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Nitrogen Limitation of Algal Standing Crop in Strip Mine Lakes

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ABSTRACT

Water quality of anthropogenic lakes is an important issue in Illinois. The nature of these lakes and their often unusual biotic and abiotic conditions can influence the rate of primary productivity and sustainability of fish populations. This is of concern for statewide lake management efforts, recreational anglers, and the aquaculture industry. The purpose of this study is to provide information, which will aid in improving the water quality of artificial bodies of water. Twenty-four abandoned strip mine lakes at Ten Mile Creek Fish and Wildlife Area (TMCFWA) were sampled from March 3-5, 2000. Samples were analyzed in accordance with standard methods for chemical and physical properties. Cluster analysis was used to identify lakes that make up homogenous groups which could be suitable for future lake management studies. Carlson's Trophic State Index suggests that sufficient phosphorus is available to support higher phytoplankton density. In contrast to most freshwater systems, our results showed that nitrogen limitation (indicated by a low nitrogen to phosphorus ratio) is the defining factor affecting production in these lakes. However, as conditions will most likely vary on a seasonal basis, temporal extrapolation of our results might not be possible until further study affords a better understanding of the lentic ecosystems of TMCFWA.

Key Words: strip mine lakes, trophic state, nutrient limitation, algae
Running Head: Strip mine lakes

INTRODUCTION

Ten Mile Creek Fish and Wildlife Area (TMCFWA), an abandoned strip mine now administered by the Illinois Department of Natural Resources (IDNR), is a potentially suitable site for addressing a number of questions relative to factors that influence the functioning of lentic systems. Purchased in 1988 from the Tennessee Valley Authority (TVA), Ten Mile Creek is located in southeastern Jefferson and northwestern Hamilton Counties (IL). This 2112 ha. site is comprised of several habitat types including cropland (1052 ha.), open non-cultivated areas (664 ha.), forest (538 ha.), as well as ponds/lakes (101 ha.). TMCFWA is divided to four management units, Eads, Belle Rive, Dahlgren, and Goshen Trail. Each site consists of a central area and a number of smaller surrounding tracts.

Strip mining operations have occurred on approximately one-third of the total area of TMCFWA, with most activity occurring on the Eads unit. The mined areas, all within Jefferson County, have been reclaimed to varying degrees under both old and new reclamation standards. Some areas have been returned to flat agricultural fields, while others remain steeply sloped and contain numerous lakes and ponds. Revegetation practices have been implemented to stabilize soil as well as to provide forage and cover for wildlife. Plantings have included grasses, legumes, fescue, corn, cattails, and several tree species including willow, black locust, and various oaks. In addition, portions of the cropland are enrolled in tenant lease programs to further conserve the soil and to address the needs of wildlife.

Aquatic areas consist of over twenty-five strip mine lakes, which vary in size from less than one to over eighteen hectares and have depths ranging from less than one to nearly seven meters. Little is known about other morphometric features of these lakes; however, strip mine lakes generally are quite deep with small surface area. Furthermore, these lakes often are very acidic and fairly devoid of life (Miller et. al. 1996). A number of the TMCFWA lakes contain fish species such as large and smallmouth bass, channel catfish, crappie, bluegill, green sunfish, and blackstripe topminnow. Lakes are managed by the IDNR in a variety of ways ranging from stocking the lakes with the aforementioned fish species, fertilization, and/or herbicide application.

Our primary objective was to determine if the lakes at TMCFWA are homogeneous, if they can be grouped into discrete categories, or if they are in fact each a unique physical, chemical, and biological environment. In addition, we hope to ascertain which, if any, abiotic variable has primacy in controlling productivity and the phytoplankton standing crop. Lastly, and possibly most importantly, since most lakes and ponds in Illinois are of an anthropogenic origin, results we generate could be generalized to provide direction for management of lakes and ponds to maintain maximum aquatic biodiversity in Illinois.

METHODS

Twenty four lakes located on the Eads unit of the Ten Mile Creek State Fish and Wildlife Area (TMCFWA) were sampled from March 3-5, 2000 (Fig 1). When available, lake identification numbers and estimated surface areas were obtained from the IDNR (Kurt Daine, personal communication). If not available, lake identification numbers were assigned based on proximity to the nearest lake with an established number. Global Positioning System (GPS) coordinates and maximum depth of a single centrally located sampling site were recorded for each lake (Table 1) because in general, " One centrally located station adequately represents open-water chemical and biological characteristics" (Pederson et al., 1976).

All samples were collected and evaluated according to standard methods (APHA 1995). Surface water grab samples were collected in acid-rinsed 1L glass bottles from approximately 33 cm beneath the surface. Bottom samples were collected using a transparent PVC Van Dorn sampler suspended approximately 33 cm from the lake bottom. Samples were stored at 4° C in dark conditions until analyzed (1-6 days). Temperature, dissolved oxygen (DO), pH, and conductivity profiles were measured with a YSI 60 water quality analyzer at 1 m increments. Maximum depth was determined using a hand held sonar unit, and Secchi depth (SD) was recorded.

