U. S. FOREST SERVICE RESEARCH NOTE NE-60
1967

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FOREST SERVICE, U. S. DEPT. OF AGRICULTURE, 6816 MARKET STREET, UPPER DARBY, PA.

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A SYSTEMATIC BIAS IN THE INTERPRETATION OF CFI RESULTS

Abstract. It is not generally recognized that a serious bias arises in the estimates of annual ingrowth and accretion, two of the growth components available from continuous forest inventory (CFI). The bias is demonstrated, and suggestions for correction are given.

The continuous forest inventory (CFI) system originated by Stott and described by Stott and Semmens (1960) has become an integral part of many inventory systems in practice on public and private lands. Although most of these systems are modified versions of Stott's CFI concept, the principle of remeasured, fixed-radius plots has been widely accepted for volume-growth estimates. Generally these growth estimates are broken down into these various components: ingrowth, accretion, gross growth (ingrowth + accretion), mortality, net growth (gross growth — mortality), cut, and net change (net growth — cut).

These components are usually converted to an annual basis from periodic measurements taken at the beginning and the end of a 5-to-10-year measurement interval. Average annual growth rates are easily obtained by differencing the two volume measurements of each tree, dividing by the measurement interval, and placing the resultant volumes in the appropriate growth-component summaries. Unbiased estimates of average annual growth-component rates for the period are consequently obtained for net change, cut, net growth, mortality, and gross growth. However, it is not generally recognized that a serious bias arises in the estimates of gross-growth components—annual ingrowth and accretion.

The Problem Defined

Gilbert (1954) defined ingrowth as "the volume, at the end of the period, of those trees that grew into the lowest inventoried diameter class during the period" and accretion as "growth on the initial trees. These are all trees that were measured at the beginning of the period." Depending on the objectives of the inventory, ingrowth and accretion may or may not include the growth on trees that died (mortality) and/or were cut during the interval.

The CFI remeasurement interval may vary from as little as 3 years to as many as 15 years. However, the interval specified by the conventional manner in which CFI results are presented and applied is only 1 year; that is, the average annual ingrowth, as calculated from CFI, is usually interpreted by land managers as the average volume of wood entering the merchantable-size class within a 1-year interval. Similarly, the average annual accretion is interpreted as the average volume increment on the previous year's volume.

Assuming that interpretations are to be made as in the preceding discussion, it can be shown that ingrowth is generally *overestimated* by CFI. And it follows that accretion is generally *underestimated*. This bias arises from misplacing the volume that an ingrowth tree accumulates *after* it passes the threshold diameter; that is, the increment on the ingrowth trees after the year of ingrowth is lumped with ingrowth instead of accretion. And, because the bias increases with an increase in the measurement interval, comparisons of ingrowth and accretion from inventories with different measurement intervals can be meaningless.

Example

The fictitious 1/5-acre plot in table 1 shows the trees present at each year of a 10-year interval—assuming a threshold diameter of 5.0 inches for cubic-foot volume of each tree.

By the usual method for calculating average annual ingrowth, the 1966 volume of those trees (less than 5.0 inches d.b.h.) that were not present in 1956 is divided by the measurement interval and plot size. Including trees 7 through 18 in the calculations, the result is 54.1/(10 x 1/5) = 27.05 cubic feet per acre per year. Accretion is then obtained as the volumes of trees 1 through 6 in 1966 minus the 1961 volumes. If this is divided by the interval and the plot size the result is (97.6 − 22.6)/(10 x 1/5) = 37.50 cubic feet per acre per year. Gross growth is then 27.05 + 37.50 = 64.55 cubic feet per acre per year. *Correct* results, how-

Table 1. — Cubic-foot volume of trees on a 1/5-acre plot at each year of a 10-year interval

