Trophic State Classification of Lakes with Aquatic Macrophytes[1]

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We developed an approach for assessing the trophic status of lakes having growths of aquatic macrophytes because conventional criteria for classifying trophic state emphasize conditions in the open water and ignore the nutrients, plant biomass, and production associated with macrophytes. We propose that a potential water column nutrient concentration be determined through adding the nutrients contained in macrophytes to those in the water. Potential nutrient concentrations can be used in existing indices to classify lake trophic status. This approach permits a first approximation of the potential impact of macrophytes on lake trophic state.

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Parce que les critères conventionnels de classification de l'état trophique des lacs mettent l'accent sur les conditions existant en eau libre et ignorent les substances nutritives, la biomasse végétale et la production associée aux macrophytes, nous avons mis au point une approche de l'évaluation de l'état trophique de lacs riches en macrophytes aquatiques. Nous proposons qu'on détermine une concentration potentielle de nutriments dans la colonne d'eau en ajoutant ceux contenus dans les macrophytes à ceux présents dans l'eau. Les concentrations potentielles de substances nutritives peuvent être utilisées dans les indices actuels pour classifier l'état trophique d'un lac. Avec cette approche, on peut faire une première approximation de l'impact possible des macrophytes sur l'état trophique d'un lac.

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OUR purpose in this paper is to present an approach for assessing the trophic status of lakes having growths of aquatic macrophytes. An objective trophic state classification system for lakes has long been sought by limnologists to rank and compare lakes with different structural and functional characteristics (Naumann 1919, 1932; Thienemann 1921; Birge and Juday 1927). In recent years, several trophic classification systems have been developed to characterize lakes and to predict their future conditions given various anthropogenic activities (Likens 1975; Carlson 1977, 1979; Walker 1979; Forsberg and Ryding 1980). Although these systems have several advantages including minimal data requirements, sensitivity in ranking trophic status, and ease of interpretation, they give no consideration to aquatic macrophytes. These plants, however, are an important biological component of many lakes (Wetzel 1964; Wetzel and Hough 1973). Except for the Lake Evaluation Index (Porcella et al. 1979), current methods use only the classical trophic state indicators of open-water nutrient concentrations, algal biomass, and transparency, which emphasize conditions in the pelagial zone. Even the Lake Evaluation Index, which includes a term for the percent macrophyte coverage, gives no consideration to nutrients, plant biomass, or production associated with macrophytes.

Errors in trophic state assessment will be small in lakes where macrophytes are confined to small littoral areas, but large errors can result in macrophyte-dominated lakes. This occurs because nutrient and chlorophyll concentrations can be low and Secchi disc transparency can be high in waters where there is an abundance of macrophytes. Under these conditions existing trophic classification systems would

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TABLE 1. Generalized trophic state classification standards (modified from Forsberg and Ryding 1980).

Trophic status	Total phosphorus ($mg \cdot m^{-3}$)	Total nitrogen ($mg \cdot m^{-3}$)	Chlorophyll *a* ($mg \cdot m^{-3}$)	Transparency (m)
Oligotrophic	<15	<400	<3	>4.0
Mesotrophic	15–25	400–600	3–7	2.5–4.0
Eutrophic	>25	>600	>7	<2.5

TABLE 2. Average chemical conditions for the surface waters of six Florida lakes between September 1979 and August 1980 (Canfield 1981).

Lake	pH	Total alkalinity ($mg \cdot L^{-1}$ as $CaCO_3$)	Total hardness ($mg \cdot L^{-1}$ as $CaCO_3$)	Total P ($mg \cdot m^{-3}$)	Total N ($mg \cdot m^{-3}$)	Chlorophyll *a* ($mg \cdot m^{-3}$)	Secchi depth (m)
Down	6.5	3	63	8	310	1.0	6.2
Fairview	8.0	52	65	15	450	2.5	4.8
Kerr	6.1	3	23	13	220	1.5	3.3
Lochloosa	7.4	23	31	36	1200	32	0.7
Okahumpka	8.3	50	60	14	880	5	1.2[a]
Stella	7.0	16	72	13	460	3	4.1

[a]Secchi depth represents bottom readings.

