

NITROGEN AND PHOSPHORUS FLUXES FROM A FLOODED ORGANIC SOIL¹

K. R. REDDY

*Agricultural Research and Education Center, Institute of Food and Agricultural Sciences, University of Florida,
Sanford, Florida 32771*

P. S. C. RAO

*Soil Science Department, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida
32611*

Received for publication 28 July 1981; revised 29 June 1982

ABSTRACT

Under laboratory conditions, we measured nitrogen and phosphorus fluxes from an anaerobic organic soil to the overlying water. In the anaerobic soil layer, ammonification was functioning at a rate of 0.11 g N/m²-day, and NH₄⁺ flux from the anaerobic soil layer to the floodwater and to the aerobic soil layer was 0.045 g N/m²-day. The sequential N processes functioning in a flooded organic soil include: ammonification in the anaerobic soil layer, upward diffusion of NH₄⁺ from the anaerobic soil layer to the floodwater, nitrification in the floodwater, downward diffusion into the anaerobic soil layer and denitrification in the anaerobic soil layer. Losses due to these processes accounted for about 35 percent of the mineralized NH₄⁺-N in the 21-cm organic soil column. Results also showed that ammonification and NH₄⁺ diffusion functioning at a slower rate probably are the limiting processes in N loss from a flooded organic soil.

The results also showed that the rate of soluble P production in the anaerobic soil layer was 0.016 g P/m²-day, and the flux of P, as a result of diffusion, was about 0.0098 g P/m²-day. Major processes functioning in the anaerobic layer were mineralization of organic P, adsorption-desorption of P, and diffusion from underlying sediment to the overlying water. Losses of P due to these processes accounted for about 53 percent of the solubilized P in the 21-cm organic soil column.

INTRODUCTION

Florida has approximately 1.5 million hectares of organic soils, which were formed by the accumulation of the decayed remains of sawgrass and related wetland plants over the last 5000 years (Stephens 1969). Organic soils used for agriculture are flooded during the summer months to control weeds and pests and to reduce soil subsidence. Some of the organic soils in south Florida are also used for growing rice under flooded conditions. A significant portion of Florida's wetlands, swamp and marsh sediments, and lake bottoms can also be classified as organic soils.

Flooded soils, wetlands, and sediments are characterized by the accumulation of soluble NH₄⁺ and P during anaerobic decomposition

(Patrick and Mahapatra 1968). Movement of soluble NH₄⁺ and P from the anoxic sediments depends on the N and P removal rate in the overlying water. Ammonium N was shown to be readily oxidized in the surface aerobic soil layer or in the overlying water, and the NO₃⁻ thus formed diffuses back into the anoxic zones of the sediment and undergoes denitrification (Reddy et al. 1976). Phosphorus diffusing from anoxic zones can form insoluble complexes with Fe³⁺ and Mn⁴⁺ or Ca²⁺ in the surface aerobic soil layer. A portion of soluble NH₄⁺ and P diffusing into overlying waters can also be assimilated by algae and aquatic macrophytes.

Flooded soils and sediments can function as a source or a sink of N and P to the overlying water (Lee 1973; Byrnes et al. 1972; Rosenfeld 1981; Reddy and Graetz 1981). The amount of soluble NH₄⁺ and P released into overlying waters of flooded organic soils, wetlands and lake

¹ Florida Agricultural Experiment Station Journal Series no. 3941.

bottoms, swamps and marsh sediments, and shallow water bodies depends on solubilization of organic N and P into inorganic forms and diffusion of inorganic N and P from the sediments to the overlying waters. These processes determine whether the concentration of N and P in the interstitial and overlying water is adequate for the nutritional requirements of plants and aquatic organisms.

The purpose of this laboratory study was to (1) quantitatively measure the potential net movement of soluble N and P from underlying organic soil to the overlying floodwater, (2) calculate the net flux of soluble NH_4^+ and P from a flooded organic soil, and (3) determine the processes controlling the upward movement of N and P from flooded organic soil.

MATERIALS AND METHODS

The soil used in this study was obtained from the plow layer of an organic soil (Lithic Medisaprists, euic, hyperthermic) located at the Agricultural Research and Education Center's experimental farm in Zellwood, Florida. The soil had a total P content of 0.13%, total N content of 2.5%, total C content of 45.1%, and a pH of 7.1.

