NUTRIENT CYCLING IN OAK-HICKORY FORESTS
I. PRECIPITATION, THROUGHFALL AND STEMFLOW

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The study was conducted between 1973 and 1975 in oak-hickory forests at the University of Illinois, Dixon Springs Agricultural Center, in Pope County, Illinois. Three plots (each 0.04 hectares) were established at each of two sites (one xeric and the other mesic) for monitoring precipitation, throughfall and stemflow. Samples were analyzed for N, P, K, Ca and Mg.

Oak-hickory forests intercepted 17% (22.14cm) of total precipitation (130.40cm), with 65% (15.14cm) reaching the forest floor as stemflow. Interception was low (10%) during the summer but increased (27%) in the winter. Stemflow, as % of total interception, was high (80%) in the summer and decreased (41%) during the winter. Nutrients were susceptible to leaching in the following order: K > Ca > Mg > N > P. Their concentrations in precipitation were in the order N > K > Ca > Mg > P; for throughfall and stemflow the order was K > Ca > Mg ≈ N > P. The major source of K and Mg was the foliage but bark, twigs and limbs contributed most of the Ca. The major source of N and P was precipitation. The concentration of all nutrients in precipitation, throughfall and stemflow was 3.5 ppm for the year, but increased to 4.3 ppm during the summer and decreased to 2.5 ppm during the winter.

The total water associated nutrients reaching the forest floor was 115.5 kg/ha/year; of which 38% was contributed by precipitation, 35% by throughfall and 27% by stemflow; the majority of this total was K (48 kg) and Ca (36 kg). Total nutrient input by precipitation, throughfall and stemflow was equivalent to 34% of the estimated annual nutrient uptake (343.8 kg/ha) (Duvigneaud and Denaeyer-DeSmet 1970). The respective nutrient contributions of precipitation, throughfall and stemflow were 13, 12 and 9%.

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INTRODUCTION

The advent of more intensive forestry, large scale afforestation, and the increasing value of forest products necessitates a greater emphasis on fundamental investigations and their application to resource management. The importance of basing resource management on sound scientific grounds unfettered by preconceived notions has been stressed by

many authors (Peace 1961). It was emphasized by Ovington (1962) that if forest research is to be fully effective, it needs to be oriented towards obtaining a better appreciation of ecosystem dynamics. Quantitative studies of biological and physical processes affecting productivity, biomass accumulation, transformation, and flow of energy and material (water, organic matter, nutrients) through different forest ecosystems will provide much needed data. Present knowledge of the quantitative aspects of forest dynamics is unfortunately very incomplete yet these processes constitute a significant expression of the forest ecosystem.

As manifestations of the function of natural ecosystems, cycles of essential elements are convenient points of entry into the analysis of ecosystems. The flux of materials is essential to the continuity and stability of any living system. Moreover, flux is often a good indicator of metabolic activity following the pathway of energy through food webs (Pomeroy 1970). The interchange of nutrients between physical and biological components of a forest ecosystem forms an extremely intricate system, essentially of a cyclic nature. The circulation of different nutrients, however, does not always form a closed system; the nutrient pool of an ecosystem changes somewhat as chemical elements are added to or removed from it in various ways, since the rate of movement of different chemicals is highly variable.

The present study was initiated in the fall of 1973 to develop an understanding of the biogeochemical dynamics of mature oak-hickory forests. The specific objectives were: 1) to determine the magnitudes of precipitation, throughfall, stemflow; 2) to determine the annual input or flux of N, P, K, Ca and Mg into the forest ecosystem from precipitation, throughfall and stemflow.

Description of the Study Area

The study was conducted in oak-hickory forests near the University of Illinois, Dixon Springs Agricultural Center, in Pope County, Illinois.

Soils have developed under forest vegetation in varying depths of loess over residual sandstone with smaller areas of limestone. Three soil series were included in the study area: 1) Typic Fragiudalf; fine-silty, mixed, mesic (Grantsburg silt loam); 2) Aquic Fragiudalf; fine-silty, mixed, mesic (Robbs silt loam); 3) Ultic Hapludalf; fine-silty, mixed, mesic--Typic Dystrochrept; fine-loamy, mixed, mesic complex (Wellston-Muskingham complex).

