# Fuel Reduction—Nutrient Status and Cycling Relationships Associated with Understory Burning in Larch/Douglas-Fir Stands

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## INTRODUCTION

THROUGHOUT recorded history, natural and man-caused fires have generated several important unanswered questions. These questions can be summed up as; "How do different atmospheric conditions, fuel loadings, fuel moisture, residence times, air and fuel temperatures, soil characteristics, and post burn meteorological conditions influence soil ecology, smoke dispersal and particularly nutrient cycling?"

Large quantities of old fuels in the form of pitchy stumps and logs have accumulated on the forest floor in western Montana and today pose a serious fire hazard. Natural decomposition is too slow to reduce these fuels as fast as they accumulate. Any fire adequate to completely reduce these fuels might also kill the overstory trees and destroy large volumes of timber in some forest types. The concept of progressive burning under standing timber (called BUST burning*)

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* The BUST term was used by Gardner Ferry, in his Master's Thesis, "Prescribed burning conditions for western Montana." 1970. University of Montana.

may be an answer to this problem. BUST burning is done under cooler and moister conditions than normally encountered in wildfires. Instead of one fire, the land manager would schedule two or three burns under standing timber over a 10 to 15-year period. Thus, fuel reduction would be accomplished in increments so that each burn would release small amounts of nutrients adequate to stimulate growth without great nutrient losses or serious fire damage to the trees. Insect and disease problems are closely tied to the burning frequency and demand careful study. Also, low temperature burns may produce large volumes of smoke which must be studied to develop techniques that will accomplish rapid dispersal.

This portion of the study was initiated in cooperation with the Northern Forest Fire Laboratory of the U.S. Forest Service to examine the nutrient cycling aspects of 20 control burns with 10 unburned control plots. Fuel, climatic, and fire measurements during the controlled burns were conducted by Rodney Norum of the Northern Forest Fire Laboratory, and the smoke dispersal problems were studied by Robert W. Steele of the School of Forestry, University of Montana.

The objective of the nutrient portion of this research was to study nutrient movement in the soil after burns of different intensities and under different conditions. Specifically, the ability of the soil to hold nutrients was calculated, and the amount of each element released for the ash by the equivalent of 1 year's precipitation over a known surface area was measured in leaching tests. The actual loss of nutrients from the system below the root zone was measured and compared to the predicted loss based on the storage capacity of soil and infiltration data.

Nutrient loss occurs from forest ecosystems most of the time unde natural conditions. Some nutrient loss results from natural erosion especially after heavy storms or sudden snow melt in areas wher man has had little influence. Nutrient loss also occurs as water move over the soil surface or through the soil to levels below the ro zone. Natural nutrient losses are usually not great, except under th influence of 100-year floods or deluges.

Man's use of the land usually causes an acceleration of nutrie loss because many of his actions disturb the soil or change drainage or infiltration characteristics.

The seriousness of any natural or man-caused nutrient loss from an ecosystem can only be judged in relation to the "biological life" of the soil associated with that ecosystem. The reasoning behind the "Biological Life of a Soil" is as follows:

1. We have always thought of our forests as renewable natural resources.
2. Forests are renewable only as long as there is a proper balance of biologically important elements in available form in the soil.
3. Once one or more biologically important elements such as calcium or phosphorus are depleted from the soil so that they become limiting to tree growth, then the forest is no longer a renewable resource.
4. Forest managers have traditionally concerned themselves with timber harvest on a short-term basis, but they have neglected the long-term capabilities and limitations of the soil.
5. For the good of mankind, it is essential for forest managers to take a longer view and to begin to consider the biological life of a soil.
6. The biological life of a soil is the length of time on the geologic time scale that a soil can supply adequate levels of nutrients to support forest vegetation, (vegetational changes resulting from climatic fluctuations are not considered, as long as the soil *could* support trees).
7. When rock is formed by the cooling of molten lava, or by secondary deposition, the balance of biologically important nutrients is fixed for all time.
8. As soil weathers from rock under the influence of climate, vegetation, water, and physical-chemical forces, elements originally trapped in the minerals of the rock are slowly released and made available to plants. Precipitation adds annually to the total store of nutrients, but in relatively small amounts.
9. The biological recycling of elements from dead organic matter to soil to roots perpetuates these elements by making them avail-

able to many generations of trees. Nutrients are added to the system in dust, deposition, and bulk precipitation.

10. There are inevitable losses of elements from the cycling of nutrients in the forest through leaching of elements below the root zone, or overland by surface runoff.
11. It is the rate at which elements are lost from the root zone that determines the length of the biological life of a soil.
12. The rate of nutrient loss is influenced by many land use practices, particularly the frequency and intensity of burning. In theory, the biological life of a soil can be shortened by too frequent or too intense burning, resulting in massive nutrient losses from below the root zone. The fire frequency of the forest before the control of fires may closely approximate the most beneficial fire frequency in terms of tree growth.

In western Montana, coniferous forest is the climax vegetation type. The rate at which soil forms is dependent on the weathering rate, which cannot be accurately measured at this time. Weathering and the annual precipitation acting on certain physical characters of the soil will determine the length of the "biological life" of a soil under natural conditions. Soil disturbance alters this time span.