Undisturbed soil columns were obtained by driving a 5-cm-o.d. PVC pipe into the flooded organic soil field using a sledge hammer. The bottom portion of the soil column was sealed with a rubber stopper. All soil columns were incubated in the dark at 30°C with an overlying floodwater depth of 5 cm. The bulk density and soil water content of the soil column were 0.26 g cm^3 and 0.54 cm^3/cm^3 , respectively. Floodwater was continuously aerated with air at a flow rate of about 10 ml/min. Floodwater was removed and replaced with fresh deionized distilled water each day (during the first week), every 2 days (up to the third week), and once a week during the remaining incubation period. Floodwater removed was filtered through 0.2- μm filter paper and analyzed for NH_4^+ , NO_3^- , and ortho-P. At the end of 0, 30, 60, 110, and 160 days, triplicate soil columns were sectioned into 0.75-cm sections, using the procedure described by Reddy and Patrick (1976). Each sectioned soil sample was transferred into a flask containing 50 ml of 0.01 M CaCl_2 and filtered through 0.2- μm filter paper after a 30-min shaking. The filtered solutions were analyzed for NH_4^+ , NO_3^- , and ortho-P.

On selected anaerobic organic soil samples, NH_4^+ was extracted with distilled water (1:2 ratio) and 2 M KCl (1:5 ratio) to evaluate the suitability of 0.01 M CaCl_2 as an extractant for soluble NH_4^+ .

Soil samples (0 to 12 cm) obtained from the flooded field were used to evaluate the P adsorption characteristics of the anaerobic organic soil. Five grams of organic soil (oven-dry basis) and 20 ml of 0.01 M CaCl_2 were transferred into duplicate centrifuge tubes and incubated for 1 week at 30°C under anaerobic (N_2 atmosphere) conditions. At the end of preincubation, duplicate tubes were amended with 5 ml of 0.01 M CaCl_2 solutions containing various levels of P as KH_2PO_4 and 3 drops of toluene equilibrated under continuous shaking for 24, 48, 72, 96, and 240 h. Soil solutions were centrifuged and filtered through 0.2- μm filter paper and analyzed for ortho-P. Equilibrium P concentration was determined from the adsorption isotherm.

Analytical methods

Ammonium and NO_3^- in the extracted samples were analyzed by steam distillation (Bremner 1965). Ortho-P in the extracts was analyzed, using the single reagent method (Murphy and Riley 1962).

RESULTS AND DISCUSSION

Ammonium N fluxes from anaerobic organic soil to the overlying water

Use of 0.01 M CaCl_2 in extraction to measure soluble NH_4^+ resulted in the removal of a significant portion of exchangeable NH_4^+ . The ammonium concentration, presented in Fig. 1, represents about three times the actual pore water NH_4^+ and about 75% of the total NH_4^+ (water-soluble + exchangeable). At the start of the incubation period, NH_4^+ concentration in the 21-cm soil profile was about 8 $\mu\text{g N}/\text{cm}^3$ of soil except in the surface layers (0 to 5 cm) where NH_4^+ concentration ranged from 0.5 to 5.4 $\mu\text{g N}/\text{cm}^3$ of soil. The disappearance of NH_4^+ from the surface soil layers was more striking in the columns incubated for 30 to 160 days, and at the same time NH_4^+ concentration in the soil increased from 8 to 41 $\mu\text{g N}/\text{cm}^3$ of soil. This increase was primarily due to the ammonification of organic N in the soil column. Ammonium that was mineralized diffused into the surface aerobic soil layer and floodwater, where it was

