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Nutrient budget of a Douglas-fir forest on an experimental watershed in western Oregon

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Abstract

Annual loss of nitrogen, phosphorus, silica, and the cations sodium, potassium, calcium, and magnesium followed the same patternas annual runoff which is heavily dominated By winier rainstorms arising from the Pacific Ocean. Even though 170 and 135 cm of water passed through this Douglas-fir ecosystem for the 2 years reported here, this ecosystem conserved nitrogen effectively as indicated by an average annual dissolved nitrogen outflow of 0.5 kg/ha from an annual average input of 1.0 kg/ha in precipitation. There was a small annual net loss of phosphorus (0.25 kg/ha). Cation input in precipitation was less than 10 percent of sources from mineral weathering—indicating that mineral weathering was the principal source of cations to the system. Average annual net losses of calcium, sodium, magnesium, and potassium were: 47, 28, 11, and 1.5 kg/ha, respectively. Silica loss of 99 kg/ha-yr was the largest of all constituents and came entirely from within the forest system. Although loss of sediment was low during the period of study, loss of nutrients by soil erosion may become of major importance over a longer time scale due to widely spaced unsampled catastrophic erosion.

Introduction

The purpose of this study was to measure the inputs, losses, and retentions of specific plant nutrients.

Forested watersheds have been used for decades to study the hydrologic cycle. Bormann and Likens (1967) indicated that small watersheds are suitable for studies of chemical cycles if the ecosystem is located on a watershed with relatively impermeable bedrock. Then, all annual chemical fluxes into and out of the forest system can be attributed to a definable forest ecosystem, and errors due to deep seepage can be minimized. Small watersheds containing soil-plant systems have been generally accepted as useful units for ecological research.

Nutrient cycles begin with the establishment of vegetation, and the quantity of nutrients cycled undoubtedly increases as the forest passes through successional phases. At all points, along this developmental sequence, the supply of nutrients in the soil-plant system is regulated by the balance between (1) the inputs from the atmosphere and mineral weathering and (2) the outflow by soil erosion or chemicals dissolved in stream water. A continued level of fertility of the system therefore depends upon the retention of nutrients in the cycle from loss by leaching and soil erosion.

Nutrient budget studies were begun ,on two small watersheds at the H. J. Andrews Experimental Forest in 1967. Only the initial results from one of these and the chemicals in solution will be reported here. The following questions were asked:

1. What quantities of nitrogen, phosphorus, the cations (sodium, potassium, calcium, magnesium), and silica reach the site in precipitation?

2. How effectively are these chemicals retained by the forest?
3. What hypotheses can be made about the processes that regulate the gain or loss of these chemicals from the forest?

The 10.1-hectare study watershed, designated number 10 in Forest Service studies, occupies strongly dissected topography characteristic of the west side of the Cascade Range. It rises from 430 m elevation at the stream gaging station to 670 m at the highest point on the back ridge. The overall slope is 44 percent, but side slopes and the headwall range up to 90 percent due to deep incision of the basin into the main ridge. Soils, from weathered tuff and breccia materials, have weakly developed profiles that often overlie saprolite up to 6 m deep. Tree roots are most abundant in the surface 0.6 m and probably do not penetrate much deeper than 2.4 m. The saprolite is porous and therefore can transmit water. The average annual precipitation is 230 cm.

Forest vegetation on the watershed consists of remnants of a 450-year-old Douglas-fir *(Pseudotsuga menziesii)* stand and islands of various younger age classes which originated when the old-growth stand was broken up by windthrow, disease, or fire. Because the basin is oriented toward the southwest, the side slopes within it face south, west, and north. A considerable diversity in vegetation on these slopes has recently been classified for the Experimental. Forest by Dyrness, Franklin, and Moir (personal communication). Douglas-fir climax forests occupy ridgetop and upper slope south aspect positions on the watershed. A dense evergreen shrub layer, composed mainly of golden chinkapin *(Castanopsis chrysophylla)*, Pacific rhododendron *(Rhododendron macrophyllum)*, and salal *(Gaultheria shallon)* codominates the site beneath a sparse stand of old-growth trees. Western hemlock climax forests make up the remainder of the vegetation on the watershed. On these habitats, the dominant overstory is mainly Douglas-fir and western hemlock *(Tsuga heterophylla)*. Proceeding from west to north aspects along a gradient of increasing moisture, the shrub cover shifts from vine maple *(Acer circinatum)-salal*, to rhododendron-Oregon grape *(Mahonia nervosa)* and finally to vine maple-western sword fern *(Polystichum munitum)* on moist, north-facing middle and lower slopes.

Methods

Precipitation and streamflow are sampled by the following techniques. Precipitation at the top and bottom of the watershed is measured by standard rain gages; samples for chemical analysis *are* obtained from a special collector mounted on a tower 18 m tall in the center of a nearby clearcut. At the outlet of the watershed, an EI-flume gages streamflow and a proportional water sampler, capable of sampling both dissolved and suspended materials from the stream, composites discrete water samples in a polyethylene carboy (Fredriksen 1969). The samples are removed at approximately 3-week intervals throughout the year. In 1970 and 1971, grab samples were taken from low summer flows; and during the winter of 1971-72, a series of grab samples were collected from streamflow during storm runoff events. In the laboratory, solids are removed by filtration through a fine glass fiber filter (Whatman GF/C) from both precipitation and streamflow samples and chemical analyses were performed on both fractions. The fraction that passes the filter is considered to be dissolved although we recognize that the filtered water may contain some particles smaller than 2 microns in diameter. Since the concentration of each chemical constituent is an estimate of the mean for the time during which the sample was collected, the input or loss for each sampling period is the product of precipitation or streamflow, respectively, and the concentration of each constituent.

Chemical analyses were done in duplicate as follows: Ammonium and dissolved organic nitrogen by distillation and digestion, respectively, on 1/2-liter samples and detection by Nesslerization; nitrite by the sulphanilamide method; nitrate by reduction and detection as nitrite; orthophosphorus by the molybdate blue method; total phosphorus by the molybdate blue method following a persulfate-sulfuric acid digestion in the autoclave; reactive silica by the molybdate yellow method; cations sodium and potassium by flame emission; and calcium and magnesium by atomic absorption following addition of lanthanum as a masking agent.

Detection limits (mg/l) for the following chemicals were: organic nitrogen, 0.005; nitrate and nitrite, 0.0005; phosphorus, 0.005; sodium, 0.05; potassium, 0.1; calcium, 0.4; magnesium, 0.05; and silica, 0.1.

