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ESTIMATION OF BIOMASS AND NUTRIENT CAPITAL IN STANDS OF OLD-GROWTH DOUGLAS-FIR

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INTRODUCTION

Sampling has long been established as an acceptable way of obtaining estimates in circumstances in which, for one reason or another, a complete enumeration or analysis was undesirable or impossible. An extensive theory and history of application support any effort in this direction, and ready access of computers allows routine use of sophisticated methods.

Faced with the formidable task of determining biomass and nutrient content of a 450-year-old Douglas-fir tree, we naturally explored the sampling possibilities. At about the same time, some of our colleagues, with the assistance of one of us (Overton), developed a sampling methodology for estimation of epiphyte biomass on trees in the same stand (Denison et al., (1972) and Denison (1973). This methodology had an elaborate procedure for describing each "branch system" of the entire tree and a detailed examination of several sample branch systems, such that data from these sample branches could be expanded to estimates for the entire set of branch systems on the tree. We decided to use the entire sampling system as a base for our biomass sampling and to select one of their sample branch systems for destructive sampling. Thus, our sample constituted a second "calibration" phase imposed on their one-phase, multi-stage sampling procedure.

Root biomass was sampled differently. In conjunction with yet another group of colleagues who were estimating biomass of small trees, shrubs, forbs and grasses, we sampled root cores within the polygon of occupancy of the sample large trees for estimation of small roots. Large roots were studied in relation to individual trees by examination of the excavated root system of these trees.

METHODS AND PROCEDURES

An Overview of the Methodology

Figure 1 is an overview of the biomass system being sampled. This is viewed as hierarchical, with trees (and other organisms) within the forest; branch systems, root systems, and other parts within the tree; branchlets and "axes" within a branch system; and twigs and needles within a branchlet. Sampling follows the same hierarchy. One selects sample trees to represent the forest and estimates properties of the forest from the properties of the sample trees. From the set of all branch systems on a tree, one selects sample branch systems from which to estimate the collective properties of the entire set on that tree. The bole is measured at sample points in such a manner that bole volume can be calculated. The degree of precision and the detail of attention then are imposed to accommodate the goals of the survey.

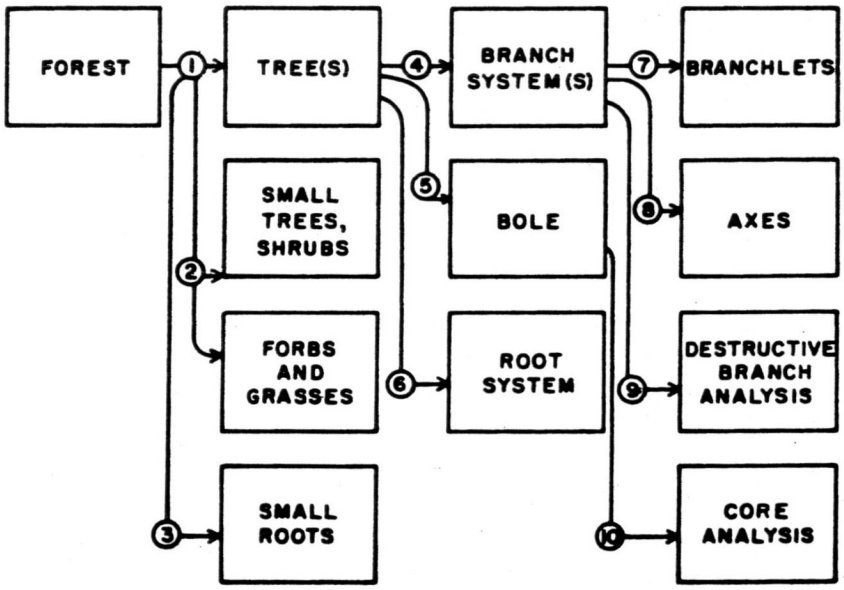

Figure 1. The hierarchy of plant biomass systems, as sampled and estimated. The sampling schemes discussed in this paper are identified as
a. Number 9, which provides estimates through 4 to whole trees.
b. Number 10, which provides estimates through 5 to whole trees.
c. Number 6, which provides estimates for whole trees, and indirectly through 1 to estimates for the forest.
d. Number 3, which provides estimates for the forest through 1.

