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PHOSPHORUS INPUTS AND ALGAL BLOOMS IN LAKES

Roger W. Bachmann[2] **and** ***John R. Jones***[3]

ABSTRACT. The summer standing crops of plankton algae in a diverse group of lakes were significantly related to the annual inputs of total phosphorus divided by the lake volumes. Based on the relationship between Secchi disk transparency and chlorophyll-a concentrations, phosphorus inputs would have to be reduced below about 0.02 mg/1 before significant increases in water transparency would be achieved as a result of reduced algal standing crops.

Many lakes have high densities of plankton algae that reduce water transparency and otherwise degrade water quality. For this reason lake management plans often seek to reduce algal populations. A common approach that has had varying success has been to decrease the amounts of plant nutrients entering a lake. Significant reductions in algal levels have been achieved in Lake Washington (Edmondson, 1969; 1970; 1972) after diversion of sewage effluents, but nutrient-reduction programs in Lake Mendota (Lee, 1966; Sonzongni and Lee, 1974), Lake Sammamish (Emery, Moon and Welch, 1973), Snake Lake (Born et al., 1973), and Lake Norrviken (Ahlgren, 1972) have been less successful.

Quantitative relationships are needed to predict the response of a lake to a given nutrient reduction so that the costs of nutrient control can be weighed against the potential benefits. To this end Vollenweider (1968) separated oligotrophic and eutrophic lakes on the basis of mean depth and annual inputs of nitrogen and phosphorus per unit of surface area (g/m^2). He established critical surface loading values above which an oligotrophic lake of a given depth would be degraded to a eutrophic lake. We have extended his approach by recognizing the many intermediate conditions that exist between the most sterile oligotrophic lakes and the most productive eutrophic lakes.

As an index of trophic status, we measured the average conventrations of planktonic chlorophyll-a in July and August in four lakes in northwestern Iowa (Lake West Okoboji, Lake East Okoboji, Spirit Lake, and Lower Gar Lake) during each of 3 years (Jones and Bachmann, in prep.). Annual inputs of total phosphorus and inorganic nitrogen for each year were estimated by sampling the rainfall and the inputs of the tributary streams. We followed the procedure of Edmondson (1961) and divided the annual inputs of each element by the lake volumes to find the potential concentrations in the lakes. In Lower Gar Lake where the annual water input exceeded the lake volume, we used the average concentrations of the inflowing streams as the potential concentrations.

We found a high correlation between the summer chlorophyll-a values and the potential concentrations of either total phosphorus ($r=0.82$, $P=0.01$) or inorganic nitrogen ($r=0.74$, $P=0.01$). This relationship was consistent over all lakes and over years within individual lakes. Because the potential concentrations of phosphorus and nitrogen were highly correlated ($r=0.84$, $P=0.01$) and the ratio of inorganic nitrogen to total phosphorus (19:1 by weight) exceeded the ratio commonly found in plankton algae (Vollenweider, 1968), we confined our remaining analyses to phosphorus alone.

In Figure 1, we have combined our data with comparable information for other lakes with published data on phosphorus inputs and summer chlorophyll-a levels (Ahlgren, 1967;

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[2] Professor, Department of Zoology and Entomology, Iowa State University, Ames, Iowa 50010.

[3] Graduate Research Assistant, Department of Zoology and Entomology, Iowa State University, Ames, Iowa.

