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RELATIONSHIPS OF PRODUCTIVITY AND PROBLEM CONDITIONS TO AMBIENT NUTRIENTS:
National Eutrophication Survey Findings for 418 Eastern Lakes

WORKING PAPER NO. 725

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RELATIONSHIPS OF PRODUCTIVITY AND PROBLEM CONDITIONS TO AMBIENT NUTRIENTS:
National Eutrophication Survey Findings for 418 Eastern Lakes

by

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FOREWORD

The National Eutrophication Survey was initiated in 1972 in response to an Administration commitment to investigate the nationwide threat of accelerated eutrophication to freshwater lakes and reservoirs. The Survey was designed to develop, in conjunction with State environmental agencies, information on nutrient sources, concentrations, and impact on selected freshwater lakes as a basis for formulating comprehensive and coordinated national, regional, and State management practices relating to point source discharge reduction and nonpoint source pollution abatement in lake watersheds.

The Survey collected physical, chemical, and biological data from 815 lakes and reservoirs throughout the contiguous United States. To date, the Survey has yielded more than two million data points. In-depth analyses are being made to advance the rationale and data base for refinement of nutrient water quality criteria for the Nation's freshwater lakes.

ABSTRACT

Data collected by the National Eutrophication Survey (NES) team from 418 eastern lakes were utilized to determine correlations between chlorophyll *a*, an indicator of lake productivity, nutrient, and other water quality parameters.

High linear correlations were determined between mean total phosphorus and mean chlorophyll *a* levels, especially in lakes with retention times of greater than 14 days. These basic relationships were compared for populations of lakes subdivided on the bases of stratification, vegetation dominance and fishery type. Significant regional differences were noted in the basic relationships of chlorophyll *a* to total phosphorus. Correlations determined for chlorophyll *a* with phosphorus, Kjeldahl nitrogen, pH and total alkalinity were positive; those with Secchi disk transparency and nitrogen/phosphorus ratio were negative.

Relationships between lake "problems," and nutrient or other water quality parameters were established by comparing historical and field observational data of general lake conditions with physical, chemical and biological values obtained from NES sample analyses. The distributions of lakes with algal blooms, aquatic macrophyte problems, low dissolved oxygen concentrations, and/or fishkills are presented as functions of mean total phosphorus and chlorophyll *a* concentrations. Except for algal blooms, these lake problems were not consistently associated with extremes of chlorophyll and total phosphorus levels.

CONTENTS

INTRODUCTION

In evaluating the impact of eutrophication or nutrient enrichment it is important to consider the primary uses to which the water body will be put. The addition of phosphorus to a lake or impoundment may be blessing or bane depending upon existing nutrient levels and the lake's intended purpose. In general, the addition of phosphorus to natural waters will increase their productivity. Only waters with great excesses of nutrients or some superimposed toxic effects would be expected <u>not</u> to respond to phosphorus enrichment.

Increased productivity may, in some waters, give rise to excessive aquatic weed growths, algal blooms, fishkills, or reduced dissolved oxygen levels affecting the nature and distribution of the lake's biotic community. On the other hand, the manifestations of nutrient enrichment may include increased fishery productivity, not unwelcome in surface waters managed primarily for sport and commercial fishing.

The National Eutrophication Survey (NES) was initiated in 1972, to investigate the role of nutrients and their sources in accelerated eutrophication (aging) of freshwater lakes and reservoirs. Consistent with this objective, relationships between ambient nutrient concentrations and existing lake conditions are being examined. The NES staff has brought statistical and computer techniques to bear upon major segments of the 2½ million values generated during the 4-year sampling program and contained in STORET, (the U.S. Environmental Protection Agency's water quality data STOrage and RETrieval system). Presently, in-depth analysis has been conducted for 418 lakes east of the Mississippi River, sampled at least three times each. Of these, 191 lakes sampled in 1972 represent the "Northeast States":

Connecticut	New Hampshire
Maine	New York
Massachusetts	Rhode Island
Michigan	Vermont
Minnesota	Wisconsin

while 227 lakes sampled in 1973 represent the "Southeast States":

Alabama	Kentucky	Pennsylvania
Delaware	Maryland	South Carolina
Florida	Mississippi	Tennessee
Georgia	New Jersey	Virginia
Illinois	North Carolina	West Virginia
Indiana	Ohio	

Key questions revolve about the nature and extent of water quality <u>changes</u> to be effected per unit change in phosphorus. "Phosphorus" is used here rather than "nutrient," as the Survey data strongly reinforce the relationship between phytoplankton productivity and phosphorus. The effects of nitrogen, while obviously important in all biological systems, are very difficult to quantify, much less control, in an "open" natural system. Those NES lakes found to be "nitrogen-limited" in their growth responses were often so because of excessive phosphorus rather than low nitrogen levels.

The analysis of NES lake data has sought to answer several basic questions:

(1) What physical, chemical, and hydrologic parameters affect lake productivity?

(2) With what confidence can we predict the changes in lake productivity resulting from phosphorus enrichment?

(3) Do lake groups established on the bases of stratification, primary nutrient limitation, fishery type, or aquatic weed dominance differ with respect to the productivity responses noted in question 2?

(4) At what phosphorus and chlorophyll *a* (chl *a*) levels do such problems as algal blooms, excessive weeds, fishkills and dissolved oxygen depression appear?

(5) Of what value are the planktonic algae as water quality indicators?

(6) What environmental factors can be altered to eliminate nuisance algal blooms?

The purpose of this report is to summarize major study findings to date with respect to ambient nutrient/water quality relations and answer, to the extent possible, some of the questions posed above.

CONCLUSIONS

The following conclusions can be drawn from our study:

1. Productivity, as indicated by mean chl *a* concentrations, is strongly related to ambient phosphorus levels, especially in lakes with hydraulic retention time greater than 14 days.

2. Significant regional differences in chl *a* response per unit total phosphorus have been discovered; further studies are ongoing to determine the basis of these differences.

3. No differences in the response of chl *a* to phosphorus were noted in comparing populations of lakes divided on the bases of stratification, vegetation dominance or fishery type.

4. Algal bloom response is dramatic to high ambient phosphorus levels. No algal blooms were noted in lakes with mean total phosphorus concentrations less than 19 micrograms (μg) per liter.

5. Aquatic weed "problems" generally occurred at lower phosphorus levels than did algal blooms. Phosphorus source control is unlikely to have significant impact upon aquatic macrophyte populations in many cases.

6. Fishkills were found to be generally unrelated to mean phosphorus or chl *a* levels or even to chronic low-oxygen conditions.

7. In the Southeast, many of the oxygen "problems," as defined in this report, arise from the establishment of trout fisheries in marginal habitats.