Within 12 h of sample acquisition, alkalinity, hardness, and turbidity of surface and bottom samples were determined by acidity color change, EDTA titrimetric method, and a La Motte 2020 Turbidity meter, respectively. Phytoplankton were concentrated by filtering 100 mL of surface sample through a Gelman GA-6 metricell membrane filter (pore size = 0.45 μm, D=45 mm) and stored at 0° C for later determination of pigment concentrations.

Lab analyses were conducted from March 6-9, 2000. Solids fractions, total phosphorus (TP), and total oxidized nitrogen (TON) were determined for surface and bottom samples. Subsamples ranging from 150-250 mL (depending on turbidity of the sample) were passed through a rinsed, dried, and pre-weighed 25 mm glass fiber filter housed in a Gooch crucible. Samples were oven-dried at 103° C for 1 h, cooled in a dessicator, and then weighed for use in determination of total suspended solids (TSS). Subsamples of 70 mL were poured into in a 100 mL pre-weighed porcelain evaporating dish, placed in a drying oven at 90° C for 1 h, and then dried at 103° C for 24 h. Subsequently samples were cooled to room temperature in a dessicator and weighed to determine total solids (TS). Total dissolved solids (TDS) were calculated as the differences between TS and TSS. Phosphate-phosphorus was determined via the ascorbic acid colorimetric procedure followed by the persulfate digestion method. Total oxidized nitrogen (NO_2-N+NO_3-N) was determined using the cadmium reduction method. Chlorophyll was extracted from phytoplankton previously concentrated on membrane filters using a 4:1 mixture 90 % acetone:DMSO extracts and then analyzed spectrophotometrically. Concentrations of chlorophyll *a*, *b*, and *c* were calculated according to the trichromatic equations and phaeophytin *a* was estimated by the monochromatic equation.

Trophic State Indices (TSI) were calculated based on SD (TSI_{SD}), chlorophyll *a* concentrations (TSI_{chl}), and total phosphorus (TSI_{TP}) according to Carlson (1977). Statview was used to create a correlation matrix of all variables and correlation analyses. Simple regression analysis was used to investigate potential cause and effect relationships between highly correlated variables. Cluster analyses were conducted using Data Desk 4.1 in order to identify groups of lakes which most closely resemble each other based on a limited subset of values.

RESULTS

Correlation analysis revealed several significant relationships among those variables which were measured in 24 lakes at Eads unit (Table 2). However, most of those correlations which were significant appeared to be uninformative and revealed already established relationships (Table 3). For example, surface conductivity was positively correlated with TS (r = 0.994) and hardness (r = 0.829), while turbidity of surface water samples was inversely related with SD (r = -0.775). Variables used in cluster analysis were alkalinity, N:P ratio, chlorophyll *a*, pH, conductivity, DO, SD, and temperature.

We found little correspondence of TSI values calculated from chlorophyll *a*, SD, and TP (Table 4). The original intent of Carlson's TSI (Carlson 1977) was to provide a numerical scale, thereby eliminating the need for somewhat arbitrary typological classification of lakes. Nonetheless, lakes with TSI values of 0-40 are generally considered oligotrophic, those with a TSI of 40-50 are mesotrophic, and 50 and above indicate eutrophy (Carlson 1979). Based on our data, TSI_{SD} indicates that all but one of the lakes are eutrophic whereas TSI_{TP} categorizes 12 lakes as eutrophic, 10 as mesotrophic, and 2 as oligotrophic. In contrast, when based on chlorophyll *a*, the TSI_{chl} indicates that all lakes are oligotrophic.

Alkalinity provides an indication of the amount of inorganic carbon in a lake. Total alkalinity ranged from 15 to 170 mg L^{-1} (Fig. 2), and 20 of 24 lakes had total alkalinity in excess of 48 mg $CaCO_3$ L^{-1}. Ratios of available nitrogen to available phosphorus were calculated by dividing total oxidized nitrogen with total phosphorus measured at the surface of each lake. Our results indicate that the N:P ratios in TMCFWA lakes were less than 7:1 in 21 of the lakes sampled (Fig. 3).

DISCUSSION

Cluster analysis is a computer-generated procedure that groups sampling units together based on an overall measure of similarity; ones that are more similar are grouped first and then linked to other clusters that are not as closely related. The greater the distance between clusters, the less related the combined data are. For example, from the observations gathered at the Eads unit, cluster analysis has determined that lakes 107a and 106 are most closely related to one another (Fig. 4). The value of this procedure relates to the future of experimental studies. Using this assessment of similarities, one could possibly determine the effectiveness of management applications, such as fertilization to increase productivity, in order to improve overall lake quality. Since lakes 107a and 106 are so closely related, they can be considered replicates and would be logical choices for evaluating the outcome of lake management procedures. Antithetically, lakes 118b and 116a are so dissimilar from each other and all other lakes that any differences resulting from management techniques would be masked.

In any study which seeks to describe lake trophic state, an important task is to determine which factor controls primary productivity. Inorganic nutrients obviously should be considered because of their essential role in algal metabolism. Hutchinson (1973) states that "eutrophication should mean the process of becoming well-fed" - therefore, a eutrophic lake would have a large supply of nutrients. Characteristics associated with eutrophic lakes are usually related to the resultant elevation of primary productivity which typically is expressed as increased algal standing crop. In contrast, oligotrophic lakes will have low primary productivity (they will be strongly limited by nutrient availability), and mesotrophic lakes will be intermediate to the two typological extremes.

