A RATIONAL BASIS FOR ESTIMATING ELEMENTAL SUPPLY RATE FROM WEATHERING

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Abstract.--Based on a nutrient supply study conducted in the Idaho batholith, I have estimated the amounts of cations released by chemical weathering that are retained in a mixed Douglas-fir ponderosa pine forest ecosystem. The estimate includes cations adsorbed by new secondary minerals formed during weathering plus net nutrient uptake by biomass. This provides a more realistic estimate of potential nutrient supply to soil by weathering than previous published weathering rates that include a large component that is leached from the ecosystem. Maximum rates of nutrient retention occur during maximum foliar increment, a situation approximated by the stand conditions in the study watershed. Net annual uptake of cations in biomass greatly exceeds annual increase in soil retention. Approximately half the K^+, Ca^{++}, and Mg^{++} released by primary mineral weathering are retained in the ecosystem.

INTRODUCTION

Land managers considering intensive tree harvesting, short rotation management, or even conventional harvesting on depauperate soils are often concerned with the implications of harvest to the nutrient capital of their site. Nutrient loss to the system must be counterbalanced by resupply over a reasonable time, or fertilization is required. Estimates of nutrient supply to ecosystems by primary mineral weathering are uncommon in the literature, although nutrient budget studies frequently include an estimate of weathering release based upon dissolved cation efflux rates from watersheds. The implication is that this weathering rate defines the upper bound of potential elemental supply to the ecosystem. This upper bound greatly exceeds the maximum actual retention of cations released by weathering in temperate forest ecosystems. Actual nutrient supply rates to the system are time variant, and may be considered equal to the net accrual to the soil and biotic pools.

Nutrient budgets in forested ecosystems have been studied intensively over the past 20 years. Seminal papers by Duvigneaud and Denaeyer-DeSmet

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(1964), Ovington (1962, 1965), and Tamm (1964) pointed to the concerns regarding perpetuation of a supply of nutrients to forested lands in Europe that have been under management (widescale clearing and natural regeneration) for well over 1,000 years. They suggest that the nutrient capital of soils is gradually depleted by successive croppings, and the ultimate and necessary result is a decline in timber production.

In the past decade, study results have generally indicated that tree bole harvest removes nutrients and causes accelerated leaching losses at rates compatible with natural nutrient inputs (Wells and Jorgensen 1979). However, concern has shifted from normal, sawlog harvesting to more complete or total utilization of the tree crop, which greatly increases removal of nutrient capital from the site (Boyle et al. 1973; Weetman and Webber 1972; Malkonen 1973; Kimmins 1977; Alban et al. 1978; Leaf 1979). Weaver and Forcella (1977) estimated that whole tree harvest of climax Rocky Mountain forests would result in increased nutrient drains of 3, 6, 4, and 3 times bole removal rates for N, P, K, and Ca, respectively. Johnson et al. (1982) reported increased export of N, P, K, and Ca from whole tree harvest ranging from 2.6 to 3.3 times conventional bole removal rates from a mixed oak forest at Oak Ridge National Laboratory. They concluded that soil amendments might be necessary to sustain Ca supplies to this ecosystem under whole tree harvest management.

Much of the merchantable timber in the Western United States is located on steep, mountainous landscapes with high natural erosion rates. Soils on these sites are often shallow and weakly developed. Following logging, accelerated erosion can occur, depleting the soil nutrient pools in these ecosystems. Fertilization to replace nutrients in forest ecosystems that have lost productivity can only be considered a practical solution in highly productive stands under intensive management. Kimmins (1977) correctly pointed out that nutrient management would be important in the future.

Nutrient budgeting has been used extensively to predict the long-term consequences of particular harvest strategies. However, nutrient budgeting is still an inexact science, prone to numerous errors. Leaf (1979) expressed the concern that in our haste to provide data on nutrient cycles to land managers, our sampling techniques may have been so crude that we have provided a measure of disservice rather than of service. This may be most apparent for estimates of nutrient supply rates to the ecosystem from primary mineral weathering. Clayton (1979) reviewed a variety of techniques for arriving at estimates of nutrient supply from weathering, and concluded that nutrient budgeting techniques probably provide the current most accurate numbers.

