WETLAND FUNCTIONS AND VALUES: THE STATE OF OUR UNDERSTANDING

Edited by

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Proceedings of the
NATIONAL SYMPOSIUM ON WETLANDS
held in
Disneyworld Village
Lake Buena Vista, Florida
November 7-10, 1978

Sponsored by

American Water Resources Association
National Wetlands Technical Council

in cooperation with
The Conservation Foundation
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Minneapolis, Minnesota 55414 U.S.A.

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NOVEMBER AMERICAN WATER RESOURCES ASSOCIATION 1978

NUTRIENT DYNAMICS IN FRESH WATER WETLANDS

Dennis F. Whigham and Suzanne E. Bayley[1]

ABSTRACT: The purpose was to determine if definable trends appear when comparisons are made between the nutrient absorption capacities of various types of fresh water wetlands. The review showed that there are few data available for comparison, with the exception of N and P in above ground vegetation. Data from mass balance studies are almost nonexistent, which makes it impossible to determine the conditions necessary for specific types of wetlands to annually lose, gain, or be in balance with regard to nutrient fluxes. The only discernable trend was that wetlands with predominantly organic substrates accumulated less N and P in the above ground vegetation, yet the peat substrates seem to be capable of long-term storage of N and P. Recommendations for future research on nutrient dynamics in fresh water wetlands are discussed.
(KEY TERMS: nutrient dynamics; fresh water; wetlands; nitrogen; phosphorus.)

INTRODUCTION

Nutrient pathways in fresh water wetlands are well known in a qualitative sense (Kadlec, 1978; Sloey, *et al.*, 1978), but there are few data on the magnitude of flow rates along the pathways or the sizes of the nutrient standing stocks for various wetland compartments (Klopatek, 1978; Prentki, *et al.*, 1978; Richardson, *et al.*, 1978; Zoltek, *et al.*, 1978; Davis and van der Valk, 1978). There have been few studies (Prentki, *et al.*, 1978; Zoltek, *et al.*, 1978) where most of the important flows and storages have been simultaneously measured. Consequently, quantitative aspects of nutrient dynamics for entire wetlands are poorly understood. Presently, two general approaches are used to study the fate of nutrients in wetlands. One is the mass balance approach, while the other is an analysis of the nutrients within the wetland system. Using the mass balance approach, the wetland is conceptualized as an integrated unit and all inputs (+) and outputs (–) are measured (Figure 1). The approach enables one to determine if a particular wetland annually accrues nutrients (inputs greater than outputs), is at a steady state (inputs equal outputs), or releases nutrients to the receiving waters (inputs less than outputs). The second, and most frequently used, approach is to study one or more of the internal compartments shown in Figure 1. Conceptually, a study that enables determination of the amounts of nutrients that annually enter and leave all of the major storage compartments

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would provide the same results as the mass balance approach. Unfortunately, both of the types of studies just described are almost nonexistent and, as we will show, most researchers have ignored system inputs and outputs and have focused on very few of the internal compartments.