underestimate the lake's trophic status. For example, Secchi disc transparencies were greater than 5 m, total phosphorus concentrations averaged 11 $mg \cdot m^{-3}$, and chlorophyll *a* concentrations were less than 3 $mg \cdot m^{-3}$ in Lake Baldwin, Florida, when abundant growths (156 g dry $wt \cdot m^{-2}$) of hydrilla (*Hydrilla verticillata*) covered 80% of the lake's bottom (J. V. Shireman, unpublished data). For these conditions, trophic state index (TSI) values would be low and the lake would be classified as oligotrophic (Table 1) even though the abundance of hydrilla clearly demonstrates that the lake is productive. Current trophic classification systems only classified Lake Baldwin as eutrophic after the loss of hydrilla resulted in a structural and functional shift to plankton. Secchi disc transparencies decreased to less than 2 m, total phosphorus concentrations averaged 30 $mg \cdot m^{-3}$, and chlorophyll *a* values averaged 21 $mg \cdot m^{-3}$.

We propose, therefore, that as a preliminary approach the trophic status of lakes having growths of aquatic macrophytes may be assessed by adding the nutrients in the macrophytes to the nutrients in the water. This approach is consistent with Hutchinson's (1969) suggestion that trophic state determinations should be based on the total potential concentrations of nutrients in the lake, since low concentrations in the water may result because part of the lake's nutrient supply is located elsewhere (e.g. sediments or in the bodies of organisms such as macrophytes). It is also consistent with methods that use in-lake nutrient concentrations determined by nutrient loading, hydrology, and lake morphology as a major component of trophic state assessment (Dillon 1975; Vollenweider 1976). Our approach may also provide a basis for predicting the nutrient content and algal biomass of lakes when natural factors or management practices alter macrophyte abundance.

Materials and Methods

During September and October 1981 (the period of peak macrophyte abundance in Florida lakes), we sampled six Florida lakes with different limnological characteristics (Table 2) to determine the biomass of submersed aquatic macrophytes. In each lake, vegetation coverage was determined along transects that crossed different areas of the lake by use of a Raytheon DE-719 fathometer (Maceina and Shireman 1980). Along the fathometer transects, buoys (30–50 depending on lake size and the extent of macrophyte coverage) were placed in areas representing different macrophyte abundance. At each buoy, a single plant biomass sample was taken with a biomass sampler (Nall and Schardt 1978) modified to include an improved sampling bucket designed by the U.S. Army Engineer Waterways Experiment Station (Vicksburg, MS). Surface water (0.5 m) samples were collected randomly for determination of lake phosphorus concentrations. Phosphorus was emphasized as the criterion for trophic state assessment because phosphorus is often the limiting nutrient in lakes (Dillon and Rigler 1974; Jones and Bachmann 1976; Canfield 1981) and our study lakes had nitrogen–phosphorus ratios greater than 10 (Table 2), thus suggesting phosphorus limitation. Nitrogen, however, could be used in nitrogen-limited lakes (see Kratzer and Brezonik 1981). All water and plant samples were placed on ice until they could be analyzed the next day.

In the laboratory, plant samples were thoroughly rinsed, separated by species, and dried at 70°C to a constant weight. Each sample was weighed and plants were ground in a Wiley Mill until fragments were <0.85 mm. Phosphorus analysis of plant tissue (100 mg) included a 1-h digestion on a Tecam DG-1 digestion block at 350°C with a 1 mL of 20% H_2SO_4. After cooling, samples were reheated for 15 min with 1 mL of 30% H_2O_2. This procedure was repeated until the sample became clear. Total phosphorus concentrations were then determined with an ascorbic acid–molybdate reduction method modified from Mehlich (1978) and the American Public Health Association (1976). Surface water samples were analyzed for total phosphorus by using the procedures of Murphy and Riley (1962) with a persulfate digestion (Menzel

and Corwin 1965).

