Soil Solution Phosphorus Dynamics in a Whole-Tree-Harvested Northern Hardwood Forest

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ABSTRACT

Forest harvest drastically alters nutrient cycling, yet stream water and mineral-soil solutions typically show little change in P concentrations after forest disturbance. Changes in P availability and movement are more likely to be detected in forest-floor solutions, since P can be strongly sorbed in soil. Tension-free lysimeters were used to compare forest-floor and mineral-soil solution total-P concentrations in whole-tree-harvested and undisturbed forest sites for 2 yr after harvest in the Hubbard Brook Experimental Forest in New Hampshire. Mean total-P concentrations in solution in the forest floor (Oa horizon) were significantly higher in whole-tree-harvested sites (248 μg P L^{-1}) than in undisturbed forest sites (67 μg P L^{-1}), presumably due to reduced plant uptake of P. Mean P concentrations in mineral-soil solution remained low after whole-tree harvest (32 μg P L^{-1} in the Bh and 15 μg P L^{-1} in the Bs), consistent with the high P-sorption capacity of the mineral soil. Phosphorus flux in soil solution from the Oa to the B horizon, calculated from monthly mean P concentrations and monthly water flux simulated by a hydrologic model, was greater in whole-tree-harvested sites (1.0 kg P ha^{-1} yr^{-1}) than in undisturbed forest sites (0.3 kg P ha^{-1} yr^{-1}) in the first 2 yr after the disturbance. This redistribution of P from the forest floor to the mineral soil far exceeds stream-water export of dissolved P (0.02 kg P ha^{-1} yr^{-1}) but is small compared with forest-floor stores (85 kg P ha^{-1}).

THE WHOLE-TREE HARVEST of Watershed 5 (W-5) at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire provided an opportunity to study the effects of forest disturbance on P cycling within the ecosystem (Yanai, 1990). Phosphorus concentrations in stream water change little after forest harvest at this or at other sites (Hobbie and Likens, 1973; Likens and Bormann, 1974; Douglas and Swank, 1975; Fredriksen et al., 1975), in contrast to N concentrations, which can rise dramatically (Pierce et al., 1972; Corbet et al., 1978; Bormann and Likens, 1979; Vitousek and Melillo, 1979). Soil solutions have also failed to show increased P concentrations after forest cutting (Richardson and Lund, 1975; McColl, 1978), despite the drastic alteration of nutrient cycling caused by deforestation. Both the low concentrations of P observed in stream water and soil solutions and the lack of response to clear-cutting can be explained by P sorption in the soil (Wood et al., 1984). Since the forest

floor lacks this P-sorption capacity, solution concentrations in the forest floor are more likely to display changes in P availability and movement following forest disturbance than are mineral-soil solutions or stream water.

In the undisturbed HBEF, biological cycling of P is most active in the well-developed forest floor (Wood et al., 1984). Decomposer organisms, absorbing roots, and organic-P input via litterfall and fine-root turnover are concentrated in the Oa horizon. Because P uptake by vegetation is severely reduced immediately following whole-tree harvest, while decomposition and P mineralization continue and may even accelerate (Bormann and Likens, 1979), concentrations of P in soil solution in the forest floor were expected to increase after harvest. Accordingly, more P was expected to leach from the forest floor into mineral soil in harvested sites than in undisturbed forest. Phosphorus concentrations in mineral-soil solutions were expected to remain low, due to the high P-sorption capacity of the B horizons.

Increased P loss from the forest floor as a result of forest disturbance could represent an important perturbation of the P cycle, since the undisturbed forest relies heavily on the forest floor for P supply (Yanai, 1990). Although P adsorption retains most of the translocated P in the mineral soil, mineral-soil P is less available to plants than is forest-floor P (Hoyle and Bjorkbom, 1969; Wood, 1980). Therefore, accelerated loss of P from the forest floor to the mineral soil could have important consequences for the supply of P for future forest growth.

