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PHOSPHORUS DYNAMICS IN PONDS [1]

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INTRODUCTION

Phosphorus is generally recognized as a key nutrient in the fertility of fish ponds. This nutrient frequently limits plant production and ultimately influences fish production. Conversely, too much phosphorus is sometimes responsible for excessive production of blue-green algae or other nuisance plant species in ponds. Since phosphorus is extremely important in pond management schemes, an understanding of its physicochemical and biological dynamics is valuable to fishery biologists. This report is a description of phosphorus relationships in ponds. The discussion is a general consideration of the phosphorus cycle rather than an exhaustive review. No attempt was made to summarize data on correaltions between phosphorus fertilization and fish production.

SOURCES OF PHOSPHORUS

When a pond is constructed, the newly inundated soil and vegetation is the only *in situ* supply of phosphorus. However, there are a number of possible inputs of phosphorus. The relative importance of each input will vary between ponds.

Watershed. Runoff from the watershed may contain considerable quantities of phosphorus. Fippin (1945) reported an average annual loss of 5.3 lb./acre of phosphorus from row crops in the Tennessee River Valley. Drainage from Illinois farm land (Englebrecht and Morgan,

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1961) removed from 0 to 13.9 lbs. of phosphorus per acre annually (av = 0.33). Mackenthun and Ingram (1964) and Mackenthun (1965) summarized a number of studies on the phosphorus content of runoff. Values vary with soil type, amount of watershed in cultivation, type of vegetation, amount of fertilization, and degree of slope. Some phosphorus in runoff is dissolved phosphate, while considerable quantities are associated with eroding soil particles. Most of the particulate phosphorus will accrue as sediment. Stream inflow is a major source of phosphorus in some ponds.

Atmospheric. Precipitation contains from a trace to as much as 0.50 ppm phosphorus, but most samples have less than 0.1 ppm. The annual input of phosphorus in rainfall at five sites in Britain ranged from 0.12 to 0.40 lb./acre (Allen et al., 1968). Gore (1968) reviewed data that ranged from 0.04 lb./acre annually in Sweden (Tamm, 1958) to 1.04 lb./acre in Nigeria (Jones, 1960). Gore obtained a 6-year average of 0.34 lb./acre for a station in Britain. Values for individual years ranged from 0.11 to 0.75 lb./acre. Polisini, Boyd and Didgeon (1970) reported 0.12 lb./acre/year of phosphorus in rainfall at Aiken, South Carolina.

Dry fall out (dust particles, etc.) contains significant amounts of many nutrients (Gorham, 1961). Presumably dry fall out is also a source of phosphorus.

Plant materials. Many ponds are partially or completely surrounded by trees and shrubs. Leaf fall directly into ponds is often a significant contribution of phosphorus. Polisini et al., (1970) reported that 0.13 lb. of phosphorus entered a 3.25-acre pond in leaf fall. Considerable amounts of leaves and other plant debris are washed or blown into many ponds. Pollen is possibly another important input of phosphorus.

Animal sources. Ponds are breeding areas of many species of amphibians and reptiles. Although most of these animals depart upon cessation of breeding, some may die or be eaten by fish while in the pond. Furthermore, large quantities of eggs are deposited. Gibbons (personal communications) found that the annual breeding migration of toads and frogs into a 3.25-acre South Carolina pond numbered in the thousands of individuals. Droppings from waterfowl are major sources of phosphorus in some situations (Mackenthun, 1965).

Fertilization. Additions of phosphorus containing fertilizers to ponds often overshadow natural phosphorus inputs. Fertilizer phosphates are inorganic (orthophosphate) and readily available to plants. Many of the natural sources represent organic phosphorus. The availability of organic phosphorus and the rate of conversion to inorganic phosphate is not known. Considerable amounts of organic phosphorus is added to some ponds in fish feeds.

PHOSPHORUS DYNAMICS

Forms of phosphorus in the water. Orthophosphate is the form most frequently measured. Concentrations of orthophosphate are usually low (0.001-0.05 ppm as phosphorus) and represent only a fraction of the total phosphorus content. Rigler (1964) found that dissolved orthophosphate comprised from 4.8 to 7.8% of the total phosphorus in nine lakes. Larger quantities of soluble organic phosphorus (12.5-31.7% of the total phosphorus) were present. Most of the phosphorus was contained in seston. A similar situation is expected to exist in ponds. Orthophosphate is readily available to plants. The availability of soluble organic phosphorus is not known.