The principal shortcoming of previously published nutrient supply rates is that elemental release rates from weathering, are considered equivalent to maximum potential supply rates. These supply rates are based on elemental loss from ecosystems by soil solution transport below lysimeters or as dissolved transport in streams, and thus include a component not available for tree nutrition. In temperate forest ecosystems of the world, rates of nutrient release from weathering generally exceed nutrient retention, principally because of: (1) lack of an efficient sink mechanism in the soil for immobilizing elements released from weathering, and (2) lack of an effective exploitation of the soil volume by roots. Obviously, these forest ecosystems have evolved within the nutrient retention limitations of the existing soil sink and root exploitation strategy. The land manager's concern and need for realistic estimates of nutrient replenishment rates is directed to managed forest ecosystems, where large nutrient removals result from harvesting.

A more rational upper bound for potential nutrient supply rate from weathering can be computed from annual net elemental accrual in vegetation and litter, plus annual increases in cation adsorption sites in the soil arising from secondary mineral formation and changes in soil organic matter. Vitousek and Reiners (1975) presented a hypothetical relationship between the degree of maturity of an ecosystem and its ability to retain nutrients. They suggested that the difference between net input and output of a nutrient element is proportional to the rate of accrual of that element into the biomass increment.

The research reported here presents a concept for estimating nutrient gains to a forested ecosystem in southwestern Idaho in which litter layer and soil organic matter content are assumed to be in a steady state. These assumptions are reasonable in view of the age and profile development of the soils, and in view of the forest stand maturity and lack of recent fire activity. A mass balance approach to arrive at a geochemical budget for a watershed is used to investigate the potential and actual supply rates of five essential elements to a forested ecosystem. The macronutrients Ca, K, Mg, S, and P are considered in this study. Cycling of the nonessential element Na is also considered because of its magnitude and similarity of transport to other cations in the biogeochemical cycle. Results indicate that weathering release of S is considerably lower (not detectable) than meteoric inputs to the Idaho batholith. This result was not unexpected (Strahler and Strahler 1973). Therefore, weathering is not an important pathway to consider in the S budget of this ecosystem. Weathering release rates of P from primary minerals are difficult to determine because of the lack of mobility of P. The rate of supply of P from weathering is discussed in light of this problem.

SITE CHARACTERISTICS, SAMPLING, AND LABORATORY ANALYSIS

This research was conducted on watershed SC-5, one of the Silver Creek research watersheds located in the southwestern Idaho batholith (44°25'N latitude and 115°45'W longitude). SC-5 is a 1.09-km^2 watershed draining in a southeast direction. Slopes on the watershed range from 20 to 65 percent, and commonly have south or east facing aspects. Elevation at the mouth of the watershed is 1395 m and the highest elevation is 1775 m. Bedrock in this area of the batholith is a coarse-grained quartz monzonite, typical of the main inner facies of the southern Idaho batholith (Ross 1963). The modal rock in SC-5 contains quartz, plagioclase (An_{16-21}), orthoclase, and minor amounts of biotite (Clayton, in press). Rock near the surface is moderately well-weathered to well-weathered according to the classification scheme of Clayton et al. (1979). These classes of weathering indicate rocks of low mechanical strength, and quartz grains are the only minerals to appear fresh to the unaided eye. Feldspars and biotite show considerable alteration to clay minerals in thin section.

Soils in the area were mapped on Forest Service Resource Photography base photos (1:15,840) at the family level. Soils are generally shallow, coarse textured, and weakly developed, exhibiting only A and C horizons. Typic and Lithic Xerorthents predominate on southerly slopes. Cryorthents, Cryumbrepts, and Cryopsamments are common on other aspects. Textural classes are sandy or sandy-skeletal. Single samples of major horizons from the four soils most common to SC-5 were sampled from 28 soil pits for laboratory analysis. Bulk densities were determined in the field by coring. Laboratory analyses included:

1. pH - saturation paste
2. Cation exchange capacity by Na saturation (Chapman 1965)
3. Exchangeable bases, neutral, 1 M NH_4OAc extract
4. Exchange acidity, $BaCl_2$ - TEA method (Peech 1965)
5. Percent organic matter, Walkley - Black method (Allison 1965)

No samples for nutrient analysis were taken below C horizons, although many of the soil contacts with bedrock are classified as paralithic. Both weathering and tree roots are commonly observed in bedrock in the batholith, often to depths greater than 10 m. Roots are generally confined to fractures in rock, but presumably they derive both water and nutrients from this zone during some periods of the year. Primary mineral weathering below the soil is slow compared to rates in the soil because of the abundance of primary minerals in young batholith soils, higher specific surface of grains in the soil, presence of organic acids, more frequent leaching and greater temperature fluctuations (Clayton et al., 1979).