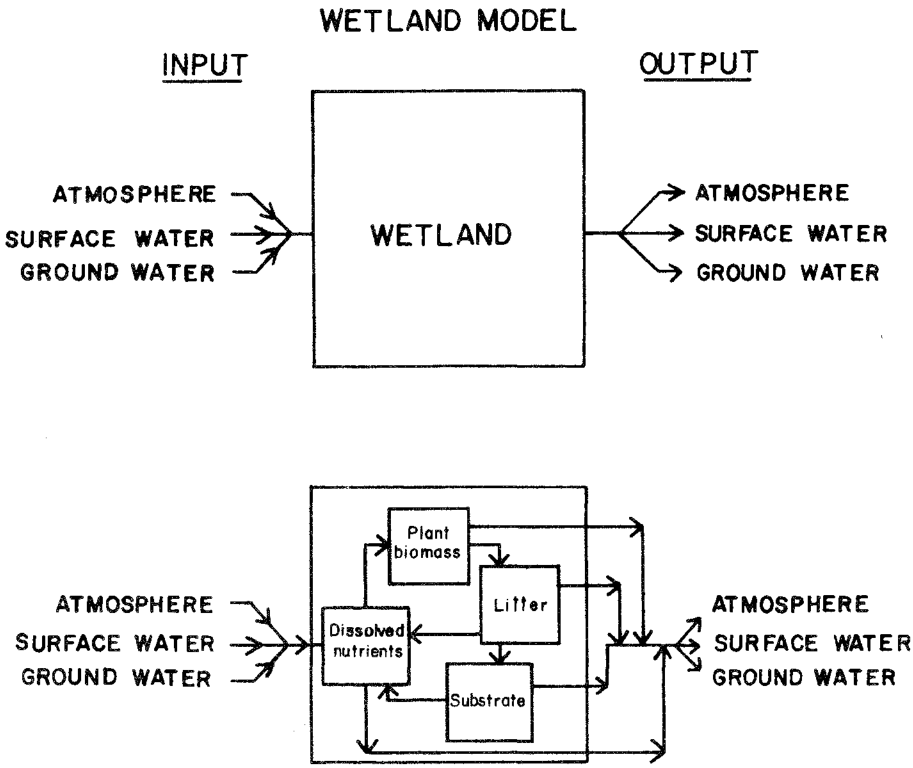

Figure 1. Diagrammatic Representation of Wetland Ecosystems. (The upper diagram represents a nutrient mass balance approach to the study of nutrient dynamics. The lower diagram represents an approach that would include nutrient mass balance studies but also study the major compartments through which nutrients move and in which they are stored.)

It is especially important to understand the quantitative aspects of nutrient mass balance because it is often suggested that some fresh water wetlands could successfully be used for tertiary treatment of municipal waste water (Boyt, *et al.*, 1976; Brinson, 1977; Ewel, 1976; Kitchens, *et al.*, 1975; Richardson, *et al.*, 1976; Simpson, *et al.*, 1978; Whigham and Simpson, 1976; Sloey, *et al.*, 1978; Tourbier and Pierson, 1976). We will not focus on the subject of management of wetlands for waste water treatment because a thorough review of the topic is provided elsewhere in this volume and a recent review by Sloey, *et al.* (1978), is also available. We need to emphasize, however, that there is a close link between those papers and our efforts in this review. We consider the broader question of the importance of wetland nutrient recycling dynamics to determine if there are discernable patterns in nutrient absorptive capacities, when comparisons are made between various types of fresh water wetlands dominated by herbaceous plants.

For simplification, we categorized fresh water wetlands (Table 1) into a scheme that is based on Sloey, *et al.* (1978), and Gosselink and Turner (1978). Riverine wetlands occur along the shores of rivers or other types of situations where water is primarily restricted to a stream channel. Lacustrine wetlands are associated with the littoral zone of lakes, while palustrine wetlands are nontidal wetlands that are not associated with stream channels or lake margins. Palustrine wetlands include a wide variety of wetlands and we have chosen to categorize them according to nutrient content and source of the inflowing water. Wetlands with nutrient rich inflowing water are minerotrophic-palustrine, while those low in nutrients are ombrotrophic-palustrine. Meadow-palustrine wetlands occur in areas where the primary source of water is sheet flow, while raised-convex-palustrine wetlands receive water from precipitation or capillary action. Fresh water tidal wetlands are riverine wetlands associated with the tidally influenced fresh water portions of coastal estuaries.

TABLE 1. Examples of Studies of Nutrient Dynamic in Fresh Water Wetlands. Wetland Types are Based on Sloey *et al.* (1978), and Gosselink and Turner (1978).

Type of Wetland	Location	Study No.	Author
Palustrine (Minerotrophic)	New York	9	Bernard and Solsky (1977)
Lacustrine and Riverine	Alabama	11	Boyd (1969)
Lacustrine and Riverine	South Carolina	12	Boyd (1970)
Palustrine (Minerotrophic)	South Carolina	14	Boyd (1971a)
Lacustrine and Riverine	South Carolina	13	Boyd (1971b)
Palustrine (Raised-convex)	Alaska	1	Chapin *et al.* (1975)
Palustrine (Minerotrophic)	Iowa	6	Davis and van der Valk (1978)
Palustrine (Ombrotrophic)	Florida	15	Ewel and Deghi (1977)
Palustrine (Minerotrophic)	Wisconsin	4	Fetter *et al.* (1978)
Palustrine (Minerotrophic)	Wisconsin	5	Klopatek (1978)
Riverine	Wisconsin	7	Lindsley *et al.* (1976)
Palustrine (Ombrotrophic)	Florida	16	Nessle (1978)
Lacustrine	Wisconsin	8	Prentki *et al.* (1978)
Palustrine (Ombrotrophic)	Michigan	3	Richardson *et al.* (1978)
Palustrine (Meadow)	Florida	18	Steward and Ornes (1975)
Tidal	New Jersey	10	Whigham and Simpson (1978)
Palustrine (Meadow)	Florida	17	Zoltek *et al.* (1978)
Artificial	Wisconsin	2	Spangler *et al.* (1976)