The hardwood vegetation is part of temperate deciduous forest biome of drier soils characterized by oak, hickory and maple (Kormondy 1969). In the study area, oaks (*Quercus alba* L. and *Q. rubra* L.) were highly dominant (Table 1). The next important species were maple (*Acer saccharum* Marsh.) and hickory (*Carya glabra* [Mill.] Sweet). Winged elm (*Ulmus alata* Michx.), dogwood (*Cornus florida* L.), crab apple (*Pyrus cornaria* L.) and American pawpaw (*Asimina triloba* (L.) Dunal.) were also present with decreasing frequency.

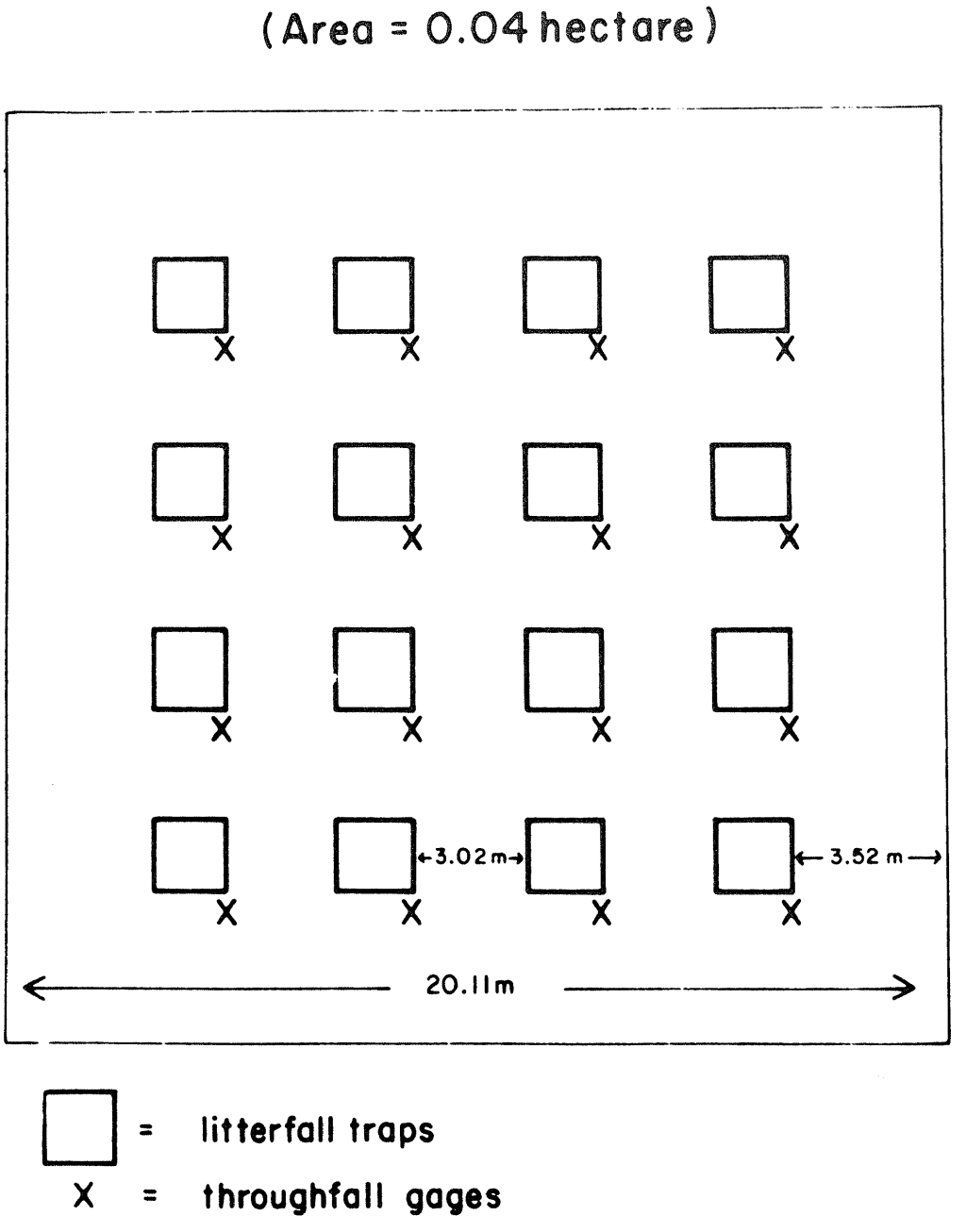
Table 1. Proportion of biomass and density by size class for major species or species groups (average of 6 plots).