To test the predictions regarding soil solution-P concentrations, tension-free lysimeters were used to compare total P concentrations in solution in the forest floor and mineral soil in whole-tree-harvested and undisturbed small-watershed ecosystems for 2 yr after harvesting. To quantify P loss from the forest floor following disturbance, leaching of total dissolved P through the monitored soil horizons was calculated from P concentrations and from water flux simulated by a hydrologic model. These calculated P transfers were used in constructing P budgets of the undisturbed forest and of the recovering forest in the first 2 yr postharvest (Yanai, 1990).

METHODS

Site Description

The HBEF, located in the White Mountains of north-central New Hampshire (43°56′N, 71°45′W), originated after

logging between 1910 and 1917 (Bormann et al., 1970). American beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), and yellow birch (*Betula alleghaniensis* Britt.), dominate the canopy, with red spruce (*Picea rubens* Sarg.), balsam fir (*Abies balsamea* [L.] Mill.), and white birch (*Betula papyrifera* Marsh.) increasing in importance at higher elevations (Bormann et al., 1970). Aboveground biomass totaled 230 Mg ha^{-1} in 1985 (D. Wang and T.G. Siccama, 1987, personal communication). The climate is humid continental with mean temperatures of -9 °C in January and 19 °C in July; annual precipitation is 130 cm, with 39 cm falling as snow (Likens et al., 1977). Slopes average 12 to 13° and are generally southeast in aspect (Bormann et al., 1970); elevation ranges from 510 to 750 m.

Soils of the HBEF have developed in granitic glacial till overlying granitic gneiss. Watershed 5, the whole-tree-harvest area, was mapped before harvest; the soils are coarse-loamy to loamy, mixed, frigid Typic or Lithic Haplorthods of the Tunbridge–Lyman rock-outcrop complex and Berkshire series, with lesser areas in Skerry, Becket (coarse-loamy, mixed frigid Typic and Aquic Haplorthods), and Lyme (coarse-loamy, mixed, acid, frigid Aeric Haplaquept) series (Huntington et al., 1988). The forest floor (Oi, Oe, and Oa horizons) of W-5 has a mean thickness of 7 cm; the mineral soil averages 54 cm deep (Huntington et al., 1988).

Soil properties important to P dynamics at the HBEF were studied by Wood (1980); some of his results are reproduced in Table 1. Extractable and total P concentrations are significantly higher in the forest floor than in the mineral-soil horizons. Wood found P-adsorption capacity to be much higher in mineral than organic soil horizons and highly correlated with extractable Fe and Al (Table 1), as is commonly observed (Parfitt, 1978; Wada and Gunjigake, 1979).

Lysimeter Design and Installation

Since it proved impossible to maintain tension on lysimeters between the monthly collections at this remote site, tension-free lysimeters (Jordan, 1968; Haines et al., 1982; Turner et al., 1985) were chosen for this study. These lysimeters were installed and sampled in cooperation with other researchers studying acid-base chemistry, S (Fuller et al., 1987a), and trace metals (Fuller et al., 1987b; Driscoll et al., 1988).

Thirty tension-free lysimeters consisting of 10-cm-diam. polyethylene funnels filled with acid-washed quartz sand were installed in August and September 1983. To increase replication, 18 more lysimeters were added in November 1984. The second group of lysimeters was made of shallow polyethylene boxes (20 by 14.5 by 3.5 cm) filled with acid-washed Teflon boiling beads. Three lysimeters, one in the Oa horizon, near its base, one in the Bh, and one in the Bs horizon, were installed at each of 16 sites. Eight sites were in the clear-cut, ranging in elevation from 600 to 750 m, and eight were in undisturbed forest at similar elevations and 300 to 400 m distant from the sites in the clear-cut.

Both types of lysimeters were installed by tunneling in from the side of a pit. The roof of the tunnel was excavated until the desired horizon was reached, and the lysimeter was pressed upward into undisturbed soil. Since the Bh horizon boundaries are commonly irregular, parts of Bh lysimeters were probably sited in E and Bs soil. The Bs lysimeters were placed at an average depth of 44 cm from the bottom of the O horizon. Lysimeters were placed uphill from the pit to minimize disruption of soil water movement. The lysimeters drained through Tygon tubing to a 1- or 2-L collection bottle in the pit. The tunnel and pit were refilled with tamped soil. Tubes extending from the bottle to the soil surface permitted accumulated water to be evacuated without further disruption of the soil. The collection bottles were vented to the atmosphere.