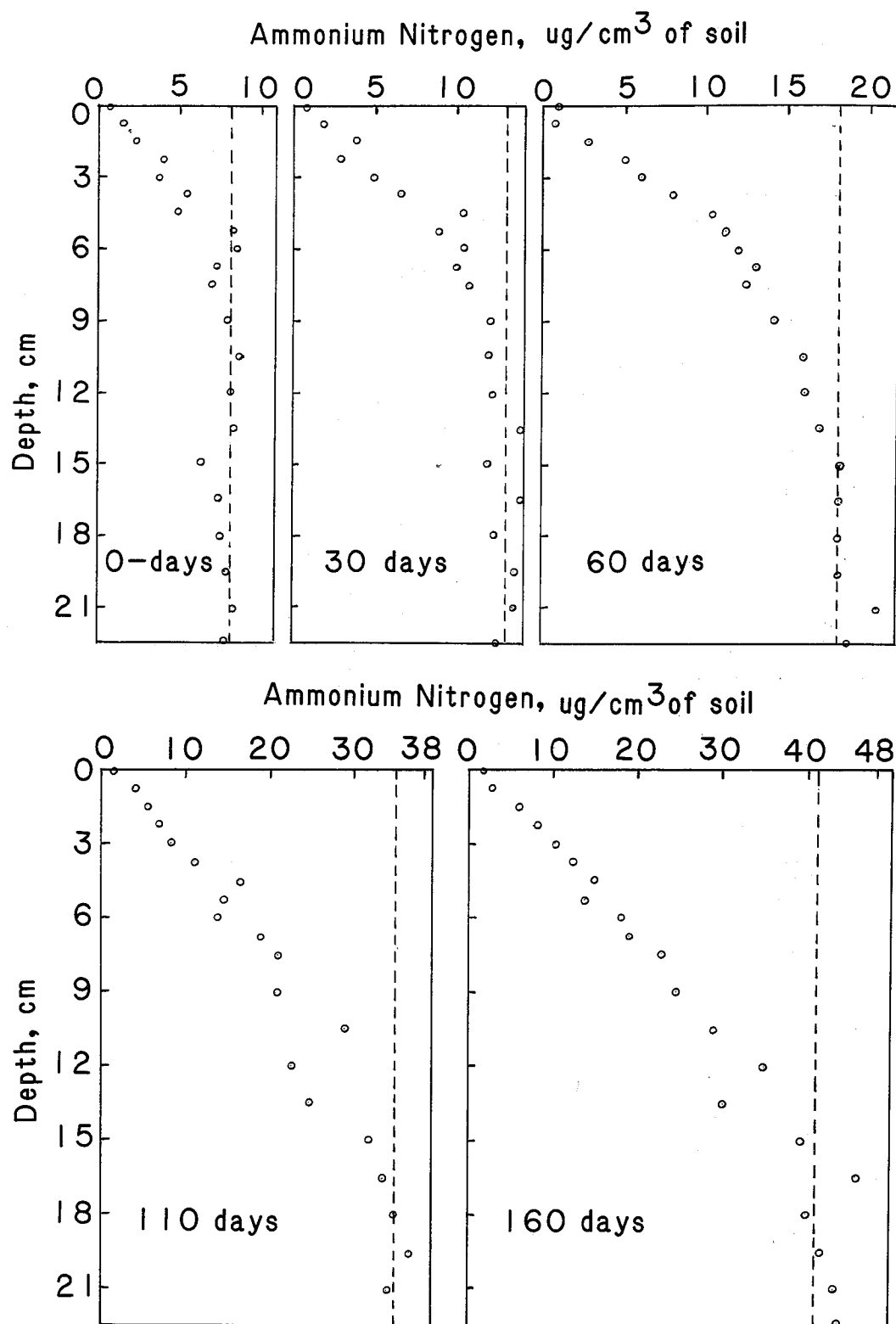


FIG. 1. a, b. Soluble NH_4^+ (measured in 0.01 M CaCl_2) concentration of the flooded organic soil.

either oxidized to NO_3^- or lost through volatilization. In the present study, nitrification of NH_4^+ probably accounted for most of the N loss from the organic soil, because the pH of the floodwater was less than 7.0 and significant amounts of NO_3^- were observed in the floodwater. Ammonium concentration of the floodwater never exceeded $0.3 \mu\text{g N/ml}$, indicating rapid nitrification, and NO_3^- concentration of the floodwater was in the range of 0.3 to $0.8 \mu\text{g N/ml}$ (Fig. 2). Low NO_3^- levels of the floodwater indicate rapid diffusion into the soil column where it underwent denitrification.

