Precipitation nutrients in the open and under two forests in Minnesota

ELON S. VERRY
North Central Forest Experiment Station, USDA Forest Service, Grand Rapids, MN, U.S.A. 55744

AND

D. R. TIMMONS
Soil and Water Conservation Research Division, USDA Agricultural Research Service, Morris, MN, U.S.A. 56267

Received June 29, 1976[1]
Accepted October 19, 1976

VERRY, E. S., and D. R. TIMMONS. 1977. Precipitation nutrients in the open and under two forests in Minnesota. Can. J. For. Res. 7: 112–119.

Concentrations of N, P, K, Ca, Mg, and Na were measured in rain and snow in the open, and in throughfall and stemflow under black spruce and aspen forests in north-central Minnesota. Concentrations of total P in rain and black spruce throughfall were inversely related to storm size. Annual precipitation nutrient inputs to the forest floor were calculated for each site. In general, nutrient contributions from snow were less than 10% of the annual nutrient input from precipitation at each site, and differences in snow nutrient input between sites were minimal. Rainfall nutrient input differed significantly between sites. Rain and snow passing through both forest canopies were enriched with nutrients except inorganic nitrogen. Total annual nutrients added to the forest floor under the black spruce stand averaged 1.7 times that added in the open; the annual amount added under the aspen stand averaged 5.2 times that added in the open.

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On a mesuré les concentrations de N, P, K, Ca, Mg et Na dans la pluie et la neige, à découvert, dans les précipitations traversant la voûte foliacée et dans le ruissellement des tiges sous couvert d'épinette noire et sous couvert de peuplier, dans la partie nord-centrale du Minnesota. Les concentrations de P dans la pluie et les précipitations traversant la voûte foliacée étaient en relation inverse avec l'importance de l'orage. Pour chacune des stations, on a calculé les apports annuels d'éléments au sol en provenance des précipitations. En général, la contribution de la neige à cet apport d'éléments était inférieure à 10%; elle était sensiblement la même dans les deux stations. Les contributions de la pluie dans une station et dans l'autre montrent des différences significatives. La pluie et la neige traversant la voûte foliacée des deux forêts étaient enrichies d'éléments à l'exception d'azote minéral. Les apports annuels totaux d'éléments au sol sous couvert d'épinette noire étaient en moyenne 1.7 fois plus élevés qu'à découvert; les apports au sol sous couvert de peuplier étaient 5.2 fois plus élevés qu'à decouvert.

[Traduit par le journal]

Introduction

Knowing the amount of nutrients in precipitation is often necessary for making decisions in land use and water management. For example, comparisons of nutrient removals with nutrient replacements are useful in evaluating the impacts of shortwood, tree-length, and full-tree harvesting systems on site quality throughout the rotation (Weetman and Webber 1972; Boyle and Ek 1972; White 1974). Agricultural practices are similarly assessed on an annual basis (Schuman and Burwell 1974; Burwell *et al.* 1975). Changes in nutrient uptake and leaf leaching in fertilized stands can be evaluated by throughfall nutrient analysis (Mahendrappa and Ogden 1973; Päivänen 1974). Also, lake eutrophication models use precipitation nutrient input as a major variable in evaluating lake carrying capacity (Vollenweider 1968; Dillon 1975). Nutrient input values for northern Europe and the U.S.S.R. vary widely (Weetman and Webber 1972), indicating that regional data

[1]Revised manuscript received October 5, 1976.
[2]Mention of trade names does not constitute endorsement of the products by the USDA Forest Service.