Species or Species Group	Proportion of biomass (%)	Number of trees per hectare DBH (cm) Larger than 38.1	25.4 to 38.1	12.7 to 25.4	3.81 to 12.7	Smaller than 3.81 (seedlings)
Quercus alba *Quercus rubra*	85.29	66	50	83	50	50
Carya glabra	6.43	--	--	58	618	74
Acer saccharum	7.35	--	8	54	741	1236
Ulmus alata	0.67	--	--	--	186	202
Cornus florida	0.26	--	--	--	83	128
Pyrus cornaria	--	--	--	--	8	25
Asimina triloba	--	--	--	--	--	440

Materials and Methods

Three representative 0.04 hectare plots based on slope position (lower, middle and upper) were established in each of two types of oak-hickory forests, the purpose being to cover a wide range of conditions. One type, east hardwoods, tended towards xeric conditions while the other, Spout Spring hardwoods, was mesic in character. Plots were subjectively selected with the help of aerial photographs. The following factors were kept in mind while selecting the location of plots: stand density, slope, aspect, soil type, soil depth and accessibility. Following plot location, a 100% inventory was completed.

Four rain gages of 15.24cm diameter were established in two open fields adjacent to the research areas. In addition, data from one U.S. Weather Bureau standard rain gage (located approximately 1 kilometer from each of the two community types) was obtained. In order to monitor throughfall, 16 gages of above cited size were systematically established in each plot (Fig 1). Three representative trees per plot were selected and provided with stem flow traps. Each stem flow trap consisted of an aluminum collar spirally arranged around the bole of the tree, a drainage pipe and an underground water storage tank sealed with plastic sheet (Fig 2). In total, 19 trees were selected (Table 2). The total amount of



Note:

① In addition, at least 3 trees were provided with stemflow traps.

② Precipition gages were established in the open outside the forest.

Figure 1. Layout of one experimental plot.

stemflow per tree was divided by the tree crown area to determine stemflow on an area basis. Arithmetic averages of stemflow were obtained for each of three major species. A weighted average was then calculated (relative biomass being used as weight) to obtain an estimate of stemflow for the whole forest.

