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Elemental transport changes occurring during development of a second-growth Douglas-fir ecosystem

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Abstract

Mineral cycling processes in a second-growth Douglas-fir ecosystem have been monitored for nearly 10 years at the A. E. Thompson Research Center in western Washington. In this interval, substantial year-to-year differences in quantities of elements transferred have been observed. For example, a comparison of transfers during the 1964-65 and 1970-71 measurement years showed that input of calcium by precipitation increased roughly 300 percent while calcium transfer by throughfall, stemflow, and leaching from the forest floor increased roughly 600 percent, 350 percent and 220 percent, respectively. In the same interval, the mass and elemental content of the standing crop increased roughly 15 percent while forest floor mass and elemental content remained constant. A portion of this difference is related to the increased mass accumulated in the standing crop. However, the major factor causing this large difference is climatic variation. These differences in elemental transfer indicate the need for continuous observation of transfer processes to resolve the effects of ecosystem development on mineral cycling against this background of climatic variation.

Introduction

The growth and development of a coniferous forest ecosystem does not normally occur in a steady linear fashion. Rather, intervals of rapid stand growth may be interrupted by periods of slower growth reflecting changes in growing conditions. In turn, the cycling of elements within a forest ecosystem can be expected to reflect these changes.

Intensive study of the mineral cycling processes in second-growth Douglas-fir stands has been in progress at the A. E. Thompson Research Center since 1961. During this time, a substantial body of information has been collected concerning the amounts, pathways, rates of transfer, and mechanisms controlling transfer of elements by the mineral cycling processes of this ecosystem. Between 1961 and 1966, research was concentrated largely on detailed descriptions of ecosystem components (Cole, Gessel, and Dice 1967).

Research at the Thompson site since 1966 has had two major objectives: (1) to provide information describing the changes in mineral cycling processes as the stand grows and (2) to examine the year-to-year variation in mineral cycling processes. More recently, a third objective has been to examine the relationships between climatic factors and the various mechanisms controlling rates of transfer along the different transfer pathways.

During the course of research at the Thompson site, a number of changes in the patterns of elemental cycling have been observed. Some of these changes are related to changes in the structure or mass of the ecosystem; other changes are related to short-term variations in climatic factors. The purpose of this paper is to examine several of the changes in mineral cycling processes as they have been observed during the 10 years of research at the Thompson Research Center.

Experimental Area

These studies were conducted at the A. E. Thompson Research Center, an area specifically developed for the study of elemental cycling in second-growth Douglas-fir stands. It is located about 64 km southeast of Seattle, Washington, at an elevation of 215 m in the foothills of the Washington Cascades. A full description of the geology, soils, vegetation, and climate is given by Cole and Gessel (1968).

The study site is located on a glacial outwash terrace along the Cedar River. This outwash terrace was formed during the recession of the Puget lobe of the Fraser ice sheet about 12,000 years ago.

The soil underlying the research plots is classified as a typic haplorthod (U.S. Department of Agriculture 1960) and is mapped as Everett gravelly, sandy loam. This soil contains less than 5 percent silt plus clay and normally contains gravel amounting to 50-80 percent of the soil volume. The forest floor is classified as a duff-mull (Hoover and Lunt 1952) and ranges from 1 cm to 3 cm thick. This forest floor represents the accumulation since 1931 when the present stand was established following logging (around 1915) and repeated fires.

The present overstory vegetation is a planted stand of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) which was established about 1931. Currently, the trees average about 19 m high with a crown density of about 85 percent.

The principal understory species are salal (*Gaultheria shallon* Pursh), Oregon grape (*Berberis nervosa* (Pursh) Nutt.), red huckleberry (*Vaccinium parvifolium* Smith), and twinflower (*Linnaea borealis* L. ssp. *americana* (Forbes) Rehder). Various mosses are the principal understory vegetation beneath the denser portions of the canopy.

