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Phosphorus dynamics on organic and inorganic substrates in streams

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With 4 figures and 2 tables in the text

Introduction

The importance of phosphorus in freshwater ecosystems is clearly reflected by the multitude of studies of this nutrient in limnological literature. The preponderance of these studies has been directed toward lentic ecosystems or large rivers which are heavily influenced by man. The dynamics of P in streams, while similar to those in lakes and large rivers, are more strongly influenced by benthic processes. Previous studies of P translocation in streams by ^{32}P tracer techniques reveal that P is quickly removed from the water as it flows downstream (as much as 95 % within 100 m of stream) and that it is initially absorbed by the microflora of the stream and subsequently transferred to higher trophic levels by ingestion (BALL & HOOPER 1963; NELSON et al. 1969). The lack of appreciable water column processes in most low to intermediate order streams makes most of this retention attributable to benthic processes.

The goal of this research was to examine the physical and biological sorption processes of P onto organic and inorganic stream substrates. Physical adsorption of P onto inorganic sediments, especially clay minerals, accounts for a portion of the removal of P from solution in aquatic ecosystems (POMEROY et al. 1965; GARDER & SKULBERG 1966; NELSON et al. 1969). Thus, differentiation between physical and biological sorption is necessary to understand the relative importance of these processes in streams. Secondly, the relative potential for P uptake onto different forms of organic substrates in streams may differ. Microbial colonization of organic matter in streams has been shown to affect the nutrient content of allochthonous detritus (KAUSHIK & HYNES 1968; TRISKA & SEDELL 1976; TRISKA & BUCKLEY 1978). Uptake of ^{32}P onto leaves in a stream in Tennessee was highly variable (NELSON et al. 1969), a response which might result from different residence times and, therefore, microbial colonization of individual leaves. Variable absorption of P onto allochthonous detritus may also be a function of the form of organic matter, such as deciduous versus coniferous detritus. Thirdly, uptake of P by aquatic primary producers in streams, a relatively rapid process (BALL & HOOPER 1963), may account for various patterns of removal in that different forms of primary producers may have different rates of uptake. The objectives of this study were to examine these aspects of P translocation in the following manner:

1) to determine the relative magnitudes of physical and biological sorption onto inorganic stream substrates, leaves, and conifer needles;
2) to relate uptake of ^{32}P onto leaves and needles to microbiol metabolism;
3) to determine the relative assimilation capacities of periphyton (Aufwuchs), filamentous green algae, monostromatic sheetlike green algae, and herbaceous riparian vegetation.

Materials and methods

Physical versus biological sorption

Physical adsorption of ^{32}P onto stream substrates was measured by sterilizing the substrates with gamma radiation from a ^{60}Co source. Uptake of ^{32}P onto sterilized substrates was attributed to physical adsorption while uptake onto non-sterilized substrates was assumed to result from both physical adsorption and biological absorption. The difference between the two was attributed to biotic uptake of P.

Rock samples of volcanic origin were collected from streams in the H. J. Andrews Experimental Forest in Oregon, scrubbed free of periphyton, and rinsed in 90 % acetone. Benthic core samples were collected from Oak Creek, Benton County, Oregon and separated into size classes of 10 mm — 0.991 mm, 0.990 — 0.500 mm, 0.499 — 0.175 mm, and 0.174 — 0.116 mm. Alder leaves were obtained from natural leaf accumulations in Oak Creek. Conifer needles were collected at abcission and conditioned in Oak Creek for 60 days. Portions of each substrate type were sterilized by ^{60}Co gamma radiation.

Sterilized and unsterilized substrates were placed in a flow-through plexiglass chamber (McIntire et al. 1964) and 300 μCi of ^{32}P were continuously dripped in a mixing chamber ahead of the chamber for 1 hour. The flow rate in the chamber was 10 l/min, resulting in a maximum ^{32}P concentration of 1.1×10^4 dpm/ml of water. Samples were removed at the end of the hour and prepared for radiation measurement.

Rock samples were soaked in a 2 N HCl 1 % HF solution for 24 hours, rinsed, and removed for surface area measurement. The acid solution was neutralized and evaporated to a crystalline state. The crystal was dried at 50 °C, weighed and subsampled. The crystal subsamples were placed in tared planchets, weighed, and monitored for radioactivity. Surface area of the rocks was determined by coating the rock with collodion, removing the collodion film, and measuring its area. Leaf samples, conifer needles, and sediment samples were each placed in tared planchets, dried at 50 °C for 24 hours, weighed, and measured for radioactivity. After radiation measurements, leaf, needle, and sediment samples were placed in a muffle furnace at 500 °C for 4 hours to determine ash-free dry weights. A gas-flow Geiger-Müller detector was used for radiation measurements and all ^{32}P data were corrected for radioactive decay and background noise.