At each sampling step, one constructs the frame--the set of descriptive materials that forms the base for sampling. Then one constructs the sampling method so as to best utilize the information in the frame. Estimates then are obtained by the procedures appropriate to the sampling method. In our studies, aboveground biomass samples were based on the frame elaborated by Denison. Sample cores of fine roots were obtained from the tree sampling frame through definition of area of occupancy. Sampling of large roots was not connected by this formal structure to the population of interest.

The Tree-Sampling Structure

The procedure for sampling trees has been described elsewhere (Overton, 1973a) in considerable detail. It suffices here to summarize the pertinent features of the approach used. The watershed was stratified into 11 strata of homogeneous soil and vegetation composition, and was stem-mapped completely

for all trees greater than 15 cm. (Hawk, undated). The list of trees, their species, coordinates, and dbh, by stratum, constituted the frame. An expanding sample was drawn within each stratum such that for sample sizes of 1, 2, 3, 6, 9, or 12 trees, one could estimate any collective property of the set of trees in the stratum. In the small-root, core-sampling phase, the sample size was two trees within the subset of trees consisting only of Douglas-fir. This tree-sampling structure was not implemented with regard to the other aspects of the studies here reported.

The sampling methodology was variable-probability systematic on the set ordered by dbh and with inclusion probability proportional to dbh. The estimator is of the form

$$\hat{T}_y = \sum_S y/\pi, \qquad (1)$$

where $\hat{T}_y$ is an estimator of T_y, the sum of the quantity y defined on the individual trees, over the set of trees in the stratum, where π is the inclusion probability for the sample trees varying from tree to tree and where $\sum_S$ indicates summation over sample trees.

In the root-core sampling phase, this formula was applied with y the estimated total biomass of fine roots in the polygon of occupancy of the selected tree, and the *quantity estimated* is the total biomass of fine roots in all the polygons occupied by Douglas-fir. This estimator is easily structured according to recognizable classes of the sampled roots.

Sampling Within Polygons

Sampling within the polygons of occupancy (Figure 2) followed a newly developed sampling method, the radial geometric sample (Overton, 1973b), which is described briefly as follows:

1. An occupancy polygon is described physically by the specification of chords from the center of the sample tree to the center of each neighbor tree. If each "chord" is bisected, and the perpendicular constructed at each bisection point, then the connected perpendiculars circumscribe the polygon of occupancy, such that the sample tree is closer to each point in the polygon than is any other tree. It is only necessary to record *azimuth* and *midpoint distance* for each "chord."
2. The sampling method is to take a sample at
   i. the midpoint,
   ii. half the distance from sample point to tree center, and
   iii. repeat ii until the indicated sample point is too close to the tree to obtain a sample.

   Because of the formal relation between the location of the successive samples, it is not necessary to record additional distances, but rather only the order of collection.

Advantages of this scheme are:

1. Ability to adjust easily to varying densities of trees, without undue additional sampling load in number of cores.

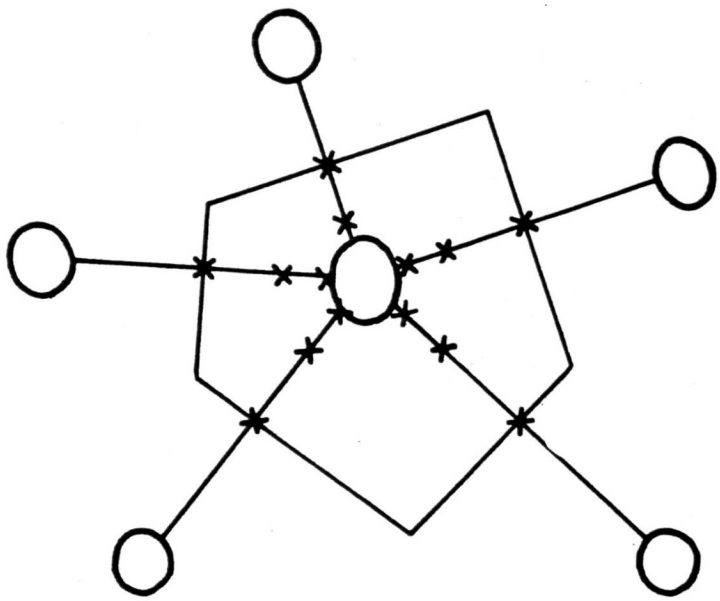

Figure 2. An illustration of an occupancy polygon and the sampling configuration used for sampling fine roots.