Disappearance of phosphorus from water. When phosphate is added to a pond, it rapidly disappears from the water. Concentrations present immediately after fertilization usually decline by 90% or more within a few days (Nisbit, 1951; Zeller, 1952; Hepher, 1958). Although some of the decrease is a result of phosphate uptake by phytoplankton, macrophytes, and bacteria (Rigler, 1956, 1964; Hayes and Phillips, 1958), most of the phosphate decline is usually the result of adsorption of phosphate by sediment. Obviously, in ponds containing very dense plant populations large amounts of phosphorus will be removed by

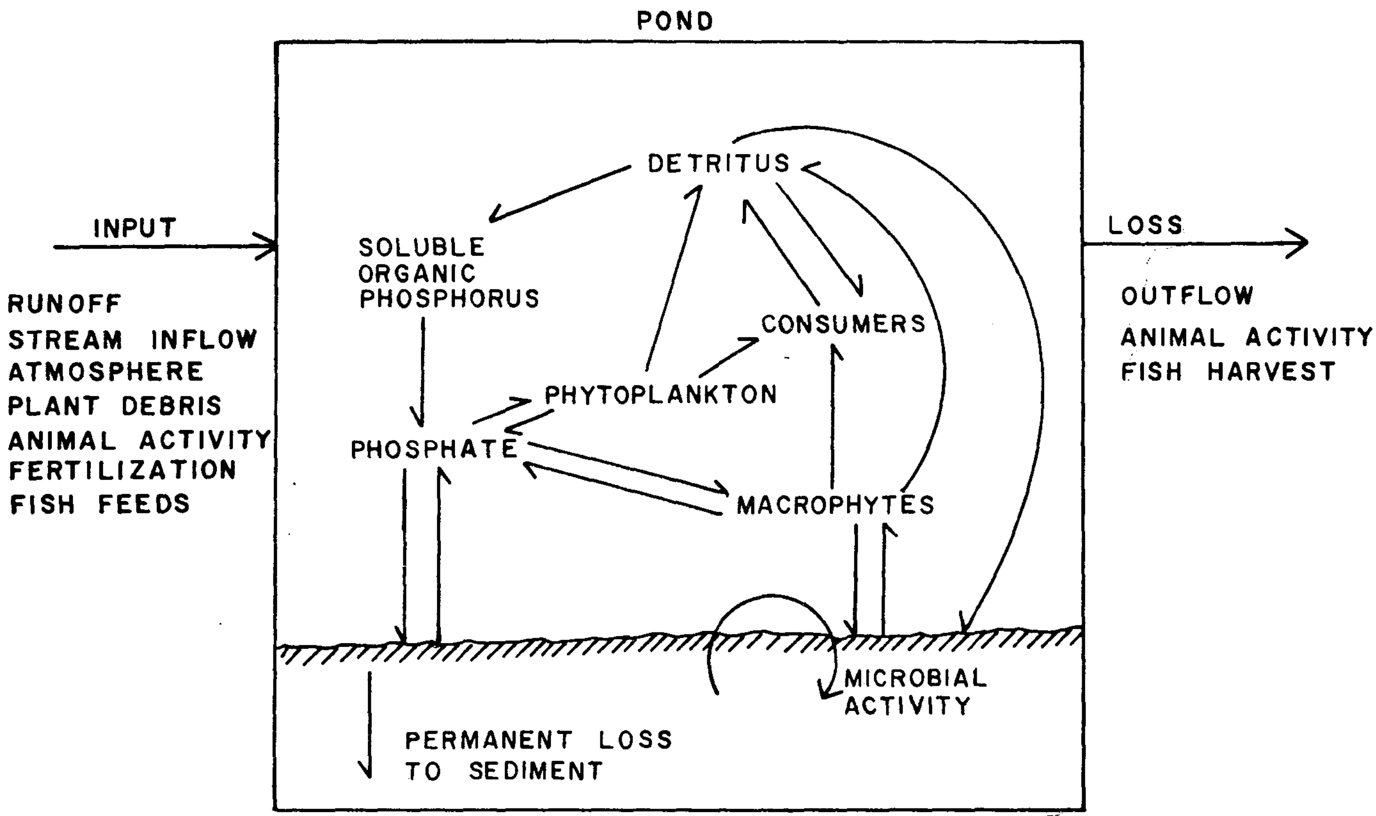

FIG. 1. A qualitative model of the phosphorus cycle in a fish pond.