We can measure the total elemental content of soil or rock using acid digestion with HF-$HClO_4$ and establish its long-term nutrient balance (percent which each cation or anion is of the total cations or anions). This balance will alter with differential uptake. From nutrient solution formulae for conifers or from nutrient balance in living trees, we can determine the nutrient percentages needed by the trees. This balance can be checked against the balance of total nutrients in the soil to determine which biologically important element is most likely to become limiting to tree growth. Either cation balance or cations plus anion balance can be determined. Hence, any nutrient loss occurring naturally or from man's actions can be evaluated in terms of the rate of loss of the one or two elements most likely to become limiting to conifer growth at some time in the future. For example, if burning causes excessive losses of calcium below the root zone in a soil which is low in total calcium, and where weathering is judged to be fast due to soil temperatures and moisture, then burning will shorten the biological life of that soil. If the calcium losses below the root zone after burning are very small (i.e. close to the natural levels of calcium loss), then burning on that soil will cause little damage to the nutrient budget and can be considered as practical from a nutrient cycling point of view. Our task is to prescribe fire to minimize nutrient loss. Any other forest land use such as logging or recreation can be evaluated in the same way.

In referring to the "biological life" of a soil, we are concerned with geologic time, or millions of years. Foresters and land managers have seldom thought in this time frame before. As a result, our forestry practices have been short-term, demanding frequent changes in management policies as economic or political needs change. Thinking in terms of the "biological life" of a soil will extent our planning capabilities to include the true potential of any specific site and will make it possible for mankind to make the greatest possible use of the soil resource over long periods of time within limits of economic restraints. It also will allow ecologically sound forest management in the future.

Throughout the world today there are very few soils which are becoming worn out or depleted of biologically important nutrients. Although soil depletion is not a serious problem world-wide in 1974, our land use practices must be examined carefully to ascertain how much damage is occurring to existing soils.

Brazil, Guyana, Surinam (Stark, 1970), and Venezuela have soils which have suffered from nutrient depletion and have lost their fertility. These are white sands (spodosols) which were formed from heavily leached sediments derived from nutrient-poor granites in the Guiana Highlands and the Brazilian shield. After transport, these sediments formed soils which weathered rapidly under the influence of high temperatures, moist conditions, and acid-producing vegetation (Stark, 1971a). Heavy rains and permeable soils produced strong leaching losses of nutrients. The weathering of rock poor in calcium and phosphorus produced soils which weathered rapidly and in time became deficient in calcium and phosphorus eventually forming a substrate too poor in these nutrients to support the existing forest vegetation (Stark, 1971b). The depletion process can proceed to a point where only small grasses and lichens which obtain most of their nutrients from precipitation, can grow on the soil. Forests do exist on poor white sands in South America today because of the direct nutrient cycling pattern which has evolved there. Mycorrhizal fungi with the aid of bacteria, free-living fungi, and some litter animals are thought to decompose the forest litter and pass biologically important nutrients from the litter directly to the roots, by-passing the depleted soil (Stark, 1968). Most coniferous forest areas rely on indirect nutrient cycling in which the roots pick up nutrients from the soil solution, not from litter. Some direct nutrient transfer via mycorrhizal fungi probably does occur in coniferous forests, but much of the nutrient up-take is from the soil with the aid of mycorrhizal fungi. The decline of the fertility of these white tropical sands can be traced to about 100 years of cutting and burning, which has depleted the large reserves of biologically important nutrients that were stored up in the vegetation over millions of years. Similar patterns of soil decline can occur on temperate soils also, but the rate will probably be slower because of low temperatures and low rainfall. Climatic fluctuations may also be more frequent than in the tropics.

The most important point of the discussion of nutrient depletion on tropical soils is that extremely low cation exchange capacities (0.5-3 me/100g) and high precipitation (3000 mm/yr) have allowed massive nutrient losses after logging and fire resulting in a brief 1-2 year growth stimulus for crops followed by accelerated decline of the productivity of the soil. Fire, if misused on a soil of this type, can drastically shorten the "biological life." Fire on another soil can temporarily enrich that soil if frequency and intensity are balanced against the ability of the soil and plants to store nutrients.

The overall objective of this cooperative research was to begin to develop a fire prescription that would provide a series of simple measurements which could eventually be made by a land manager on any forest or soil type to achieve the following results:

a. some reduction of old fuels to lessen the hazard of holocaust fires
b. minimal damage to the standing timber, but in some case thinning of the understory
c. short-term smoke accumulations with no serious dispersal problems

d. enough nutrient release to stimulate growth but not excessive nutrient loss below the root zone or through overland flow.

Thus, by burning under the right climatic and fuel moisture conditions, it should be possible to select situations which will make fire a useful tool in old fuel reduction and return fire to the ecosystem. The ignition and control systems and the fuel moisture meter used here (McLeod, 1974; Norum, 1974) would allow small crews to burn large areas of Douglas-fir—larch forest in western Montana with a minimum of risk from escape fires, modest cost, and with predictable, low nutrient losses.

## METHODS

A satisfactory description of the methods used in this study is not possible in the space allotted. Details of these methods will be published at a later date.

The studies were conducted on the Lubrecht Experimental Forest in 1973 at 1464m elevation in a Douglas-fir (*Pseudotsuga menziesii*) (Mirb.) Franco)—larch (*Larix occidentalis* Nutt.), north slope, second growth ecosystem.