The watershed is forested, and the principal overstory species are ponderosa pine (*Pinus ponderosa* Laws.) and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco). The timber stand is uneven aged, multicanopied, and averages about 24 MBF/acre (Scribner) in trees >27 cm diameter at breast height (d.b.h). The oldest trees are approximately 400 yr in age, and all ponderosa pine. Intermediate Douglas-fir and ponderosa pine trees are in a 180 to 200 yr age class, and there is a discontinuous pole-sized class of Douglas-fir, 80 yr old. There have not been any fires larger than 0.4 ha in SC-5 in the last 60 yr, and no evidence of major fires for over 80 yr. Basal area averages 25.2 m^2 ha^{-1}. Two habitat types (Steele et al. 1981) predominate on the watershed: Douglas-fir/ninebark (*Physocarpus malvaceus* (Greene) Kuntze), ponderosa pine phase; and Douglas-fir/white spirea (*Spiraea betulifolia* Pall.), ponderosa pine phase.

Incremental phytomass growth and standing crop estimates for SC-5 were determined in the following way:

Two hundred forty-five 0.008-ha plots were established to provide a 3 percent cruise of SC-5. On all trees, d.b.h. and height by species were recorded; increment cores were taken on a one out of five random subsample to provide the heartwood-sapwood transition and last 5 years' diameter increment. Using the current diameter, diameter increment, and height, various allometric equations predicted incremental growth by plant part. The foliage and branch estimates for ponderosa pine and Douglas-fir are predicted using equations from Brown (1978). Boles of pine <39 cm d.b.h. are predicted using unpublished equations provided by Patrick Cochran, Bend Silviculture Laboratory, Bend, OR. Pine boles >39 cm d.b.h. and Douglas-fir boles and roots are predicted from equations of Gholz et al. (1979). No equations for ponderosa pine roots were deemed suitable for the research area, so they were estimated using the assumption that pine has the same branch:root ratio predicted for Douglas-fir.[2/] Understory plants other than ponderosa pine and Douglas-fir constitute <5 percent of the total vascular plant phytomass in the watershed.[3/]

Tissue chemistry data for ponderosa pine and Douglas-fir from Clayton and Kennedy (1980) are coupled with the standing crop and incremental growth data to provide annual uptake, net uptake, and standing crop of elements in the stand. Half the samples collected by Clayton and Kennedy are from SC-5; the other half were from an adjacent watershed in the Silver Creek study area.

Streamflow and precipitation in SC-5 have been monitored continuously since 1960. Water chemistry studies were begun in 1973 and precipitation chemistry studies in 1974. Stream and precipitation chemistry sampling and techniques for computing annual elemental fluxes into and out of the watershed by these pathways are described by Clayton (in press). Precipitation influxes are computed for each element assuming 98 cm mean annual precipitation, which is arrived at from an isohyetal map of SC-5 based on 18 years of record from three rain gages. Chemical composition of snow is different from rain in Silver Creek, and the volume ratio 65:35 snow:rain is used in computing chemical content (Megahan et al. 1983). Finally, chemical concentrations from 93 station samples of rain and 11 station samples of snow are used to compute elemental inputs in precipitation.

Dissolved effluxes in streamwater are computed using equations that correlate concentration in mg/liter and instantaneous stream discharge in m^3/sec. These equations predict a mean daily flux from mean daily flow. Annual efflux in kg ha^{-1} yr^{-1} is computed by summing mean daily flux over the number of days in the year. Long-term average effluxes are not computed by averaging the 10 years of available record. Instead, I have used a strong relationship that exists between annual efflux and annual water yield in cm, and the 21-year mean annual water yield figure of 33.5 cm for SC-5 to predict long-term average annual efflux. I describe this procedure in greater detail elsewhere (Clayton, in press).

In order to test if the watershed is tight, i.e., if there are any losses of water and dissolved nutrients to deep seepage below the flume, and to test if there are water sources from springs, the Cl^- budget for the watershed was examined from 1978 through 1981. The sole source of Cl^- input is from precipitation, and there are no large biotic or abiotic sinks for Cl^- in the

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[2/] The author is indebted to David Perry, Dept. of Forest Science, Oregon State University for providing the standing crop and incremental growth data.

[3/] Estimate made by Russell A. Ryker, Research Forester, Intermountain Forest and Range Experiment Station, Boise, Idaho.

system. Over the 3-year period, there was a 4 percent excess of Cl^- outflux over influx in precipitation (Clayton, in press). Because of the errors associated with sampling and computing the fluxes, the significance of the 4 percent difference is unknown.