The climate is typical of foothill conditions in the Puget Sound Basin. Temperatures have ranged from −18° C to 38° C, but these extremes are seldom reached. The average temperature for July is 16.7° C and for January is 2.8° C. The average annual precipitation is 136 cm, almost all falling as rain. Precipitation rates are generally less than 0.25 cm/hour and over 70 percent falls between October and March.

Field Plots

The facilities at the research site are designed to provide precision measurement of the flux of elements within this forest ecosystem. Some transfers are monitored continuously; others, with less potential for rapid change, are measured at regular intervals. A detailed description of the collection facilities at this site is given by Cole and Gessel (1968). The following section will briefly describe these facilities with emphasis on recent changes in the system.

Sampling

Precipitation collections are made at two locations in the stand. One collector is at the top of a 30-m tower and is fitted with a flowmeter; the other is an automatic collector (Wong Laboratories) which opens at the onset of precipitation and is mounted on a 10-m tower in a clearcut adjacent to the plots.

Canopy drip (foliar leaching) is collected in six randomly located screened funnels mounted in the necks of collection flasks. Stemflow is diverted from the stem of the six sampled trees at breast height (1.35 m) by soft rubber collars and is collected in covered 160-liter polyethylene trash cans. Litter is collected on eight randomly located 0.21 m^2 plastic litter screens. Leaching through the forest floor and soil is measured using the tension lysimeter system developed by Cole (1968). This system permits direct measurement of the flux of ions through the soil. In this plot, 3 lysimeters per soil horizon are located in the soil at the base of the forest floor, at the base of the A_1 horizon (4 cm) and B_2 horizon (30 cm) and at 100 cm in the C horizon.

Instrumentation

Meteorological measurements including air and soil temperature profiles, are made on a continuous basis utilizing a data logging system. Details of this instrumentation are given by Cole and Gessel (1968).

The data logging system also permits the continuous monitoring of the pH and conductivity of water moving through this ecosystem. These facilities are described by Cole (1968). Volumes of water flow between different components of the system are measured using the resistance flowmeter described by Cole (1968).

Chemical Analysis

Analytical methods used on samples from this site have changed over the years. For methods used in earlier studies, the reader may consult the following reports: Rahman (1964); Cole and Gessel (1965); and Cole, Gessel, and Dice (1967). The methods currently in use will be briefly described in the following paragraphs.

Water Analysis

Determinations of calcium, magnesium, potassium, and sodium are normally made directly on water samples using an Instrumentation Laboratories-353 atomic-absorption spectrophotometer. Calcium is determined in a nitrous oxide-acetylene flame; and magnesium, potassium, and sodium are determined in an air-acetylene flame. Nitrogen and phosphorus are determined from a hydrogen peroxide-sulfuric acid digest (Linder and Harley 1942) of a 10-fold concentration of the solutions. Nitrogen is determined using a micro-Kjeldahl distillation (Jackson 1958). Phosphorus is determined using the chlorostannous-reduced molybdophosphoric blue color method of Jackson (1958). Total ion concentration is estimated from specific conductance using an empirical method (Logan 1961) and pH is determined instrumentally using established methods. Further details of water analysis are given by Grier (1972).

Soil Analysis

Total soil nitrogen is determined using the standard Kjeldahl digest and distillation of Jackson (1958). Cation exchange capacity is determined using the neutral ammonium acetate leaching method (Jackson 1958). Exchangeable cations are determined spectrophotometrically from the ammonium acetate leachate. Soil carbon is determined instrumentally using a Leco carbon analyzer. Phosphorus is extracted from the soil by digestion in 36 N sulfuric acid and 30 percent hydrogen peroxide; concentrations are then determined following the same procedures as for water samples.

Tissue and Forest Floor Analysis

Elemental assays of forest floor and plant tissue are done using methods described by Grier and McColl (1971).

Results and Discussion

Table 1 shows how organic matter, calcium, potassium, nitrogen, and phosphorus were distributed among different components of the ecosystem at the Thompson site at the end of 1965 (Cole, Gessel and Dice 1967). Since the time of this determination, transfers between these various components have been monitored to assess the changes and rates of change of elemental distribution in the stand.