Residence time studies and deciduous-coniferous comparison

Leaf bags of bigleaf maple and conifer needles were placed in Berry Creek, Benton County, Oregon at 3-day intervals for 60 days to obtain a series of deciduous and coniferous detritus of known conditioning time. At the end of 60 days the leaf bags were removed and taken into the laboratory. Discs were cut from each leaf and needles were separated into two groups for measurement of microbial respiration and ^{32}P uptake. The leaf discs and conifer needles to be used for ^{32}P uptake measurement were separated into two groups, one of which was sterilized by gamma radiation from a ^{60}Co source. The leaves and needles were then treated identically to the organic matter in the previous study. Leaf discs and conifer needles to be used for the measurement of microbial respiration were placed in Warburg flasks in a Gilson Differential Respirometer at 13 °C. Oxygen consumption was measured for three 1-hour intervals. The leaf discs and needles were then dried at 50 °C for 24 hours and weighed. Results for each leaf type were expressed as dpm of ^{32}P/g of leaf (1 hour exposure) and μlO_2/g of leaf/hr. Excess leaf and needle material was used for N analysis.

^{32}P absorption by aquatic primary producers

^{32}P in the form of orthophosphate was released to a section of Mack Creek in the H. J. Andrews Experimental Forest in the Cascade Mountain Range in Oregon in July 1973. Mack Creek is a third order, mountain stream which drains a 650 ha watershed

with side slopes with a 77 % gradient and a stream gradient of 10 %. The stream section flows north with the west side of the stream bordered by a Douglas-fir Hemlock forest and the east side by a 10-year old clearcut. Introduction of ^{32}P into the stream was similar to that described by NELSON et al. (1969). ^{32}P concentrations in streamwater averaged 1600 dpm/ml over the 75 minute introduction period. One hour after the ^{32}P release, samples of periphyton were taken at 10 m intervals for a 65 m reach of stream. At each station samples of *Zygnema* sp., a filamentous green algae, *Prasiola* sp., a monostromatic sheetlike green algae, and sweet colt's foot, *Petasites frigidus*, a herbaceous riparian plant were collected if present. Periphyton samples were obtained by thoroughly scraping rocks with a nylon brush on a Dremel Moto-Tool and rinsing with distilled water. The solution containing the periphyton was then filtered through a 0.8 μ Millipore filter, dried, at 50 °C for 24 hours, weighed, monitored for radioactivity, ashed, and weighed. Radioactivity measurements were corrected for radioactive decay, background, and detector efficiency. Weights were corrected for filter ash and leaching. Samples of *Prasiola* and *Zygnema* were treated identically as periphyton samples except for filtration. The sweet colt's foot was separated into root, stem, and leaf material prior to analysis.

Results

Physical versus biological sorption

Sorption of ^{32}P onto sterilized stream substrates was less than uptake onto unsterilized substrates (Table 1). The sterilized rock samples sorbed 226.4 dpm/

Table 1. ^{32}P concentrations on sterilized and unsterilized stream substrates following a 1 hour exposure to ^{32}P in a flow-through chamber (mean ± one standard error).

	Sterile		
Sample	dpm/mg dry weight	dpm/mg ash-free dry weight	dpm/cm²
Basaltic rocks	218.1 ± 42.2		226.4 ± 47.2
Alder leaves	17.9 ± 2.1	22.5 ± 4.7	83.6 ± 10.4
Conifer needles	5.7 ± 1.3	7.3 ± 2.0	27.7 ± 4.8
Sediment cores:			
10—0.991 mm	0.05	0.77	
0.991—0.550 mm	0.26	2.33	
0.500—0.175 mm	1.16	10.82	
0.175—0.116 mm	2.74	18.74	
	Non-sterile		
Sample	dpm/mg dry weight	dpm/mg ash-free dry weight	dpm/cm²
Basaltic rocks			
Alder leaves	133.2 ± 12.2	159.2 ± 12.6	651.1 ± 57.4
Conifer needles	18.8 ± 2.9	22.4 ± 3.3	85.1 ± 13.1
Sediment cores:			
10—0.991 mm	0.49	8.86	
0.991—0.550 mm	0.74	6.00	
0.500—0.175 mm	2.65	17.80	
0.175—0.116 mm	6.77	36.32	