The rocks of the slope are varied in size and nearly abundant enough to constitute talus. These quartzitic argillites are derived from the Bonner formation.

The soils are of the Holloway Series and are thin, poorly developed rocky soils of generally sandy texture.

The climate is warm and dry in summer (to 36C) and cold and wet in winter (to −35C) with 3-4m of snow. Annual precipitation is about 450 to 560 mm (Steele, 1973).

Twenty plots were burned in 1973, (in cooperation with Rodney Norum and Robert Steele), leaving ten unburned control plots. Preburn data were taken on: (a) the total and extractable elements (Ca, Cu, Fe, K, Mg, Mn, Na, P, Zn, total N and pH) in the soil above (0-5 cm), within (20-25 cm), and below the root zone (55-60 cm); (b) the elemental content of green living vegetation per meter square; (c) the elemental content of litter; (d) cation exchange capacity; (e) infiltration rate; (f) bulk density; (g) particle density; (h) percent base saturation; (i) extractable hydrogen; (j) root biomass; (k) soil moisture (monthly); (1) soil separates to 2mm; and (m) the percent sand, silt and clay in the fraction under 2mm in diameter.

After the burns, weekly measurements of soil water quality were made above, within, and below the root zone at the same depths as for soil samples and for the same 10 elements plus F-, NO-, and pH. Monthly post-burn soil samples (180-380 samples/month excluding December-April) were taken for determination of extractable elements as with the pre-burn samples, and as available, collections of overland flow, precipitation, and thrufall were made. Litter decomposition studies compared decay on burned versus unburned sites. Analyses of cations were made on a Techtron AA-5 atomic absorption spectrophotometer; fluoride, pH, and nitrate were analyzed with specific ion electrodes; total nitrogen was measured with semimicroKjeldahl (Hesse, 1971); and phosphate was measured colorimetrically (Farber, 1960).

Ash leaching studies introduced the concept of "nutrient supplying power of ash" and the combined physical and chemical measurements on the soil laid the basis for quantifying the "nutrient storage capacity" of the soil.

It is sufficient to indicate that all soil, water, and plant parameters bearing on nutrient cycling which could be measured were measured. A few exceptions had to be made: (a) nutrient uptake rate by plants; (b) nutrients lost in smoke; (c) the weathering rate of soil; and (d) extensive studies of soil and litter microbial and faunal populations. These are key and important aspects which could not be covered within the scope of this study.

## RESULTS

If one were to ask the question, "What parameters should be measured if we want to *understand* the influence of fire on nutrient cycling," one might make a list something like this:

I.Above-Ground Fire Characteristics[*]

✓A. Fuel loading minus stumps (5.55-16.67 kg/$m^2$, Norum, 1974).

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[*] Checked items are those for which data are available from this study. Data are relative to a block of soil 1m x 1m x 0.6m the latter is the limit of the feeder root zone.

Table 1. Range of nutrient content of fuels from the burn tests, Lubrecht Experimental Forest.

| RANGE | Ca | Cu | Fe | K | Mg | Mn | N | Na | P | Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| *Litter* | | | | | | | | | | |
| µg/g | 5400 | 12 | 110 | 500 | 500 | 200 | 7140 | 31 | 530 | 24 |
| (av. 3585g/$m^2$) | 17500 | 32 | 5000 | 5000 | 18000 | 2350 | 15180 | 140 | 3950 | 310 |
| me/$m^2$ | 968 | 1.35 | 21.2 | 45.8 | 147 | 39.2 | — | 4.8 | — | 2.6 |
| | 3137 | 3.6 | 963.7 | 458 | 531 | 460 | — | 21.8 | — | 34 |
| Total Cations—Litter 1230-5609me/$m^2$ | | | | | | | | | | |
| *Herbs & Shrubs* (live) | | | | | | | | | | |
| µg/g | 3250 | 9 | 115 | 2500 | 750 | 40 | 5460 | 28 | 430 | 10.5 |
| (av. 153g/$m^2$) | 10000 | 30 | 420 | 15750 | 2350 | 3750 | 9800 | 205 | 4750 | 340 |
| me/$m^2$ | 24.9 | .04 | .95 | 9.78 | 9.4 | 0.33 | — | 0.19 | — | 0.05 |
| | 76.5 | .14 | 3.45 | 61.6 | 29.6 | 31.4 | — | 1.4 | — | 1.6 |
| Total Cations, Herbs & Shrubs 46-206me/$m^2$ | | | | | | | | | | |
| *Wood* | | | | | | | | | | |
| µg/g | 840 | 5.0 | 105 | 118 | 100 | 58 | — | 23 | 308 | 9.3 |
| (av. 6021g/$m^2$) | 2650 | 8.2 | 258 | 265 | 300 | 134 | — | 60 | 1524 | 19.4 |
| (minus stumps) | | | | | | | | | | |
| me/$m^2$ | 253 | 0.9 | 33.9 | 18.2 | 49.5 | 19.1 | — | 6.0 | — | 1.7 |
| | 798 | 1.6 | 83.7 | 40.8 | 148.5 | 44.1 | — | 15.7 | — | 3.6 |
| Total Cations—Wood 382.3-1136me/$m^2$ | | | | | | | | | | |
| Total me/$m^2$ | 1167 | 2.0 | 46 | 68 | 191 | 53 | — | 9.1 | — | 3.9 |
| | 3763 | 4.8 | 1025 | 548 | 663 | 522 | — | 34.0 | — | 38.1 |