Utilizing the data presented in Fig. 1, we calculated fluxes of NH_4^+ (Reddy et al. 1976), and the flux of NH_4^+ as a result of diffusion was about $0.045 \text{ g N/m}^2\text{-day}$ (165 kg N/ha-year), and the mineralization rate of organic N was about $0.11 \text{ g N/m}^2\text{-day}$ (375 kg N/ha-year). The percentage of mineralized NH_4^+ lost as a result of diffusion amounted to about 40% at any given incubation period. Less than 7% of the mineralized N was recovered as inorganic N in the floodwater, and the remaining N was lost from the system. Reddy et al. (1976) observed NH_4^+ fluxes of about $1 \text{ g N/m}^2\text{-day}$ from a flooded Crowley silt loam soil treated with NH_4^+ fertilizer, and they concluded that more than 50% of the $\text{NH}_4^+\text{-N}$ transported was due to diffusion from the anaerobic soil layer to the aerobic soil

layer. Using the pore water concentration of Long Island Sound sediment, Berner (1976) calculated that about 70% of the $\text{NH}_4^+\text{-N}$ liberated below the 10-cm depth was lost from the sediments by diffusion and mixing.

Nitrogen transformations involved in the loss of N from a flooded soil include (1) ammonification, (2) nitrification, (3) denitrification, and (4) ammonia volatilization. Ammonia volatilization in the floodwater could be active under conditions where the pH of the water is greater than 8.5. Preliminary investigations in this study showed that NH_3 volatilization was insignificant in the soil columns incubated in the dark, where the pH of the floodwater was less than 7.0 during the incubation period. Potential rates (measured in independent experiments, unpublished results) of nitrification in the floodwater and denitrification in the anaerobic organic soil layer were 0.25 and 3.71 day^{-1} , respectively, and the ammonification rate in the anaerobic soil layer was $0.11 \text{ g N/m}^2\text{-day}$. Both nitrification and denitrification rates measured in independent experiments were shown to depend on initial concentration. Nitrification rate at the sediment-water interface could be much higher than the nitrification rate measured in the floodwater, primarily due to greater activity of nitrifying bacteria at the oxidized soil surface. For the flooded organic soil evaluated rates of N

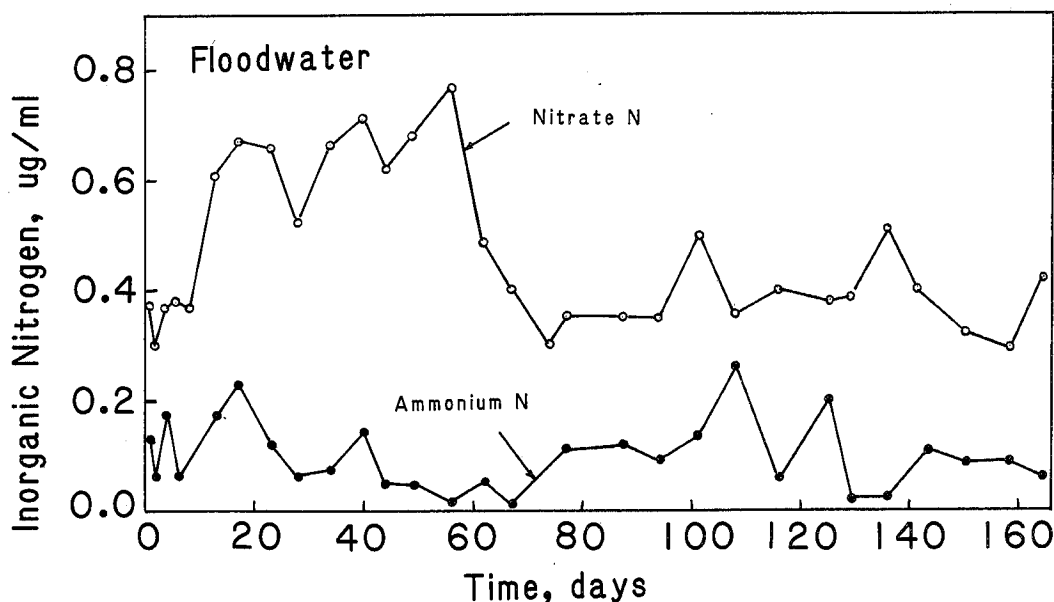


FIG. 2. Inorganic N concentration of the floodwater with an underlying organic soil.