ANALYSIS OF DATA

Clayton (1979) suggested that a mass balance equation of the form $I_{rw} = (I_{out} - I_{in}\ [ppt]) + \Delta I_{p+s}$ can be used in a watershed study to estimate elemental release from weathering. In this example I_{rw} = annual release of element I from rock weathering, I_{out} = annual dissolved efflux of I in the stream, I_{in} (ppt) = annual input in precipitation, and ΔI_{p+s} = the annual change in storage of element I in the plant and soil compartments of the ecosystem. The following section develops the data base required to solve this equation.

Precipitation and Stream Chemistry

The concentration of nutrients in snow and rain are presented in table 1, with the number of samples and coefficient of variation.

Table 1.--Average concentration of various elements collected in rain and snow samples, Silver Creek study area. CV = coefficient of variation; n = number of samples.

Element	Concentration					
	Snow	CV	n	Rain	CV	n
	mg/liter			mg/liter		
Na	0.06	55	11	0.18	72	93
K	0.09	17	11	0.26	46	93
Ca	0.22	27	11	1.37	32	93
Mg	0.014	26	11	0.064	57	93
S	0.28	29	11	0.68	49	53
P	0.001	54	11	0.009	66	53

Using the 65:35 assumption of snow:rain ratio and using 98 cm as the long-term average annual precipitation, chemical influxes in precipitation are presented in table 2. In addition, stream effluxes and efflux minus influx data are presented in table 2. The difference between efflux and influx is the magnitude of elemental release from weathering that is lost from the ecosystem by leaching. This provides data for the first half of the mass balance equation.

The mobility of elements in the soil-water system or, more generally, the mobility of elements when not tied up by plants greatly influences the flux data presented in table 2. This is particularly the case for phosphorus, which is immobilized in the soil in both organic compounds and inorganic

Table 2.--Annual precipitation influx and stream efflux entering and leaving watershed SC-5.

Element	Stream efflux	Precipitation influx	Difference
	$kg\ ha^{-1}\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$	$kg\ ha^{-1}\ yr^{-1}$
Na	12.6	1.00	11.6
K	3.41	1.53	1.88
Ca	16.1	6.10	10.0
Mg	1.55	0.31	1.24
S	3.22	3.6	-0.38
P	0.049	0.033	0.016

complexes with Ca, Fe, Al, and clays (Jackson 1964). More information about the reaction sequence: primary mineral P⟶non-labile P⟶labile P is required to describe P supply rate from weathering. A mass balance of elemental fluxes within the watershed does not supply the detail necessary to estimate primary mineral P release, and the reaction rate of non-labile P⟶labile P may be more important in controlling available supply rate to tree roots.

Incremental Growth and Net Nutrient Uptake

Table 3 presents an estimate of standing crop, average yearly net increment, and yearly mortality for ponderosa pine and Douglas-fir in SC-5.

The annual tissue shedding for foliage is 712 kg ha^{-1} for ponderosa pine and 549 kg ha^{-1} for Douglas-fir. New foliage production is 752 and 658 kg $ha^{-1}\ yr^{-1}$, respectively, leading to the net incremental growth figures for foliage presented in the table. Other incremental growth figures are predicted directly by the allometric equations previously discussed.

Plant chemistry data of Clayton and Kennedy (1980) were used to convert incremental growth and mortality data into net changes in standing crop of nutrients. The budgeting procedure is straightforward except for foliage, and requires multiplying the annual increment by elemental concentration. Foliage chemistry data include concentrations in current year, 1-year-old, and 2-year-old needles. However, the incremental growth models provide no data on needle retention. Therefore I chose to use the average concentration of elements for the three age classes of needle chemistry data to compute annual uptake and return by litterfall. The assumption that recently abscised needles contain nutrients in concentrations similar to concentrations in third-year needles was tested. The assumption is good for some elements (Ca, Mg) and poor for

Table 3.--Standing crop, annual net increment and annual mortality of uneven aged stands of ponderosa pine and Douglas-fir in SC-5. All values are in kg ha-1 ± standard error.

