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FLOODWATER NUTRIENT PROCESSING IN A LOUISIANA SWAMP FOREST RECEIVING AGRICULTURE RUNOFF

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ABSTRACT

Donor-controlled nutrient models were used to analyze bi-weekly field data from a 64 ha swamp forest impoundment in the headwaters of Louisiana's Barataria Estuary. Nitrogen and phosphorus fluxes at this site were measured for a single year and estimates made of the capacity of this type of wetland to remove nutrients from agricultural runoff. The roles of redox condition and heterotrophic immobilization in determining floodwater nutrient concentrations were examined both in the field and in microcosms maintained in the laboratory. Forty-four percent of nitrogen and 40% of phosphorus introduced into the system were retained in the swamp impoundment. Nearly all of this removal takes place as a result of settlement of nitrogen and phosphorus rich particulates. The swamp removes dissolved inorganic nitrogen, but adds dissolved phosphate and organic nitrogen to waters passing over its surface. Floodwater dissolved oxygen was inversely related to dissolved phosphate and dissolved organic nitrogen indicating that benthic flux of these two species is regulated by heterotrophic oxygen demand at the sediment/water interface. Results indicate that denitrification is a significant pathway for permanent nitrogen loss. An additional long-term sink for both nitrogen and phosphorus lies in the eventual burial of partially decomposed organic matter under reduced conditions. The swamp acts as a buffer to down-stream systems assuring steady releases of waters with a stable nutrient composition. This equilibrium is disrupted when canals shunt drainage waters past the swamp directly into estuarine lakes. Study results

indicate that a well-planned return to overland flow hydrology would reduce water quality problems in the upper Barataria Basin and improve timber and wildlife productivity without sacrificing upland drainage objectives.

INTRODUCTION

Interdistributary forested wetlands form some of the most scenic and productive sections of Louisiana's great deltaic plain estuaries. These freshwater, peat-producing swamps are connected by sluggish, meandering bayous to the brackish marshes of the lower estuary. Runoff from natural levee uplands once passed through the swamp prior to discharge into open lakes and bays. Floodwaters, sediments, and nutrients were retained in the swamp and released slowly to downstream systems.

Canals dredged for logging, oil extraction, navigation improvement, road construction, and drainage have greatly changed natural water routing. Canals designed to drain sugarcane fields have had the greatest impact in the freshwater reaches. These canals serve as conduits that speed the movement of water and materials through the swamp, while spoil banks limit the exchange between wetlands and waterways (Fig. 1). The overland flow system that once characterized most of the forested wetlands is today reduced to small remnants. Lac des Allemands, northernmost of the chain of large lakes in Louisiana's largest estuary, the Barataria Basin (Fig. 2), has been severely affected by these changes. Extensive blue-green algal blooms and fish kills are now common in what was once a clear, brown-water lake (Lantz 1970; Day et al. 1977). Nutrient loading in Lac des Allemands has been estimated at 30 and 4 $g\text{-}m^{-2}yr^{-1}$ for nitrogen and phosphorus, respectively (Craig et al. 1977). These high rates have been attributed to material shunted from the cultivated and developed natural levees surrounding the swamp watershed (Day et al. 1977; Craig et al. 1977; Kemp and Day 1980; Seaton 1979). Craig et al. (1977) warned that the continued downstream progression of eutrophic conditions might soon threaten critical nursery grounds in the brackish zone of the estuary.

Carter et al. (1973); Kitchens et al. (1975); Conner and Day (1976); Brinson (1977); Day et al. (1977); Schlesinger (1978); Mitsch and Ewel (1979); and Mitsch et al. (1979) have all discussed ecological aspects of nutrient cycling in southeastern swamp forest systems. The potential of swamps for the tertiary treatment of nutrient-rich point-source or nonpoint-source waste streams has been considered by Wharton (1970), Boyt et al. (1977), Odum et al. (1977), and Littlejohn (1977). All of this work has focused primarily on the potential for nutrient immobilization through uptake by swamp vegetation. In the present study, we concentrate on the nutrient pathways associated with heterotrophic activity at the sediment-water interface.

This paper presents the results of two years' research on the dynamics of nutrient retention and release in a swamp receiving upland runoff and provides the information necessary to evaluate land treatment options for eutrophication abatement in the northern Barataria estuary. By using simple donor-controlled models to quantify nitrogen and phosphorus fluxes in a 64-ha swamp impoundment, we estimated the capacity of this type of wetland to remove nutrients from upland runoff. Additionally, we examined the role of redox in determining floodwater nutrient concentrations both in the field and in microcosms maintained in the laboratory. We tested the hypothesis that water quality deterioration in the upper estuary can be directly related to the cessation of overland water processing formerly performed by the swamp. We wanted to understand what critical processes are now no longer operative and what potential exists for their reinstatement.

The objectives of this study were:

1. Measure N and P dynamics in a swamp that receives agricultural runoff.
2. Calculate N and P budgets to determine if there is net uptake or release.
3. Conduct laboratory experiments to determine the influence of leaf litter decomposition and floodwater dissolved oxygen on nutrient retention by the swamp.
4. Develop guidelines for ecosystem management.

STUDY SITE

The experimental site is a 320 ha section of swamp forest located in St. James Parish, Louisiana, at the northern margin of a 700-km^2 swamp forest stand (Fig. 3). The area was an overflow swamp of the Mississippi River until completion of flood control levees early in this century curtailed the annual cycle of inundation. Presently, water levels in the swamp basin are controlled by wind-induced "tides" in the lower Barataria estuary (Wax 1977) and locally by the balance between precipitation and evapotranspiration. Swamp elevation is less than 1 m above mean sea level (MSL). Runoff enters the swamp system from the natural levees of the Mississippi River and Bayou Lafourche. These uplands have a maximum elevation of 5 m above MSL and are largely planted in sugarcane. The swamp is normally flooded for nine to ten months per year.

Baldcypress (Taxodium distichium [L.] Rich) and water tupelo (Nyssa aquatica L.) dominate the forest community in low areas where the swamp floor is rarely free of water. The importance of bottomland hardwood species such as red maple (*Acer rubrum* var. *drummondii* [H&A] Sarg), boxelder (*Acer negundo* L.) and cottonwood (*Populus heterophylla* L.) increases in areas of somewhat higher elevation and better drainage. The composition and productivity of the swamp forest in this area have been described by Conner et al. (1975) and Conner and Day (1976). Swamp sediments are highly organic to a depth of 0.5 to 1.0 m, where a laterally continuous alluvial clay lens is encountered. This pan acts as a barrier to vertical groundwater movement (Whitehurst et al. 1977).

Locations for water sampling were chosen along a 2200 m transect extending from a field drainage ditch (Sta. 1) into a section of swamp ringed by levees and managed for crayfish production (Fig. 3). Water levels are artificially regulated in this "two-pond" system by pumps and weirs (Fig. 4). In the fall, water is pumped into the 64-ha western pond (Pond 1) from the Vacherie Canal (Sta. 2). When this pond is filled, water overtops a weir set in the levee and flows into the 256-ha eastern pond (Pond 2). Water drains slowly out of Pond 2, back into the Vacherie Canal via three small culverts at the eastern end. The pump is operated irregularly from September to May to keep water circulating, but is not used during the summer when the ponds are allowed to drain naturally. We believe that the controlled hydrology closely approximates that which was once normal for undisturbed swamps in this area.

METHODS

Hydrology

Water levels in the experimental ponds were measured continuously with two Stevens Type F recorders. Bulk precipitation was measured and collected in two Taylor gages placed in a clearing in the swamp. These gages were emptied, acid-washed, and replaced at 14-day intervals. When additional water was pumped into the two ponds, an initial calibration of the resulting water level allowed the calculation of a water budget, once corrections were made for atmospheric exchange. Actual evapotranspiration was assumed to approach the climatic potential defined by Thornthwaite and Mather (1955). Leaching and groundwater exchange were assumed negligible.

Water Chemistry Sampling and Analysis

Surface water samples were collected at two week intervals when the study site was flooded, at eight stations located along a 2200-m transect (Fig. 3 and 4). Station 1 is a sugarcane field drainage ditch 2 m wide, which flows into the Vacherie Canal (10 m wide). Station 2 is located in the Vacherie Canal at the crayfish farm pump intake. The remaining stations were positioned in the crayfish farm by survey and marked with wooden stakes. Stations 3 through 5 were in Pond 1, and 6 through 8 in Pond 2.

Water samples were collected in 500-ml polyethylene bottles for nutrient analyses and in 300-ml glass BOD bottles for dissolved oxygen measurements. Nutrient samples were stored on ice in the field, passed through washed Gelman Metricel 0.45 mm filters, and frozen (10°C) upon return to the lab. Dissolved oxygen samples were either fixed in the field and returned to the lab for titration, using the Winkler method, or analyzed directly upon collection with an Orion Model 97-08 polarographic electrode. Filtered water samples were analyzed for ammonium nitrogen (NH4), nitrate + nitrite nitrogen (NO3), organic nitrogen (DON), orthophosphate (P04), and total phosphorus (TP). Particulate nitrogen (PN) and particulate phosphorus (PP) were determined on persulfate digests of the ground filters (Table 1). Methods used are those outlined by the Environmental Protection Agency (1974) for chemical analysis of water and waste. Nutrient analyses were generally completed within 14 days of sampling.

Nutrient Budget Computation

Nutrient fluxes in Pond 1 were calculated for each two-week sampling interval using the following relation:

$$F = (R * C_{rt_2} + P * (\frac{C_{pt_1} + C_{pt_2}}{2}) - 0 * (\frac{C_{wt_1} + C_{wt_2}}{2}))$$

where

F = net flux (kg • sampling interval^{-1})

R = precipitation input ($10^4 m^3$ H_20)

C = nutrient concentration (kg• m^{-3})

P = pump input ($10^4 m^3$ H_20)

0 = outflow ($10^4 m^3$ H_20)

and subscripts indicate location and times of sampling

r = precipitation gage

p = pump intake bay in Vacherie Canal (Sta. 2)

w = weir at east end of Pond 1 (Sta. 4)

t_1 = sampling date at start of 2 week interval

t_2 = sampling date at end of 2 week interval

Fluxes were added over the 18 sampling intervals to yield totals for the 268 day period when water flowed through Pond 1.

Microcosms

Mud and water were collected from the swamp study area. The mud was sieved through a 1 cm mesh screen and swamp water was added to make up a 1:2 mud-water slurry which was kept in suspension by continual stirring. Eighty-four 3-ℓ slurry subsamples were removed to 4-ℓ glass jars. The jars were allowed to stand open, in the dark, for two months. Distilled water was added as needed to counteract evaporation.

Eight grams of dried (75°C) tupelo leaves (*Nyssa aquatica* L.) collected from litter traps in the study area were placed in 1 mm mesh nylon bags and added to half the bottles. All jars were then sealed, fitted with individual gas traps (Fig. 5), and randomly assigned to three gas treatments: argon (ARG), air (AIR), and oxygen (OX) (Table 2). Gas flow in the microcosms was standardized by adjusting the rates of bubble evolution at the gas traps. The bottles were then returned to the dark.

Eight days after gas flow was initiated, 12 bottles--two from each experimental cell--were removed for analysis of water, sediment, and litter. Floodwater pH was determined by glass electrode. Redox potential (Eh) was measured with a bright platinum electrode, both in the water column and in the sediment at a depth of 1 cm. Dissolved oxygen was measured by polarographic electrode (Orion Model 95-08). A 500 ml water sample was siphoned from the jar, filtered (0.45 um Gelman metricel), collected in a polyethylene bottle, and frozen for nutrient analysis.

Litter bags were removed, carefully rinsed, placed in a drying oven at 75°C for 48 hours, cooled in a desiccator, and weighed to determine loss rate. The leaves were then ground to pass through a 60-mesh screen. Subsamples were analyzed for total nitrogen (Kjeldahl method), total phosphorus (Kjeldahl digestion followed by molybdate extraction), and total organic carbon (LECO induction furnace). Sediment samples were treated the same way, except that a dilute HCl treatment was used to remove carbonates prior to organic carbon analysis.

Field Decomposition Experiment

Nylon mesh litter bags, containing tupelo leaves somewhat fresher than those placed in the laboratory microcosms, were distributed in the field in October 1979 to provide decomposition data comparable to that generated by the lab experiment. Litter bags were collected every 30 to 40 days and processed like those in the microcosm experiments to determine weight loss rates and nutrient composition trends.

RESULTS AND DISCUSSION

Input, retention, and export of dissolved nutrient species in Pond 1 were computed, using donor-controlled models forced by the water budget. The effects on nutrient concentration of varying dissolved oxygen levels in floodwater were monitored in the field and examined experimentally in the laboratory microcosms. An attempt was made to separate nutrient responses related to dissolved oxygen from those that could be directly attributed to heterotrophic immobilization and release.

Swamp Water Budget

Precipitation accounted for 23% of the total water input to Pond 1 and evapotranspiration for 11% of losses during the period from September 1978 to June 1979 when the pond was flooded (Table 3). The remainder of the water flux was directly attributable to pumping activity (Fig. 6). Mean water depth in Pond 1 reached a maximum of 0.52 m in February 1971.

Average residence time, which was calculated assuming a weir-top volume of $2.7 * 10^5 m^3$, was approximately 14 days.

Water Chemistry

Nutrient concentrations, both in waters entering the swamp and in the swamp itself, were highly variable from one sampling date to the next. Standard deviations are generally of the same magnitude as mean values (Table 4). It was, thus, impossible statistically to separate the various waters sampled on the basis of mean values alone. The temporal variability observed is evidence that the response of nutrient concentrations to environmental forces is dynamic, changing in less time than the 14-day sampling interval. It is worth noting, however, that P04 values are among the highest reported in a natural swamp setting (Kuenzler et al. 1980).

The data on dissolved nutrients do not indicate strong seasonal trends; however, spring and fall maxima and a winter minimum do appear on most individual nutrient concentration plots (Fig. 7a-7e) and are quite pronounced for P04 (Fig. 7d). Floodwater dissolved oxygen showed a quite different seasonal response. During the months of January and February, when nutrients are at their lowest levels, dissolved oxygen concentrations rise nearly to the saturation point (Fig. 8). This peak is significant after correction for the temperature dependence of oxygen solubility and must be considered a consequence of reduced heterotrophic demand.

Uncontaminated precipitation samples contained variable levels of dissolved nitrogen, but generally only trace concentrations of dissolved phosphorus. Contamination by birds and insects was a severe problem. In one case, over 100 caterpillars were found drowned in a collection gage. Nutrient concentrations determined on obviously contaminated samples were not considered in computing the means in Table 4 or the nutrient budgets. These mean values are comparable with levels reported for precipitation in North Carolina swamps (Brinson 1977, Kuenzler et al. 1980).

Particulate nitrogen (PN) and particulate phosphorus (PP) were determined only for the canal station and at station 4 in the swamp; thus, these data are more limited than those for the dissolved nutrients. The available data suggests, however, that more than 90% of the nitrogen and phosphorus in the canal is associated with particles greater than 0.45 um. The percentage in the swamp is approximately 50%. Visual examination of the material retained on the filters indicates that particulates from the two locations are quite different. Particulates in the canal are a mix of green algal cells and light-colored inorganic clays eroded from croplands. Suspended matter in the swamp had a reddish-brown color and appears to be generated *in situ* through the breakdown of organic matter.

Development of nutrient gradients along the 2200-m sampling transect was variable both in date and nutrient species. Four trends were recognized in the data plots. Among the dissolved nutrient forms, PO_4 consistently increased with distance from the pump (Table 5). On 88% of the days sampled, NH_4 fell into one of the recognized patterns; however, these patterns were not consistent from one date to the next. Dissolved oxygen always decreased as a function of distance into the swamp. It is apparent that oxygen transfer across the air-water interface in the swamp does not keep pace with biological uptake except in the winter.

Swamp Nutrient Budget

Concentrations alone give an incomplete view of nutrient dynamics in systems like the swamp, which experiences a wide range in water volume. The concept of nutrient loading developed by Brezonik and Shannon (1971), in which composition and flow are integrated, is more useful here. Inherent in the use of donor-controlled models to generate loading data is the assumption that instantaneous concentration measurements can be used in conjunction with continuous flow data to provide realistic flux estimates. Kortman (1980) points out that errors arising from this assumption may be as high as ± 45% of nutrient input or removal. A further assumption made here is that we can extend our results from a nine-month data base to a full annual budget (Table 6). Atmospheric nutrient inputs to Pond 1 from June through August, when the swamp was dry, were estimated by comparing concentration data collected during the study with precipitation records compiled by the U.S. Weather Service at Thibodaux, Louisiana, 24 km from the study site. No surface water flow occurred in the pond during this period; thus, precipitation was the only active component in the budget calculation.

Approximately 10 metric tons of nitrogen and three tons of phosphorus were introduced into the 64-ha pond during the year studied. Of these totals, 70% of the nitrogen and 74% of the phosphorus were pumped from the canal in a particulate form (> 0.45 um). Atmospheric sources accounted for only 3% of the total nitrogen and 1% of the total phosphorus entering the pond; however, in terms of dissolved inorganic nitrogen, (TIN) the contribution amounted to 30% of the total input of these forms. Meteorologic contributions of DON and PO4 to the yearly budget were insignificant. Total nitrogen loading through precipitation was

0.64 $gN\text{-}m^{-2}yr^{-1}$ (Table 6). This value falls between that obtained by Eaton et al. (1973) at Hubbard Brook in New Hampshire (0.18 $gN\text{-}m^{-2}yr^{-1}$) and the level reported by Carlisle et al. (1966) from England (0.87 $gN\text{-}m^{-2}yr^{-1}$). Brinson et al. (1977) found that the yearly meteorologic nitrogen loading in a North Carolina swamp was 0.58 $gN\text{-}m^{-2}$, a value very close to that presented here. Our estimate of atmospheric phosphorus input, 0.04 $gP\text{-}m^{-2}\text{-}yr^{-1}$, is considerably less than 0.10 $gP\text{-}m^{-2}yr^{-1}$, a value considered typical for urban areas (Wetzel 1975), but is comparable to 0.05 $gP\text{-}m^{-2}yr^{-1}$ obtained by Brinson et al. (1977) in a rural setting.

Outflows of nitrogen and phosphorus from Pond 1 amounted to 56% and 60% of total annual inputs, respectively. The swamp, then, is an net nutrient sink, retaining approximately 40% of the nitrogen and phosphorus introduced annually. The settling of nutrient-rich particulate matter, however, accounts for almost all of this effect. Working in an alluvial cypress swamp in southern Illinois, (Mitsch et al. (1979) similarly found that more than 90% of the annual phosphorus input could be attributed to the deposition of phosphorus-rich sediments during periods of overbank flooding. In fact, although the swamp retains dissolved inorganic nitrogen ($0.79gN{\cdot}m^{-2}{\cdot}yr^{-1}$) it exports nearly the same amount of dissolved organic nitrogen ($0.74gN{\cdot}m^{-2}\text{-}yr^{-1}$) as well as dissolved phosphorus ($0.20gP{\cdot}m^{-2}\text{-}yr^{-1}$) (Table 6).

The nutrient budget analysis indicates that the swamp removes dissolved inorganic nitrogen, but adds dissolved PO4 to waters passing over its surface. The atomic ratio of inorganic nitrogen to phosphorus (N:P), then, should be a more sensitive index of swamp processing than concentration values alone. N:P ratios for swamp floodwaters ranged from 0.1 to 6.0 : 1 but clustered around a mean of 2 : 1 (SD = 1.8).

Canal water, in comparison, ranged from 0.3 to 23.0 : 1 and showed considerable scatter around a mean of 6.0 : 1 (SD = 6.7). The swamp then acts to buffer the relative concentrations of inorganic nitrogen and phosphorus, so that downstream systems receive water with a relatively stable inorganic nutrient composition. Kemp (1978) has shown that very wide N:P ratios are associated with major runoff events. He has suggested that the routing of agricultural runoff lacking compositional stability directly into Lac des Allemands is responsible for increasing the dominance of cyanophytes in the lake's phytoplankton population.

