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METHODS EMPLOYED IN FOREST NUTRIENT CYCLING STUDIES AT CEDAR RIVER

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Introduction and Definitions

Forests generally grow in present land use patterns on soils with limited amounts of essential elements. Therefore, cycling of nutrients within a forest ecosystem is important to the continuous production of organic matter. Understanding the details of forest elemental cycles is now almost a necessity for forest management and adherence to forest practice laws. Even so, reasons for studying nutrient cycles vary considerably, and thus the intensity of data collection and the methods employed will vary accordingly. This paper will present descriptions of procedures developed at the College of Forest Resources over fifteen years of research with the expectation of further development and standardization.

The study of nutrient cycling encompasses many fields of research including tree nutrition, tree physiology, soil science, succession, stand structure, and hydrology. Much of the present terminology is vague and for clarification definitions are given below. The first definition involves the concept of the "complete" nutrient cycle. This cycle can be defined as a combination of the biological and geochemical cycles. The biological cycle is relatively closed and is composed of:

(a) uptake or absorption by plants.
(b) return or restitution of nutrients from the plants to the forest floor or soil.
(c) redistribution or translocation of nutrients within the vegetation.
(d) retention or storage of nutrients within the nutrient pools; these pools being grouped under the major classifications of soil, trees, understory and forest floor.

The geochemical cycle is relatively open and involves the input and output of nutrients in relation to the forest ecosystem. Input includes precipitation, dryfall, weathering, animal inputs and fertilization while output includes leaching, erosion, animal losses and cropping. This cycle is considered as a nutrient budget in opposition to the short-term process or mechanism studies in which specific nutrient transfers are studied.

Relationships of these components can be shown as in Fig. 1 (a) from Cole et al. (1968, 1973). Main pools and transfers are indicated in these diagrams and two or more ecosystems can be compared. A major omission in these earlier conceptualizations was that of total soil nutrient amount largely because of the great size of this pool. A relatively simple nutrient cycling diagram was developed by Switzer and Nelson (1972) while a more detailed diagram in which all individual transfers are listed was used by Curlin (1968). Curlin's diagram shows the biological cycle but does not show the inputs and outputs of the geochemical cycle or the understory component.

Using Fig. 1 for reference, further details of the nutrient cycle will be given. As nutrient cycling is time dependent, units discussed for transfers are mass per unit area per unit time (kg ha^{-1} hr^{-1}) while pools are mass per unit area (kg/ha).