Results

Nutrient Input in Precipitation

Total amounts of nutrients dissolved in precipitation and the annual rainfall are given in table 1. Nitrogen enters the forest system mainly in organic substances; nitrate averaged only 13 percent of all nitrogen forms for the 8-year period. In that period, only trace amounts of ammonia nitrogen were detected, and a small quantity of nitrite in 1970. The phosphorus came mainly in organic form in two collections in the fall of 1969. Of the cations, input of calcium was the greatest followed by sodium, magnesium, and potassium in descending order. Traces of silica were found in only five of the 14 collections in 1970.

There was also an input of particulate matter from the atmosphere that measured upwards of 3 to 5 kg/ha-yr. Although the average dustfall for 3 years was nearly equally divided between the dry season (April-October) and the wet season (November-March), the proportion in the wet season varied from 33 to 65 percent of the total for individual years.

Nutrient Loss in Streamflow

Nitrogen is transported in the stream almost entirely in the form of organic matter (table 2). Though water samples from this watershed were contaminated with nitrate from the exhausts of propane heaters, the nitrate nitrogen outflow from another un-

Table 1.—Nutrient input in precipitation for the period October 1 through September 30

Constituent in rainwater	1969	1970
	kg/ha-yr	
NO_3-N	0.06	0.20
NO_2-N	0	.01
Organic N	1.02	.69
All N	1.08	.90
Ortho P	(1)	.01
Total P	(1)	.27
Na	1.17	2.34
K	.27	.11
Ca	7.65	2.33
Mg	.72	1.32
Si	(1)	(2)
Precipitation (*cm*)	251	215

[1] Missing data.

[2] Trace.

Table 2.-Nutrient budget for dissolved constituents of precipitation and runoff for the period October 1 through September 30

Element	1969			1970		
	Input	outflow	Net	Input	outflow	Net
	kg/ha-yr					
N	1.08	0.58	+0.50	0.90	0.38	+0.52
Total P	(1)	(1)	(1)	.27	.52	-.25
Na	1.17	33.66	-32.49	2.34	25.72	-23.38
K	.27	1.24	-.97	.11	2.25	-2.14
Ca	7.65	53.65	-46.00	2.33	50.32	-47.99
Mg	.72	12.70	-11.98	1.32	12.44	-11.12
Si	(1)	(1)	)	(2)	99.3	-99.3
H_2O-cm	251	170	81	215	135	80

[1] Missing **data.**

[2] **Trace.**

disturbed watershed nearby was 0.004 kg/ha-yr. A similar nitrogen outflow can be expected for the study watershed. Ammonium and nitrite do not occur in measurable concentrations.

Total phosphorus outflow, both organic and inorganic, was about in the same order of magnitude as outflow for nitrogen. The organic form predominates in spring, summer, and fall seasons but reaches minimum values in midwinter when the forest and soils are repeatedly flushed by rainwater. Orthophosphorus concentration remained nearly constant throughout the year, varying from 0.01 to 0.02 mg/1.

Cation and silica outflows were much larger than those of nitrogen and phosphorus. Potassium export was much smaller than that of other cations. Silica outflow was the largest of all the dissolved constituents. Transport of suspended sediment was 67 and 37 kg/ha-yr for 1969 and 1970, respectively.

Net Loss from the Watershed

The nutrient budget in table 2 results from the subtraction of the nutrient outflow in the stream and the input in precipitation. Net loss or gain is indicated by positive and nega. tive values, respectively.

The small annual nitrogen gain of about 0.5 kg/ha was nearly the same for the 2 years. Foi all other mineral constituents of runoff, more. was lost than was gained in precipitation Phosphorus losses are relatively small and in the same order of magnitude as nitrogen losses. The cation and silica losses were frorr one to two orders of magnitude larger thar those of nitrogen and phosphorus. **Of** tht cations, calcium losses were greatest followec in descending order by sodium, magnesium and potassium. Of all constituents, silica losses were greatest. Though precipitation and runoff were greater in 1969, the use of wate: by the forest was nearly equal for the 2 years

Time Trends of Outflow and Concentration of Selected Chemicals

Movement of water in the forest system is obviously the dominant factor regulating the flow of chemicals. However, moderation of the annual chemical outflow pattern can be expected from processes such as organic decomposition, uptake into plants, and mineral weathering. These processes may be regulated by the hydrologic and thermal state of the forest system.

The time trends of soil temperature and water content are indicated on figure 1. Because precipitation occurs mainly during the fall and winter months with less than 2 percent of the annual total in July and August, substantial withdrawals of water from the soil are made by the forest during the summer. Water content of the top 30 cm of soil reaches minima, near the wilting point, usually in late August or early September. Fall rainstorms normally recharge the soil mantle to field capacity by the end of December, although recharge of the surface soil may occur from 1 to 2 months earlier. The soil temperature cycle is the inverse of the soil water cycle. Maxima near 14" C occur in August and minima from 0" to 2" C are common from December through March.

Precipitation and runoff for 1970 are illustrated in figure 2 for the periods that composite streamflow and precipitation samples were taken. Precipitation exceeded runoff by a wide margin in the fall of 1969 until soils reached field capacity sometime in late December or early January. The soil remained near field capacity until precipitation fell to low levels in early May. Wetting fronts from precipitation and snowmelt can pass through the soil mantle of the watershed during this period. Runoff declined rapidly with the increase of evapotranspiration and reduction of precipitation in the spring and summer months.

Organic nitrogen, calcium, and silica were chosen to illustrate the differences that exist in annual concentration and outflow patterns (figs. 3, 4, and 5). The influence of water can be seen immediately from the general correspondence of the stream runoff and chemical outflow cycles. Minimum chemical outflow occurs in summer and fall while streamflow is low; maximum chemical outflow comes with high runoff in the winter months. However, the concentration patterns vary considerably between the three, and there are notable differences in outflow between organic nitrogen and the other two (calcium and silica) during the winter season.

Organic Nitrogen

The high concentration of organic nitrogen in October 1969 (fig. 3) came at a time when soils were dry (fig. 1) and could store all precipitation except that which falls directly into the stream or runs off rock and shallow soil areas adjacent *to* the stream. After a decline in early November (fig. 3), the concentration and outflow rose to a peak in December when soils probably had reached field capacity (figs. 1 and 2) and wetting fronts from precipitation could pass through the soil mantle. Organic nitrogen outflow remained high and reached a secondary peak in late January at peak runoff (fig. 3). As precipitation and runoff declined in February, concentration and outflow reached low values (figs. 2 and 3). The concentration and outflow rose again in late winter and early spring as precipitation increased (figs. 2 and 3). Outflow and concentration declined in April and May as precipitation declined and soil water storage dropped below field capacity (figs. 1, 2, and 3). Increased concentration in summer had little effect on outflow due to very low runoff (fig. 3).