	Ponderosa pine			Douglas-fir		
	Standing crop	Annual net increment	Mortality[a/]	Standing crop	Annual increment	Mortality
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Foliage	3,844 ± 403	40.6 ± 3.6	11.8	3,506 ± 289	108 ± 8.0	18.6
Branches:						
<0.64 cm	127 ± 12	2.1 ± 0.5	5.0	1,631 ± 131	48.7 ± 3.6	10.5
0.64 - 2.5 cm	4,504 ± 469	37.3 ± 3.4	23.4	2,694 ± 227	86.3 ± 6.5	49.6
2.5 - 7.6 cm	5,446 ± 678	57.1 ± 5.6	44.3	1,869 ± 268	85.8 ± 10.5	19.6
>7.6 cm	4,502 ± 787	59.0 ± 8.8	0	82 ± 19	4.5 ± 1.0	0
Sapwood	42,381 ± 4937	514.4 ± 48.1	365	42,556 ± 5,085	1,768 ± 176	518
Heartwood	9,878 ± 1,269	130.1 ± 14.7	40.7	9,164 ± 1,421	436 ± 56	112
Bark	7,873 + 821	83.5 ± 7.3	64.2	7872 ± 928	324 ± 32	123
Roots	33,049[b/]	425	158	14,227 ± 1,848	618 ± 67	173
Total	111,604	1,349	711	83,601	3,479	1,024

a/ Mortality figures refer to death only, not annual tissue shedding.

b/ Pine roots are estimated using the same root:top ratio as Douglas-fir.

others (K, P, S). However, those elements that are redistributed through the plant in phloem tissue prior to abscission satisfy a requirement that otherwise would be met through the pathway litterfall, decay and uptake from the soil. The mass balance equation is not pathway dependent for net uptake, and so the requirement of the plant is the same in either case. The same reasoning is used with regard to root shedding. Sollins et al. (1980) assumed 30 percent of fine roots (≤5 mm) died back annually in the western Cascades of Oregon. Presumably, the elemental content of these roots may differ during the year, particularly when comparing the time of active growth to senescence. I chose to take the mean elemental concentration of fine roots and apply it to the net incremental growth to compute net uptake.

Net annual uptake in kg ha^{-1} yr^{-1} based upon the above discussion is as follows: Na = 1.94, K = 2.42, Ca = 10.1, Mg = 1.18, S = 0.59, P = 0.61.

Change in Soil Storage

Elements released from weathering are retained in the soil as: (1) soluble salts present in pore water, (2) adsorbed as ions on exchange sites, (3) incorporated into the lattice of secondary minerals, or (4) incorporated in living or dead organic matter. As pointed out previously, the great majority of P in soils is incorporated in organic compounds or highly insoluble complexes with Al, Ca, and Fe. Most of the S in well-drained soils of humid regions is incorporated in organic matter. Under the assumption that soil organic matter is in a steady state in SC-5, it appears that S is in a tight economy in Silver Creek. Precipitation inputs (3.64 kg ha^{-1} yr^{-1}) slightly exceed solution losses (3.22 kg ha^{-1} yr^{-1}), and the difference approximates the net annual vegetation requirement (0.59 kg ha^{-1} yr^{-1}). Bedrock in the Idaho batholith is low in S content (Larsen and Schmidt 1958), the modal content ranging from a trace to 0.03 percent. Clayton (1981) estimated denudation in a nearby watershed at 6.3 mm/1000 yr. Assuming S release rates parallel denudation rates, weathering would provide less than 0.05 kg ha^{-1} yr^{-1} S using the 0.03 percent figure and a bulk density of 2.6 g/cm^3 for the rock.

The four cations are retained principally on cation exchange sites in the soil. Cations incorporated in organic matter (nonadsorbed) and the lattice of secondary minerals, plus free salts of the cations in pore water, constitute a smaller pool in the soil. Under the assumption of organic matter steady state, this smaller pool represents no net gain to the soil. Clayton (1974) and Clayton et al. (1979) found that kaolinite is the secondary mineral commonly formed in batholith soils from feldspar weathering. Plagioclase weathers directly to form kaolinite. Orthoclase frequently forms a fine-grained dioctahedral mica intermediate, sericite, which subsequently weathers to kaolinite. This intermediary holds some K^+ in unavailable interlayer positions; however the fact that K^+ is leached from the watersheds indicates that it is released in sufficient amounts to occupy new exchange sites and satisfy plant growth requirements.

To estimate the annual change in cation storage in the soil one needs information on: (1) the amount of kaolinite formed annually, (2) the exchange capacity of the kaolinite, and (3) what ratios cations are arrayed on the exchange sites. The amounts of feldspar weathered annually can be estimated from the mass balances on cations from the rock weathering equation, ignoring the change in soil storage for a first approximation. For example, sodium released annually from weathering of albite is equal to stream losses minus precipitation inputs plus net vegetation uptake. In equation form:

$$\begin{aligned} Na_{rw} &= (\text{solution loss} - \text{precipitation input}) + \Delta v \\ &= (12.6 \text{ kg ha}^{-1} \text{ yr}^{-1} - 1.00 \text{ kg ha}^{-1} \text{ yr}^{-1}) + 1.94 \text{ kg ha}^{-1} \text{ yr}^{-1} \\ &= 13.5 \text{ kg ha}^{-1} \text{ yr}^{-1} \end{aligned}$$