2. Freedom from tedious calculations in the field to adjust samples to plots of various size.
3. Compatibility with other methods of selecting trees, such as by the point-nearest-tree method.
4. Uniform density of sampling at distance from tree, regardless of polygon size (tree density).
5. In addition, there are several nice theoretical properties, which are described by Overton (1973b).

The estimating equation for total biomass of fine roots per polygon is:

$$\hat{y} = \frac{C}{m} \sum_{i=1}^{m} \sum_{j=1}^{k_i} w_{ij} y_{ij} \qquad (2)$$

where m is the number of chords along which samples are taken, y_{ij} is the weight in grams for the j^{th} core on the i^{th} chord, and w_{ij} is the weight

assigned to the observation y_{ij}, and is a function of the distance from the target tree to the sample point. C is a constant to yield the desired units of weight in y.

This quantity is then inserted into the equation for $\hat{T}_y$ to obtain an estimate of fine-root biomass for the watershed.

The Branch-Sampling Structure

The procedure for estimating biomass and other quantities of the set of branch systems included first an enumeration of all branch systems and a characterization of each by essentially occular means from a vantage point on the bole, close to the branch system. The method by which this was done has been described by Denison et al (1972), whose study provided the frame materials for the base for the study here reported.

Denison et al also selected a sample of five branch systems in each of several trees, the method of selection being variable-probability systematic, with branch systems ordered according to their height in the tree and with inclusion-probability proportional to an importance factor, which was a weighted average of several occular epiphyte and biomass values.

Of these five sample branch systems, we selected one with probability proportional to the index of foliar biomass, where the index was constructed from occular values from the initial branch-system characterization. This branch system constituted the sample taken for the present study, and was removed from the tree and taken to the laboratory for analysis.

Processing and Analytic Techniques for Fine Root Samples

Samples for estimates of fine-root biomass were taken in the occupancy polygons of 22 trees in accordance with a sampling scheme discussed earlier in this paper (Figure 2). Soil samples were taken at each sampling point with a steel core, 100 cm long and 5 cm in diameter. Preliminary checks showed 95-97 percent of fine roots to occur in the first 100 cm depth. Samples were removed from the core, put in a plastic bag, and brought into the laboratory for drying and weighing. Larger roots were picked by hand and the remaining roots separated from the soil by means of a South Dakota blower.

Analyses are not completed because separation of fine roots required far more time than originally anticipated. Preliminary analysis yields an arithmetic average of 2.37 grams of fine roots (less than 10 mm in diameter) per core, which converts to approximately 12 metric tons per hectare. Correlation with dbh of trees, strata and topographic features, and other characteristics are still to be worked up, as are the estimates of root biomass via the sampling equation. Completed analyses will be reported by Santantonio (M.S. Thesis, in preparation).

Measurement and Estimation of Roots on Excavated Root Systems

Root systems of three partially and recently wind-thrown trees were excavated for study of the biomass of individual root systems of old-growth

Douglas-fir trees. The ones selected represented three different types in regard to rooting depth. Tree No. 1 was deep rooted, tree No. 3 was shallow rooted, and tree No. 2 was intermediate in rooting depth between trees No. 1 and 3. None of these root systems showed any signs of root rot.

Correction for the portion of broken roots that had remained in the soil was accomplished by the following procedure. All broken roots with a diameter larger than 50 mm at the point of breakage were recorded by size. Roots with a diameter of less than 50 mm at the point of breakage were sampled within randomly selected squares, 40 by 40 cm in size, from a grid system established for sampling purposes, and the frequency of root size-class recorded. These sample frequencies were projected to estimate the total number of breaks over the whole range of diameter sizes for each root system.