In the interval between 1966 and the present, the volume of woody tissue in the stand has increased by an average of 11 $m^3/ha/yr^{-1}$. This represents approximately a 15-percent increase in volume since 1966. Increases in mass and elemental content of most components of the standing crop are estimated—using estimation procedures developed for these stands by Dice (1970)—to be proportional to the increase in woody tissue mass. However, the foliar mass has probably remained about constant in this interval. Thus at the present time, the quantities of elements and organic matter in the standing crop at this site are about 15 percent greater than shown in table 1.

In the same interval, other components of the ecosystem have shown relatively little change. For example, the forest floor was intensively sampled in 1961,[1] 1965 (Cole, Gessel, and Dice 1967), and 1969 (Grier and McColl 1971). Results of these studies are summarized in table 2. With the exception of magnesium content, the forest floor of this

[1] D. W. Cole. Unpublished data on file at the College of Forest Resources, University of Washington, Seattle.

Table 1.—Distribution of N, P, K, Ca, and organic matter (g/m^2) in a 35-year-old second-growth Douglas-fir ecosystem at the Thompson Research Center (Cole, Gessel, and Dice 1967)

Component		N	P	K	Ca	Organic matter
TREE						
Foliage	current	2.4	0.5	1.6	0.7	199.0
	older	7.8	2.4	4.6	6.6	710.7
Branches	current	.4	.1	.3	.2	51.3
	older	4.0	.9	3.2	6.5	1,337.3
	dead	1.7	.2	.3	3.9	814.5
Wood	current	1.0	.2	1.0	.4	748.5
	older	6.7	.7	4.2	4.3	11,420.2
Bark		4.8	1.0	4.4	7.0	1,872.8
Roots		3.2	.6	2.4	3.7	3,298.6
Total tree		32.0	6.6	22.0	33.3	20,452.9
SUBORDINATE VEGETATION		.6	.1	.7	.9	101.0
FOREST FLOOR						
Branches		.5	.1	.4	.8	142.3
Needles		3.5	.4	.5	2.7	300.5
Wood		1.4	.2	.8	1.7	634.5
Humus		12.1	1.9	1.5	8.5	1,199.9
Total forest floor		17.5	2.6	3.2	13.7	2,277.2
SOIL						
0-15 cm		80.9	116.7	7.9	31.3	3,837.2
15-30 cm		86.8	119.5	6.6	19.6	3,693.5
30-45 cm		76.1	98.0	5.2	15.2	2,829.0
45-60 cm		37.1	53.6	3.7	8.0	795.5
Total soil		280.9	387.8	23.4	74.1	11,155.2
TOTAL ECOSYSTEM		331.0	397.1	49.3	122.0	33,986.3

Table 2.—Forest floor composition changes during an 8-year period in a Douglas-fir ecosystem at the Thompson Research Center

Year sampled	g/m²					
	Dry weight	N	P	Ca	Mg	K
1961	1,542	15.4	2.2	11.2	3.8	2.4
1964	1,500	16.1	2.4	12.0	3.7	2.4
1969	1,430	14.0	—	12.3	1.9	2.7

ecosystem has changed only slightly since 1961 indicating that litterfall is balanced by decomposition. Similarly, there has been no significant change in elemental capital in the soil (table 3) due both to the large reserves of most nutrients in this soil and to efficient cycling processes within the ecosystem. The decrease in magnesium capital in the forest floor between 1965 and 1969 may indicate increased rates of internal redistribution of magnesium within the standing crop. However, this is doubtful in view of the small change in magnesium capital in the soil (table 3).

The quantities of cations transferred between components of the ecosystem generally increased between 1964-65 and 1970-71 (table 4). Comparison of some transfers during the 1970-71 measurement year with those of the 1964-65 measurement year (table 4) reveals some rather substantial differences in both the overall amounts transferred and in the relative importance of the various pathways.