We have further restricted our analysis to nitrogen (N) and phosphorus (P) dynamics in wetlands because those nutrients are most often studied. We have not provided a detailed analysis of the chemical composition of wetland plants. The topic has been reviewed by Boyd (1978). We agree with his conclusions that there is no average chemical composition of individual wetland species and that actual measurements need to be made when investigators are performing wetland nutrient studies.

LITERATURE REVIEW

Papers listed in Table 1 were reviewed and N and P data were categorized according to the scheme shown in Table 2. The list of papers is certainly not exhaustive, but we believe that we have reviewed most of the relevant North American studies. We attempted to determine if there are discernable differences and/or similarities between major types of wetlands and, secondly, if nutrient absorptive capacities could be compared with: (1) latitude, (2) length of the growing season, (3) hydroperiod, (4) turnover rate of water in the wetland, (5) nutrient status of water that enters the wetland, (6) composition of the wetland substrate, and (7) the diversity of plant species within the wetland.

Nitrogen and phosphorus have been most extensively studied in palustrine wetlands and most of the research has been conducted in the eastern and midwestern portions of the country (Table 1). With the exception of Boyd (1969, 1970, 1971a, b), most recent nutrient related research has been conducted in Florida and Wisconsin. The purpose of most recent studies has been to determine how wetlands respond to the addition of waste water (Boyt *et al.*, 1975; Ewel and Deghi, 1978; Sloey *et al.*, 1978; Richardson *et al.*, 1976, 1978; Whigham and Simpson, 1978; and Zoltek *et al.*, 1978).

Table 2 demonstrates that there is a real paucity of data on the amounts of N and P that enter (input) and leave (output) fresh water wetlands. For example, only 7 of the 18 papers reviewed contained input or output data. Only annual fluxes of N and P in the above ground portions of emergent macrophytes have been extensively studied. There are few data from nutrient mass balance studies, and even fewer data on N and P accumulations in wetland compartments other than the above ground vegetation. Methodology is lacking for studying many important aspects of wetland ecology, particularly nitrogen and sulfur dynamics. We focus on the availability of precious few data only as a means of reinforcing the recent comments of Kadlec (1978), Prentki *et al.* (1978), Richardson *et al.* (1978), Simpson *et al.* (1978), and Valiela and Teal (1978), who have all shown or suggested that research on nutrient cycling in fresh water wetlands needs to be expanded and that there is an urgent need to include mass balance studies, as well as expanded research, on the exchange of nutrients between compartments.

As stated, most of the data that we had for purposes of making comparisons were from studies of the amounts of N and P that annually accumulated in above ground vegetation. We used the data when making comparisons with variables that were listed earlier. It was obvious that there is much variation within individual wetlands (Table 2) and that there were no trends when N and P data were plotted against growing season (Figure 2). Nitrogen and phosphorus showed no trend when data were plotted against latitude or some measure of species diversity. There were not sufficient data to make comparisons based on water quality, hydroperiod, or turnover rate of water. Distinct patterns were found only when we compared N and P accumulations in wetlands with organic versus inorganic substrates (Table 3). Vegetation in wetlands with organic substrates, primarily peat, seem to accumulate less N and P than vegetation in wetlands with inorganic substrates. Table 3 shows N accumulated in above ground vegetation ranged from 0.6 to 6.2 $g/m^2/yr$ in wetlands with organic substrates, to 3.0 to 44.3 $g/m^2/yr$ in wetlands with inorganic substrates. Phosphorus accumulation in above ground vegetation ranged from 0.12 to 2.4 $g/m^2/yr$ in wetlands with organic substrates to 0.4 to 3.8 $g/m^2/yr$ in wetlands with inorganic substrates. The comparison is weakened because most authors did not provide quantitative measurements of the amount of organic matter in the substrate and we estimated whether they were organic or inorganic. For convention, we followed the distinction that organic substrates were those with more than 50 percent organic matter (Sather, 1976).