Though the forest system retains more organic nitrogen than it loses (table 2), the gain is not uniform throughout the year. From mid-December to mid-February, the forest system lost more in outflow than it gained in precipitation; for the remaining 10 months, there was a net retention of organic nitrogen (fig. **6**). For the 2-month midwinter period, the outflow in runoff (0.28 kg/ha) exceeded the input in precipitation (0.16 kg/ha) by 0.12 kg/ha. There was an increasing margin during the 2 months.

Contributions to the stream from the forest

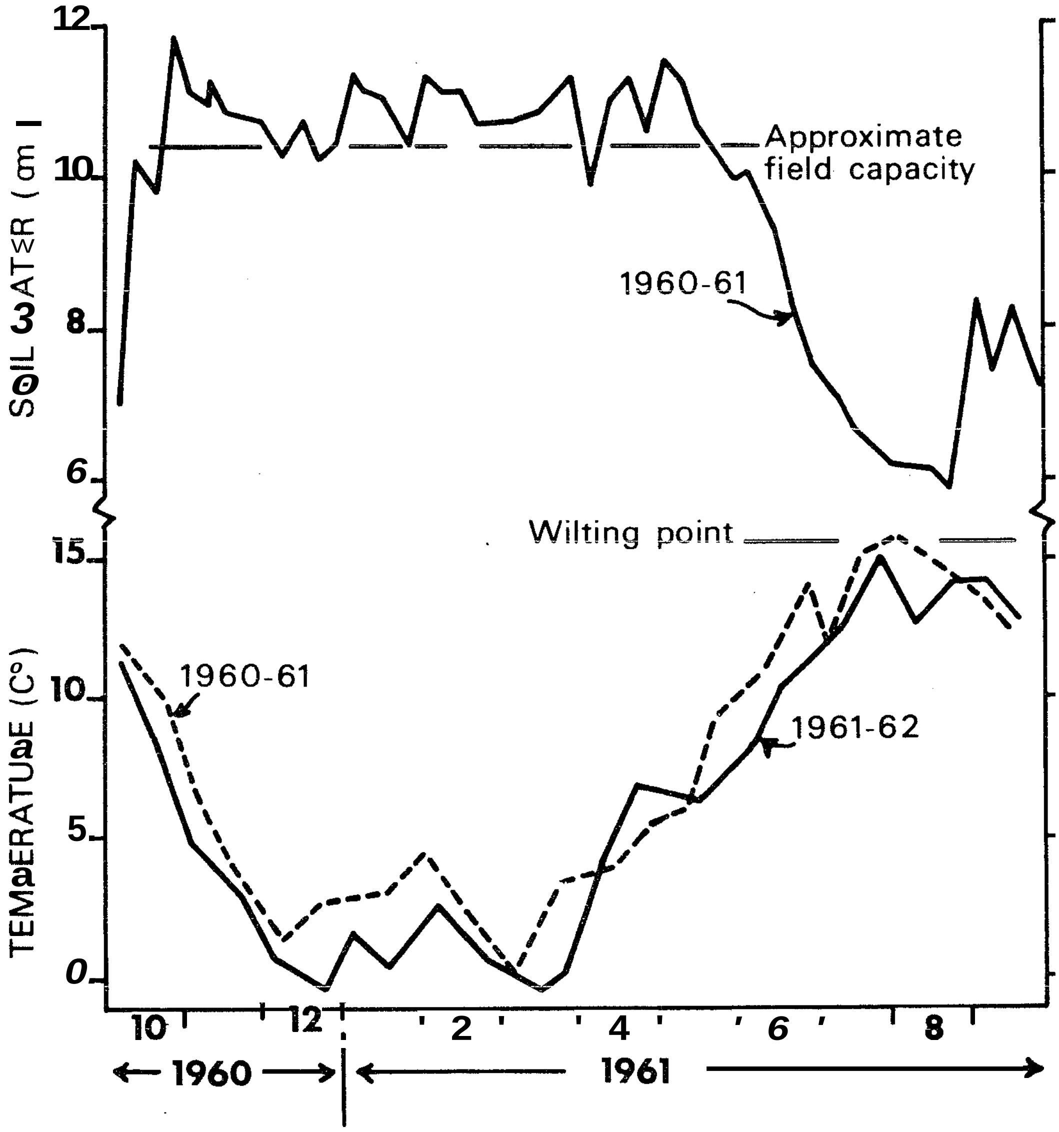

Figure 1. Water content of the surface 30 cm and temperature at 15 cm in the soil of an old-growth Douglas-fir forest.