For example, input of calcium and potassium by precipitation is roughly four-fold greater now than in 1964-65. This increase may reflect a general increase in atmospheric pollution in the Puget Sound basin. The quantities of calcium and potassium returned to the soil from the aboveground vegetation have also increased since the 1964-65 measurement. As an example, return of calcium and potassium by stemflow has increased 25- and 35-fold, respectively, since measurement during 1964-65. Increases in return by foliar leaching also were observed (table 4) but these were not of the same magnitude as the increased return by stemflow. No explanation has been found for the differential increases in return by stemflow and foliar leaching.

Return of elements by litterfall also increased between 1964-65 and 1970-71 (table 4). These differences are probably due both to normal year-to-year fluctuation of litterfall and also to the increasing proportion of branch material observed as a component of the litter.

Increases were also observed in leaching of elements through the soil profile. Leaching of calcium and potassium from the forest floor roughly doubled between 1964-65 and 1970-71 (table 4). A portion of this increase may result from increased rates of litter decomposition as well as the increased input in precipitation.

As previously noted, the forest floor mass appears to have approached a steady state condition (table 2); the present mass representing a quasi-equilibrium state, achieved since the stand was established in 1931, after repeated fires through the area. On the other hand, litterfall quantity has increased during the period of observation of this stand. In table 5, monthly litterfall measured at this site in 1962-63 (Rahman 1964) is compared with measurements made during 1970-71; the annual mass of litterfall has apparently increased roughly 50 percent over this 8-year period. Thus the increased quantities of ele-

Table 3.—Elemental capital in the soil of a second-growth Douglas-fir ecosystem at the Thompson Research Center as determined in 1965 and 1971

Depth	g/m²				
	N	P	K	Ca	Mg
A) 1965:					
0-15	81	117	7.9	31	3.7
15-30	87	120	6.6	20	3.5
30-45	76	98	5.2	15	2.5
45-60	37	54	3.7	8	1.2
Total soil	281	389	23.4	74	10.9
B) 1971:					
0-15	86	123	8.3	40	3.2
15-30	82	111	6.6	21	3.3
30-45	71	104	5.3	10	2.7
45-60	40	52	4.2	11	1.5
Total soil	279	390	24.4	82	10.7

Table 4.—Transfers of elements between components of a Douglas-fir ecosystem at the Thompson Research Center during two stages of development[1]

Item	Calcium (g/m²)		Magnesium (g/m²)		Potassium (g/m²)		Sodium (g/m²)	
	1	2	1	2	1	2	1	2
Precipitation	0.28	0.93	ND	0.22	0.08	0.47	ND	1.68
Throughfall	.35	2.05	ND	.49	1.07	2.83	ND	2.59
Stemflow	.11	3.85	ND	.60	.16	4.00	ND	2.30
Litterfall	1.11	1.78	ND	.20	.27	.47	ND	.07
Leaching from forest floor	1.74	3.87	ND	1.10	1.05	2.60	ND	2.18

[1] 1=transfers measured during 1964-65 measurement year. Reported by Cole, Gessel and Dice (1967). 2=transfers measured during 1970-71 measurement year.

Table 5.--Monthly amounts of litterfall during two intervals in the development of a second-growth Douglas-fir ecosystem

Month	Quantity (g/m^2)	
	1962-63	1970-71
October	73.0	89.0
November	17.9	44.5
December	9.2	14.2
January	6.5	10.0
February	15.9	3.8
March	6.2	13.8
April	7.4	5.8
May	12.8	([1])
June	11.4	([1])
July	5.2	39.1[1]
August	5.5	21.0
September	12.3	41.6

[1] Litterfall amounts for May, June, and July 1971 are combined in July collection.

ments leached from the forest floor are at least partially due to increased litter decomposition rates.

Many of the changes in amount and relative importance of the transfer pathways since 1965, are probably due to changes in the mass and structure of this forest ecosystem. However, many of the changes are completely out of proportion to estimates of increased mass of the standing crop.