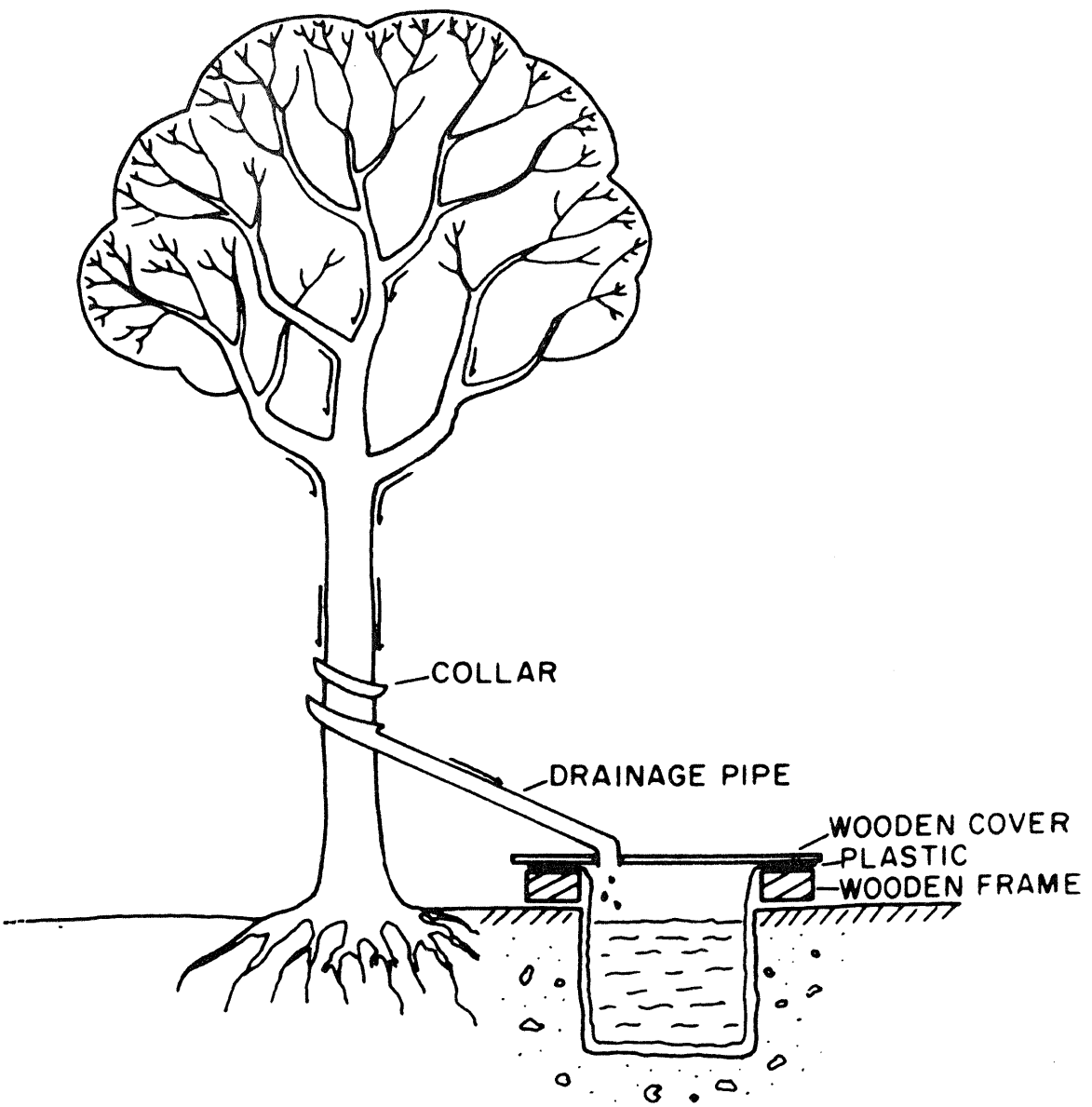


Figure 2. Stemflow trap.

Table 2. List of trees fitted with stemflow traps. Letter designations are as follows: E (east hardwoods), S (Spout Spring hardwoods), L (lower slope), M (middle slope) and U (upper slope).

Species	Bole diameter (breast height) (cm)	Crown diameter (m)	Location with respect to research plots
Quercus alba	42.29	3.95	EL
Quercus alba	49.78	5.58	EL
Carya glabra	10.16	2.24	EL
Quercus alba	45.72	5.30	EM
Quercus alba	49.53	5.83	EM
Acer saccharum	16.38	2.85	EM
Quercus alba	43.69	5.10	EU
Quercus alba	55.25	6.65	EU
Acer saccharum	13.59	1.56	EU
Liriodendron tulipifera L.	38.74	4.19	SL
Quercus rubra	46.10	6.28	SL
Carya glabra	23.62	3.08	SL
Quercus rubra	50.29	6.02	SM
Quercus rubra	37.97	4.04	SM
Quercus rubra	20.83	2.51	SM
Carya glabra	23.11	2.24	SM
Quercus rubra	26.20	3.69	SU
Quercus rubra	33.02	3.43	SU
Carya glabra	7.62	1.03	SU

The study period extended from November 1973 to August 1975 and included 21 sample collections. The interval between any two collections depended upon the occurrence of storms. The samples were then stored in a freezer until analysis. Water samples of precipitation, throughfall and stemflow were analyzed by atomic absorption spectrophotometery for K, Ca and Mg and by colorimetry for P (Murphy and Riley 1962). Total N was determined by regular Kjeldahl method (Black 1965).

RESULTS AND DISCUSSION

Precipitation, Throughfall and Stemflow

Table 3 compares the relative distribution of precipitation for 1974 with other studies. Results of this study are in the general range of reported data and compare favorably with those for loblolly and shortleaf pine plantations growing in the same locality (Miceli *et al.* 1975). Oak-hickory forests were almost equally effective in permitting throughfall as shortleaf pine plantations (i.e., 83 and 84 percent respectively) but were less effective than loblolly pine (70 percent). In comparison, the throughfall in northern hardwoods in Michigan varied from 65 to 89 percent depending upon distance from the bole and rainfall intensity (Willis *et al.* 1975). They also reported increasing throughfall (89 percent) with increasing storm intensity. Their data suggest an average throughfall of approximately 83 percent. Both oak-hickory and shortleaf pine allowed comparatively higher proportion of precipitation, to reach forest floor as throughfall. The relative proportion of total precipitation reaching the forest floor through stemflow was 11% for oak-hickory as compared to 6 and 10% for shortleaf and loblolly pine plantations, respectively. This percentage was rather high in the reported data and may be largely due to species characteristics such as branch angle and leaf area index. Relatively high throughfall by oak-hickory forest coupled with the high proportion of stemflow suggested that oak-hickory would allow more precipitation to reach the forest floor. This in turn, might lead to greater water flow in the streams draining these watersheds.