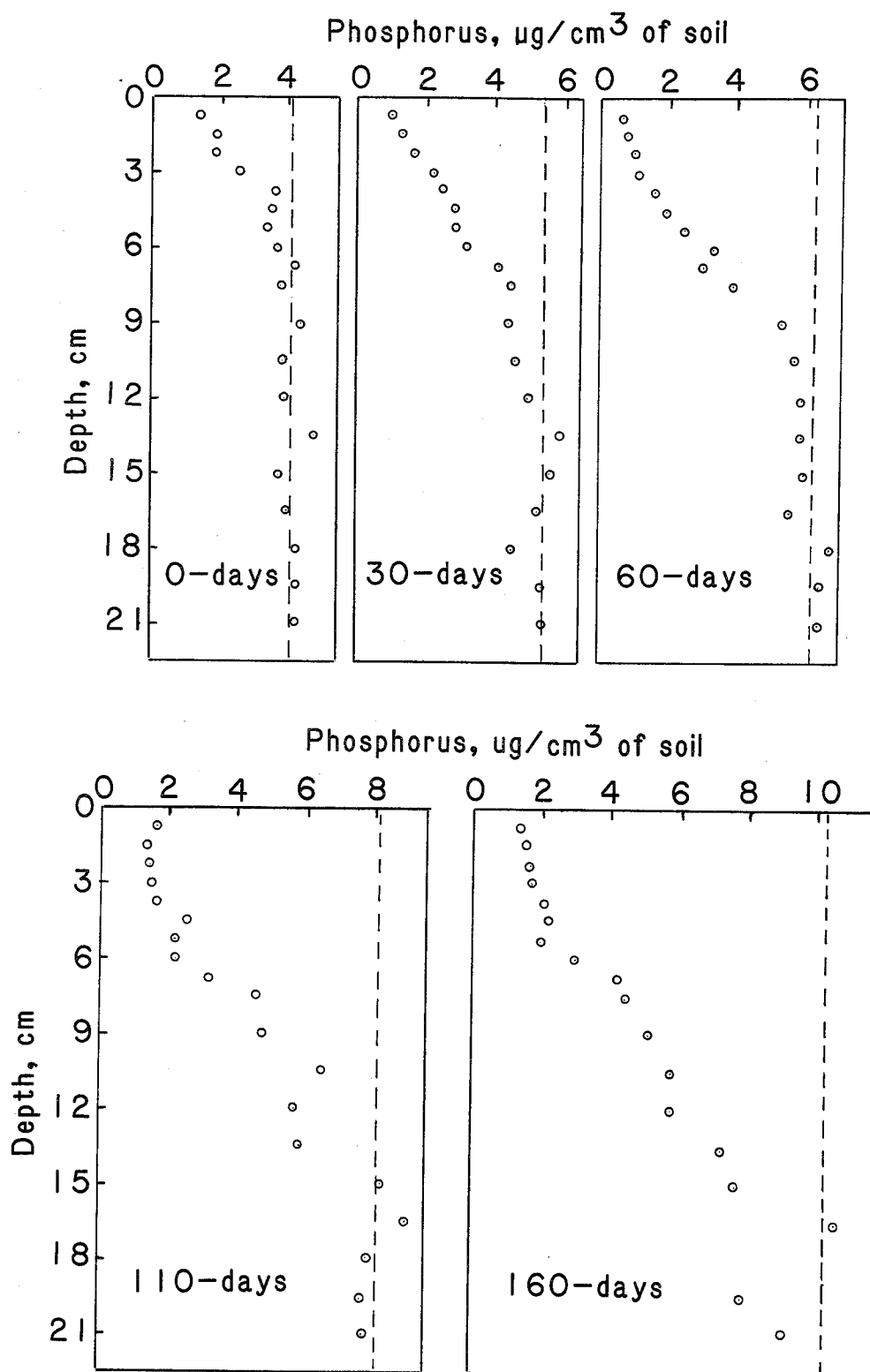


FIG. 3. a, b. Soluble P (measured in 0.01 M CaCl_2) concentration of the flooded organic soil.

processes were in the order of denitrification > nitrification > ammonification.