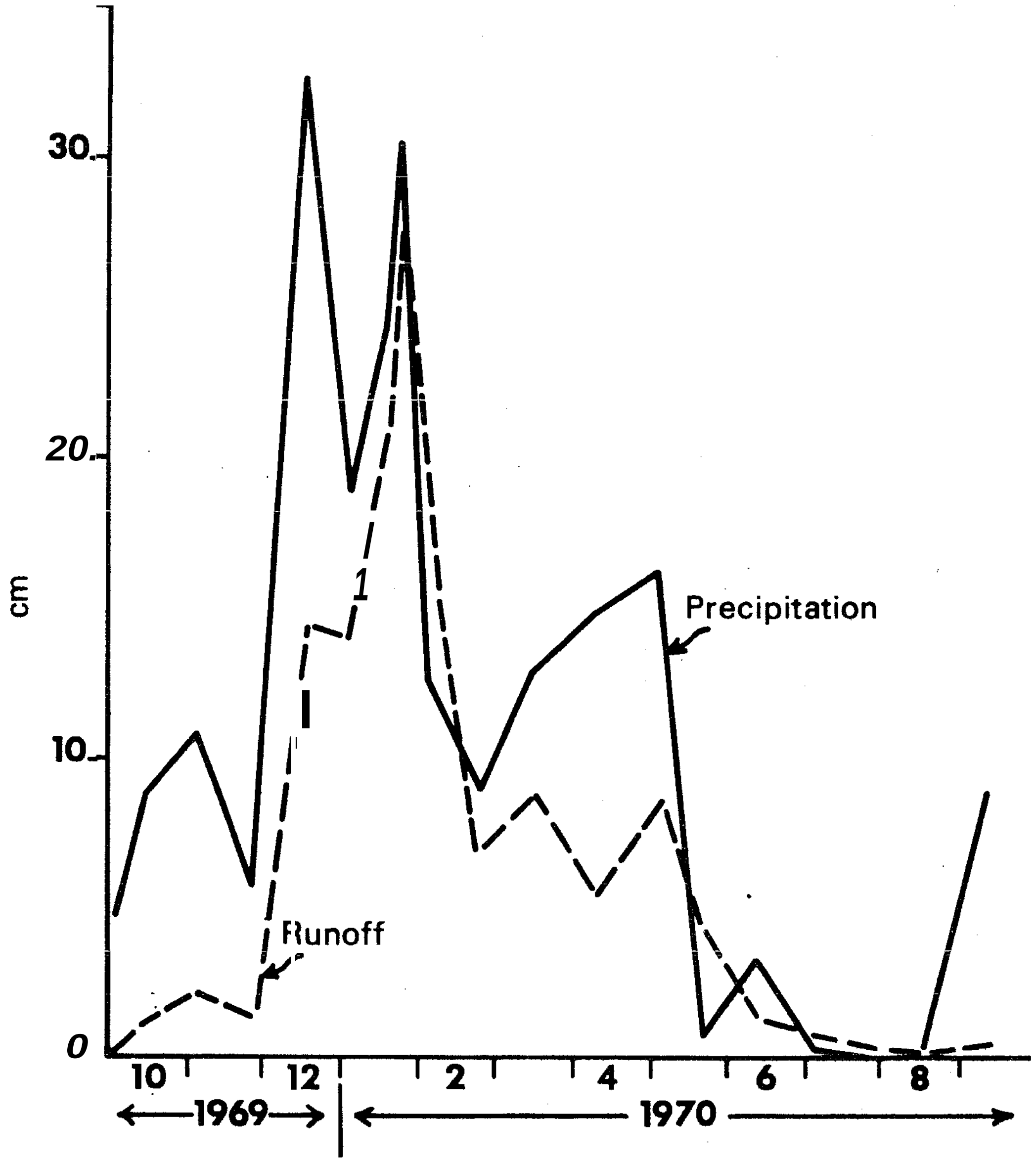

Figure 2. Precipitation and runoff for an undisturbed Douglas-fir forest for each sampling period, 1969-70.

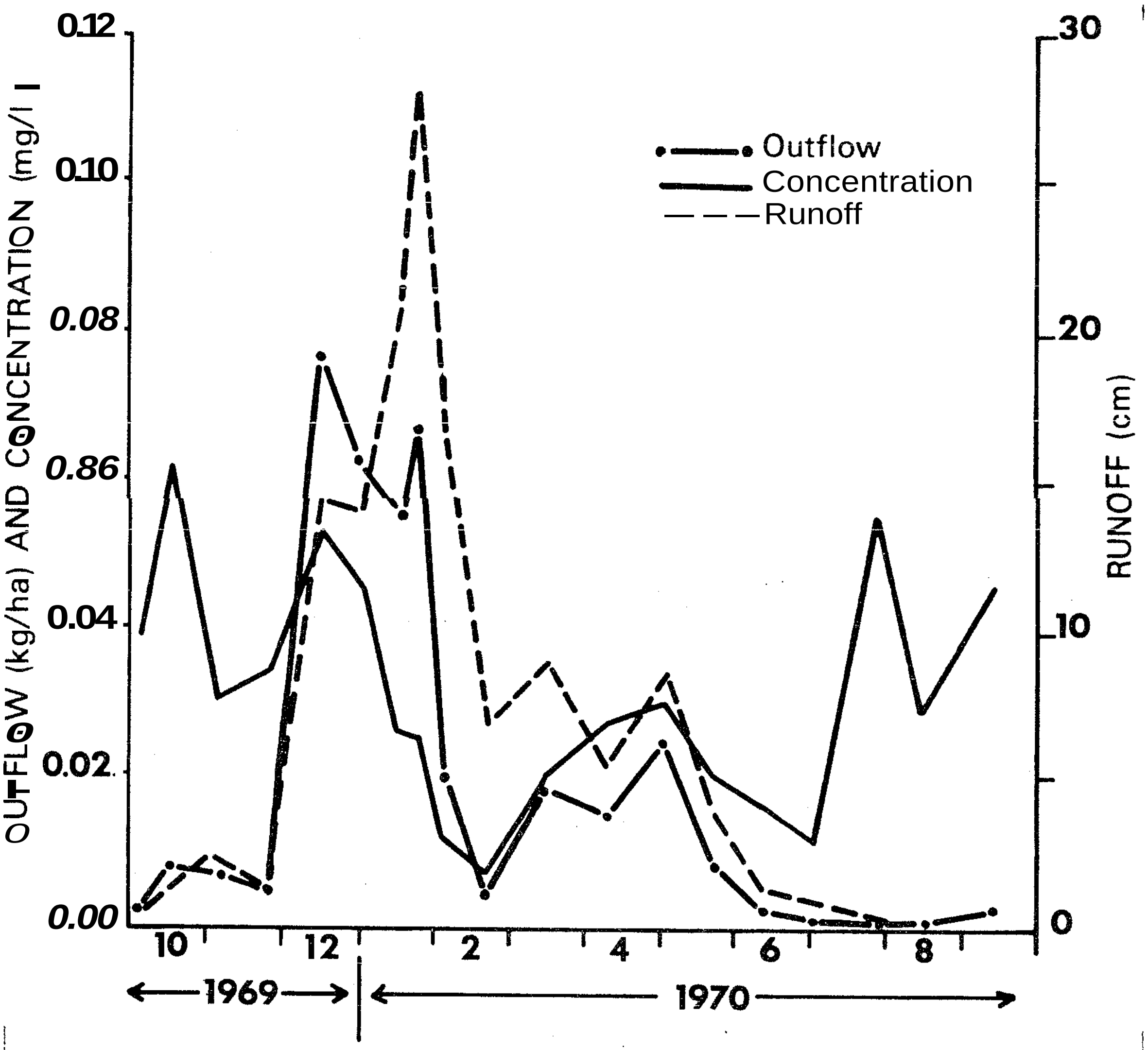

Figure 3. Concentration and outflow of organic nitrogen dissolved in stream water and runoff per sampling period from an undisturbed Douglas-fir forest, 1969-70.