Microcosm Water Chemistry

The microcosm experiments helped to identify the mechanisms responsible for the floodwater processing summarized in the nutrient budget. Although the laboratory apparatus did not completely exclude oxygen, even under the most reduced treatment, a spectrum of redox environments was produced that spans the range found in natural surface waters (Baas-Becking 1960). Individual microcosm pH measurements ranged from 6.4 to 8.4, but values were clustered tightly around means that ranged from 7.0 to 7.6 (Table 7). The experimental systems, like the swamp itself (McNamara 1978), were buffered toward neutral or slightly alkaline conditions. This buffering was independent of redox condition.

The highest mean dissolved nutrient concentrations for all species except NO3 were found under the lowest dissolved oxygen treatment (ARG) (Fig. 9a-e). Both NH4 in the most reduced systems (ARG) and NO3 in the most oxidixed systems (OX) peaked at 180 days. NO3 began to appear in the ARG treatments after this point, but NH4 was never present in the OX microcosms. These observations draw attention to the two phases of inorganic nitrogen transformations that are important to water column nutrient dynamics: nitrification and denitrification. Highly oxidized floodwater conditions result in the rapid nitrification of NH_4 diffusing out of the sediments. Denitrification is apparently restricted or slowed to the point that dissolved NO_3 builds up in the water column. Under highly reduced conditions, the cycle is limited by the rate of the nitrification step, and NH_4 diffusing out of the sediments into the water column is unable to enter the denitrification phase and tends to remain in the floodwater. Either of these extreme conditions restricts nitrogen losses; however, neither can be considered representative of the swamp, which is characterized by an intermediate redox condition. Relative rates of nitrification and denitrification vary under these conditions as a function of oxygen recharge. DON also accumulated in the ARG systems and, after 240 days, reached a peak concentration of 12 mg l^{-1} (Fig. 9c). In comparison, DON in the OX systems was relatively constant at 1 mg-l^{-1}. PO_4 in the ARG microcosms ranged up to 3 mg-l^{-1}, while the maximum in the OX systems was less than 0.5 mg-l^{-1} (Fig. 9d). Both DON and TP concentrations were significantly negatively correlated with dissolved oxygen.

Microcosms containing leaf material (LITTER) were depleted in dissolved oxygen relative to controls (NO LITTER). This difference was significant, however, only in the systems under the AIR treatment (Table 7). Mean DO in the AIR-NO LITTER bottles was 4.7 mg-l^{-1} compared with 1.9 mg-l^{-1} in the AIR-LITTER system. Dissolved NH_4 and NO_3 concentrations were unaffected by the presence of leaf material, but DON, PO_4, and DOP concentrations in the water were significantly higher in the AIR system containing litter bags (Fig. 10a-e). Nutrient levels in the ARG and OX systems showed no response to the LITTER treatment (Table 7).

In the LITTER systems receiving the AIR treatment, oxygen demand by the heterotrophic community colonizing the litter material was effective in creating a more reducing environment than that in the control (NO LITTER) systems. Relatively minor decreases in oxygen availability appear to greatly increase the rate at which DON and PO4 enter the water column. The lack of such a nutrient response in the ARG and OX LITTER systems, where the leaf decomposer community could not significantly influence redox condition, suggests that nutrient cycling at the leaf substrate by itself was not important in controlling water column concentrations. The process, then, whereby nutrients are added to the water column must be a redox-mediated flux from the sediments.

Dissolved Oxygen: Effects on Dissolved Nutrient Concentrations

In order to test the hypothesis that DO levels exert an important influence on floodwater nutrient concentrations, least squares regression analyses (SAS 79, GLM) were used to develop predictive quadratic equations from which correlation coefficients (R^2) were computed for each nutrient in both the lab and field setting (Table 8). Significant negative correlations were found between DO and the dissolved nutrients NH4, DON, PO4, and TP, but the strongest relationship in both the field and the lab was that between DO and PO4. Correlation coefficients were between 0.50 and 0.60. The fact that over 50% of the observed variability in floodwater PO4 is explained by DO alone is remarkable considering the seasonal changes in flow in the swamp and the range of conditions over which the lab systems were incubated.

The relationship between DO and PO4 molalities both in the field and in the experimental systems are closely approximated by linear functions of the log transformations (Fig. 11). It should be noted that lab PO4 levels for a given oxygen molality are consistently an order of magnitude higher than those measured in the field. We attribute this difference to turbulent and advective transport of oxygen in the field, processes that were minimized in the lab microcosms. These oxygen recharge mechanisms, which are active in the natural swamp environment, increase the effectiveness with which DO at any concentration limits PO4 flux from the sediments (Lerman 1979).

Best-fit equations derived from the LITTER and NO LITTER lab data are nearly identical (Fig. 12). Higher PO4 values generated in the LITTER group then fit the model relating PO4 flux from the sediments to DO in the water column. Oxygen availability, whether regulated by heterotrophic demand, by gas solubility, or by turbulent mixing, is the critical factor. Nutrient cycling associated with the organisms metabolizing the leaf material in the litter bags appeared to have no direct impact on floodwater PO4 concentrations.

Litter Decomposition: Sediment and Leaf Nutrients

Decomposition in the laboratory microcosms was most complete under the OX treatment, slowest in the ARG systems, and intermediate under the AIR treatment (Fig. 13). Although the patterns of weight loss in the laboratory closely follow those of the field samples, decomposition in the field was more rapid and complete than in even the most oxidized laboratory treatment. The greater efficiency of breakdown in the field litter bags may be because of the activities of macrofauna, which were excluded from the lab systems. The decomposition process in all the lab and field environments studied appears to have two stages. An early phase of rapid weight loss terminates at approximately 200 days and is followed by a second stage of moderate or, in some cases, negligible loss, which extends to the end of the one-year monitoring period. The break in the curve may represent the point at which easily metabolized litter material is exhausted, leaving only more resistant structural components. The level at which this point is found in the various lab redox environments provides a good index of the relative efficiencies of microbial utilization. The inflection is found in the most reduced ARG system when 45% of the original leaf material has been lost. The effectiveness increases to 65% in the OX system and to 75% under field conditions.

When losses of organic carbon, nitrogen, and phosphorus from the leaf material are plotted with the per cent of weight loss, organic carbon consistently plots below the weight loss curve, while nitrogen and phosphorus are above (Fig. 14). It is apparent that carbon is being utilized at a more rapid rate than nitrogen or phosphorus. Annual losses of nitrogen and phosphorus from the laboratory litter bags were minor, but amounted to 45% for both nutrients in the field. This value contrasts, however, with a field weight loss of nearly 80%. Differential loss of constituents and an initial priming of the litter material with microbial nitrogen and phosphorus leads to substantial enrichment of the substrate with nitrogen and phosphorus and depletion of organic carbon (Table 9).

The nutrient composition of the swamp sediment placed in the lab bottles did not change significantly over the 360 days of the experiment (Table 9) and can be considered the ultimate decompositional endpoint for the litter material. It is possible, then, to speculate about long-term nutrient storage. Concentrations of nitrogen and carbon in the sediments are approximately half those of the litter material. Phosphorus concentration in the sediment and final litter values are, however, roughly equivalent (Table 9). We might then expect, in a longer experiment, to see decreases in carbon and nitrogen concentrations in the litter material, but little change in the phosphorus levels (Fig. 15). It appears that in the swamp system there is a significant microbial demand for nitrogen and carbon, but little for phosphorus. This may then explain why phosphorus levels in the swamp floodwater are negatively correlated with dissolved oxygen concentrations. The exchange of PO4 between the sediments and water column appears to be independent of any direct biological mediation. It is, however, indirectly influenced when biological oxygen demand controls sediment redox condition. Abiotic redox-dependent Fe (II, III) phosphate reactions have long been recognized as potential mechanisms for buffering PO4 concentrations in natural waters and sediments. Mortimer (1941, 1942) observed that phosphate flux across the mud-water interface in lakes undergoing seasonal stratification was dependent on hypolimnetic oxygen level and on the redox condition of the sediments. PO4 enrichment was greatest under reduced conditions and least when surface sediments were oxidized. Experiments with undisturbed sediment cores have quantitatively related exchange across the mud surface to redox condition, PO4 concentration gradient, and sediment properties (Pomeroy et al. 1965, Stumm and Leckie 1971, Shukla et al. 1971, Li et al. 1972, Kamp Nielsen 1974). Attention has focused recently on the reversible nature of PO4 uptake and release by non-calcareous sediment suspensions (Patrick and Khalid 1974, Khalid et al. 1977, Holford and Patrick 1979). This research has presented evidence that PO4 is retained on sediments by redox-sensitive sorption reactions involving a mixture of $Fe(OH)_2$-$FE(OH)_3$ compounds. Our results, both in the field and in the laboratory microcosms, also suggest a reversible mechanism. Swamp floodwater PO4 concentrations respond rapidly and relatively predictably to redox-dependent changes in the capacity of the sediments to bind PO4. The swamp system exports excess PO4 downstream. The lack of demand for PO4 relative to NH4 and NO3 leads to the low N:P ratios of swamp-processed water.

General Discussion

Our results indicate that significant portions of N and P entering the swamp are retained. In a review of the role of wetlands in nutrient cycling, Yarbro (1979) suggests that, because they are a boundary between aquatic and terrestrial systems, they act as sinks for materials from both types of ecosystems (Grant and Patrick 1970; Kitchens et al. 1975: Lee et al. 1974; Boyt 1976; Odum and Ewel 1976, Richardson et al. 1976; Mitsch et al. 1977; Sloey et al. 1978). This generalization does not, however, hold true for all wetlands. Some systems export materials, particularly nitrogen and phosphorus, rather than conserve them (Crisp 1966; Gardner 1975; Heinle and Flemer 1976; Kemp 1978). Retention may be only seasonally active (Bender and Correl 1974; Burke 1975; Axelrad et al. 1976; Woodwell et al. 1977; Richardson et al. 1978; Spangler et al. 1976, Simpson and Whigham 1978; Tilton and Kadlec 1979), or may occur for only a short period of time, after which the ecosystem becomes "saturated" (Steward and Ornes 1973, 1975; Valiela et al. 1973; McPherson et al. 1976; Valiela and Vince 1976). Nutrient retention may significantly modify ecosystem characteristics over successional or perhaps evolutionary time (Steward and Ornes 1973, 1975; Hartland-Rowe and Wright 1975; Richardson et al. 1978). Some ecosystems appear to retain a significant portion of their inputs of phosphorus through internal recycling (Burke 1975; Butler 1975; Viner 1975a; Hartland-Rowe and Wright 1975; Gaudet 1976; Odum et al. 1976, 1977; Day et al. 1977; Boyt et al. 1977; Kuenzler et al. 1977; Nessel 1978; Yonika and Lowry 1978). If the swamp forest is to be considered as a site for the processing of upland runoff, we need to understand as best we can (1) the nutrient pathways of the swamp under natural conditions, (2) the long-term impacts of such a program on existing pathways, and (3) the impacts on other aspects of swamp forest ecology.

The Swamp as a Buffer

The swamp acts as a buffer in time, concentration, and composition. Concentrations of dissolved inorganic nitrogen, particulate nitrogen, and particulate phosphorus were lower in swamp water than in input water, while levels of dissolved organic nitrogen and dissolved phosphorus were somewhat higher in the swamp. The chemical composition of water overlying the swamp is different from that of the input water. The ratio of particulate to dissolved fractions for both N and P is much lower for the swamp water and the composition of the particulate suspended matter in the swamp seems basically different from that in the input water. Particulates pumped into the swamp are inorganic silts and clays and phytoplankton cells. Particulates leaving the swamp appear to be made up primarily of organic materials generated within the swamp.

Dissolved inorganic N:P ratios in swamp water are relatively constant at a value around 2:1. Inorganic N:P ratios in channeled upland runoff that did not flow through the swamp averaged 6:1. Kemp and Day (1981) have shown that this ratio is strongly influenced by rainfall and was as high as 22:1 following major runoff events (Fig. 16).

It is apparent then that a significant portion of N and P entering the swamp is retained. Nutrients exported to swamp bayous and lakes are released slowly over time.

Long Term Nutrient Processing

The results of this study are for one year. Can the rates of nutrient retention measured for this year be expected to hold for longer periods? As mentioned earlier, several workers have found that rates of retention and release may change or reach saturation after a short period of time. We believe that this swamp forest system, however, can continue to be a sink for N and P for long periods. The two major processes that act to enhance the role of the swamp as a sink are denitrification and sedimentation-subsidence.

Research has recently shown that denitrification is an important avenue for "permanent" nitrogen loss in wetlands and shallow aquatic systems (Valiela and Teal 1979, Haines et al. 1977, Nixon 1979, Nixon et al. 1980, Boynton et al. 1980; Delaune and Patrick 1980). The closeness of the oxidized-reduced boundary to the sediment surface makes conditions for linkage between the nitrification and denitrification pathways favorable.

The swamp forest as part of the Mississippi River deltaic plain is situated on a section of the Gulf Coast geosyncline, which is undergoing rapid local and regional subsidence from the loading and compaction of alluvial sediments. The process has been going on for millions of years. Baumann (1980) measured a subsidence rate of 0.60 cm/year at two sites in the swamp forest. Thus, sediments laid down in the swamp are slowly incorporated into deep sediments and "permanently" lost in terms of current ecological dynamics. Delaune and Patrick (1980) have documented this process for saline marshes in the lower Barataria Basin.

Other Impacts of Overland Flow

Reintroduction of overland flow would actually mean a return to historical patterns of nutrient cycling. Before flood-control levees were constructed along the Mississippi River, floodwater flowed through the swamp each spring. Nutrients were processed and exchanged, and sedimentation and subsidence interacted to produce a relatively constant surface elevation. It seems clear that a return to overland flow hydrology will promote the uptake of N and P in the swamp. What does this mean for other aspects of swamp forest ecology?

The most obvious effect is that N and P loading to swamp bayous and lakes will be reduced. Nutrient loading to Lac des Allemands is currently 30 $gNm^{-2}yr^{-1}$ and 4 $gPm^{-2}yr^{-1}$ (Craig and Day 1977). The results of this study suggest that a return to overland flow conditions could reduce these loading rates by 40 to 50%.

Shannon and Brezonik (1972) showed a highly significant correlation between P supply and trophic state of 55 Florida lakes. Seaton (1979) reported a significant correlation between trophic state and aquatic primary production in the Barataria Basin (Fig. 17). Craig and Day (1977) estimate that the critical P loading rate for coastal waterbodies in Louisiana is probably between 1-2 $gPm^{-2}yr^{-1}$. The information presented here suggests that the trophic status of Lac des Allemands might be lowered from hypereutrophic (Day et al. 1977, Craig and Day 1977) toward a mesotrophic state.

The reinstatement of overland flow would increase swamp productivity. Conner and Day (1976) showed that optimum swamp productivity in the southeastern U.S. occurs with a seasonal flooding and drying regime. Conner et al. (1981) reported that swamp production in the crayfish pond studied here was twice that of an adjacent impounded area.

A hydrodynamic model of the swamp indicated that overland flow would increase discharge from the upper basin and lower stages in Bayou Chevreuil (Hopkinson and Day 1980a, 1980b). This would occur because without spoil banks water would flow through the swamp and not be confined to canals and channeled bayous. The model also indicated that the present drainage network in the swamp does not significantly reduce the flooding of upland agricultural fields and, thus, does not accomplish design objectives.

Finally, we believe that overland flow would improve the wildlife and fisheries value of the swamp. Paille (1980) showed that an impounded area adjacent to the crayfish pond produced almost no crayfish. An impounded swamp cannot serve as a refuge or nursery for fish species. Sportsmen in the area have told us that hunting is poor in swamplands without active overland water flow.

Conclusions

1. Under overland flow conditions, the swamp can remove a significant amount of incoming nutrients. Forty-four percent of total N and 40% of total P were retained in the swamp.

2. Practically all of the removal takes place because of the settling of particulate N and P. Particulate nutrients entering the swamp are primarily associated with eroded upland soils and algal cells. Particulates leaving the swamp seem to be generated within the swamp.

3. For two reasons it is not likely that the swamp will become saturated with N and P. First, the results indicate that denitrification is a significant pathway for the permanent loss of nitrogen. Second, the swamp is subsiding at a significant rate. This means that much of the suspended sediments that settle on the swamp floor will become buried. If these nutrients s are not taken up by rooted vegetation, they will be permanently lost to the deep sediments.

4. In spite of nutrient retention in the swamp, significant amounts are still exported to swamp bayous and lakes. The swamp, however, acts as a buffer in time and composition, as well as concentration. Nutrients are released slowly over a longer time rather than in the erratic pulses associated with channeled runoff.

5. Dissolved oxygen in the water column is the single most important factor determining sediment-water exchange of PO_4.

Recommendations

1. The results of this study indicate that a return to overland flow hydrology would reduce water quality problems in the upper Barataria Basin. As a step toward the reintroduction of overland flow, we suggest a pilot project on a larger scale than the one reported here. Hopkinson and Day (1980) identified 11 upland subcatchments in the upper Barataria Basin (Fig. 2). One of these could serve as a natural laboratory. The pilot project would involve two steps. First, necessary changes would be made in the drainage system to change channelled runoff to overland flow. Second, selected physical, chemical, and biological parameters would be measured to determine water levels, flood potential, water quality, and productivity.

2. On a broader scale a study should be initiated to develop a plan by which much of the upper basin could be returned to overland flow hydrology. This study should identify specific sites, engineering techniques, and funds required to accomplish this.

   Economic, sociological, and legal aspects will have to be considered in addition to technical considerations. Representatives of local government, land owners, sportsmen, and the general public should be included in the study. Education should be an important part of the study to inform the above groups about functioning of the swamp system and the benefits of overland flow hydrology.

3. The state of Louisiana should commit itself to the protection of swamp forest ecosystems. The return of overland flow would have positive benefits in terms of primary production, timber growth, flood control, and wildlife habitat. Channelization of bayous and construction of new canals should not be allowed in swamp forests. Steps should be taken to reintroduce natural hydrological conditions.

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Table 1. Nomenclature

Symbol	Name	Comments
NH4	Dissolved ammonium nitrogen	free ammonia and ammonium ion
NO3	Dissolved intrate and nitrite	total inorganic nitrogen (TIN) less NH4
TIN	Total dissolved inorganic nitrogen	NH4 + NO3
DON	Dissolved organic nitrogen	kjeldahl nitrogen less ammonia nitrogen
PO4	Dissolved orthophosphate	free phosphate
TP	Total dissolved phosphorus	PO4 plus that released in a persulfate disgestion
DOP	Dissolved organic phosphorus	TP-PO4
PN	Particulate nitrogen	kjeldahl nitrogen associated with particles greater than 0.45 μm in size
PP	Particulate phosphorus	total phosphorus associated with particles greater than 0.45 μm in size
DO	Dissolved oxygen	
pH	Hydrogen ion activity (log)	
Eh	Redox potential	
TOC	Total organic carbon	total carbon less carbonate carbon

Table 2. Experimental design of microcosm experiment

	Argon	Air	Oxygen
Litter	14	14	14
No Litter	14	14	14
			TOTAL: 84

Table 3. Summary of water budget for Pond 1 September 8, 1978, to June 1, 1979

INFLOWS	VOLUME	% TOTAL INFLOW
Pump	$295 * 10^4 m^3$	77
Precipitation	$86 * 10^4 m^3$	23
REMOVAL	VOLUME	% TOTAL LOSS
Flow over weir	$350 * 10^4 m^3$	89
Evapotranspiration	$33 * 10^4 m^3$	11

Table 4. Mean dissolved nutrient concentrations ($mg\text{-}\ell^{-1}$) standard deviations in parentheses

	Canal	Swamp	Precipitation
NH4	0.12 (0.10)	0.07 (0.08)	0.10 (0.06)
NO3	0.09 (0.11)	0.05 (0.03)	0.10 (0.11)
TIN	0.20 (0.16)	0.11 (0.10)	0.20 (0.14)
DON	0.73 (0.25)	0.79 (0.27)	0.15 (0.16)
PN	3.35 (2.38)	1.53 (1.33)	
PO4	0.15 (0.12)	0.16 (0.10)	0.01 (0.01)
TP	0.22 (0.16)	0.23 (0.13)	0.02 (0.02)
PP	1.05 (0.82)	0.25 (0.22)	
DO		0.34 (1.93)	

Table 5. Transect concentration trends (percent of sampling days observed)

TREND 1: Concentration decreases simply with distance from pump.

