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Alden L. Kollman

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ECOLOGY OF SAGO PONDWEED (*POTAMOGETON PECTINATUS* L.) COMMUNITIES

by

Alden L. Kollman

Bachelor of Science, University of North Dakota, 1970
Bachelor of Philosophy, University of North Dakota, 1970

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

December
1974

This Thesis submitted by Alden L. Kollman in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

(Chairman)

Vera Facey

John D. Williams

A. William Johnson
Dean of the Graduate School

Permission

Title ECOLOGY OF SAGO PONDWEED (POTAMOGETON PECTINATUS L.) COMMUNITIES

Department Department of Biology

Degree Master of Science

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Signature Alden L. Kollman

Date December 3, 1974

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ABSTRACT

Potamogeton pectinatus L., a submerged, marl forming macrophyte, grows as a natural monospecies community in Fox Lake, 16 km northeast of Devils Lake, North Dakota. The water, sediment, dissolved oxygen, temperature and productivity relationships were studied in this small (0.4 X 1.2 km), shallow (60-75 cm) lake. Five replicate samples of the macrophyte, sediment, water and dissolved oxygen were taken at two week intervals during the 1972 growing season. In August of 1973, seven P. pectinatus sites in North Dakota, from the Minnesota to the Montana borders, were sampled. The sediments were analyzed for pH (7.8), electrical conductivity (9.8 Mmhos/cm), organic matter (4.1%), particle size (44% sand, 31% silt, 25% clay), 14 cations and four anions. The waters were analyzed for dissolved oxygen at two depths (114% saturation at 10 cm and 98% saturation at 40 cm), pH (9.2), electrical conductivity (15.8 Mmhos/cm), 13 cations and five anions. The plant biomass (maximum of 293 gm/m^2) was determined and samples were analyzed for caloric content (2972 cal/gm), carbon (54.3% not corrected for marl), nitrogen (1.47%) and 13 cations. The values in parentheses are means for Fox Lake over the 1972 growing season.

The temperatures were found to decrease with depth. The dissolved oxygen was higher in the surface waters for all dates, except the earliest sampling periods, when the macrophytes were very short. The temporal trends of all parameters were determined and phenograms based on correlation matrices were used to group environmental variables according to similarities in their trends, principal components analysis showed the same groups, but interpretation of the factor matrix was found to be more difficult. The ions in the water formed three groups, those in the sediments formed four groups and those in the plants formed four groups.

The characteristics of aerobic and anaerobic sediments in Fox Lake and the North Dakota transect are discussed in terms of their effects on the nutrient concentrations. Chelation of cations by dissolved organic materials in the water and adsorbed on the marl was found to be a possibility, especially for trace elements. Carbonate (marl) formation and bicarbonate utilization were found to be of major importance in the maintenance and productivity of the monotypic *P. pectinatus* community in Fox Lake.

INTRODUCTION

Many studies relating substrate-water relationships to the macrophyte distribution are available (Misra 1938, Mortimer 1941, 1942, 1971, Moyle 1945, Steemann Nielsen 1954, Spence 1967, Lerman and Brunskill 1971, to cite a few). However, few studies have documented the temporal relations of nutrient dynamics in relation to the growth and productivity of macrophytes. The major emphasis of the present study was an attempt to determine the nutrient dynamics of Potamogeton pectinatus communities. Fox Lake was chosen for intensive analyses for several reasons; it has an almost uniform cover of P. pectinatus throughout the body of the lake (Fig. 1). Moore (1913) and Turrill (1963) have also reported extensive underwater meadows of this species elsewhere. Because it is a small and shallow lake, changes in water and sediment conditions would be expected to be attributable to the macrophyte. The system is closed except for ground water import and export, and watershed runoff. Since it is shallow, the water chemistry should be relatively uniform with depth.