plants. Fitzgerald (1970a) showed that 0.4 g dry mud could absorb about 0.05 mg phosphorus in less than 30 minutes. Roughly 90% of the phosphate added to undisturbed mud-water systems was adsorbed by the mud within 4 days (Kimmel and Lind, 1970). Similar findings were reported by other workers (Hepher, 1958; Holden, 1961; Harter, 1968; Williams et al., 1970; Latterell, Holt and Timmons, 1971). Phosphorus adsorption by sediment is an anion exchange process that involves the inorganic fraction of sediments (Hepher, 1958). In calcareous sediment, the reaction is primarily between phosphate and calcium carbonate to form insoluble calcium phosphates. The phosphorus retention capacity of calcareous mud is less than that of noncalcareous mud (Williams et al., 1970). In noncalcareous sediment, phosphate reacts to form insoluble iron and aluminum phosphates (Frink, 1967, 1969a, 1969b). Some calcium phosphates are also formed in neutral to slightly alkaline muds. Adsorption of phosphate as iron and aluminum compounds is strongly dependent upon the redox potential, with phosphorus retention being greater at higher potentials. The adsorption reaction is also pH dependent. Detailed information on the adsorption processes are found in standard soil fertility and clay mineralogy texts.

Hayes and Phillips (1958) reported that bacteria associated with sediments were more important than the sediments in removing phosphorus from water. However, the findings of other workers mentioned above indicate that sediment is much more decisive than bacteria in removing phosphate.

Studies of the phosphorus cycle in a lake by Rigler (1956) using 32 phosphorus as a tracer did not reveal as large an accumulation of isotope in the sediment as expected from the discussion above. This discrepancy is probably a result of the larger water volume to sediment surface ratio in lakes as compared to ponds or experimental cores.

In highly turbid waters, suspended inorganic colloids likely adsorb phosphate from solution. Hepher (1958) demonstrated that phosphate may be precipitated from calcareous water as calcium phosphate with no sediment involvement.

Availability of phosphorus in sediment. Phosphate is released from iron and aluminum combination when reducing conditions develop from oxygen depletion (Mortimer, 1941-1942). The surface layers of sediment above the thermocline are oxidized. However, iron and aluminum phosphates released into the hypolimnion may become available to plants at overturns.

Iron, aluminum, and calcium phosphate compounds in aerobic pond muds are not entirely insoluble. A dynamic equilibrium exists between sediment and overlaying water so that a small amount of phosphorus is maintained in solution (Hayes et al., 1952; Pomeroy, Smith and Grant, 1965; Olsen, 1964; Hepher, 1966; Boyd, 1971). Presumably, if phosphate is absorbed from the water by plants, more phosphate is released from the sediment to maintain the equilibrium. Many pond culturists have assumed that the sediment contained a store of phosphorus which was available for phytoplankton growth. However, before any general statement is advanced, the literature on the availability of phosphorus in sediment to phytoplankton should be considered. Gessner (1960), Carritt and Goodgal (1954), Olsen (1958) presented circumstantial evidence (based on the exchange of phosphorus between sediment to water) that sediments buffer concentrations of phosphate in water. Pomeroy et al. (1965) determined exchange rates of phosphorus between sediment and water and concluded that the phosphate release was large enough to maintain continued plant growth. Pomeroy and associates claimed that phosphate from the sediment was responsible for phytoplankton "blooms" which are observed to persist for extended periods even though phosphate levels in the water are not adequate to support the observed rates of photosynthesis for more than a day. Consult Pomeroy, Haskins and Ragotzkie (1956), Ragotzkie and Pomeroy (1957), or Ryther et al. (1956) regarding such "blooms". Golterman, Bakels and Jacobs-Magelin (1968) obtained good growth of *Scenedesmus* with mud as a source of phosphate. Some workers have conveyed a negative opinion regarding the availability of phosphate in sediment. Latterell et al. (1971) found that orthophosphate concentrations in water must be extremely low before sediment will release phosphate. They concluded that sediment was a phosphate sink and phosphate from sediment did not contribute to eutrophication. Fitzgerald (1970a, b) reported that lake muds do not provide readily available phosphorus for the growth of certain algae and aquatic weeds. He also suggested that aerobic lake muds could be used to remove phosphorus from highely eutrophic lakes.

The question of the availability of sediment phosphate is unanswered. However, much merit is found in the logical assessment by Hepher (1966). He obtained productivity data for fertilized and unfertilized ponds in Israel.