TABLE 2. Summary of Data From Principal Studies.*

	1a. Chapin, *et al.*	1b. Chapin, *et al.*	2. Spangler, *et al.*	3. Richardson, *et al.*	4. Fetter, *et al.*	5. Klopatek	6. Davis & van der Valk	7. Lindsley, *et al.*	8. Prentki, *et al.*	9. Bernard & Solsky	10. Whigham & Simpson	11. Boyd	12. Boyd	13. Boyd	14. Boyd	15a. Ewel & Deghi	15b. Ewel & Deghi	16. Nessle	17a. Zoltek, *et al.*	17b. Zoltek, *et al.*	18. Steward & Ornes
Input																					
Atmosphere				0.50					2.40							18.0-19.0			0.92	0.92	
				0.03					0.10							0.10	0.10	0.14	0.04	0.04	
Surface Water									43.00							3.50			0.00	0.00	0.02
				-	14.8				5.60							0.20	0.10	4.25	0.00	0.00	0.02
Ground Water									0.80												
									0.01												
Other																120.0			36.70	1.90	
																13.90			37.90	0.34	
Storage Compartments																					
Above Ground Biomass	0.60	2.40		6.20		15.4	6.0-16.0	3.0 14.0	31.00	14.40	29.0	12.1-44.3	24.10	5.0-12.0	16.0				4.80	9.00	4.10
	0.10	0.33	0.9-3.8	0.41	1.0	3.3	1.3-3.1	0.6-3.5	3.20	1.75	3.6	0.6-2.8	0.39	0.7-1.8	2.0	2.20	2.40	0.73	3.50	0.60	0.10
Below Ground Biomass						5.3		1.6-12.0	12.40	3.30	24.4								14.90	19.30	
			4.70			2.0		0.25-4.5	0.74	0.50	2.9							0.28	13.50	1.00	
Litter				9.80		8.1	0.7-8.3												11.20	5.30	
				0.43		1.1	0.8-2.1									1.00	0.20	0.63	2.30	0.40	
Substrate				6.80		14.7															
			6.12	24.20		3.4										18.50	16.3	85.0	26.30	0.00	
Output																					
Atmosphere																10.00			28.80	0.00	
Surface Water									0.20										0.00	0.00	
					10.0											1.60		2.08	0.00	0.00	
Ground Water																12.0-13.0			7.90	2.60	
									5.00							8.60	0.10	0.28	0.94	0.18	
Other									0.60												
									0.05												
Latitude	71°18′	71°18′	44°5′	44°2′	44°1′	44°3′	44°30′	43°	43°	42°10′	40°10′	32°20′	28°50′	28°50′	28°50′	29°50′	29°50′	29°50′	28°50′	28°50′	26°
Growing Season (Days)	80	80	115	115	115	130	115	120	135	135	200	240	220	220	220	260	260	260	280	280	290
Hydroperiod (Months)				12	12	12	12	12	12		12	12			12				7	7	9
Depth of Flooding (m)					1-1.5		1.5	1			<1	0.9		<1.0	0.7				<0.5	<0.5	<0.5
Species Diversity (No. Dominant Sp.)	3	3	1	7+	3	7	5	6	1	1	15	3	2	2	1				5+	5+	1
Type of Substrate	O	O	I	O&I	I	I	I	I	I	I	I	I	I	O&I	I	O	O	O	O	O	O
Water Quality			+	+	+	+		+	+	+	+	+		+						+	

*Input, Storage Compartment, and Output sections of the table contain N and P data (g/m^2/yr). Data are entered as pairs, with N data positioned above P data. Two sets of data are provided for articles 1, 15, and 17. Part a of each of the studies lists data based on natural conditions, while Part b lists data for the same wetland after nutrients had been added to the system. A dash, throughout the table, indicates that data were not provided. A (+) indicates the studies that contained variable water quality information. Latitude and length of growing season, when not provided, were estimated from Reader (1973). Substrates were categorized as organic (O) or inorganic (I) after Sather (1976).

When we compared ranges of N and P annually accumulated in vegetation of different types of wetlands (Table 2), it appeared that palustrine wetlands, especially those with organic substrates, accumulate smaller amounts of N and P in the above ground emergent vegetation under natural conditions. However, these wetlands may have the greatest potential for assimilating nutrients in waste water because, when enriched, more N and P are accumulated in the peat directly (Richardson *et al.*, 1976; Zoltek *et al.*, 1978) or indirectly by increased accumulation in the vegetation (Zoltek *et al.*, 1978). Wetlands with inorganic substrates do not appear to assimilate large amounts of added nutrients (Sloey *et al.*, 1978; Whigham and Simpson, 1978).