Table 1. Properties of Hubbard Brook soils.†

Parameter	Oa horizon	Bh horizon	Bs horizon
Loss on ignition (%)	54.1 ± 4.4	12.6 ± 0.9	7.1 ± 0.6
Clay content (%)		6.2 ± 0.3	6.7 ± 0.7
pH (H$_2$O)	3.45 ± 0.06	3.82 ± 0.04	4.63 ± 0.06
pH (CaCl$_2$)	3.15 ± 0.06	3.43 ± 0.04	4.17 ± 0.03
Phosphorus concentrations (g P kg^{-1} soil)‡			
Organic P	0.48 ± 0.02	0.23 ± 0.02	0.17 ± 0.01
Secondary compound P	0.03 ± 0.01	0.14 ± 0.01	0.12 ± 0.01
Total P	0.67 ± 0.03	0.39 ± 0.02	0.50 ± 0.04
Extractable P (mg P kg^{-1} soil)§			
Dilute-acid extractable	5.4 ± 1.1	0.06 ± 0.02	0.04 ± 0.02
Strong-acid extractable	11.9 ± 1.6	1.9 ± 0.2	18.3 ± 5.7
Phosphorus-adsorption capacity (g P kg^{-1} soil)¶			
	0.05 ± 0.05	0.95 ± 0.04	0.98 ± 0.06
Extractable Fe and Al (g kg^{-1} soil)#			
Al (pyrophosphate)	1.3 ± 0.2	4.2 ± 0.3	8.3 ± 1.0
Al (NH$_4$OAc)	1.4 ± 0.2	4.2 ± 0.3	8.3 ± 1.1
Fe (NH$_4$OAc)	1.9 ± 0.4	14 ± 2	5.0 ± 0.6
Fe (citrate–dithionite)	3.8 ± 0.7	18 ± 2	7.0 ± 0.9

† Measured by Wood (1980). Means and standard errors are for $n = 10$, except for extractable Fe and Al, for which $n = 6$.

‡ Organic P was determined using the ignition method. Secondary mineral P was determined by citrate–dithionite P extraction minus a correction for water-soluble P. Total P was determined by HF–HClO$_4$ digestion.

§ Dilute-acid extractant was 0.001 M H$_2$SO$_4$; strong acid was 0.05 M HCl + 0.0125 M H$_2$SO$_4$.

¶ Phosphorus-sorption capacities were measured from 31 mg P L^{-1} solutions for 24 h. Complete methods are given by Wood (1980).

Pyrophosphate extraction indicates the amount of Al in Al–humus complexes; NH$_4$OAc extracts Al and Fe from allophane, imogolite, and ferrihydrite; citrate–dithionite additionally dissolves crystalline oxides such as goethite and hematite (Parfitt and Childs, 1988).

During periods of high water flux, some of the bottles filled completely during the collection period (approximately 1 mo). Collected solution could not move back into the soil, but flow paths around the lysimeter must have been altered until the evacuation of the bottle. There was no discernable effect on subsequent collections.

Whole-Tree-Harvest Treatment of Watershed Five

A 22-ha watershed (W-5) at the HBEF was clear-cut between November 1983 and May 1984 by a commercial contractor using whole-tree-harvest techniques. All trees >2-cm-diam. at breast height were cut and removed from the site using feller-bunchers, chain saws, and skidders. Lysimeter sites were protected from machine traffic during the harvest operation.

Vegetation was allowed to reestablish naturally. After 2 yr, pin cherry (*Prunus pennsylvanica* L.f.), American red raspberry (*Rubus strigosus* Mich.), American beech, and wood fern (*Dryopteris spinulosa* Muell.) dominated (Hughes, 1987). Aboveground living biomass was 1.4 Mg ha^{-1} 2 yr after harvest and contained 1.7 kg P ha^{-1} (Yanai, 1990).