Observations made since 1966 at the Thompson site indicate that the return of elements to the soil and their subsequent distribution through the soil profile is sensitive to certain climatic factors; primarily precipitation and temperature. Variations in these climatic factors have been observed to cause substantial variation in quantities transferred along most pathways. As an example, the return of elements to the soil by stemflow and foliar leaching were found to be partially regulated by the distribution of precipitation; especially precipitation occurring during the summer. Figure 1 shows the monthly return of potassium by stemflow from one tree for 1970 and 1971; the total amounts transferred being 0.50 gm during 1970, and 0.75 gm during 1971. Much of the greater amount returned during 1971 was returned during a few summer rainstorms. Foliar leaching, although not shown, exhibits a similar pattern of behavior. Apparently the extent of removal of potassium and other elements by leaching from Douglas-fir foliage is related to its phenological stage. This suggests that precipitation occurring in certain critical parts of the year may remove elements that would otherwise remain in the plant.

Temperature, the other major factor causing variation in year-to-year transfer rates, exerts its control on transfers primarily through its effect on organisms active in decomposition. Decomposer activity regulates the availability of nutrient elements in two ways; first, by regulating the rate of mineralization of elements and second, by its influence on levels of the mobile bicarbonate anion in the soil solution.

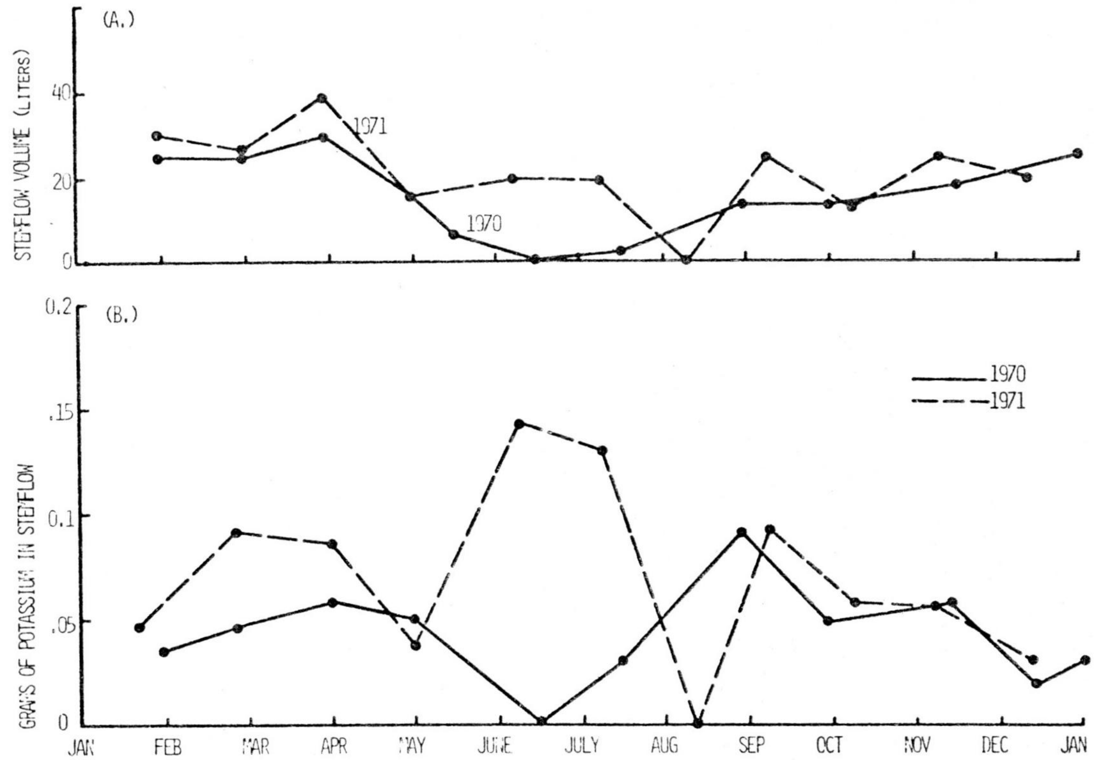

Figure 1.