TREND 2: Concentration increases simply with distance from pump.

TREND 3: Concentration decreases in Pond 1, but increases in Pond 2.

TREND 4: Concentration increases in Pond 1, but decreases in Pond 2.

	Trend Type				
Nutrient	1	2	3	4	No Trend
NH4	18	35	35	0	12
NO3	35	18	6	6	29
TIN	24	29	24	0	24
DON	6	29	6	0	59
PO4	29	47	0	12	12
TP	24	47	0	6	24
DO	76	0	6	0	12

Table 6. Swamp nutrient input and removal in $g\text{-}m^{-2}\text{-}yr^{-1}$

Nutrient	Pump	Precipitation	Total Input	Outflow	Out-In	% Input Retained (-) or Exported (+)
NH4	0.46	0.16	0.62	0.25	-0.36	-58%
NO3	0.45	0.23	0.69	0.26	-0.43	-62%
TIN	0.91	0.40	1.30	0.51	-0.79	-61%
DON	3.16	0.24	3.40	4.13	+0.74	+22%
PN	10.83	--	10.83	7.03	-3.80	-35%
PO4	0.71	0.02	0.73	0.83	+0.11	+15%
TP	1.04	0.04	1.08	1.27	+0.20	+19%
PP	3.12	--	3.12	1.24	-1.88	-60%
ΣN	14.90	0.64	15.54	11.67	-3.87	-26%
ΣP	4.16	0.04	4.20	2.51	-1.69	-41%

Table 7. Results of one year microcosm study mean values (n = 14) standard deviations in parentheses Floodwater nutrient concentrations in $mg\text{-}l^{-1}$

TRT	DO	p^H	Eh_{H_2O} (mv)	Eh_{SED}(1cm) (mV)	NH4	NIT	ORGN	PO4	TOTP
				LITTER					
ARG	0.86 (0.80)	7.15 (0.50)	+182 (52)	+144 (27)	2.19 (1.13)	0.12 (0.30)	7.95 (7.11)	2.06 (0.80)	3.52 (1.78)
AIR	1.86 (1.21)	7.30 (0.41)	+313 (55)	+200 (55)	0.37 (0.48)	0.11 (0.12)	2.16 (0.86)	1.49 (0.85)	2.19 (1.03)
OX	14.00+	7.04 (0.35)	+408 (45)	+367 (88)	0.05 (0.05)	0.63 (0.69)	1.16 (0.28)	0.37 (0.35)	0.50 (0.53)
				NO LITTER					
ARG	1.01 (0.91)	7.59 (0.55)	+169 (74)	+131 (35)	2.39 (0.75)	0.20 (0.39)	5.06 (3.40)	1.53 (0.83)	2.17 (1.00)
AIR	4.72 (1.62)	7.28 (0.71)	+352 (39)	+254 (74)	0.26 (0.49)	0.17 (0.14)	0.85 (0.53)	0.61 (0.39)	0.95 (0.81)
OX	14.00+	7.28 (0.30)	+411 (42)	+368 (98)	0.07 (0.10)	0.64 (0.51)	0.82 (0.27)	0.13 (0.08)	0.15 (0.09)

Table 8. Coefficients of correlation (R^2): field and lab data

Model		Field Sites		Microcosms	
Independent Variable	Dependent Variable	Pond 1	Pond 2	Litter	No Litter
DO	NH4	0.05*	0.13	0.23	0.41
DO	TON	0.09*	0.31	0.18	0.20
DO	PO4	0.41	0.57	0.59	0.53
DO	TP	0.34	0.63	0.62	0.43

*Not significant ($P < 0.01$)

Table 9. Results of 360 day tupelo leaf decomposition experiment. All concentrations in ug-at-g dry wt $^{-1}$

TRT	Wt % Left After 1 year	Initial[1] N	Final N	Initial P	Final P	Initial C	Final C
ARG	53 (5)[2]	1233 (59)	1887 (88)	8.50 (0.03)	21.72 (5.37)	41625 (8)	35833 (833)
AIR	47 (1)	1268 (9)	2766 (701)	8.52 (2.28)	45.24 (1.87)	40525 (1058)	34167 (833)
OX	33 (14)	994 (311)	2134 (261)	10.36 (0.32)	40.12 (15.75)	38167 (2875)	33333 (2500)
FIELD	20	842	1698	20.50	43.22	--	--
SEDIMENT	--	794 (50)	915[3] (86)	32.65 (2.86)	37.39 (6.96)	13725 (608)	--

[1]Initial refers to first sampling which occurred 7 days after placing litter in bottles.

[2]Standard deviation.

[3]Nutrient analysis on sediment samples was not continued after 240 days as no trend was observed.

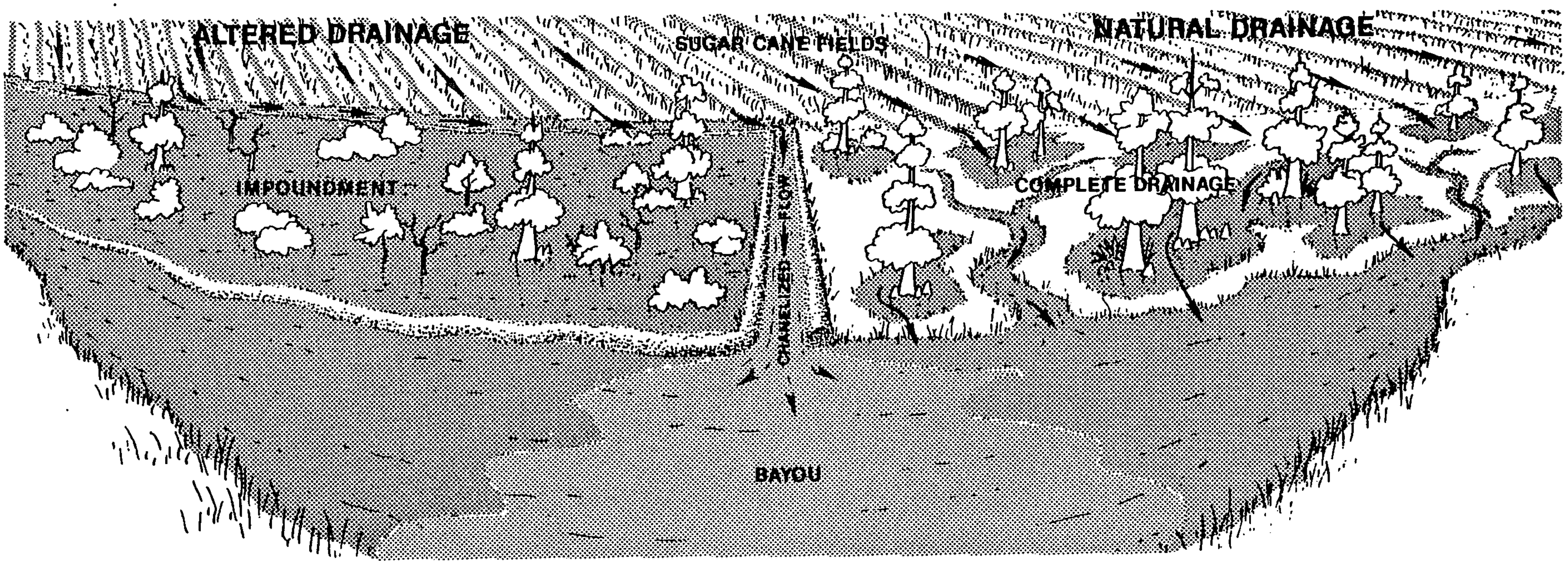


Figure 1. Swamp hydrology - overland flow versus channelized flow.

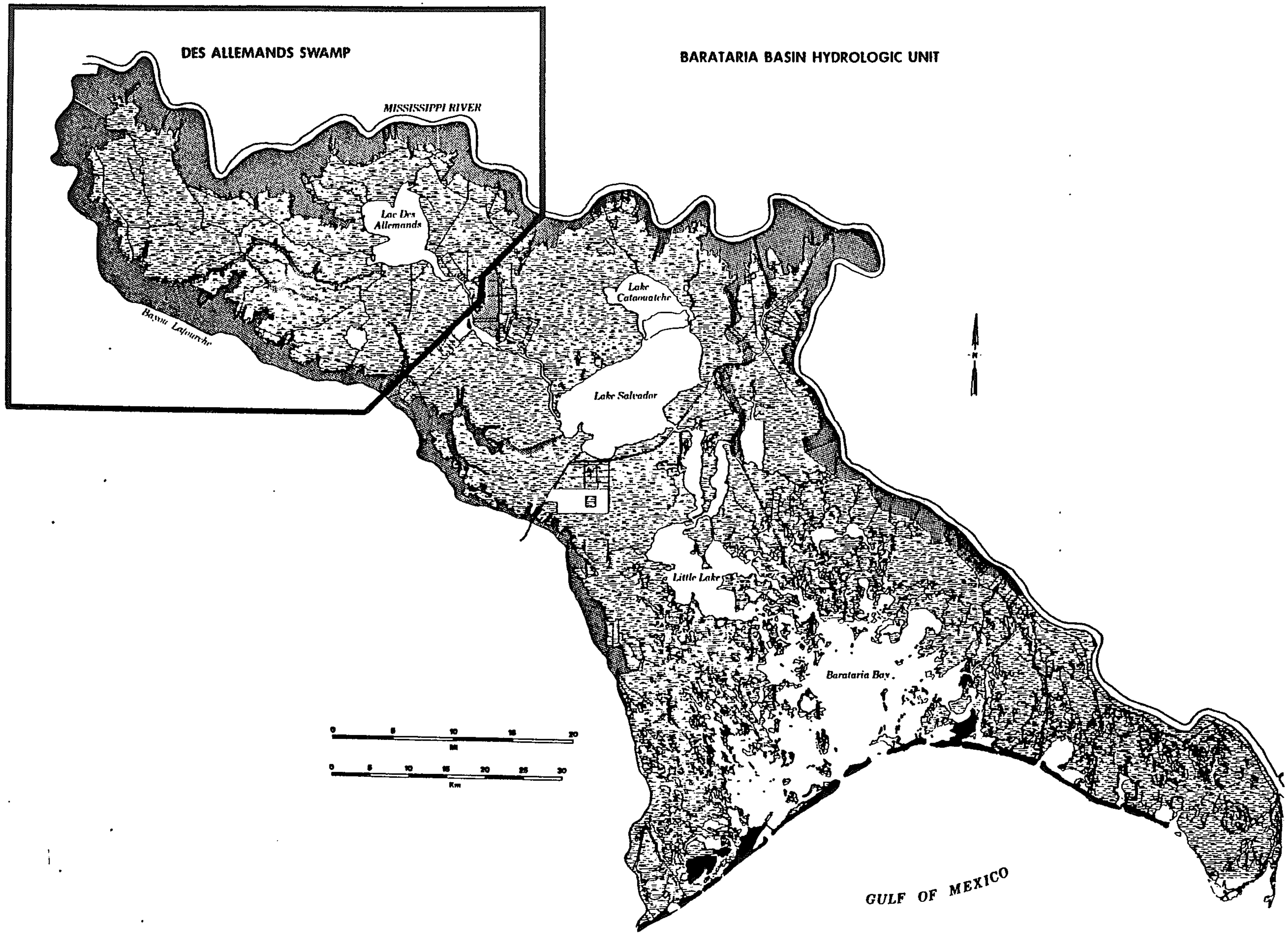


Figure 2. Barataria Basin - lakes and Marsh types.

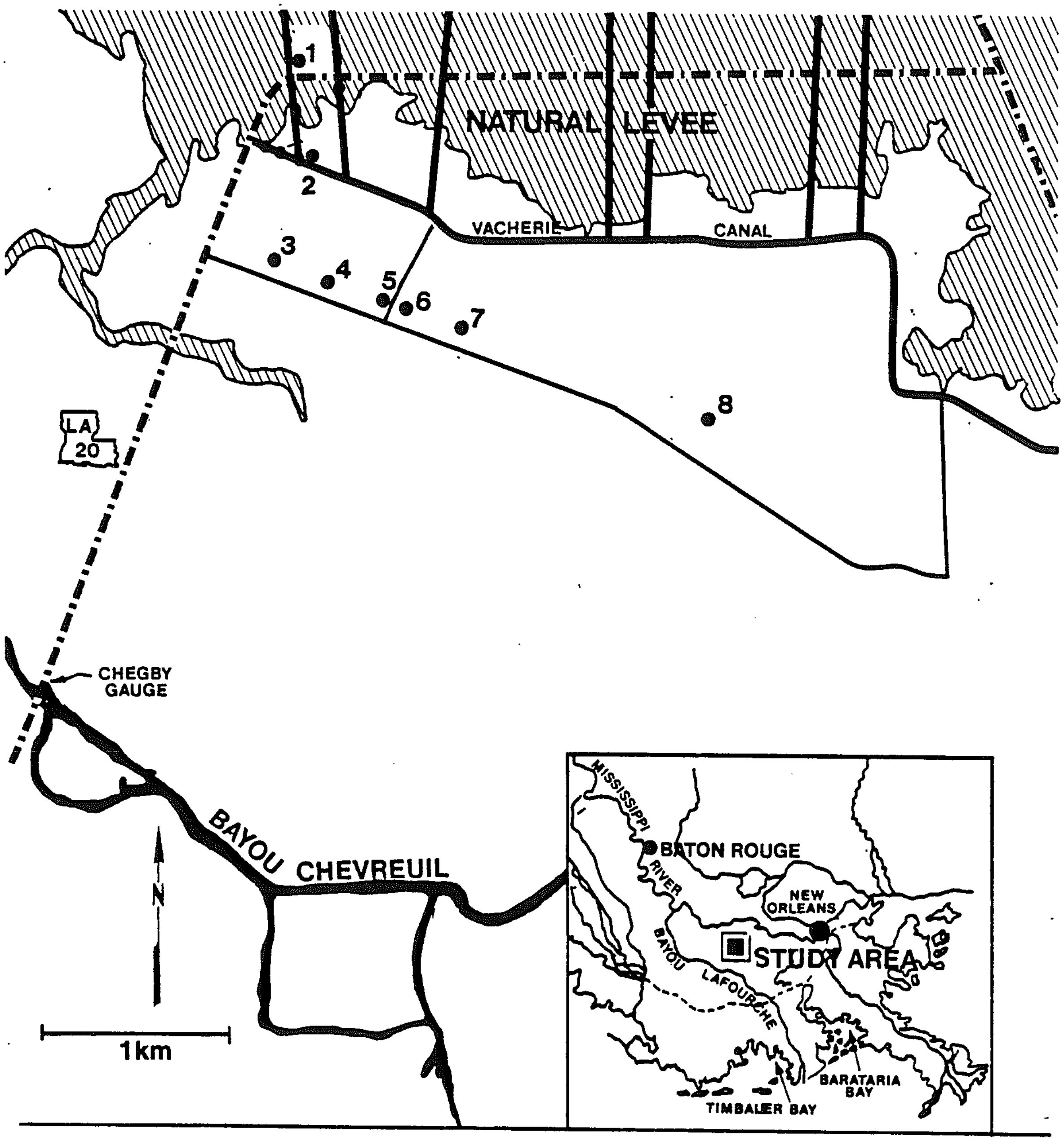


Figure 3. Study area - regional map showing relationship of crawfish farm to other geomorphic features.

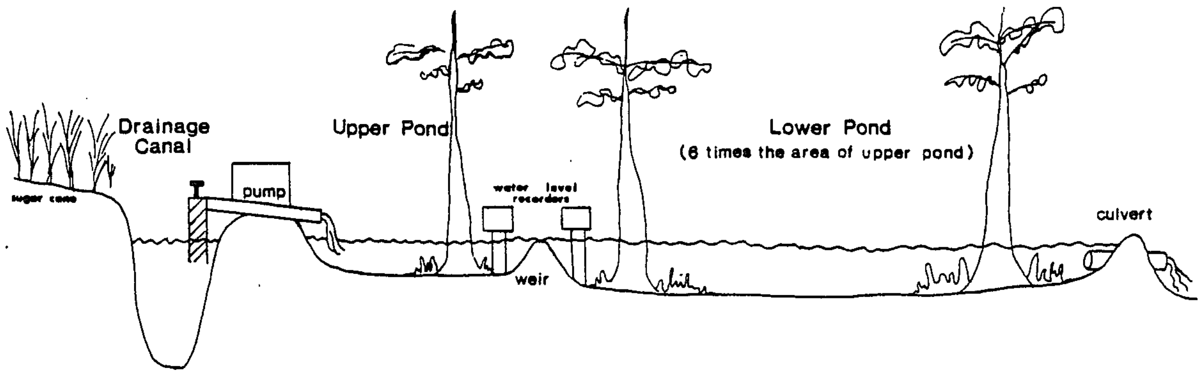


Figure 4. Schematic cross-section of crawfish farm.

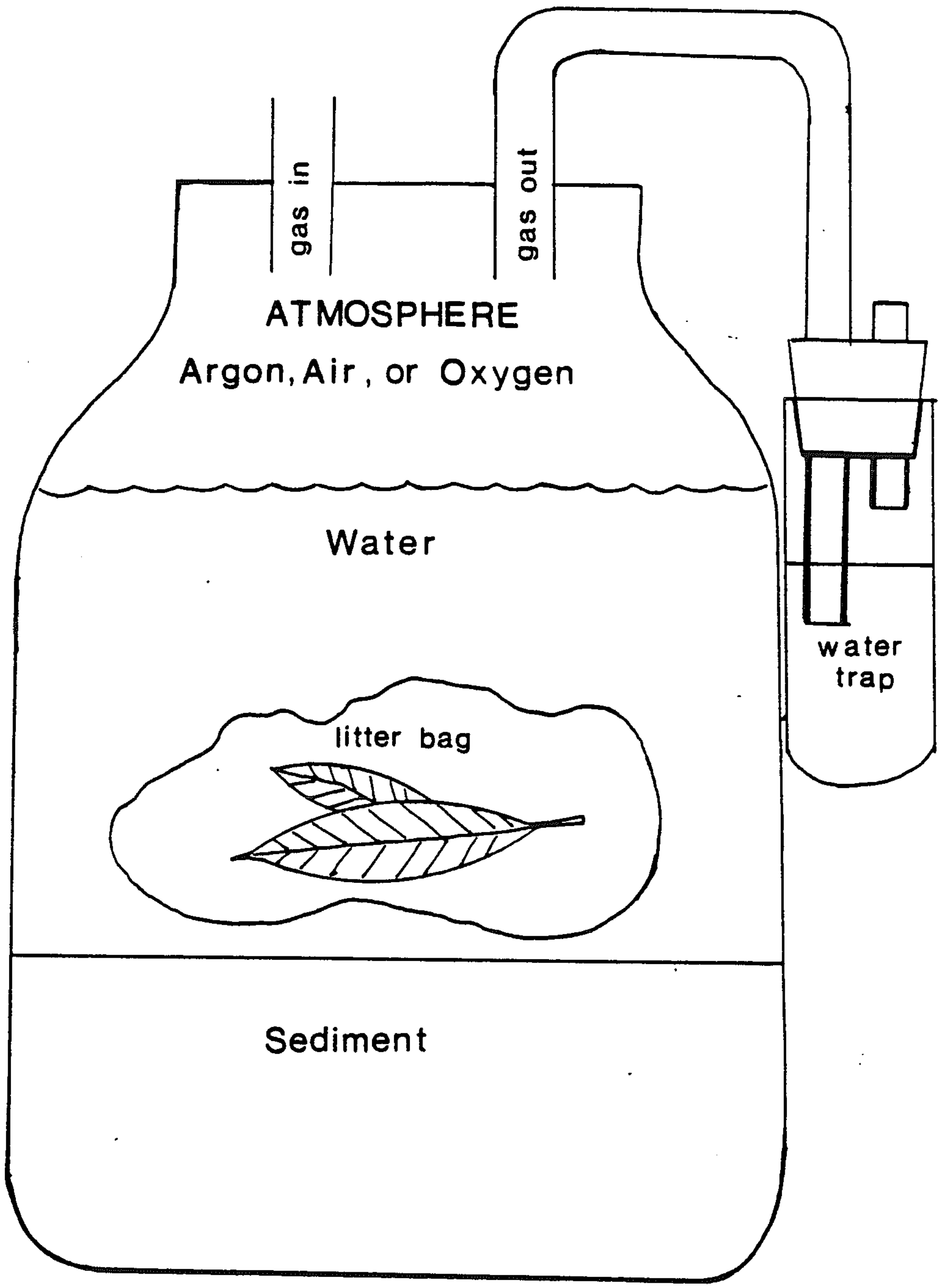


Figure 5. Microcosm apparatus.