Sample Collection and Phosphorus Analysis

Lysimeter solutions were collected at approximately monthly intervals for 2 yr following harvest, from January 1984 to December 1985. During the summer months, when soil moisture was low, and during winter periods of subzero temperatures, many lysimeters failed to collect water. When the amount of accumulated water was <200 mL in any sampling period, P was not analyzed (other analyses, not reported here, took priority). Finally, several lysimeters entirely ceased to collect water after the first year of operation. Thus, of the possible 846 lysimeter collections, 55% provided samples for analysis of total P. On rare occasions, I analyzed P from collections of <200 mL; these data were included

in analysis of the volume–concentration relationship but were omitted from the comparison of lysimeter means because they were not systematically obtained.

Because of the probable transformations of organic and inorganic P in the collection bottles between sampling dates, only total P was measured in this study. Soil-solution samples were stored at 4 °C or frozen prior to analysis. To measure total P, soil solution was digested with persulfate, oxidizing ester–P to dissolved inorganic phosphate. Phosphate was then complexed with molybdate (USEPA, 1979) and the resulting blue color measured by spectrophotometer. Raw data are given by Yanai (1990).

Phosphorus concentrations measured sequentially from the same lysimeter are not independent samples of the soil solution. To assess the statistical significance of the effect of whole-tree-harvest treatment on solution P concentration, only lysimeter means (means of all P concentrations measured from a given lysimeter over the 2-yr period) should be compared. The sample size was therefore, at most, eight lysimeters for each horizon–treatment combination. Solutions from the two lysimeter types were not significantly different and were combined in this analysis. Lysimeters that yielded fewer than two samples were not included in the analysis. Lysimeter values were not weighted by the duration of the sampling interval nor by the amount of solution collected, which was too often limited by the size of the collection vessel. Treatments were compared using a paired t-test for each horizon with $\alpha = 0.05$ (SAS Institute, 1985).

Calculation of Phosphorus Flux

Calculation of solute flux through the soil horizons requires an estimate of soil water flux as well as solute concentration. Because small lysimeters do not provide a reliable estimate of percolation volume (Cochran et al., 1970; Haines et al., 1982; Radulovich and Sollins, 1987), the magnitude of soil water flux was estimated by simulation modeling. A hydrological model, BROOK, developed with data from the HBEF and from Coweeta Hydrologic Laboratory, North Carolina (Federer and Lash, 1978a,b), was applied to the HBEF whole-tree-harvested and undisturbed-forest watersheds for the time period of this lysimeter study (Hornbeck et al., 1987). I used the results of these simulations to estimate water flux through the soil horizons in which the lysimeters were placed.

The BROOK model does not distinguish soil horizons; the amount of water draining from the root zone is simulated, but this amount is less than water flux at higher levels in the soil due to removal of water throughout the root zone by transpiration. To calculate water flux past each lysimeter depth, I added to drainage from the root zone a fraction of the transpiration stream equal to the fraction of fine roots below that depth. This method assumes that water is equally available throughout the profile. In fact, the water content of surface soil probably varies more than that of soil at depth, with plant uptake varying accordingly; this process is not included in the model.

The fraction of fine roots below each lysimeter depth was calculated from a combination of studies. The proportion of fine roots in the forest floor was measured in the whole-tree harvest and in undisturbed forest in the fall of 1987, when the regrowth vegetation was 4 yr old (T.J. Fahey and Z. Xu, 1989, personal communication; Table 2). I made no correction for changes in root distribution that may have occurred after the first 2 yr of growth, the period covered by the lysimeter study. The distribution of roots, and thus the allocation of water uptake across depths, was held constant in this calculation.

The distribution of roots in the mineral soil in the undisturbed forest was measured by Wood (1980) as a function

Table 2. Depth distribution of fine roots and resulting allocation of transpiration between monitored soil horizons.