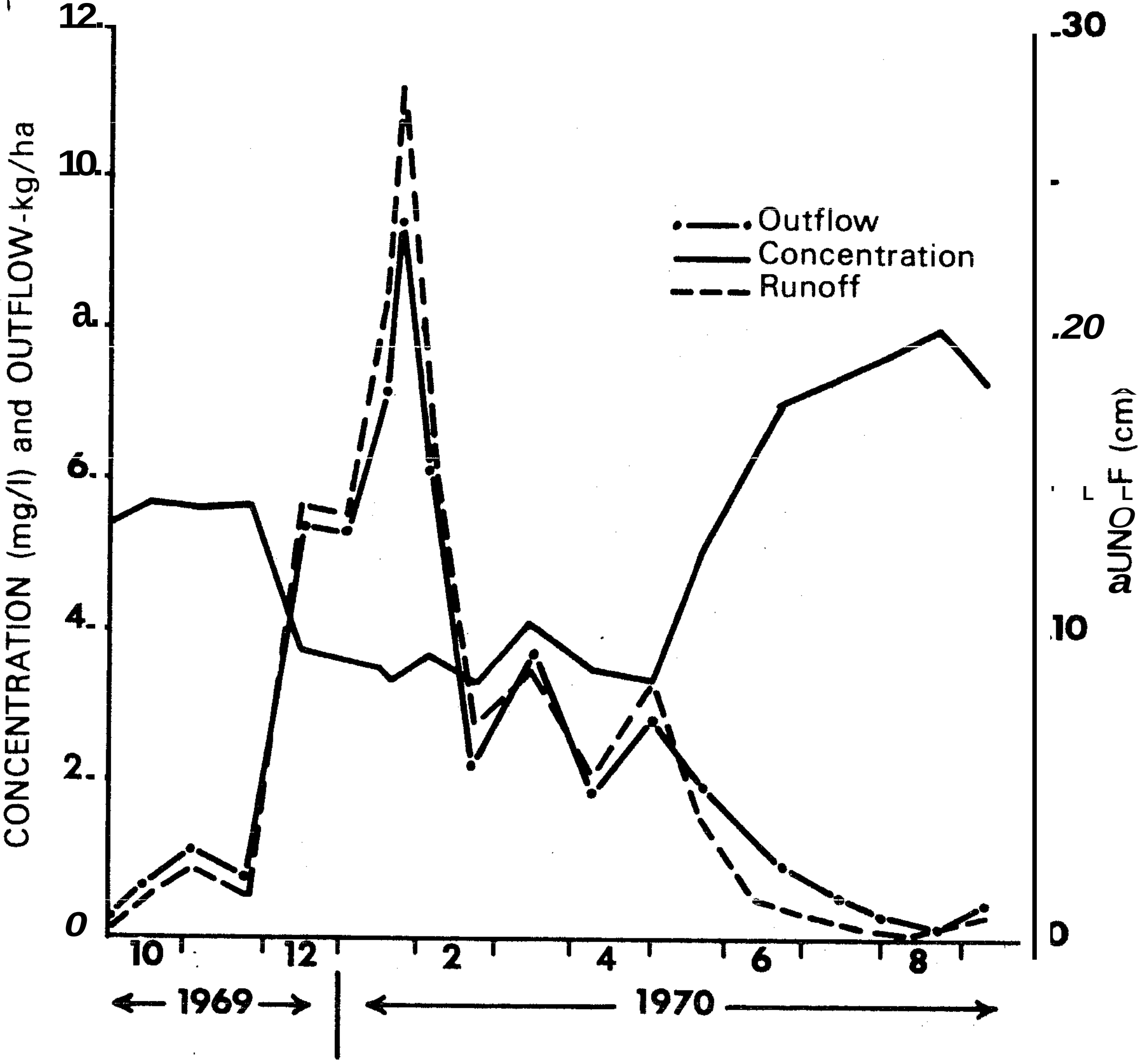

Figure 4. Concentration and outflow of calcium dissolved in stream water and runoff per sampling period from an undisturbed Douglas-fir forest, 1969-70.

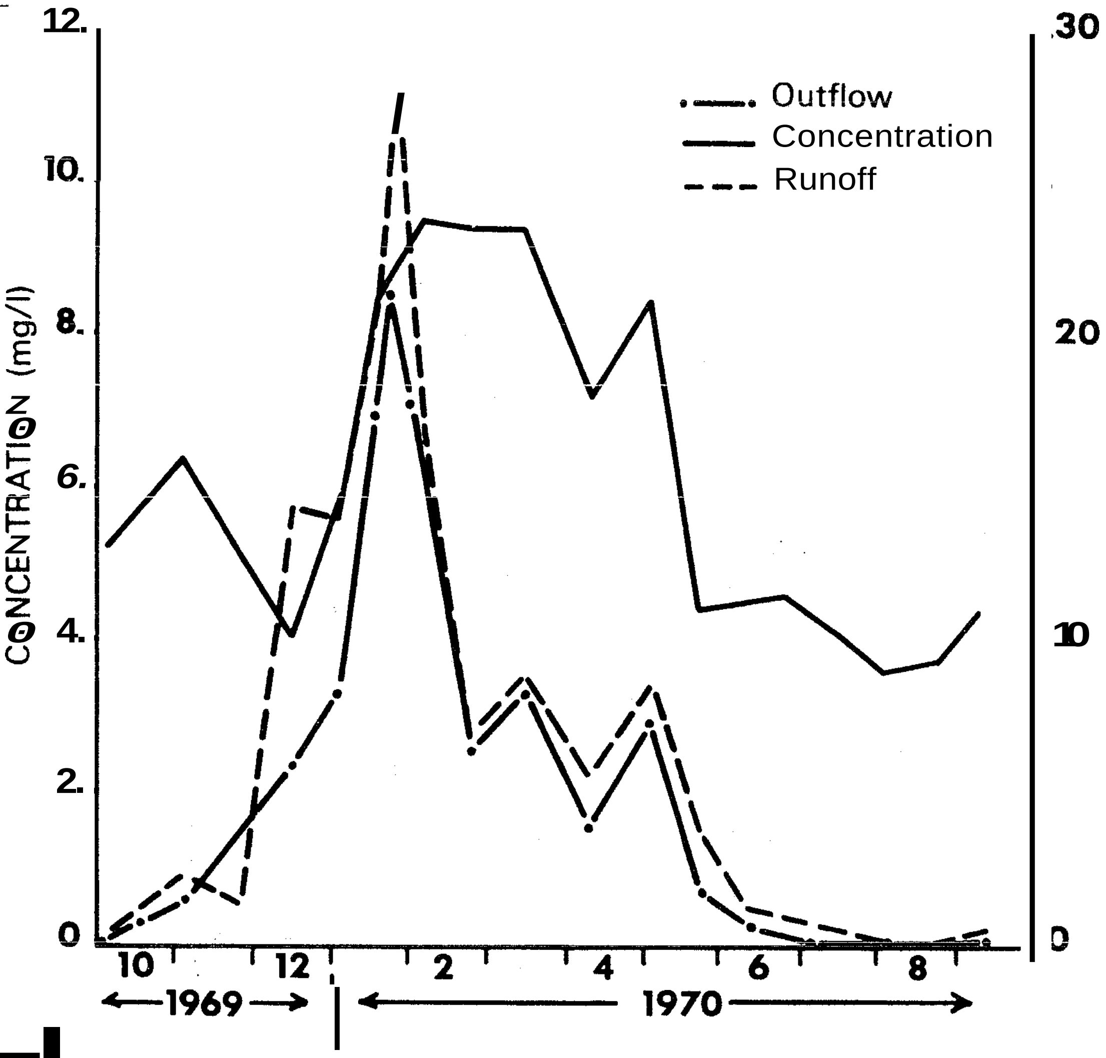

Figure 5. concentration and loss of siiica dissolved in stream water and runoff per sampiing period from an undisturbed Douglas-fir forest, 1969-70.