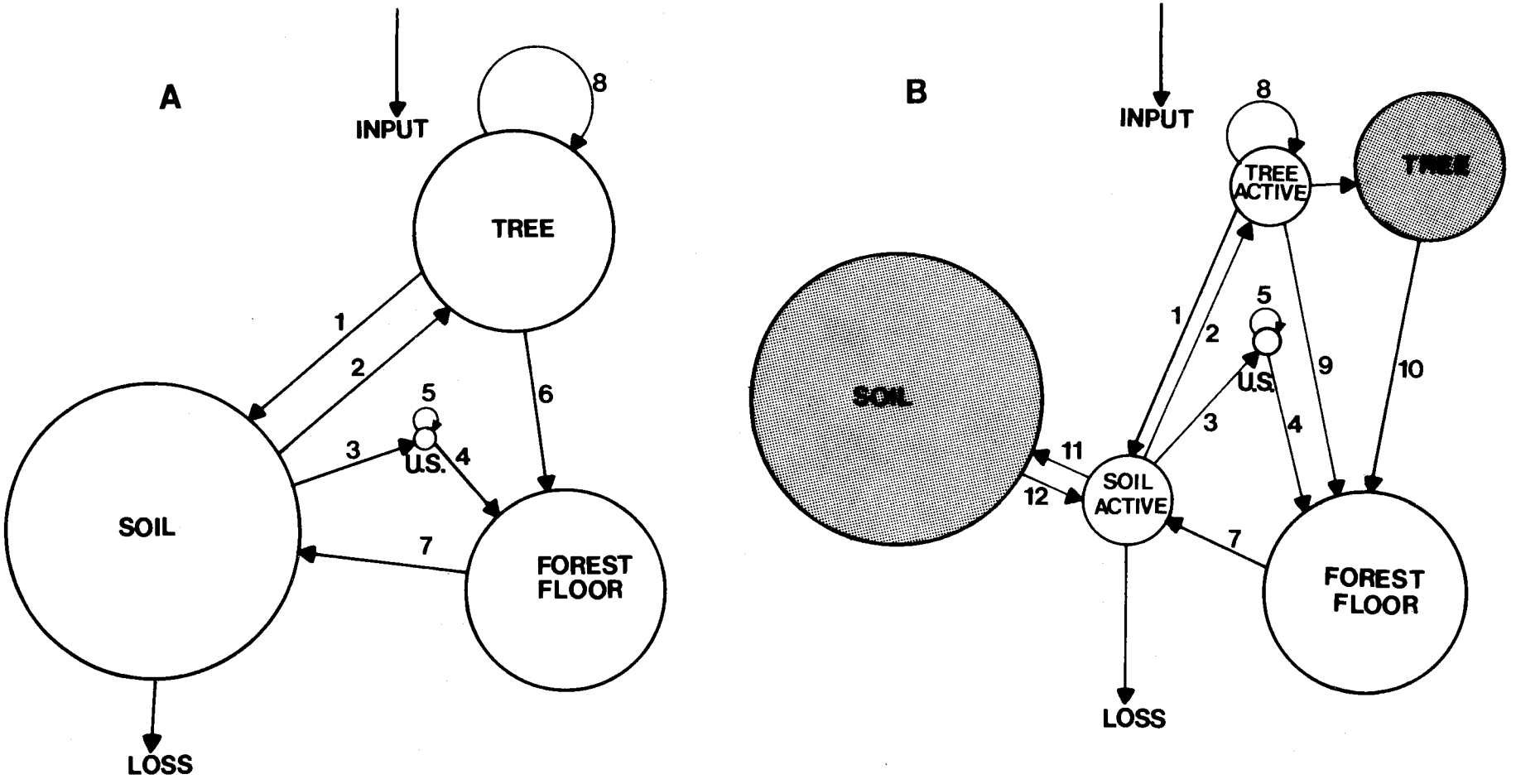

Figure 1. Conceptual models of nutrient cycling in forest ecosystems. A is modified from Cole et al. (1973) and shows total pools and transfers while B subdivides the pools into active (in same time period) and storage (shaded). The transfers are: 1 - root loss, 2 - tree uptake, 3 - understory uptake, 4 - understory loss, 5 - understory redistribution, 6 - return to forest floor (stem, litter, throughfall, stemflow), 7 - forest floor loss, 8 - tree redistribution, 9 - tree return to forest floor (active), 10 - tree return to forest floor (storage--mainly stem), 11 - soil fixation, 12 - soil mineralization.

Retention is defined as the storage of nutrients within a nutrient pool or component. How a component is defined depends upon the aim of study so that the four previously listed pools (tree, understory, forest floor and soil) in Fig. 1 may be subdivided into smaller components. The tree pool could be:

tree pool = foliage + branch + trunk + roots

thus, dividing the tree into relatively uniform tissues. Each of these components may be further subdivided. For example:

total tree foliage = 1 year foliage + 2 year foliage + 3 year foliage . . . etc.

and,

trunk = bark + 1 year wood + 2 year wood, etc.

Total soil is commonly shown as nutrients in (0-5 cm) depth, etc., but could be shown according to extraction techniques (and dissolution) or by specific soil horizons (A_0, A_1, A_2, B_1, etc.).

Return or **restitution** is defined as the return of nutrients to the forest floor and soil and is the sum of total plant organic return (litterfall, root loss, etc.), throughfall, stem-flow and return from animals. Each of these can again be subdivided both for better understanding and convenience. The total restitution is measured as the sum of separate size classes divided essentially according to convenience of measurement. This can be illustrated by Fig. 2, which shows that the various proportions depend upon the stand being studied.

Redistribution within the tree and understory is defined as the removal of nutrients from one part of the plant to another. This generally involves removal from older to younger tissue but may represent removal from wood to needles. The poorly understood role played by root grafting could probably be included here.

Uptake is defined as nutrient absorption by vegetation from the soil via roots and absorption from rainfall and dryfall via foliage.

Requirement is defined here (from Switzer and Nelson 1972) as the amount of nutrients accumulated in current tissue. In many past studies, because nutrient retranslocation was ignored, requirement, as measured by the amount of nutrient in the current tissue, was equated with uptake.