To correlate diameter at the break with weight of the broken-off part, 216 intact roots, ranging in diameter from 2 to 190 mm, were cut from the cleaned root system and were measured for fresh weight and root diameter at the cut end. From these data, a correction factor was determined for broken-off roots on a fresh-weight basis. Details of the process, computation, and results will be given by Santantonio (M.S. Thesis, in preparation) and are summarized in Table 1.

Table 1. Results of the analysis of three root systems of old-growth Douglas-fir. Root system defined as part below litter line.

Measurement	Tree 1	Tree 2	Tree 3
Age, *years* (based on ring count at root-stem interface)	495	470	150
Dbh, *cm*	135	110	94
Height, *m*	67	64	58
Root fresh weight, *kg* (corrected for missing roots)	8,950	4,720	3,910
Amount of correction (fresh wt.)	1,180	832	435
Roots dry weight, *kg*	5,900	3,050	2,390

Processing and Analytic Techniques for Sample Branch Systems

Immediately after the sample branch was removed from the tree, it was dissected in the following sequence (Figure 3):

1. All branchlets were labelled with the number assigned to each when the branch was examined in the tree. The various parts of the branchlet retained this numbered identity during the entire dissection-and-analysis procedure described below.

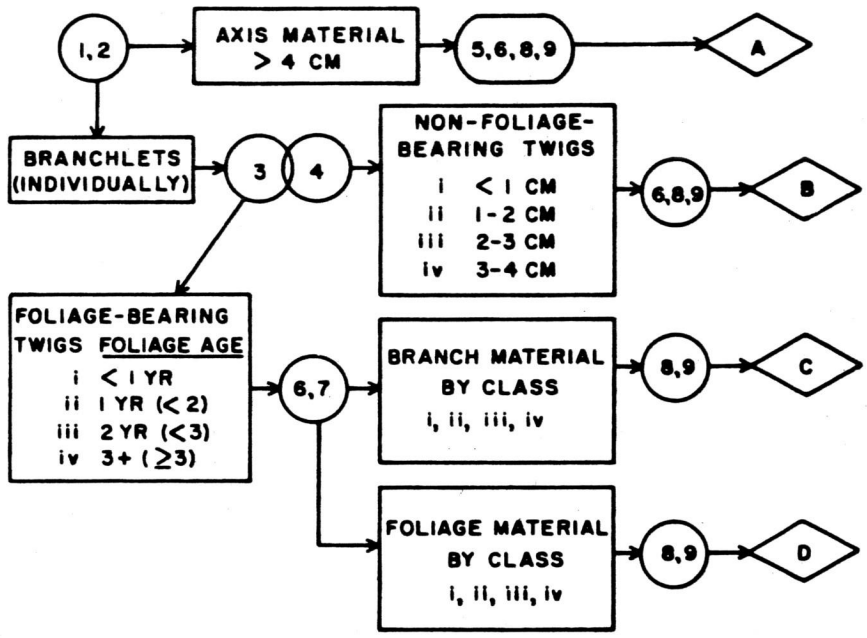

Figure 3. The flow of operations in destructive branch-processing and analysis. A, B, C, and D represent the four main classes of materials for which dry weights and chemical analyses were made, by indicated sub-classes. Classes B, C, and D are structured further by individual branchlets. The operations codes refer to the steps outlined in the text, and are summarized below:

1. Labeling branchlets
2. Dissecting
3. Dissecting
4. Dissecting
5. Labeling
6. Drying
7. Separating
8. Weighing and grinding
9. Chemically analyzing sub-samples.

2. Axis material, defined as branch sections greater than four cm in diameter, was identified and the branchlets were removed from the axes.
3. Each branchlet was dissected into twigs bearing current, one-year-old, two-year-old, and greater than two-year-old foliage, and non-foliage-bearing twigs.
4. The non-foliage-bearing twigs from each branchlet were dissected and the pieces sorted into the following diameter classes: less than 1 cm; 1-2 cm; 2-3 cm; and 3-4 cm.