In flooded soils and shallow water bodies, NH_4^+ movement from the anaerobic soil layer into the overlying water and aerobic soil layer is largely due to diffusion, unless appreciable wave and current stirrings occur at and near the sediment interface. The upward flux of NH_4^+ is governed by (1) the concentration gradient established as a result of NH_4^+ consumption in the overlying floodwater and at the sediment-water interface, (2) NH_4^+ regeneration rate (ammonification), (3) rate of nitrification and NH_3 volatilization in the floodwater and at the sediment-water interface. Results of this study suggest that ammonification and NH_4^+ diffusion functioning at a slower rate probably are the limiting processes in controlling N loss from a flooded organic soil.

Soluble P fluxes from anaerobic organic soil to the overlying water

Initial soluble P (measured in 0.01 M CaCl_2) concentration in the soil profile was about $4.1 \mu\text{g P}/\text{cm}^3$ of soil, except in the surface layers (0 to 4 cm), where P concentration ranged from 0.5 to $3.8 \mu\text{g P}/\text{cm}^3$ of soil (Fig. 3). The disappearance of soluble P was more striking in the col-

umns incubated for 30 to 60 days, and at the same time soluble P concentration increased from 5 to $10 \mu\text{g P}/\text{cm}^3$ of soil. This increase was primarily due to mineralization of organic P and solubilization of inorganic P. The soluble P that was mineralized rapidly diffused into the surface soil layer and to the floodwater, as a result of establishment of concentration gradient. Phosphorus that was diffused from the sediment was recovered in the floodwater. Phosphorus concentration of the floodwater never exceeded $1.7 \mu\text{g P}/\text{ml}$ (Fig. 4). The cumulative P recovery in the floodwater was approximately equivalent to the amount of P diffused from the sediments.

Data on P adsorption by a flooded organic soil are shown in Fig. 5. Relatively rapid equilibrium was reached within 48 h after incubation at all levels of P addition. The average adsorption coefficient (K) estimated using the linear isotherm was $10.8 \pm 1.8 \text{ ml/g}$, and from the literature data, Krom and Berner (1980) estimated K values from 1 to 50 ml/g for anoxic soils and sediments. Soluble P diffuses slowly from the sediments with high K values compared with those having low adsorptive capacity. Other processes controlling the movement of P in anaerobic soils include mineralization of organic P and solubilization of inorganic P. Flux of P from