Methods of Data Collection

Measurement of the previously described nutrient pools or transfers requires the estimation of a mass (either organic matter or water) and the nutrient concentration of the mass, that is:

nutrient content = mass x concentration

The accuracy of measurement of nutrient content is related to the variability of the component that is being measured and the precision of measurement techniques. For example, to estimate the nutrient content of the foliage of Douglas-fir, the variation in nutrient concentration, age, position in the crown, season and the dominant position of the tree should be taken in account (Turner et al. 1977).

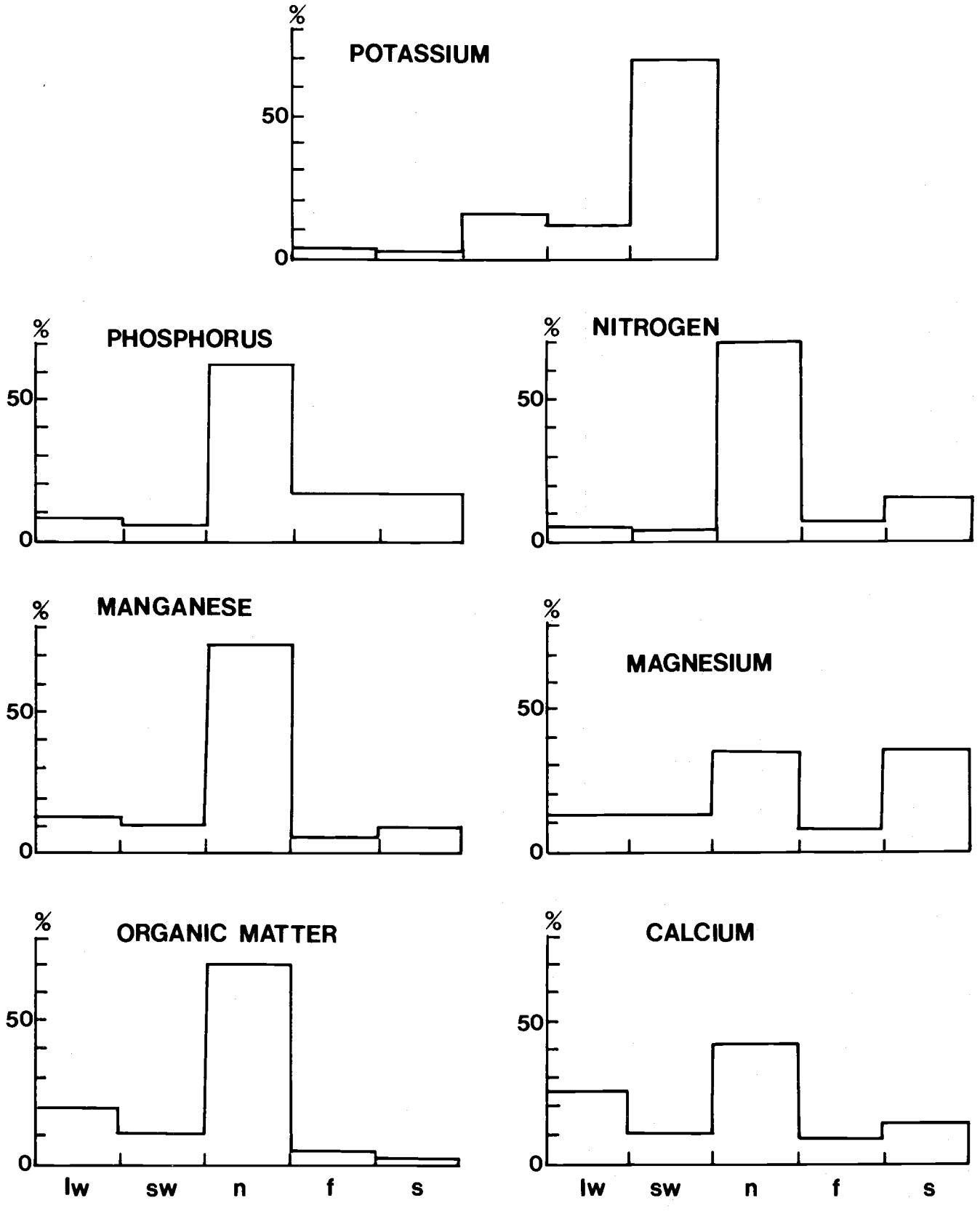

Figure 2. The proportion of nutrients returned to forest floor by various agents these being, lw = large wood, sw = small wood, n = needles, f = fine material and s = solution. The stand used was 30-year-old Douglas-fir.