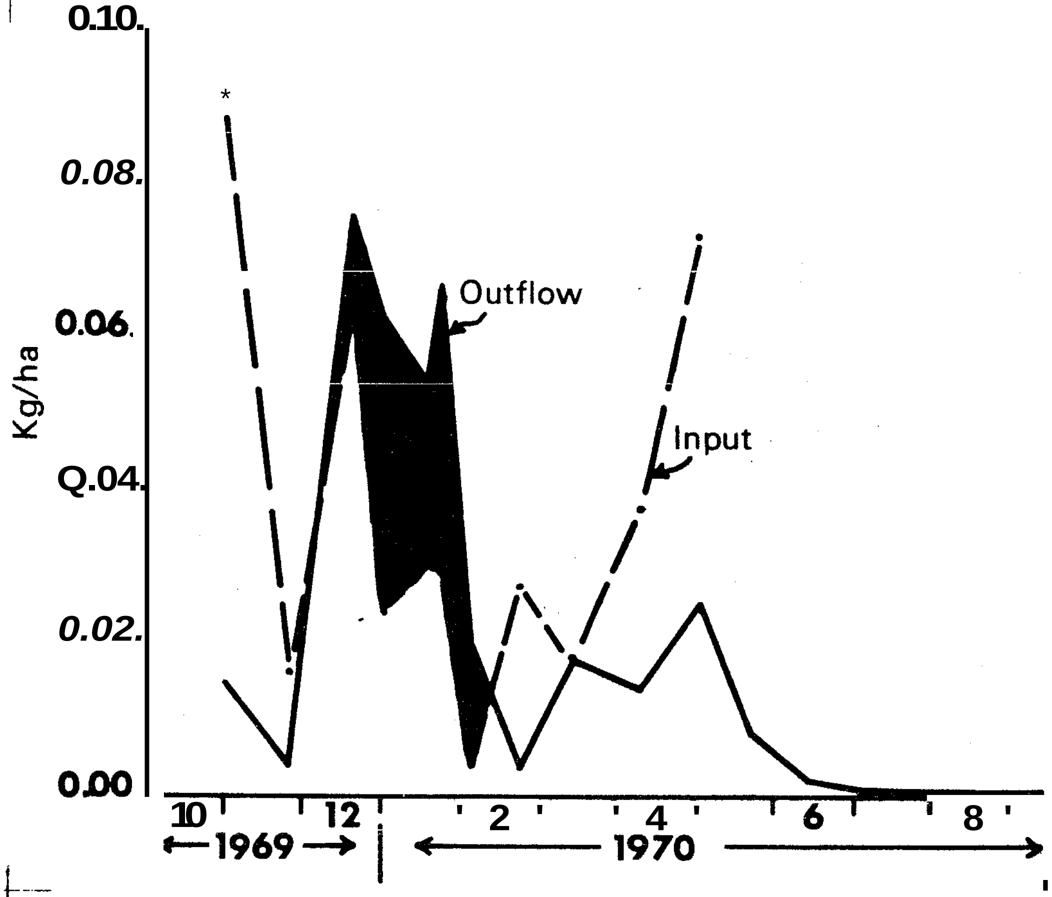

Figure 6. Input in precipitation and loss in runoff of dissolved organic nitrogen for each sampling period, 1969-70.

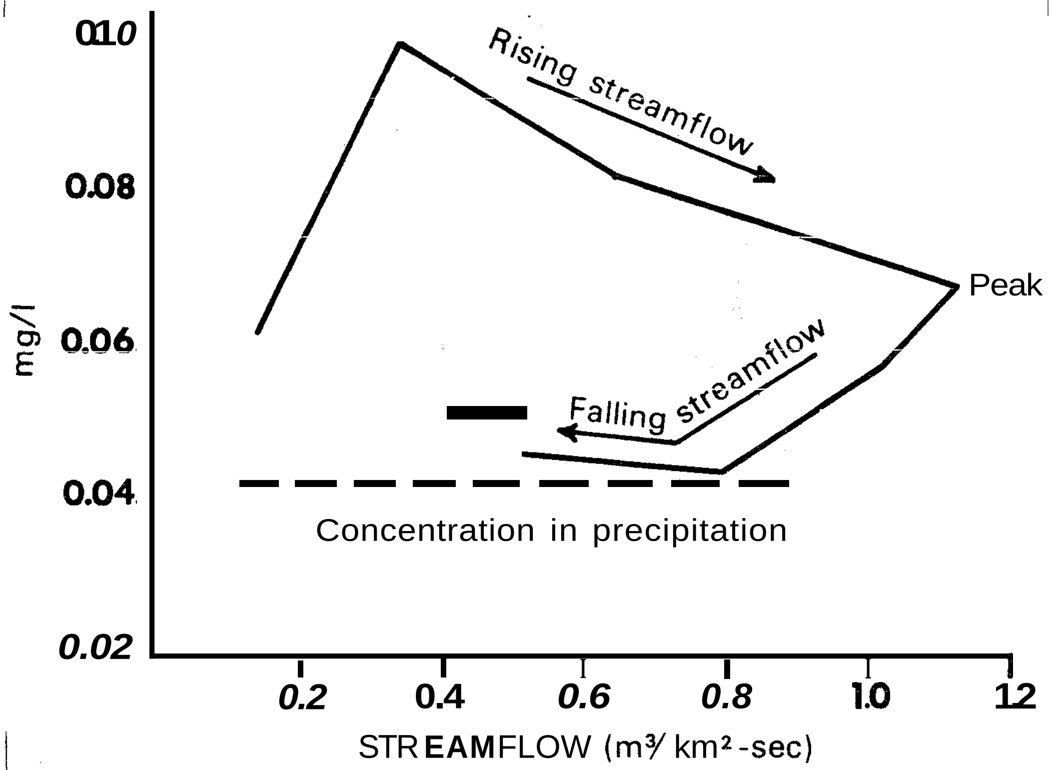

Figure 7. Concentration of organic nitrogen dissolved in streamflow during a Storm runoff event November 25-29,1971.

and precipitation can be illustrated from a set of samples taken during a storm runoff event in late November 1971 (fig. 7). The rapid initial rise of organic nitrogen concentration can be attributed to flushing of available sources within the vegetation, soil, and atmosphere. The concentration declined as sources within the system were depleted and streamflow rose by about one order of magnitude to peak flow. The concentration rapidly declined on the recession curve to values slightly larger than the mean concentration in precipitation.