MATERIALS AND METHODS

LAKE SELECTION

Selection of lakes and reservoirs included in the National Eutrophication Survey in 1972 and 1973 was limited to lakes 40 hectares or more in surface area, with mean hydraulic retention times of at least 30 days, and impacted by municipal sewage treatment plant effluent either directly or by discharge to an inlet tributary within 40 kilometers of the lake. Specific selection criteria were waived for lakes of special State interest. As a result, a broader range of water quality was represented than would have been possible had the selection criteria been rigidly enforced. Although lakes selected were not necessarily representative of average conditions existing in the study area, the relationships observed between ambient nutrients and lake water quality should not be biased.

LAKE SAMPLING

Sampling was accomplished by two teams, each consisting of a limnologist, pilot, and sampling technician, operating from pontoon-equipped helicopters. With few exceptions, each lake was sampled under spring, summer, and fall conditions. Sampling site locations were chosen to define the character of the lake water as a whole and to investigate visible or known problem areas, e.g., algal blooms, sediment or effluent plumes.

The number of sites was limited by the survey nature of the program and varied in accordance with lake size, morphological and hydrological complexity, and practical considerations of time, flight range, and weather. At each sampling depth, water samples were collected for oxygen determinations. Contact sensor packages were used to measure depth, conductivity, turbidity, pH, dissolved oxygen, and temperature. Fluorometric chlorophyll (chl *a*) analyses were performed at the end of each day in a mobile laboratory. Nutrients and alkalinity were determined by automated adaptations of procedures described in "Methods for Chemical Analysis of Water and Wastes" (U.S. EPA 1971). Survey methods are detailed elsewhere (U.S. EPA 1974, 1975).

DATA MANAGEMENT

Data collected were stored in STORET and manipulated, as prescribed by Bliss, Friedland, and Hodsen (1976). Basic calculations for parameters measured in sampled lakes were performed in such a way as to give equal weight to each depth sampled at a station, each sampling station sampled on an individual lake during a sampling round, and each sampling round on an individual lake during a sampling year.

Mean parameter values for each sampling station were calculated as follows:

$$\overline{\text{Par}}_j = \sum_{i=1}^{D} \text{Par}_i / D \qquad \text{(Eq. 1)}$$

where $\overline{\text{Par}}_j$ = mean value for a parameter at the j^{th} sampling station during a sampling round

Par_i = value for the i^{th} depth

and D = the number of depths for which a parameter was measured at the j^{th} sampling station during a sampling round

Mean parameter values for each sampling round were calculated as follows:

$$\overline{\overline{\text{Par}}}_k = \sum_{j=1}^{S} \overline{\text{Par}}_j / S \qquad \text{(Eq. 2)}$$

where $\overline{\overline{\text{Par}}}_k$ = mean value for the k^{th} sampling round on a given lake

S = number of sampling sites

Mean lake parameter values for a given sampling year were calculated as follows:

$$\overline{\overline{\overline{\text{Par}}}} = \sum_{k=1}^{3} \overline{\overline{\text{Par}}}_k / 3 \qquad \text{(Eq. 3)}$$

where $\overline{\overline{\overline{\text{Par}}}}$ = mean parameter value for a given sampling year

Lake parameter values were calculated only when values were available for the first, second, and third sampling rounds during a given sampling year from a lake. Formulas 1, 2, and 3 were used to determine parameter values for total phosphorus, dissolved phosphorus, dissolved orthophosphorus, total alkalinity, ammonia-N, nitrate-nitrite-N, and Kjeldahl-N in milligrams per liter (mg/liter), temperature in degrees Celsius, turbidity in percent transmission, pH in standard units, Secchi disk in inches and hydraulic retention time in days.

Nitrogen and phosphorus values calculated at the sampling station level (equation 1) were used to compute nitrogen/phosphorus (N/P) ratios as follows:

$$\frac{N}{P} = \frac{\text{ammonia-N + nitrate-nitrate-N}}{\text{total dissolved phosphorus}} \qquad \text{for 1972 lake data; (Eq. 4)}$$

and

$$\frac{N}{P} = \frac{\text{ammonia-N + nitrite-nitrate-N}}{\text{total phosphorus}} \quad \text{for 1973 lake data} \qquad \text{(Eq. 5)}$$

Any total or dissolved phosphorus value for which a corresponding nitrog enous elemnt was missing was deleted. The N/P ratios thus obtained were then handled as the other preceding parameters to establish lake means for the sampling year. A change in laboratory analyses occurred after the 1972 sampling year resulting in substitution of dissolved orthophosphorus for total dissolved phosphorus. Total phosphorus was considered to better represent the bioavailable phosphorus pool than does orthophosphorus (Lean 1973) and was therefore selected as the denominator in equation 5.

Unlike the above parameters where measurements were made at various depths, only one chl *a* measurement was made at any individual sampling station during a sampling round. Therefore,

$$\overline{\text{chl}}\ a_j = \text{chl}\ a \qquad \text{(Eq. 6)}$$

where $\overline{\text{chl}}\ a_j$ = the mean chl *a* concentration in micrograms/liter (μg/liter) for the j^{th} sampling station during a sampling round

chl *a* = the chl *a* concentration in μg/liter for an integrated water sample from the surface to 4.6 meters or to a point just off the bottom when the depth was less than 4.6 meters

When photic zone determinations were made during the 1973 sampling year, the compensation point (1% of incident light remaining) provided the greatest depth of integration, if it exceeded 4.6 meters.

RESULTS AND DISCUSSION

FACTORS AFFECTING PRODUCTIVITY

Those physical, chemical and biological parameters found to be most highly correlated with lake productivity (as measured by chl *a* levels) are listed below in approximate order of importance:

	log-log Correlation Coefficient (r)	
	Northeast	Southeast
Total phosphorus	0.74	0.74
Secchi disc transparency	-0.74	-0.60
Kjeldahl (organic) nitrogen	NA	0.82
Dissolved phosphorus	0.66	NA
Dissolved orthophosphorus	NA	0.59
pH	0.49	0.71
Nitrogen/phosphorus ratio	-0.51	-0.40
Total alkalinity	0.37	0.46
Ammonia-N	0.48	0.19

NA - Parameter not measured

The relationship of Kjeldahl-N to chl *a* noted is not unexpected as the chlorophyll-containing autotrophs are primary sources of the organic nitrogen in surface waters. The pH response likely reflects increased carbon assimilation in waters as chl *a* levels increase. Low N/P ratios have generally been associated with high phosphorus levels in the NES lakes; the negative correlation of chl *a* with N/P ratio therefore roughly mirrors the positive chl *a* response to total phosphorus. The negative correlation of chl *a* with Secchi disk transparency suggests a positive correlation between suspensoids and chl *a*, and between suspensoids and total phosphorus. The following equation (after Verduin, et al 1976) provides an estimate of suspensoids:

$$S = \frac{2}{0.12SD}$$

where S is dry weight of suspensoids expressed in grams per cubic meter of water, SD is the Secchi disk depth in meters, the numerator (2) represents a coefficient which relates Secchi transparency to the depth of the photic zone, and the factor 0.12 represents the light extinction per gram dry weight of suspensoids (in square meters per gram).