The estimation of nutrient concentrations depends on specific laboratory procedures for each element. The nutrients emphasized in the coniferous Forest Biome studies are N, P, K, Ca, Mg, Mn, S and C. Mass is usually determined by drying and weighing but in the case of large tree systems, various kinds of mensurational estimates have been developed.

Nutrient Pools

The critical problems in measuring nutrient budgets are associated with obtaining sufficient levels of resolution of the component quantities, sample variability and rates of change. A summary of the methods used to determine these parameters is below.

1. Tree biomass. Part of the problem of tree biomass estimation has been discussed by Turner and Cole (1973) and many of the relevant references are included there. Two important questions are, what is the biomass of the various tree components per unit area and how fast is it changing with stand development? A plot of known dimensions with each tree measure for total height and "diameter breast high outside bark" (dbhob) needs to be established to secure necessary data. These measurements are used to determine size and number of sample trees to be used for estimation of biomass, according to alternative methods.

i. Mean of model tree approach in which a tree of mean dimensions is felled and weighed. This tree mass is converted to biomass per unit area by multiplying by the number of stems per unit area. The principal problem is to decide what constitutes a tree of mean dimensions (i.e., mean dbhob, height, BA, etc.), since a tree of mean diameter may not be the tree of mean biomass.

ii. Stratified mean tree method involves stratifying the stand in some way, usually by size classes or species, and then selecting one or more trees from each strata, usually the mean-sized tree of the strata. These results are converted to biomass/unit area by either multiplying each strata by the number of trees, adding the strata or by basal area allocation.

iii. Total area cropping involves removing and weighing all the trees from some known area. This generally is used to test other methods as it precludes any further studies on that specific site. This method has been used twice in the Cedar River watershed by Dice (1972) to test Douglas-fir biomass equations and by the present authors to study alder biomass equations.

vi. Regression technique (erroneously called "allometric relations") is the most commonly used technique whereby a range of tree sizes is cropped and regression equations relating the weight of some components to a simple parameter such as dbhob are calculated. For examples of equations for use in Douglas- see Dice (1970). Use of this method does not disturb the study area and by periodic remeasurement, biomass changes can be followed. Error estimates associated with regression can be made using this technique, whereas no error estimates are possible for the previous methods.

2. Understory biomass. The understory biomass can be estimated by unit area clipping techniques of plots located randomly or systematically. The sample can then be sorted into species and components (leaves, woody tissue, etc.). Error because of consumption by animals can be avoided by fencing.

3. Forest floor weight. The forest floor mass (i.e., the weight of organic matter over the mineral soil) is estimated by collection of standard size units. The samples from the floor are then sorted into various components such as wood, leaves, humus, etc. With large quantities of wood (dead stems) on the forest floor, it has been the practice to establish larger (9 m) plots to estimate this specific component. In some cases the forest floor samples have been sorted to remove moss, and these samples used to estimate moss biomass. This is sometimes easier than using the regular understory plots as moss is often well integrated with the forest floor organic matter. The sampling procedure to estimate forest floors should be established in relation to the specific study purposes.

4. Soil. Soils may be sampled either from pits or by coring with various types of augers. Pits are frequently preferable if time and expense allows because of the opportunity for better descriptions and more complete sampling of the soil profile. Surface soil cores are useful for determination of variability if a pit is the principal sampling point. Both density and gravel content need to be determined for each horizon sampled in order to convert elemental constituents to a weight-area basis. For specific soil sampling details, the reader should refer to soils books or ask advice from soils experts.

In the case of all sample components considered, the desired end result is estimates of total weight in the ecosystem. Securing of this number generally means laboratory preparation computation. These procedures are not addressed in this publication and the reader should refer to other publications or experts for advice.

Nutrient transfers

The estimation of nutrient transfers involves measuring increases or transfers of biomass, the movement of water within the system and the nutrient concentrations of these carriers. The methods are illustrated in Fig. 3.

Litterfall is estimated from litter traps of known dimensions of 45.7 $cm^2$and underlain by fine mesh to allow water to percolate through. Very fine material in litterfall is lost from these traps and must be determined by other menas. From the trap small litter can be collected and sorted into various components (needles, branches, cones, etc.). Collection should be on at least a monthly basis. The shorter the interval the less will be lost by leaching and the better will be the relationship to specific events such as high wind. Larger litter such as tree trunks can be determined from the growth plot data.