Total cations potentially available from a 100% burn=1658-6951me cations/$m^2$

✓B. Nutrient content of fuels (1540-6598 me/$^2$ for cations, minus stumps which defy accurate measurement (Table 1).
✓C. Fuel moisture (8 to 27%, branchwood 0.6-2.5cm diameter; Norum, 1974; McLeod, 1974).
✓D. Burn temperatures (103-650C, at 5cm in the soil, 650C to 15cm; Norum, 1974).
✓E. Burn intensity (temperature-duration, 33-213 Kcal/sec./m$^2$; Norum, 1974).
✓F. Amount of fuel reduction (1.68-10.83 kg/m$^2$; Norum, 1974, or ash production (0.17-1.08 kg/m$^2$) and percent of plot with different levels of fuel reduction.
✓G. Volume of smoke produced (8,000 to 1,400,000 m$^3$, Steele, 1974) and meteorological conditions associated with the burns, burning index 2-50, National Fire Danger Rating System.
H. Elemental content of smoke and nutrient loss at different burn temperatures (laboratory studies in progress).✓

II. Post-Burn Conditions
✓A. Nutrients available in ash, cation balance, and anion balance, based on me/m$^2$ (Table 2).
✓B. Amount of bulk precipitation (565 *l*/m$^2$/yr.).
✓C. Nutrient content of bulk precipitation and thrufall, plus pH as (free H+) absolute hydrogen ion concentration and cation balance, anion balance (percent of total anions, or cations). Total cation input—125 me/m$^2$/yr. (Table 3).
✓D. Infiltration rate (297 *l*/m$^2$/min., wet after burn; with percent soil moisture 0-5cm=38%, 20-25cm=23.5%, 50-55cm=15.0%; 1653 *l*/m$^2$/min. (moist) before burn; 1696 *l*/m$^2$/min. (moist) after burn (difference not significant). Depth, duration, timing of freezing, organic and clay content, surface moisture and soil temperature influence infiltration. Maximum snow depth in March 52.8cm, minimum depth 17. cm; snow water equivalent .11—.196, soil surface ice dept 0—8.3cm.
✓E. Percolation rate—extremely high, 54% rock over 2mm di meter.

Table 2. Nutrients available in ash as $\mu g/g$, mg/kg, me/$m^2$ and percent balance (6NHCL extract).

| RANGE | Ca | Cu | Fe | K | Mg | Mn | N | Na | P | Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| $\mu g/g$ | 36,000 | 15 | 1500 | 3800 | 2500 | 1000 | 550 | 165 | 6500 | 100 |
|  | 100,000 | 91 | 11,000 | 40,000 | 15,000 | 15,000 | 550 | 850 | 21,000 | 950 |
| me/kg | 1.8 | 0.0005 | 0.081 | 0.09 | 0.21 | 0.055 | — | 0.007 | — | 0.003 |
|  | 5.0 | 0.003 | 0.59 | 1.02 | 1.23 | 0.82 | — | 0.037 | — | 0.029 |
| 0.644 kg ash/$m^2$ (X$10^3$) |  |  |  |  |  |  |  |  |  |  |
| Kg ash/$m^2$=2.75 |  |  |  |  |  |  |  |  |  |  |
| 10.7 kg/m2 |  |  |  |  |  |  |  |  |  |  |
| me/$m^2$=4.95 |  |  |  |  |  |  |  |  |  |  |
| 53.5x$10^3$ |  |  |  |  |  |  |  |  |  |  |
| RANGE |  |  |  |  |  |  |  |  |  |  |
| % Balance |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  | Cations |
| me/kg | 79.86 \ | 0.03 | 3.33 | 8.43 | 5.54 | 2.22 | — | 0.37 | — | 0.22 |
|  | 54.68 | 0.05 | 6.01 | 21.87 | 8.20 | 8.20 | — | 0.47 | — | 0.52 |
| Av. | 67.27 | 0.04 | 4.67 | 15.2 | 6.87 | 5.21 | — | 0.42 | — | 0.37 |

Table 3. Nutrient content of bulk precipitation and thrufall combined from four stations—Lubrecht Fire Study.

| | Ca | Cu | Fe | F | K | Mg | Mn | $NO_3$ | *Na | $PO_4$ | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Av. mg/ℓ | 0.75 | 0.02 | 0.06 | 0.03 | 2.49 | 0.15 | 0.08 | 1.33 | 2.28 | 0.43 | 0.03 |
| Av. mg/m$^2$/yr | 423.0 | 11.3 | 33.9 | 16.9 | 1406 | 84.7 | 45.2 | 750.8 | 1287.1 | 242.7 | 16.9 |
| Total mg/m$^2$/yr (cations)=3307.7 | | | | | | | | | | | |
| Av. me/m$^2$yr (mg/m$^2$/yr 565ℓ m$^2$/yr) | 21.2 | 0.36 | 1.82 | — | 35.95 | 6.94 | 2.47 | — | 55.98 | — | 0.52 |
| Total me/m$^2$/yr as me—125.24 | | | | | | | | | | | |
| Cation % Balance as me/m$^2$yr | 16.92 | 0.28 | 1.45 | — | 28.71 | 5.54 | 1.97 | — | *44.71 | — | 0.42 |
| as mg/m$^2$/yr | 12.79 | 0.34 | 1.02 | — | 42.50 | 2.56 | 1.37 | — | 38.91 | — | 0.51 |

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*Note—high sodium levels are from the leaching of burned tissue which is dead, not from other contamination. Bulk precipitation and thrufall are combined in a 1/3 ratio to approximate the quality of water actually reaching the forest floor.