Although the Survey lakes share some common features as a result of their selection criteria, they reflect a broad range of size, depth, type (natural, artificial, level-enhanced), location, hydraulic retention time (hours to years), degree of nutrient enrichment, geologic substrate, watershed land use, and primary water use (drinking water, fisheries, general recreation, industrial, etc.).

The relationships of the parameters listed above, as well as some others were compared in subpopulations of lakes grouped according to primary limiting nutrient, stratification pattern and vegetation dominance (Lambou, et al., 1976). Lakes with short retention times were excluded. In many cases the response relationships were stronger and better defined as the lake groups became more nearly homogeneous. For example, in northeastern "P-limited" lakes with hydraulic retention times greater than 14 days, the "coefficient of determination," (r^2) is 0.83 ($r = 0.91$); therefore 83 percent of productivity changes could be accounted for by changes in total phosphorus alone. The degree to which this can be considered cause and effect and the "independence" of phosphorus activity in general lake productivity is being further examined by National Eutrophication Survey (NES) staff.

PRODUCTIVITY PREDICTION

A high correlation was found between chl *a*, averaged over three seasons, and ambient phosphorus concentrations determined for the same period. The following table presents levels of chl *a* as a function of total phosphorus, predicted by three different equations:

Total Phosphorus (μg/liter)	Chl *a* (μg/liter)		
	A	B	C
0.005	2.5	2.4	0.8
0.010	3.9	3.9	2.3
0.015	5.0	5.2	4.2
0.020	6.1	6.3	6.5
0.025	7.0	7.4	8.9
0.050	10.9	12.0	25.0
0.100	17.0	19.5	68.0

The regression equations used to predict the above chl *a* levels are:

A. log μg/liter chl *a* = 1.87 + 0.64 log μg/liter total phosphorus, based upon all 418 eastern NES lakes.
($r = 0.73$)

B. log μg/liter chl *a* = 1.99 + 0.70 log μg/liter total phosphorus, based upon all eastern NES lakes with retention times greater than 14 days (318 lakes).
($r = 0.81$)

C. log μg/liter chl *a* = 3.29 + 1.46 log μg/liter total phosphorus, modified after Jones and Bachmann (1976), based upon 143 lakes of wide distribution.
($r = 0.95$)

The two NES regression equations (A and B) are based upon phosphorus and chl *a* values averaged over three seasons; the Jones and Bachmann equation (C) is derived entirely from summer values. The inclusion of a high percentage of "N-limited" lakes, low spring and fall responses, and the high turbidity levels of many of the waters sampled contribute to the relatively low overall response relationships reflected in the NES equations.

The relationship of chl *a* to phosphorus was found to be weak in northeastern lakes with short (less than 14 days) hydraulic retention times ($r = 0.35$); the algae appear to be flushed from the lake system before maximum densities can be achieved. A potential problem is temporarily "solved" by exporting it downstream. The short-term weak response seen in northeastern lakes improved dramatically in analysis of similar lakes in the Southeast.

If the eastern United States is bisected by an east-west line formed by the Roanoke, New, and Ohio Rivers, the States north of this line show significantly higher average summer chl *a* to total phosphorus response relationships (0.41 μg chl *a*/mg total phosphorus) than those States south of the line (0.29 μg chl *a*/mg total phosphorus). Preliminary analyses suggest that much of the phosphorus in the southern waters is associated with inorganic suspended materials and not readily bioavailable. The chl *a* to total phosphorus response average for those lakes of Secchi disk light penetration <30 inches appears to be only about 60 percent of that found for lakes of greater than 70-inch Secchi disk. Florida lakes represent an exception to the low southern lake response, perhaps because the overwhelming preponderance of large man-made impoundments in the southern lake group does not extend to Florida. Further analyses are ongoing to establish the bases for such regional response differences.

In the Northeast the response of chl *a* to total phosphorus was significantly higher in those lakes with a high nitrogen/ phosphorus (N/P) ratio called "P-limited", than in those with low N/P ratios, called "N-limited." An intermediate or "transition" range was identified within which neither phosphorus nor nitrogen exerted independent growth control. Southeastern lakes, whether considered "P-limited" or "N-limited" on the basis of algal assay or N/P ratio, showed no differences in chl *a* responses to increased phosphorus levels. This is consistent with the findings of Schindler and his co-workers (Schindler 1977) studying Canadian Shield lakes. Productivity was more highly correlated with total phosphorus levels than with inorganic nitrogen levels, even in "N-limited" lakes.

Comparison of the chl *a* phosphorus relationships in stratified and non-stratified, phytoplankton dominated and macrophyte dominated, coldwater fishery and warmwater fishery lakes revealed no significant response differences by lake population.

LAKE PROBLEMS

The frequency with which such lake problems as algal blooms, fishkills, dissolved oxygen depressions, and excessive weed growths occur has been examined both as a function of ambient phosphorus concentrations and chl *a* levels.

The criteria for placing lakes in problem categories were as follows:

(1) Aquatic weeds - Lakes which exhibited extensive reaches of submerged or floating higher aquatic plants, with histories of recurrent weed problems, and/or reported to be problem lakes in this regard, based upon field observations, historical information, and contact with State and local personnel.

(2) Algal blooms - Lakes in which readily observable color or turbidity changes were attributed to high phytoplankton concentrations as recorded by field limnologists or reported by State personnel.

(3) Dissolved oxygen depression - Lakes in which dissolved oxygen levels of less than 4 mg/liter (a) were present in the hypolimnion of thermally stratified lakes managed for trout, (b) extended into the epilimnion of warm-water fishery lakes, or (c) were present under thermally mixed conditions, regardless of lake use.

(4) Fishkills - Lakes which exhibited sudden large-scale fish deaths reported by State or local personnel; lakes with annual occurrences such as spring shad die-offs or kills due to known releases of toxic pollutants were not included.

Examination of the distribution of lake problems by phosphorus or chl *a* level is enlightening (Figs. 1-8). Aquatic weeds may be present in high concentrations at extremely low phosphorus concentrations. It is unlikely that source control of this nutrient will significantly reduce such macrophyte populations. Many submerged aquatic plants are highly competitive for nutrients at low levels in the water (except perhaps carbon), or survive quite well on nutrients absorbed through their root systems. The bulk of aquatic weed problems occur at lower phosphorus and chl *a* levels than do algal blooms. A probable explanation for this is shading by high phytoplankton densities present at elevated nutrient levels; the reduced penetration of light into the water discourages submerged aquatic weed growth.