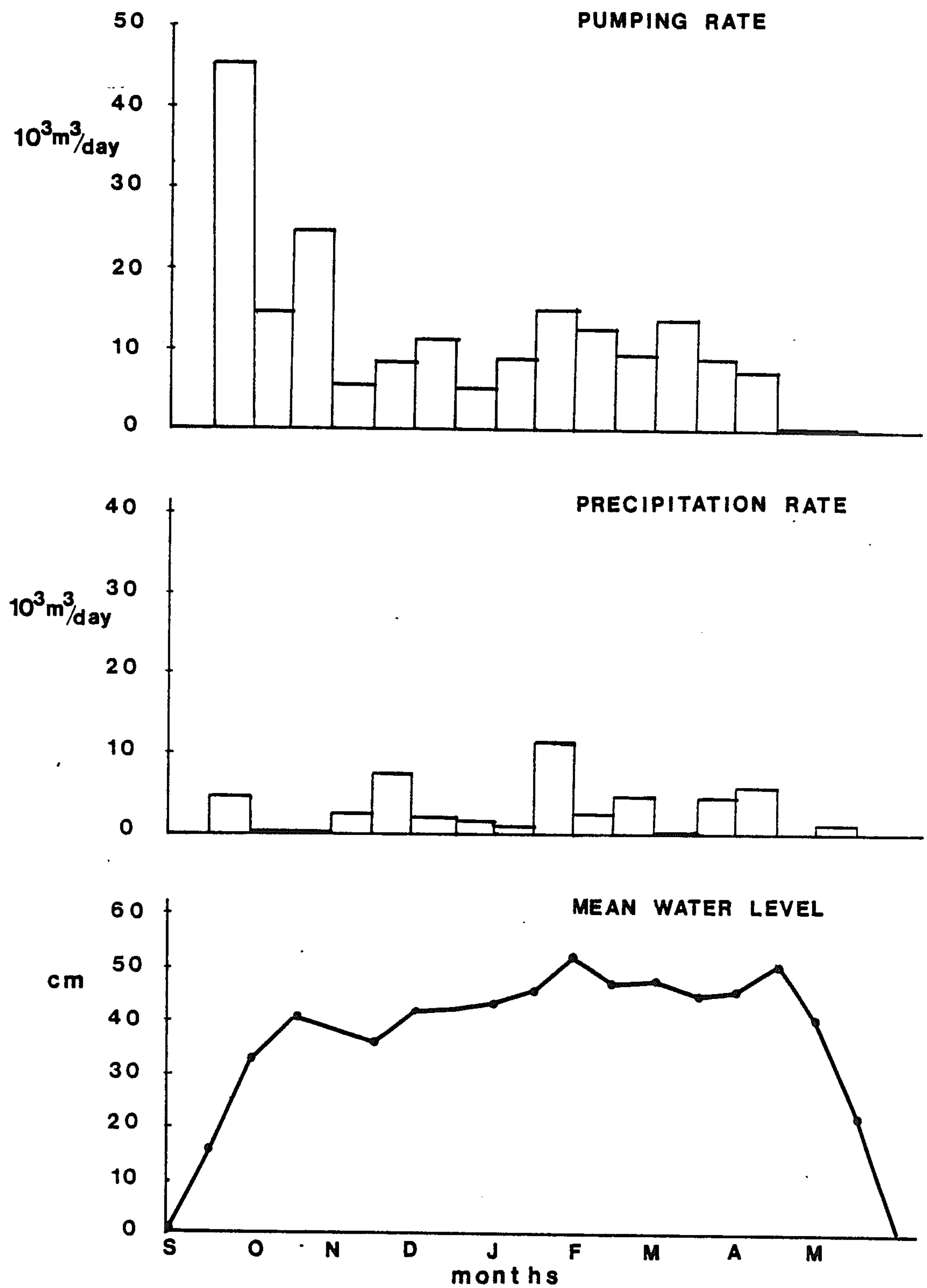


Figure 6. Water budget parameters for Pond 1.

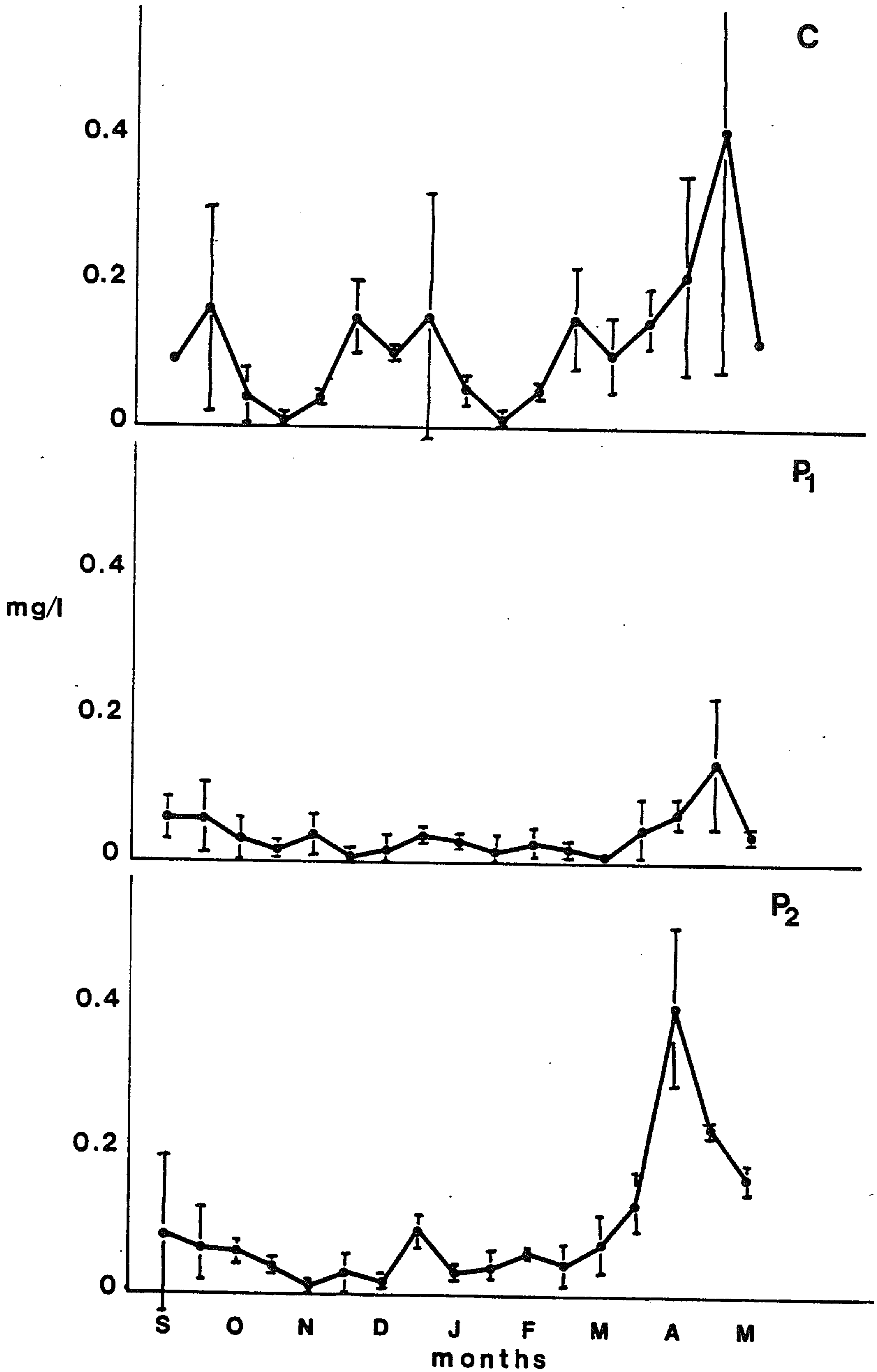


Figure 7a. Mean NH4 concentrations in (C) canal, (P_1) Pond 1, and (P_2) Pond 2. Bars indicate standard error.

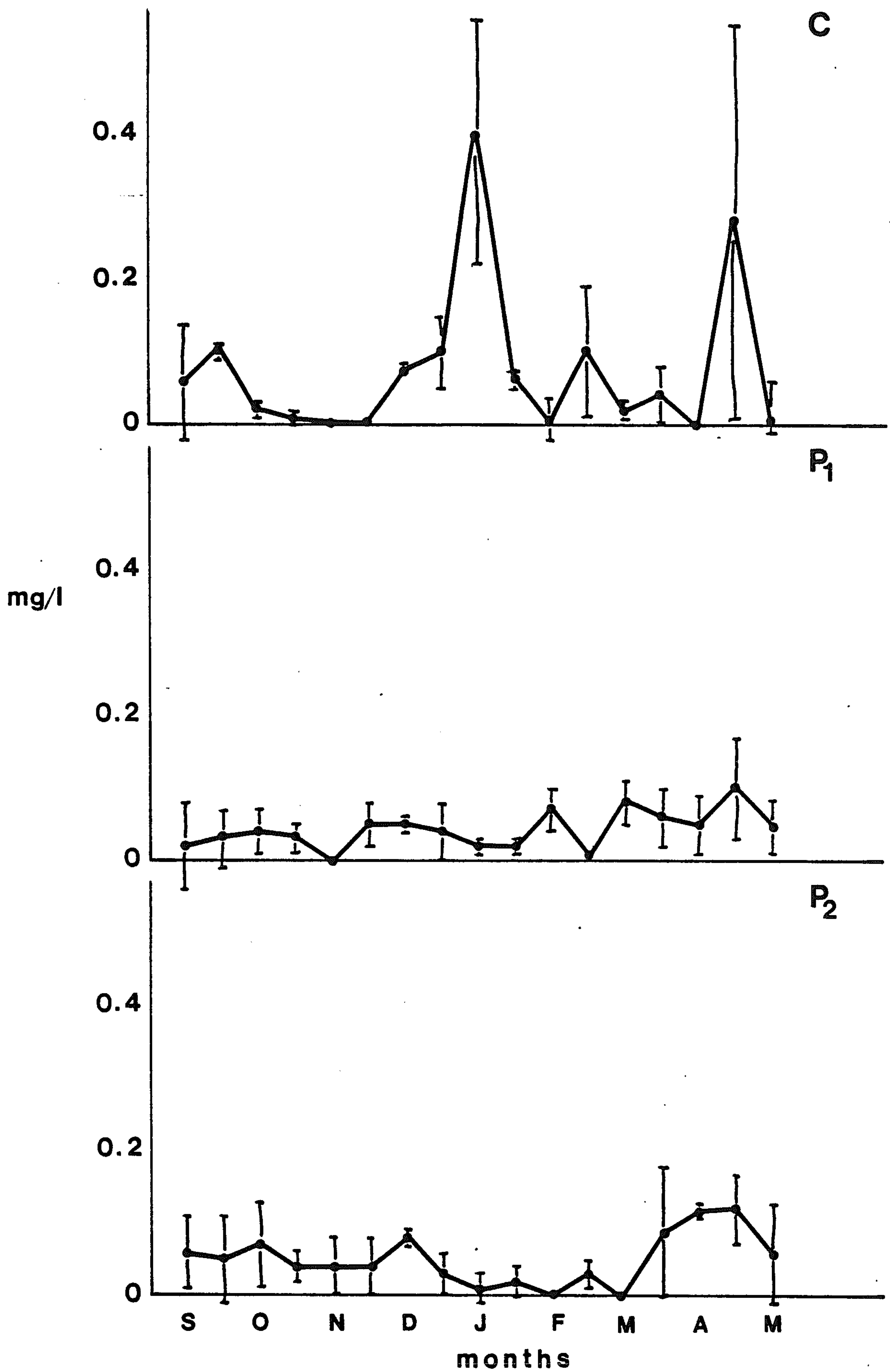


Figure 7b. Mean NO3 concentrations in (C) canal, (P_1) Pond 1, and (P_2) Pond 2. Bars indicate standard error.

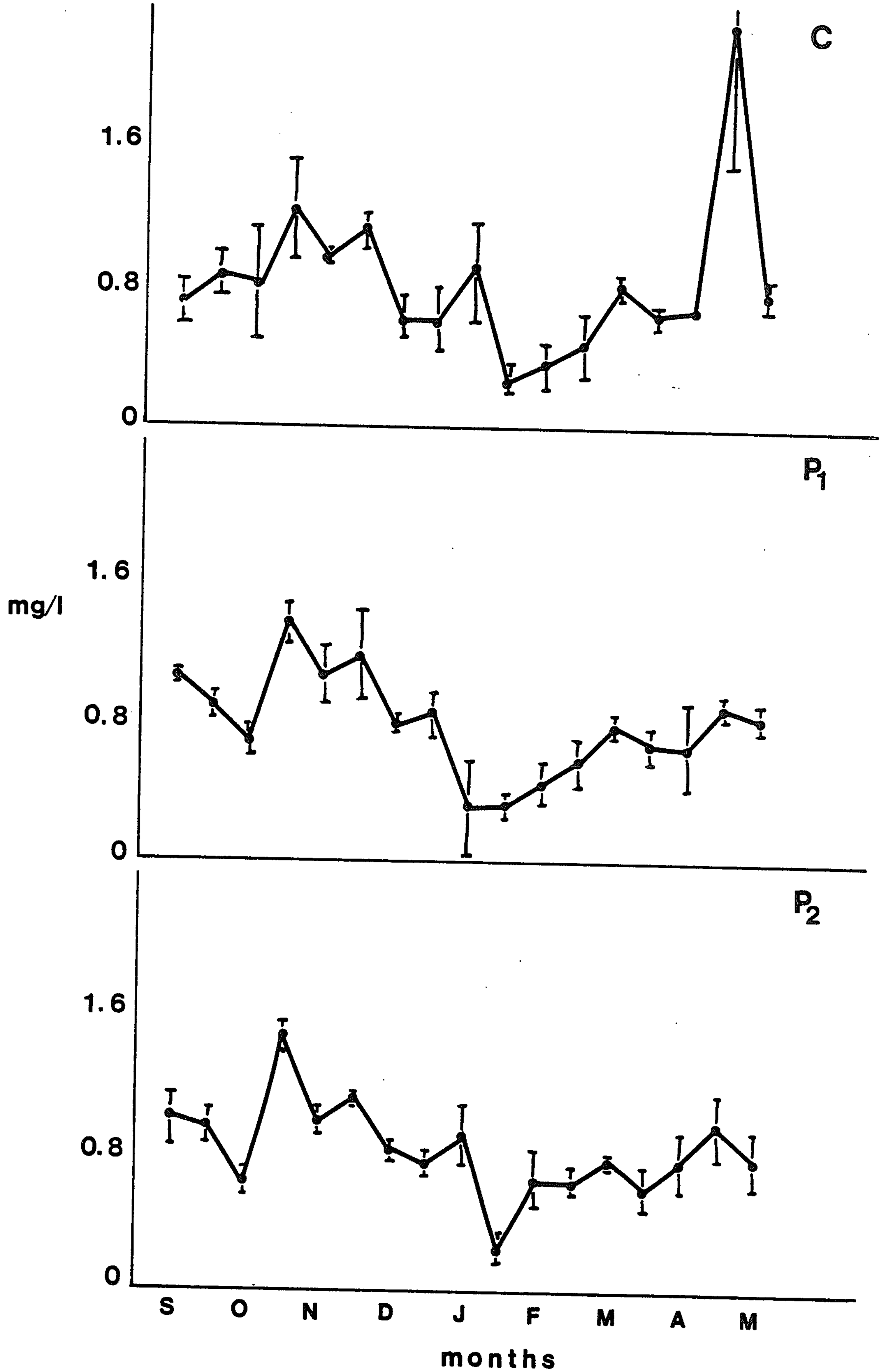


Figure 7c. Mean DON concentrations in (C) canal, (P_1) Pond 1, and (P_2) Pond 2. Bars indicate standard error.

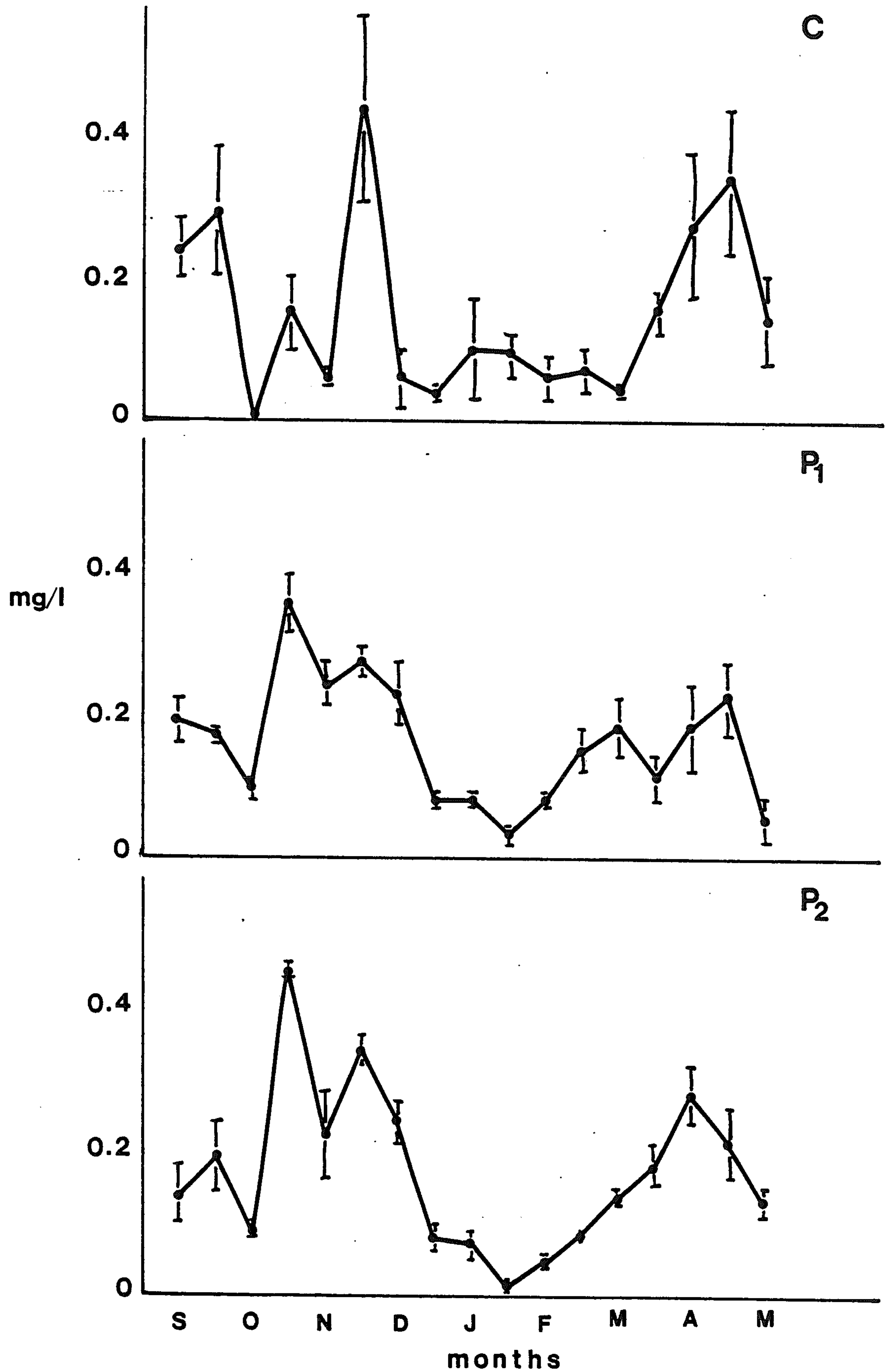


Figure 7d. Mean PO4 concentrations in (C) canal, (P_1) Pond 1, and (P_2) Pond 2. Bars indicate standard error.