TABLE 1. Forest characteristics

Forest site and components	Basal area, m²/ha	Stem density, no./ha	Crown ht., m	Crown coverage, %	Age, yr	Site index 50, m	pH of soil surface[a]
Mineral soil upland of glacial till[b]							
Aspen[c]	23.0	1 112	23.2	82	52	23	6.0
Hazel	—	42 000	2.6	80	—	—	—
Bracken	—	32 900	—	52	1	—	—
Ombrotrophic *Sphagnum* bog							
Black spruce[c]	30.1	3 029	15.0	68	73	12	4.0

[a]Water ratio of 1:1.
[b]Aspen soil was Warba series; Typic Eutroboralf fine-loamy, mixed, frigid. Black spruce soil was Histosol.
[c]Diameters of the trees in the sampled stands ranged from 13 to 25 cm for the aspen and from 5 to 15 cm for the black spruce.

for major nutrients in precipitation in North America are needed. In addition, records of total annual nutrient inputs to the forest floor are rare (Foster 1974).

The purpose of this paper is to present concentrations and annual nutrient inputs for N, P, K, Ca, Mg, and Na, in rain and snow in the open, under a black spruce (*Picea mariana* (Mill.) B.S.P.) forest, and under an aspen (*Populus tremuloides* Michx.) forest (Table 1). These are baseline data from north-central Minnesota that can be combined with data from other regions to provide insight into the variability of precipitation nutrient inputs in North America and their modification by forests.

Methods

A black spruce stand, an aspen stand, and an open area were instrumented on the Marcell Experimental Forest in north-central Minnesota (about 47°32′ N, 93°28′ W). Rainfall in the open was collected and composited from five standard-height rain gauges in an open bog. Stemflow was collected from 12 trees in each forest stand and composited. Throughfall was collected in 25 rain gauges in each stand and composited. In the aspen stand the rain gauges collected throughfall below a hazel (*Corylus americana* Walt. and *C. cornuta* var. *cornuta* Marsh.) canopy. There were no tall shrubs in the black spruce stand. All collection surfaces were painted with Fischer Labcote,[2] and Tygon[2] tubing was used for all connections.

Samples of wet fall plus dry fall were collected after each storm for storms greater than 5 mm. Any water collected from storms less than 5 mm was discarded because it did not yield a sample large enough for analysis. The amount of water discarded each year for storms less than 5 mm amounted to 4 mm, occurring in five to eight events; this was less than 0.07% of the annual rainfall. Rainfall was sampled in 1971, 1972, and 1973, from mid-May to late October. Six snow samples were collected from the maximum snowpack at each site on one date in 1975. After collection, all samples were refrigerated at 2–3 °C until analyzed. Seven samples of rain in the open were contaminated by needles and discarded. Rain gauges under forest canopies had funnels with a 2- to 3-mm seep hole so that litter fall between storms remained on the funnels. All water samples were filtered in the field through a 0.10-mm stainless steel screen to exclude any occasional litter bits that passed through the seep holes.

Unfiltered portions of each sample were analyzed for Kjeldahl nitrogen (KN; TKN = total Kjeldahl nitrogen) by the macro-Kjeldahl method, for total P by digestion with perchloric and nitric acids, and for color development using the Murphy and Riley method. Inorganic N (NH_4-N and $NO_2 + NO_3$-N), soluble inorganic-P, K, Na, Ca, and Mg concentrations were determined on portions of sample filtered through a 0.45 μm filter. During 1971 and 1972, NH_4-N and $NO_2 + NO_3$-N were determined by steam distillation. Beginning in 1973, NH_4-N and $NO_2 + NO_3$-N were determined on a Technicon Auto Analyzer II[2] using the Bertholot reaction for NH_4-N and copper–cadmium reduction plus reddish-purple azo dye color development for $NO_2 + NO_3$-N. An atomic adsorption spectrophotometer was used to measure K, Na, Ca, and Mg concentrations. Organic N was estimated as Kjeldahl N less NH_4-N, and total N as the sum of organic N, NH_4-N, and $NO_2 + NO_3$-N.