Calcium

Calcium outflow closely followed the runoff cycle (fig. 4). The twofold to threefold increase in concentration from winter to the warm seasons had only minimal control on calcium outflow compared with the hundredfold variation in annual runoff. The abrupt concentration drop in late November and the rise in May corresponds approximately to the time that the soil reaches field capacity in the winter and falls below field capacity in the spring (fig. 1).

The calcium and bicarbonate carbon content of the streamflow follow a similar pattern (fig. 8). Winter season values were nearly constant whereas warm season stream contents rose sharply for streamflow values less than 0.1 m^3/km^2-sec. The change in slope (fig. 8) corresponds approximately to the change in streamflow regimes (fig. 4) and the time that soil water content rises to field capacity in the winter and departs from it in summer (fig. 1).

Silica

The occurrence of minimum silica concentration in the dry and warm seasons of the year and maxima in the winter and early spring (fig. 5) strongly contrasts calcium concentration-time trends (fig. 4). The silica concentration increase in December and January corresponds to the time of expected recharge of the soil to field capacity. The continued elevation of silica concentration through the winter season suggests that soluble silica is either released by weathering processes at that time or that it accumulated during the warm season of the year and is removed when wetting fronts flush the soil mantle in midwinter. The reduction of concentration in late April corresponds to the time that subsoils drain as the forest responds to evaporative demand and precipitation lessens.

Discussion

Organic nitrogen has seldom been identified in precipitation. Tarrant et al. (1968) found values of nitrogen input (1.49 kg/ha-yr) similar to those reported here (table 1) and in the same proportions of organic to nitrate nitrogen (87 and 13 percent, respectively). Organic nitrogen from 0.02 to0.20 mg/lwas also found in New Zealand snows by Wilson (1959). Only trace amounts of ammonium were found in the present study and in that by Tarrant et al. (1968). However, Moodie (1964) reported from 1 to 6 kg/ha-yr of ammonium nitrogen at several agricultural sites in western Washington. Values of input for cations, sodium, potassium, calcium, and magnesium (table 1)were generally similar to those reported by Moodie.

Atmospheric particulate matter may contribute substantially to nitrogen and phosphorus input. A large proportion of this is undoubtedly of local terrestrial origin during the dry season and arises from road dust, pollen, and smoke particles. From November through March, when the local environment is regularly dampened by precipitation, particulate matter is thought to be carried from the Pacific Ocean in prevailing westerly winds. Presumably, the finest particles pass the filters we use to separate solids from water and contribute to the "dissolvednutrients." Nearly all the phosphorus and 72 percent of the nitrogen resulted from a digestion of substances in rainwater collected during the dry seasons (table 1).

This forest system retains nitrogen very effectively. The net gain of 0.5 kg/ha (table 2) is nearly equal to that reported by Cole et al. (1967). The fact that this result was duplicated on two Douglas-fir stands, very diverse

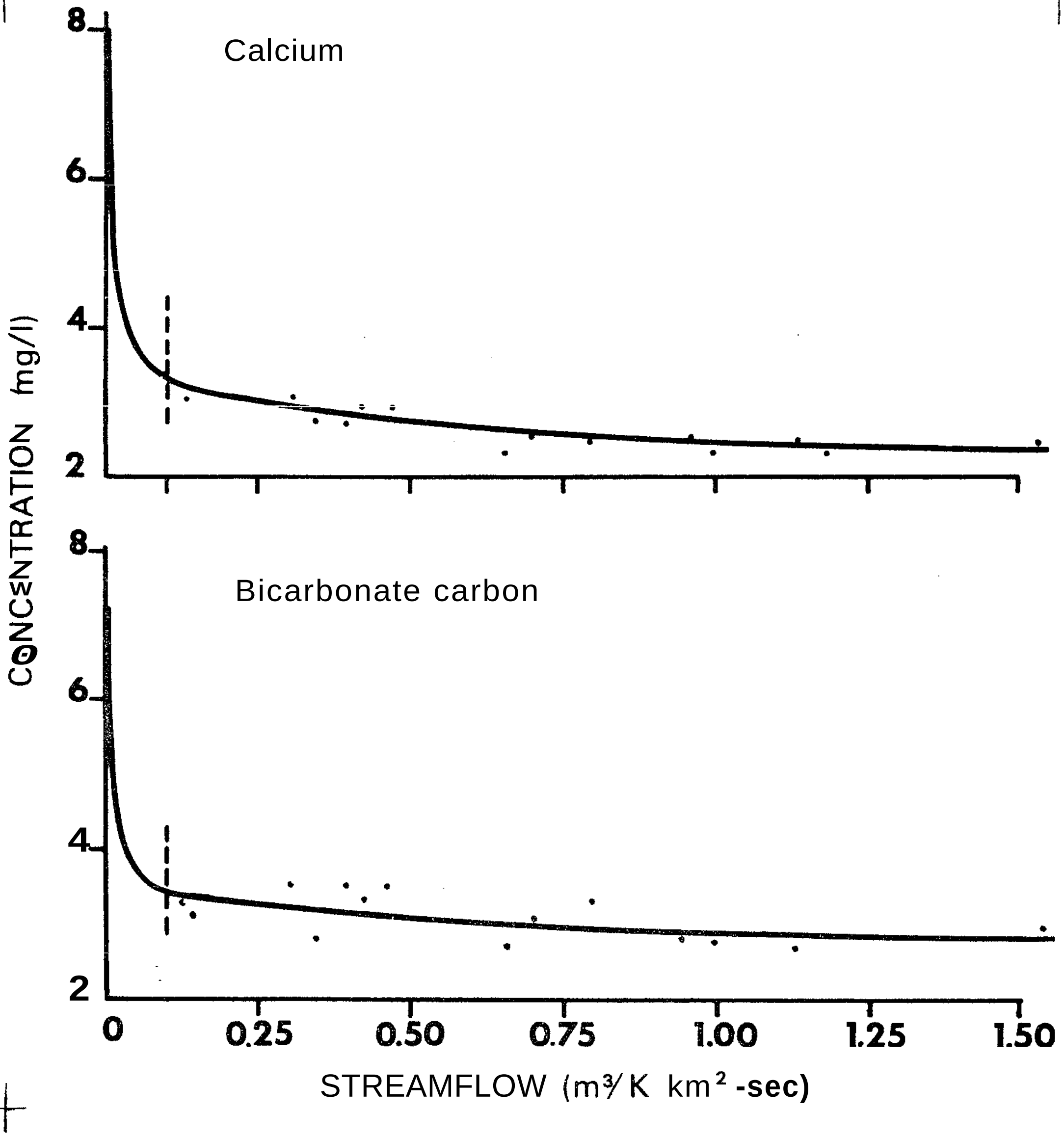

Figure *8.* Concentration cf calcium and alkalinity as bicarbonate *carbon* in streamflow, 1970-72.