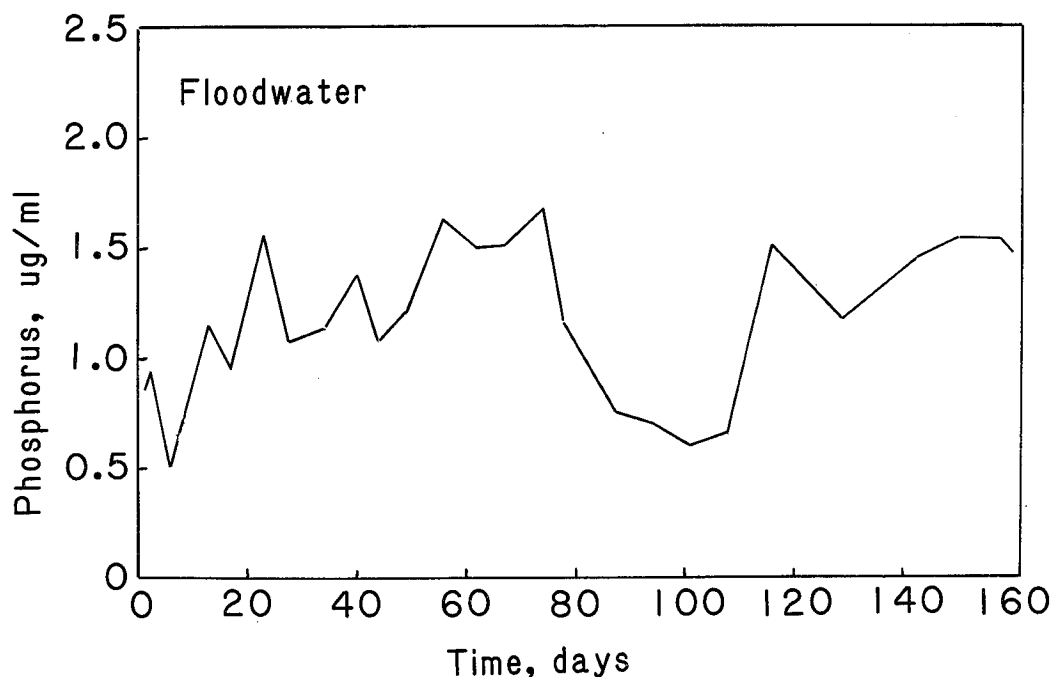


FIG. 4. Soluble P concentration of the floodwater with an underlying organic soil.

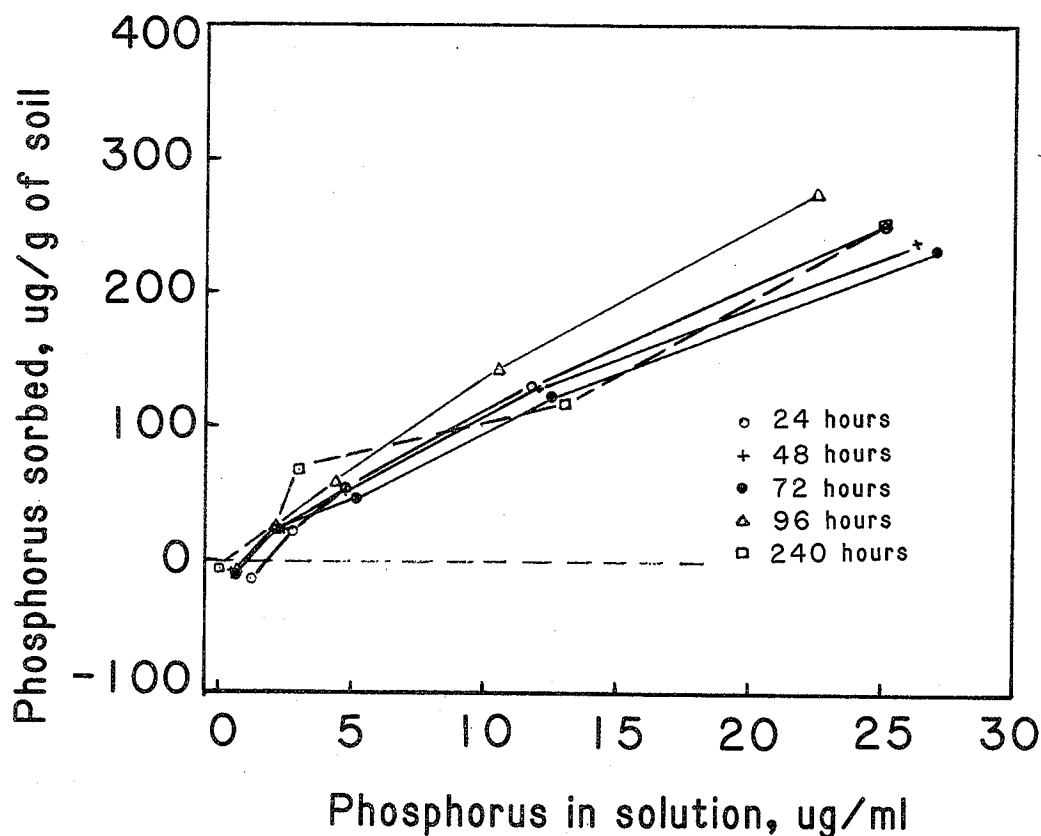


FIG. 5. Phosphorus adsorption isotherms of a flooded organic soil.

sediments to the overlying waters can also be controlled by the concentration gradient established across the mud-water interface as a result of P depletion in the water column due to uptake by aquatic organisms and plants and removal or replacement of floodwater with the water low in P.