Understory litter return generally requires indirect methods. Annuals and geophytes are assumed to all return as are the leaves of the deciduous species. Corrections for weight loss during senescence will be necessary. For perennial species such as ferns, only a small proportion of the standing biomass is assumed returned each year, e.g., if moss or fern frond life is four years, one quarter of the

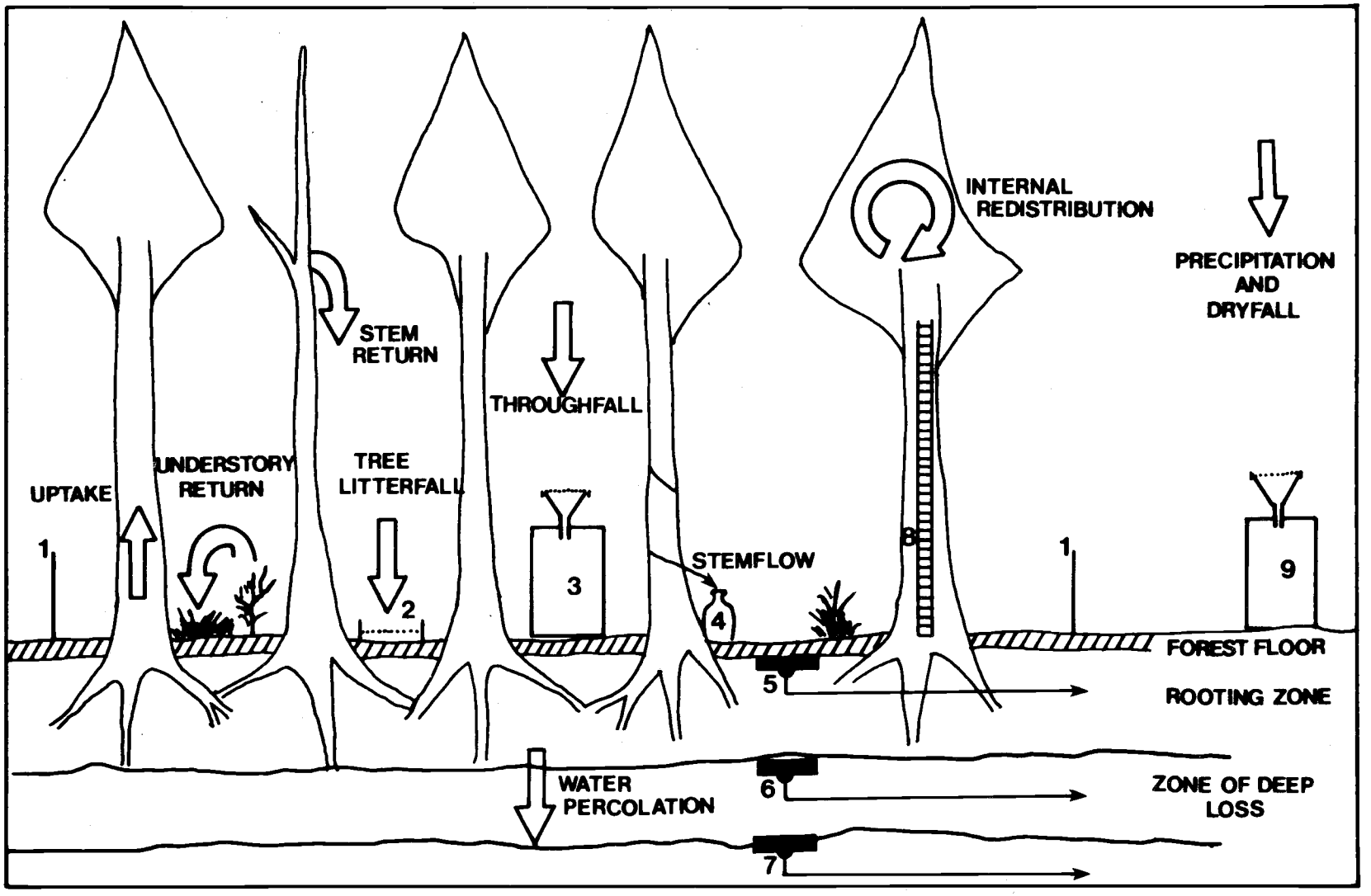

Figure 3. Schematic diagram of data collection for a forest nutrient cycling budget. Main transfers are named on the diagram. Numbers denote a method of collecting the transfers: 1 - plot boundary (tree tally), 2 - litter trap, 3 - throughfall collector, 4 - stemflow, 5 - forest floor lysimeter plate, 6 - rooting zone lysimeter plate, 7 - deep loss lysimeter plate (the lysimeter plates being used for leachate collection), 8 - ladder for tissue collection for uptake and internal redistribution (understory is also sampled), 9 - input collectors.