According to Leibig's Law of the Minimum, distribution of a photosynthetic organism or its success (biomass, productivity, etc.) throughout its range is determined by that nutrient which is in shortest supply relative to need (Horne and Goldman 1994). Carbon, nitrogen, and phosphorus are taken up by phytoplankton in accordance with their composition (by weight, plants are composed of 40C:7N:1P (Valentyne 1974)). And while carbon or nitrogen may limit algal growth over shorter periods of time (Parker 1977), most often, phosphorus is limiting on a long-term basis (Schindler 1974, 1975; Schindler and Fee 1974). This is because the watershed normally is the only source of phosphorus, but the atmosphere is an almost limitless reservoir of carbon and nitrogen. Our data provide a means for assessing which of these factors (carbon, nitrogen or phosphorus) controls algal standing crop (and productivity).

Total alkalinity is a measure of the buffering capacity of water and, in lakes with a pH of less than 8.3, alkalinity is due almost entirely to carbonate and bicarbonate buffers (APHA 1985). As a result, alkalinity measurements also can be used as an index of availability of inorganic carbon which derives from either the atmosphere or from dissolution of carbonate bearing substrates (e.g., limestone) in the watershed. According to Moyle (1949), lakes with measured total alkalinity in excess of 48 mg $CaCO_3$ L^{-1} tend not to be limited by carbon availability (Moyle 1949). Therefore, this study shows that no more than four of the lakes we sampled (52112, 52116, 52116a, and 52118b) have the potential for carbon limitation during the spring.

Carlson (1977) developed a trophic state index (TSI) for lakes to be calculated from Secchi depth as well as surface concentrations of total phosphorus and chlorophyll *a*. Given that phosphorus is the limiting nutrient and that Secchi depth is dependent mainly upon phytoplankton density, each variable should provide comparable values when converted to the trophic scale. The indication of eutrophy based on SD in all but one of the lakes sampled at TMCFWA , but of oligotrophy in the same lakes based on chlorophyll *a* suggests that the extent to which light penetrates into the water column may be determined by something other than attenuation by phytoplankton. Furthermore, the indication of at least mesotrophy by data on total phosphorus concentration leads to the conclusion that there is sufficient phosphorus to support greater phytoplankton densities than were observed. Likely something other than phosphorus availability limits productivity in the majority of the lakes we studied.

Mass ratios of available nitrogen to available phosphorus can be used in determining which of these two nutrients is "in short supply relative to need." Chiaudani and Vighi (1974) used algal assays to demonstrate that nitrogen is limiting at mass ratios of less than 5:1, while phosphorus was the limiting nutrient at mass ratios greater than 10:1. Although either nutrient can be limiting if the N:P mass ratio in natural waters is between 5:1 and 10:1, when we define the boundary between likely limitation by nitrogen or phosphorus as 7:1, only three lakes in this study (52119, 52116a, and 52118b) have the possibility of being phosphorus limited during the spring. Rather, algal standing crop at this time of the year most likely is limited by nitrogen availability in nineteen of the 24 lakes we studied.

Information gathered in this study provides a foundation for further research of strip mine lakes. Studies by Burner and Leist (1953) and Gash and Bass (1973) seemed to indicate that surface mine lakes were not productive ecosystems. We concur, but in contrast to most freshwater systems, nitrogen was found to be the limiting factor of algal standing crop in the majority of lakes at TMCFWA. However, because our samples are representative of a discrete time frame, nitrogen limitation may occur only on a seasonal basis. Further, cluster analysis indicates that not all lakes of a given mine site are homogeneous in nature despite their proximity to one another. Based on overall similarity, certain groups of lakes may be presumed to depict replicate sites useful for determining the effects of lake management procedures. But caution should be exercised prior to general application of any technique intended to enhance productivity because inherent differences in lakes may generate uncertainty with regard to anticipated outcome of management.

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Table 1. Maximum depth, area, and GPS location of sampling site for 24 lakes at Ten Mile Creek Fish and Wildlife Area.