Table 3. Relative distribution of total precipitation.

Type of Forest	Throughfall	Stemflow	Reference
Oak-hickory forest	83	11	Present study
Shortleaf pine plantation	84	6	Miceli *et al.* 1975
Loblolly pine plantation	70	10	Miceli *et al.* 1975
Northern hardwood forest	65 - 89	--	Willis *et al.* 1975
Douglas fir stand	68	4	Heuveldop *et al.* 1972
Juniper forest	73	4	Botman 1974

Figure 3 shows the breakdown of 1974 precipitation into major components for various portions of the year. Throughfall decreased from 90% during summer (leaf on) to 73% during winter (leaf off) respectively. Decreased throughfall during winter could be attributed to light showers, low viscosity of water and the nature of precipitation such as snow, sleet and freezing rain. On the other hand, heavier showers, high viscosity of water and presence of waxy foliage appeared to be responsible for increased throughfall during the summer. The relative proportion of total precipitation that reached the forest floor through stemflow increased slightly from 8% during the summer to 11% during the winter. This prolonged retention of moisture in the form of snow and ice by the canopy.

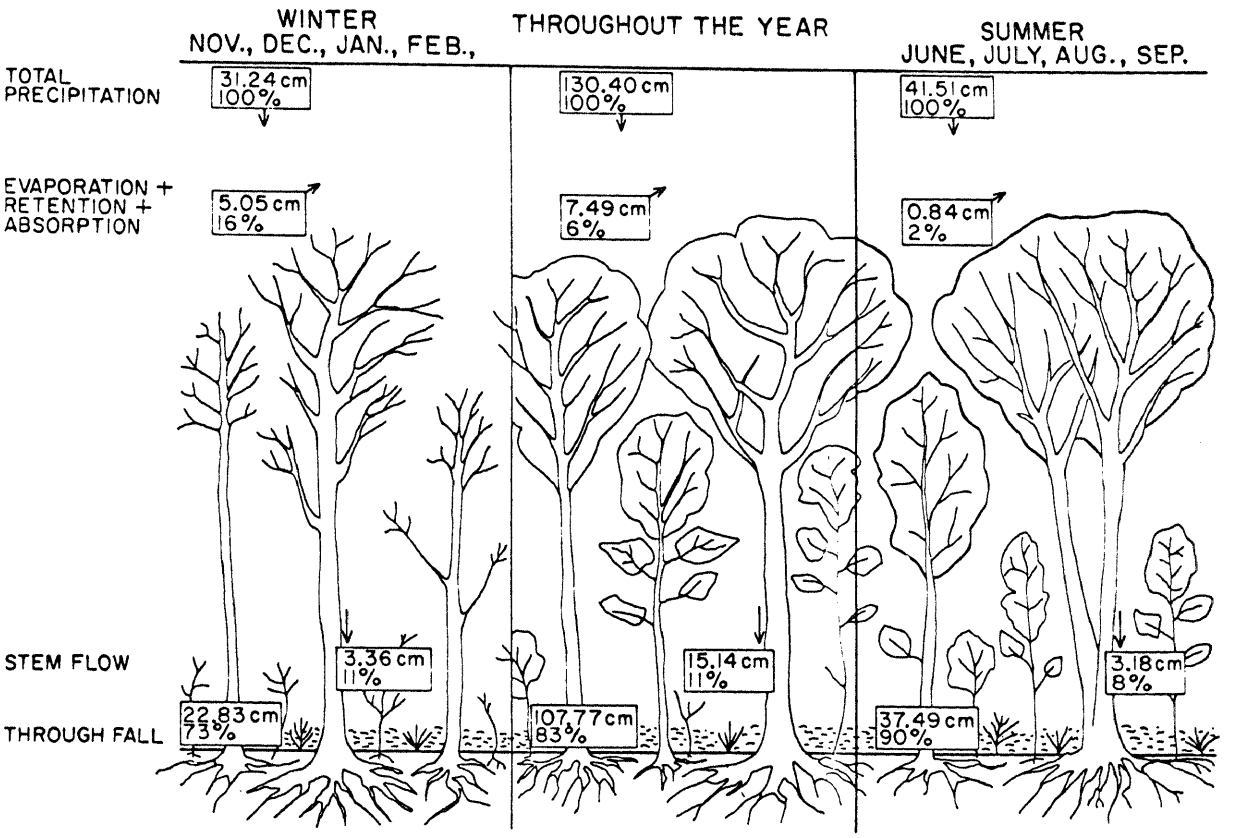


Figure 3. Distribution of precipitation into major components for 1974.