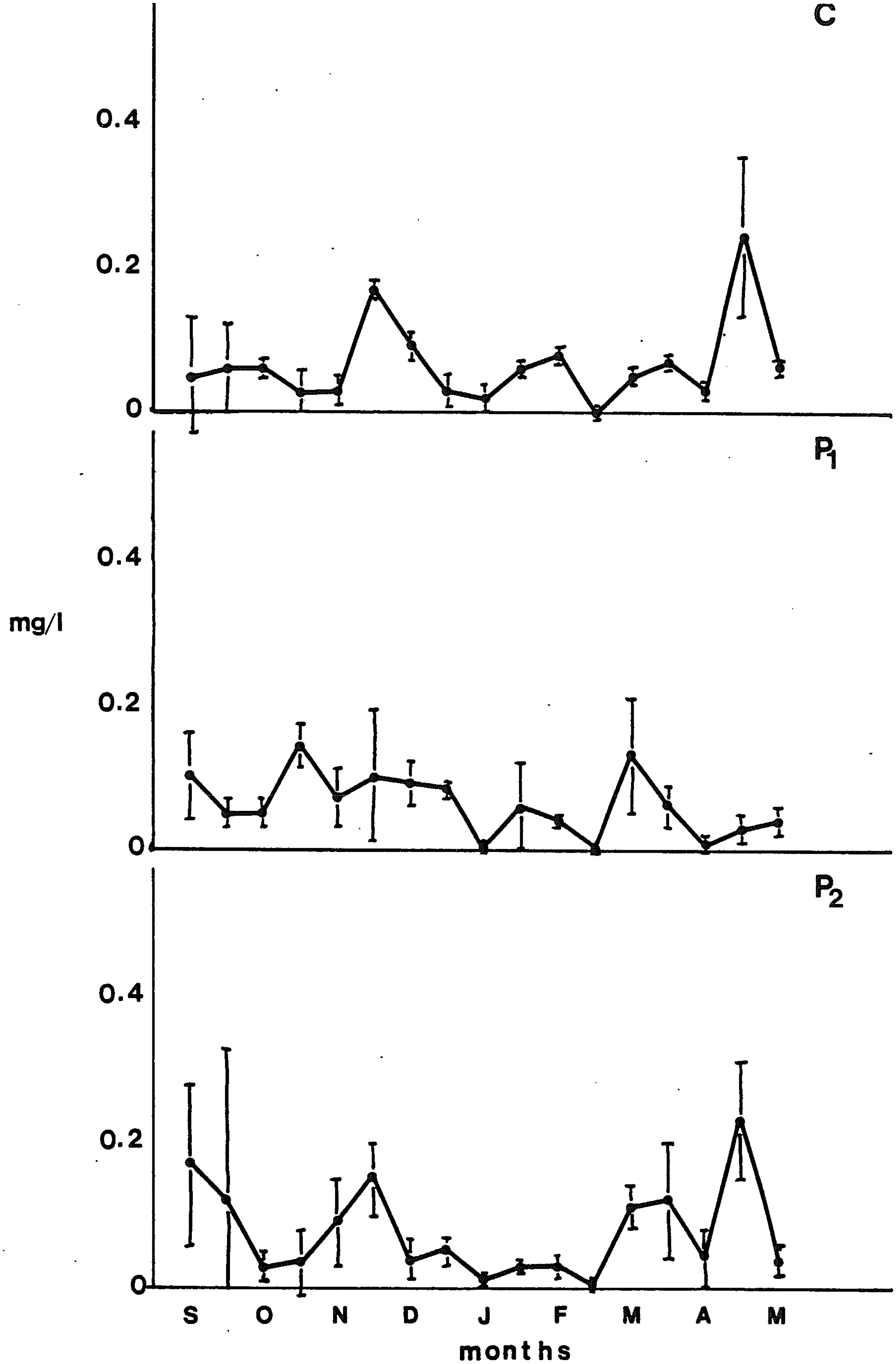


Figure 7e. Mean DOP (TP-PO4) concentration in (C) canal,)P_1) Pond 1, and (P_2) Pond 2. Bars indicate standard error.

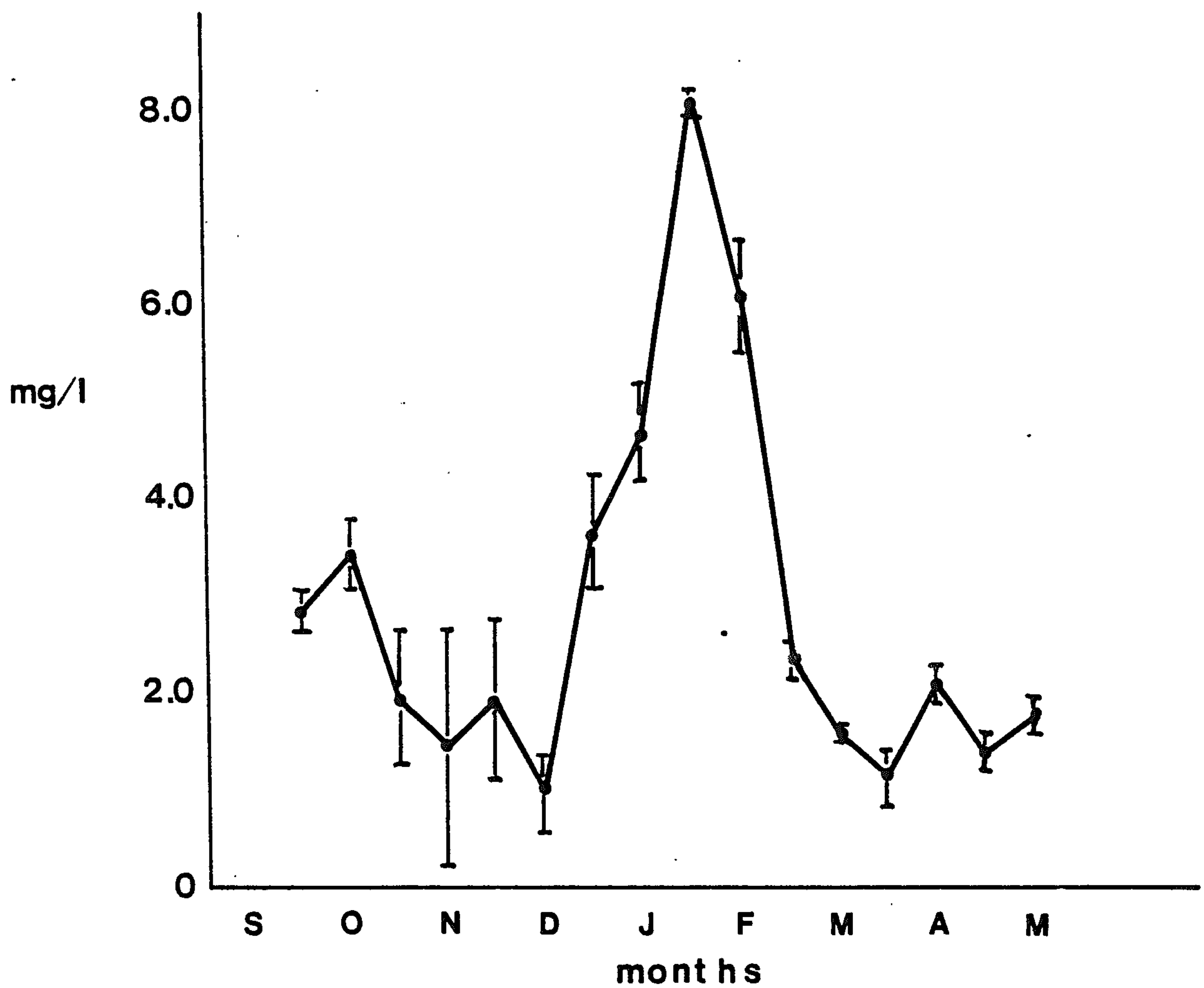


Figure 8. Mean DO, Ponds 1 and 2. Bars indicate standard error.

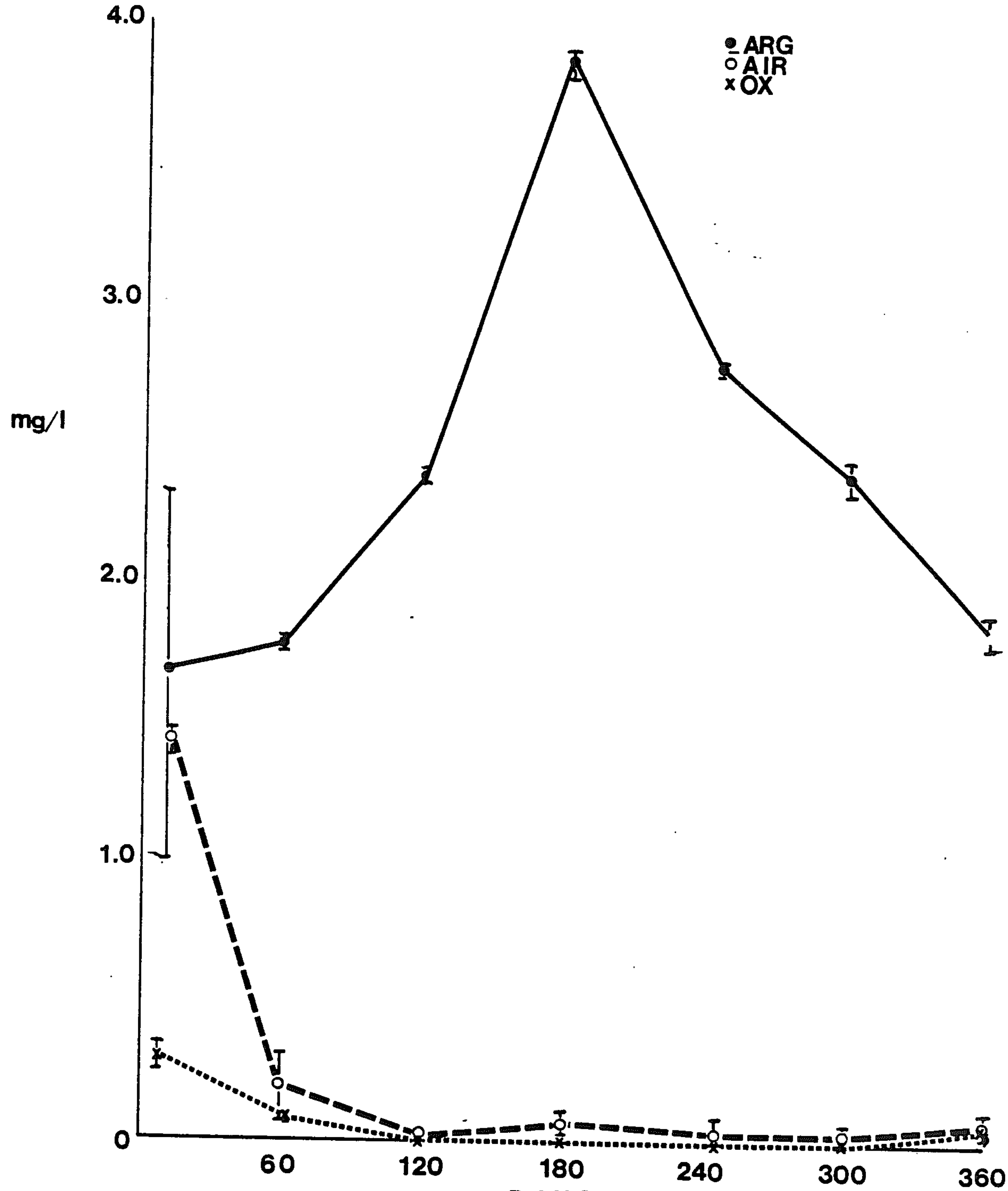


Figure 9a. Mean HN4 concentrations in NO LITTER microcosms.

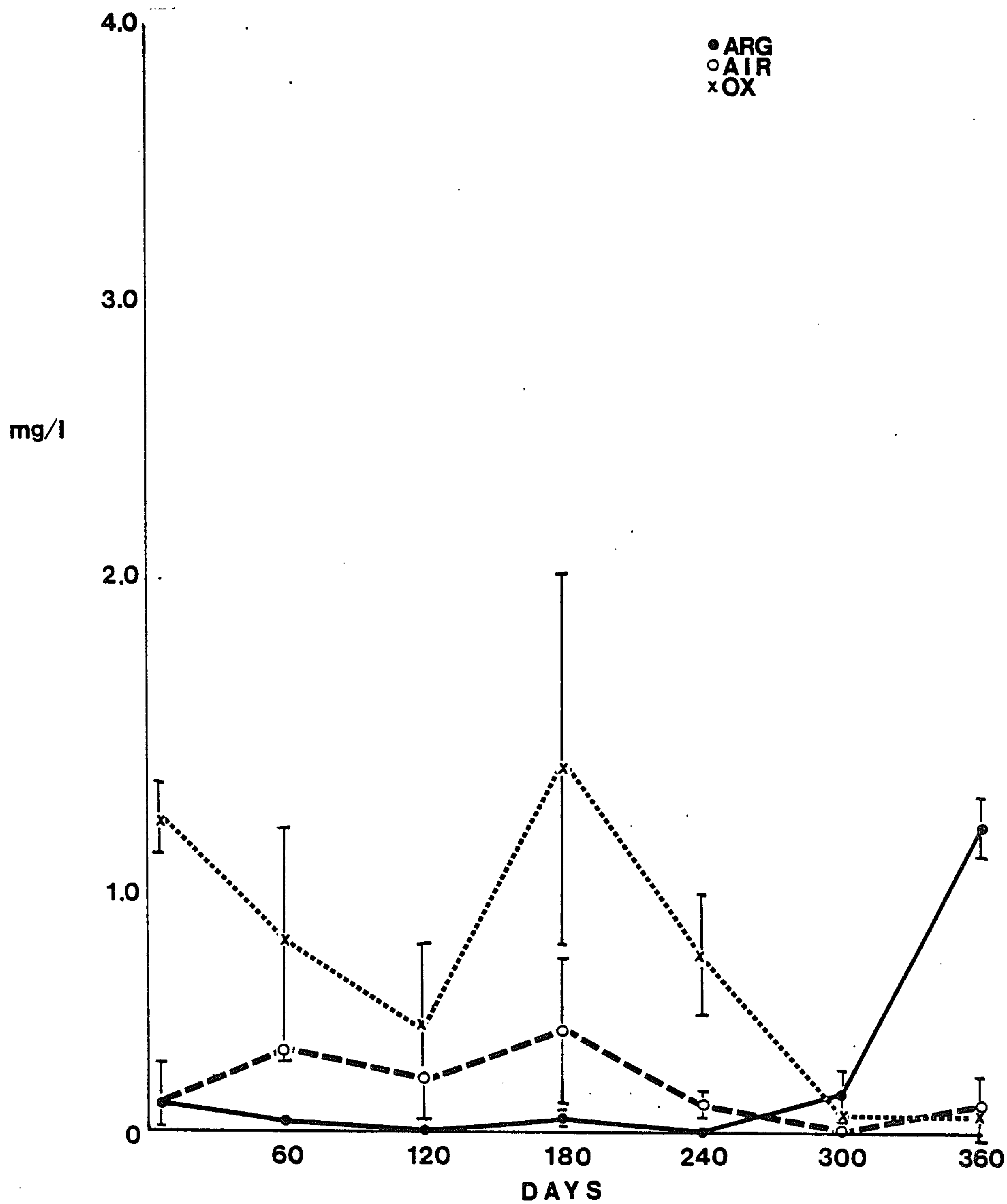


Figure 9b. Mean NO3 concentrations in NO LITTER microcosms.

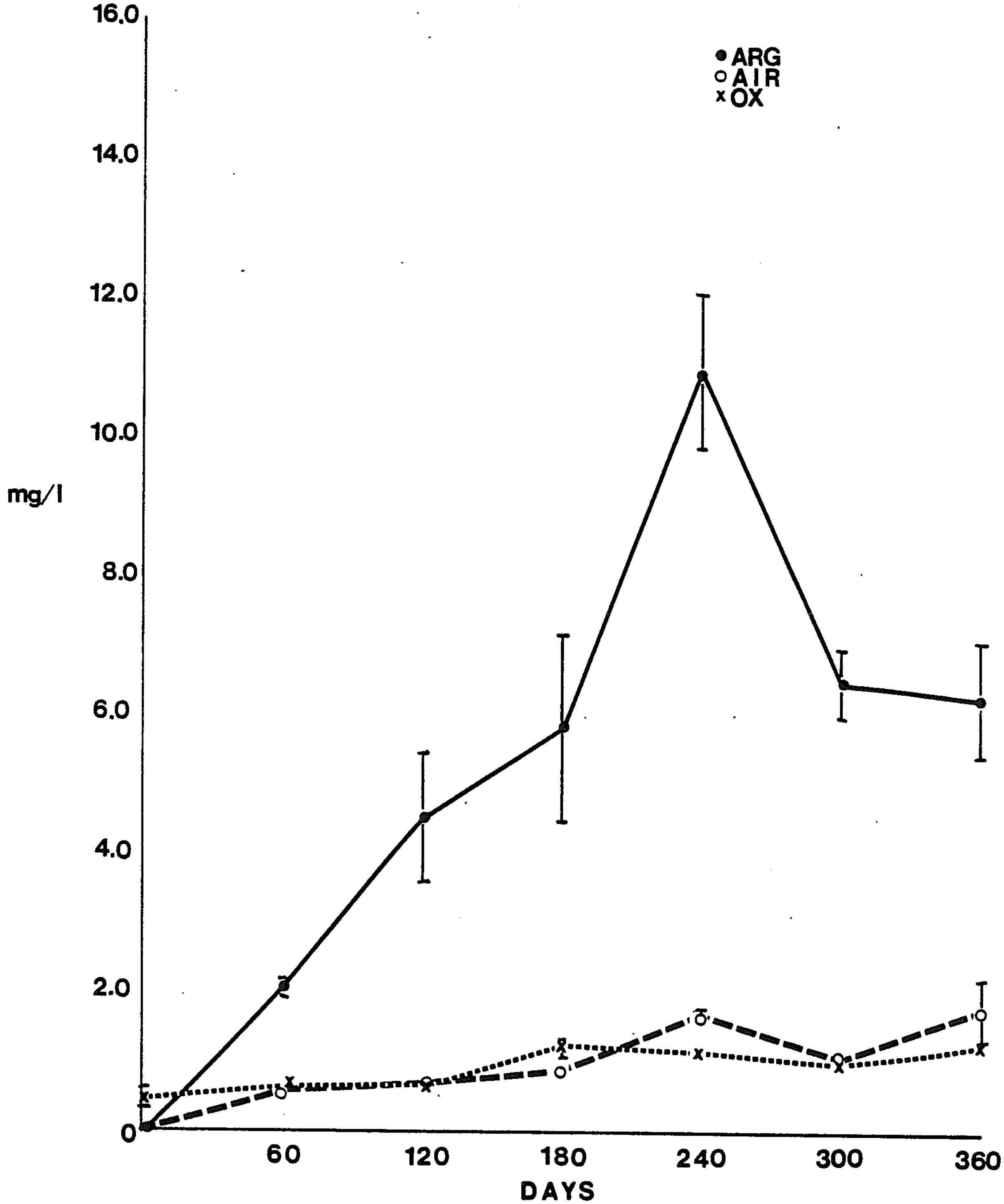


Figure 9c. Mean DON concentrations in NO LITTER microcosms.

