surface area is disrupted with changing branch angles. Figure 25 suggests at less than 30^{o} branch angle, the surface area of stem disruption increases greatly.

For example, a branch with a branch angle of 60^{o} increases the stem disruption area by +16% compared with a 90^{o} branch angle branch of the same proportional size, and disrupts the stem surface area an additional +9% over the same size of stem and branch (BR) with a branch angle of 70^{o}.

Conclusions

Stem disruption measures #1 - #4 are simple geometric estimates of proportional branch disruption of a stem where it is attached. Each is a different type of measure, but each could be used to estimate stem circumference, area, or volume occupied or disrupted by the presence of a branch of a given size. Various stem and branch shapes, branch angles, growth rates, and original formation of a branch will all modify these values. The most clear summary of these measures is the greater percent of a stem disrupted by a branch at the branch node, the greater potential branch attachment weakness and less resistance to failure.

References & Further Readings

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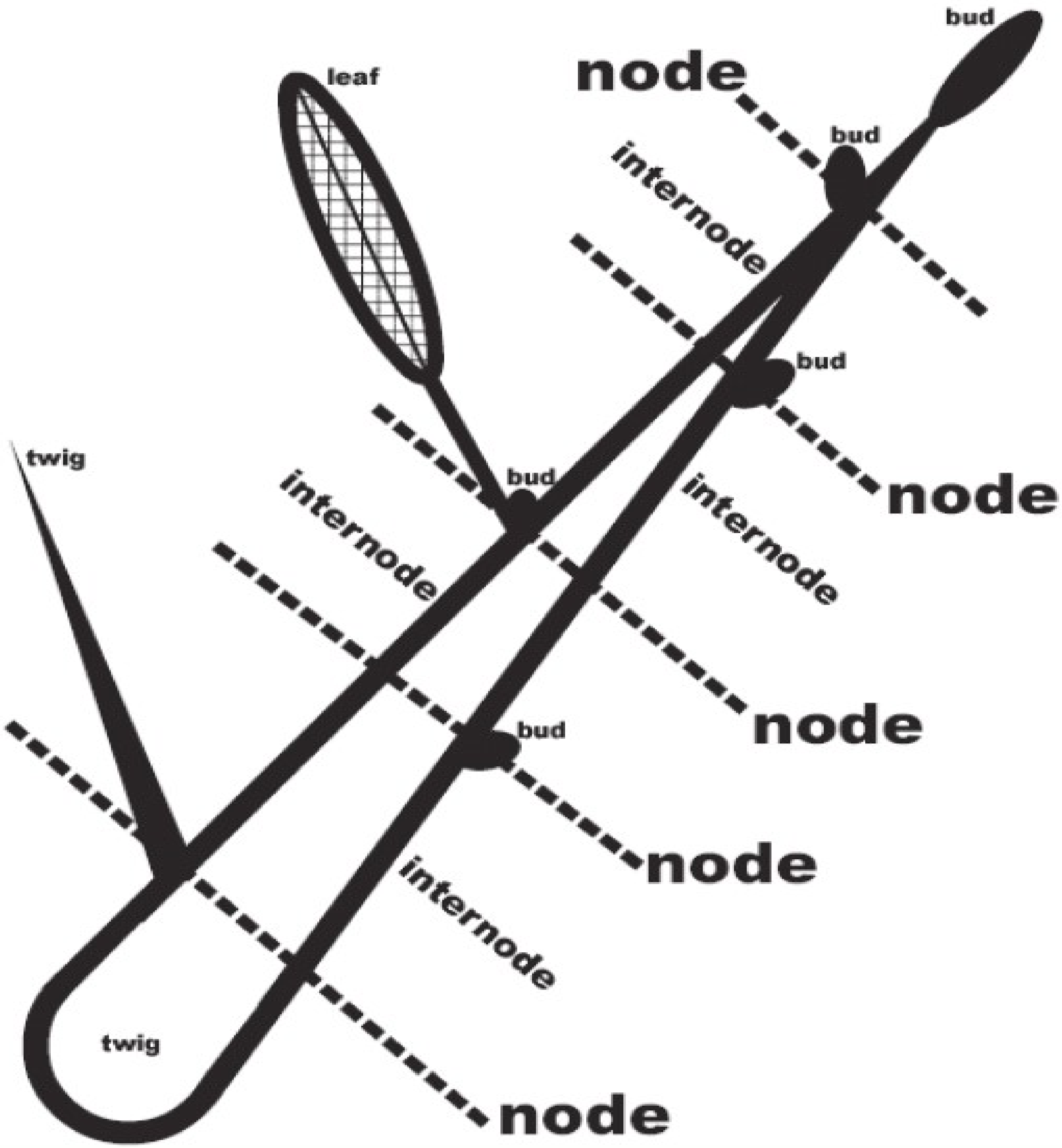


Figure 1: Internodes with nodes generated between as twigs and branches grow, demonstrate the modular or segmented nature of trees. Branches emerge from branch nodal areas disrupting stem internode lengths.