DNR Number	GPS Coordinates	Max depth (m)	Area (Ha)	Graph ID #
52100	N 38 12 32 57; W 88 45 41 65	2.6	8.58	1
52101	N 38 12 58 82; W 88 45 35 04	6.5	3.24	2
52102	N 38 13 20 21; W 88 46 09 80	6.7	4.21	3
52104	N 38 13 02 35; W 88 45 44 53	3.8	1.42	4
52105	N 38 12 13 41; W 88 45 20 66	2.5	1.90	5
52106	N 38 12 08 88; W 88 45 27 05	5.3	0.40	6
52107	N 38 12 05 57; W 88 45 32 86	3		7
52111	N 38 13 26 82; W 88 46 28 76	1.6	2.23	8
52112	N 38 13 28 50; W 88 46 20 27	1.6	1.34	9
52113	N 38 13 20 89; W 88 46 18 17	3.5	1.58	10
52116	N 38 12 27 39; W 88 45 22 49	3.5	1.13	11
52117	N 38 12 17 52; W 88 45 25 54	5.6		12
52118	N 38 12 53 15; W 88 45 41 88	3	2.71	13
52119	N 38 12 30 24; W 88 46 09 94	3.6	12.79	14
52100a	N 38 12 42 87; W 88 45 49 10	2.7		15
52100b	N 38 12 43 73; W 88 45 43 76	4.8	0.36	16
52100c	N 38 12 42 98; W 88 45 38 40	3.5	0.36	17
52100d	N 38 12 30 12; W 88 45 51 67	2.4		18
52107a	N 38 12 00 82; W 88 45 30 69	2.3		19
52116a	N 38 13 23 34; W 88 45 21 19	1.8		20
52117a	N 38 12 19 37; W 88 45 39 19	3.5		21
52118a	N 38 12 49 58; W 88 45 56 01	4.3		22
52118b	N 38 12 52 04; W 88 45 58 14	0.7		23
52118c	N 38 12 54 94; W 88 46 01 01	1.1		24

Table 2. Correlation matrix of variables measured in 24 lakes at Ten Mile Creek Fish and Wildlife Area. Description of abbreviations: chlorophyll *a* (Chl a), total phosphorus (PO4-P), hardness (hard), nitrogen/phosphorus (N/P), trophic state index (TSI), Secchi depth (SD), total oxidized nitrogen (TON), top (surface samples), bot (bottom samples).

	Chl *a*	Top PO4-P	Top Hard	Bot Hard	Top N/P	TSI chl *a*	TSI PO4-P	TSI SD	Top TON
Chl *a*	1.000	0.639	0.076	0.115	-0.019	0.860	0.467	0.370	0.064
Top PO4-P	0.639	1.000	-0.071	-0.043	-0.317	0.605	0.852	0.246	-0.202
Top Hard	0.076	-0.071	1.000	0.958	-0.011	0.150	0.077	0.400	0.066
Bot Hard	0.115	-0.043	0.958	1.000	-0.044	0.186	0.108	0.342	0.035
Top N/P	-0.019	-0.317	-0.011	-0.044	1.000	0.071	-0.339	0.266	0.966
TSI chl *a*	0.860	0.605	0.150	0.186	0.071	1.000	0.557	0.610	0.190
TSI PO4-P	0.467	0.852	0.077	0.108	-0.339	0.557	1.000	0.303	-0.129
TSI SD	0.370	0.246	0.400	0.342	0.266	0.610	0.303	1.000	0.369
Top Total Ox N	0.064	-0.202	0.066	0.035	0.966	0.190	-0.129	0.369	1.000

23 observations were used in this computation.
One case was omitted due to missing values.

Table 3. List of determined characteristics for each lake. Department of Natural Resources (DNR), total suspended solids (TSS), total dissolved solids (TDS), total solids (TS), Secchi depth (SD), turbidity (Turb), Temperature (Temp), dissolved oxygen (DO), conductivity (conduct), hardness (Hard), alkalinity (Alk), total oxidized nitrogen (TON), chlorophyll (Chl), Top (surface sample), Bot (bottom sample).

DNR Number	Top TSS (mg L^{-1})	Bot TSS (mg L^{-1})	Top TDS (mg L^{-1})	Bot TDS (mg L^{-1})	Top TS (mg L^{-1})	Bot TS (mg L^{-1})	Top Turb (NTU)	Bot Turb (NTU)	SD (m)
52100	1.40	3.33	59.70	61.70	61.10	65.03	13.40	19.10	0.50
52101	0.08	0.07	36.60	37.60	36.68	37.67	4.20	4.81	1.50
52102	0.08	0.40	82.70	83.60	82.78	84.00	3.89	5.13	1.60
52104	0.84	0.47	38.60	36.00	39.44	36.47	6.41	6.87	1.15
52105	1.00	0.47	69.70	70.10	70.70	70.57	5.02	7.06	0.75
52106	0.52	0.53	53.90	56.30	54.42	56.83	3.31	4.41	1.25
52107	1.73	0.47	69.30	68.40	71.03	68.87	7.84	6.13	1.00
52111	0.56	0.47	54.00	54.00	54.56	54.47	6.68	7.79	1.50
52112	1.24	1.53	34.70	36.30	35.94	37.83	8.66	9.40	1.40
52113	0.80	0.80	109.00	171.00	109.80	171.80	5.32	7.26	1.30
52116	0.56	0.67	27.70	27.40	28.26	28.07	4.61	3.34	1.75
52117	0.64	0.27	53.40	53.70	54.04	53.97	3.37	3.16	1.75
52118	0.32	0.27	47.00	48.60	47.32	48.87	6.74	7.16	1.00
52119	0.04	1.07	38.10	38.90	38.14	39.97	3.22	3.19	1.50
52100a	0.60	1.20	131.00	130.00	131.60	131.20	7.97	10.36	0.50
52100b	0.12	1.40	51.10	51.10	51.22	52.50	3.16	5.05	1.50
52100c	0.12	1.40	124.00	126.00	124.12	127.40	3.79	13.60	1.50
52100d	0.84	1.73	170.00	180.00	170.84	181.73	19.10	16.60	0.50
52107a	1.44	2.00	52.90	72.10	54.34	74.10	9.80	50.40	1.10
52116a	1.16	1.33	44.00	1.00	45.16	2.33	9.91	8.73	0.75
52117a	1.64	0.47	77.00	82.00	78.64	82.47	3.32	5.80	1.80
52118a	3.52	0.27	52.10	53.60	55.62	53.87	2.25	2.93	2.25
52118b	0.80	2.40	83.00	83.30	83.80	85.70	9.05	12.10	0.60
52118c	0.44	1.20	88.30	88.00	88.74	89.20	9.86	9.53	0.75