Phytoplankton algae, however, respond dramatically to phosphorus, as evidenced by the distribution of algal blooms relative to phosphorus levels in northeastern and southeastern lakes. Algal blooms were recorded in 70 of the northeastern and 124 of the southeastern NES lakes. No blooms were noted in lakes in which the mean total phosphorus concentration was less than 19 μg/liter (log P = 1.28), However, blooms were recorded in lakes with mean chl *a* concentrations below 1 μg/liter. This apparent paradox may be partially explained by the nature of the sampling operation. It was noted that surface films of high algal concentration were, on rare occasion, swept aside by downdraft from the helicopter (turbine engine-equipped helicopters are not shut down while on sampling station) to reveal highly transparent waters beneath. Values of chl *a* obtained under these unique circumstances would likely be low, while the highly visible surface film of algae would invariably be noted as a bloom.

Twenty percent of the algal blooms recorded occurred with corresponding mean chl *a* levels of 10 μg/liter or less.

The distribution of reported fishkills presented in Figs. 7 and 8 is rather remarkably unrelated to either phosphorus concentrations above 25 μg/liter (log P = 1.40) or chl *a* levels. Following up this surprising finding, the distribution of reported fishkills and that of recorded dissolved oxygen problems were also found to be unrelated. Fishkills, with some exceptions, result from low dissolved oxygen conditions accompanying the decomposition of organic materials, as during the collapse of an algal bloom. The NES data suggest, however, that such events are precipitous, and bear little relationship to the chronic low oxygen conditions noted in many Survey lakes. The chronic oxygen problem lakes were found to be nearly free of recorded fishkills (though <u>not</u> free of fish). Only 1 of 27 fishkills occurred in a lake with recorded oxygen problems. A NES limnologist was at hand to observe the simultaneous anoxic conditions of the singular incident.

In contrast to the northeastern lakes, lakes in the Southeast showed few dissolved oxygen problems at high levels of phosphorus or chl *a*. The bulk of the dissolved oxygen problems in the latter group appeared at the <u>low</u> ends of the respective ranges. More than one-half (17 of 30) of the low oxygen problems noted in 1973 data appeared in southeastern lakes managed as "coldwater" (trout) fisheries. These habitats must be considered marginal for coldwater fisheries and compare with only five such fisheries free of oxygen problems. In general, the lakes considered to be marginal as coldwater fisheries would not have been considered problems were they being managed as warmwater (bass, pike, walleye, etc.) fisheries. The majority of the oxygen problems noted in the Southeast resulted from creating trout fisheries by stocking waters in artificial impoundments which are only marginal for them. However, it should be noted that these fisheries are making use of habitat in the lake which is generally too cold to support warmwater fish.

The mean total phosphorus level at which dissolved oxygen problems were found was <u>10 times</u> as high in warmwater fisheries as in trout-managed lakes (209 μg/liter vs. 22 μg/liter). That these problems exist at such very different ranges of nutrient enrichment clearly points up the need to evaluate water quality "suitability" with respect to its primary beneficial uses.

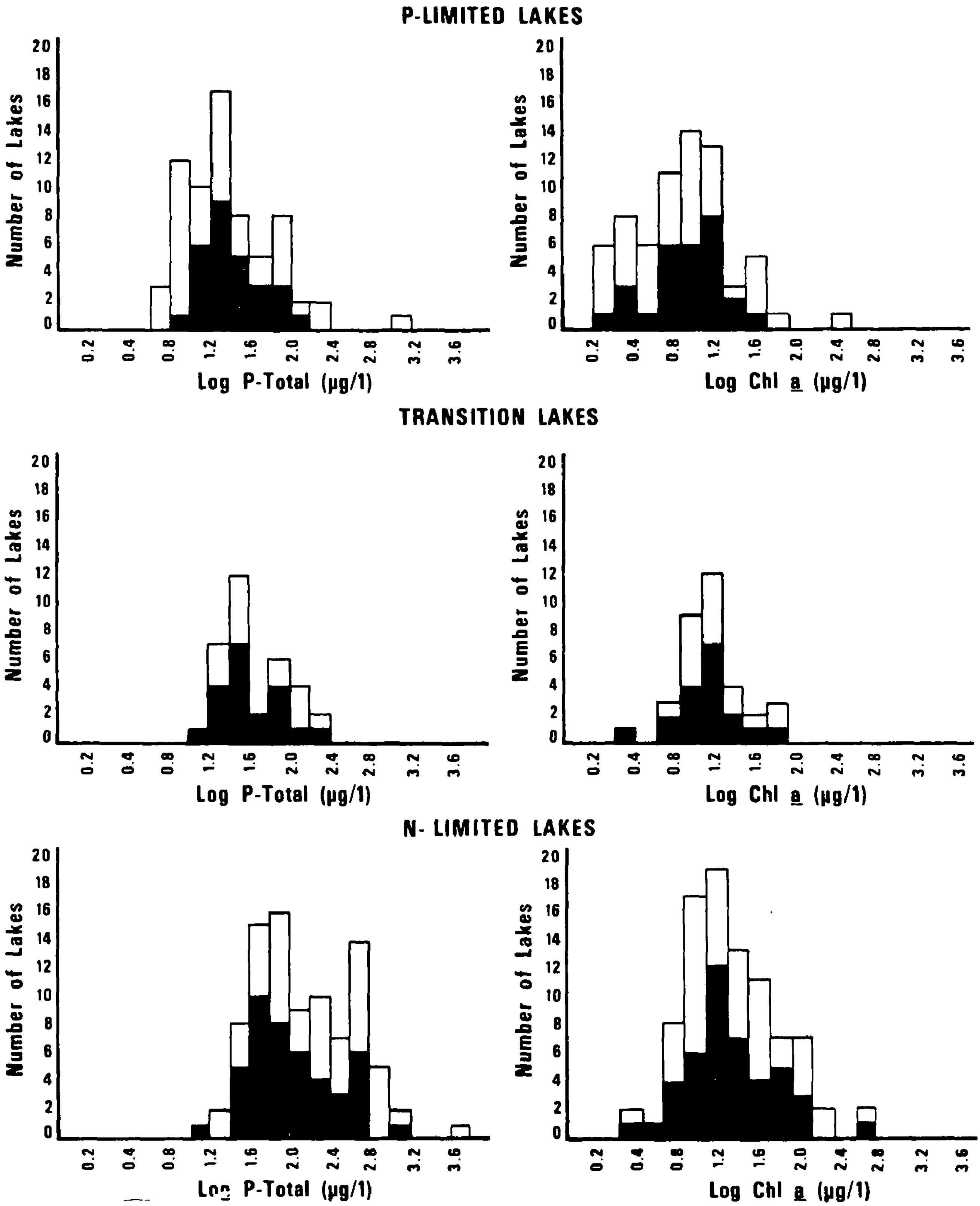

Figure 1. Distribution of aquatic weed problems by phosphorus and chlorophyll a levels in northeastern NES lakes (problem lakes shaded).