Adjusting the mass of Na weathered by the ratio: formula weight of albite/atomic weight of Na results in 149 kg ha^{-1} yr^{-1} of albite weathered. Similar calculations for orthoclase and anorthite give 31 and 138 kg ha^{-1} yr^{-1} weathered respectively. Hydrolysis of 1 mole of albite or orthoclase forms 0.5 mole of kaolinite; 1 mole of anorthite hydrolyzes to form 1 mole of kaolinite. Table 4 summarizes the annual feldspar weathering and kaolinite formation rates.

Table 4.--Estimated feldspar weathering and kaolinite formation in SC-5 based on annual release of Na^+, K^+, and Ca^{++}.

Mineral	Primary mineral weathered		Kaolinite formed	
	kg ha^{-1} yr^{-1}	mols ha^{-1} yr^{-1}	mols ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}
Orthoclase	31	112	56	14
Albite	149	569	284	73
Anorthite	138	495	495	128
Total	318	1,176	835	215

The exchange capacity of kaolinite was estimated as follows. Cation exchange capacity (CEC) of A and C horizons from the four common soils in SC-5 were plotted versus percent organic matter. CEC was considered the sum of the exchangeable bases plus exchange acidity. A linear least squares fit (r^2 = 0.84) gave an intercept at 0 percent organic matter of 0.009 moles of charge per kg of soil. Finally, the CEC was corrected for percent clay in the soil. Clay content ranges from 5 to 10 percent; modal clay content is 8.5 percent. CEC of the clay fraction was computed to be 100/8.5 x 0.009 or 10.5 cmoles of charge per kg of clay. This rather gross technique for computing the CEC of kaolinite provides a reasonable value, near the midpoint of the accepted range of CEC values for kaolinite presented by Van der Marel (1958). Assuming 215 kg ha^{-1} yr^{-1} of kaolinite formed, this yields 22.6 moles of charge per ha annually.

I arrayed cations on the new exchange sites to correspond with the mean saturation percentage of each cation from the lab analyses of SC-5 soils.

These means are weighted by areal occurrence of soils mapped in the watershed. These percentages were determined by setting the sum of the exchangeable bases plus exchange acidity equal to 100 percent. Table 5 presents the data on annual cation accretion retained on new exchange sites on kaolinite created from feldspar weathering.

Table 5.--Estimated cation distribution adsorbed on kaolinite formed from feldspar weathering assuming 22.6 moles per ha of new exchange sites created annually.

Cation	Percent saturation	Moles of cation retained	Mass retained
			kg ha^{-1} yr^{-1}
Na+	0.3	0.068	0.0016
K+	3.0	0.68	0.027
Ca++	25.9	2.93	0.117
Mg++	5.7	0.64	0.016
H+ (acidity)	65.1	--	--

I also considered cyclic changes in cations stored in the soil pool associated with periods of rapid or slow stand growth. One might expect depletion of soil Ca or K during periods of rapid nutrient accrual to the stand, and subsequent replenishment of the soil pool following stand maturity. I was unable to document this by comparing the same soils in an adjacent watershed under a mature forest stand to soils in SC-5. Apparently, cation release from primary mineral weathering is capable of sustaining sufficient cation activity to maintain similar saturation percentages of adsorbed cations in spite of vegetation demand. Alban (1982) found a similar situation when comparing soil K pools under Populus and Pinus stands in which Populus had three times the demand for K. Similarly, they suggested that release of K from nonexchangeable mineral forms had kept pace with uptake.

DISCUSSION

Table 6 compares masses of the four cations released from weathering to the masses retained in the ecosystem as annual accrual to the soil and vegetation pool. The percentages of cations released by weathering that are retained in the ecosystem, either in incremental biomass growth or on new cation exchange sites, are presented as "Percent efficiency" in table 6. It is readily apparent that under the present stand structure, the plant pool is accreting these cations in much larger amounts than is the soil. Further, the data in table 6 suggest that following a disturbance such as fire or clearcutting, the successional dynamics of plant reestablishment will control the rate of cation accretion to the ecosystem. The rates of nutrient supply presented in this paper should be evaluated in light of the current stand growth dynamics, and what we know about successional dynamics.

Table 6.--Total weathering release of Na, K, Ca and Mg, and amount retained in the soil and vegetation as annual incremental gains to these two pools. Percent efficiency refers to the percent of cation released that is retained in the ecosystem.