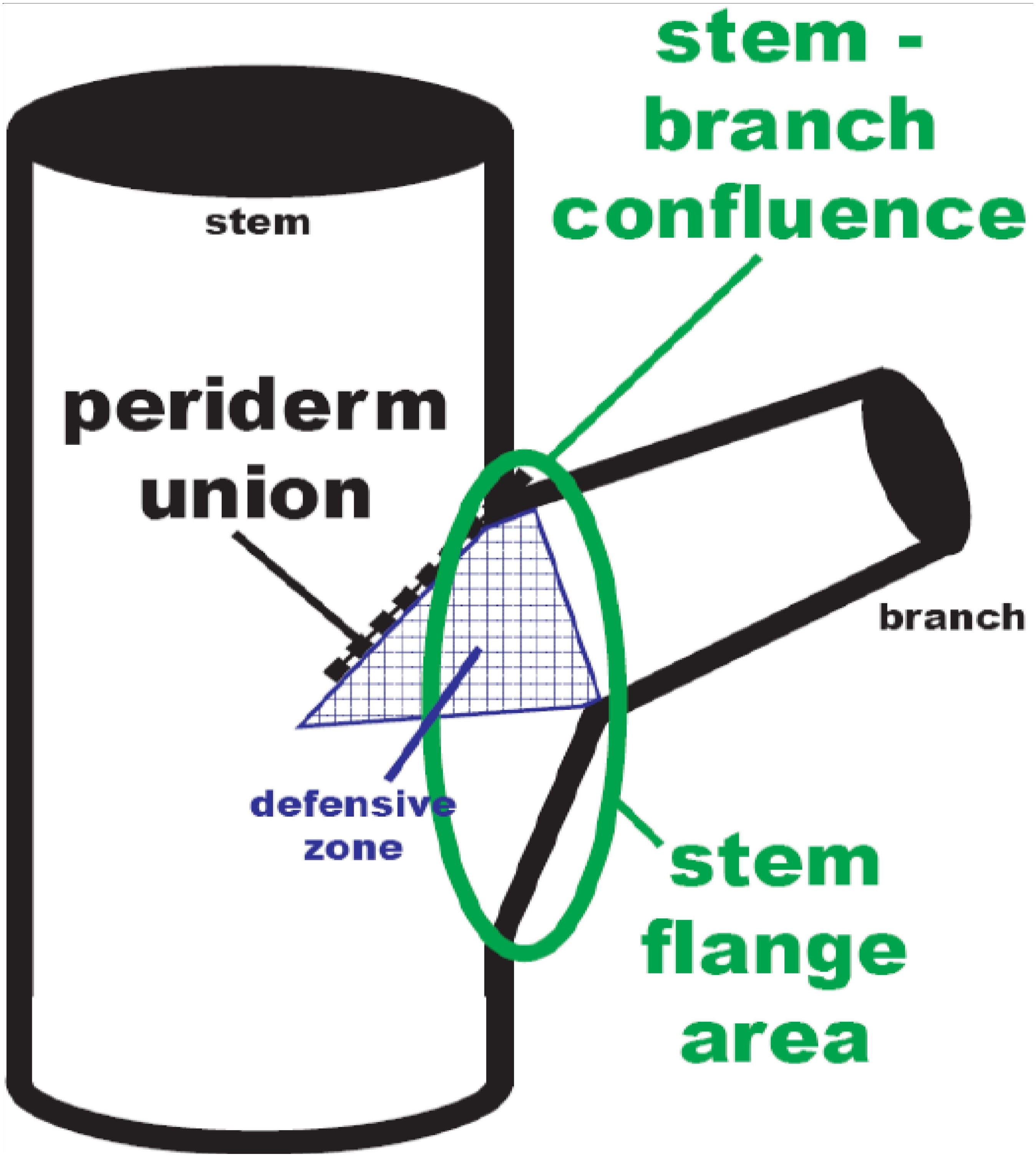


Figure 2: Nodal area of branch attachment showing stem / branch confluence, periderm union, confluence defensive zone, and stem flange area.

TYPE 1: disruption of stem <u>circumference</u>
(percent of stem circumference)

TYPE 2: disruption of stem <u>cross-sectional area</u>
(percent of stem cross-sectional area)

TYPE 3: disruption of stem <u>volume</u>
(percent of stem segment volume)

TYPE 4: disruption of stem <u>surface area</u>
(percent of stem surface area)

Figure 3: Four simple geometric estimations of two and three dimensional measures for proportional branch disruption impacts on supporting stems.

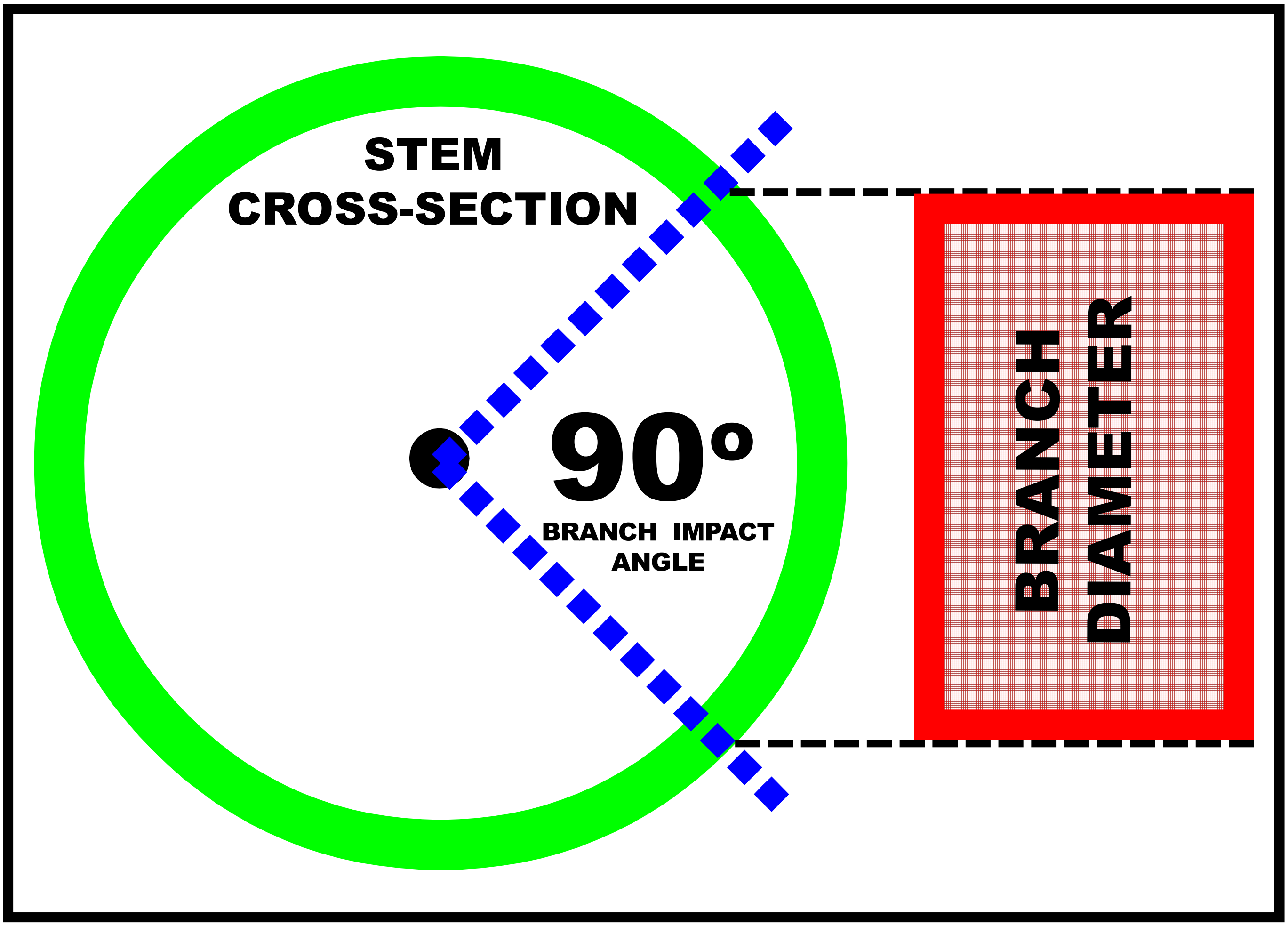


Figure 4: Two-dimensional stem circumference impact angle in degrees from a branch connection.
In this example, the stem circumference impacted by the branch connection is across a 90° angle and the branch ratio is 0.71.