biomass is assumed returned each year. These methods can be sumarized:

a. Large woody material ——— growth plot

b. Tree needles (green and brown)
cones
branches
lichen
fires
——— litter traps - lower limit of fine material related to trap mesh

c. Understory annuals, geophytes, and deciduous

d. Understory perennials

e. Understory mosses

——— indirectly from biomass estimates

Throughfall and stemflow are collected in containers as described by Cole and Gessel (1968) with the addition of a fine mesh (the same mesh as the litter trap) over the throughfall funnel.

Movement through the forest floor and soil can be monitored using lysimetric methods (Cole and Gessel 1968). Optimally this would also include a watershed approach or deep tubes to estimate total system loss. Input from rainfall can be monitored using standard collectors with wet-dry collectors for dust input.

Further studies, for specific processes, may include forest floor decomposition studies (possibly using litter bag weight loss).

Within tree processes

Uptake and within tree process measurements provide other problems. Either can be utilized without the direct methods such as radio-isotopes or indirect methods such as mass balance. The method employed at Cedar River was to estimate tissue mass and nutrient concentration by age classes. The nutrient content of the current tissue was then classified as requirement for new growth. Requirement represents uptake and retranslocation so that by estimating nutrient removal from older tissue, and taking into account loss by leaching, a coarse estimate of retranslocation was made. By difference, uptake was estimated. The synthesis of all this data on a yearly basis will give the budget of the nutrient cycle for an ecosystem.

Utility of Methods

Collection of sufficient data to establish an annual nutrient cycle requires a great deal of work and organization. Generally a progressive scheme for collection of data in stages works best. An example follows:

(1) The first stage of study is to monitor the nutrient budget within a plot for several years to estimate annual variation or other systematic changes. Over a much longer period of time (10^{+} years), the details of stand development can also be accumulated. Knowledge of annual and systematic variation helps to understand the data in comparison to other sets.

(2) Within the intensive plot, further intensive studies can be carried out to understnad specific mechanisms (such as soil nutrient leaching or proportion of return by insects).

(3) A further development involving both (a) large woody material and (b) tree needles is the manipulation of the forest stand, for example by fertilizer application, thinning, irrigation, clearcutting, and underplanting.

(4) Another extension of data collection process is the applicability of intensive site studies to other locations. This will mean studying stands in other locations, different ages, site qualities, densities and species. the alternatives for study are to have a series of intensive plots or have a lot of less intensive plots or a mixture of both.

An alternative method of laying out a nutrient cycling study is to consider a series of stages. The stages, with parameters to be established are:

Stage 1: Nutrient Distribution

Requirements are a study plot which is tallied for dbhob and height. Preferably a growth plot with a past history is used, otherwise increment cores are taken. The environment, species, age and site quality of the stand are described. Stand biomass is determined, generally by regression and tree samples by tissue age class are taken for nutrient content. Biomass is estimated and samples are taken as the need arises. The end result can be put in tabular form of distribution as shown in Table 1.

Stage 2: Organic Transfers

Essentially the estimation of organic matter transfers involves plot remeasurement, litter trap collections, and estimation of understory losses and growth in previously described methods.

Stage 3: Water Movement

The movement of water above ground can be estimated in the form of throughfall, stemflow and precipitation and involves relatively simple equipment.

Stage 4: Monitoring Water Movement

Soil water movement can be monitored using lysimeter plates, stand tubes and/or a watershed. To maintain a study of this level requires a full-time technician.

By stage 4, a fairly complete cycle can be otained. To develop the cycle even further would involve specific studies such as root studies, decomposition estimates or radio-isotopes. Actual figures are shown in Figure 4.