Concentration data were tested for correlation with storm size at the 5% level. Annual precipitation nutrient inputs were calculated from average concentrations and seasonal totals of precipitation, or from storm-size weighted concentrations and individual storm amounts where appropriate. Amounts of water were taken from rainstorm and seasonal snowfall records at the Marcell Experimental Forest to represent a general precipitation year for the western Great Lakes area (Table 2). Throughfall and stemflow for black spruce, aspen, hazel, and bracken fern (*Pteridium aquilinum* (L.) Kuhn) in each stand were calculated using equations of Verry (1976) and Clements (1971). Rainstorms were divided into two classes, dormant season (leaves off) and growing season (leaves on), in order to use interception equations developed for those conditions. Growing-season rainfall was defined

TABLE 2. Amounts of precipitation components (mm) for a representative year of 775 mm

Precipitation component	Rainfall: Growing season[a]	Dormant season[b]	Total rain	Snow-fall	Annual total
		Aspen forest			
Throughfall	294	141	435	137	572
Stemflow					
Aspen	16	9	25	—	25
Hazel	18	7	25	—	25
Bracken	27	—	27	—	27
Total	355	157	512	137	649
		Black spruce forest			
Throughfall	—	—	480	116	596
Stemflow	—	—	trace[c]	—	trace
Total	—	—	480	116	596
		Open area			
Gross precipitation	450	175	625	150	775

[a]Growing season is May 15 to October 1.
[b]Dormant season includes two periods: October 1 until the first snow, and the last snow until May 15.
[c]Black spruce stemflow amounted to 0.4 mm on an area basis.

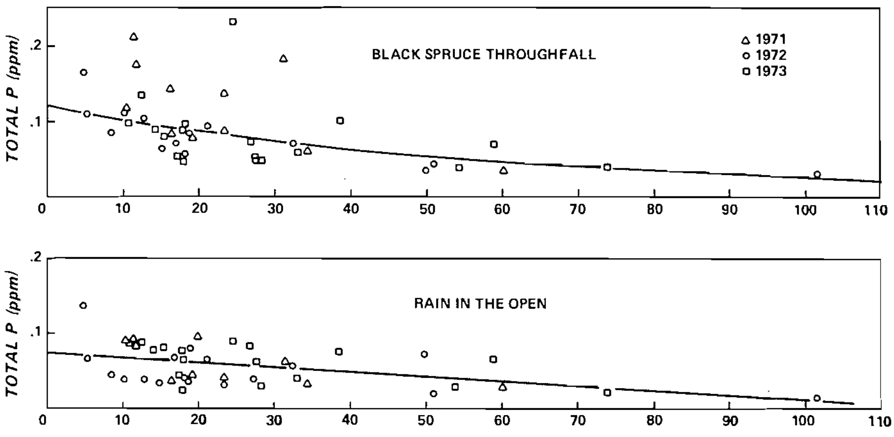

FIG. 1. Relationship of total phosphorus concentration to storm size for open rain and black spruce throughfall. Regressions significant at the 95% confidence level (see text for equations).

as May 15 to October 1. Dormant-season rainfall included two periods: October 1 until the first snow to stay on the ground, and from the last snow until May 15.

Concentration data for bracken fern throughfall and stemflow and for hazel stemflow were not measured. It was assumed (1) that bracken fern throughfall and stemflow were similar to aspen–hazel throughfall because both are derived from green tissue, and (2) that hazel stemflow concentrations are similar to aspen stemflow concentrations because both are derived from bark tissue. Carlisle *et al.* (1967) measured N, P, Ca, Mg, and Na concentrations in a composite sample of bracken fern throughfall and stemflow beneath an oak overstory and found that they were within the range of concentrations measured below the oak canopy alone. However, potassium concentrations in their study were twice as high under the bracken fern as under the oak canopy alone. We are not aware of any nutrient data for hazel stemflow. These assumptions allowed us to account for bracken fern interception losses during the growing season rainfall and hazel interception losses during the total rainfall season. Loss of precision from the concentration assumptions is not known.

