Textos extraídos de:

Anuchin, N.P. 1970. Forest Mensuration. Israel Program for Scientific Translation, Jerusalem. 454 p.

Stem analysis is the name applied to special investigations purporting to study the growth dynamics of a tree or the variation of its dimensions with age.

The choice of a tree for stem analysis depends upon the investigation purpose, the thickest and tallest tree being selected in certain cases, while other cases require a mean tree representative of the given stand. An investigator embarking on stem analysis must not select a tree at random, but must select a tree suitable to his purpose.

The tree selected for stem analysis must first of all be described while standing. The description must include its development class, the shape of its crown, the size of the latter's projection, the distance from the neighboring trees, their arrangement with respect to the selected tree, their species, d.b.h. and height. A detailed description must also be furnished of the natural condtiions under which the tree originated and grew (site, soil, surrounding stand, regeneration, underwood, ground cover), the degree of self-pruning and other data. All this information is entered in a special form.

The tree is marked for its northern and its southern sides; the investigator must also locate the root collar, the correct determination of which can affect the accuracy of age determination.

Before the tree is felled, the area around it must be suitably prepared for convenient work with the saw and the axe; the root collar must be thoroughly cleared of moss and forest litter (and also of earth if it is sunken).

The felling direction is chosen in such a manner that the tree would not remain hanging on the surrounding trees. Poles are laid across the area on which the tree will fall, in order to facilitate its processing.

The axe cut should be made below the planned cut line in order that the root collar section be preserved intact. In general, all necessary measures should be taken to avoid spoiling the butt end and to preserve intact all parts of the stem up to the very top while the tree is felled.

After the tree has been felled, the distance from the stem base to the first dead and the first live branches is first measured, followed by

measurement of the distance to the beginning of the crown. The stem is pruned free of branches (preservation of the top is mandatory) and marked into longitudinal sections (Figure 101). All the sections may either be of identical length, or else the first section is made equal to double the distance between the root collar and the breast height, i.e., 2.6 m, while the remaining stem is marked in sections 2 m long. The sections may also be of a
381 different length depending upon the purpose of stem analysis and the required accuracy.

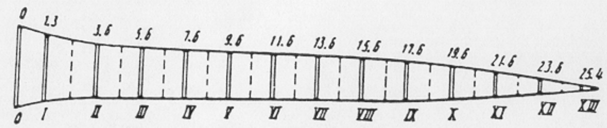

FIGURE 101. Diagram of the subdivision of a tree stem for analysis

The marking of the stem into sections includes the marking of their midpoints, i.e., the spots for the cutting of disks for analysis, the last disk being cut at the base of the top. The spots earmarked for the cutting of disks are also marked with north or south, according to the marks made at the breast height and the root collar of the standing tree.

The cutting of disks starts from the base and proceeds toward the top, the first cut being made through the mark and the second in the direction of the top at a distance from the first cut equal to the intended thickness of the disk. If a mark falls at the base of a branch, it is transferred to a lower position.

The disks should be 1 to 4 cm thick, depending upon the cross-section diameters, and must be cut perpendicular to the stem axis.

Each disk cut from the stem is assigned a serial number, the numeration proceeding in the following order. If the tree was taken from a sample plot, the disks are marked with the number of the sample tree and their own serial number, thus: the number of the sample plot and the sample tree in the numerator and the serial number of the disk itself in the denominator. If the tree selected for stem analysis was not taken from a sample plot, the disks are marked only with their serial number. The marks are made on a somewhat smoothed top of the disk, while the lower faces of the disks, i.e., those facing toward the stem base, are used for the counting of annual rings and for the measuring of diameters.

Cutting of the disks completes the stem analysis in the forest, further investigations being performed in the office. It is recommended that the disks be processed immediately, their storage being permitted only in extreme cases; in such cases they should be stored in a cool place for no longer than three days to avoid cracking, shrinkage by drying and deformation.

The first step in the processing of a disk is the smoothing of the side to be used for the counting of annual rings; this facilitates the procedure. Depending upon the purpose of investigation and its accuracy, the surface may be made perfectly smooth, and sometimes it is even polished, or else a chisel is used for cutting grooves in the disks along the north—south and the east—west diameters.