Table 3. (continued)

DNR Number	Top Temp (°C)	Bot Temp (°C)	Top DO (mg L^{-1})	Bot DO (mg L^{-1})	Top Conduct (micromhos)	Bot Conduct (micromhos)	Top Hard (mg $CaCO_3$ L^{-1})	Bot Hard (mg $CaCO_3$ L^{-1})
52100	12.20	10.30	11.91	10.44	600.00	568.00	321.92	309.85
52101	11.10	10.30	10.05	8.83	375.90	370.10	229.37	233.39
52102	10.80	10.90	10.55	9.96	807.00	806.00	370.21	390.33
52104	10.80	10.00	10.24	9.17	398.00	388.50	201.20	205.22
52105	12.20	10.60	8.79	8.10	666.00	642.00	408.44	408.44
52106	10.80	6.10	10.75	0.48	535.00	491.00	299.79	378.26
52107	10.70	8.40	11.78	0.21	615.00	660.00	400.39	456.72
52111	10.00	10.10	9.25	8.76	525.00	525.00	354.11	305.82
52112	10.70	10.70	8.07	7.06	353.00	356.00	217.30	169.01
52113	10.80	11.40	11.44	3.25	1024.00	1432.00	498.98	748.46
52116	12.60	11.10	9.89	9.23	296.00	286.00	154.92	158.95
52117	11.40	10.30	10.04	7.49	526.00	511.00	350.09	323.93
52118	10.40	9.70	10.14	9.35	470.00	463.00	276.63	289.73
52119	11.60	10.10	10.15	10.50	407.60	390.40	245.46	229.37
52100a	13.00	9.70	9.60	0.01	1160.00	1063.00	788.70	768.58
52100b	12.80	8.60	9.91	2.25	535.00	484.00	354.11	430.57
52100c	12.80	10.40	10.09	9.65	1145.00	1074.00	784.68	757.85
52100d	11.90	9.70	10.21	9.20	1444.00	1376.00	972.47	992.59
52107a	10.50	9.50	10.66	4.67	502.00	552.00	313.87	468.80
52116a	11.20	10.30	9.07	8.50	422.00	400.00	443.04	466.78
52117a	12.50	10.70	9.40	8.67	765.00	734.00	893.33	961.74
52118a	11.50	9.60	9.06	4.80	536.00	522.00	333.99	321.92
52118b	9.40	9.40	11.14	11.14	691.00	691.00	402.40	402.40
52118c	10.30	9.30	10.58	9.98	819.00	789.00	398.38	420.51

Table 3. (continued)

DNR Number	Top Alk (mg L^{-1})	Bot Alk (mg L^{-1})	Top TON (mg L^{-1})	Bot TON (mg L^{-1})	Top P04-P (mg L^{-1})	Bot PO4-P (mg L^{-1})	Top N/P	Top pH	Bot pH
52100	95.00	100.00	0.059	0.090	0.07	0.08	0.90	8.40	8.40
52101	80.00	80.00	0.023	0.032	0.02	0.03	1.20	8.25	8.02
52102	145.00	145.00	0.090	0.057	0.02	0.03	5.30	8.30	8.29
52104	90.00	90.00	0.023	0.034	0.11	0.19	0.20	8.30	8.08
52105	110.00	130.00	0.026	0.030	0.05	0.06	0.60	8.01	7.99
52106	150.00	150.00	0.062	0.059	0.02	0.06	3.10	8.12	7.97
52107	136.00	154.00	0.052	0.055	0.13	0.09	0.40	8.09	7.74
52111	110.00	110.00	0.032	0.032	0.06	0.07	0.60	8.73	8.16
52112	40.00	40.00	0.023	0.033	0.06		0.40	10.23	8.00
52113	170.00	195.00	0.062	0.059	0.06	0.12	1.10	8.43	7.92
52116	30.00	20.00	0.030	0.044	0.02	0.03	1.50	8.14	7.99
52117	90.00	95.00	0.023	0.033	0.07	0.03	0.40	8.13	8.04
52118	80.00	90.00	0.079	0.094	0.04	0.07	1.80	8.45	8.05
52119	70.00	60.00	0.023	0.093	0.00	0.02	13.40	8.17	8.10
52100a	120.00	90.00	0.168	0.178	0.06	0.09	2.90	8.05	7.91
52100b	120.00	120.00	0.037	0.059	0.02	0.04	1.60	8.35	7.95
52100c	90.00	100.00	0.026	0.069	0.02	0.04	1.20	8.07	7.88
52100d	60.00	100.00	0.052	0.051	0.03	0.17	1.80	7.80	7.70
52107a	140.00	170.00	0.020	0.033	0.07	0.13	0.30	8.08	7.88
52116a	15.00	10.00	0.189	0.190	0.02	0.06	8.10	5.20	5.08
52117a	100.00	110.00	0.034	0.047	0.03	0.04	1.30	7.39	7.66
52118a	120.00	120.00	0.043	0.094	0.02	0.06	2.70	8.16	7.77
52118b	30.00	70.00	1.140	1.123	0.02	0.08	56.50	8.08	8.08
52118c	60.00	70.00	0.019	0.875	0.08	0.08	0.20	7.87	7.78