The flux of P as a result of diffusion and desorption was about $0.0098 \text{ g P/m}^2\text{-day}$ (36 kg P/ha-year), and soluble P production in the anaerobic soil was about $0.016 \text{ g P/m}^2\text{-day}$ (68 kg P/ha-year). Loss of P as a result of net diffusion from the anaerobic soil layer to the overlying floodwater accounted for about 53% of mineralized soil P. Using an equation developed by Berner (1971), Pollman and Brezonik (1979) calculated the potential diffusion of P from Lake Apopka (located in Zellwood in central Florida) sediments to the overlying water to be $5.25 \text{ mg P/m}^2\text{-day}$. The flooded organic soil used in this study was similar in physical and

chemical characteristics of the sediments of adjacent Lake Apopka, because these organic soils were once part of Lake Apopka sediments until they were drained for agricultural purposes. Phosphorus fluxes measured in this study were higher ($9.8 \text{ mg P/m}^2\text{-day}$) than the values estimated by Pollman and Brezonik (1980). These studies suggest that P-rich lake sediments, shallow water bodies, and flooded fields can be an important source of P to the overlying water and promote the aquatic growth and enhance the eutrophic status of the water body.

It can be concluded from this study that N and P transformations functioning in the sediment control the N and P concentration of the overlying waters. This study has shown that nitrification and NO_3^- diffusion are not limiting N loss from the sediment, but ammonification and NH_4^+ diffusion functioning at a slower rate probably are the limiting processes in N loss from the sediment. Phosphorus loss from the

sediment is governed by the mineralization of sediment organic P, solubilization of inorganic P, and diffusion of P into overlying waters.

ACKNOWLEDGMENTS

This research was supported in part by funds from the Center for Environmental and Natural Resources Program, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida.

REFERENCES

- Berner, R. A. 1971. Principles of chemical sedimentology. McGraw-Hill, New York.
- Berner, R. A. 1976. Inclusion of adsorption in the modelling of early diagenesis. *Earth Planet. Sci. Lett.* 29:333-340.
- Bremner, J. M. 1965. Inorganic forms of nitrogen. In *Methods of soil analysis*. C. A. Black (ed.). Agronomy 9:1179-1237. Am. Soc. Agron. Madison, Wis.
- Byrnes, B. H., D. R. Keeney, and D. A. Graetz. 1972. Release of ammonium N from sediments to waters. *Proc. 15th Conf. Great Lakes Res. Inter. Nat. Assoc. Great Lakes Res.*, pp. 249-259.
- Krom, M. D., and R. A. Berner. 1980. Adsorption of phosphate in anoxic marine sediments. *Limnol. Oceanogr.* 25:797-806.
- Lee, G. F. 1973. Role of phosphorus in eutrophication and diffuse source control. *Water Res.* 7:111-128.
- Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chem. Acta* 27:31-36.
- Patrick, W. H., Jr., and I. C. Mahapatra. 1968. Transformation and availability of nitrogen and phosphorus in waterlogged soils. *Advance* 20:323-359.
- Pollman, C. D., and D. L. Brezonik. 1979. Nutrient characteristics and nutrient exchange dynamics of Lake Apopka sediments. Progress report to Florida Dept. of Environmental Regulations. Dept. Environ. Eng. Sci., Univ. of Florida, Gainesville, Fla.
- Reddy, K. R., and W. H. Patrick, Jr. 1976. A method for sectioning saturated soil cores. *Soil Sci. Soc. Am. J.* 40:611-612.
- Reddy, K. R., and D. A. Graetz. 1981. Use of shallow reservoirs and flooded soil systems for wastewater treatment: Nitrogen and phosphorus transformations. *J. Environ. Qual.* 10:113-119.
- Reddy, K. R., W. H. Patrick, Jr., and R. E. Phillips. 1976. Ammonium diffusion as a factor in nitrogen loss from flooded soils. *Soil Sci. Soc. Am. J.* 40:528-533.
- Rosenfeld, J. K. 1981. Nitrogen diagenesis in long island sound sediments. *Am. J. Sci.* 281:436-462.
- Stephens, J. D. 1969. Peat and muck drainage problems. *Am. Soc. Civ. Eng. J. Irrig. Drainage Div.* 95:285-305.