Results

There were no apparent differences among years for nutrient concentrations in open rain-

TABLE 3. Nutrient concentrations (ppm) in rain and snow for open, black spruce, and aspen sites[a]

Nutrient and component	Black spruce, Mean ± 5% C.I.	Aspen–hazel, Mean ± 5% C.I.	Component	Open precipitation, mean ± 5% C.I.
Total P				
Throughfall	0.096±0.018	0.265±0.075[b]	Rain	0.059±0.008
Stemflow	0.119±0.015[c]	0.298±0.087		
Snowpack	0.078±0.013	0.070±0.003	Snowpack	0.063±0.003
Soluble P				
Throughfall	0.021±0.011	0.137±0.064[b]	Rain	0.010±0.004
Stemflow	0.018±0.006[c]	0.139±0.072		
Snowpack	0.008±0.004	0.009±0.002	Snowpack	0.006±0.001
TKN				
Throughfall	1.05 ±0.15	1.15 ±0.23	Rain	0.72 ±0.10
Stemflow	2.39 ±0.28[c]	1.38 ±0.15		
Snowpack	0.35 ±0.10	0.46 ±0.09	Snowpack	0.36 ±0.09
NH_4-N				
Throughfall	0.30 ±0.09	0.34 ±0.15	Rain	0.40 ±0.10[b]
Stemflow	0.23 ±0.04[c]	0.17 ±0.07		
Snowpack	0.17 ±0.03	0.19 ±0.01	Snowpack	0.18 ±0.02
NO_3-N				
Throughfall	0.26 ±0.05	0.20 ±0.06	Rain	0.28 ±0.05[b]
Stemflow	0.20 ±0.05[d]	0.05 ±0.01		
Snowpack	0.37 ±0.01	0.48 ±0.07	Snowpack	0.35 ±0.06
K				
Throughfall	0.80 ±0.16	2.08 ±0.44[b]	Rain	0.16 ±0.03
Stemflow	3.43 ±0.80[c]	11.34 ±1.94		
Snowpack	0.13 ±0.09	0.14 ±0.04	Snowpack	0.04 ±0.02
Na				
Throughfall	0.21 ±0.04	0.22 ±0.03[b]	Rain	0.15 ±0.04
Stemflow	0.36 ±0.06[c]	0.20 ±0.04		
Snowpack	0.13 ±0.07	0.12 ±0.02	Snowpack	0.12 ±0.02
Ca				
Throughfall	0.99 ±0.13	1.90 ±0.32[b]	Rain	0.48 ±0.11
Stemflow	11.26 ±1.95[c]	11.85 ±1.24		
Snowpack	0.37 ±0.04	0.73 ±0.40	Snowpack	0.33 ±0.10
Mg				
Throughfall	0.27 ±0.04	0.48 ±0.08[b]	Rain	0.10 ±0.03
Stemflow	1.57 ±0.27[c]	2.21 ±0.22		
Snowpack	0.01 ±0.02	0.13 ±0.03	Snowpack	0.07 ±0.07

[a]Sample size is 45 storms for throughfall, stemflow, and rain; and 6 for snowpack.
[b]Sample size = 44 storms.
[c]Sample size = 43 storms.
[d]Sample size = 41 storms.

fall, throughfall, or stemflow. Neither were there any apparent differences between growing season and dormant season throughfall or stemflow concentrations in the aspen stand, although only six dormant-season storms were measured. Total P concentrations for rain in the open and for throughfall in the black spruce stand were inversely ($\alpha = 0.05$) related to storm size (Fig. 1). For rain in the open, total P $= 0.7342 - 0.0006$ (storm size) ($r^2 = 0.21$); and for black spruce throughfall, ln total P $= -2.1173 - 0.0159$ (storm size) ($r^2 = 0.39$), where total P is in parts per million and storm size is in millimetres. The data range for these equations is 5 to 100 mm (Fig. 1). Unweighted means, confidence intervals (C.I.), and sample sizes for all nutrients are given in Table 3.