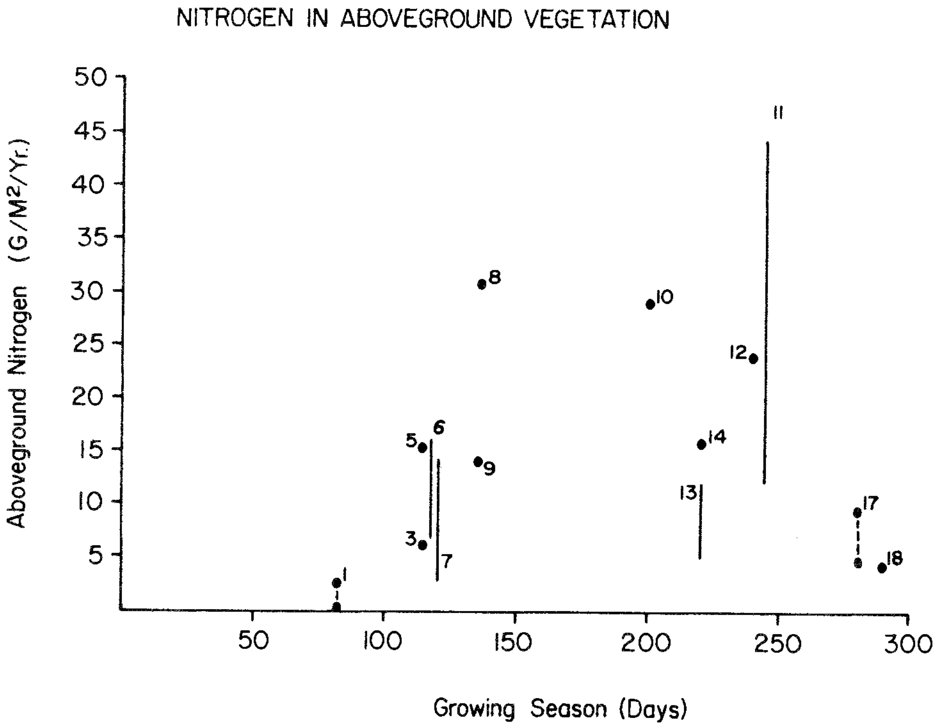

Figure 2. Annually Accumulated Nitrogen (g/m^2/yr) in Above Ground Vegetation Plotted Against Growing Season. (Refer to Tables 1 and 2 for details of the numbered studies. Solid vertical lines represent ranges while dashed vertical lines represent changes that resulted after the addition of sewage.)

DISCUSSION

Since most previous studies focused on internal dynamics of nutrients, but most present management questions deal with inputs and outputs of nutrients to the system, it is important to know the relationship between data gathered using the mass balance approach and data gathered from studies of one or more of the compartments shown in Figure 1. Figure 3 is a hypothetical example of this situation. An investigator finds, for example, that herbaceous macrophytes annually assimilate 40 g/m^2/yr N and 5 g/m^2/yr P. From the data, it is concluded that wetlands have a large capacity to assimilate nutrients. The data are only for the growing season months and the investigator does not know what happens during the remainder of the year. If the same study were to be repeated using the mass balance approach, any of the results shown in Figure 3 could hypothetically be obtained.

Considering the four input and output combinations shown in Figure 3, only the combination identified as *Case 1*, with high inputs and low outputs, would verify the initial conclusions because most of the input N and P remained in the wetland and, possibly, was assimilated by the vascular plants. Results similar to those of *Case 4*, with low inputs and high outputs, would show that the original conclusions were erroneous because the annual output of N and P were much larger than the inputs. This might be an example of a wetland which is eroding, perhaps from ditching, and in which large amounts of nutrients are being released from the eroding sediments. *Case 2,* with low inputs and outputs, and *Case 3,* with high inputs and outputs, would also show that the initial conclusions could not be predicted from the standing stock data. A wetland that responds like *Case 3* could, for example, be a highly eutrophic littoral cattail wetland, such as the Lake Wingra wetland studied by Prentki *et al.* (1978). *Case 2* may be similar to some low nutrient wetlands of Florida.

TABLE 3. Comparison of Above Ground N and P for Wetlands with Organic and Inorganic Substrates. (Refer to Tables 1 and 2 for details of studies cited. All data are g/m^2/yr.)