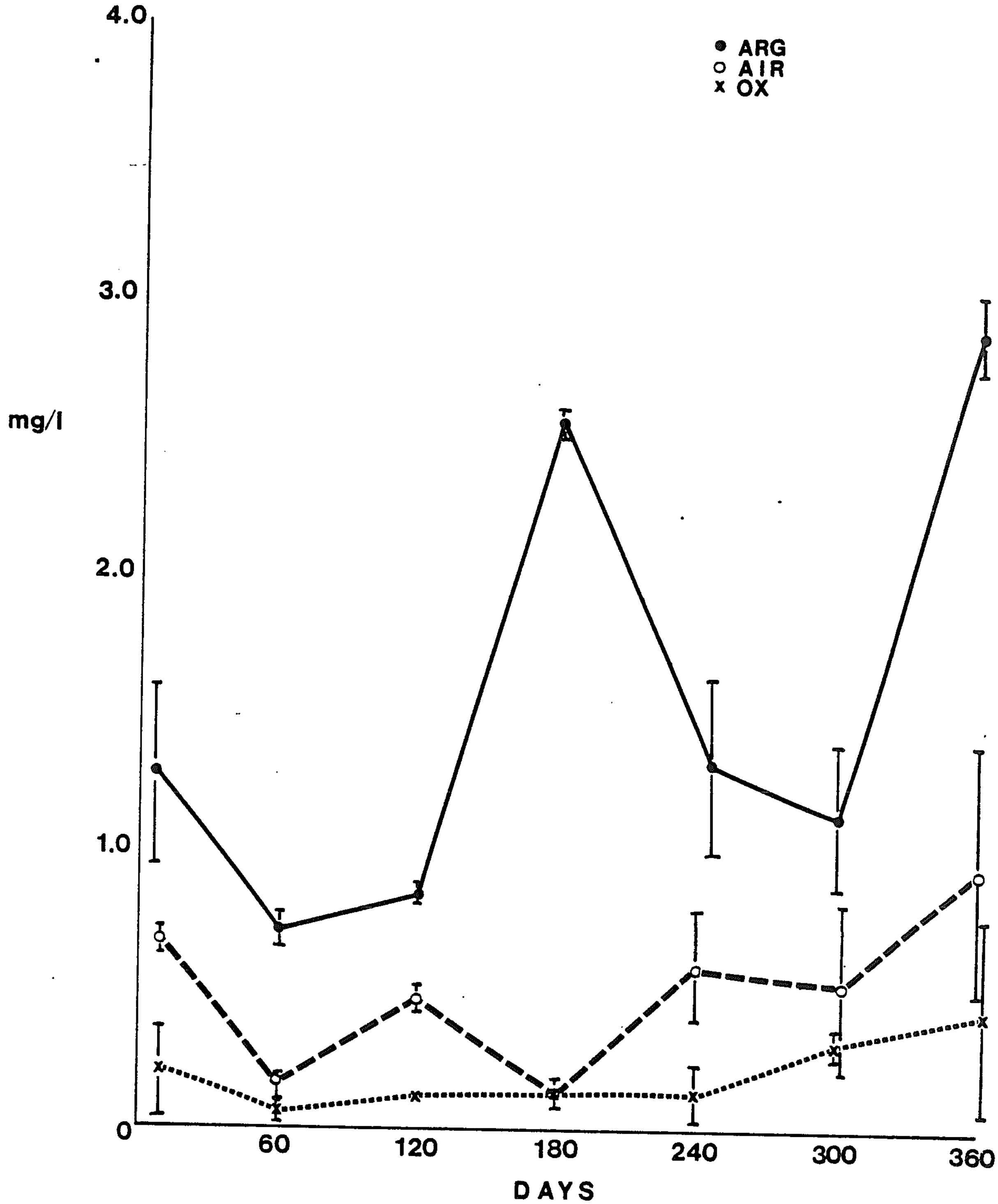


Figure 9d. Mean PO4 concentrations in NO LITTER microcosms.

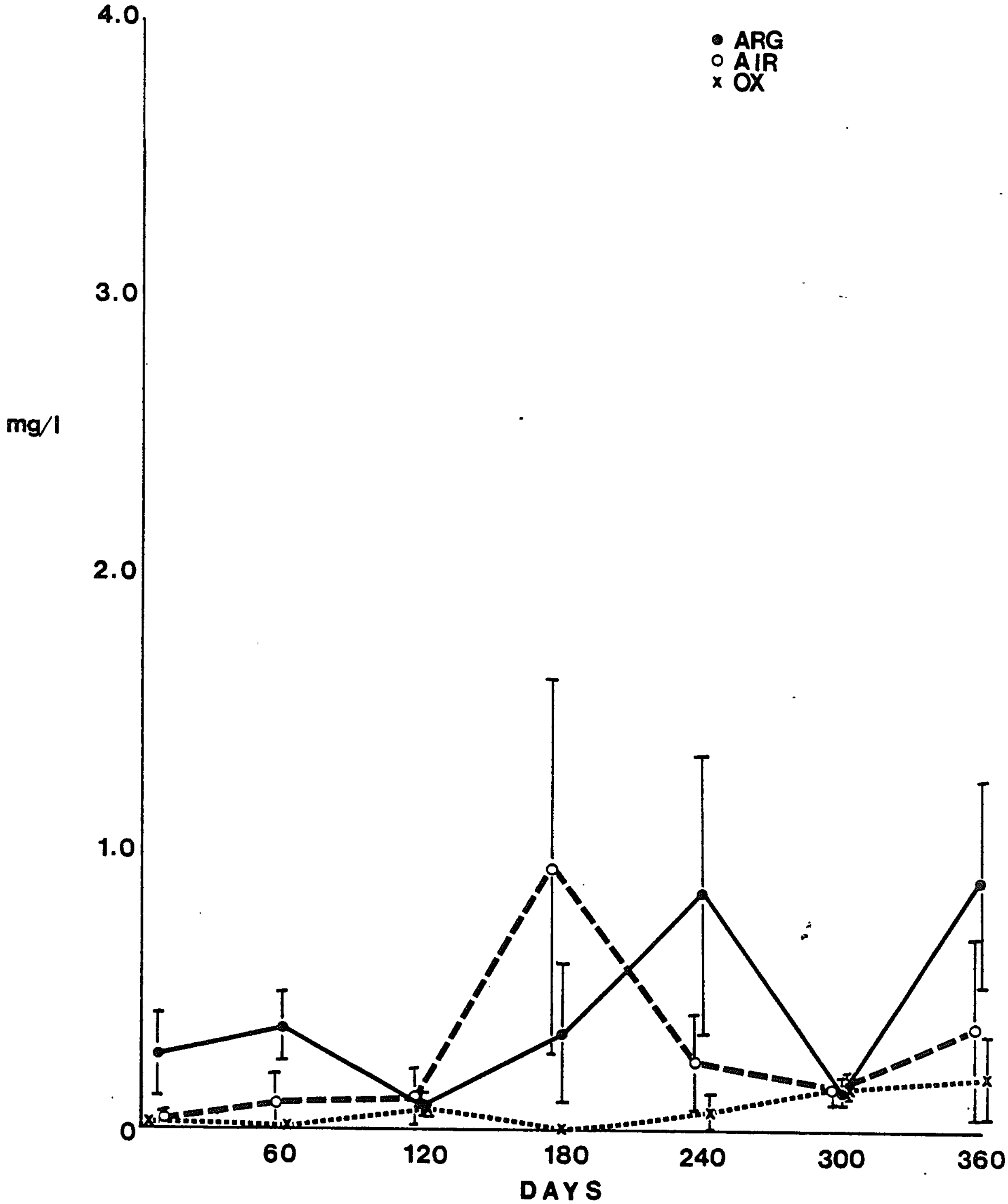


Figure 9e. Mean DOP (TP-PO4) concentrations in NO LITTER microcosms.

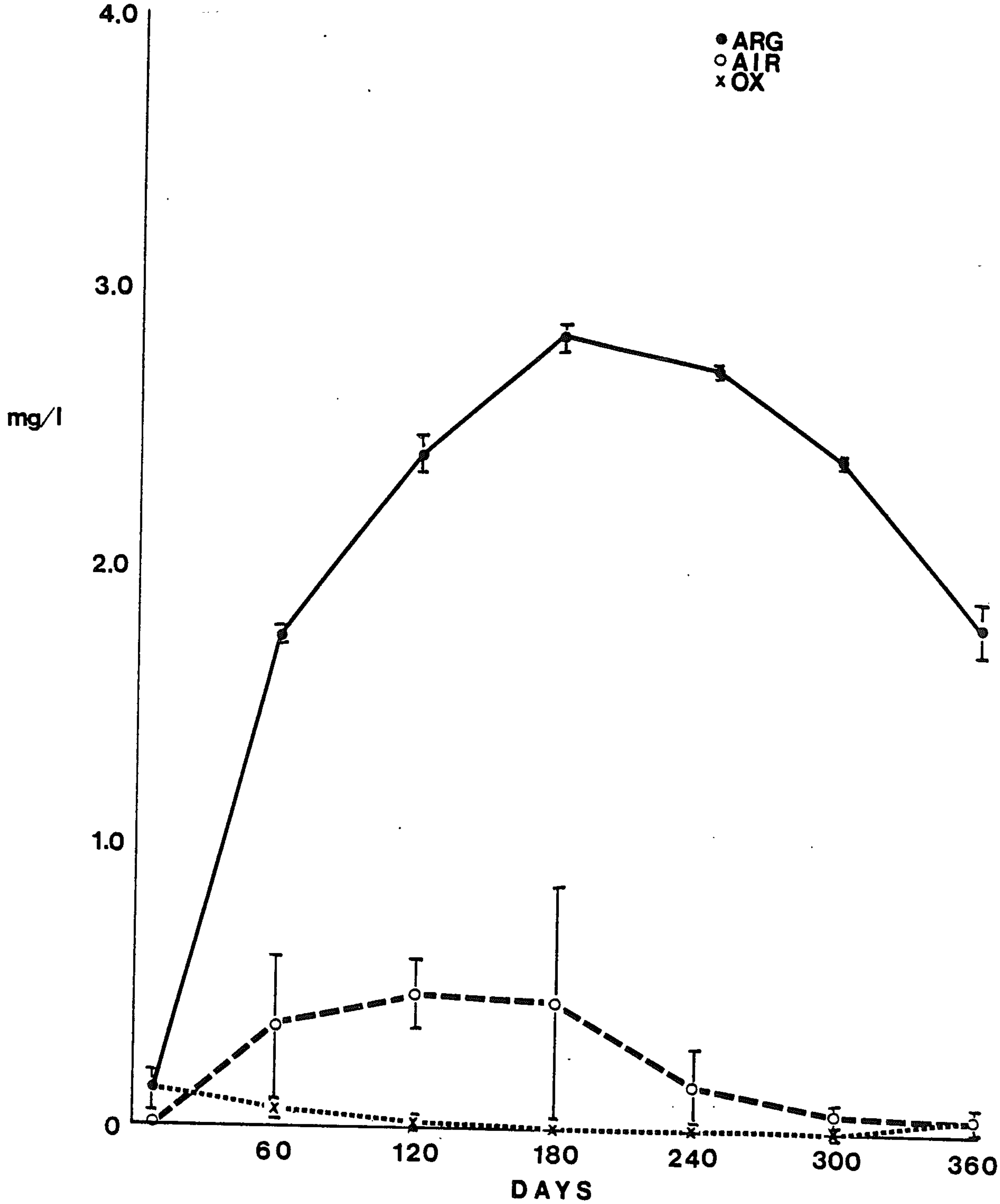


Figure 10a. Mean NH4 concentrations in microcosms with LITTER.

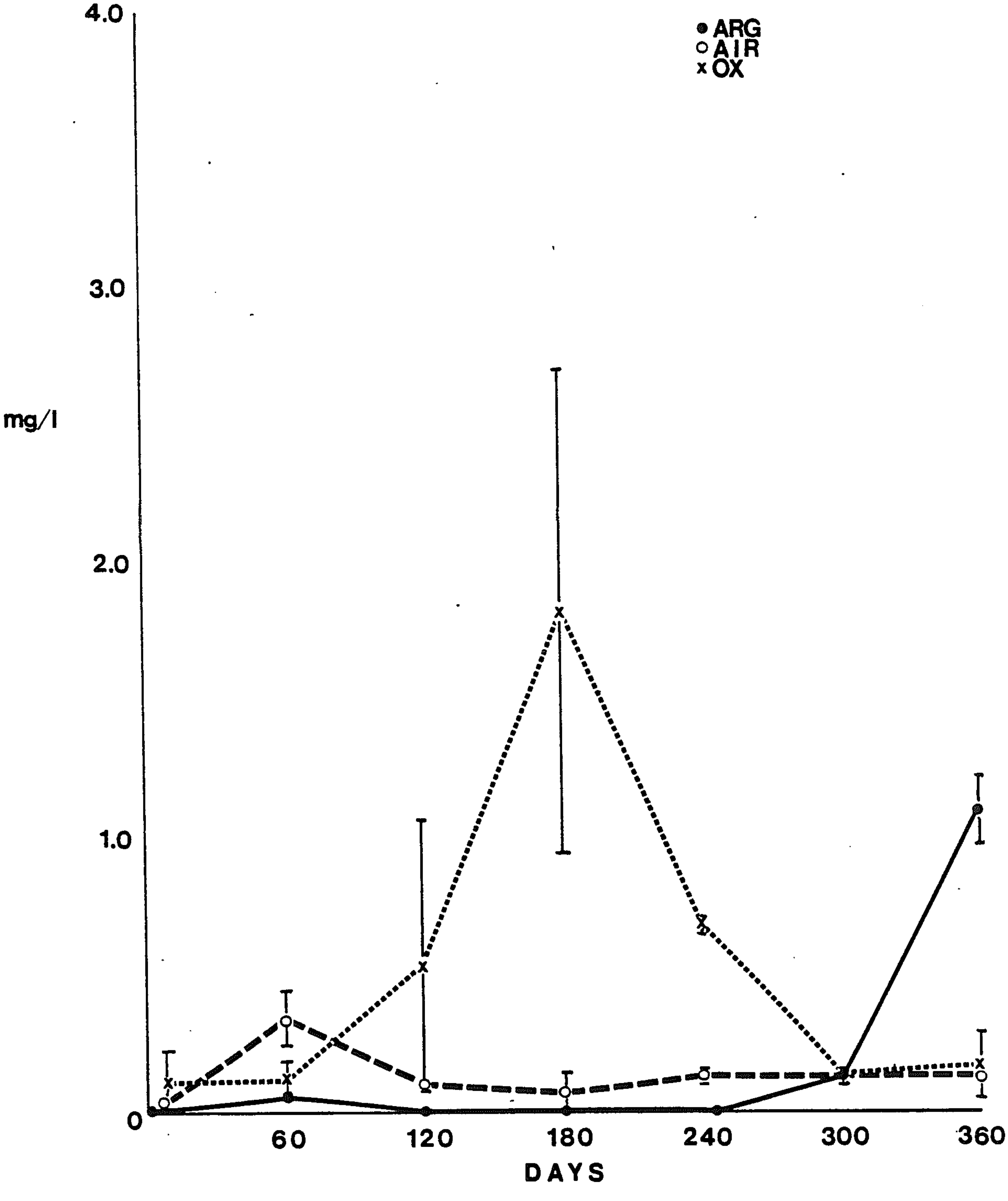


Figure 10b. Mean NO3 concentrations in microcosms with LITTER.

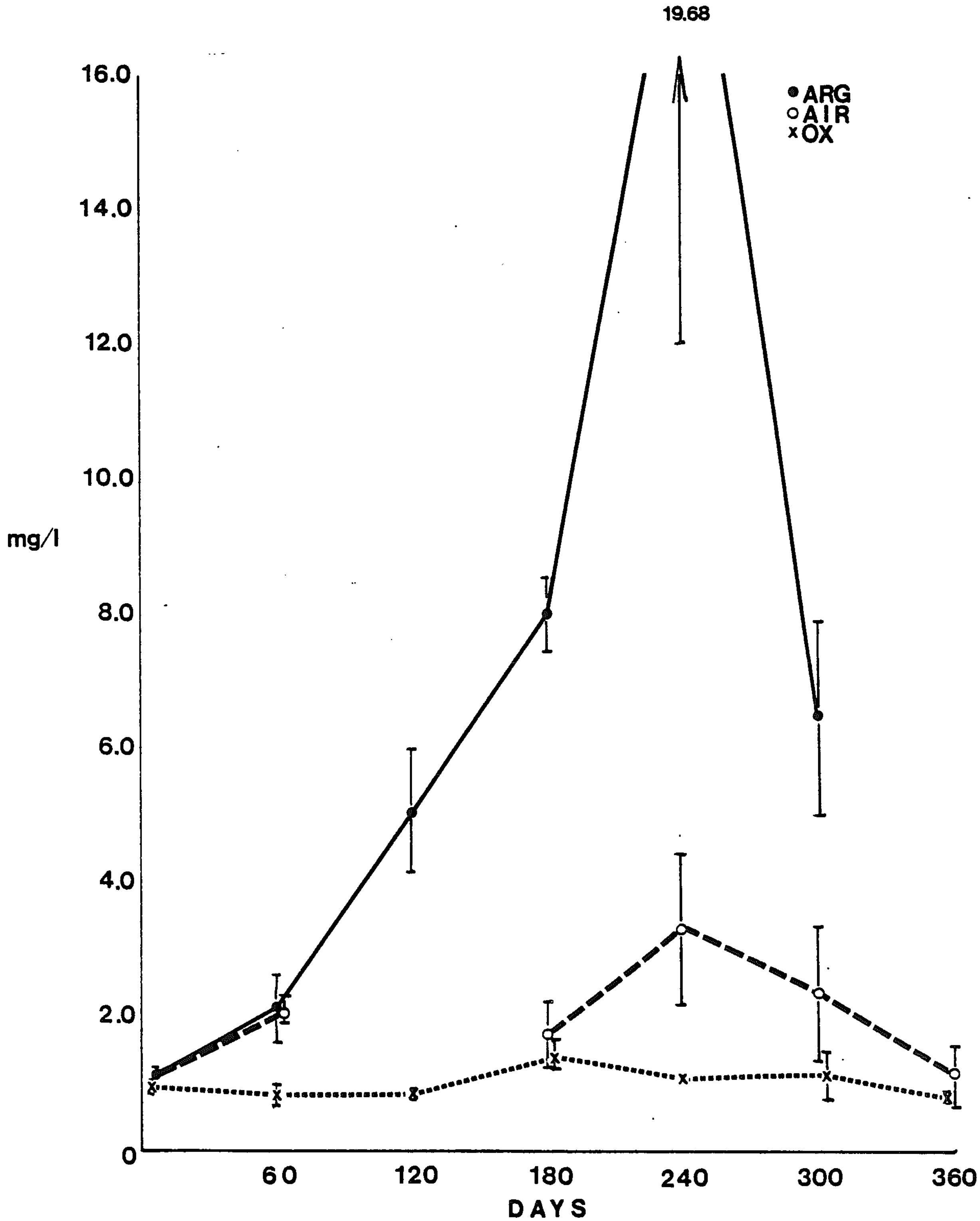


Figure 10c. Mean DON concentrations in microcosms with LITTER.