cm^2 during the 1-hour study period. Later studies in the stream in the Cascade Mountains indicated that similar natural substrates sorbed 10 times as much ^{32}P for a 75-minute release as did the sterilized substrates. Unsterilized leaf discs sorbed 7 times as much ^{32}P per unit ash-free dry weight and 8 times as much ^{32}P per unit area as the sterilized leaf substrates. Unsterilized conifer needles accumulated 3 times more ^{32}P per unit ash-free dry weight and per unit area than sterilized conifer needles. In the three lower size classes of sediments, the unsterilized samples sorbed twice as much ^{32}P as the sterilized samples; the unsterilized sediment sample in the 10 mm—0.991 mm size class sorbed 10 times as much ^{32}P as the sterile sample. Sorption of ^{32}P was consistently greater on unsterilized stream substrates than on sterilized samples. Except for fine stream sediments and conifer needles, the amount of ^{32}P on sterilized samples was always less than 20 % of the unsterilized natural substrates. Fine stream sediments and conifer needles likely contain more refractory organic material than the other stream substrates. The lessened biological activity and greater surface to volume ratio of the fine sediments could account for the greater importance of physical adsorption on fine sediments and coniferous detritus.

Residence time studies and deciduous-coniferous comparison

Both bigleaf maple leaves and conifer needles were able to adsorb more ^{32}P per unit ash-free dry weight the longer they were incubated in the stream (Fig. 1). Uptake onto bigleaf maple was significantly greater than sorption on conifer needles ($p < 0.01$). Microbial respiration showed a similar pattern to ^{32}P ab-

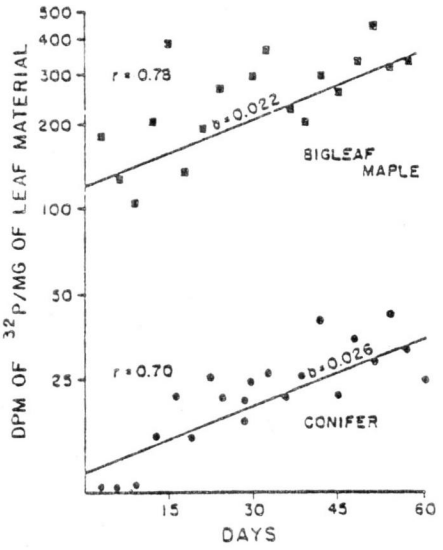

Fig. 1. Uptake of ^{32}P onto bigleaf maple and conifer incubated in Berry Creek from 3 to 60 days during February—March 1973.

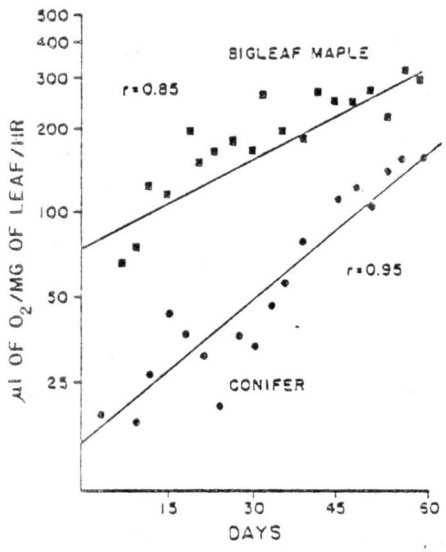

Fig. 2. Consumption of oxygen by bigleaf maple and conifer incubated in Berry Breek from 3 to 60 days during February—March 1973.

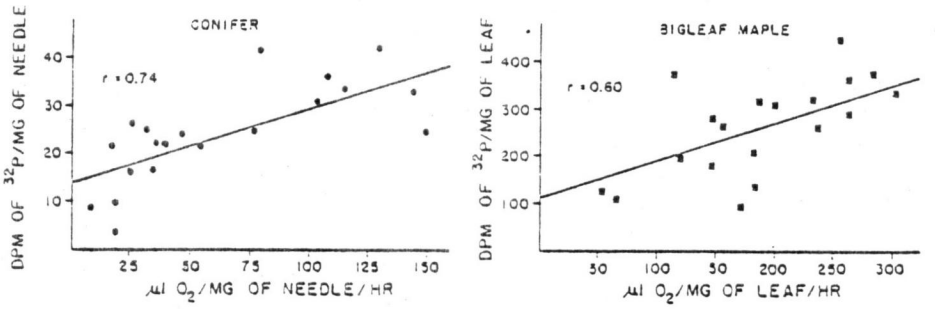

Fig. 3. Uptake of ^{32}P versus consumption of O_2 by bigleaf maple and conifer incubated in Berry Creek during February—March 1973.

sorption on both leaf types (Fig. 2). Again, microbial respiration was greater on bigleaf maple leaves than conifer needles. Uptake of ^{32}P was directly related to microbial respiration on both conifer needles and bigleaf maple leaves (Fig. 3) with much more active metabolism on deciduous detritus. Higher microbial metabolism would be expected to also result in higher N increases in the detritus (KAUSHIK & HYNES 1968; TRISKA & SEDELL 1976; TRISKA & BUCKLEY 1978). Such a pattern of increasing N content in the leaf material was observed (Fig. 4), which supports the explanation of greater P uptake as a function of microbial colonization.