	Organic Substrate				Inorganic Substrate		
Study No.	Location	N	P	Study No.	Location	N	P
1	Alaska	0.60*	0.12*	13	South Carolina	5.0-12	0.7-1.8
18	Florida	4.1	0.1	7	Wisconsin	3.0-14	0.6-3.5
17	Florida	9.0+	0.60+	6	Iowa	6.1-16	1.3-3.1
3	Michigan	6.20	0.41	11	Alabama	12.1-44.3	0.6-2.8
16	Florida	–	0.73	9	New York	14.4	1.75
15	Florida	–	2.40	5	Wisconsin	15.4	3.3
				10	New Jersey	29	3.6
Range:		0.6-6.2	0.12-2.4	14	South Carolina	16	2.0
				12	South Carolina	24.1	0.39
				8	Wisconsin	31	3.2
				2	Wisconsin	–	0.9-3.8
				4	Wisconsin	–	1.0
				Range:		3.0-44.3	0.39-3.8

*Increased to 2.4 g/m^2/yr N and 0.33 g/m^2/yr P in areas that were artifically fertilized.
+Changed 4.8 g/m^2/yr N and 3.7 g/m^2/yr P in areas where sewage was added.

There have been few studies complete enough to perform either a mass balance analysis or an analysis of how nutrients are partitioned within most of the major compartments shown in Figure 1. The studies of Zoltek *et al.* (1978), and Prentki *et al.* (1978), permit comparisons between two types of wetlands, as well as comparisons between mass balance and compartmental studies of the same wetland.

Zoltek *et al.* (1978), studied a low nutrient system with negligible amounts of N and P input and output by way of surface water (Table 2). They found that, under natural conditions, only small amounts of P annually accumulated in the above ground vegetation. From the data, one might conclude that the wetland had little potential for assimilating waste water. Under experimentally enriched conditions, however, nutrient assimilation was high. Phosphorus in the above ground vegetation increased more than 5-fold and there was more than a 7-fold increase in the P in above ground components of the vegetation. Most of the added P, however, entered the peat substrate. This type of Florida wetland appears to be capable of processing waste water; Richardson *et al.* (1976) and Nessle (1978) have found similar results studying other wetlands with peat substrates.

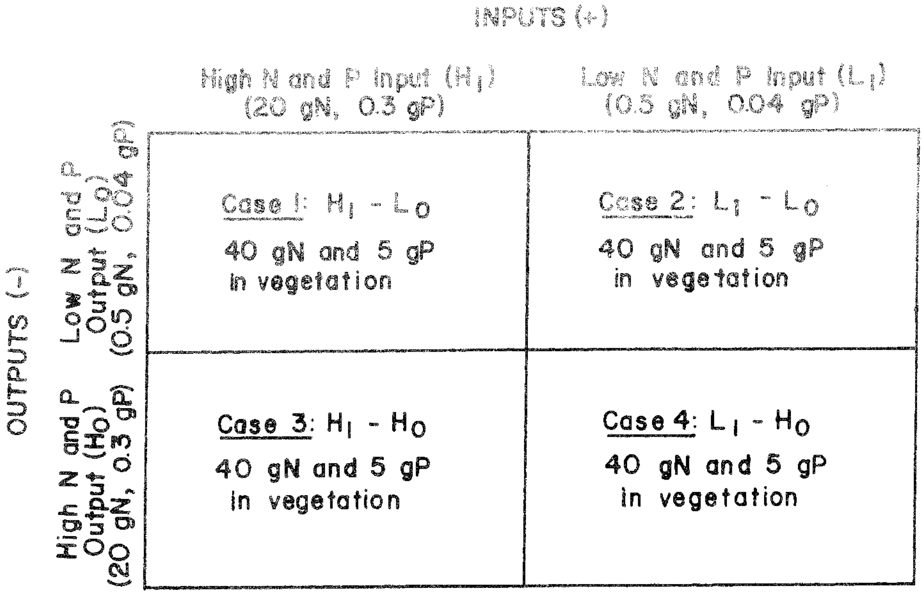

Figure 3. Results of a Hypothetical Wetland Study. (Nitrogen and phosphorus INPUTS to and OUTPUTS from the wetland could be either large (H_I, H_O) or small (L_I, L_O). For this example, independent of the 4 input-output combinations ($H_I - L_O$, $L_I - L_O$, $H_I - H_O$, $L_I - H_O$), the wetland vegetation accrues the same amount of N and P. All values are $g/m^2/yr$.)