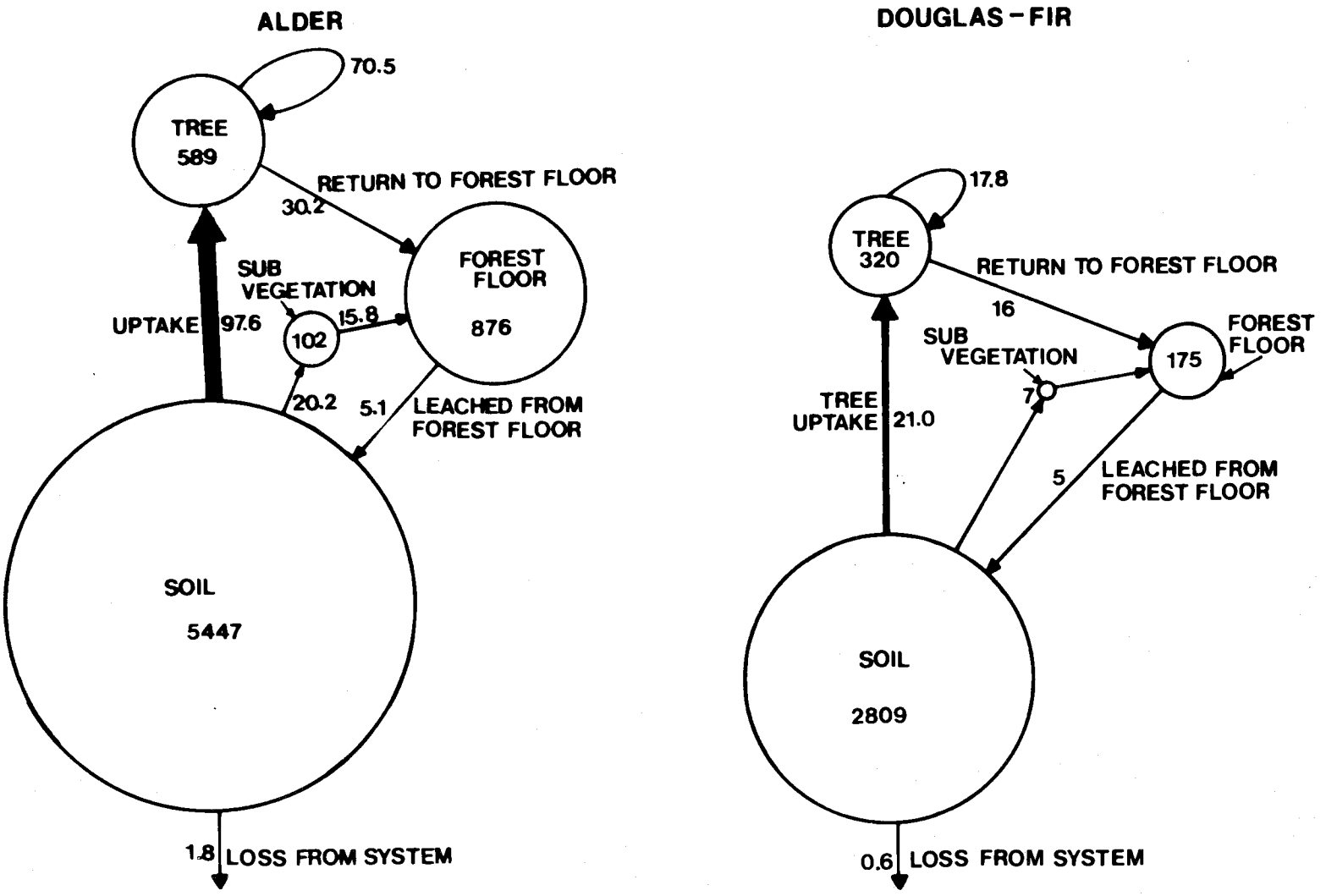

Figure 4. Comparison of an alder and Douglas-fir ecosystem in regards to the accumulation and cycling of nitrogen. Area of circles are proportional to size of nutrient pools. Values are expressed in kg ha^{-1}. Rates are for a period of one year.

Table 1. Ecosystem nutrient distribution summary sheet.