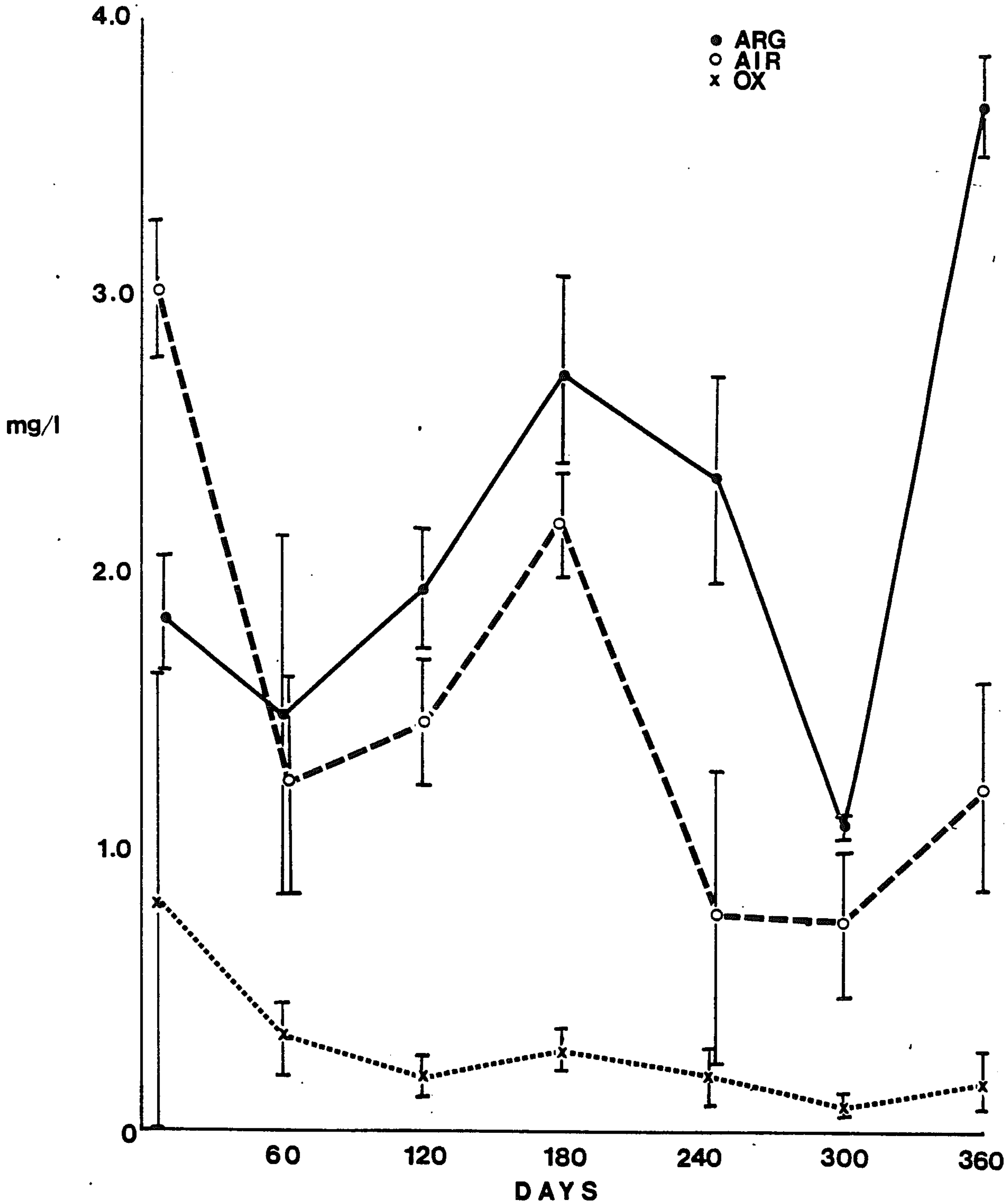


Figure 10d. Mean PO4 concentrations in microcosms with LITTER.

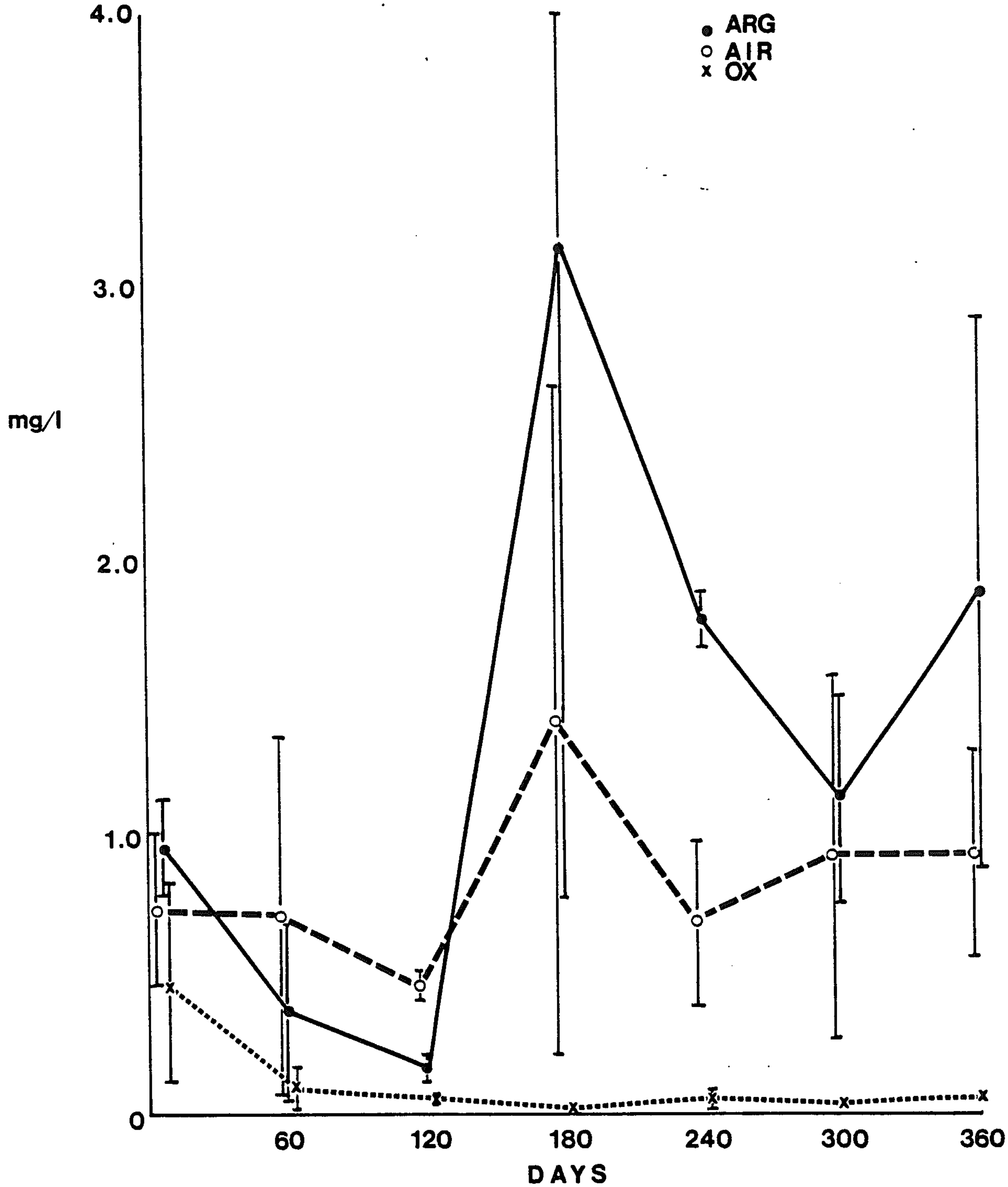


Figure 10e. Mean DOP (TP-PO4) concentrations in microcosms with LITTER.

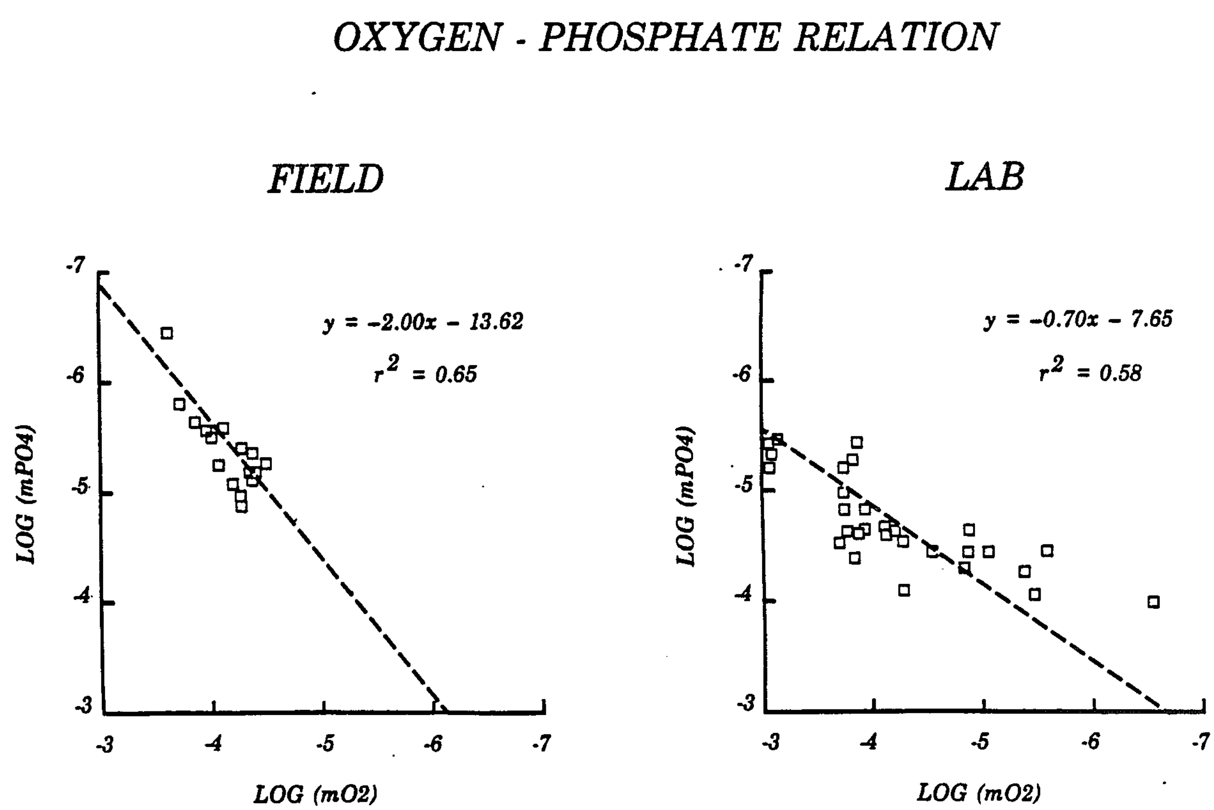
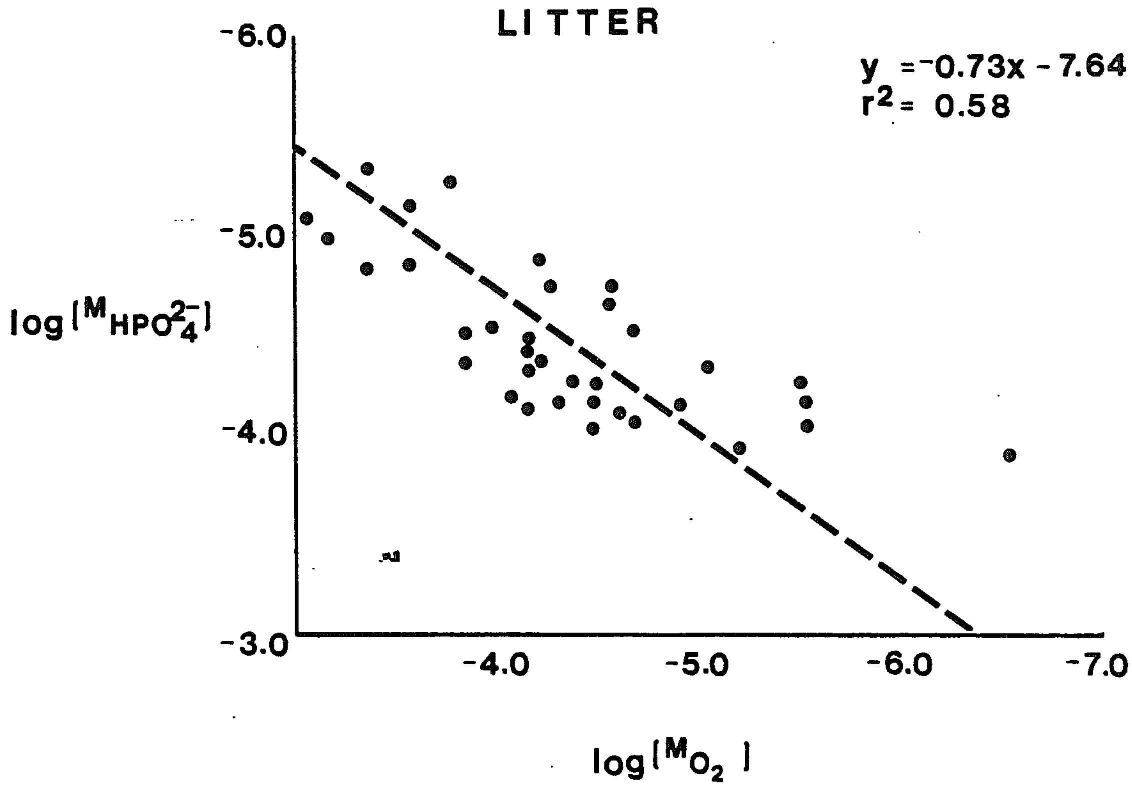


Figure 11. Comparison of PO4/DO relationships developed from field and laboratory microcosm data.



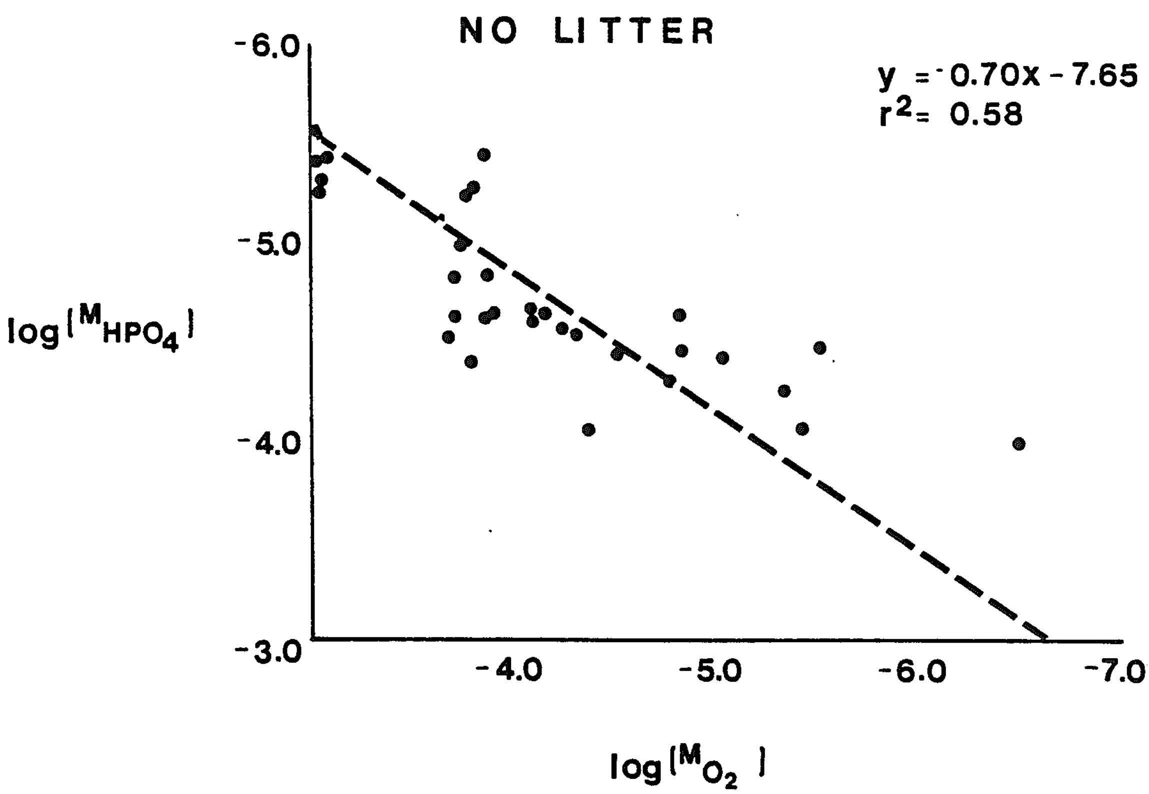


Figure 12. Comparison of PO4/DO relationships developed from LITTER and NO LITTER microcosm data.

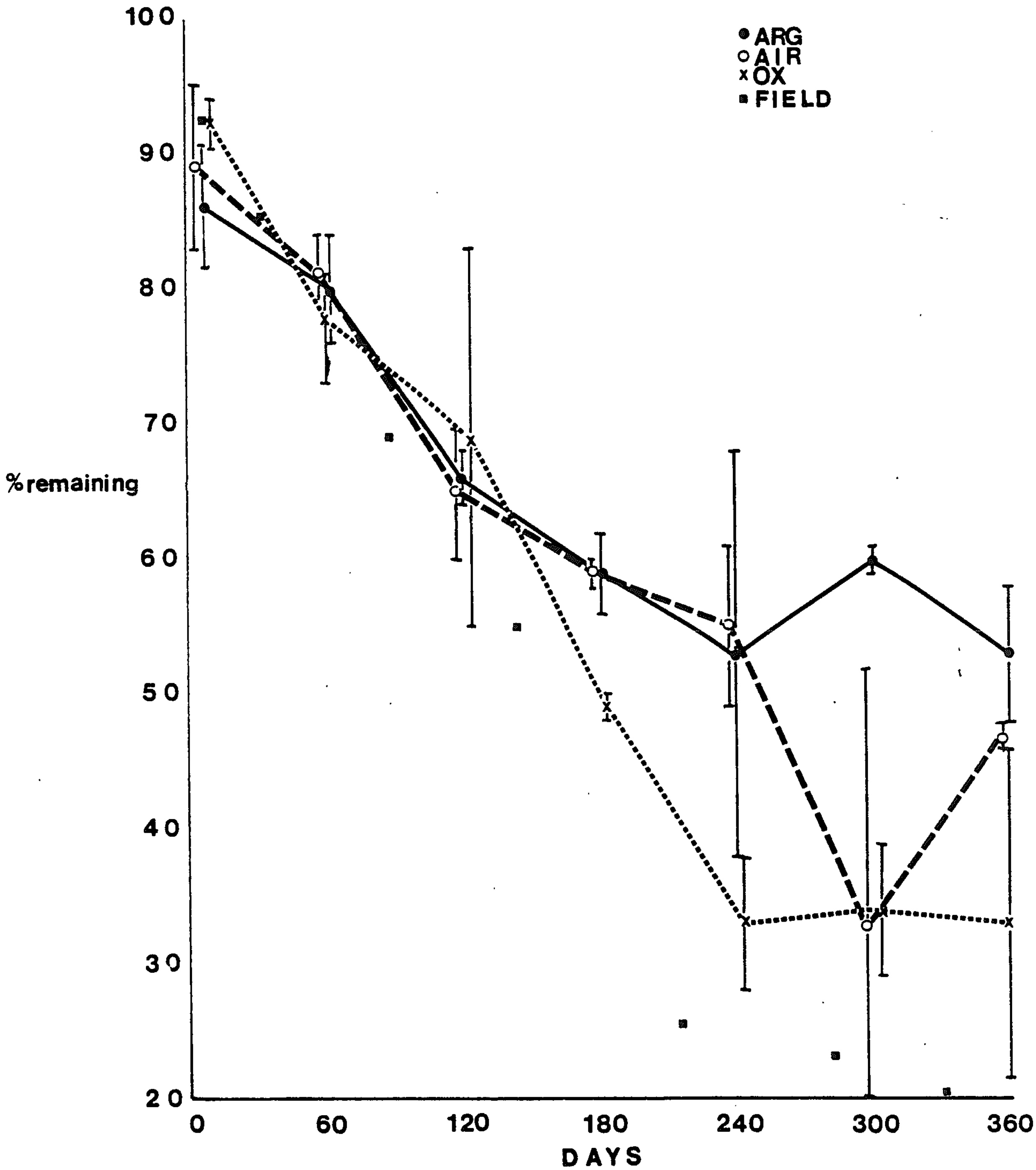


Figure 13. Effect of environment on rates of tupelo litter weight loss.