The total biomass of submersed aquatic macrophytes in each lake was determined by

$$(1)\quad \mathrm{TSMB} = \mathrm{SA} \times \mathrm{C} \times \mathrm{B}$$

where TSMB = total submersed macrophyte biomass (kilograms), SA = lake surface area (square metres), C = percent cover of submersed aquatic macrophytes, and B = average macrophyte biomass collected with the biomass sampler (kilograms per square metre). The value C was calculated from the fathometer transect data by

$$(2)\quad \mathrm{C} = \sum_{a=1}^{N} (\mathrm{WF}_a \times \%\mathrm{TC}_a)$$

where WF = individual transect length (metres) divided by the sum of all transect lengths (metres) and %TC = vegetated length of transect (metres) divided by the transect length (metres). To determine the quantity of phosphorus contained in the macrophyte beds of each lake, we first estimated the biomass of the individual species by multiplying our estimates of total submersed macrophyte biomass by the proportion each individual species contributed to the samples taken with the biomass sampler. We then multiplied the biomass estimates of the individual species by the average phosphorus content of the species, as determined by our tissue analyses. Values are given in Table 3. These estimates were summed to obtain a value for the total amount of phosphorus associated with macrophytes in the lake. To estimate the total phosphorus content of the water column (WCP values), mass balance calculations were made by using measured lake volume, the phosphorus content of the water, and the phosphorus content of the macrophytes assuming 100% decomposition (Jewell 1971; Hill 1979) and recycling into the water column. Although there are errors associated with the measurement of total phosphorus in the water and plants, the largest source of error in estimating WCP values is generally associated with the estimate of macrophyte biomass. To calculate empirical 95% confidence limits for our WCP values, we assumed that all the error was in the estimate of total submersed macrophyte biomass. Phosphorus content of the sediments was not considered.

Results and Discussion

In our lakes, total submersed macrophyte biomass ranged from 18 100 kg dry wt in Lake Kerr to 2 170 000 kg dry wt in Lake Lochloosa (Table 4). For our calculated potential water column phosphorus concentrations, 20–96% of the phosphorus was in the submersed macrophytes and WCP values were 1.2–26 times the measured open-water concentrations (Table 4). Based on these data, there is considerable organic matter and nutrients associated with aquatic macrophytes. The effect of these macrophytes on WCP values and, therefore, trophic state assessment depends on the amount of macrophytes relative to the total lake volume. For example, Lake Fairview has extensive growths (49 g dry wt·m^{-3}) of hydrilla, pondweed (*Potamogeton illinoensis*), and stonewort (*Nitella* sp.). Using our measured open-water total

TABLE 3. Comparison of lake macrophyte species. B, individual species biomass in kg dry wt; %P, percent phosphorus content; P, phosphorus standing crop in kg; NC, not collected.

Macrophyte species	Lake																	
	Down			Fairview			Kerr			Lochloosa			Okahumpka			Stella		
	B	%P	P	B	%P	P	B	%P	P	B	%P	P	B	%P	P	B	%P	P
Hydrilla verticillata	NC	—	—	134 000	0.14	188	9 296	0.40	37	2 170 000	0.26	5 640	492 000	0.21	1 033	138 000	0.13	179
Najas guadalupensis	NC	—	—	253	0.11	0.28	NC	—	—	NC	—	—	NC	—	—	NC	—	—
Ceratophyllum demersum	NC	—	—	8	0.22	0.02	417	0.41	1.7	NC	—	—	255	0.22	0.56	612	0.19	1.2
Potamogeton illinoensis	NC	—	—	49 800	0.14	70	NC	—	—	NC	—	—	4 640	0.17	7.9	NC	—	—
Vallisneria americana	NC	—	—	NC	—	—	NC	—	—	NC	—	—	2 720	0.20	5.4	83	0.29	0.24
Mayaca aubletii	82 600	0.16	132	NC	—	—	3 860	0.26	10	NC	—	—	NC	—	—	NC	—	—
Bacopa caroliniana	NC	—	—	NC	—	—	3 440	0.35	12	NC	—	—	NC	—	—	NC	—	—
Egeria densa	NC	—	—	NC	—	—	18	0.17	.03	NC	—	—	NC	—	—	NC	—	—
Myriophyllum pinnatum	NC	—	—	NC	—	—	326	0.17	.55	NC	—	—	NC	—	—	NC	—	—
Eleocharis baldwinnii	NC	—	—	NC	—	—	561	0.38	2.1	NC	—	—	NC	—	—	NC	—	—
Sagitaria subulata	NC	—	—	1 000	0.13	1.3	235	0.53	1.3	NC	—	—	NC	—	—	NC	—	—
Nitella sp.	NC	—	—	25 000	0.16	40	NC	—	—	NC	—	—	NC	—	—	NC	—	—
Filamentous algae	166	0.05	0.08	463	0.13	0.60	NC	—	—	NC	—	—	NC	—	—	NC	—	—

TABLE 4. Comparison of total submersed macrophyte biomass (TSMB), total submersed macrophyte phosphorus (TSMP), surface area (SA), volume (V), measured total phosphorus concentration (TP), potential water column phosphorus assuming 100% release of phosphorus from the macrophytes (WCP), and macrophyte concentration (TSMB·V^{-1}) measured in six Florida lakes during September–October 1981. Numbers in parentheses for TSMB are 95% confidence intervals. For other variables, numbers represent empirical 95% confidence intervals calculated assuming all errors are associated with measurements of TSMB.