The effect of various species on rates of stemflow was distinct and is shown in figure 4. However this effect was confounded by a weak negative correlation between ln dbh (diameter breast high) and stemflow. Sugar maple and hickory trees used for stemflow estimation were generally of much smaller size (average dbh 15.75) than oak and tulip poplar trees (average dbh 42.26). A negative relationship between basal area of individual trees and stemflow for a range of precipitation classes has been reported (Pressland 1973). Willis et al. (1975) suggested that relatively smooth bark and ascending branches of small trees versus the scaly bark and wide spreading branches of large trees might account for the greater stemflow observed for small trees. However, in this study, the species effect appeared to be dominant.

Nutrient Fluxes (N, P, K, Ca and Mg)

The total amount of precipitation, its distribution during the year, and relative proportion of throughfall and stemflow and their respective nutrient concentration all had a definite effect on nutrient movement through the forest ecosystem. The concentration of cations in precipitation decreased in the order: N > K > Ca > Mg > P. For throughfall and stemflow, the nutrients were present in the following order: K > Ca > Mg ≈ N > P. Nutrient concentrations in throughfall and stemflow with respect to amounts present in the foliage and bark indicated a susceptibility to leaching in the following order: K > Ca > Mg > N > P. This data could be favorably compared with the concentration of cations in stemflow of most eastern Canadian tree species which decreased in the order K > Ca > Na > Mg (Mahendrappa 1974). It has been substantiated that nutrients associated with organic molecules such as N and P move more slowly from the forest canopy to the forest floor whereas nutrients more commonly found in an ionic form such as K move more rapidly (Eaton et al. 1973). The concentration of nutrients in precipitation, throughfall and stemflow changed during the year (Table 4). Their concentrations were several times higher (excluding Ca) during summer than winter. The higher winter concentrations in throughfall and stemflow (Table 4, C and B) may be due to leaching of Ca from the outer bark of twigs, limbs and bole. Also, bark which normally has high Ca concentrations was observed to be loosened during the winter because of alternate freezing and thawing. The total concentration (additive) of all nutrients (i.e. P, K, Ca and Mg) in precipitation, throughfall and stemflow decreased from 4.27 ppm during the summer to 2.53 ppm during the winter (Table 4, D). These temporal variations may be related to atmospheric factors such as source, frequency and intensity of precipitation, pattern of dustfall, presence or absence of foliage, and or seasonal farm activities in the adjoining areas.

Annual input of nutrients by precipitation, throughfall and stemflow as reported by various authors, from different parts of the world is given in table 5. Although there is lot of variation and the data is somewhat incomplete, even then one can have an idea of the magnitude and relative importance of various pathways.

Considering the total water carried nutrients (115.5 kg/ha/year), 38% (43.9 kg) was contributed by precipitation, 35% (40.4 kg) by throughfall and 27% (31.2 kg) by stemflow. The quantities of different cations and their relative proportions in precipitation, throughfall and stemfall are given in table 6. Throughfall had a higher proportion of K and Mg but stemflow contained slightly higher Ca concentrations. The primary