5. The axis material was tagged to maintain the identities assigned in the tree.
6. All the above materials were placed in properly labelled paper bags and returned to the laboratory for drying to constant weight at 70°C.
7. The needles were separated from the foliage-bearing twigs.
8. All foliage classes and twig classes were weighed and the weights were recorded to the nearest one-tenth gram. All foliage, twig, and axis materials were then ground in a micro-Wiley mill to pass a 40-mesh screen.
9. Analyses for nitrogen, phosphorus, potassium, and calcium were made for each of the above tissue classes.

DISCUSSION

This paper has presented the methodology for estimation of biomass and nutrient capital in which the scope of the destructive element of analysis has been reduced greatly. The overall focus of the methodology is the integration of many diverse objectives into a tightly integrated scheme of sampling and estimation, within which each part depends on many other parts.

The basic advantage of such an orientation is provided by the simple consideration that much of the information required by one sampling objective (e.g., estimation of epiphyte biomass on a large tree) is also required by another objective (e.g., estimation of surface area of the tree). Thus, if all sampling methodologies are structured in a conventional manner, with well-defined variables, it is conceptually a simple matter to "hang" satellite sampling programs onto a basic program. Such is the nature of the destructive analysis of a single branch system from the study tree, 174. The estimates in Table 3 are constructed from the results of this analysis, and based on the data from the larger study, Table 2.

This design, of a single branch system taken per sample tree, does not admit estimation of sampling error on that tree. The design was not intended to be used in the context of estimation for the specific tree, but rather in estimation of stand totals, such estimates to be based on the sampling of 20-30 trees. In this context, the variation relevant to uncertainty of estimation is that variation from tree to tree, and the indeterminacy of estimation error for single trees is of no concern. Rather, one wishes to put all possible sampling power into the determination of the best possible estimates for the sample trees, with appropriate measures of precision for the stand.

The data presented in Tables 2, 3, and 4 represent estimates of the above-ground dry weight and nutrient content of one old-growth Douglas-fir tree. The results obtained by the above methodology for the three other sample trees demonstrate a similar pattern, but discussion of these values must be qualified by the fact that data obtained through analyses of the four trees are not sufficient to characterize old-growth Douglas-fir or even describe the

Table 2. First-phase estimation table for quantities relevant to second-phase sampling. These entries of the rows for Branch System 62 and $\hat{T}$ become the columns, x and $\hat{T}_x(1)$ of Table 3. These data were collected by Denison, et al, and are used here with their permission.

Branch system	Characterization phase: π	Characterization phase: Foliage index	First sampling phase: Axis volume	First sampling phase: Dead twigs	First sampling phase: Live twigs <1 cm	Live twigs 1-2 cm	Live twigs 2-3 cm	Live twigs 3-4 cm
23	0.20878	2.73750	0.09187	1,307	4,040	1,843	1,497	3,391
33	.18452	2.05313	.04702	0	3,113	1,225	2,400	1,485
62	.29244	2.73750	.03282	63	4,299	1,416	1,996	1,773
72	.01206	0.82125	.00409	0	1,028	99	409	1,014
97	.11919	0.82125	.03348	0	1,503	319	1,743	0
T:	5.00000	107.44688						
$\hat{T}$:		108.58692	1.42712	6,476	148,772	31,194	75,540	114,432

population on the experimental watershed. There are, however, two determinations that differ sharply from similar data recorded for younger Douglas-fir, and attention is directed to these.

1. Of the foliage, 61% was determined to be more than 2 years old. This is in strong contrast to data reported by Silver (1962), Mitchell (Russell G., personal communication, 1973), and Dice (1970), who noted that the majority of the foliage of Douglas-fir trees is less than 2 years old.
2. The nitrogen content of the foliage, by age, is substantially less than that generally reported for young-growth Douglas-fir foliage (Lavender and Carmichael, 1966; Lavender, 1970). The results of the analyses for the remaining elements are comparable to those reported elsewhere for second-growth foliage. We can present no explanation for the observed differences.