F. Run-off rate (0.036$l/m^2$/yr; estimated short-transit; average of 138.3g solids transported from each of eight 280 $m^2$ micro-watersheds per year (Table 4).

✓G. Nutrient content of run-off for controls and burns (mg/$l$) average over one year (0.018 me/$m^2$/yr for cations; nutrient balance (% of total) for controls and burns).

✓H. Average storm duration (intensity) 0.07 cm/hr., maximum =0.45 cm/hr.; minimum=0.003 cm/hr., or 0.03 to 4.46$l/m^2$/hr.

✓I. Nutrient release rate from ash (experimental), 5g samples leached with 1000ml of precipitation, total cations=3220 −4831me/$m^2$ or 10 to 64% of total cations present in ash (Table 5). Estimated loss in me/$m^2$/yr.=946−5870 me/$m^2$/yr.

✓J. Input of nutrients from decomposition of organic matter (me/$m^2$/yr); 25.9% weight loss of Douglas-fir needles on a burned substrate compared to 22.7% weight loss of needles on an unburned substrate after one year; estimated average nutrient release=776 me/$m^2$/yr cations).

K. Animal losses and removal of nutrients in vegetation in me/$m^2$/yr.

L. Additions to dead organic load from attack by bark beetles; spruce budworm and other insects, loss of biomass (Norum, 1974); lost growth.

✓M. Growth increase per year (stimulation) and mortality Norum, 1974).

III. Nutrient Cycling Below Ground

✓A. Nutrient storage capacity of the soil for a block 100 x 100 x 60 cm (depth of feeder root zone)=volume of soil in the root zone per $m^2$, x bulk density (corrected for the weight of air), minus % roots, minus % rocks over 2mm (with low C.E.C.)÷100 (100g base for C.E.C.) x C.E.C. in me/100g corrected for 100−% base saturation (corrected for 20% estimated cation storage on large rocks, roots)=true cation storage capacity of the soil=6786 me/0.6$m^3$ of root zone. (C.E.C. calculated on the basis of maximum figures instead of averages results in a C.E.C. of 14,559 me/0.6$m^3$.

Table 4. Nutrient content of run-off as mg/ℓ and me/$m^2$/yr, and pH as absolute hydrogen ion concentration, and percent balance, Lubrecht Fire Study.

| CONTROLS | | pH | CaCu | Fe | F | K | Mg | Mn | $NO_3$ | Na | $PO_4$ | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mg/ℓ | -05<br>.1224 | 1.82 | 0.025 | 0.054 | 0.044 | 6.67 | 1.01 | 0.17 | 0.81 | 3.42 | 1.51 | 0.05 |
| me/$m^2$/yr | | 0.003 | 0.00003 | 0.00001 | – | 0.000061 | 0.003 | 0.00003 | – | 0.0053 | – | 0.00005 |
| (mg) displaced on slopes 27-42% 0.0357 /$m^2$/yr. from watersheds of 280 $m^2$ area= 0.0179me/$m^2$/yr | | | | | | | | | | | | |
| % Balance Cations (me) | | 16.78 | 0.17 | 0.56 | – | 34.12 | 16.78 | 1.68 | – | 29.64 | – | 0.27 |
| BURNS | -05<br>.1190 | | | | | | | | | | | |
| mg/ℓ | | *8.05 | 0.033 | 0.091 | 0.096 | 10.411 | 2.941 | *0.473 | *1.315 | 5.809 | 2.246 | 0.046 |
| me/$m^2$/yr, Total= 0.043m3/$m^2$/yr✓ | | 0.014 | 0.00004 | 0.0002 | – | 0.0098 | 0.0086 | 0.0009 | – | 0.0090 | – | 0.00006 |
| % Balance | | 32.86 | 0.09 | 0.48 | – | 23.00 | 20.19 | 2.11 | – | 21.13 | – | 0.14 |

*Levels of elements in burn plots are significantly higher than those in the control plots at the 0.5% level.

✓2.4 x the nutrient (cation) loss of the controls; but not significant on a watershed scale because of the short transit.

Table 5. Nutrient release from ash under the influence of natural precipitation.

| | Ca | Cu | Fe | K | Mg | Mn | $NO_3$ | Na | P | Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| Av. mg/ℓ (10 x, 100mlea 5g sample) | 177.4 | 0.20 | 0.13 | 606.6 | 23.96 | 0.24 | 41.57 | 7.19 | 9.78 | 0 |
| me/ℓ/g ash | 1.77 | 0.0012 | 0.0014 | 3 | 0.394 | 0.003 | — | 0.063 | — | 0 |
| Est. me/m²/yr (565ℓ/m²) (weighted) | 1069 | 0.725 | 0.846 | 1872 | 238 | 1.812 | — | 38.05 | — | 0 |
| 3220-4831 me/m²/yr | 1604 | 1.088 | 1.269 | 2808 | 357 | 2.718 | — | 57.08 | — | 0 |

✓B. Content of acid extractable (0.002N$H_2SO_4$) and readily available cations in the soil, *above*=newly freed nutrients at 0–5cm; *within*=nutrients made available to roots at 20–25cm; *below*=nutrients lost to roots at 50–55cm the root zone for a range of 20 burn intensities and 10 controls for the first year—data under analysis.