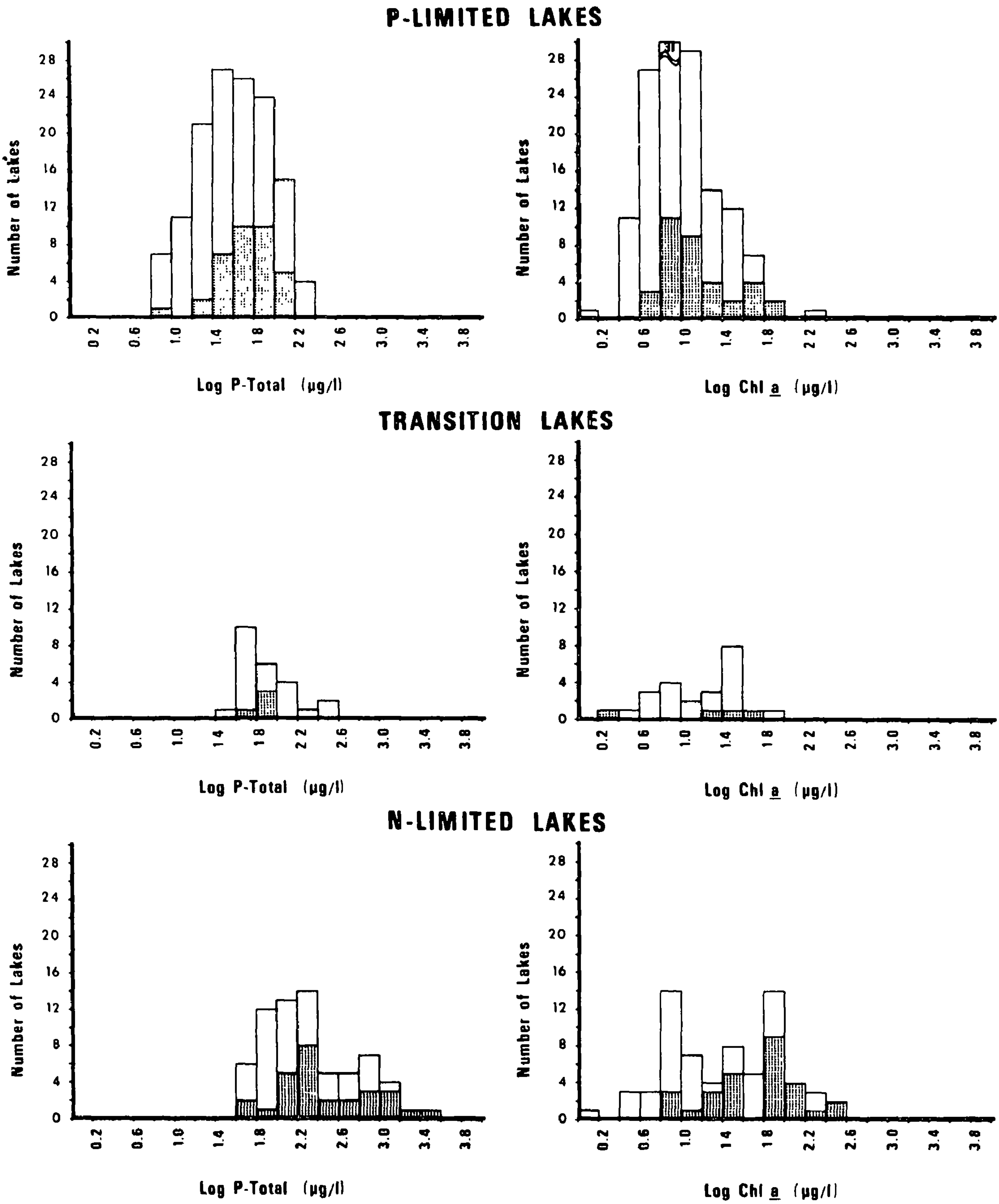

Figure 2. Distribution of aquatic weed problems by phosphorus and chlorophyll a levels in southeastern NES lakes (problem lakes shaded).

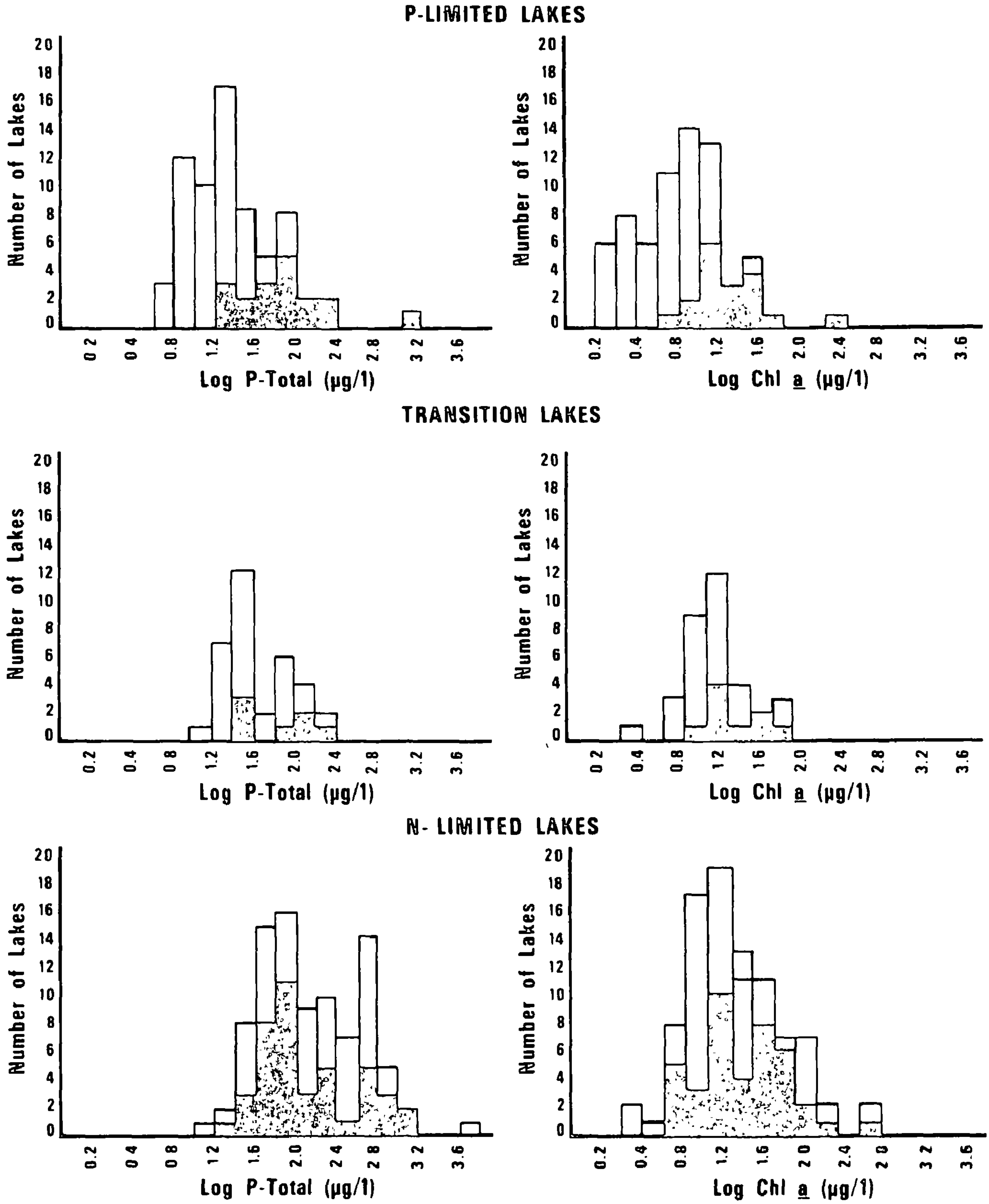

Figure 3. Distribution of algal blooms by phosphorus and chlorophyll a levels in northeastern NES lakes (problem lakes shaded).