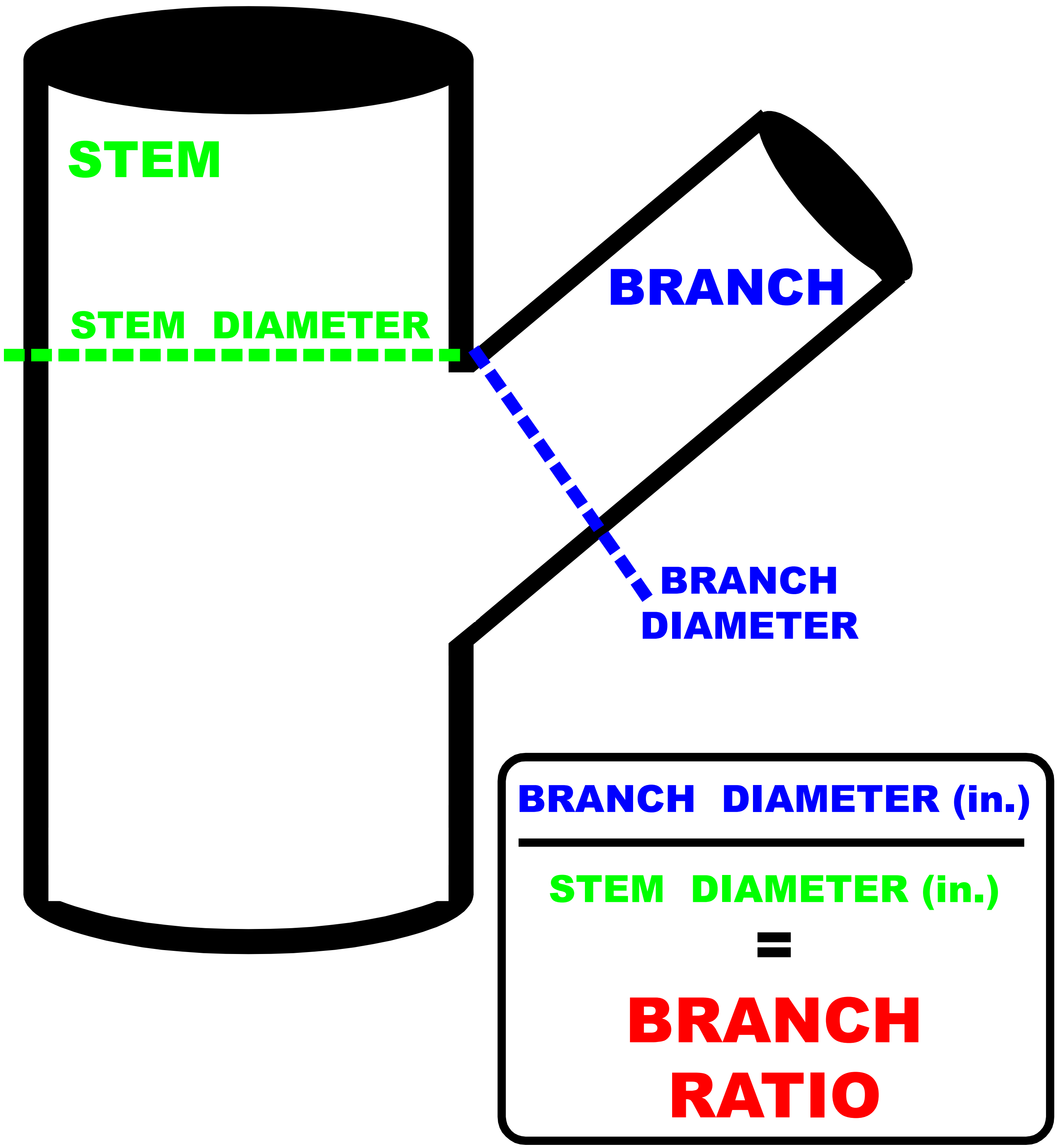


Figure 5: Simplified view of a branch / stem confluence and how branch ratio is determined.
In this example the branch ratio is 0.5.

circumference impact angle (degrees)	sine (0.5 X impact angle) or branch ratio
10°	0.0872
20°	0.1736
30°	0.2588
40°	0.3420
50°	0.4226
60°	0.5000
70°	0.5736
80°	0.6428
90°	0.7071
100°	0.7660
110°	0.8192
120°	0.8660
130°	0.9063
140°	0.9397
150°	0.9659
160°	0.9848
170°	0.9962
180°	1.0000

Figure 6: Stem circumference impact angle in degrees of a branch where it connects with stem, and the associated sine of one-half this impact angle which represents the branch ratio.