#_____

Location:
Species:
Age (year):
Density (St/ha):
Mean DBHob (cm):
Height (M):
Basal Area (M^2/ha):
Altitude (M):
Rainfall (cm):

Temp ^oC:

Biomass and nutrient distribution (kg/ha):

Tree	Biomass	N	P	K	Ca	Mg
foliage-current						
-older						
cone						
branch						
total crown						
stem wood						
bark						
Total tree						
Root						
Understory - Vascular						
- non-vascular						
Forest Floor						
Soil 0-5						
5-20						
10-50						
50+						
TOTAL:						

COMMENTS:

Calculations

Tree Nutrient Content

Foliage

(a) year one biomass x nutrient concentration
(b) year two biomass x nutrient concentration
(c) year three biomass x nutrient concentration
(d) year four biomass x nutrient concentration
(e) total foliage = Σ (a) + (b) + (c) + (d)

Branch

(f) current biomass x nutrient concentration
(g) older biomass x nutrient concentration
(h) total branch = Σ (f) + (g)

Stem

(i) bark biomass x nutrient concentration
(j) current wood biomass x nutrient concentration
(k) older wood biomass x nutrient concentration
(l) total stem = Σ (i) + (j) + (h)
(m) root biomass x nutrient concentrations
total tree (above ground) = Σ (e) + (h) + (l) + (m)
(if root are available)

Understory nutrient content

(n) Biomass species 1, 2, 3... x nutrient concentration species

1, 2, 3, ... respectively

Forest floor and soil nutrient content

(o) As for tree but the components are large wood, small wood, leaf, humus, etc.

Transfers

Litterfall nutrient content

(a) Mass leaf litter x concentration leaf litter;similarly for wood, cones, fine material.

Throughfall and stemflow nutrient return

(b) Volume of water in throughfall collector 1 x nutrient concentration of water = mb/area of collector and then adjust this to the square meter and then caclulating the mean of all collectors.

(c) Stemflow contribution is calculated by multiplying water volume by concentration. This is converted to a square metre basis by basal area allocation, i.e., estimating the basal area of the trees with stemflow collectors and proportioning this in relation to the basal area per hectare.

Transfers internal to the tree

(d) Requirement is the nutrient content of the current tissue of the tree.

(e) Redistribution is calculated by estimating the reduction (or increase) in concentration as the tissue ages. That is, if M_1 = mass of current tissue, M_2 is one year old, etc. and C_1 = concentration of current tissue and C_2 is concentration of one year old.

M_1C_1 = nutrient content of current tissue

M_1C_1 = nutrient content of one year tissue

M_1C_1 = nutrient content of two year tissue

At the end of one year the current tissue concentration will have changed to C_{11}, as the one year to C_{21} the two year to C_{31}. Current tissue generally increases in concentrations until stabilized (possibly the receiver of redistributed nutrients, to the extent that it is usually the older tissue which redistributes, and thus is $M_2(C_2-C_{21}) + (C_3-C_{31}) + \ldots$).

(f) Uptake = requirement = redistribution adjusted for loss by litter or throughfall. A decision has to be made as to whether throughfall is leaching or the washing off of dust.

LITERATURE CITED

Cole, D. W., and S. P. Gessel. 1968. Cedar River Research - A program for studying pathways, rates and processes of elemental cycling in a forest ecosystem. For. Resources Monog. No. 4. Univ. of Washington, Seattle. 53 p.

Cole, D. W., S. P. Gessel, and S. F. Dice. 1968. Distribution and cycling of nitrogen phosphorus, potassium, and calcium in a second-growth Douglas-fir ecosystem. IN: H. E. Young (ed.), Primary productivity and mineral cycling in natural ecosystems. p. 197-213. (AAAS Symp.), Univ. of Maine Press, Orons. 245 p.

Cole, D. W., S. P. Gessel, and J. Turner. 1973. Elemental cycling and even-age forest management. IN: R. K. Hermann and D. P. Lavender (ed.) Even-Age Management, Oregon State University, Corvallis, Ore. 250 p.

Curlin, J. W. 1968. Nutrient cycling as a factor in site productivity and forest fertilization. IN: C. T. Youngberg and C. R. Davey (ed.) Tree Growth and Forest Soils. p. 313-326. Third N. Amer. Forest Soils Conf. 527 p.

Switzer, G. L., and L. E. Nelson. 1972. Nutrient accumulation and cycling in Loblolly pine (Pinus taeda L) plantation ecosystems: the first twenty years. Soil Sci. Soc. Amer. Proc. 36:143-147.

Turner, J. and D. W. Cole. 1973. A review of forest biomass accumulation. Coniferous Forest Biome Internal Report No. 56.

Turner, J., S. F. Dice, D. W. Cole, and S. P. Gessel. Variation of nutrients in forest tree foliage - A review. Coniferous Forest Biome Internal Report No. 166.