The nutrient data of Table 3 are badly imbalanced, with regard to precision, in consideration of totals over the tree. The data regarding nutrient percentages have roughly the same precision. When these are expanded by biomass of the various components, the variances are inflated by the square of the expansion factor. Thus, the nutrient estimates for foliage and twigs are roughly comparable in precision, the variance of the axis nutrients some 6 times greater, and the variance of the bole estimate of nutrients some 400 times greater than that for the axes.

These thoughts can be utilized in planning a follow-up study. The chemical analyses of the various segments should be structured in such a way as to obtain some degree of balance in the precision of estimated totals, if the objective is to estimate total nutrient capital.

Table 3. Estimates of total aboveground biomass (dry cut) and nutrient capital of tree 174. Note that the bole estimates are least accurate. The estimated volume of 43.697 cubic meters was expanded into weight by the assumed specific gravity of 0.44. Nutrient content of the bole was calculable from only two cores, at 5 and 30 ft. The other quantities in the table were derived from the destruction branch analysis (Figure 2) imposed on the data of Table 2. Branch system 62 was analyzed destructively.

Tree part	y	x	y/x	$\hat{T}_x$(1)	Weight $\hat{T}_y$(2)	Percentage by weight N	P	K	Ca	Weight N	P	K	Ca
					Gm	%	%	%	%	Gm	Gm	Gm	Gm
Bole	—	—	0.44×10^6	43.697	19.23×10^6	0.0440	0.0025	0.0265	0.0595	8,460	481	5,096	11,440
Axes	19,134.2	0.03282	—	1.42712	974,729	.144	.020	.086	0.442	1,404	195	838	4,308
Foliage													
< 1 yr	574.5	.	200.0	.	21,717	.83	.158	.99	0.40	180	34	215	87
1-2 yr	524.2	.	191.5	.	20,794	.87	.215	.67	0.89	181	45	139	185
2-3 yr	572.7	2.7375	209.2	108.5869	22,716	.86	.262	.89	1.10	195	60	157	250
3 + yr	2,542.7	.	928.8	.	100,856	.78	.282	.56	1.79	787	284	565	1,805
Sum	4,178.1	.	1,529.5	.	166,084					1,343	423	1,076	2,327
Twigs													
< 1 cm	2,237.4	4,299	0.52045	148,772	77,428	.326	.065	.303	1.103	252	50	232	854
1-2 cm	1,159.9	1,416	0.81914	31,194	25,552	.157	.027	.147	0.638	40	7	38	163
2-3 cm	1,489.3	1,996	0.74614	75,540	561,363	.129	.023	.126	0.582	73	13	71	328
3-4 cm	446.6	1,773	0.25189	114,432	36,381	.154	.024	.125	0.508	56	9	45	185
Dead	—	63	—	6,476	—								
Sum					192,725					421	79	389	1,530
					20,564,000		Totals for tree:			11,628	1,178	7,399	19,605

Table 4. Calculation of volume outside bark for Tree 174, Watershed 10, Andrews Experimental Forest. Data collected by Denison et al.

Bole section	Height where measured	Diameter	Method 1, Cylinder		Method 2, Frustrum of cone			
			Section length	Volume	Section length	D1	D2	Volume
	M	*M*	*M*	M^3	*M*	*M*	*M*	M^3
1	0	1.60	0.5	1.005	1	1.60	1.52	1.912
2	1	1.52	1.0	1.815	1	1.52	1.30	1.565
3	2	1.30	2.0	2.655	3	1.30	1.35	4.137
4	5	1.35	4.0	5.726	5	1.35	1.25	6.640
5	10	1.25	5.0	6.136	5	1.25	1.13	5.566
6	15	1.13	5.0	5.014	5	1.13	1.17	5.194
7	20	1.17	5.0	5.376	5	1.17	1.06	4.886
8	25	1.06	5.0	4.412	5	1.06	0.92	3.855
9	30	0.92	5.0	3.324	5	0.92	0.82	2.976
10	35	0.82	5.0	2.641	5	0.82	0.79	2.545
11	40	0.79	5.0	2.451	5	0.79	0.73	2.269
12	45	0.73	5.0	2.093	5	0.73	0.44	1.371
13	50	0.44	5.0	0.760	5	0.44	0.35	0.615
14	55	0.35	4.5	0.433	2	0.35	0.30[a]	0.166
TOTAL				43.841				43.697

[a]This value is extrapolated from the observed tops. The tree is broken topped, and no record was made of diameter just below the "terminal" branch system.