	Undisturbed forest	Whole-tree-harvest area
	%	
	Depth distribution of fine-root biomass	
Forest floor†		
Oa horizon	46	75
Mineral soil‡		
9 to 17 cm	17	10
17 to 53 cm	27	10
Below 53 cm	10	5
	Proportion of transpiration stream passing lysimeter depths§	
Oa horizon (9 cm)	54	25
Bh horizon (17 cm)	37	15
Bs horizon (53 cm)	25	10

† T.J. Fahey and Z. Xu (1988, personal communication) measured fine-root biomass in soil cores from undisturbed forest and from the whole-tree harvest in the fall of 1987. Root densities counted by intersections in buried screens confirmed these distributions.

‡ Mass of nonwoody fine roots was measured at 10-cm increments in the B horizon and underlying parent material by Wood (1980).

§ The proportion of simulated transpiration assumed to pass by each lysimeter depth is the proportion of roots below that depth.

of depth, not soil horizon. I used the mean horizon depths reported by Wood (1980) to apportion his fine-root densities among my lysimeter depths (Table 2). The rooting depths used to parameterize BROOK for the two watersheds were 63.5 cm for the forest and 37.5 cm for the whole-tree harvest.

Simulated daily soil water flux was summed for the period between lysimeter collections. The mean of all P concentrations measured on that collection date was multiplied by water flux to give P flux. If no P concentration was available, P flux was calculated using the next measured concentration. This procedure was carried out separately for each of the six combinations of watershed and lysimeter depth. Calculated water and P fluxes for each sampling interval are given by Yanai (1990).

RESULTS

Phosphorus Concentrations in Soil Solution

Phosphorus concentrations in soil solution collected by tension-free lysimeters declined markedly with depth (Fig. 1). Whereas lysimeters collecting solution from the Oa horizon averaged 67 μg P L^{-1}, Bh and Bs horizon lysimeters averaged 16 and 10 μg P L^{-1}, respectively, in the undisturbed 70-yr-old northern hardwood forest. Phosphorus concentrations also declined with depth in whole-tree-harvested sites, where mean concentrations fell from 248 μg P L^{-1} in the Oa to 32 μg P L^{-1} in the Bh horizon and 15 μg P L^{-1} in the Bs horizon. Thus, mean P concentrations in Oa horizon lysimeters were more than three times higher in the whole-tree-harvested sites than in the undisturbed sites. Phosphorus concentrations in the B horizons were also higher in disturbed sites, but the increases were small and not statistically significant.

Temporal variation in P concentrations was high (Fig. 2), especially in whole-tree-harvested sites. Some of this variation was associated with hydrologic changes; many of the lowest P concentrations occurred during snowmelt and the highest during the late summer months, when the soil was driest. A slight but significant inverse relationship existed between the
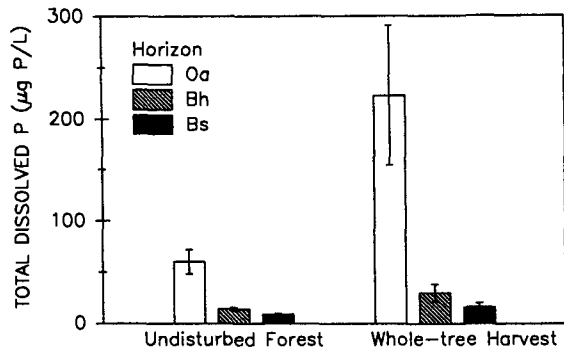
Fig. 1. Mean total P concentrations in lysimeter solutions in undisturbed forest and whole-tree-harvested sites. Vertical bars show ± 1 standard error.
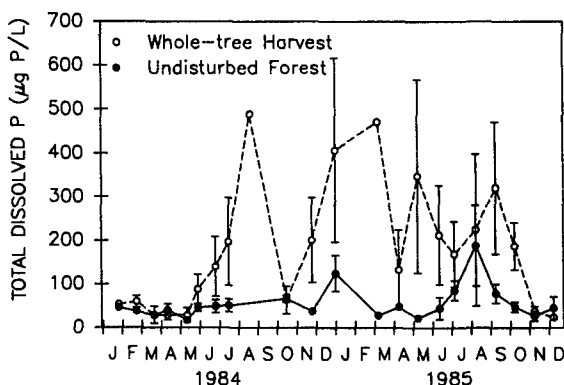