in terms of soil and stand structure, suggests that this retention property may be general for Douglas-fir forests west of the Cascade Range in the Northwestern United States. Although an explanation for this retention must await the completion of research now in progress, it appears from the small organic nitrogen outflow that most of the soluble organic substances released from decomposition of detritus and organism excretions are rapidly incorporated by the organisms of the forest. Nitrate nitrogen outflow is also regulated to levels much less than the input in precipitation. Either nitrification rates are very low in the soils or the nitrate is retained and rapidly incorporated by the forest system. Nitrification is active in the acid soils of conifer forests on the Oregon coast (Bollen and Lu 1968), but this information is lacking for soils of the H. J. Andrews Experimental Forest.

The status of nitrogen capital of a Douglas-fir forest is the result of a number of processes including input in precipitation, fixation by free living organisms such as blue-green algae and soil bacteria, and fixation by microorganisms living in symbiotic association with a host plant. If the forest gains 0.5 kg/ha annually, as is indicated by this short period of record, 8,000 years would be required to accumulate the 4,000 kg/ha of organic nitrogen found in the more fertile soils of the study watershed. Additions of nitrogen symbiotically fixed by *Ceanothus velutinus* may be somewhat larger. If *Ceanothus velutinus* stands persist for 20 years and fix 20 kg/ha annually as Zavitkovski and Newton (1968) suggest, and if generations of these brush stands are induced by fire at intervals of 200 years, then 16,000 kg/ha of nitrogen would accumulate in 8,000 years. From this, deductions must be made for losses by soil erosion and microbial and fire volatilization. In any case, inputs of nitrogen in precipitation must be considered of importance compared with other mechanisms of gain and loss by the forest.

Phosphorus outflow from the forest was similar to that of nitrogen (table 2). Loss occurs as both organic phosphorus and orthophosphorus. The organic form predominates in the warm seasons of the year when there is a rapid biological turnover of phosphorus by the forest. Concentration of the ortho form remains fairly constant throughout the year and is thought to arise from mineral weathering.

The losses of the cations sodium, potassium, calcium, and magnesium were large compared with those of nitrogen and phosphorus and represent excess amounts of these cations to the annual requirements of the forest vegetation (table 2). These losses are approximateiy four times those reported for the Hubbard Brook ecosystem in New Hampshire except for the potassium values which were nearly equal to those reported here (Likens et al. 1970). Cole et al. (1967) also reported lower losses of potassium and calcium. The cation and silica losses (table 2) are estimates of the annual release of these chemicals by mineral weathering. In this regard, it is interesting to note that the ratio of Si:Ca:Na:Mg weathering rates for 1970 are 8.9:4.3: 2.1:l.

Another mechanism for nutrient loss is the particulate matter that is transported by the stream. This material may arise from soil erosion or from organic detritus from the forest. Losses of suspended sediment from this study (67 and 37 kg/ha-yr) were much lower than the 12-year annual average of 133 kg/ha from another undisturbed watershed in the Experimental Forest (Fredriksen 1970). Although we have not quantified the chemical loss by this means in this study, previously published annual losses of 0.16 kg/ha for organic nitrogen represent less than half of the dissolved component loss (table 2), still an important part of the total nitrogen loss (Fredriksen 1971). Cation loss was much less than 1 percent of the loss in dissolved form. However, since erosion losses are very sporadic and dependent on extremes of storm runoff events, and the results (Fredriksen 1971) are indicative of the chemical loss during a relatively quiescent period, they should be taken as minimum estimates of nutrient loss by soil erosion, processes.

Biological and chemical processes of the forest that control nutrient mobilization and retention are undoubtedly closely linked to environmental factors. The movement of water is dominant because flowing water is required to transport materials to the sites of physical-chemical and biochemical activity and to remove byproducts that appear in the outflow of experimental watersheds.

Definite concentration changes in the stream occur at the transition periods from drying to wetting of the forest system (figs. 3, 4, and 5). A key feature is either retention of precipitation (and reaction byproducts) in soil storage or the passage of wetting fronts through the soil mantle when the soils are at field capacity. It is not surprising that, of the annual totals, 77 percent of the calcium, 80 percent of the organic nitrogen, and 83 pescent of the silica were exported from the forest in the 5 months from December 1969 through April 1970. During this period, the soil mantle was at field capacity and wetting fronts from winter rainstorms reguiariy flushed the entire forest system.

For organic nitrogen (fig. 3), the period of maximum outflow corresponds to the time when wetting fronts begin to pass through the soil mantle in early December. The widening margin between input and outflow (fig. 6) indicates an increasing contribution to outflow of organic nitrogen from the forest system. Although we do not know how much organic nitrogen from precipitation directly supplements streamflow, the increased concentration and content in precipitation and streamflow in late January suggest that sources of organic nitrogen in precipitation may directly augment the outflow from this experimental catchment.

There is a definite change in the calcium content of streamflow **as** the hydrologic state of the forest system changes from winter to summer (fig. 8). The calcium outflow was closely paralleled by the content of carbonate and bicarbonate—the predominant anions of the stream. McColl and Cole (1968) demonstrated that cation mobilization is effectively controlled by these mobile anions that are formed by the carbonation of water with carbon dioxide released by respiring organisms of the forest. As yet, we cannot explain the processes that maintain a nearly constant concentration of calcium and these mobile anions over the range of winter streamflow.

Silica is nearly absent in precipitation and is therefore entirely generated within the soil-forest system (fig. 5). Although the parent materials of soil are the primary source of silica, silica is cycled in generous amounts by forests as indicated by litterfall studies (Remezov et al. 1955) and the occurrence of plant opal crystals in forest soils (Paeth 1970). Silica in streamflow may originate from primary mineral weathering, secondary mineral dissolution, or release from decomposition of detritus. Silica may be taken out of solution by formation of secondary minerals within the soil. The occurrence of minimum silica concentration in the dry and warm seasons of the year and maxima in the winter and early spring strongly contrasts calcium concentration-time trends (fig. 4).

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