This point leads to a more general observation of our experience. With the various phases of the study being conducted by different and nearly autonomous groups of scientists and technicians, the problems of integrating working definitions and tasks, and of ensuring the flow of materials and data from one group to another, became acute. To illustrate, we can recount two examples. We intended that a bole core be taken at each measurement point, so that the profile of nutrients could be examined. Only two cores showed up at the laboratory. After drying and weighing, some samples of axis material apparently were misplaced on the way to chemical analysis. These, and other similar problems, can be credited only to insufficient attention at the planning and supervisory levels. The more sophisticated and intricate the procedure, the more critical become problems of this sort.

Although lack of funding forced termination of the present study far short of the initial goal (that is, estimation of the biomass of the old-growth trees on an experimental watershed in the Oregon Cascade Mountains) the work reported here does demonstrate two significant points.

1. Properly planned, sophisticated sampling techniques may greatly reduce the effort expanded in ecological studies, even when the experimental

material is as large and complex as an old-growth Douglas-fir.

2. Advance planning permits integration of data from several parties investigating different phenomena to support an entirely different investigation. Detailed advance planning, however, is necessary to assure that all relevant data, recorded on standard forms, are present if such projects are to be conducted effectively.

ACKNOWLEDGMENTS

Many people contributed to the collection and analysis of the data utilized in one manner or another in this paper. The data on which Tables 2 and 4 are based were collected by the project headed by W. C. Denison. Kim Isles and Dean Stuck, under John Bell, made the initial steps of the branch-system analysis, and Richard Stratton and Al Doerksen the final stages and chemical analyses (Table 3). Dan Santantonio collected and analyzed the fine roots and the large-root systems (Table 1). Greg Luckini and Jonna Gourley conducted the computer analyses.

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REFERENCES

Denison, William C., Diane M. Tracy, Frederick M. Rhoades, and Martha Sherwood. 1972. Direct, Nondestructive Measurement of Biomass and Structure in Living Old-Growth Douglas-Fir. In Proceedings-Research on Coniferous Ecosystems - a Symposium. Edited by Jerry F. Franklin, L. J. Dempster and Richard H. Waring. U.S. Dept. Agric., Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 322 p.

Denison, William C. 1973. Life in Tall Trees. Scientific American 228(6):74-80.

Dice, Steven Farnham. 1970. The Biomass and Nutrient Flux in a Second Growth Douglas-Fir Ecosystem (A Study in Quantitative Ecology). PhD. Thesis. University of Washington. 165 p.

Hawk, Glenn M. (undated). Vegetation and Stem Mapping of Watershed 10, H. J. Andrews Experimental Forest. Coniferous Forest Biome, Internal Report 97. 36 pp. + appendix.

Lavender, Denis P. 1970. Foliar Analysis and How It Is Used: A Review. Research Note 52. Forest Research Laboratory, School of Forestry, Oregon State University, Corvallis. 8 p.

Lavender, D. P. and R. L. Carmichael. 1966. Effect of Three Variables on Mineral Concentrations in Douglas-Fir Needles. Forest Science 12(4):441-446.

Overton, W. S. 1973a. An Expanding, Variable-Probability Sampling Scheme for a Multiple-Objective Survey, With Specific Orientation to a Survey of the Properties of an Old-Growth Forest. (Manuscript in preparation.)

Overton, W. S. 1973b. The Radial Geometric Sample for Occupancy Polygons of Forest Trees. (Manuscript in preparation.)

Silver, G. T. 1962. The Distribution of Douglas-Fir Foliage by Age. Forestry Chronicle 38(4):433-438.