Fig. 2. Mean P concentrations in Oa horizon soil solution at each sampling date. Means without error bars (± 1 standard error) are based on only one sample (n ranged from one to eight sites).
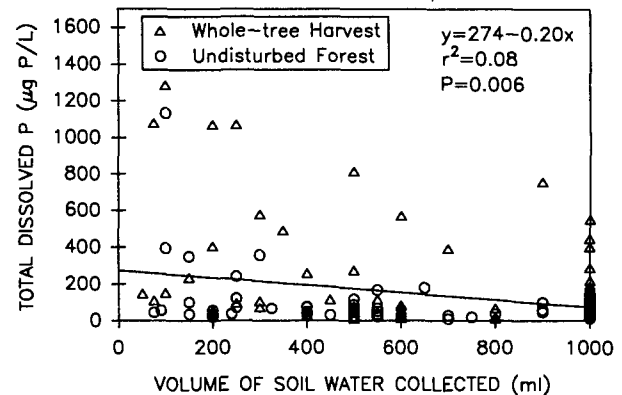

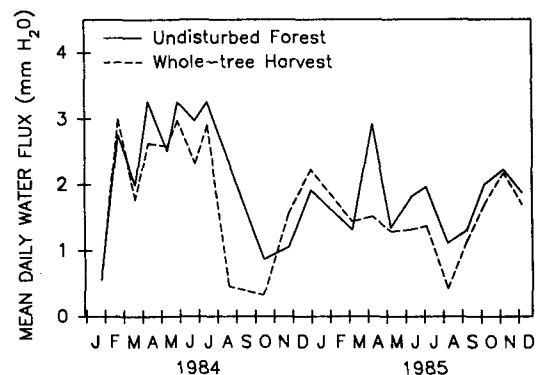Fig. 3. Phosphorus concentrations in Oa horizon soil solution as a function of the volume of solution collected.

Fig. 4. Simulated water flux from the Oa horizon to the mineral soil during each lysimeter sampling interval.

volume of soil water collected and its P concentration (Fig. 3), at least in the Oa horizon, despite the limited collection volume of the lysimeters.

On the first five sampling occasions, concentrations in whole-tree-harvested sites were similar to those in forested sites (Fig. 2). The harvest operation began in November 1983, about 2 mo before the first solution collections, but since biological activity is low during the winter months in this climate, differences in solution concentrations did not appear until May 1984, when the harvest was complete and the vegetation active. The initial similarity of the whole-tree-harvested and forested sites supports the reasonable but untestable assumption that subsequent differences between sites in the two watersheds were caused by the whole-tree-harvest treatment.

Phosphorus Flux in Soil Solution

Modeled water movement through the soil, like P concentration, changed seasonally (Fig. 4). The highest water flux through soil occurs at snowmelt; the lowest water fluxes occur at the height of summer when evaporation and transpiration are high and during the winter when the only source of water to the soil is melt from the bottom of the snowpack (Federer, 1965).

Measured precipitation and simulated infiltration into the forest floor were very similar between the two watersheds (Table 3). Simulated evaporation from the

soil was greater in the harvested watershed, because there was less shading by vegetation. Transpiration was much greater in the forest. As a result, more water drained from soil into streams in the clear-cut, especially in the summer months. In the forest floor, however, where much of the transpiration stream has not yet been removed by roots, water flux was higher in the forested watershed than in the whole-tree harvest (Fig. 4). These fluxes were only modeled, not verified by observation. The fact that measured monthly stream flow agrees fairly well with model results (Hornbeck et al., 1987) suggests that internal water transfers were reasonably modeled at this time scale.

The product of simulated water flux and measured P concentrations gives an estimate of P flux through the soil. The sum of incremental P fluxes, based on the P concentration of soil solution collected at approximately monthly intervals and simulated daily water flux summed across the same time interval, shows a threefold increase in P leaching from the forest floor between the undisturbed forest and whole-tree harvest, from 0.34 to 1.02 kg P ha^{-1} yr^{-1}. Phosphorus fluxes through the Bh and Bs horizons were much lower both before and after whole-tree harvest (Table 4). Because of the seasonal variation in both soil water movement and P concentrations, the product of annual water flux and unweighted mean P concentration would give a less accurate estimate of P flux than this sum of monthly fluxes.