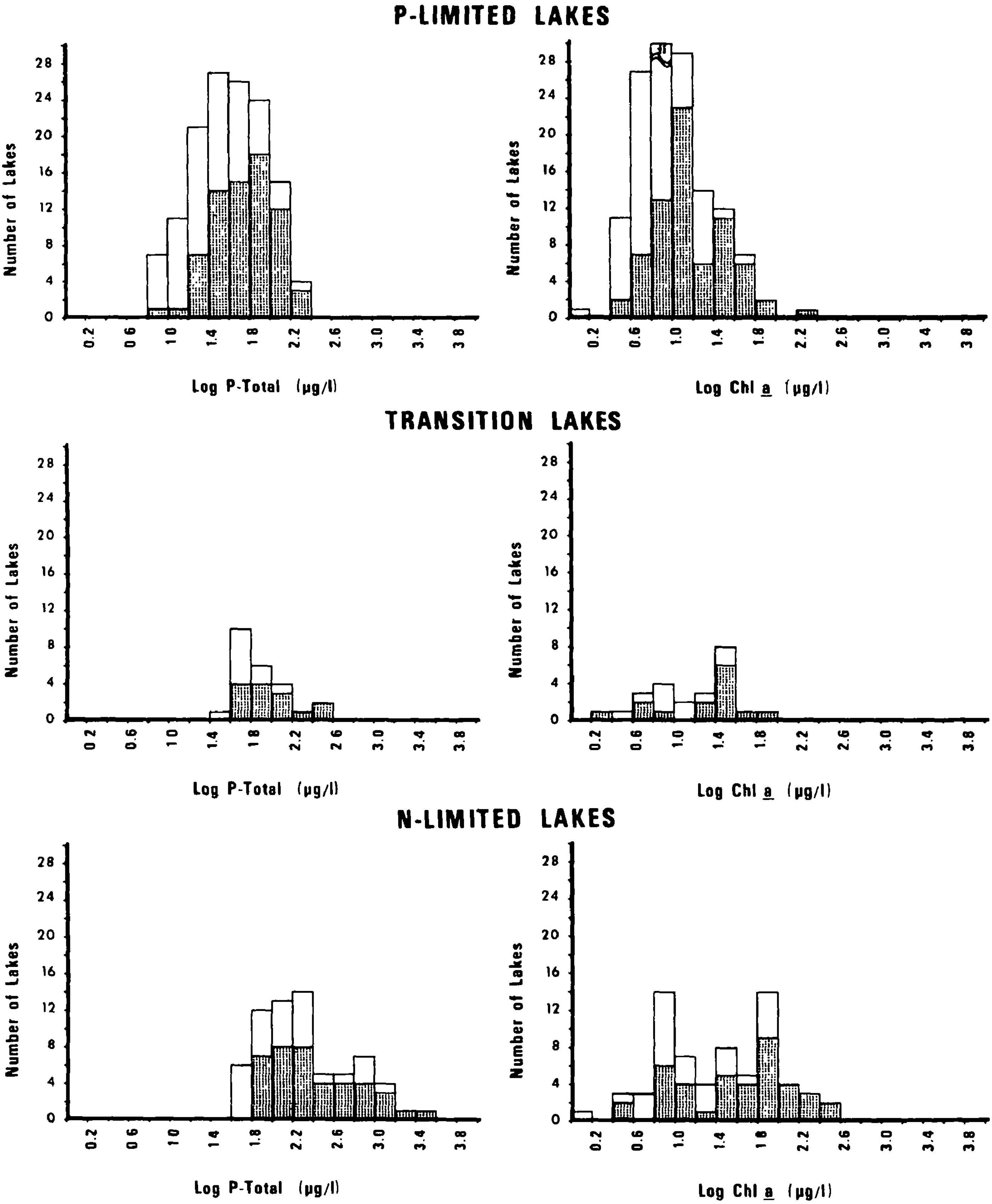

Figure 4. Distribution of algal blooms by phosphorus and chlorophyll a levels in southeastern NES lakes (problem lakes shaded).