Element	Released by weathering	Retained by vegetation	Retained by soil	Efficiency
	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}	percent
Na	13.5	1.94	0.002	14
K	4.3	2.42	0.03	57
Ca	20.1	10.1	0.12	51
Mg	2.4	1.18	0.02	50

The direction of succession in Douglas-fir/ninebark habitat types in the Idaho batholith has been studied in some detail.[4] From this one can speculate about succession in the Douglas-fir/spirea habitat type, and thus, have a good picture of succession in SC-5. This report provides data on species coverage changes with time following disturbance by fire or logging. In SC-5 we might expect greater than 90 percent coverage within 10 years of a disturbance. Species present would depend on whether or not fire played a role in the disturbance. For example, following burning, *Ceanothus velutinus* might cover 60 to 80 percent of the area; without burning (but with considerable ground disturbance) *Ceanothus velutinus* might be present on only 5 percent of the area with a concommittant increase in *Ribes viscosissimum* and *Ribes cereum*. There were slight increases in average shrub canopy volume 5 years following clearcutting and burning in a watershed adjacent to SC-5. Restocking of conifers is slow and coniferous biomass increment is less than that of shrubs for at least 20 years.

As conifers slowly replace shrubby vegetation, incremental growth rates are maintained at a high level or increase. The structure of the stand is important at this point in determining nutrient increment. Stands with large crown ratios require abundant nutrients, so well-stocked stands with good spacing between trees probably present a situation of high nutrient increment. Watershed SC-5 is carrying somewhat low volumes due to understocking in lower diameter classes. Density related mortality is occurring on only 13 percent of the area, although all plots with mortality were in the larger diameter classes. Timber stand improvement might increase nutrient increment in SC-5. However, the data presented here may be a reasonable maximum for a natural stand in the Silver Creek area.

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[4] Steele, Robert, and Kathleen Geier-Hayes. 1983. The Douglas-fir/ninebark habitat type in Central Idaho - succession and management. Draft Report, USDA Forest Service, Intermountain Forest and Range Experiment Station and Intermountain Region, 76 p.

LITERATURE CITED

Alban, D. H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. Soil Sci. Soc. Amer. J. 46:853-861.

Alban, D. H., D. A. Perala, and B. E. Schlaegel. 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. Can. J. For. Res. 8:290-299.

Allison, L. E. 1965. Organic carbon. In Methods of soil analysis, C. A. Black (ed.) p. 1367-1378. Amer. Soc. of Agron., Madison, Wis.

Boyle, J. R., J. J. Phillips, and A. R. Ek. 1973. "Whole tree" harvesting: nutrient budget evaluation. J. For. 71:760-762.

Brown, J. K. 1978. Weight and density of crowns of Rocky Mountain conifers. USDA Forest Service Research Paper INT-197, 56 p. Intermountain Forest and Range Experiment Sta., Ogden, Utah.

Chapman, H. D. 1965. Cation exchange capacity. In Methods of soil analysis, C. A. Black (ed.) p. 891-901. Amer. Soc. of Agron., Madison, Wis.

Clayton, J. L. 1974. Clay mineralogy of soils in the Idaho batholith. Geol. Soc. Amer. Bull. 85:229-232.

Clayton, J. L. 1979. Nutrient supply to soil by rock weathering. In Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling. p. 75-96. State Univ. of New York, Syracuse, N.Y.

Clayton, J. L. 1981. Magnitude and implications of dissolved and sediment elemental transport from small watersheds. In Proceedings: Interior West Watershed Managment Symposium, D. M. Baumgartner (ed.) p. 83-98. Washington State Univ. Coop. Ext., Pullman.

Clayton, J. L. (in press). An estimate of plagioclase weathering rate in the Idaho batholith based upon geochemical transport rates. In Rates of weathering of rocks and minerals, S. M. Colman (ed.) Academic Press, New York.

Clayton, J. L. and D. A. Kennedy. 1980. A comparison of the nutrient content of Rocky Mountain Douglas-fir and ponderosa pine trees. USDA Forest Service Research Note INT-281. 13 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Clayton, J. L., W. F. Megahan, and D. Hampton. 1979. Soil and bedrock properties: weathering and alteration products and processes in the Idaho batholith. USDA Forest Service Research Paper INT-237. 35 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Duvigneaud, P., and S. Denaeyer-De Smet. 1964. Le cycle des éléments biogènes dans l'écosystème forêts (forêts tempérées caducifoliées). Lejeunia 28:1-148.