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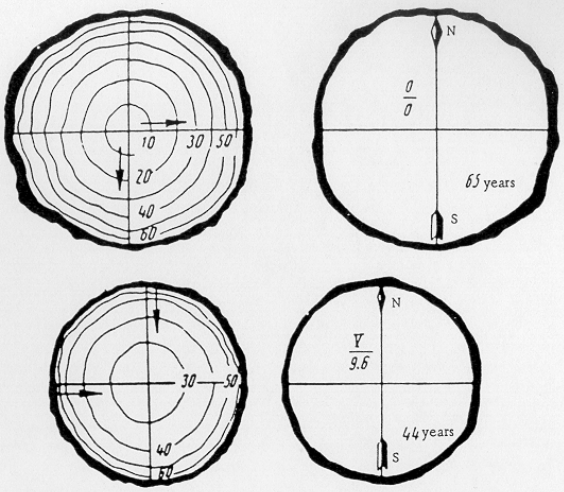

FIGURE 102. Counting the layers from the pith toward the periphery on the disk cut at the root collar (top of figure) and from the periphery toward the pith on a disk cut at the height 9.6 m (lower part of the figure)

This is followed by counting the annual rings on the disks; counting is usually done in tens or fives. The first count is made on the zero disk (Figure 102), the count on it proceeding from the pith toward the periphery. Every ten or five rings are separated with a closed circle pencilled around the entire annual ring, the last, peripheral group of annual rings usually being incomplete (less than 10 or less than 5 layers).

While counting the annual rings, the cruiser notes the characteristic ones, which differ markedly from one another in width, color, thickness of the summer xylem, etc. These characteristic layers serve to check the tens in the following disks, such layers usually being easily identified in nearly all the disks. The counting of the annual rings on the other disks, beginning with disk No. 1, proceeds from the periphery toward the pith, by first marking off the incomplete "ten" or "five" group of annual rings that remained at the end of counting on the zero disk, and then proceeding
383 to count by tens or fives. This procedure is important in making possible the determination of the dimensions of the analyzed stem during different periods of its growth.

Let an analyzed stem be 65 years old. Subtraction of the total width at the five outermost lines from the diameter width yields the diameter of the same stem at the age of 60 years at the level represented by the given sample disk.

The number of rings counted on each disk is recorded in the corresponding column of the form used for stem analysis.

The counting and marking of the annual rings is followed by measurement of the diameter on each disk of cross sections formed by demarcation by decades or five-year periods. The diameters are measured in millimeters or fractions of a millimeter within 0.25 mm, depending upon the required accuracy.

If the chiseled grooves running from north to south and from east to west appear as the diameters of the demarcated circles, not as their chords, these diameters can be measured along the grooves. If the grooves appear as chords in certain cross sections, the latter's diameters are drawn for purposes of measurement in somewhat different directions with respect to the cardinal points.

Such lines need not pass through the pith, because, in these cases the pith does not constitute the center of the circles.

The diameters may be measured also in other directions, for instance along the maximum and the minimum diameters, depending upon the investigation purposes and the required accuracy.

The measured diameters are recorded in the left part of the analysis form (Table 66). The diameters of circles referring to specified periods (10, 20, 30 years, etc.) are entered in the pertinent columns, so that the form includes the diameters measured at different levels for each reference period, according to the location of spots in which the disks were cut (at the base, and at the levels 1.3 m, 3.6 m, etc., if the butt section is 2.6 m long and all the other sections 2 m long).

The midsection diameters of the sections make possible the determination of their volumes, which are assumed to be cylindrical. The entire stem volume is computed as the sum of the volumes of the cylinders plus that of the top (beginning at the end of the last section). The determination of the volume of the stem top for different periods requires knowledge of the stem height in that period and the length of its top. The first step in this calculation is determination of the ages at which the tree reached the levels represented by the sample disks. These ages are computed as the difference between the number of annual rings on the zero disk and the number of rings on the disks cut at the different levels.

386 The first step in stem analysis is determination of the course of height growth, by comparing the number of annual rings in disks cut at different distances from the root collar.

In our example, the number of annual rings was 65 at the root collar and 60 at breast height (1.3 m). By subtraction, it is found that the tree reached the height 1.3 m in the course of 65—60 = 5 years. The number of rings in the disk cut at the level 3.6 m is 56. By subtracting this number from 65 (65 - 56 = 9 years), we determined the age at which the tree reached the height 3.6 m. The age at which the tree reached the heights of all the successive cross sections can be found in the same manner.