Table 3. (continued)

DNR Number	Chl a (mg m^{-3})	Chl b (mg m^{-3})	Chl c (mg m^{-3})	Pheophytin a (mg m^{-3})
52100	1.08	0.40	0.35	56.28
52101	0.18	0.19	0.18	5.06
52102	0.18	0.04	0.07	7.74
52104	0.18	0.04	0.09	9.43
52105	0.34	0.12	0.13	14.79
52106	0.28	0.12	0.03	14.00
52107	2.14	0.26	0.44	123.57
52111	0.25	0.05	0.04	13.60
52112	0.38	0.07	0.04	18.56
52113	0.71	0.20	0.10	34.48
52116	-0.02	-0.06	-0.06	-4.76
52117	0.12	0.03	0.07	4.84
52118	0.30	0.26	0.28	14.27
52119	0.09	0.10	0.12	19.75
52100a	0.61	0.11	0.07	35.83
52100b	0.12	0.11	0.11	4.27
52100c	0.03	1.99	-0.52	9.43
52100d	0.28	0.14	0.19	18.06
52107a	0.21	0.10	0.13	9.83
52116a	0.13	0.06	0.10	8.34
52117a	0.09	0.07	0.06	5.56
52118a	0.08	0.06	0.02	3.18
52118b	0.46	0.12	0.11	28.49
52118c	0.26	0.07	0.03	12.61

Table 4. Trophic State Indices (Carlson 1977) calculated from Secchi depth, chlorophyll *a*, and total phosphorus for 24 lakes at Ten Mile Creek Fish and Wildlife Area.

DNR Number	TSI Chl	TSI PO4-P	TSI SD
52100	31.35	60.94	70.00
52101	13.60	43.13	54.15
52102	13.66	40.74	53.22
52104	13.65	67.30	57.98
52105	20.08	54.63	64.15
52106	17.93	43.13	56.78
52107	38.04	69.58	60.00
52111	16.83	57.85	54.15
52112	21.13	59.25	55.15
52113	27.26	58.13	56.21
52116	0.00	43.13	51.93
52117	9.95	59.95	51.93
52118	18.64	54.12	60.00
52119	7.34	7.69	54.15
52100a	25.66	58.51	70.00
52100b	9.42	45.17	54.15
52100c		44.19	54.15
52100d	18.22	48.56	70.00
52107a	15.14	60.29	58.62
52116a	10.62	45.17	64.15
52117a	6.40	46.97	51.52
52118a	5.16	39.38	48.30
52118b	22.89	43.13	67.37
52118c	17.23	63.02	64.15

Figure 1. Ten Mile Creek Fish and Wildlife Area in Jefferson County showing location and label numbers of the lakes sampled.