Concentrations of total P, soluble P, organic N, K, Na, Ca, and Mg in rain and snow were increased as they passed through the crowns or flowed down the stems of either black spruce or aspen–hazel crowns. Inorganic N concentrations in rain and snow decreased when rainfall passed through the crowns or flowed down the stems

TABLE 4. Total rainfall nutrients (kg/ha) under the aspen and the black spruce forests

Forest component and season	Total P	Soluble P	NH_4-N	NO_3-N	Organic N	Total N	K	Na	Ca	Mg
					Aspen forest					
Growing season										
Throughfall	0.778	0.403	1.001	0.602	2.378	3.980	6.098	0.653	5.586	1.395
Stemflow										
Aspen	0.047	0.022	0.027	0.009	0.191	0.226	1.789	0.031	1.869	0.348
Hazel	0.054	0.025	0.031	0.010	0.218	0.259	2.046	0.035	2.139	0.398
Bracken	0.073	0.038	0.094	0.056	0.222	0.372	0.570	0.061	0.523	0.130
Dormant season										
Throughfall	0.373	0.193	0.480	0.288	1.140	1.909	2.924	0.313	2.679	0.669
Stemflow										
Aspen	0.027	0.013	0.016	0.005	0.111	0.132	1.041	0.018	1.088	0.203
Hazel	0.021	0.010	0.012	0.004	0.083	0.099	0.781	0.013	0.816	0.152
Total in annual rainfall	1.373	0.704	1.661	0.974	4.343	6.977	15.249	1.124	14.700	3.295
					Black spruce forest					
Growing and dormant season										
Throughfall	0.493	0.103	1.465	1.243	3.603	6.311	3.857	1.025	4.747	1.292
Stemflow	<0.001	<0.001	0.001	0.001	0.009	0.011	0.014	0.001	0.046	0.006
Total in annual rainfall	0.493	0.103	1.466	1.244	3.612	6.322	3.871	1.026	4.793	1.298

of either black spruce or aspen–hazel. However, total N concentrations were changed little by contact with stems or crowns (Table 3).

Concentration data alone cannot be used to assess the total effect of forest vegetation on precipitation nutrients reaching the forest floor. Changes in amounts of water caused by interception losses must also be considered.

Total rainfall nutrients for throughfall and stemflow in black spruce and aspen forests are given in Table 4. Although nutrient totals from stemflow in the black spruce stand are negligible on an area basis as a result of low stemflow (Table 2), concentrations of K, Ca, and Mg are relatively high and may be biologically significant in micro-sites at the base of trees (Table 3). From 9 to 19% of the total amount of all nutrients in rainfall (except K, Ca, and Mg) flowed down the stem during a year in the aspen–hazel–bracken forest; for K, Ca, and Mg the stemflow accounted for 41, 44, and 37%, respectively, of the annual amount.

Annual snow and rain nutrient amounts for each site are summarized in Table 5. Inorganic nitrogen amounts are reduced by 30 to 40% after passing through both black spruce and aspen forests. However, this reduction is offset by organic nitrogen, resulting in a total nitrogen increase of about 13% in the aspen forest, and no increase in total nitrogen under the black spruce forest.

Increases in Na inputs under the forest stands are relatively small at 1.1 and 1.2 times that in the open, and there is little difference between the black spruce and aspen forests. However, the aspen forest adds considerably more to the net nutrient inputs of P, K, Ca, and Mg than the black spruce forest does.

The total P input under aspen was 3 times that in the open, and soluble P was 10 times greater. Total P and soluble P inputs under black spruce were only 1.3 and 1.6 times greater than that in the open. Potassium was the most easily leached nutrient in both stands. The annual amount under black spruce was 3.8 times the amount in the open, and under aspen it was 14.6 times the amount in the open. Calcium and magnesium inputs under black spruce were 1.5 and 1.9 times the input in the open but under aspen they were 4.5 and 5.0 times the input in the open, respectively.