✓C. Total elemental content of soil, average of 5cm intervals to 60cm depth, % balance (% of totals Table 6).

D. Rate of nutrient uptake by shrubs, herbs, trees (all ages), mosses, lichens, fungi, bacteria, microarthropods, nutrient storage on root surfaces (rhizosphere), changes in microbial ATP✓, population fluctuations, root death, "sink" organisms.

E. pH changes in soil✓, ionic interactions✓, concentration effects, physical characteristics.

F. Rate of nutrient conversions to insoluble forms, trapping by clays.

✓G. Nutrient balance of coniferous vegetation, nutrient solution used for conifers, soil water as a means of evaluating the seriousness of nutrient loss (Table 7).

✓H. Nutrient movements through the soil profile in soil water and *loss below the root zone* as mg/*l* and me/m$^2$/yr from soil water, and pH as absolute hydrogen ion concentration, cation and anion balance (%); levels of cations and anions (me/m$^2$/yr) in water on burned plots *above, within,* and *below* the root zone as compared to those for the same levels in control plots (Table 8).

I. Rate of nutrient additions from weathering (not readily measurable).

For practical purposes it would be impossible for a land manager to measure all of these parameters. This overall study will ultimately define the few parameters which are essential to the reasonable prediction of tree damage, smoke build-up, growth stimulation, and nutrient loss. Further testing is needed before these parameters can be defined so that a land manager could use the prescription with ease. A clear understanding of interrelationships and prediction levels is essential to completion of the prescription. Detailed statis-

Table 6. Total elemental content of Lubrecht soils and percent balance of nutrients with and without nitrogen and phosphorus.

| | Ca | Cu | Fe | K | Mg | Mn | N | Na | P | Zn |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Elemental Content $\mu$g/g av. of 5 cm depths to 50cm | 2247 | 10.3 | 13.237 | 20,274 | 1312 | 334 | 615 | 3574 | 596 | 257 |
| me/kg | 112.4 | 0.32 | 710.9 | 518.5 | 107.9 | 18.3 | — | 155.5 | — | 7.86 |
| % Balance ($\mu$g/g) | 5.46 | 0.02 | 32.09 | 49.16 | 3.18 | 0.81 | — | 8.66 | — | 0.62 |
| Cations (me/kg | 6.89 | 0.02 | 43.57 | 31.78 | 6.61 | 1.12 | — | 9.53 | — | 0.48 |
| Cations+Anions ($\mu$g/g) | 5.29 | 0.02 | 31.18 | 47.75 | 3.09 | 0.79 | 1.45 | 8.42 | 1.40 | 0.61 |

Table 7. Nutrient balance in nutrient solution used for the growth of conifers, soil water after burns; and trees (as a sum of the parts) on the basis of mg/ℓ.

| | | Ca | Cu | Fe | K | Mg | Mn | N | Na | P | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|
| % Balance, Nutrient Solution | | 28.00 | 0.006 | 0.28 | 27.4 | 6.73 | 0.07 | 30.0 | 3.08 | 4.35 | 0.007 |
| % Balance, Soil | | 43.96 | 0.09 | 0.49 | 26.91 | 10.79 | 2.03 | 6.84 | 7.33 | 1.47 | 0.09 |
| Water | Burn | 43.96 | 0.09 | 0.49 | 26.91 | 10.79 | 2.03 | 6.84 | 7.33 | 1.47 | 0.09 |
| All Depths | Control | 41.57 | 0.27 | 1.42 | 23.64 | 10.03 | 0.54 | 7.17 | 9.62 | 5.59 | 0.15 |
| % Balance, Needles, Wood, Bark, Douglas-fir | | 12.3 | 0.09 | 0.91 | 24.2 | 3.5 | 1.5 | 39.6 | 0.7 | 17.0 | 0.2 |
| Shrubs (5 species) | | 3.2 | 0.03 | 0.34 | 29.27 | 3.7 | 2.9 | 44.22 | 0.24 | 16.05 | 0.05 |

Table 8. Average nutrient levels in soil leachate from all burns and controls by depth (A=0-5 cm, B=20-25cm; C=50-55cm), and percent nutrient balance.