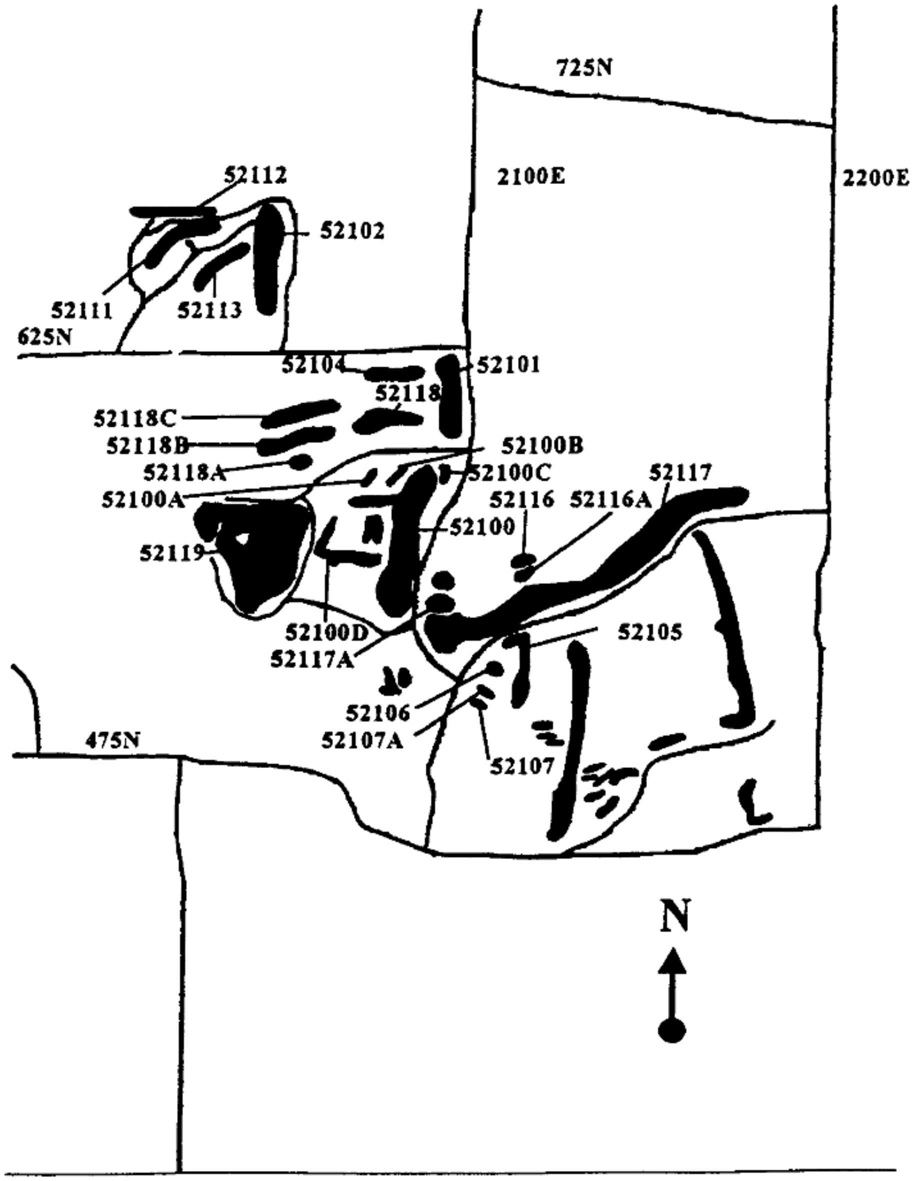

Figure 2. Alkalinity levels in lakes showing primary production limited by carbon (lakes having an alkalinity below 48 mg $CaCO_3$ per liter). Refer to Table 1 for graph ID numbers.