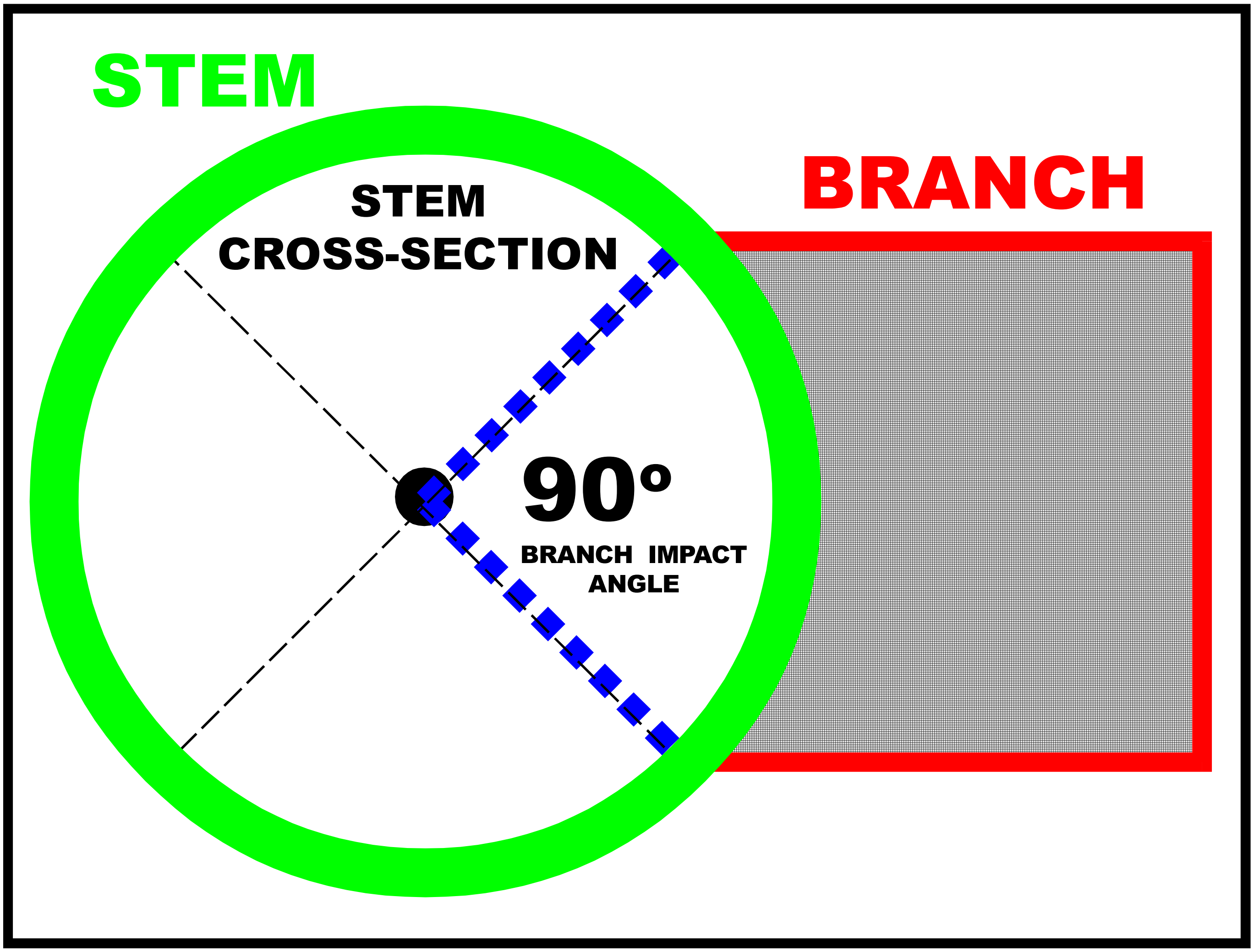


Figure 7: Two-dimensional disruption of stem circumference by a branch union.

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).

branch ratio	stem circumference disruption (decimal %)	branch impact angle (degrees)
BR 0.1	0.03	12°
BR 0.2	0.07	24°
BR 0.3	0.10	36°
BR 0.33 (1/3)	0.11	39°
BR 0.4	0.13	47°
BR 0.5	0.17	60°
BR 0.6	0.21	74°
BR 0.66 (2/3)	0.23	84°
BR 0.7	0.25	89°
BR 0.75	0.27	97°
BR 0.8	0.30	106°
BR 0.9	0.36	128°
BR 1.0	0.50	180°

Figure 8: Two dimensional disruption of stem tissue circumference, in a decimal percent, caused by branch connection size (branch ratio).

TYPE 1 CALCULATIONS

BD” = SD” X sine (½ X ANGLE°) = branch diameter impact on stem.

BD” / SD” = sine (½ X ANGLE°) = branch ratio.

BD” = BRANCH RATIO X SD” = branch diameter impact on stem.

ARC LENGTH = 0.0175 X ANGLE° X ½ SD” = stem circumference disrupted by branch.

STEM CIRCUMFERENCE DISRUPTION (in decimal percent) = ARC LENGTH / STEM CIRCUMFERENCE

BD” = branch base diameter in inches.
SD” = stem diameter in inches at point of branch connection.
ANGLEo = angle in degrees from center of tree to outside edges of branch base at stem circumference.
BRANCH RATIO = BD”/SD” = branch ratio or aspect where connected to stem.
ARC LENGTH = length of circumference arc on stem impacted by branch.

Figure 9: Calculations of TYPE 1 table values for branch ratio and stem circumference disruption values.

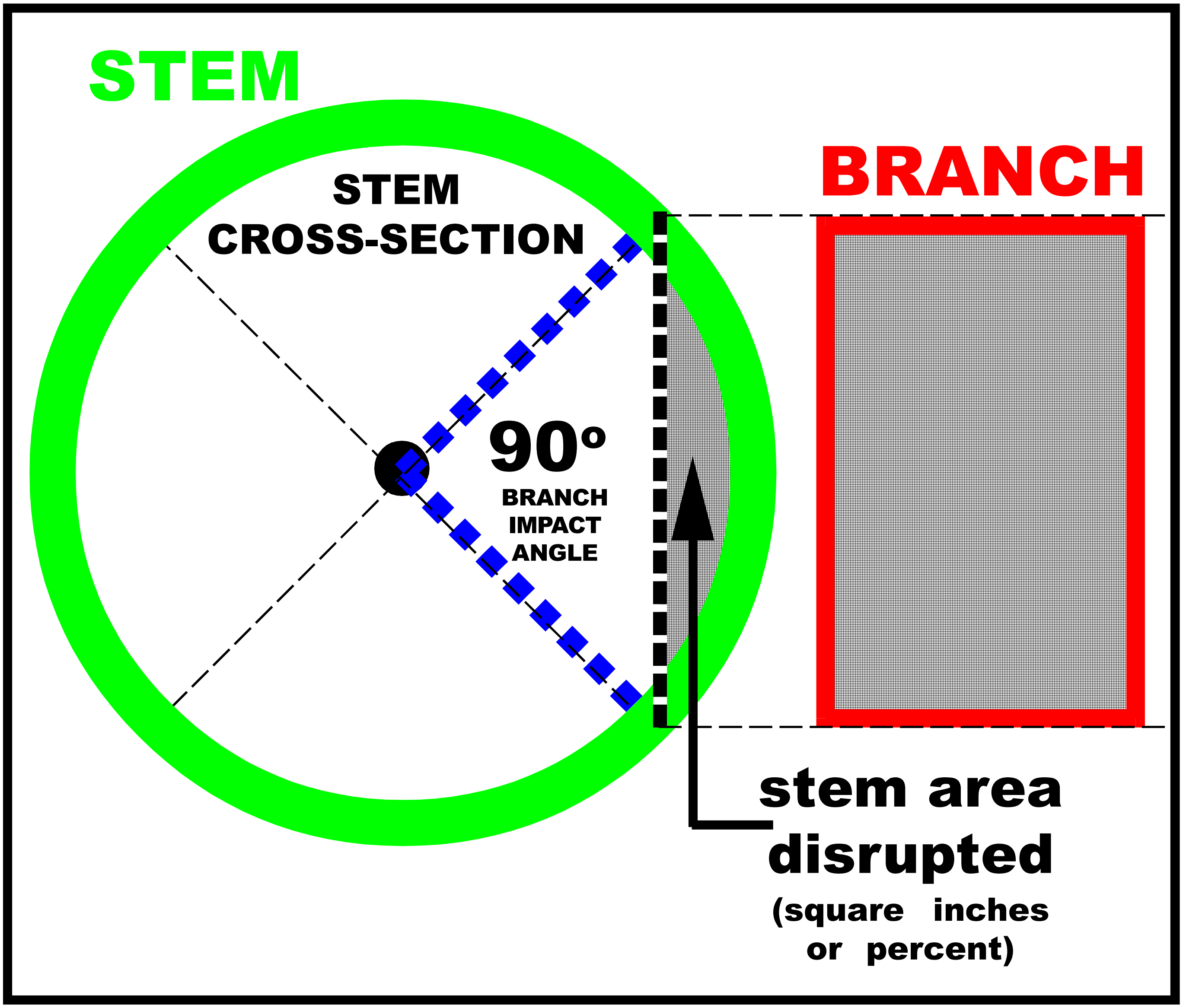


Figure 10: Two-dimensional disruption of stem cross-sectional area by a branch union.
In this example, the stem cross-sectional area impacted by a branch connection is 9% (across a 90° angle with a branch ratio of 0.71).