Having determined the stem heights at the ages of 5, 9, 13, 16 years, etc., it is possible to construct a graph by plotting these ages on the x-axis and the corresponding heights on the y-axis. The plotted points are joined with a smooth curve, which is the height growth curve of the analyzed stem. The heights of a stem at ages of 10, 20, 30, 40, 50 and 60 years can be read off this graph, the resultant data being entered in the stem analysis form.

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TABLE 66. Example of field stem analysis form

Serial No. of section	Section length, m / Number of rings	Orientation of the diameters	Section diameters (cm) at following ages							
			65 years		60 years	50 years	40 years	30 years	20 years	10 years
			over bark	under bark						
0	0/65	East—west	37.0	34.5	32.7	28.8	–	–	–	–
		North—south	35.0	33.5	32.1	29.0	–	–	–	–
		Intermediate	36.0	34.0	32.4	28.9	25.0	20.6	14.5	7.0
I	1.3/60	"	28.7	26.7	25.6	22.8	20.3	16.9	13.0	5.7
II	3.6/56	"	26.0	25.0	24.4	21.8	19.0	16.0	11.7	(2.3)
III	5.6/52	"	23.8	23.0	22.1	20.8	18.0	13.9	7.6	–
IV	7.6/49	"	22.8	22.0	21.5	19.5	16.3	12.0	4.2	–
V	9.6/44	"	21.8	21.0	20.5	18.7	14.9	8.5	–	–
VI	11.6/41	"	20.7	20.0	19.5	16.4	12.5	6.7	–	–
VII	13.6/37	"	19.5	18.8	17.9	14.7	9.4	(1.6)	–	–
VIII	15.6/32	"	18.3	17.7	16.4	12.6	6.3	–	–	–
IX	17.6/28	"	16.2	15.6	14.3	10.4	(2.5)	–	–	–
X	19.6/24	"	13.9	13.6	11.9	6.4	–	–	–	–
XI	21.6/18	"	10.6	10.3	8.3	(2.4)	–	–	–	–
XII	23.6/12	"	15.8	5.5	3.7	–	–	–	–	–
XIII	24.6/5	"	(2.0)	(1.9)	–	–	–	–	–	–
Height, m			26.3	26.3	25.4	22.6	19.1	14.9	9.2	4.2
Length of tops, m			1.7	1.7	0.8	1.7	1.9	1.1	0.5	1.4
Diameter, cm			2.0	1.9	2.0	2.4	4.4	3.6	1.6	4.0

Note. The figures in parentheses are diameters at the base of top.

Age at which tree reached level of cutting of disk	Section length	Basal areas (cm^2) at following ages							
		65 years		60 years	50 years	40 years	30 years	20 years	10 years
		over bark	under bark						
–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–
5	2.6	646.9	559.9	514.7	408.3	323.6	224.3	132.7	25.5
9	2.0	530.9	490.9	467.6	373.2	283.5	201.1	107.5	–
13	2.0	444.9	415.5	383.6	339.8	254.5	151.7	45.4	–
16	2.0	408.3	380.1	363.1	298.6	208.7	113.1	13.8	–
21	2.0	373.2	346.4	330.1	274.6	174.4	56.7	–	–
24	2.0	336.5	314.2	298.6	211.2	122.7	35.3	–	–
28	2.0	298.5	277.5	251.6	169.7	69.4	–	–	–
33	2.0	263.0	246.1	211.2	124.7	31.2	–	–	–
37	2.0	206.1	191.1	160.6	84.9	–	–	–	–
41	2.0	151.7	145.3	111.2	32.2	–	–	–	–
47	2.0	88.2	83.3	54.1	4.5	–	–	–	–
53	2.0	26.4	23.9	10.7	–	–	–	–	–
60	1.7	–	–	–	–	–	–	–	–
Total basal area of sections 2 m long, cm^2		3,127.7	2,914.3	2,642.4	1,913.4	1,144.4	557.9	166.7	–
Total volume of sections 2 m long, m^3		0.6255	0.5829	0.5285	0.3827	0.2289	0.1116	0.0333	–
Volume of sections 2.6 m long, m^3		0.1682	0.1456	0.1338	0.1054	0.0841	0.0583	0.0345	0.0066
Volume of tops, m^3		0.0006	0.0006	0.0001	0.0008	0.0011	0.0005	0.0001	0.0006
Total stem volume, m^3		0.7943	0.7291	0.6624	0.4889	0.3141	0.1704	0.0679	0.0072

The length of tops less than 2 m and their basal diameters are determined by constructing the longitudinal stem sections at the stipulated periods, i.e., at the age of 10, 20 and 30 years, etc. A longitudinal section may be constructed on diameters (full section) or on radii (half section).