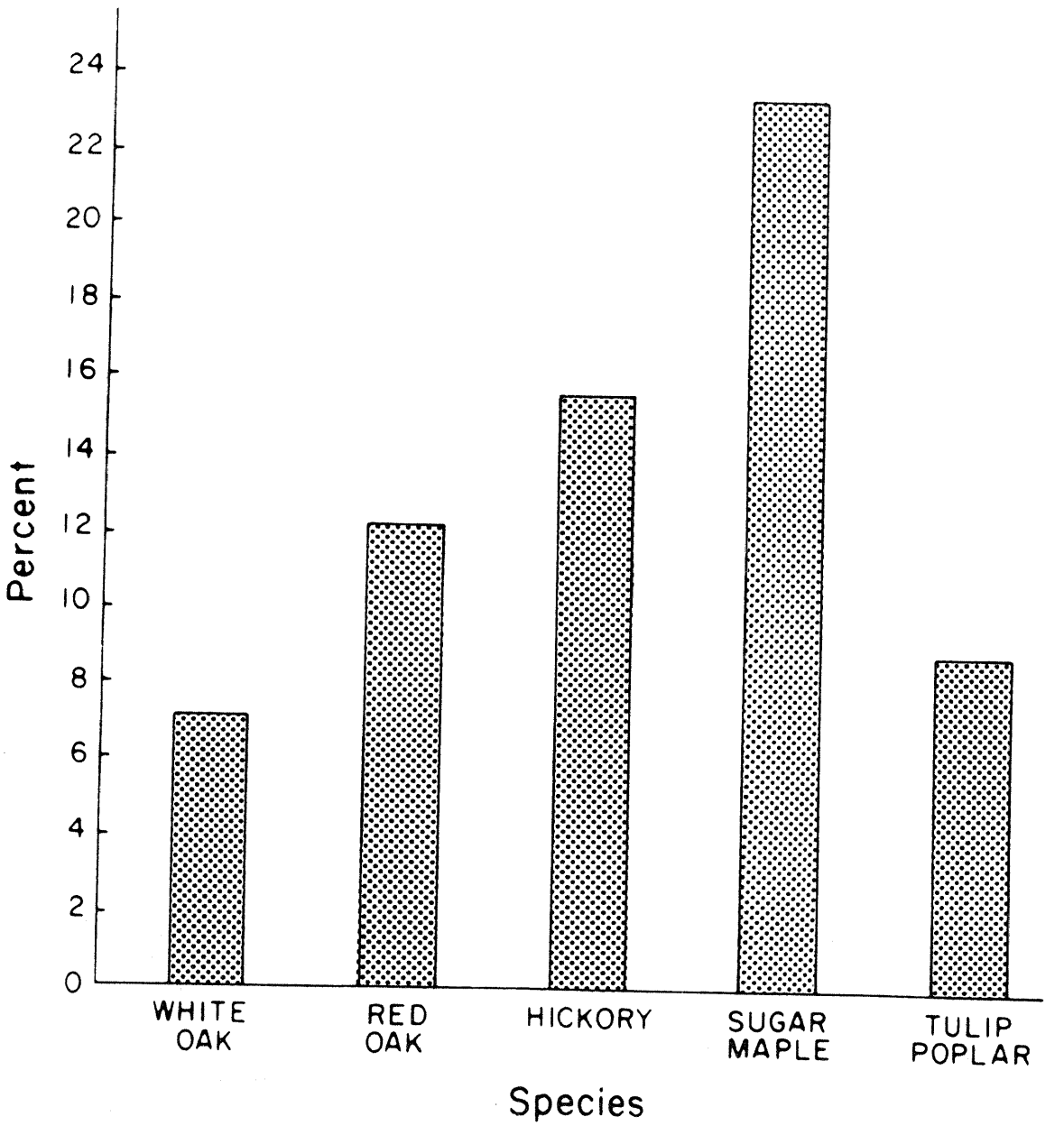


Figure 4. Effect of species on stemflow.

Table 4. Seasonal variation in nutrient concentration.

Nutrients	Average Concentration (ppm) during		
	4 Winter months (leaf off)	4 Summer months (leaf on)	Year (12 months)
		A -- Precipitation	
N	----[1]	----	1.335
P	0.005	0.103	0.173
K	0.438	1.615	0.930
Ca	0.741	1.148	0.848
Mg	0.091	0.178	0.133
Total w/o N	1.275	3.044	2.011
Total with N	----	----	3.366
		B -- Throughfall (excluding nutrient concentration in precipitation)	
N	----	----	0.306
P	0.015	0.182	0.073
K	1.167	2.695	2.940
Ca	1.014	0.992	1.102
Mg	0.191	0.403	0.328
Total w/o N	2.387	4.272	3.443
Total with N	----	----	3.749
		C -- Stemflow (excluding nutrient concentration in precipitation)	
N	----	----	0.681
P	0.024	0.130	0.031
K	6.380	9.361	9.283
Ca	7.750	5.242	7.812
Mg	0.828	0.688	0.662
Total w/o N	14.982	15.421	17.788
Total with N	----	----	18.469
		D -- Precipitation, Throughfall and Stemflow	
Weighted average w/o N[2]	2.53	4.27	3.52
Weighted average with N	----	----	4.386

[1] Sample quantity insufficient for analysis.

[2] Total volumes of precipitation, throughfall and stemflow were used as weights.

Table 5. Annual input of nutrients by precipitation, throughfall and stemflow.