Most of the site differences in annual nutrient inputs occur in the rainfall fraction. However, annual K inputs for black spruce and aspen

TABLE 5. Annual precipitation nutrient inputs (kg/ha per year) in the open, and under the black spruce and the aspen forests for a precipitation year representative of the western Great Lakes region[a]

	Location				Location		
Nutrient	Open	Black spruce	Aspen	Nutrient	Open	Black spruce	Aspen
Total P				Total N			
Snow	0.095	0.090	0.096	Snow	1.075	0.828	1.288
Rain	0.388	0.533	1.373	Rain	6.243	6.322	6.977
Annual	0.483	0.623	1.469	Annual	7.318	7.150	8.265
× Open[b]		1.29	3.04	× Open		0.98	1.13
Sol. P				K			
Snow	0.008	0.009	0.013	Snow	0.065	0.151	0.197
Rain	0.063	0.103	0.704	Rain	0.991	3.871	15.249
Annual	0.071	0.112	0.717	Annual	1.056	4.022	15.446
× Open		1.58	10.10	× Open		3.81	14.63
NH_4-N				Na			
Snow	0.269	0.202	0.263	Snow	0.173	0.148	0.165
Rain	2.475	1.466	1.661	Rain	0.915	1.026	1.124
Annual	2.744	1.668	1.924	Annual	1.088	1.174	1.289
× Open		0.61	0.70	× Open		1.08	1.18
NO_3-N				Ca			
Snow	0.527	0.426	0.652	Snow	0.500	0.433	1.001
Rain	1.723	1.244	0.974	Rain	2.980	4.793	14.700
Annual	2.250	1.670	1.626	Annual	3.480	5.226	15.701
× Open		0.74	0.72	× Open		1.50	4.51
Organic N				Mg			
Snow	0.279	0.200	0.373	Snow	0.100	0.008	0.178
Rain	2.045	3.612	4.343	Rain	0.598	1.298	3.295
Annual	2.324	3.812	4.716	Annual	0.698	1.306	3.473
× Open		1.64	2.03	× Open		1.87	4.98

[a]Based on a maximum snowpack of 150 mm of water, dormant season rainfall of 175 mm, and growing season rainfall of 450 mm. Interception losses in the forest stands are accounted for.
[b]Ratio of amount in the forest to the amount in the open.

snowpacks were 2 and 3 times that in the open. The calcium input in the aspen snowpack was twice that in the open, but in general, absolute amounts contributed by the snowpack for all nutrients are low (averaging 9% of the annual load for all nutrients and sites). Also, differences between sites for snow nutrient inputs are minimal.

Discussion

The significant correlation between the concentration of total P in rainfall in the open and storm size indicates a significant particulate phosphorus input from the atmosphere since the concentration of soluble phosphorus was not related to storm size. Sources of particulate phosphorus in the atmosphere have not been rigorously pinpointed, but may be from pollen, soil erosion, fires, oil and coal combustion, and fertilizers (Anonymous 1973). Particulate dry fall (mineral and organic dust and aerosols) may account for some of the variation around the regression lines in Fig. 1. That is, more dry fall may be collected during long periods between storms than during short periods between storms, and thus dilution by a given amount of rain would differ for each case. The equations in Fig. 1 should be used with caution, since the few large storms give a disproportionate amount of weight to the regression lines. The largest storm used in our general precipitation year was 39 mm.