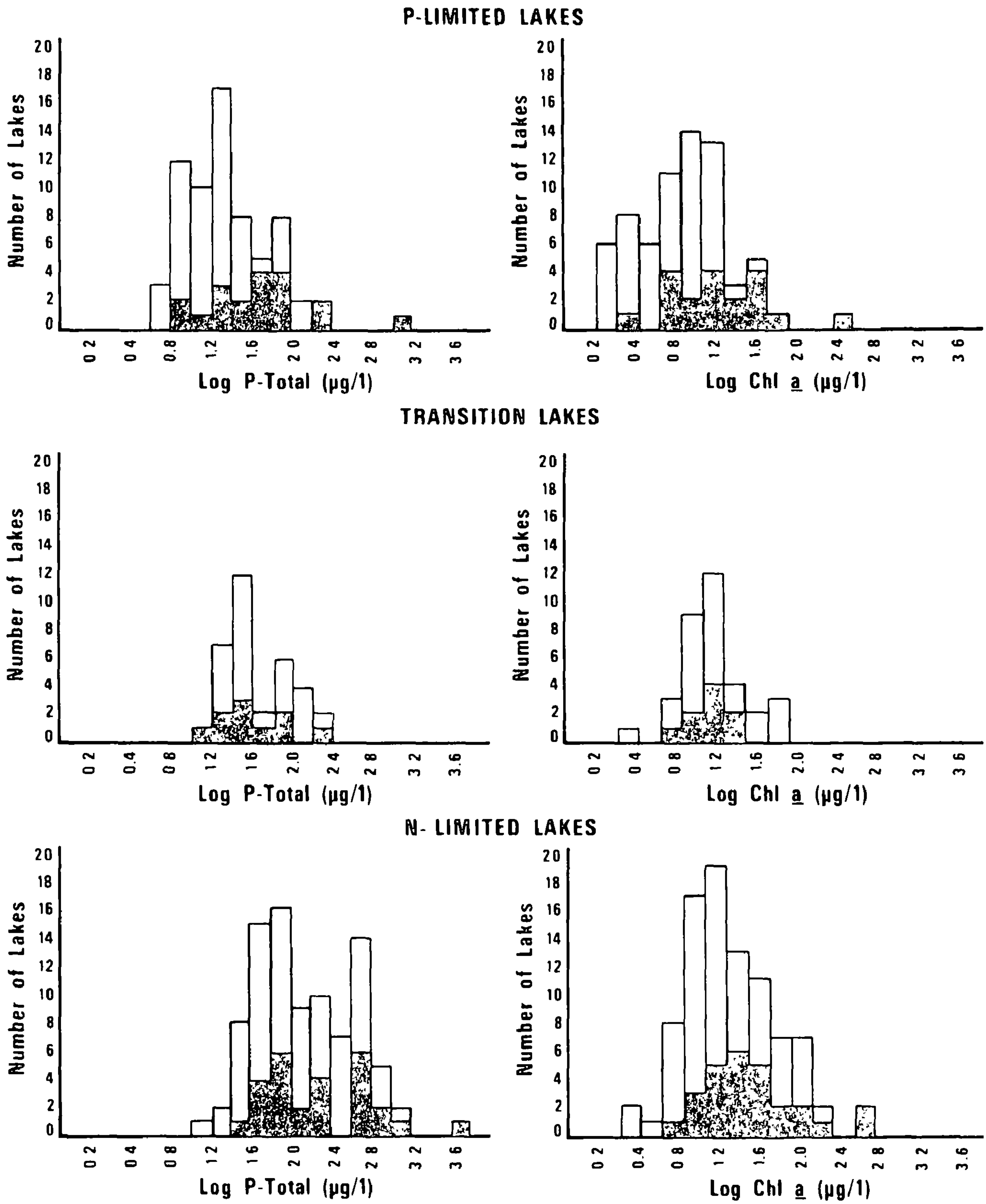

Figure 5. Distribution of dissolved oxygen problems by phosphorus and chlorophyll a levels in northeastern NES lakes (problem lakes shaded).

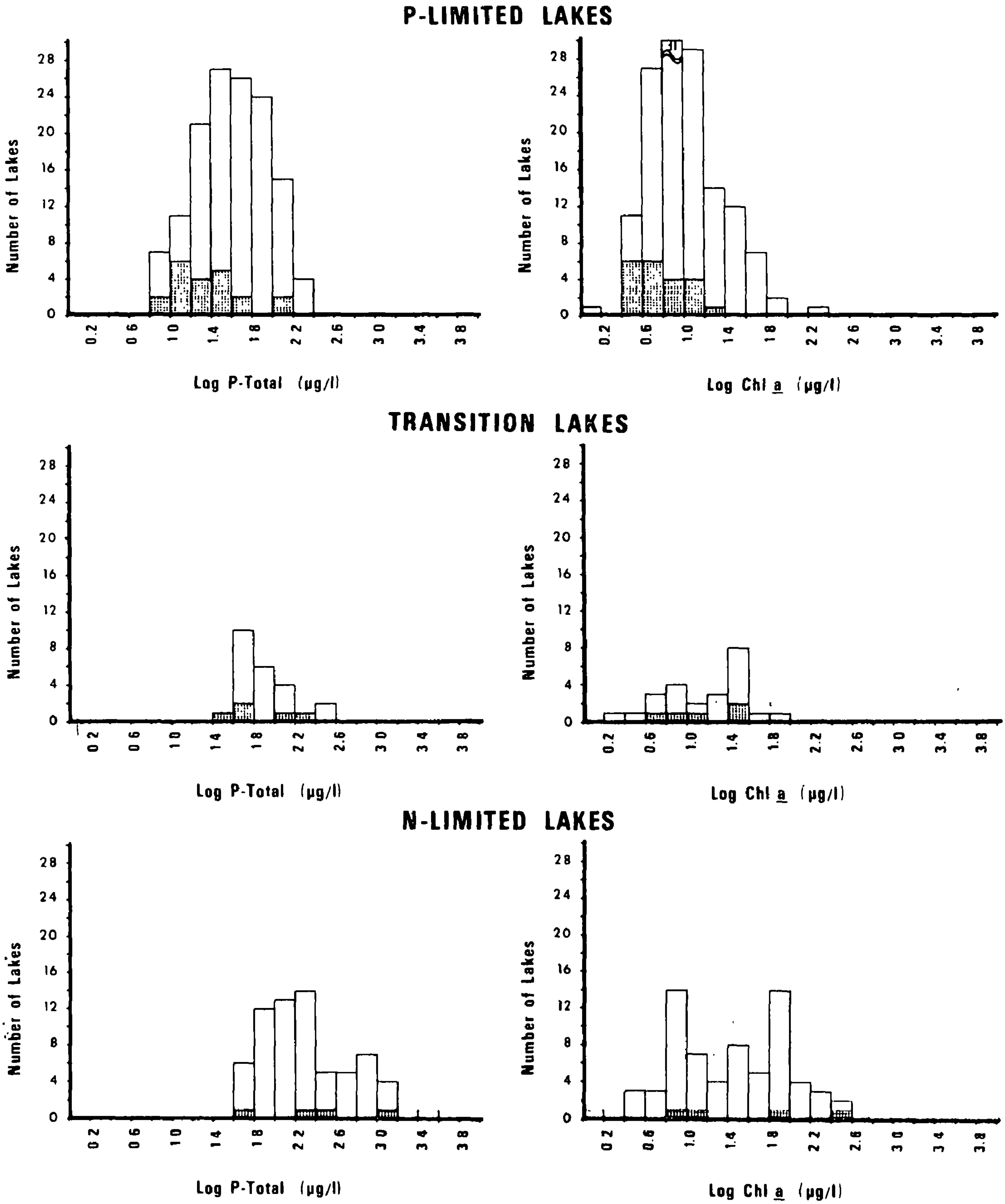

Figure 6. Distribution of dissolved oxygen problems by phosphorus and chlorophyll a levels in southeastern NES lakes (problem lakes shaded).