branch ratio	branch impact angle (degrees)
BR 0.1	12°
BR 0.2	24°
BR 0.3	36°
BR 0.33 (1/3)	39°
BR 0.4	47°
BR 0.5	60°
BR 0.6	74°
BR 0.66 (2/3)	84°
BR 0.7	89°
BR 0.75	97°
BR 0.8	106°
BR 0.9	128°
BR 1.0	180°

Figure 11: Branch impact angles in degrees for a range of branch ratios disrupting stem / branch connection area.

BRANCH RATIO	STEM DIAMETER (INCHES) 5	10	15	20	25	30	35	40	50
0.1	.01in²	.03	.06	.11	.16	.24	.32	.42	.66
0.2	.04	.17	.37	.67	1.04	1.5	2.0	2.7	4.2
0.3	.13	.55	1.2	2.1	3.3	4.8	6.5	8.4	13
0.33	.16	.66	1.4	2.5	4.0	5.7	7.8	10	16
0.4	.28	1.2	2.5	4.4	6.9	10	14	18	28
0.5	.57	2.4	5.2	9.2	14	21	28	37	58
0.6	1.1	4.1	9.5	17	26	38	52	68	106
0.66	1,5	6.2	13	24	37	54	73	95	149
0.7	1.7	7.3	16	28	44	63	86	112	175
0.75	2.2	9.1	20	35	54	79	107	140	218
0.8	2.8	12	25	44	69	100	136	178	278
0.9	4.5	19	40	72	113	163	221	288	451
1.0	9.7	41	88	157	245	355	480	628	983
total stem cross-sectional area	20	79	177	314	491	707	962	1,257	1,964

Figure 12: Amount of stem cross-sectional area (in square inches) disrupted by a branch connection based upon branch ratio and stem diameter.

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%
0.75	11%
0.8	14%
0.9	23%
1.0	50%

Figure 13: Percent of total stem cross-sectional area disrupted by a branch connection based upon branch ratio (for all stem diameters).

TYPE 2 CALCULATIONS

SADis = area of stem disrupted by branch connection in square inches =

Sr^2 / 2 X
[((3.142 X angle°) / 180) - sine (angle°)].
: if angle <90°

OR

Sr^2 / 2 X
[((3.142 X angle°) / 180) - sine (180 - angle°)].
: if angle >90°

SA = area of total stem cross-section in square inches:
0.785 X (SD”)^2.

percent of total stem cross-sectional area disrupted by branch connection =
SADis / SA.

Sr^2	=	stem radius in inches at point of branch connection.
ANGLE°	=	angle in degrees from center of tree to outside edges of branch base at stem circumference.
SD”	=	stem diameter in inches at point of branch connection.
SADis	=	area of stem cross-section disrupted by branch connection in square inches.
SA	=	area of total stem cross-section in square inches.

Figure 14: Calculations of table values for TYPE 2 stem area disruption values by branch union ratio.

branch ratio	TYPE 1 stem circumference disruption (percent)	TYPE 2 stem area disrupted (percent)
BR 0.1	3	0.03
BR 0.2	7	0.2
BR 0.3	10	0.7
BR 0.33 (1/3)	11	0.8
BR 0.4	13	1.5
BR 0.5	17	3.0
BR 0.6	21	5.5
BR 0.66 (2/3)	23	7.5
BR 0.7	25	9.0
BR 0.75	27	11
BR 0.8	30	14
BR 0.9	36	23
BR 1.0	50	50

Figure 15: Comparison of TYPE1 & TYPE 2 calculations based upon stem circumference and stem cross-sectional area showing estimated stem disruption by branch union.