Total P concentrations in the black spruce throughfall were also correlated with storm size. This may indicate a species and (or) site effect, since the spruce stand added only 48% more total P to the rainfall, while the aspen forest increased the total P input by 200%. In other words, total P in the rainfall passed through the black spruce stand with a relatively small con-

TABLE 6. Nutrient inputs (kg/ha per year) in precipitation adjusted to a common base of 775 mm per year

Location	Total N	Total P	K	Ca	Mg	Na	Reference
Ontario 46°21′ N 83°23′ W	4.0	0.08[a]	3.2	4.5	0.6	—	Foster 1974
Ontario 45°11′ N 78°43′ W	—	0.22	0.7	8.5	3.0	0.8	Schindler and Nighswander 1970
England 54°15′ N 2°52′ W	4.6	0.21	1.4	3.5	2.2	17.0	Carlisle *et al.* 1966
Upper Michigan 46°0′ N 88°30′ W	4.2	0.46	—	3.6	1.0	—	Crumrine 1975; unpubl. data[b]
Minnesota 47°32′ N 93°28′ W	7.3	0.50	1.1	3.5	0.7	1.1	This paper

[a]Soluble P.
[b]Crumrine, J. P. 1972–1975. Chemical quality of rain and snowfall samples collected in Sylvania, Ottawa National Forest. File No. 2542 Water Quality. Ottawa National Forest, Ironwood, MI.

TABLE 7. Nutrient inputs (kg/ha per year) under forests adjusted to a common base with 775 mm of precipitation in the open

Location	Forest type	Total N	Total P	K	Ca	Mg	Na	Reference
Ontario 46°21′ N 83°23′ W	Jack pine	4.3	0.13[a]	9.4	5.8	1.2	—	Foster 1974
England[b] 54°15′ N 2°52′ W	Sessile oak	4.2	0.63	13.3	8.2	4.5	26.7	Carlisle *et al.* 1966
Minnesota[b] 45°20′ N 93°15′ W	Northern pin oak	6.8	0.82	—	9.4	3.8	—	Reiners 1972
	Black ash	6.8	0.73	—	13.0	4.7	—	Reiners 1972
	White cedar	7.4	0.63	—	13.3	4.6	—	Reiners 1972
Minnesota 47°32′ N 93°28′ W	Black spruce	7.1	0.58	4.0	5.2	1.3	1.2	This paper
	Trembling aspen	8.3	1.47	15.4	15.7	3.5	1.3	This paper

[a]Soluble P.
[b]Based on throughfall samples only.

tribution from vegetation; but in the aspen stand, large contributions from the vegetation overshadowed any effect of storm size.

The aspen forest contributed higher amounts of other precipitation nutrients also. These differences may be due to both species and site effects. About 7% of the differences between the forests can be directly attributed to the greater interception losses in the black spruce stand. Compared with the open, the aspen stand has an annual interception loss of 16% and the black spruce stand 23%. Differences in leaf, needle, bark structure, and aboveground nutrient mass may also account for part of the input differences (Reiners 1972).

There are also site differences that may affect nutrient uptake and leaching. The black spruce were growing on a nutrient-poor bog site with an organic soil pH of about 4. Thus nutrient uptake may have been further limited by low availability. In contrast the mineral soil pH of the aspen stand is about 6. Here there is a larger store of nutrients and higher availability. In fertilization studies Päivänen (1974) and Mahendrappa and Ogden (1973) showed that nutrient availability (N, P, and K) in the soil can influence nutrient concentrations in throughfall and stemflow. Their work was with Scots pine (*Pinus sylvestris* L.) and black spruce, respectively.

Complete annual data from other areas is not sufficient to draw any regional conclusions. However, it is apparent that substantial differences occur both in the nutrient inputs of incident precipitation and those under forests (Tables 6 and 7). Extrapolation of these data must be done cautiously with full cognizance of nutrient sources, species differences, precipitation differences, and site (soil) differences. Precipitation differences (both net and gross) can largely be handled with simple ratios of gross precipitation if nutrient concentrations are not strongly related to storm size. Data should also be handled as snow and rain components. This conclusion is based on the data of Verry (1976) in which net precipitation under forests for high, low, and medium precipitation years showed a linear response to gross precipitation even though storm-size distributions differed. Exceptions to this observation may occur where dry fallout is a large component of the annual nutrient input. Within a given region, species and site differences can have a major impact on precipitation nutrients entering the forest floor.

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