Literature values for phosphorus uptake were then used to estimate the rates of phosphorus uptake by the observed production. The rate of release of phosphate from bottom mud was then determined. Hepher concluded that the release of phosphorus from sediments was an important source of this nutrient in unfertilized ponds. However, the calculated rates of uptake by phytoplankton populations in fertilized ponds were 4.5 to 5.5 times greater than the amounts of phosphate released from the muds. He further stated that higher production by phytoplankton is dependent upon frequent applications of phosphate fertilizer to keep dissolved phosphate levels above equilibrium concentrations. Certainly, Hepher's conclusions are compatible with observations that ponds built on certain types of soil tend to have higher phosphorus levels and greater productivity than ponds in other areas. Assuming similar natural inputs of phosphorus, it is believed that the native phosphorus status of ponds is dependent upon the capacity of sediments to release phosphate to the overlaying water.

The age and fertilization history of ponds is possibly important in the role of sediments in phosphorus fertility. As ponds age, there is an accumulation of organic matter in the sediment. Although much of this organic matter is colloidal in nature, it does not adsorb appreciable phosphate. Concomitantly, if phosphate has been added to the pond for a number of years, exchange sites in the sediment are likely saturated with phosphorus. Therefore, the equilibrium following phosphate addition may shift appreciably towards the water.

The depth of sediment that exchanges phosphorus with the overlaying water is again questionable. Hayes et al. (1952) reported that only the upper 2 cm of sediment absorbed ^{32} phosphorus which was added to a lake. Hayes (1955) found after 2 weeks that only 1 mm of sediment in undisturbed cores had absorbed ^{32} phosphorus from the water.

Zicker, Berger and Hasler (1956) reported no release of ^{32} phosphorus buried at 2.5 cm. Conversely, Holden (1961) presented evidence that 15 cm of sediment was involved in exchange processes with water. Phosphate injected 4 cm below the mud-water interface in cores moved upward into the water (Hynes and Greib, 1970). Since the process is dependent upon diffusion or water movement, the shallow depth of exchange in the undisturbed cores is not surprising. In ponds, the depth of exchange is likely several centimeters because of turbulence of shallow water, animal activity in the sediment, and stirring of the bottom by feeding fish.

Utilization of sediment phosphorus by macrophytes. Emergent plants and floating-leafed species probably absorb most of their nutrients from the sediment (Boyd, 1971). Submersed macrophytes absorb nutrients through their foliage, but are also capable of absorbing nutrients from the sediment (McRoy and Barsdate, 1970; Bristow and Whitcombe, 1971). Macrophytes occur above the thermocline and the surface muds of this area are aerobic. However, at a few centimeters depth, the sediment becomes anaerobic and phosphate concentrations increase from solubility of iron and aluminum phosphates (Boyd, 1967). Rooted plants apparently have benefit of a very large pool of phosphate in the anaerobic muds. McRoy and Barsdate (1970) found that phosphate absorbed from sediment by *Zosteria* (marine eelgrass) may subsequently leak in large amounts from the foliage into the water. A similar phenomenon was also demonstrated for salt marsh *Spartina* (R. J. Reimold, personal communications). It should be interesting to know if a similar movement of phosphorus occurs through freshwater macrophytes.

Phosphorus accumulation by aquatic plants. Phytoplankton absorb phosphorus very rapidly and most of the uptake following fertilization probably occurs within a few hours or even minutes (Coffin et al., 1949). Much of this phosphorus is stored and used for growth at a later time (Einsele, 1941; Mackereth, 1952; Goldberg, Walker and Wisenand, 1951; Hepher, 1958). Phosphorus absorption by vascular plants is apparently slower than for phytoplankton (Hayes and Phillips, 1958). Absorption by filaments algae is likely more similar to that of vascular plants than to phytoplankton. Competition of different plants for phosphorus is an important consideration in pond fertilization. If large populations of macrophytes are present, fertilizer will be absorbed by these plants at the expense of phytoplankton populations. Stands of macrophytes will keep comparatively large amounts of phosphorus tied up throughout the growing season. Phytoplankton cells, on the other hand, have a short life and upon death their phosphorus is readily shared by other cells (Fitzgerald, 1970b). The use of fertilization in controlling macrophytes by encouraging phytoplankton is discussed by Dendy (1963).

Trophic transfers. Phosphorus absorbed by plants is passed on through food webs to other organisms. Large quantities of phosphorus will accumulate in fish flesh. Upon death and decay of plants and animals, phosphorus will eventually be converted to inorganic form by microbial activity. Little is known about the regeneration of phosphorus from dead organic matter (detritus).