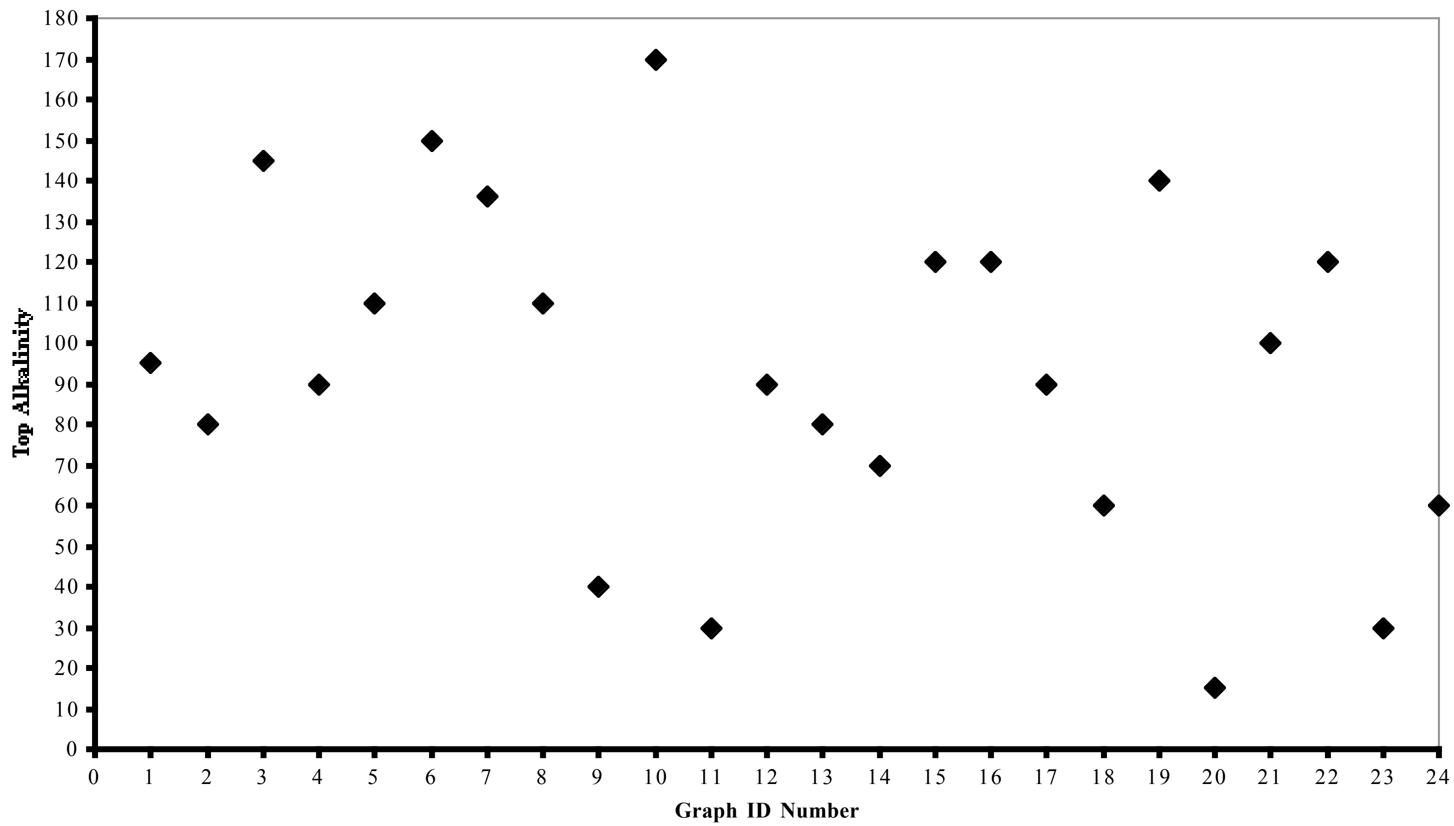

Figure 3. Nitrogen to phosphorus ratios in lakes showing primary production limitation (lakes with an N:P ratio of less than 7:1 are limited by nitrogen). Refer to Table 1 for graph ID numbers.

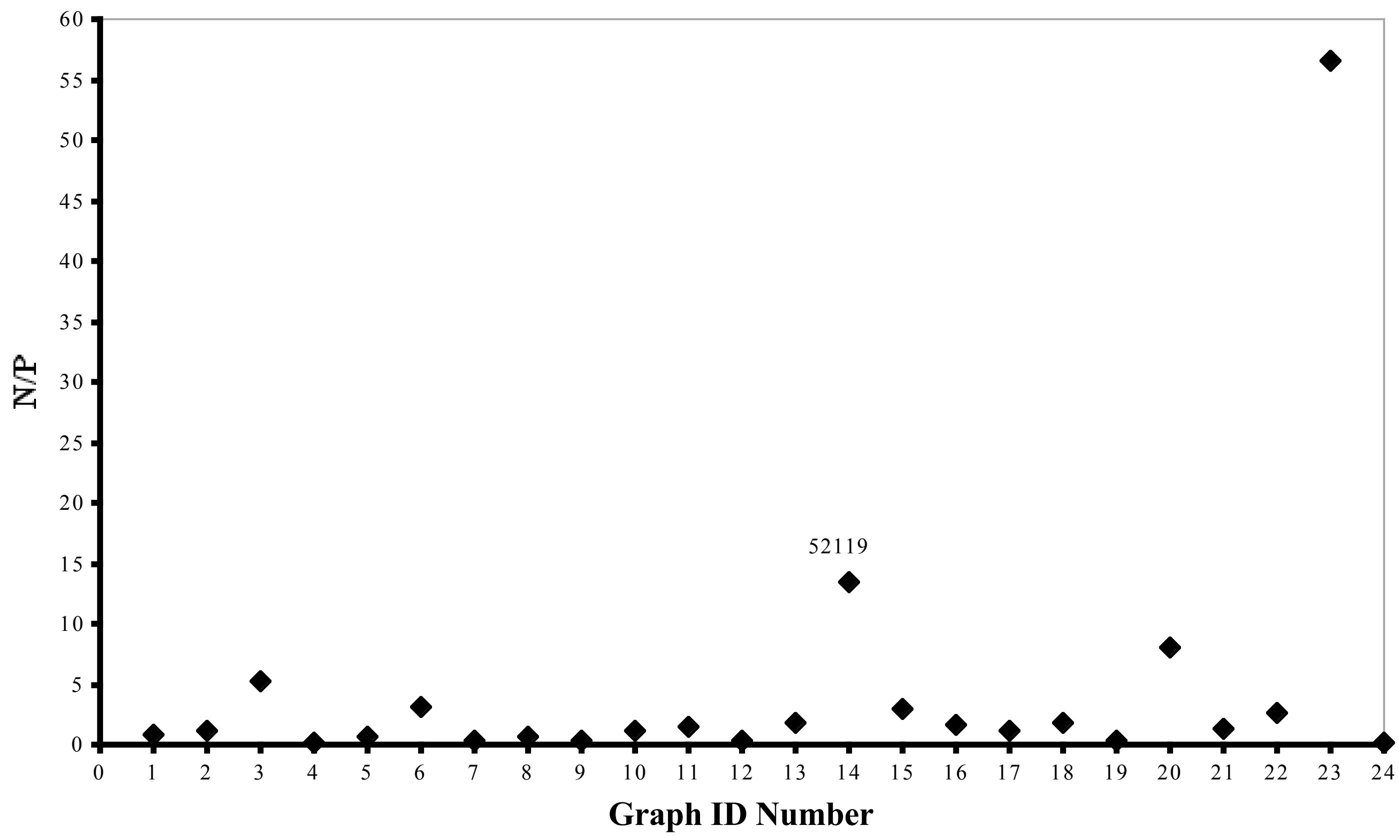

Figure 4. Cluster analysis of 24 lakes at TMCFWA based on a limited set of variables (alkalinity, N:P ratio, chlorophyll a, pH, conductivity, dissolved oxygen, Secchi depth, and temperature) measured at the surface (z=0.3m).