A. Volume of stemflow from a 15-cm diameter Douglas-fir during 2 successive years.

B. Quantity of potassium transferred to soil from a single 15-cm diameter Douglas-fir during 2 successive years.

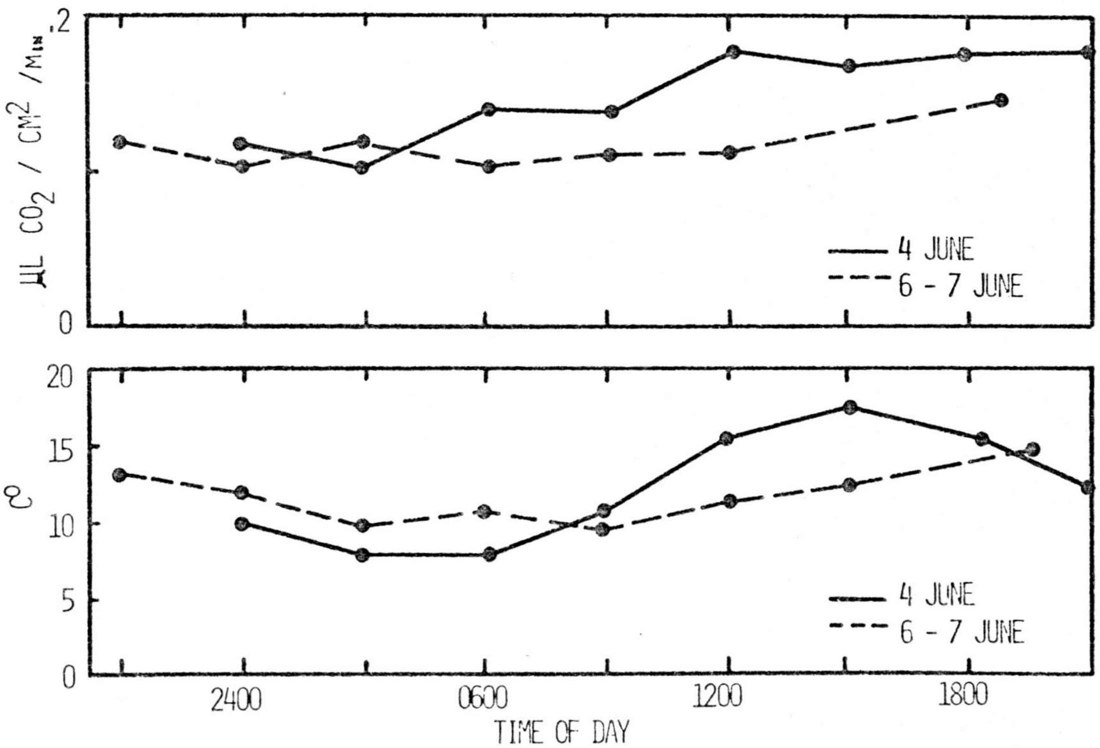

Figure 2. Temperature effects on CO_2 evolution from forest floor at Thompson Research Center (Ballard 1968).

Figure 2 illustrates how CO_2 production from the forest floor is related to temperature in this ecosystem (Ballard 1968). Temperature effects on mineralization rates are probably directly proportional to the temperature effects on CO_2 production rates.

The bicarbonate ion is the major anion in soil solutions at the Thompson site. Moreover, the concentration of this ion in the soil solution has been shown to be the major factor controlling rates of cation leaching in these soils (McColl 1969). Temperature effects on the levels of the bicarbonate ion are related to decomposer activity, since the equilibrium between CO_2 in the soil atmosphere and HCO_3^- in the soil solution is related to CO_2 concentration. Consequently, leaching rates in the soil of the Thompson site are strongly related to temperature (McColl 1969).

Figure 3A illustrates the relationship between estimated ion concentration in forest floor leachates and air temperature. As can be seen from these data, the ion concentration closely follows temperature during the year. Monthly variations in mean ion concentration of forest floor leachates for 3 successive years (figure 3B) are primarily the result of differences in mean monthly temperature.