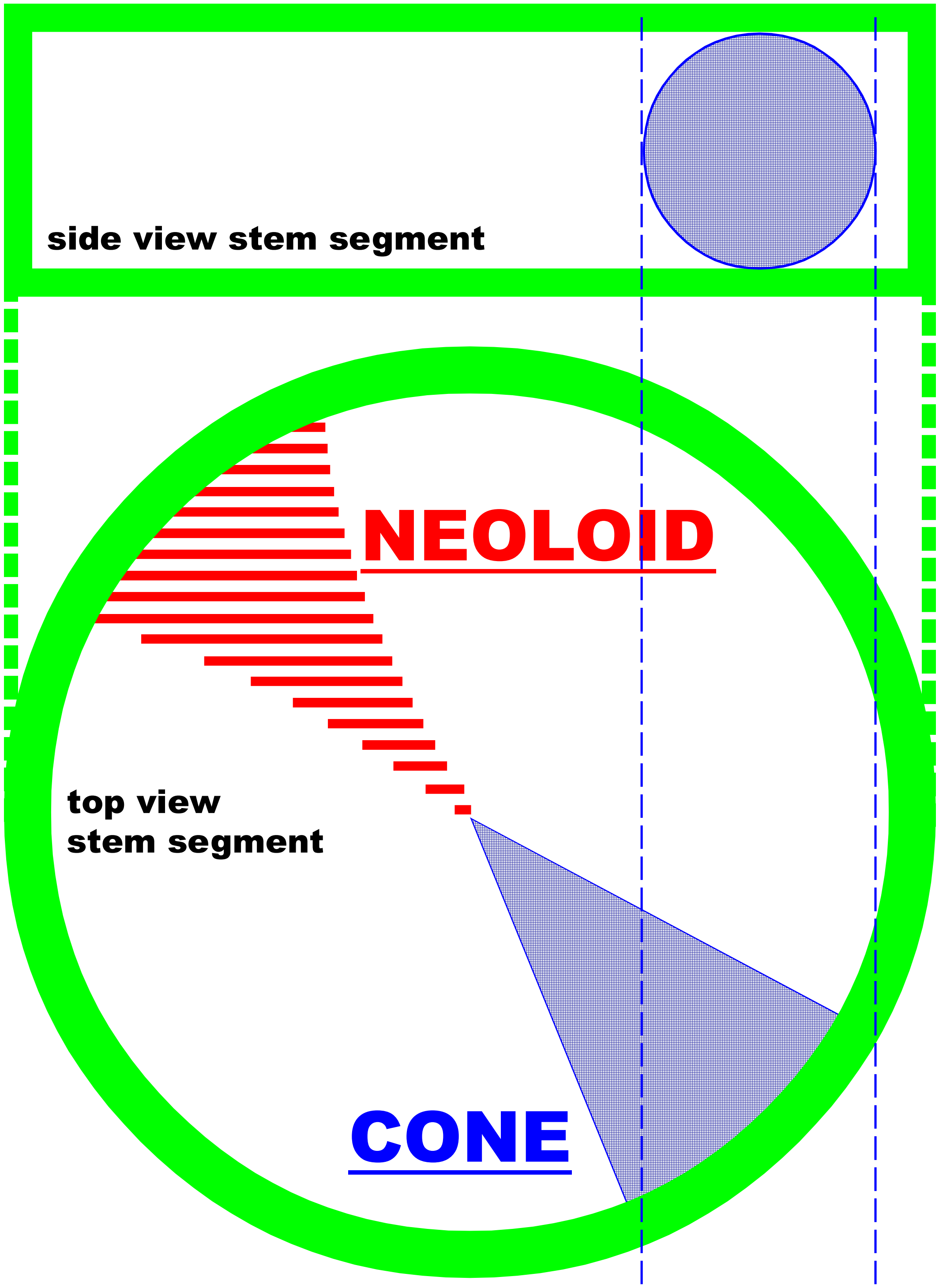


Figure 16: Three-dimension volumes in a stem segment representing one of two branch base shapes -- a cone shape or a neoloid shape.

TOTAL STEM SEGMENT VOLUME

BRANCH RATIO / STEM DIAMETER (INCHES)	5	10	15	20	25	30	35	40	50
0.1	10	79	265	628	1227	2121	3367	5027	9818
0.2	20	157	530	1257	2454	4241	6735	10,053	19,635
0.3	29	236	795	1885	3682	6362	10,102	15,080	29,453
0.33	32	259	875	2074	4050	6998	11,112	16,588	32,398
0.4	39	314	1060	2513	4909	8482	13,470	20,106	39,270
0.5	49	393	1326	3142	6136	10,603	16,837	25,133	49,088
0.6	59	471	1591	3770	7363	12,724	20,204	30,160	58,905
0.66	65	518	1750	4147	8100	13,996	22,225	33,176	64,796
0.7	69	550	1856	4398	8590	14,844	23,512	35,186	68,723
0.75	74	589	1988	4712	9204	15,905	25,256	37,700	73,631
0.8	78	628	2121	5026	9818	16,965	26,939	40,213	78,540
0.9	88	707	2386	5655	11,045	19,085	30,307	45,239	88,358
1.0	98	785	2651	6283	12,272	21,206	33,674	50,266	98,175

Figure 17: Total stem cylinder segment volume (in cubic inches) where a branch of a given branch ratio is attached, with segment height dimension equal to branch diameter in inches.

NEOLOID SHAPE BRANCH BASE

BRANCH RATIO	STEM DIAMETER (INCHES) 5	10	15	20	25	30	35	40	50
0.1	.12	.98	3.3	7.8	15	27	42	63	123
0.2	.49	3.9	13	31	61	106	168	251	490
0.3	1.1	8.8	30	71	138	238	378	565	1103
0.33	1.3	11	36	85	167	288	458	683	1334
0.4	2.0	16	53	125	245	423	672	1004	1960
0.5	3.1	25	83	196	383	662	1050	1568	3063
0.6	4.4	35	119	282	551	953	1513	2258	4410
0.66	5.3	43	144	342	667	1153	1830	2732	5336
0.7	6.0	48	162	384	750	1297	2059	3073	6003
0.75	6.9	55	186	441	861	1488	2364	3528	6891
0.8	7.8	63	212	502	980	1693	2689	4014	7840
0.9	9.9	79	268	635	1240	2143	3403	5080	9923
1.0	12	98	331	784	1531	2646	4202	6272	12,250

Figure 18: Stem segment volume (in cubic inches with a neoloid shape factor branch base) disrupted by a branch connection, based upon branch ratio and stem diameter.

Neoloid shape factor = 0.1964.

CONE SHAPE BRANCH BASE

BRANCH RATIO	STEM DIAMETER (INCHES) 5	10	15	20	25	30	35	40	50
0.1	.17	1.3	4.5	10	21	35	56	83	165
0.2	.66	5.2	18	42	83	140	225	333	660
0.3	1.5	12	41	94	186	316	507	749	1485
0.33	1.8	14	49	113	225	382	614	906	1797
0.4	2.6	21	72	166	330	562	902	1331	2640
0.5	4.1	33	113	260	516	878	1409	2080	4125
0.6	5.9	47	162	374	743	1264	2029	2995	5940
0.66	7.2	57	196	453	898	1529	2455	3624	7187
0.7	8.1	64	221	510	1011	1720	2761	4077	8085
0.75	9.3	73	253	585	1160	1974	3170	4680	9281
0.8	11	83	288	666	1320	2246	3606	5325	10,560
0.9	13	105	365	842	1671	2843	4564	6739	13,365
1.0	17	130	450	1040	2063	3510	5635	8320	16,500

Figure 19: Stem segment volume (in cubic inches with a cone shape factor branch base) disrupted by a branch connection, based upon branch ratio and stem diameter.
Cone shape factor = 0.262.

BRANCH RATIO	"NEOLOID BASE" PERCENT STEM VOLUME DISRUPTED BY BRANCH	"CONE BASE" PERCENT STEM VOLUME DISRUPTED BY BRANCH
0.1	1.3	1.7
0.2	2.5	3.3
0.3	3.8	5.1
0.33	4.1	5.5
0.4	5.0	6.7
0.5	6.2	8.4
0.6	7.5	10.0
0.66	8.2	11.0
0.7	8.7	11.7
0.75	9.3	12.5
0.8	10.0	13.4
0.9	11.2	15.0
1.0	12.5	16.8

Figure 20: Percent of total stem segment volume disrupted by a branch connection based upon branch ratios for both a neoloid shape-factor branch base and a cone shape-factor branch base within the stem segment.

TYPE 3 CALCULATIONS

Original Branches:

1. For neoloid shaped volume in cubic inches:
(moderate to fast growing branches)
(0.5 X SD”) X (BRANCH RATIO X SD”)² X 0.196 = BRANCH BASE VOLUME IN STEM (in³)

2. For cone shaped volume in cubic inches:
(slow growing branches)
(0.5 X SD”) X (BRANCH RATIO X SD”)² X 0.262 = BRANCH BASE VOLUME IN STEM (in³)

Sprout Origin Branches:

– arising in last few outer increments would have greatly decreased volume in base.