Nutrient (kg/ha)					Yearly	
N	P	K	Ca	Mg	Total	Reference
			- - - - - - PRECIPITATION - - - - - -			
2.8	0.2	7	7	11	28	Miller 1963
15.5	10.5	19.0	14.3	3.0	62.3	Miceli *et al.* 1975
9.5	0.4	3.0	11.0	4.0	27.9	Carlisle *et al.* 1966
0.8-	0.2-	1.0-	3.0-	4.0-	9.0-	Ovington 1968
4.9	10.0	10.0	19.0	11.0	45.5	
13	--	5.0	19.0	5.8	42.8	Duvigneand *et al.* 1970
--	0.4	3.0	11.0	4.0	18.4	Ovington 1962
0.8-	--	1.0-	6.0-	--	7.8-	Emanuelsson *et al.* 1954
4.9	--	4.0	19.0	--	27.9	
			- - - - - - THROUGHFALL - - - - - -			
0.9	0.6	15.0	12.0	5.0	33.5	Carlisle *et al.* 1967
0.9	0.6	16.0	6.2	5.6	29.3	Duvigneand *et al.* 1970
10.8	9.0	19.9	23.0	4.6	67.3	Miceli *et al.* 1975
13.0	10.1	24.9	26.2	5.2	79.4	Miceli *et al.* 1975
8.8	1.3	28.1	17.2	9.4	64.8	Carlisle *et al.* 1966
7.0-	0.1-	0.3-	3.5-	1.0-	8.9-	Rodin *et al.* 1967
10.0	0.3	3.3	6.0	1.8	21.4	
19.1	3.0	31.0	32.0	4.8	89.9	Jensen 1974
			- - - - - - STEMFLOW - - - - - -			
--	--	0.8	0.9	0.6	2.3	Carlisle *et al.* 1966b
--	--	2.0	2.0	--	4.0	Duvigneand *et al.* 1970
1.5	1.2	4.1	3.4	0.8	11.0	Miceli *et al.* 1975
0.8	1.0	2.6	2.6	0.5	7.5	Miceli *et al.* 1975
0.9	--	2.0	3.2	--	6.1	Duvigneand *et al.* 1970
--	0.2	4.3	1.7	1.0	7.2	Jensen 1974

reason for this difference appeared to be that the major source of K and Mg was foliage but for Ca it was the bark. The major source of N and P was precipitation. The total concentration of all nutrients in stemflow also varied with species in the following decreasing order: white oak (42 ppm), hickory (18 ppm), tulip poplar (16 ppm), sugar maple (13 ppm) and northern red oak (10 ppm). Sugar maple and northern red oak data from this study did not compare well with 31 and 35 ppm, respectively as reported by Gersper et al. 1971. Differences may be due to a combination of age of trees, intensity of precipitation and soil fertility.

Total nutrient input by precipitation, throughfall and stemflow was equivalent to 29% of an estimated annual uptake of 396 kg/ha (Duvigneaud and Denaeyer-DeSmet 1970). Precipitation alone contributed 11% of annual uptake, whereas throughfall and stemflow contributed 10 and 8% respectively. These figures indicate that precipitation constituted an important addition to the forest ecosystem and throughfall as well as stemflow were both important pathways in nutrient cycling. The importance of stemflow is further enhanced because of its localized distribution around the bole of the tree (Voight 1960).

Table 6. Nutrient content of precipitation, throughfall and stemflow.

Nutrients		Precipitation	Throughfall	Stemflow	Total
N	kg/ha	17.7	3.3	1.2	22.2
	%1/	40	8	4	19
	%2/	80	15	5	100
P	kg/ha	1.3	0.8	0.1	2.2
	%1/	3	2	1	2
	%2/	59	36	5	100
K	kg/ha	12.1	20.9	15.6	48.6
	%1/	28	52	50	42
	%2/	25	43	32	100
Ca	kg/ha	11.1	11.9	13.2	36.2
	%1/	25	29	42	31
	%2/	31	33	36	100
Mg	kg/ha	1.7	3.5	1.1	6.3
	%1/	4	9	4	5
	%2/	27	56	17	100
TOTAL	kg/ha	43.9	40.4	31.2	115.5
	%1/	100	100	100	100
	%2/	38	35	27	100

1/Relative importance of different nutrients in each water component separately as well as collectively.

2/Relative importance of different water components as a source/pathway of each nutrient separately as well as collectively.

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