Gholz, H. L., C. C. Grier, A. G. Campbell, and A. T. Brown. 1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Res. Paper 41, 39 p. Oregon State Univ. School of Forestry, Forest Research Lab, Corvallis, Org.

Jackson, M. L. 1964. Chemical composition of soils. In Chemistry of the Soil, Firman E. Bear (ed.). Reinhold Publ. Corp., New York. 515 p.

Johnson, C. M. and A. Ulrich. 1959. Analytical methods for use in plant analysis. Univ. of Calif. Agric. Exp. Stn. Bull. 766, 78 p.

Johnson, D. W., D. C. West, D. E. Todd, and L. K. Mann. 1982. Effects of sawlog vs. whole-tree harvesting on the nitrogen, phosphorus, potassium, and calcium budgets of an upland mixed oak forest. Soil Sci. Soc. Am. J. 46:1304-1309.

Kimmins, J. P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1:169-183.

Larsen, E. S., and R. G. Schmidt. 1958. A reconnaissance of the Idaho batholith and comparison with the southern California batholith. U.S. Geol. Surv. Bull. 1070-A, 32 p.

Leaf, A. L. 1979. Preface to the Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, Syracuse, N.Y. p ii.

Malkonen, E. 1973. Effect of complete tree utilization on the nutrient reserves of forest soils, p. 375-386. In IUFRO Biomass Studies, Univ. of Maine, Orono, Me.

Megahan, W. F., K. A. Seyedbagheri, and P. C. Dodson. 1983. Long-term erosion on granitic roadcuts based on exposed tree roots. Earth Surf. Proc. and Landforms 8:19-28.

Olsen, J. S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology 44:322-331.

Ovington, J. D. 1962. Quantitative ecology and the woodland ecosystem concept. Adv. Ecol. Res. 1:103-192.

Ovington, J. D. 1965. Nutrient cycling in woodlands. In Experimental Pedology, Hallsworth, E. G., and D. V. Crawford (eds.) p. 208-215. Butterworths, London.

Peech, M. 1965. Exchange acidity. In Methods of soil analysis, C. A. Black, (ed.) p. 905-913. Amer. Soc. of Agron., Madison, Wis.

Ross, C. P. 1963. Modal composition of the Idaho batholith, p. c86-c90. U.S. Geol. Surv. Prof. Paper 475-C.

Sollins, P., C. C. Grier, F. M. McCorison, K. Cromack, Jr., R. Fogel, and R. L. Fredriksen. 1980. The internal element cycles of an old-growth Douglas-fir ecosystem in western Oregon. Ecol. Monogr. 50:261-285.

Steele, R., R. D. Pfister, R. A. Ryker, and J. A. Kittams. 1981. Forest habitat types of central Idaho. USDA Forest Service Gen. Tech. Rep. INT-114, 138 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

Strahler, A. N., and A. H. Strahler. 1973. Environmental geoscience: interaction between natural systems and man. John Wiley and Sons, Inc., New York. 511 p.

Tamm, C. O. 1964. Determination of nutrient requirements of forest stands. Int. Rev. Forestry Res. 1:115-170.

Tiedemann, A. R., and T. D. Anderson. 1971. Rapid analysis of total sulfur in soils and plant material. Plant and Soil 35:197-200.

Van der Marel, H. W. 1958. Quantitative analysis of kaolinite. J. Int. Etud. Argiles 1:1-19.

Vitousek, P. M., and W. A. Reiners. 1975. Ecosystem succession and nutrient retention: a hypothesis. Bioscience 25:376-381.

Weaver, C. E., and L. D. Pollard. 1973. The chemistry of clay minerals. Elsevier Scientific Publishing Co., Amsterdam, London, New York. 213 p.

Weaver, T., and F. Forcella. 1977. Biomass of fifty conifer forests and nutrient exports associated with their harvest. Great Basin Naturalist 37:395-401.

Weetman, G. F., and B. Webber. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For. Res. 2:351-369.

Wells, C. G. and J. R. Jorgensen. 1979. Effect of intensive harvesting on nutrient supply and sustained productivity, p. 212-230. In Proceedings: Impact of Intensive Harvesting on Forest Nutrient Cycling. State Univ. of New York, Syracuse, N.Y.

Clayton, J. L. A rational basis for estimating elemental supply rate from weathering / James L. Clayton. p. 405-419 ; 20 cm. In, North American Forest Soils Conference (6th : 1983 : Knoxville, Tenn.) Forest soils and treatment impacts ... / edited by Earl L. Stone. -- Knoxville : University of Tennessee, Dept. of Forestry, Wildlife and Fisheries, c1984.