Table 3. Measured and modeled monthly water fluxes in undisturbed forest (W-6) and whole-tree-harvest (W-5) watersheds from January 1984 to December 1985.

Month	Precip†		Infilt‡		Soilev§		Transpiration		Drainage¶	
	W-6	W-5	W-6	W-5	W-6	W-5	W-6	W-5	W-6	W-5
						mm				
1984										
Jan	60	57	10	13	0	0	0	0	19	20
Feb	130	126	112	103	0	7	0	0	89	82
Mar	135	128	56	62	0	0	0	0	57	55
Apr	149	143	94	87	14	21	0	0	88	77
May	314	309	138	131	17	22	14	3	85	83
Jun	179	182	116	98	3	20	84	16	48	73
Jul	143	142	99	91	2	20	99	31	35	68
Aug	37	35	23	31	2	18	62	28	2	10
Sep	39	39	29	36	3	18	35	19	0	4
Oct	88	86	81	77	15	19	6	2	0	9
Nov	120	118	85	74	11	17	0	0	41	54
Dec	122	114	57	71	1	4	0	0	53	59
Total	1516	1480	900	873	68	166	300	100	517	593
1985										
Jan	74	67	20	20	0	1	0	0	41	41
Feb	93	90	51	53	0	0	0	0	31	31
Mar	125	111	97	65	0	10	0	0	85	70
Apr	74	69	46	54	12	17	0	0	62	40
May	106	106	76	80	17	20	13	10	46	47
Jun	129	127	93	98	3	20	70	42	14	24
Jul	57	56	42	49	2	15	78	54	7	18
Aug	90	88	72	76	2	10	58	49	1	3
Sep	156	153	124	111	3	12	68	54	14	23
Oct	116	116	74	77	16	21	9	6	60	63
Nov	145	140	85	85	10	16	0	0	69	65
Dec	93	91	24	25	0	0	0	0	35	34
Total	1258	1217	803	793	64	142	296	215	465	458

† Precipitation was measured and used as input to the model. All other fluxes were modeled.

‡ Infiltration of water into soil from precipitation after interception and evaporation in the canopy and from the snowpack.

§ Evaporation of water stored in the top 5 cm of the forest floor.

¶ Water draining from the root zone to streams.

DISCUSSION

The adoption of an ecosystem approach to P cycling precluded replication of the control and the whole-tree-harvest treatments, due to the expense and intensity of effort involved in watershed studies. As a result, differences between the whole-tree-harvested and undisturbed watersheds reflect site as well as treatment effects. The pretreatment similarity of the watersheds suggests that posttreatment differences can be interpreted as resulting from the treatment, but the relative importance of site effects cannot be assessed. The benefits of the small-watershed ecosystem approach include the quantification of hydrologic inputs and outputs and their compatibility with nutrient accumulation and flux rates measured on a per-area basis. For example, this calculation of P leaching from the forest floor, in combination with watershed-level estimates of plant uptake and detrital fluxes, allows net P mineralization in the forest floor to be deduced on the basis of mass balance (Yanai, 1990). The calculated solution transfers of P from the forest floor to the mineral soil were essential in the construction of P budgets of the undisturbed forest and of the recovering forest in the first 2 yr postharvest (Yanai, 1990), enabling these P budgets to distinguish P supply to plants from the forest floor and the mineral soil.

Table 4. Calculated P flux in soil solution in undisturbed (W-6) and whole-tree-harvested (W-5) watersheds from January 1984 to December 1985.

Horizon	P flux	
	W-6	W-5
	kg P ha^{-1} yr^{-1}	
Oa	0.34	1.02
Bh	0.078	0.13
Bs	0.048	0.073

The observed decrease of soil solution P concentration with depth is consistent with the known P-adsorption capacity of the mineral soil at the HBEF (Table 1). Similar decreases in soil solution P with depth have been observed in Spodosols under western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)–red cedar (*Thuja plicata* Donn.) (Feller, 1977) and Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco) (Windsor, 1969), andesitic Dystrochrepts (Sollins et al., 1980), ochreous and acid brown soils under hardwoods and conifers in France (Nys et al., 1981), and Alfisols and Inceptisols under pine forest in Wyoming (Yavitt and Fahey, 1986; Fahey and Yavitt, 1988).