PHOSPHORUS LOSSES

Outflow. Seepage and outflow is a major loss of phosphorus from many ponds. Both dissolved phosphorus and phosphorus contained in seston is lost in this manner. Seepage rates for ponds on the Piedmont near Auburn, Alabama was 95.5 in. for 1 year (Swingle, 1955). This amount of seepage exceeds the average depth of most ponds.

Fish harvest. Fish contain a range of about 2 to 4% of their dry weight as phosphorus (Lawrence, 1968). Therefore, the removal of phosphorus would be large in heavily fished ponds.

Animal activity. Vallentyne (1952) reported that insect emergences were not major losses of phosphorus from lakes. However, very large emeregnces occur in many ponds and insect removal of phosphorus may occasionally be large. Phosphorus is also lost in amphibian migrations and through the feeding of terrestrial animals on pond life.

Permanent loss to sediment. Phosphorus contained in sediment at the mud-water interface will eventually be buried to a depth at which it will no longer exchange with the overlaying water. The time required will depend upon the rate of sedimentation and the exchange depth for the particular pond.

CONCLUSIONS AND SUMMARY

A qualitative model of the phosphorus dynamics of a pond is presented in Fig. 1. Most of the possible inputs, transfers, and losses are likely important in infertile, unfertilized ponds. The involvement of sediment probably regulates the phosphorus status of most unfertilized ponds. Furthermore, the native fertility of ponds is directly related to the fertility of underlaying and surrounding soil. Fertilization is probably the only significant phosphorus input to well-managed ponds. In fertilized ponds the sediment is a phosphorus sink. Continual additions of phosphorus maintain the high levels of photosynthesis. Phosphorus transfers from water to phytoplankton and finally to fish are of major significance. Significant loss from fertilized ponds are uptake by sediment, seepage, and fish harvest. Once sediments become saturated with phosphorus, equilibrium concentrations will probably increase to a level where the rate of fertilization can be lowered.

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ACCUMULATION OF DDT FROM FOOD AND FROM WATER BY GOLDEN SHINER MINNOWS, Notemigonus Crysoleucas

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INTRODUCTION

This report deals with one aspect of an overall study to determine the behavior and activity of pesticides in the aquatic environment. The specific objective of the study was to determine in the laboratory the dynamics of pesticide movement in aquatic environments with particular emphasis on the mode of accumulation of these materials by organisms. Bioaccumulation of carbon-14 labelled DDT from food and water was followed in golden shiner minnows, *Notemigonus crysoleucas.*

DDT is very insoluble in water hence only small amounts can be carried by water. A much higher burden can accumulate in the food of fish especially if the food contains lipids. Carbon-14 labelled DDT was chosen both for the ease and accuracy with which it can be detected and because it could be separated from the DDT burden present in all available fish. Although not attempted here, it would also be possible to add unlabelled DDT to the water and simultaneously feed the fish food contaminated with labelled DDT. The importance of each type of contamination could then be measured in the presence of the other. The following report is a result of research to determine the rate of accumulation of DDT by golden shiners from a constant aqueous concentration and from food at a constant daily dosage.

REVIEW OF LITERATURE

Serious water pollution by pesticides began after World War II when the organic insecticides were first marketed. DDT was one of the first and most widely used insecticides (Nicholson, 1967). It belongs to the chlorinated hydrocarbon class of insecticides that degrade slowly in the environment and are the most toxic to fish (Johnson, 1968).

Several investigators have exposed fish to aqueous concentrations of DDT. Premda and Anderson (1963) found that salmon killed by six hours exposure to 1 part per million DDT-C^{14} had accumulated about 3.7 parts per million. Goldfish exposed to a sublethal 30 parts per billion DDT-C^{14} for five hours accumulated 5 parts per million (Gakstatter and Weiss, 1967). Cope (1965) exposed fish to an initial 20 parts per billion DDT and found that after two weeks the fish had accumulated 1 part per million although the aqueous DDT concentration fell greatly during this time. Holden (1962) also noticed that the concentration of DDT-C^{14} in exposure tanks fell rapidly, and he suggested that a system of maintaining a constant concentration of toxicant be used. Butler (1966) found that pinfish soon reached a maximum accumulation of aqueous DDT and suggested that uptake was balanced by metabolic losses.

Most of the work dealing with pesticides and fishes has been summarized by Johnson (1968) in an excellent literature review. He noted that a gap existed in understanding the relative importance of the digestive tract and the gills as locations for pesticide absorption. Butler (1966) believed that the dynamic maximum accumulation of aqueous DDT in pinfish was increased by adding DDT to their food source.