To construct a longitudinal section on diameters, the stem axis is drawn at right angles to the base line to a length equal to the distances from the sample disks to the zero cross section, the stem heights read off the curve being marked on this axis to scale. All the cross sections, beginning with the zero one, are marked with their diameters (also to scale) in such a manner that they are bisected by the axis. For half sections, half diameters are marked on only one side of the axis. The stem generatrix for the given age is drawn by joining together points belonging to a specified age of the tree (Figure 103). Then the boundaries of the separate sections (parts of stem) are marked on the axis of the longitudinal section with lines perpendicular to the axis to obtain the length of top, equal to the distance from the upper boundary of the last section to the end of the stem. The diameters of the top boundaries of the last sections will be diameters of top bases. The length of tops and their basal diameters for every period are entered at the bottom of the left page of the stem analysis form. This concludes the preparatory stage in the processing of stem analysis data.

The second stage consists in determination of the respective stem volumes for each stem period. In our example, it was necessary to determine the stem volume at the age of 65, then at the ages of 60, 50, 40, 30, 20 and 10 years. The stem volume for each period is determined as the sum of the volumes of the separate sections plus that of the top.

The stem volume can be found in two ways. In the first method, the volumes of stem sections are computed as cylindrical volumes from
387 diameters and lengths while the top volume is computed as that of a cone. The second method makes use of the midpoint diameters of the stem sections to calculate the basal areas. For sections of identical length, the sum of their basal areas is multiplied by their length, while if the sections are of unequal length, their separate volumes are totaled with addition of the top volumes.

In our example of stem analysis, the stem volumes at different ages were calculated by the second method and entered on the right of the stem analysis form.

The last stage of stem analysis consists of studying the numerical data, i.e., calculations of increments with respect to height, d.b.h., basal area and volume.

From these data the mean annual volume increment for each age is determined by means of formula (202c), while the current annual volume increment is determined from formula (203c).

388 Determination of the height, diameter, basal area and volume of the stem in the different age periods is followed by determination of the form factors, the results being entered in the summary table (Table 67, columns 2–9).

The series of form factors displays a decrease with increasing age. In our example, an exception is found in the form factor of the stem at the age of 50 years. This was probably due to a change in the growth conditions in that period, resulting in narrower annual rings in the lower stem and wider rings in the upper stem.

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TABLE 67. Summary table of stem analysis

Age period	Height growth, m: height	Height growth, m: height increment	Diameter growth, cm: d.b.h.	Diameter growth, cm: diameter increment	Volume, m³	Increment, dm³: mean	Increment, dm³: current	Form factor	Current form factor increment	Percentage current annual increment: diameter (P_d)	basal area (P_g)	height (P_h)	volume (P_v)	form factor (P_f)	Total percentage annual increment ($P_g + P_h + P_f$)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
10	4.2	0.50	5.7	0.73	0.0072	0.7	0.7 6.1	0.685	-0.013	7.8	13.7	7.4	16.0	-2.1	19.0
20	9.2	0.52	13.0	0.39	0.0679	3.4	10.2	0.556	-0.003	2.6	5.1	4.4	8.6	-0.5	9.0
30	14.4	0.47	16.9	0.34	0.1704	5.6	14.4	0.528	-0.002	1.8	3.6	2.8	5.9	-0.4	6.0
40	19.1	0.35	20.3	0.25	0.3141	7.8	17.5	0.508	+0.002	1.1	2.3	1.7	4.3	+0.4	4.4
50	22.6	0.28	22.8	0.28	0.4889	9.7	17.3	0.528	-0.002	1.1	2.3	1.2	3.0	-0.4	3.1
60	25.4	0.18	25.6	0.22	0.6624	11.0	13.3	0.506	-0.002	0.8	1.6	0.7	1.9	-0.4	1.9
65	26.3		26.7		0.7291	11.2		0.495							
Over bark	—		28.7		0.7943	—		0.467							