This species is cosmopolitan in distribution (Gaevskya 1969, Sculthorpe 1967). It is widely distributed in North America (Martin and Uhler 1939; Fig. 2) and is known to occupy a fairly wide range of aquatic environmental conditions (Moore 1913, Martin and Uhler 1939, Moyle 1945). The species is an economically important wildlife food species, particularly for ducks (Moore 1913, McAtee 1917, Mabbott 1920, Metcalf 1931, Kubichek 1933, Martin and Uhler 1939, Gaevskya 1966).

Major and trace elements have been variously related to plant pro-

Figure 1. The monotypic *Potamogeton pectinatus* community.

Figure 2. The North American distribution of P. pectinatus (modified from Martin and Uhler 1939).


▧ GREATEST ABUNDANCE
▨ PRINCIPAL RANGE
▩ UNCERTAIN RANGE

ductivity both in terms of limiting factors (Goldman 1960, Wetzel 1965, Gerloff and Krombholz 1966, Otsuki and Wetzel 1972, Toetz 1974) and in terms of toxic effects (Teeter 1965). However, most of these studies have examined only a few selected nutrients (often N, P, and dissolved organic materials) in their relationship to productivity. The objectives of the present study were to determine quantitatively the temporal variations in: (1) temperature and dissolved oxygen, (2) water chemistry, (3) physical and chemical characteristics of sediments, (4) biomass production and caloric content of the macrophyte, and (5) to provide a "correlative approach" relating the dynamics of nutrient and trace element relations to primary production.