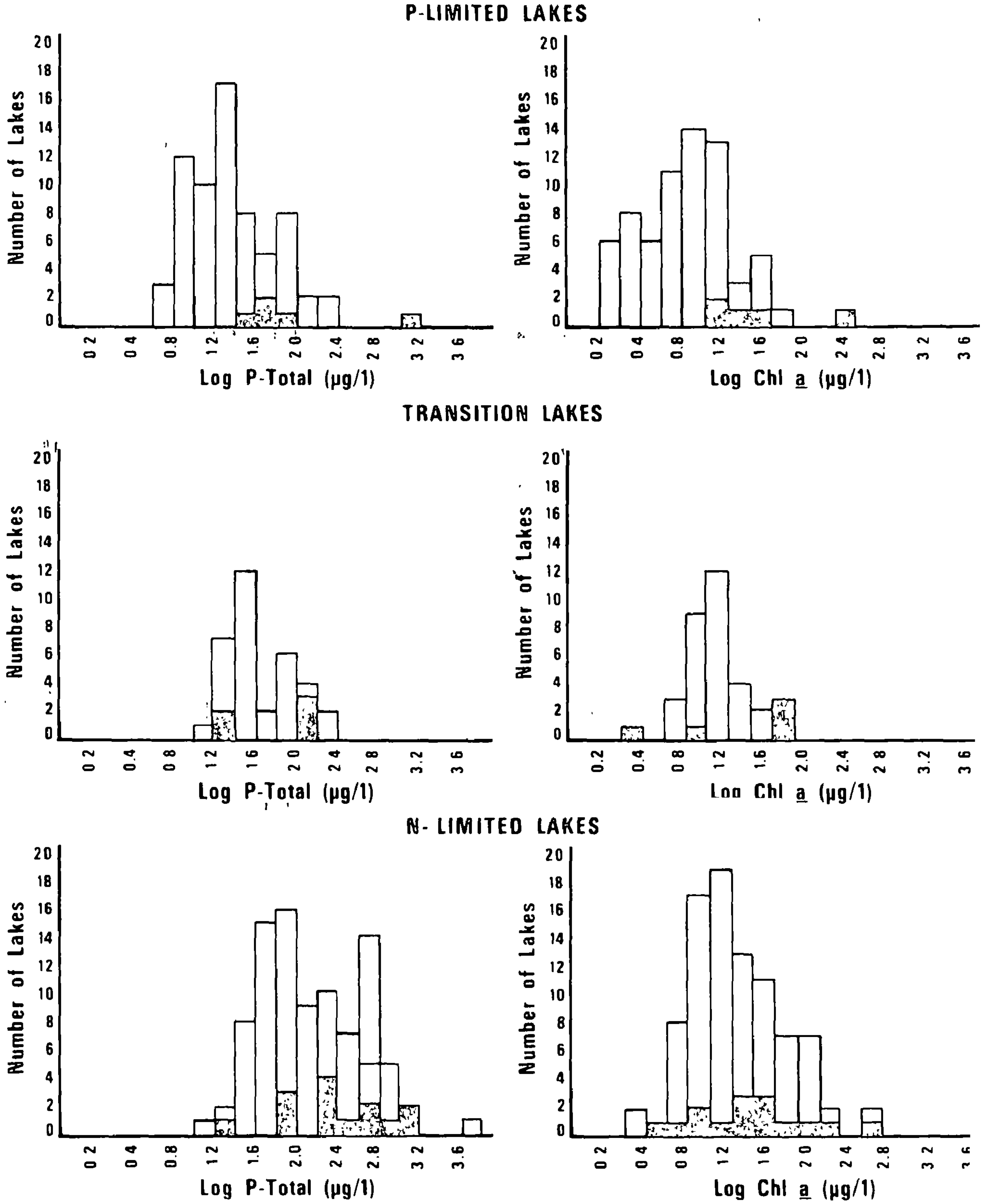

Figure 7. Distribution of reported fishkills by phosphorus and chlorophyll a levels in northeastern NES lakes (problem lakes shaded).

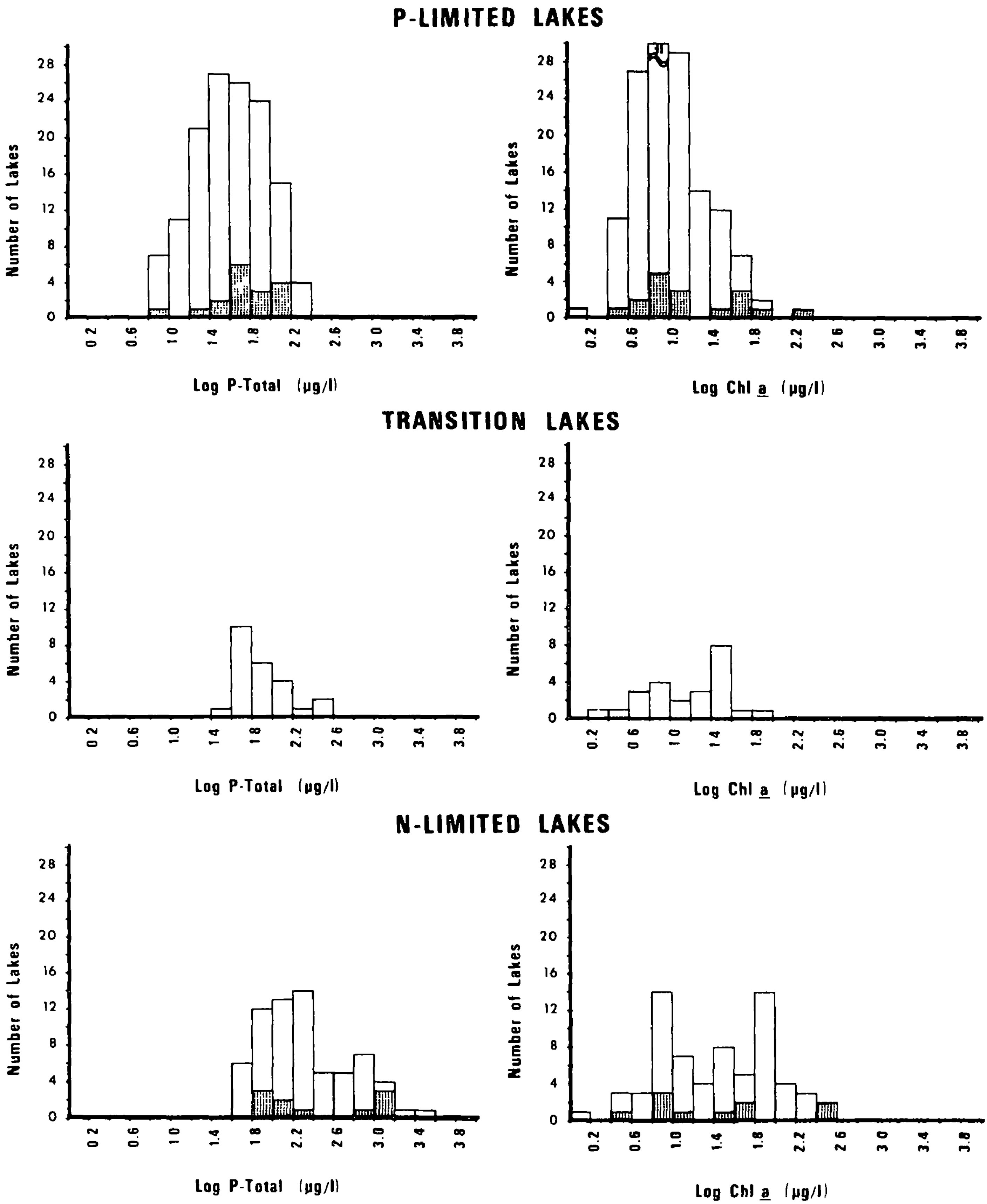

Figure 8. Distribution of reported fishkills by phosphorus and chlorophyll a levels in southeastern NES lakes (problem lakes shaded).