Variable	Lake					
	Kerr	Down	Stella	Lochloosa	Fairview	Okahumpka
TSMB (kg dry wt)	18 100 (±6100)	82 800 (±17 700)	139 000 (±30 000)	2 170 000 (±530 000)	211 000 (±48 500)	500 000 (±118 000)
TSMP (kg)	65 (±22)	132 (±28)	180 (±39)	5 640 (±1380)	300 (±69)	1 050 (±250)
SA (ha)	1 130	360	123	2 190	114	208
V (m^3)	42 000 000	12 000 000	4 300 000	46 000 000	4 300 000	2 600 000
TP (mg·m^{-3})	8	9	12	25	10	16
WCP (mg·m^{-3})	9.6 (±0.5)	20 (±2)	54 (±9)	148 (±30)	80(±16)	420 (±96)
TSMB·V^{-1} (g dry wt·m^{-3})	0.4 (±0.2)	7 (±1)	32 (±7)	47 (±12)	49 (±11)	192 (±46)

phosphorus concentrations (10 mg·m^{-3}) and the criteria in Table 1, the lake would be classified as oligotrophic and have a Carlson (1977) TSI value of 37. By use of our calculated WCP value (80 mg·m^{-3}), however, the lake would be classified as eutrophic and have a Carlson (1977) TSI value of 67, which is similar to other lakes located in the same physiographic region (Canfield 1981). In contrast, macrophyte abundance in Lake Kerr is negligible (0.4 g dry wt·m^{-3}). If the phosphorus contained in the macrophytes was released to the open water the WCP value would only be 1.6 mg·m^{-3} higher than the measured total phosphorus concentration of 8 mg·m^{-3} (Table 4). This would not appreciably alter the lake's trophic state classification.

To determine if our calculated WCP values provide reasonable estimates of open-water phosphorus concentrations when macrophyte abundance is low, we compared our WCP values to open-water phosphorus concentrations measured in other lakes located in the same physiographic region (Table 5). We made this comparison because studies of regional limnology have demonstrated relationships between regional physiography and surface geology (edaphic factors) and the chemical composition and productivity of lakes located in different lake districts (Deevey 1940; Moyle 1956; Jones and Bachmann 1978). In each region, maximum measured phosphorus values are from lakes with low macrophyte abundance. With the exception of Lakes Okahumpka and Stella, WCP values are within the range of measured open-water phosphorus values and generally similar to the phosphorus-rich lakes that have few macrophytes. Lake Stella is the only lake in its region receiving urban runoff, which may account for the WCP value being higher than observed phosphorus concentrations. We do not know why the WCP value in Lake Okahumpka is greater than maximum phosphorus values in the region, but Lake Okahumpka is situated in an area of poorly drained, nutrient-rich organic soils. Where these soils occur in Florida, phosphorus values similar to Lake Okahumpka's WCP concentrations can be found (U.S. Environmental Protection Agency 1978; Canfield 1981), which indicates that the calculated value may not be unreasonable.

We also compared our predicted WCP value with the measured open-water phosphorus concentration in Lake Baldwin, Florida, where submersed macrophytes were removed by use of grass carp (*Ctenopharyngodon idella*). In 1978, Lake Baldwin supported approximately 100 000 kg dry wt of hydrilla, which contained 140 kg of phosphorus (Shireman and Maceina 1981; J. V. Shireman, unpublished data). Open-water phosphorus values averaged 11 mg·m^{-3}. Based on these data, the WCP value for Lake Baldwin would be 52 mg·m^{-3}. After hydrilla was virtually eliminated by the grass carp, the open-water phosphorus concentration in the lake averaged 30 mg·m^{-3}, substantially lower than the calculated WCP value. However, our predicted phosphorus concentration did not account for the phosphorus retained by the grass carp (72 kg) (J. V. Shireman, unpublished data). Correcting for this, Lake Baldwin's WCP value would be 31 mg·m^{-3}, which agrees with the measured phosphorus concentration.