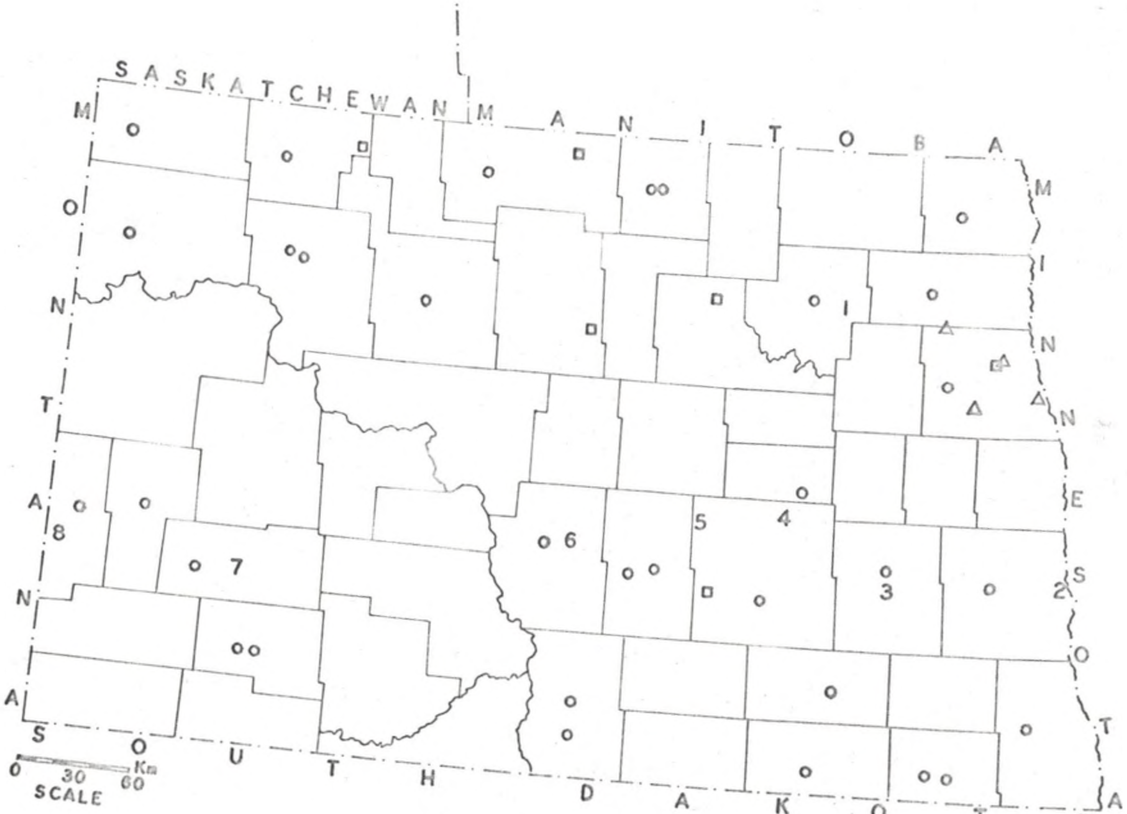
THE STUDY AREAS

Eight areas were investigated in this study: Fox Lake (site 1) and seven areas along a North Dakota transect (sites 2-8) from the Minnesota to Montana borders (Fig. 3). The most intensive effort was in Fox Lake, the other areas will be used only for comparison to Fox Lake.

Fox Lake is a small (0.4 X 1.2 km), shallow (60-75 cm) prairie pothole located in Ramsey County, North Dakota. It is very saline and alkaline (the mean electrical conductivity of the water is 9.0 millimhos/cm and the mean pH 7.9). The body of the lake has a monospecies culture of _Potamogeton pectinatus_, whereas the margins support communities of _Phragmites communis_, _Scirpus paludosus_ and _Typha latifolia_. Between the _P. pectinatus_ community and the marginal communities there is a "buffer zone" about 10 meters wide that is completely barren of macrophytes.

The North Dakota transect consists of seven areas across the state from near Fargo west to the Montana border, which contain populations of _Potamogeton pectinatus_. These areas from east to west are Harwood Slough (site 2), Lake Ashtabula (site 3), Arrowwood Lake (site 4), Mount Moriah Pond (site 5), Wing Pond (site 6), Dickinson Stream (site 7), and Golva Stream (site 8). Complete locations of all sites are given in Appendix A.

Figure 3. Distribution of Potamogeton pectinatus L. in North Dakota. Sources: Triangles (Kaloupek, 1972), circles (North Dakota State University herbarium), squares (University of North Dakota herbarium, and sites 1-8 (present study).


SASKATCHEWAN
MANITOBA
MINNESOTA
SOUTH DAKOTA
MONTANA
1
2
3
4
5
6
7
8
0 30 60 Km
SCALE

DATA COLLECTION AND METHODOLOGY

During the summer of 1972 five replicates were taken of the *P. pectinatus* community on each of seven dates. Fox Lake was sampled similarly in the spring of 1973. The North Dakota transect was taken during the first week of August in 1973, since preliminary data from Fox Lake indicated that the *P. pectinatus* should be nearing maximum productivity at that time.

Field Methods

Five sites were located at equal intervals along the long axis of Fox Lake (Fig. 4). Every two weeks throughout the growing season the plots were sampled for air temperature, sediment temperature and water temperature at the surface, and at 10, 20, and 50 cm depths below the surface. Temperatures were determined using a YSI telethermometer at the end of a graduated probe. During 1972, dissolved oxygen samples were taken from 10 cm and 40 cm depths and were field-fixed according to the modified Winkler Method given in Cox (1967). A dissolved oxygen probe was used in 1973. Water chemistry samples were collected in polyethylene containers at a depth of approximately 10 cm. The water depth to the sediment, in the center of the plots, was recorded, and the plants rooted within the plot were harvested (Fig. 5), washed in lake water, and put in plastic bags; a sediment sample was also collected from the harvested site.

On selected dates sediment samples were taken from regions within the body of the lake where there was no *P. pectinatus*.

Figure 4. The Fox Lake macrophyte populations and the sample plot locations.