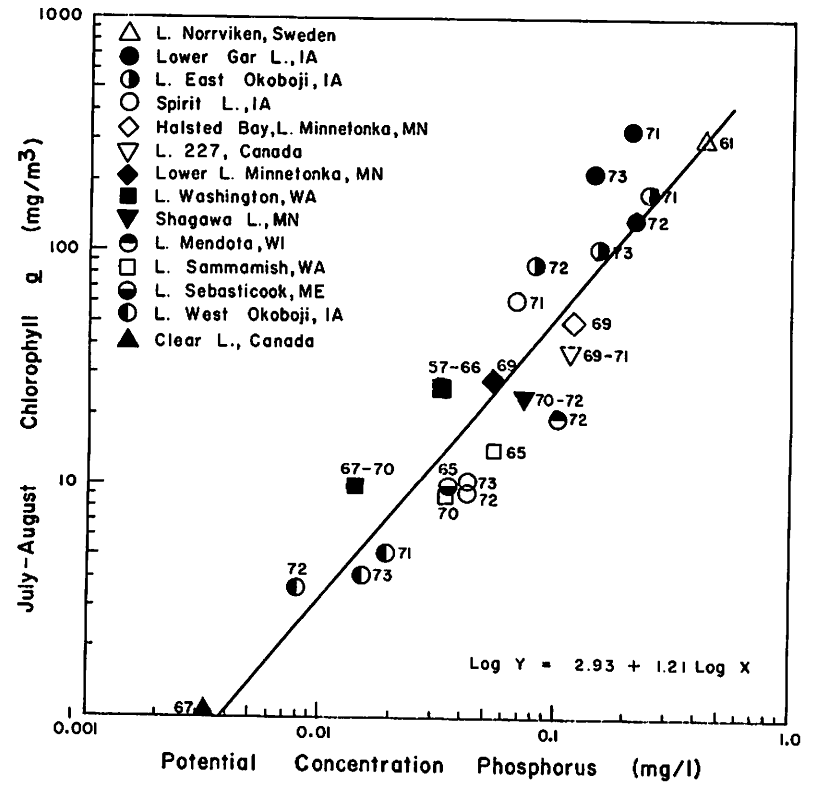

Figure 1. Mean summer chlorophyll-a concentrations (mg/m^3) as a function of potential phosphorus concentrations (mg/1) for several lakes. Numbers after symbols indicate year of data collection. For some lakes an average for several years is used. With the exception of Clear Lake, where only data on soluble reactive phosphorus was available, the phosphorus concentrations refer to total phosphorus. For Lake Sammamish we used the April-May average chlorophyll-a concentration, since the maximum was found at that time of year rather than in July-August.

Mackenthun, Keup, and Stewart, 1968; Edmondson, 1969; Ahlgren, 1970; Edmondson, 1970; Megard, 1970; Schindler and Nighswander, 1970; Schindler et al., 1973; Emery et al., 1973; Malueg, personal communication). Logarithmic scales were used to linearize the relationship. The correlation between the transformed variables is surprisingly high ($r=0.93$, $p=0.01$) considering the wide range of lakes examined, the problems involved in obtaining accurate nutrient budgets for lakes, and that phosphorus was the only nutrient considered. Further, the standing crops of macrophytes and other aquatic organisms were not considered.

Our findings confirm that the trophic status of lakes is determined to a large extent by the annual inputs of phosphorus. In the Iowa lakes the magnitude of the summer algal standing crops varied with the phosphorus inputs in the previous year. When natural changes in the annual runoff lowered the phosphorus input, the lakes responded with a smaller algal bloom. In like manner the algal crops in Lake Washington decreased as the sewage effluents were diverted from that lake (Edmondson, 1969; 1970).

Responses of individual lakes to changes in annual phosphorus input probably reflect the strong tendency for phosphorus to become bound in the sediments of most lakes, thus providing little carryover from year to year (Vollenweider, 1968). For the Iowa lakes we found no significant difference between the potential concentrations of phosphorus, as calculated from annual inputs, and the actual summer concentrations of total phosphorus measured in the summer. Other studies have shown that, in warm months, the phosphorus in the epilimnion is recycled many times (Schindler, 1973) and that the zooplankton seem important in this process (Peters and Lean, 1973; Peters and Rigler, 1973). Thus, the summer phosphorus supply remains available for phytoplankton growth during the growing season and can determine the ultimate size of the summer standing crop.

The phosphorus-chlorophyll-a relationship based on a wide sample of lakes should be a useful basis for predicting the benefits of a nutrient-reduction program. Exceptions would be (a) lakes in which light transparency is markedly reduced by inorganic turbidities or by high concentrations of humic materials (b) lakes with high flushing rates such that the phytoplankton population is lost before the maximum potential densities are attained and (c) lakes where the upper mixed layer is so thick relative to the thickness of the euphotic zone that light becomes limiting to population growth.