Total transfer by leaching is regulated both by temperature and the amount and date of

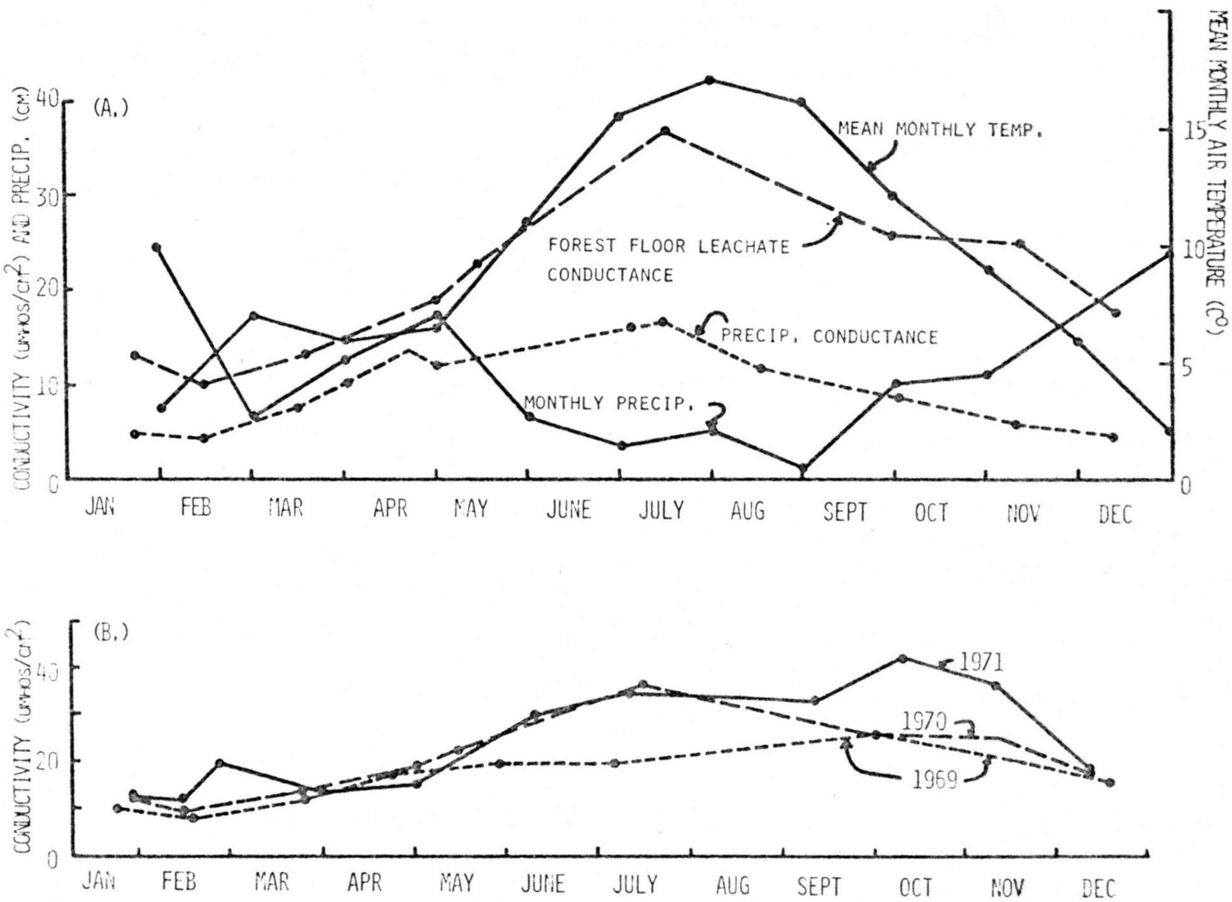

Figure 3.

A. Mean monthly precipitation, air temperature, and specific conductance of precipitation and forest floor leachates for the Thompson site during 1970.