Stem Cylinder Segment Volume =
3.142 X (0.5 X SD”)² X (BRANCH RATIO X SD”).

BD”	= branch base diameter in inches.
SD”	= stem diameter in inches at point of branch connection.
BRANCH RATIO	= BR” / SD”
	= branch ratio or aspect where connected to stem.
NEOLOID SHAPE #	= 0.196
CONE SHAPE #	= 0.262

Figure 21: Calculations of table values for TYPE 3 stem volume disruption values by branch union ratio.

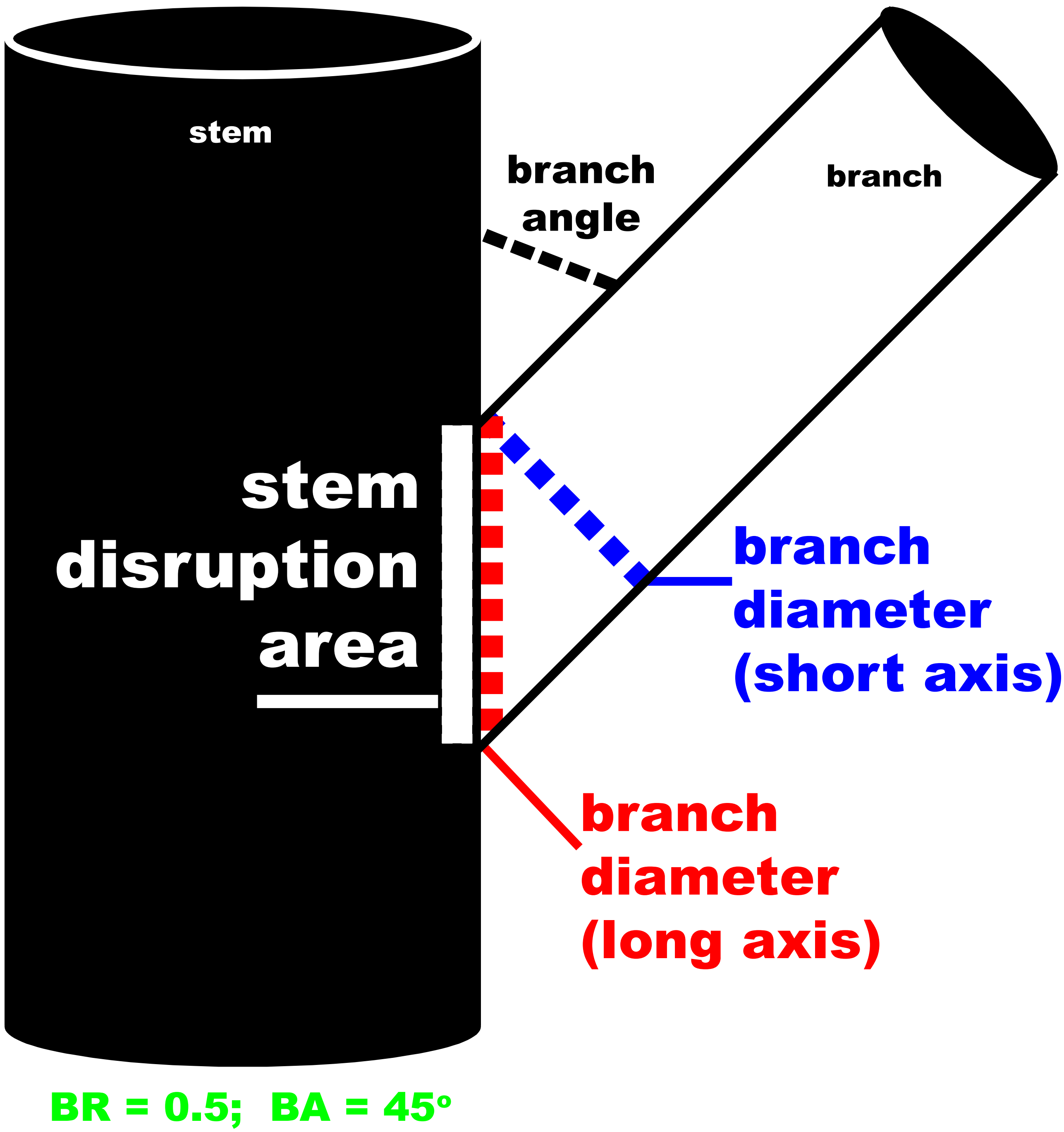
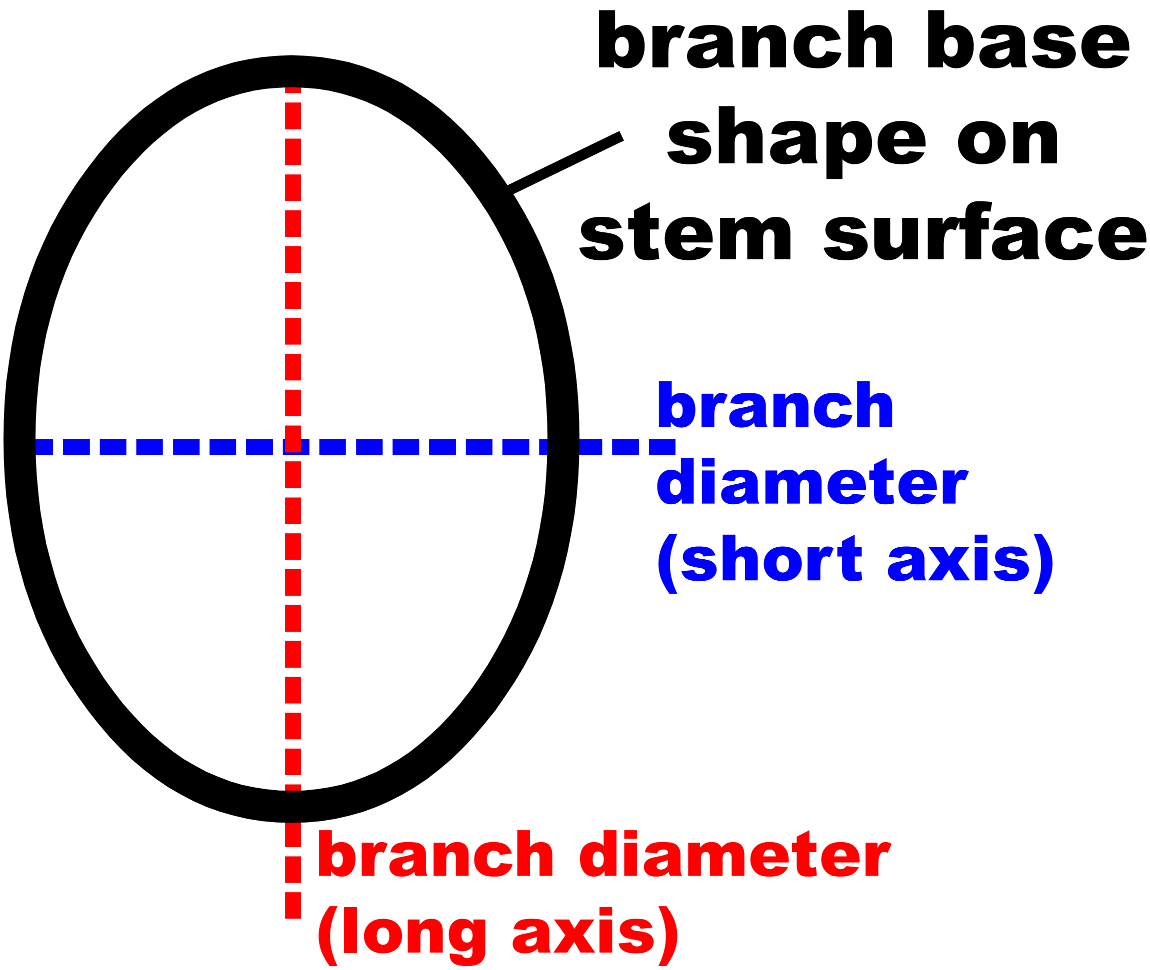