Prentki *et al.* (1978), studied a littoral wetland that received large inputs of P. Compared with the data in Zoltek *et al.* (1978), one might predict that the littoral wetland would have a large capacity to absorb nutrients because the vegetation annually accumulated a large amount of P. On the contrary, mass balance analysis showed that most of the annual P input, which entered in surface water, left the system in ground water. Whigham and Simpson (1978) found similar results in their study of a fresh water tidal wetland in New Jersey. In their study (Table 2), they found that large amounts of P accumulated in the vegetation during the growing season. When waste water was added, the wetland annually retained very little of the added nutrients and only the litter compartment showed any significant capacity for increased retention of P or N.

From these examples, it should be obvious that mass balance studies are needed to determine whether wetlands annually accumulate, lose, or are in balance with regard to nutrients. Mass balance studies of fresh water wetlands are needed, because some fresh water wetlands appear to be leaky systems. (Prentki *et al.*, 1978; Simpson *et al.*, 1978), while others appear to effectively accumulate large amounts of nutrients (Boyt *et al.*, 1976; Kitchens *et al.*, 1975; Klopatek, 1978; Zoltek *et al.*, 1978).

Can we draw any definitive conclusions from this analysis that can be used to provide recommendations? We were unable to demonstrate any definite trends when comparisons were made between wetlands, with the exception that wetlands which have organic substrates have vegetation that annually accrue smaller amounts of N and P than does vegetation in wetlands with inorganic substrates. The latter pattern has to be, at best, tentative because there were few data and the studies were performed using different methods which forced us to make judgmental decision on certain parameters.

RECOMMENDATIONS

Our first recommendation is that additional nutrient studies, especially nutrient mass balance studies, be undertaken. We found that most of the wetland nutrient studies have been focused in a few states, and, most importantly, nutrient mass balance data are available only from studies on Wisconsin, Florida, and Michigan wetlands. Therefore, we also recommend that nutrient mass balance studies be performed in all major types of wetlands in the country. Finally, the papers by Boyt *et al.* (1976), and Klopatek (1978) contained data which suggested that some types of woody plant-dominated wetlands with inorganic substrates might be capable of assimilating excess nutrients for long term storage. There are, however, not enough data to make definite conclusions. We recommend that comparative research be conducted on the nutrient absorption capacities of wetlands with inorganic substrates that are dominated by both herbaceous and woody plants. In summary, we suggest that a comprehensive National wetland research program be developed. The program should focus on the research needs cited in this and other papers in this symposium proceedings.

The program should include the establishment of regional centers where both short and long term nutrient mass balance experiements could be conducted under both natural and manipulated experimental conditions. Funding agencies should consider developing the programs on a long term basis (perhaps 5-year funding cycles) and initially establish them in areas where wetlands are being or are projected to be heavily impacted. It would be desirable to fund projects that are designed to make simultaneous comparisons between different types of wetlands, as well as cover latitudinal and other types of gradients.

ACKNOWLEDGMENTS

The authors would like to thank Ralph Good of Rutgers University, Thomas Dolan of the Maryland Coastal Zone Management Program, Robert Simpson of Rider College, and two anonymous reviewers for their valuable comments.

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Recent papers by Ewel and Odum (D. C. Ewel and H. T. Odum, 1978. Cypress swamps for nutrient removal and wastewater recycling. *In:* Advances in Water and Wastewater Treatment: Biological Nutrient Removal, W. P. Wanielista and W. W. Eckenfelder, Editors. Ann Arbor Sci. Publ. Incl, Ann Arbor, Michigan, pp. 181-198); Zoltek, *et al.* (J. Zoltek, Jr., S. E. Bayley, A. J. Hermann, L. R. Tortora, and T. J. Dolan, 1979. Removal of Nutrients From Treated Municipal Wastewater by Freshwater Marshes. Final Report to City of Clearmount, Florida, University of Florida, Gainesville, Florida, 325 pp.); and Tilton and Kadlec (D. L. Tilton and R. H. Kadlec, 1979. The Utilization of a Fresh-Water Wetland for Nutrient Removal From Secondarily Treated Waste Water Effluent. J. Envt. Qual. 8:328-334) provide additional data to demonstrate that nutrients are retained in wetlands with organic substrates.