| CONTROLS | | Ca | Cu | Fe | F* | K | Mg | Mn | $NO_3$* | Na | $PO_4$* | An |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depth A | mg/ℓ | 6.678 | 0.066 | 0.201 | 0.104 | 6.155 | 1.523 | 0.180 | 1.404 | 1.683 | 1.261 | 0.35 |
| | me/ℓ | 0.33 | 0.002 | 0.011 | — | 0.157 | 0.125 | 0.009 | — | 0.073 | — | 0.001 |
| % Bal. | mg/ℓ | 34.05 | 0.34 | 1.03 | 0.53 | 31.40 | 7.77 | 0.92 | 7.16 | 8.58 | 6.43 | 1.79 |
| | me/ℓ | 46.61 | 0.28 | 1.55 | — | 22.18 | 17.66 | 1.27 | — | 10.31 | — | 0.14 |
| Depth B | mg/ℓ | 8.139 | 0.396 | .250 | .102 | 3.108 | 2.041 | 0.032 | 1.176 | 2.061 | 1.000 | 0.073 |
| | me/ℓ | 0.406 | 0.001 | 0.013 | — | 0.079 | 0.17 | 0.002 | — | 0.09 | — | 0.001 |
| % Bal. | mg/ℓ | 44.40 | 2.16 | 1.36 | 0.56 | 16.95 | 11.14 | 0.17 | 6.42 | 11.25 | 5.46 | 0.13 |
| | me/ℓ | 53.28 | 0.13 | 1.71 | — | 10.37 | 22.31 | 0.26 | — | 11.81 | — | 0.13 |
| Depth C | mg/ℓ | 6.489 | 0.033 | 0.274 | 0.059 | 2.851 | 1.574 | 0.066 | 1.095 | 1.189 | 0.606 | 0.016 |
| | me/ℓ | 0.324 | 0.001 | 0.015 | — | 0.073 | 0.13 | 0.004 | — | 0.052 | — | 0.001 |
| % Bal. | mg/ℓ | 45.53 | 0.23 | 1.92 | 0.41 | 20.00 | 11.04 | 0.46 | 7.68 | 8.37 | 4.25 | 0.11 |
| | me/ℓ | 54.00 | 0.17 | 2.50 | — | 12.17 | 21.67 | 0.66 | — | 8.66 | — | 0.17 |
| *Burns* | | | | | | | | | | | | |
| Depth A | mg/ℓ | 21.326 | 0.045 | 0.185 | 0.079 | 14.898 | 5.408 | 1.273 | 4.847 | 3.298 | 0.787 | 0.041 |
| | me/ℓ | 1.064 | 0.001 | 0.01 | — | 0.38 | 0.445 | 0.07 | — | 0.14 | — | 0.001 |
| % Bal. | mg/ℓ | 40.86 | 0.09 | 0.35 | 0.15 | 28.55 | 10.36 | 2.44 | 9.29 | 6.32 | 1.51 | 0.08 |
| | me/ℓ | 50.40 | 0.05 | 0.47 | — | 18.00 | 21.08 | 3.32 | — | 6.63 | — | 0.05 |
| Depth B | mg/ℓ | 20.645 | 0.046 | 0.229 | 0.080 | 11.406 | 4.667 | 1.201 | 2.138 | 3.452 | 0.675 | 0.039 |
| | me/ℓ | 1.03 | 0.002 | 0.012 | — | 0.29 | 0.38 | 0.07 | — | 0.15 | — | 0.001 |
| % Bal. | mg/ℓ | 46.31 | 0.10 | 0.51 | 0.18 | 25.59 | 10.47 | 2.69 | 4.80 | 7.75 | 1.51 | 0.09 |
| | me/ℓ | 53.23 | 0.10 | 0.62 | — | 14.99 | 19.64 | 3.62 | — | 7.75 | — | 0.05 |
| Depth C | mg/ℓ | 14.885 | 0.036 | 0.208 | 0.057 | 8.500 | 3.876 | 0.151 | 1.872 | 2.721 | 0.436 | 0.032 |
| | me/ℓ | 0.74 | 0.001 | 0.01 | — | 0.22 | 0.32 | 0.008 | — | 0.12 | — | 0.001 |
| % Bal. | mg/ℓ | 45.42 | 0.11 | 0.63 | 0.17 | 25.94 | 11.83 | 0.46 | 5.71 | 8.30 | 1.33 | 0.10 |
| | me/ℓ | 52.11 | 0.07 | 0.70 | — | 15.49 | 22.55 | 0.56 | — | 8.45 | — | 0.07 |

Table 8. (continued)

| CONTROLS | Ca | Cu | Fe | F* | K | Mg | Mn | $NO_3$* | Na | $PO_4$* | An |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Burns± me/ℓ Over Controls | | | | | | | | | | | |
| Input A | +.73 | −.001 | −.001 | — | +.22 | +.32 | +.06 | — | +.067 | — | 0 |
| Growth B | +.62 | +.001 | −.001 | — | +.21 | +.21 | +.07 | — | +.060 | — | 0 |
| Loss C | +.42 | 0 | −.005 | — | +.15 | +.19 | +.004 | — | +.068 | — | 0 |

*Note, F, $NO_3$, $PO_4$ are not converted to me/ℓ since it is not possible to quantify anion exchange capacity.

tical analyses will be published later, and each burn will be examined separately.

Nutrient movement is determined according to the following model:

Total Annual Aerial Input
↓ └→ Overland Flow (Loss) ______
Annual Additions from Ash or Decomposition
↓
Storage Capacity of the Soil
↓ └→ Uptake by Organisms ______
Nutrient Loss Below the Root Zone

(Calculated and Measured, Table 9)

The unconventional data presentation in this paper is tailored to the specific needs of this model.