Figure 22: As a branch angle becomes smaller (more narrow), the stem disruption impact area becomes larger, proportional to the long axis of branch base.



STEM AREA DISRUPTED =
0.785 X
[short axis length / sine (branch angle)] X
short axis length.

Figure 23: The smaller a branch angle, the larger stem area disrupted by a branch base, as shown in this equation.
Branch bases with smaller branch angles have an elliptical stem impact area. As branch angle becomes smaller, the short axis remains the same and the long axis increases.

branch angle	stem area disruption change by branch angle degrees: increase compared to 90° branch angle	stem area disruption change by branch angle degrees: for every 10° branch angle increase
90°	1.00X	
		1.02X
80°	1.02X	
		1.06X
70°	1.07X	
		1.09X
60°	1.16X	
		1.13X
50°	1.31X	
		1.19X
40°	1.56X	
		1.29X
30°	2.00X	
		1.46X
20°	2.93X	
		1.97X
10°	5.75X	

Figure 24: Two views on how stem area disruption increases with changes in branch angle. One view is based upon stem disruption area changes from a 90° branch angle baseline, and one view is based upon each 10° branch angle change.

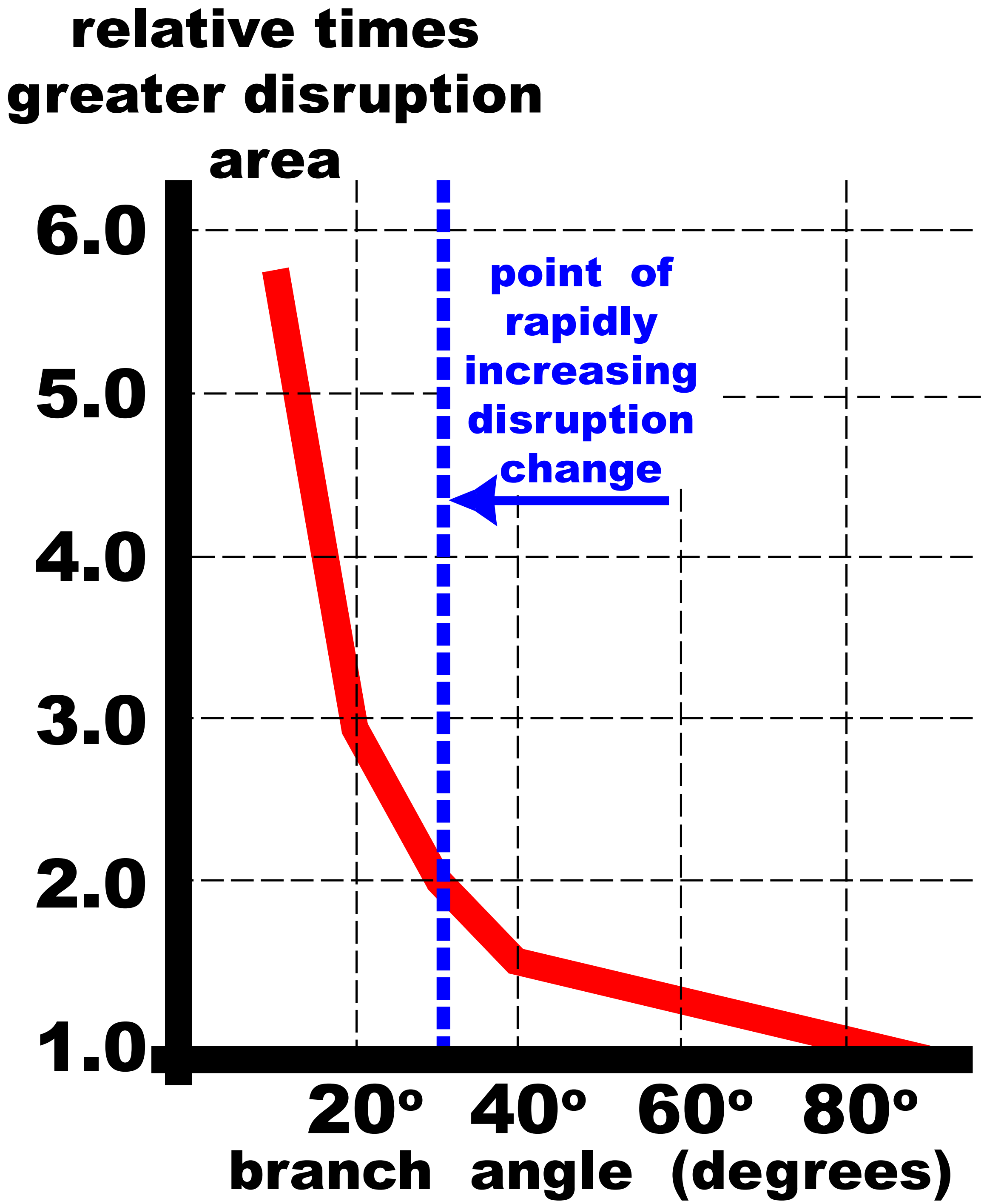


Figure 25: Stem area disruption values as branch angle changes, based upon a branch angle baseline of 90°.