(387)

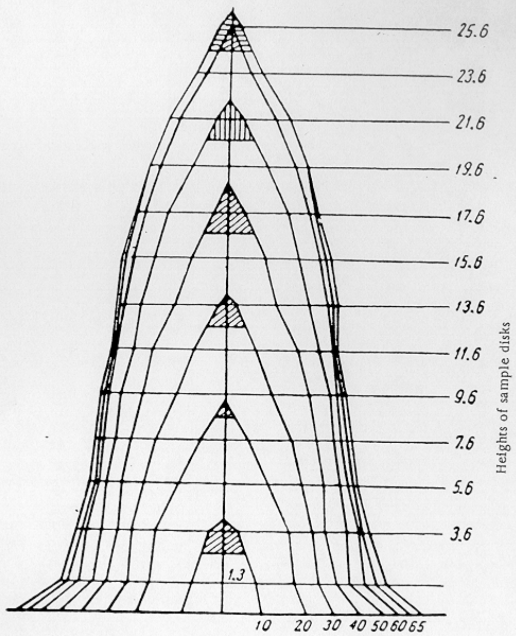

FIGURE 103. Graph of the longitudinal section of a tree stem from analytical data

Having determined the form factors for the different ages of the tree, the current annual increment is determined from the form factor by formula (203d) and the result is entered in column 10.

It is seen that the increasing age of the tree is associated with a negative form factor increment, with the exception of the age 40–50 years.

The next step is determination of the percentage current annual increment with respect to diameter, basal area, height, volume and form factor, as well as the total percentage, annual increment, the results being entered in columns 11–16 of Table 67.

Analysis of the tabulated numerical data confirms previous conclusions and permits several other practically important conclusions.

The percentage cross-sectional increments are double the percentage diameter increments on the average (see formula (50)).

Percentage volume increments are approximately equal to the total percentage increment with respect to basal area height and form factor (see formula (299)).

In trees taller than 2.6 m the form factor decreases with increasing age, so that the form factor increment is negative.

The total percentage increment with respect to basal area and height is somewhat larger than the percentage volume increment. According to observations, the percentage form factor increment amounts to 0.3 (in round numbers) of the percentage height increment. Therefore, approximate determination of percentage volume increment may be performed by means of the formula

$$p_V = p_g + 0.7p'_h. \qquad (233)$$

Let us now examine the accuracy of stem analysis, by means of formula (229):

$$p_V = p_g + p_h + p_f.$$

Let us assume that the three components of the percentage volume increment involve the respective errors p'_g, p'_h, p'_f. From the theory of
390 errors it is known that the error of a sum is equal to the square root of the sum of squared errors of the factors forming the sum. Consequently, the error of the percentage volume increment is

$$p_V = \pm\sqrt{(p'_g)^2 + (p'_h)^2 + (p'_f)^2}. \qquad (234)$$

From (50), the percentage cross-sectional increment is double the percentage diameter increment; therefore,

$$p'_g = 2p'_d.$$

Substituting in (234),

$$p'_V = \pm\sqrt{4(p'_d)^2 + (p'_h)^2 + (p'_f)^2}. \qquad (235)$$

In determinations of the diameters and heights of trees, there are some inevitable measurement errors, in the first place those involved in the rounding-off of the results.

In stem analysis the variations of diameters are accounted by decades at 1-mm intervals, in which case the rounding error is close to ±0.3 mm. If the mean width of annual rings is 1.5 mm, the diameter increment over ten years is 30 mm and its measurement error is ±1%.

Measurements of stem heights are rounded off to 10 cm. The mean rounding error is one-third of this quantity, i.e., ca. ±3 cm; for a mean ten-year increment of 3 m the rounding error is ±1%.

Because of the irregularities in the form of cross sections and the interpolations involved in determinations of the height of analyzed trees, the error involved in calculations of diameter and height may be assessed at ±1.5% and the error involved in the calculation of the form factor at ±2%. Substituting these values in formula (235),

$$p'_V = \sqrt{4 \times 1.5^2 + 1.5^2 + 2^2} \approx \pm 4\%.$$

This calculation shows that the mean error of final results is ±4% for the most careful determination of the volume increment by stem analysis.