To provide a basis for establishing a critical value for nutrient loading, we have looked at the relationship between chlorophyll-a concentrations and water transparency. Water clarity is readily evaluated by the general public, and the impetus for many nutrient-reduction programs is based on improvements in water clarity even though other limnological benefits are expected. Edmondson (1970) has pointed out that water transparency as measured by the Secchi disk depth is hyperbolically related to chlorophyll-a concentrations in Lake Washington. This relationship, including points for several other lakes (Saunders, Trama, and Bachmann, 1962; McGauhey et al., 1963; Ahlgren, 1967; Ahlgren, 1970; Schindler and Nighswander, 1970; Schindler et al., 1971; Larson, 1972; Powers et al., 1972; Willen, 1972; Emery et al., 1973; Schindler et al., 1973), is given graphically in Figure 2. Many factors besides chlorophyll-a—such as size and shape of the algal cells, inorganic turbidities, and dissolved organic materials—also determine the optical properties of lakes. Even so, transparencies of lakes with chlorophyll-a values of less than 10 mg/m^3 are extremely sensitive to changes in algal abundance, whereas transparencies of lakes with chlorophyll-a concentrations above this value differ little. A nutrient-reduction program would have to reduce algal densities below this level to achieve noticeable improvements. According to our data (Fig. 1), a chlorophyll-a value of 10 mg/m^3 would be produced by potential phosphorus concentrations in the range of about 0.014 to 0.04 mg/1. A value of about 0.02 mg/1 is obtained from the regression line. Reducing phosphorus below this level should lead to improving water transparencies by reducing algal biomass. The value derived by the use of the chlorophyll-a relationship can be compared to the dangerous loading values given by Vollenweider (1968) by dividing his specific loading rates (g/m^2) for various lakes by their mean depths to yield potential concentrations (mg/1). His eutrophic lakes all have potential concentrations of phosphorus greater than 0.02 mg/1 while his intermediate and oligotrophic lakes all have smaller potential concentrations. The two approaches seem to arrive at the same end result.

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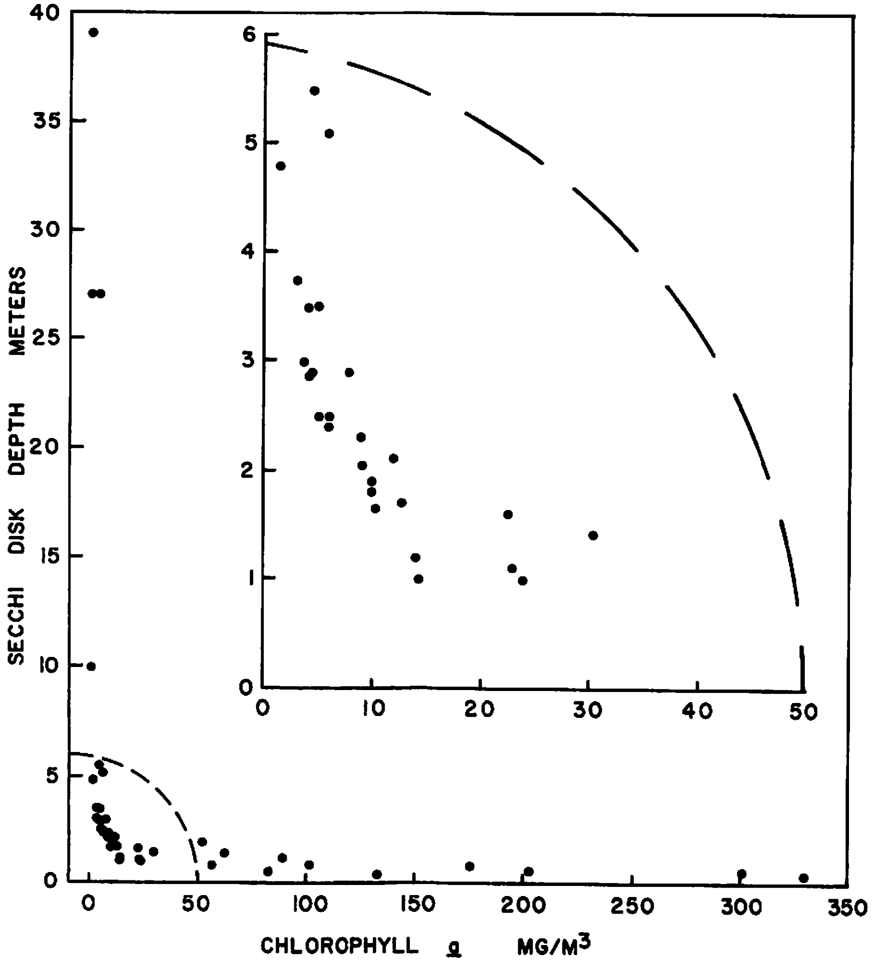

Figure 2. Relationship between mean Secchi disk transparencies for July and August and the mean July-August chlorophyll-a concentrations for 16 lakes.

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