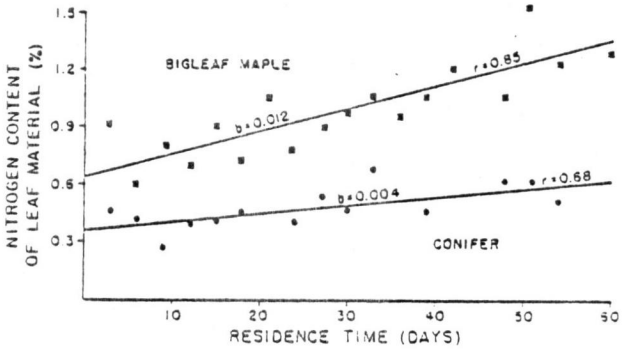

Fig. 4. Per cent nitrogen of bigleaf maple leaves and conifer needles for residence times of 3 to 60 days in Berry Creek during February—March 1973.

^{32}P absorption by aquatic primary producers

Uptake of ^{32}P was greatest for epilithic algae after the ^{32}P release in the Cascade Mountain stream, Mack Creek (Table 2). Concentrations of ^{32}P in the filamentous green algae, *Zygnema* sp., were approximately two-thirds of that in the periphyton and concentrations of ^{32}P in the monostromatic sheetlike algae, *Prasiola* sp. were a quarter of periphyton concentrations. Uptake into the herbaceous riparian vegetation, *Petasites frigidus*, was much lower than in any of the aquatic algal forms. Roots were the major site of P absorption but transfer into the leaves appeared to be rapid because the leaves contained more ^{32}P than the stems. Concentrations of ^{32}P on the roots may have been somewhat elevated because of bacteria associated with the roots but not actually in the roots.

Table 2. ^{32}P concentrations in aquatic plants after a ^{32}P-orthophosphate release in Mack Creek, H. J. Andrews Experimental Forest, Oregon.

Plant type	dpm/mg ash-free dry weight (± one standard error)
Epilithic algae	30,520 ± 7,813
Prasiola sp.	8,193 ± 2,030
Zygnema sp.	20,166 ± 9,177
Petasites frigidus	
Root	4,611 ± 173
Stem	605 ± 109
Leaf	1,112 ± 236

Discussion

The data indicate sorption of P onto substrates in streams is predominantly a biological process regulated by the quantity of algae, bacteria, and fungi present. Physical sorption is generally less than 20 % of P translocation onto benthic substrates in streams. Thus, factors which regulate the productivity of the biotic community are potentially critical in determining the P retention capacity of the stream system. The major physical factors which affect the uptake of P are those which enhance the retention time of water flowing through the stream, such as gradient, debris dams, and channel roughness and, thus, the time available for the biota to remove P in solution. The quality of detrital material in the stream plays an important role in determining the potential for P uptake. More refractory organic matter such as conifer needles or highly lignified, fine organic matter cannot support as much microbial metabolism as more labile material such as alder or maple leaves. Just as with ingestion by aquatic insects, uptake of P increases as the length of time the leaf material has been in the stream increases. Thus, the amount of organic matter, quality of that organic matter, and the history of residence of that material greatly affect the retention capacity of P in stream ecosystems.

Aquatic primary producers in streams are capable of rapid uptake of significant amounts of P. The types of primary producers as well as environmental factors which regulate the rate of primary production are critical in the actual potential for retention of P. Thin layered, epilithic algal communities in streams had the highest rates of P absorption of stream autotrophs. Filamentous forms are more obvious to the casual observer than the extensive periphyton communities in streams, but they do not have as great a potential for P uptake. Riparian vegetation may have even lower rates of uptake than algal communities in streams but may represent a major pool of P because of their higher standing crop relative to stream autotrophs. The high concentrations of ^{32}P which accumulated in the roots may serve as long term reservoir of P for stream communities. The roots of riparian vegetation stabilize stream banks and provide a sink for organic P which may be utilized after severe disturbance of the stream channel, such as floods, debris avalanches, or logging practices.

The retentive capacity for P in stream ecosystems may be enhanced by either heterotrophic or autotrophic microbial communities. Thus, high standing crops of allochthonous organic matter in heavily forested streams or autotrophic communities in open reaches both increase the uptake of dissolved P, while physical adsorption plays a relatively minor role. Thus, benthic communities and those factors which regulate biological productivity are the major determinants of P uptake and utilization in lotic ecosystems.

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