Because of the adsorption that maintains dissolved P at low concentrations in mineral soils, P concentrations in soil solution have often been observed to remain low after forest harvest (Richardson and Lund, 1975; McColl, 1978; Haines and Waide, 1979). At Hubbard Brook, mean P concentrations in Bh and Bs soil solution were elevated by only 16 and 5 μg P L^{-1}, respectively, in the first 2 yr following whole-tree harvest, differences that were not statistically significant. The chemistry of soil solution has been monitored less often in the forest floor than in mineral soil. At Hubbard Brook, mean P concentrations in the Oa horizon increased by 181 μg P L^{-1}, from 67 to 248 μg P L^{-1}. Similarly, in Sitka spruce (*Picea sitchenis* [Bong.] Carr.) plantations on peaty gley soils in northern England (Adamson and Hornung, 1990), dissolved inorganic-P concentrations in the E and B horizons stayed below 10 μg P L^{-1} even after clear-cutting, while mean concentrations in the Oa increased from 17 to 123 μg P L^{-1} (J.K. Adamson, 1988, personal communication). At another Sitka spruce site in north Wales (Stevens and Hornung, 1988), dissolved inorganic P in the forest floor increased from 100 to 300 μg P L^{-1} in the first 2 yr after clear-cutting, while concentrations in the B horizon again remained below 10 μg P L^{-1} (P. Stevens, 1988, personal communication). These observations support the hypothesis that P availability in the forest floor increases following forest disturbance but that stream-water P concentrations remain low due to adsorption in the mineral soil.

Phosphorus leaching from the forest floor to the mineral soil at the HBEF, calculated from measured P concentrations and simulated water flux, increased from 0.3 to 1.0 kg P ha^{-1} yr^{-1} following whole-tree harvest. This increase is similar to those observed at the aforementioned sites; in north England, P flux from the forest floor to the mineral soil increased from 0.4 kg P ha^{-1} yr^{-1} to 1.0 kg P ha^{-1} yr^{-1} due to clear-cutting (J.K. Adamson, 1988, personal communication). At the Welsh site, whole-tree harvest increased

P leaching from the forest floor from 0.9 to 2.4 kg P ha^{-1} yr^{-1}; bole-only harvest resulted in greater P leaching (6.6 kg P ha^{-1} yr^{-1}) from the forest floor in the first 2 yr after clear-cutting. High P fluxes in throughfall under slash suggested that the higher soil solution P after bole-only harvest was due to P leaching from slash (P. Stevens, 1988, personal communication). In both bole-only and whole-tree harvests, P flux through the B horizon remained extremely low. At Hubbard Brook, export of dissolved P in stream water increased by only 0.01 kg P ha^{-1} yr^{-1}, remaining lower than precipitation inputs (0.04 kg P ha^{-1} yr^{-1}) (Yanai, 1990). Clearly, B horizon and stream-water P concentrations cannot be relied on to indicate within-ecosystem changes in P cycling caused by forest disturbance.

The increase in P transport from the forest floor to the mineral soil via leaching after forest harvest (0.7 kg P ha^{-1} yr^{-1}) was too small to present any danger of P limitation to the regrowing forest, since this loss amounts to only a small percentage of the forest-floor P pool (85 kg P ha^{-1}; Johnson, 1989). In fact, the increase in P leaching was less than predicted from the decrease in plant uptake from the forest floor after forest harvest, which was on the order of 4 kg P ha^{-1} yr^{-1} in the first 2 yr (Yanai, 1990). The limited magnitude of P leaching from the forest floor suggests that additional mechanisms, such as a decrease in gross P-mineralization rates or an increase in microbial P immobilization, may help to minimize P loss from the forest floor after disturbance, much as P adsorption in the mineral soil serves to prevent P loss in stream water.

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