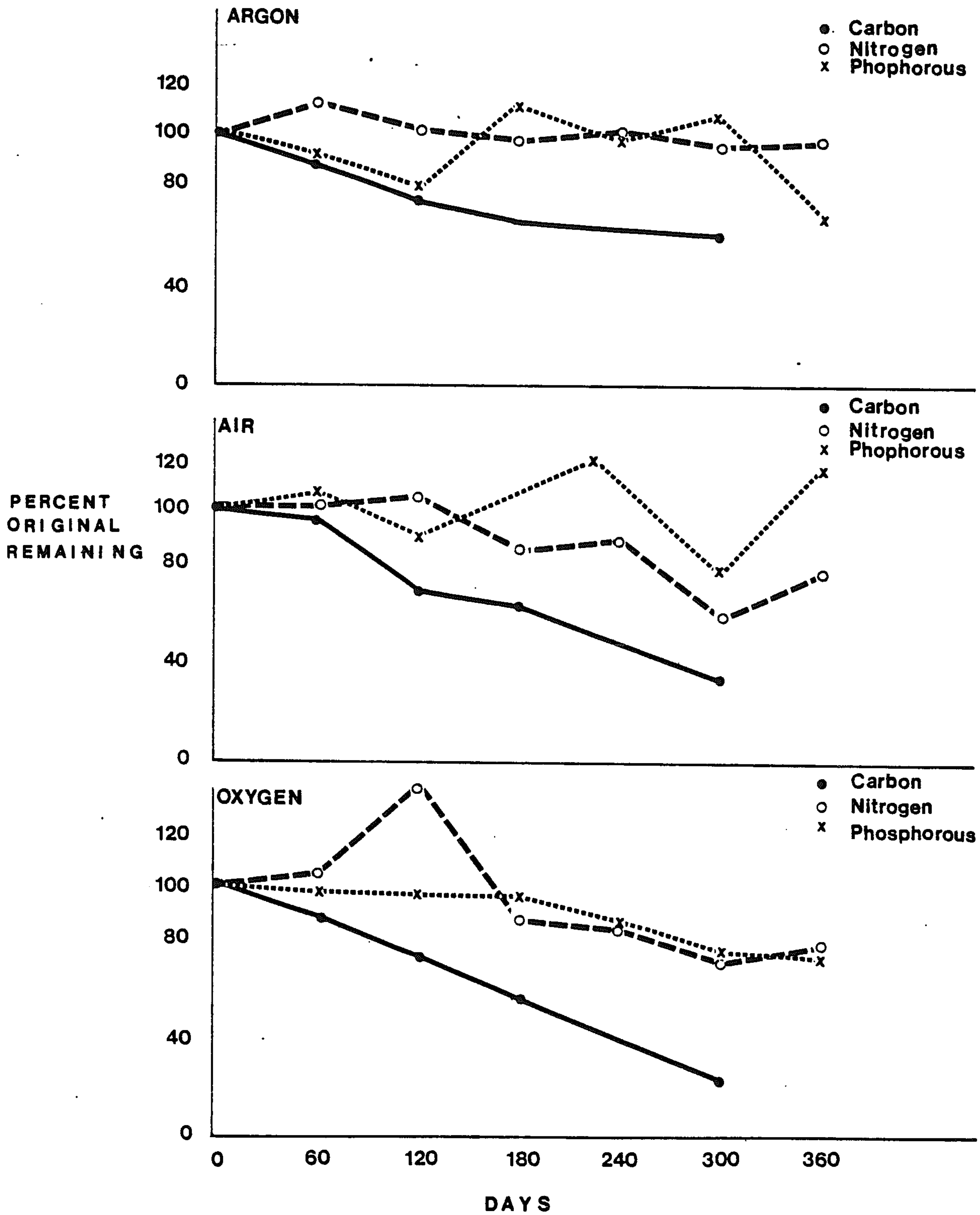


Figure 14. Rates of (C) carbon, (N) nitrogen, and (P) phosphorus loss in laboratory and field environments.

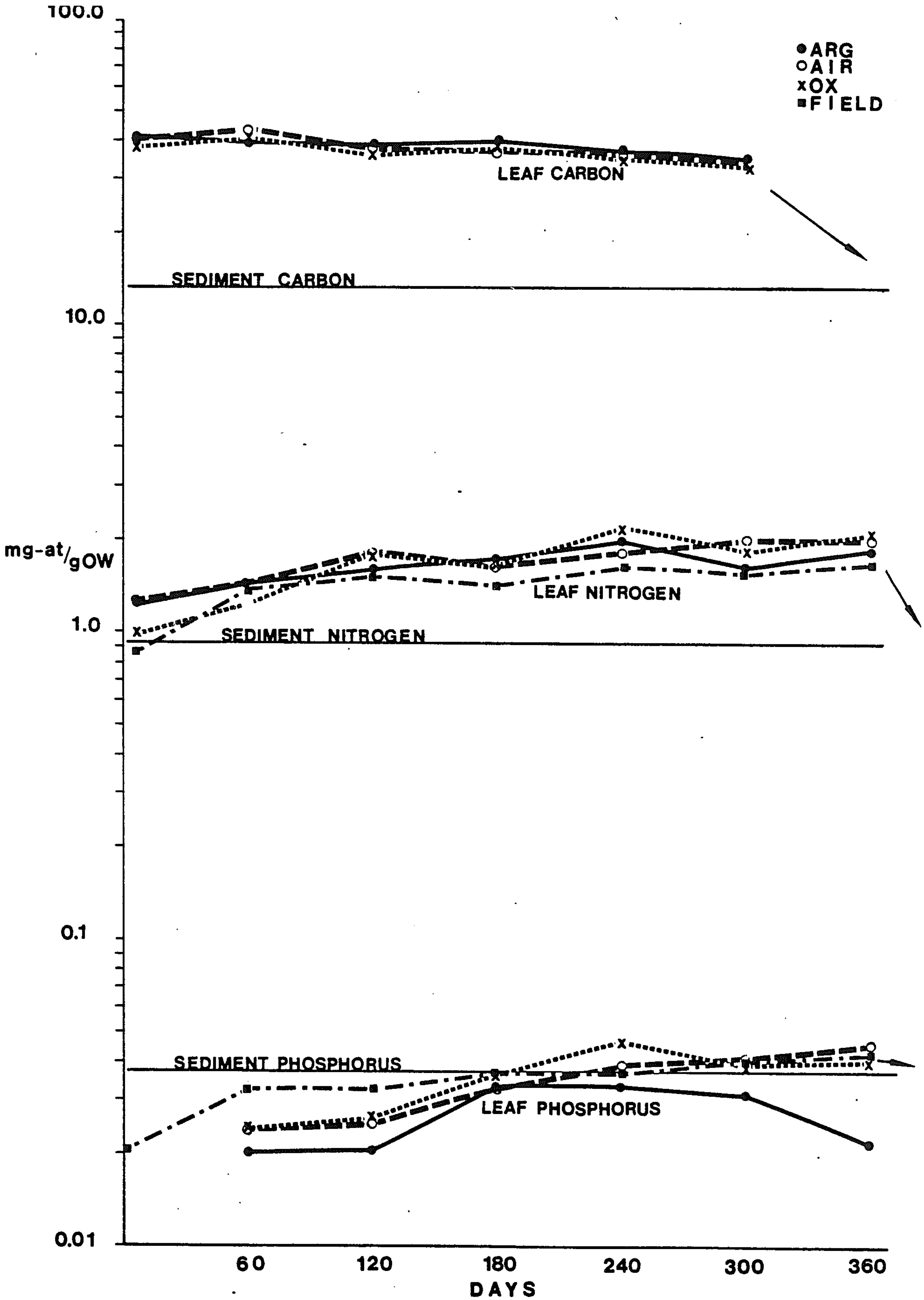


Figure 15. Carbon, nitrogen, and phosphorus concentrations of tupelo leaf litter undergoing decomposition. Camparison between litter concentrations and sediment values.

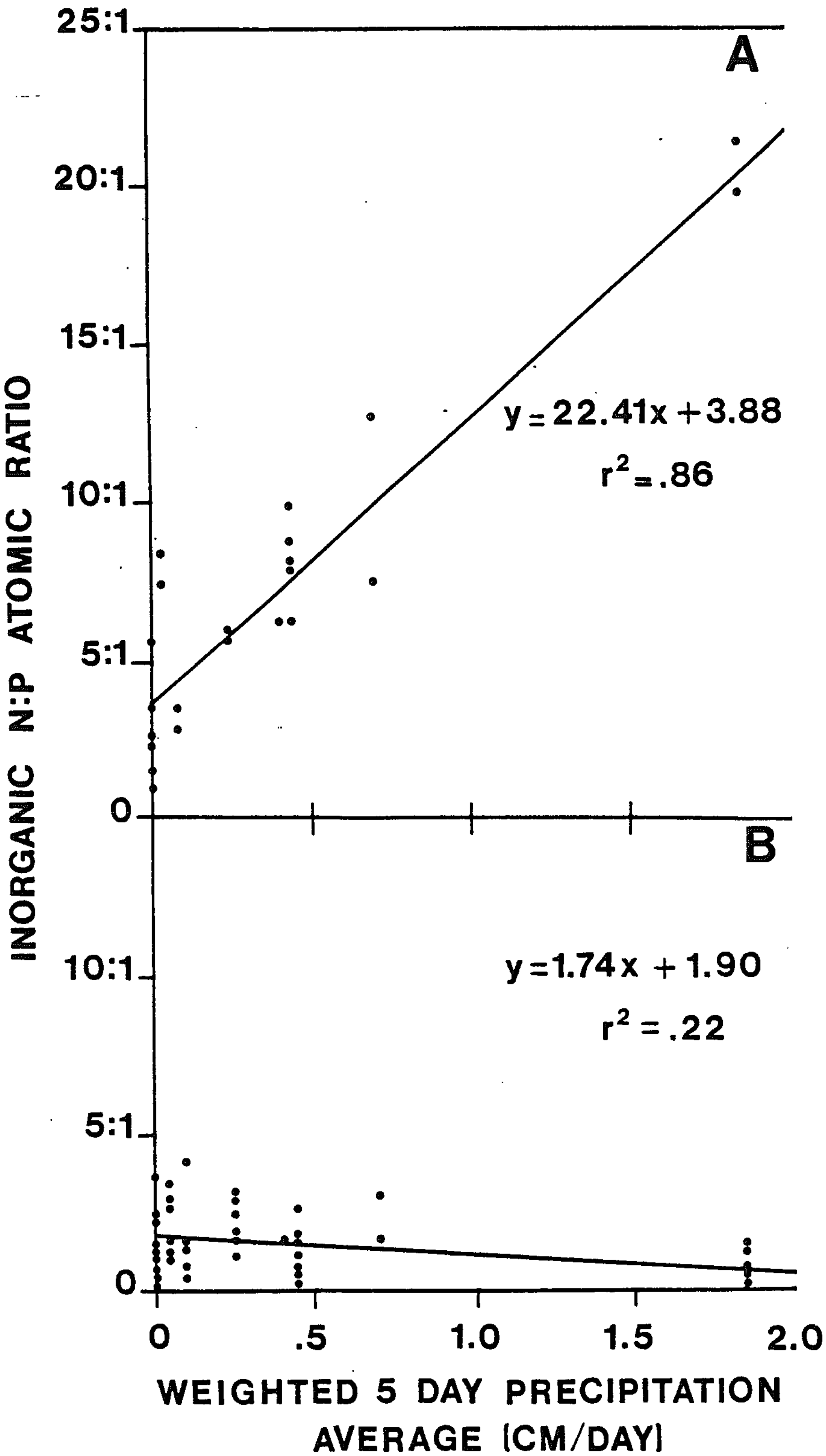


Figure 16. Relationship between TIN:PO4 ratio and recent precipitation/runoff. From Kemp (1978).

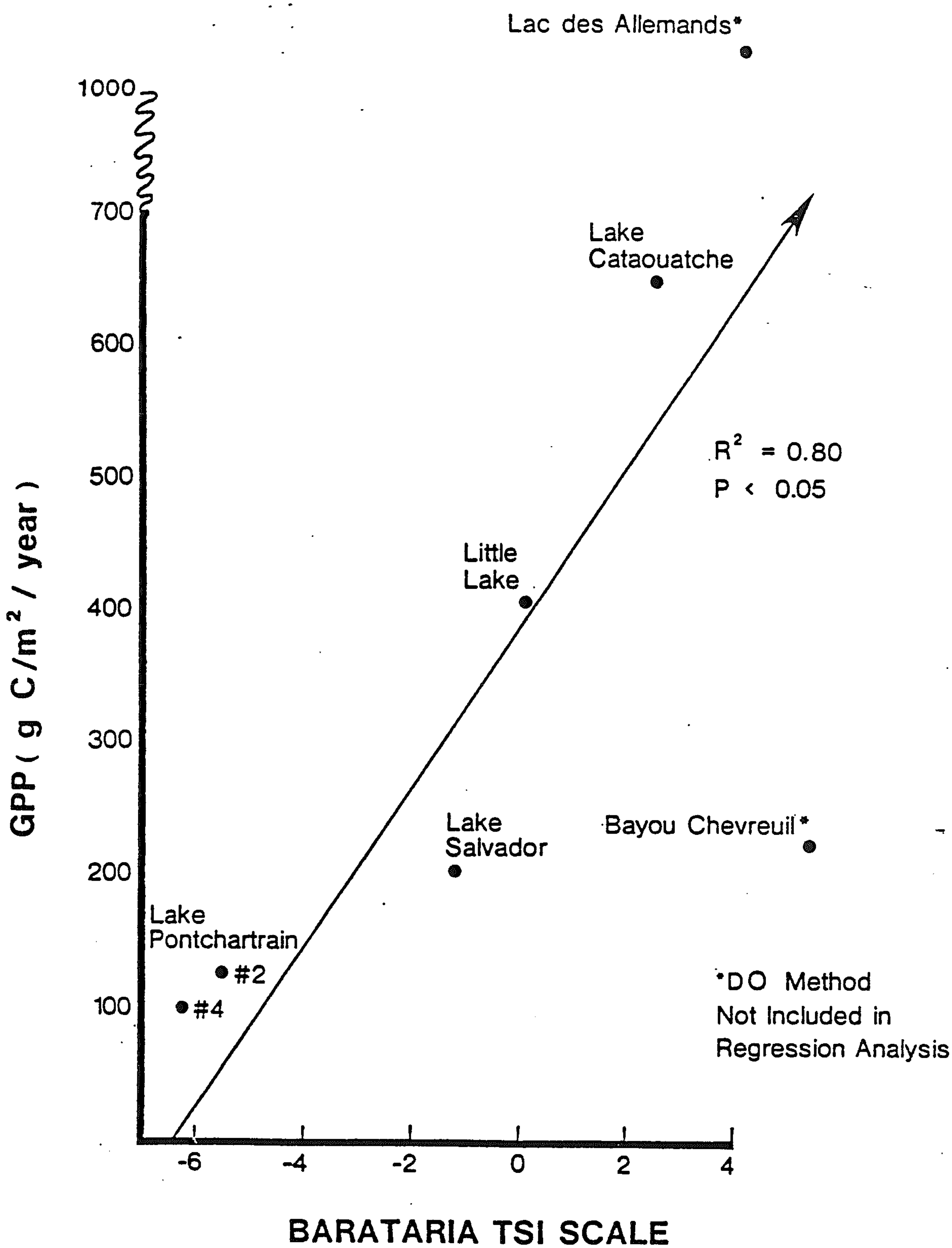


Figure 17. Relationship between aquatic primary production and trophic state in Barataria Basin. From Seaton (1979).

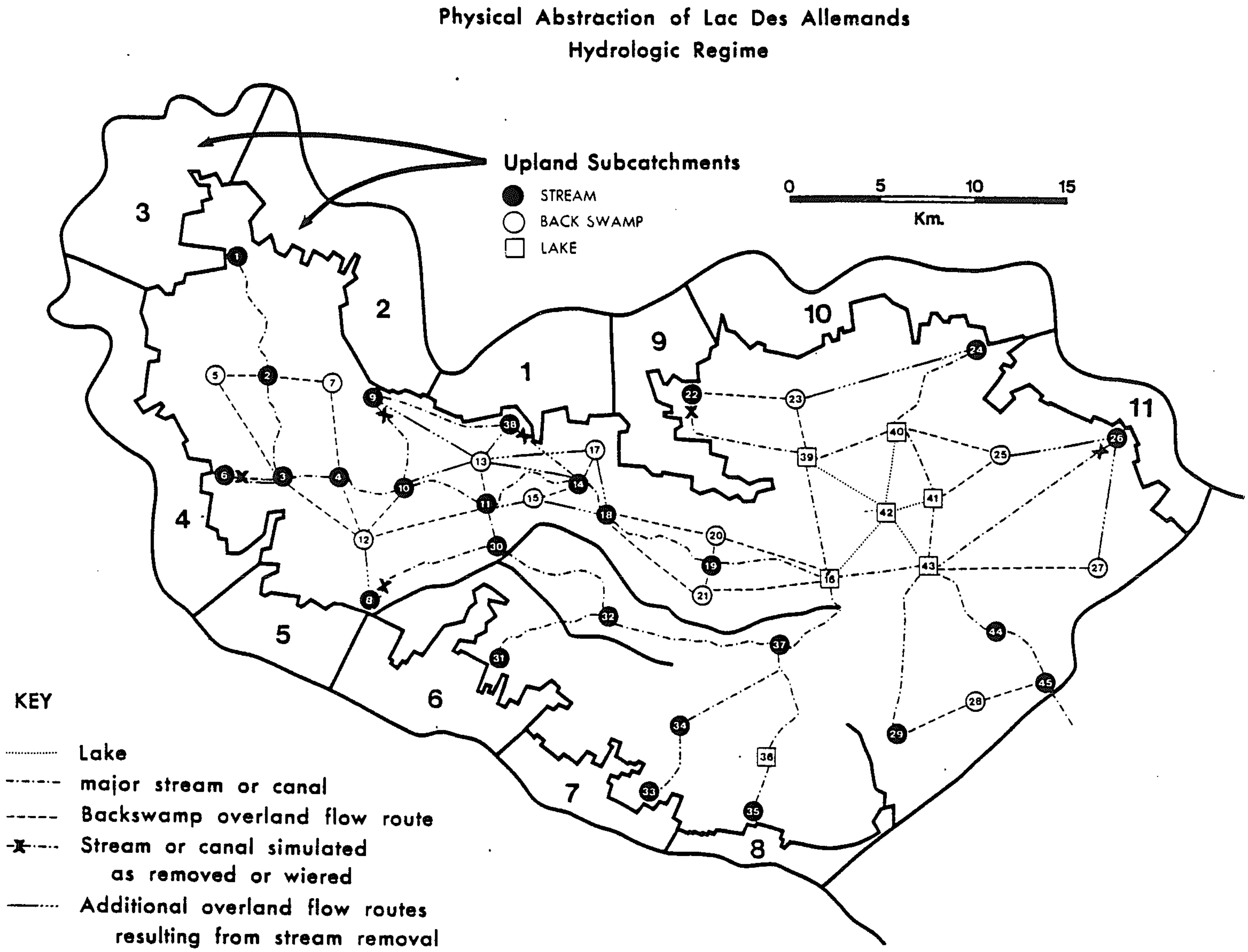


Figure 18. Sub-catchments of the Barataria Basin watershed. From Hopkinson and Day (1980b).