B. Specific conductance of forest floor leachates for 3 consecutive years at the Thompson site.

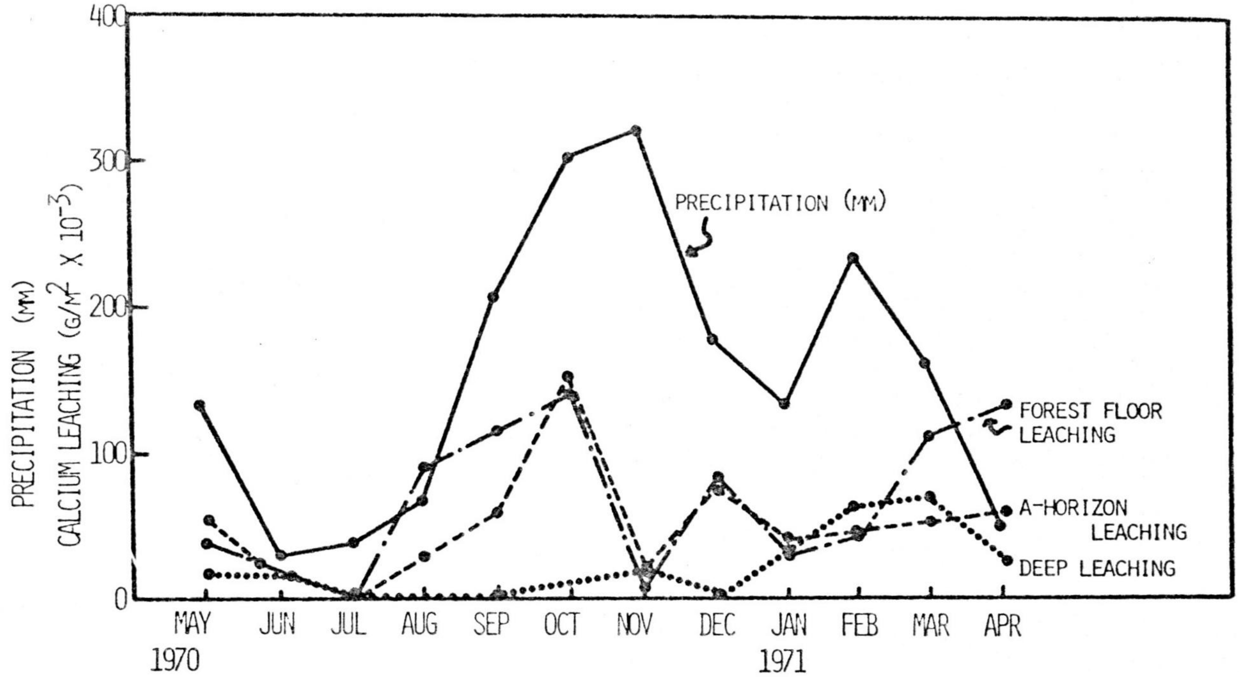

Figure 4. Rates of calcium leaching through soil profile and rate of precipitation during 1970-71 growing season.

occurrence of precipitation. The largest quantities of elements are transferred during periods of relatively high temperatures and ample precipitation. Figure 4 illustrates the relationship between leaching of calcium from the forest floor and A horizon of the mineral soil in 1970-71 and precipitation in that interval. As can be seen from these data, the greatest quantities of calcium were transferred during the spring and autumn when decomposer activity was relatively high and sufficient precipitation fell to flush the decomposition products into the soil.

Conclusions

Mineral cycling processes within a forest ecosystem are responsive to changes in the mass and structure of the standing crop and also to the shorter term effects of climatic variation. Of the two, the effects of climatic variation are the most readily seen. For this reason, any efforts to describe mineral cycling processes within a forest ecosystem must include sufficient data that effects of changes in mass and structure of the ecosystem can be resolved and separated from the large year-to-year effects of climatic variability.

Present and future mineral cycling research at the Thompson site is directed towards separating and describing the possibly interdependent effects of growth and climate on mineral cycling processes in second-growth Douglas-fir.

Acknowledgments

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