Tree No.	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
1	7.2	7.7	8.3	9.9	11.9	13.6	15.6	18.2	20.5	25.1	28.3
2	5.2	6.0	6.7	8.3	9.9	11.2	13.0	15.5	18.1	19.9	23.2
3	4.0	4.4	5.4	6.4	6.7	8.6	9.9	11.8	13.7	15.8	18.0
4	2.6	2.9	3.3	4.0	5.2	6.0	6.5	7.7	8.3	9.9	11.2
5	1.9	2.1	2.2	2.7	4.0	4.9	5.7	6.2	7.0	8.1	8.7
6	1.7	1.9	2.0	2.5	3.2	3.6	5.0	5.9	6.4	7.1	8.2
1-6	22.6	—	—	—	—	47.9	—	—	—	—	97.6
7	—	1.5	1.8	2.1	2.6	3.0	3.7	5.1	6.1	6.4	8.0
8	—	1.5	1.7	2.1	2.5	3.0	3.6	5.0	5.9	6.2	7.5
9	—	—	1.5	1.9	2.4	2.9	3.3	4.1	5.2	6.0	6.6
10	—	—	—	1.5	2.1	2.5	3.4	4.1	5.1	5.9	6.5
11	—	—	—	1.5	2.1	2.6	3.0	3.4	4.0	5.0	5.8
12	—	—	—	—	—	1.5	1.7	2.2	2.9	3.2	3.6
13	—	—	—	—	—	1.5	1.6	2.0	2.8	3.1	3.9
14	—	—	—	—	—	—	—	1.5	1.7	2.4	2.9
15	—	—	—	—	—	—	—	1.5	1.7	2.1	2.8
16	—	—	—	—	—	—	—	1.5	1.8	2.3	3.0
17	—	—	—	—	—	—	—	—	—	1.5	1.7
18	—	—	—	—	—	—	—	—	—	1.5	1.8
7-18	—	—	—	—	—	17.0	—	—	—	—	54.1
Σ	22.6	28.0	32.9	42.9	52.6	64.9	76.0	95.7	111.2	131.5	151.7

ever, are obtained by using the averages of the accretion and ingrowth volumes *for each year.* This procedure is shown in table 2.

The resulting growth rates indicate that annual ingrowth and accretion calculated by conventional methods are biased to the extent of $|(27.05 - 9.0)/9.0| \times 100 = 201$ percent and $|(37.50 - 55.6)/55.6| \times 100 = 33$ percent, respectively. In general, this bias increases as the measurement interval lengthens. For example, after only 5 years, the bias would be 62 percent for ingrowth and 20 percent for accretion.

Conclusions

The procedure for eliminating the bias is dependent on the method of volume calculation. For instance, if local volume tables are used, the solution is simple. Each ingrowth tree should automatically be placed in two slots: the volume of the tree with a 5.0 inch d.b.h. in the ingrowth slot and the volume at remeasurement minus the volume at 5.0 inches d.b.h. in the accretion slot.

Table 2. — Per-acre growth components in cubic feet for each one-year period

Component	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	Total	Annual average
Ingrowth	—	15.0	7.5	15.0	0	15.0	0	22.5	0	15.0	0	90.0	9.0
Accretion	—	12.0	17.0	35.0	48.5	46.5	55.5	76.0	77.5	86.5	101.0	555.5	55.6
Gross growth	—	27.0	24.5	50.0	48.5	61.5	55.5	98.5	77.5	101.5	101.0	645.5	64.6
Mortality	—	0	0	0	0	0	0	0	0	0	0	0	0
Net growth	—	27.0	24.5	50.0	48.5	61.5	55.5	98.5	77.5	101.5	101.0	645.5	64.6
Cut	—	0	0	0	0	0	0	0	0	0	0	0	0
Net change	—	27.0	24.5	50.0	48.5	61.5	55.5	98.5	77.5	101.5	101.0	645.5	64.6
Total volume	113.0	140.0	164.5	214.5	263.0	324.5	380.0	478.5	556.0	657.5	758.5	—	—

Because of the wide array of volume estimation models, no attempt is made in this paper to provide clear-cut solutions for every case. However, the importance of making the correction is evident and CFI users who depend on average annual rates of growth components should consider the extent to which this bias can affect their program planning and should take steps to eliminate the bias either by proper interpretation of present results or by revised calculations.

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