From these data and those in Tables 4 and 5, we suggest that the importance of using WCP values to evaluate the

TABLE 5. Comparison of potential water column total phosphorus concentrations (WCP) for the study lakes with measured phosphorus concentrations in lakes located in the same geologic and physiographic region. Data taken from Canfield (1981). Numbers in parentheses are empirical 95% confidence limits (see Table 4). *N* is number of lakes sampled.

	Phosphorus concentrations ($mg \cdot m^{-3}$)			
		Observed in other lakes		
Lake	WCP	Minimum	Maximum	*N*
Kerr	9.6 (±0.5)	0.1	35	4
Down	20 (±2)	2.1	25	8
Stella	54 (±9)	0.5	25	4
Fairview	80 (±16)	3.7	98	8
Lochloosa	148 (±30)	10	209	28
Okahumpka	420 (±96)	1.0	54	5

trophic status of lakes having aquatic macrophytes is directly related to the macrophyte abundance per volume of lake or epilimnion (our lakes were not thermally stratified). Our analysis indicates that macrophytes have little effect on trophic state assessment when <25% of the phosphorus in the water column is associated with macrophytes and the mean macrophyte concentration in the lake is less than 1 g dry $wt \cdot m^{-3}$ (Table 4). We cannot at this time, however, provide definitive criteria for when WCP values should be considered in lake assessment. Until more lakes are sampled to provide such criteria, we believe that decisions to use WCP values should be made on the basis of the extent of macrophyte coverage (percent of surface area) in relation to lake volume. For large deep lakes with small littoral areas, the effect of macrophytes on the assessment of lake trophic state will be negligible. Our approach, however, is likely to be most useful when classifying shallow macrophyte-dominated lakes.

There are, however, several problems associated with the use of WCP values. Similar to other classification systems based on a single criterion, information on the structural and functional characteristics of the biotic community may be lost when multivariate observations are summarized by a single parameter. This can be especially important when considering aquatic macrophytes because these plants have a different effect on lake productivity, nutrient cycling, and perceived trophic state characteristics than do phytoplankton. Another problem is that our approach may overestimate the trophic status of some lakes. Certain macrophytes can mobilize phosphorus from the sediments (Carignan and Kalff 1980). If these plants transport nutrients deposited during earlier periods of high nutrient loading into the stems and leaves, our trophic state assessment would not match assessments based on current nutrient loading rates. We also assumed that 100% of the phosphorus in the macrophytes would be released to the overlying water. Phosphorus release from macrophytes during die-off and decomposition, however, need not be 100% (Landers 1982); thus, phosphorus concentrations in the water following a reduction in macrophyte abundance may be less than calculated WCP values. Estimating WCP values is also a labor-intensive process (accurate measures of macrophyte biomass requires the collection of numerous samples) that is inconsistent with current approaches to trophic state classification, which require minimal data (Carlson 1977; Kratzer and Brezonik 1981; Osgood 1982).

Despite the potential problems of using WCP values, we know of no simple quantitative method for assessing the trophic status of lakes having growths of aquatic macrophytes. Until research can develop a simpler alternative, we feel that our approach reduces the danger that inappropriate assessments of trophic status will be made for macrophyte-dominated lakes. This is especially important because regulatory and management decisions are often made using open-water nutrient, chlorophyll *a*, and Secchi disc transparency data obtained from surveys of regional limnology. Values for WCP may also prove useful for predicting the impact of changes in macrophyte abundance on limnological characteristics when the nutrient supply to the lake remains unchanged. Currently, there is no method to evaluate how open-water nutrient concentrations, chlorophyll *a* values, and Secchi transparencies will change with partial to complete removal of macrophyte biomass by natural factors or management practices (harvesting, herbicides, or herbivores). Using WCP values in conjunction with simple empirical nutrient–chlorophyll and chlorophyll–Secchi models (Dillon and Rigler 1974; Jones and Bachmann 1976, 1978; Smith 1982) may provide the quantitative approach needed to estimate a lake's response to a given level of macrophyte removal.

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