## DISCUSSION

1. All data are preliminary and represent only the first year after burning.
2. Data are converted to $me/m^2/yr$ whenever possible for comparison of the reactive ability of those cations being studied. Anions was not measured in relation to the storage capacity of the soil because anion exchange capacity is not readily measurable.
3. Statistical analyses of data plot by plot and element by element, by season, by intensity, by soil depth, and by cations, anions and their balances are incomplete. Table 9 is intended to show how these data will ultimately be used. Therefore, Table 9 is to be regarded as preliminary.
4. The maximum storm intensity of 0.074 $l/m^2/min.$ (4.45 $l/m^2/hr$) does not exceed the slowest infiltration rate of 297 $l/m^2/min.$ and hence overland flow should not occur. Overland flow *did* occur only at times when the surface soil was frozen, or when

Table 9. Theoretical nutrient flow in control, light and hot burn plots, Lubrecht Fire Study, Preliminary Data.

| Parameter | Control | Light Burn Plot 14 | Hot Burn Plot 22 |
|---|---|---|---|
| Input me/m$^2$/yr | 125 | 125 | 125 |
| Overland Flow (loss) me/m$^2$/yr | 0.0179 | 0.023 | 0.043 |
| Surface Input (Total) | 124.98 | 124.97 | 124.95 |
| Additions from Ash me/m$^2$/yr (all fuels combined except stumps, weighted) | 0 | 676 (*946) | 4831 (*5870) |
| Annual Additions from Decomposition + 1 yr. me/m$^2$/yr | 776 | *567 | *274 |
| *Total Input* | 901 | 1368 (1638) | 5230 (6269) |
| Storage Capacity of the Soil me/0.6m$^3$ | 6786 | 6786 | 6786 |
| Uptake by plants—not measured | ? | ? | ? |
| Calculated Loss Below Roots (me/m$^2$/yr) | 0 | 0 | 0 |
| Measured Loss Below Roots (in excess of loss below control roots, as me/m$^2$/yr, all cations) | (53.8) | 35 | 217 |
| Loss of Ca (in excess of that for controls) me/m$^2$/yr below roots | 29.7 | 0 | 133 |
| *Time Factor* | | | |
| Fire frequency of @ 40 years | | | |
| x loss of Ca to roots over a 40-year period, | | | |
| total Ca in soil/40 year loss | | | |
| =No. of years soil can continue to supply calcium at this loss rate, and burn frequency. | | | |

*Estimated, not adequate data for measurement. The data in this Table are not final and should not be applied to field prediction at this stage.

heavy ash accumulations temporarily disrupted the normal infiltration process. Overland transport was of short transit and insignificant in nutrients loss (0.0179 me/m$^2$/yr, controls, .043 me/m$^2$/yr burns.

5. The first year after burn is most critical to nutrient movement because 10 to 60% of the cations were removed by the 56cm of precipitation. Drying of ash increases its nutrient output on subsequent leaching.
6. Decomposition of Douglas-fir needles was increased the most in medium burns, slightly less in hot burns, and least in cool burns relative to that of the controls. Decomposition may be stimulated

by nutrient release, especially if some organic substrate remains.

7. The total elemental content of the soil shows that the percentage composition of calcium is two to five times lower than it should be for good plant growth (Tables 6, 7). Iron is extremely high (114X) compared to what plants need (Tables 6, 7). Any treatment which increases the loss of calcium or concentrates soluble iron in the soil will be detrimental to the biological life of that soil. Most researchers evaluated nutrient loss in terms of the available cations only, rather than using the total of potentially available cations.
8. The more alkaline pH resulting from the burns lowers the concentration of soluble iron in the soil water, and alters the availability of many elements.
9. In general, the concentrations of calcium, potassium and magnesium in soil water decrease with depth while iron increases slightly with depth.
10. If a preliminary nutrient balance is calculated for the coolest (plot 14) and the hottest (plot 22) burns and for controls for cations only, there are considerable differences in anticipated nutrient loss (Table 9). Note that the nutrient inputs are undoubtedly too low on the basis of total fuels consumed. Although no net nutrient loss was calculated from the hottest burn, actual nutrient loss was measured from below the root zone on plot 22. If the cation input from burned stumps and plant uptake were known, the calculated and measured nutrient losses would probably be much closer. Since these are preliminary data presented to demonstrate calculation procedure, there is no cause for alarm in the difference between calculated and measured nutrient loss. Some critical data are still lacking such as nutrient input from stumps and roots which is extremely hard to measure, as is uptake by trees. The fact that a large proportion (61%) of the cation loss below the roots in plot 22 is calcium, and that calcium is proportionally low in this soil in respect to plant needs indicates that a hot burn with temperatures to 650C at 7-9cm depth is detrimental to this soil system. Burns with surface soil temperatures below 300C showed no significant nutrient loss. Regardless of weaknesses in the calculations which are still

limited by existing technology, the method of actual measurement of water quality below the root zone is the most powerful tool that we have to evaluate the influence of burning practices on nutrient cycling and long-term productivity. A major task is to establish a few simple measurements which can be tied to a refined burning index and will allow a land manager to prescribe burns which will not damage the productive potential of the soil.

Since this study is on-going, and since the statistical analyses of data and in particular the 50,000 chemical analyses of soils, are not completed, the author wishes to refrain from drawing conclusions at this time.

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