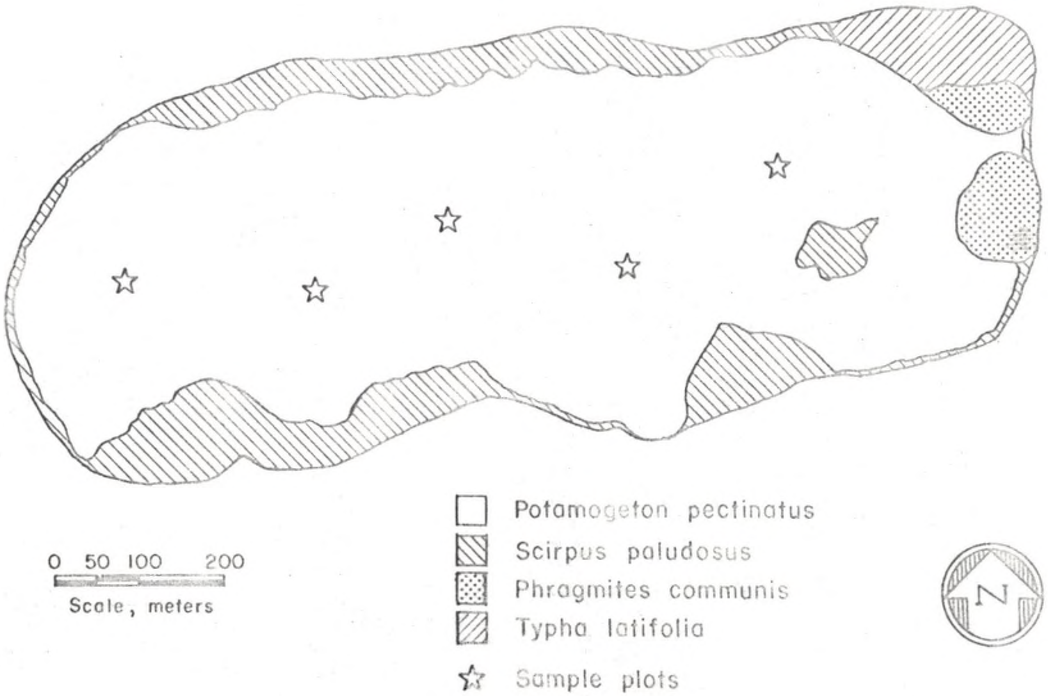

Potamogeton pectinatus
Scirpus paludosus
Phragmites communis
Typha latifolia
Sample plots
0 50 100 200
Scale, meters
N

Figure 5. A harvested Fox Lake P. pectinatus plot.

Laboratory Methods

The pH and specific conductivity of the water samples were determined, and the samples were then frozen for chemical analysis at a later date. The dissolved oxygen was determined within 24 hours of collection. The plant samples were air-dried for about one week, then oven dried at 80°C to a constant dry weight. They were weighed and later ground in a Wiley Mill. The sediment samples were air-dried, ground and passed through a 2 mm sieve.

The pH and conductivity of the sediment samples were determined in 1:2.5, sediment:water solutions. Two extraction procedures were used to determine the available cations in the sediments: the ammonium acetate extraction to determine the replaceable (water soluble plus exchangeable) calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), manganese (Mn), strontium (Li); and the disodium-ethylenediamine-tetraacetate (EDTA) extraction to determine complexed and/or chelated Mn, iron (Fe), zinc (Zn), copper (Cu), nickel (Ni), aluminum (Al), silicon (Si) and lead (Pb). Both extractions were performed as given in Wali and Krajina (1973) and Wikum and Wali (1974). Determinations were made using a Perkin-Elmer Model 403 atomic absorption spectrophotometer, with standard instrument methods (Perkin-Elmer Manual 1973).

Soil particle size analysis was determined by the hydrometer method (Bouyoucos 1951). Percent organic matter was determined by the Walkley-Black method (Jackson 1958). Sediment samples were analyzed for phosphorus using a dilute acid-flouride extraction solution (Jackson 1958) and determined by colorimetric measurement on a Bausch & Lomb Spectronic 20 at 660 nm. The Mohr method (Hach 1968) was used to determine the chloride in a filtered, double distilled water extract of the sediment.

A turbidimetric method using precipitation by barium chloride was used for the determination of sulfates (Kollman, unpublished). A 0.5 ml aliquot of the water extract was added to a Bausch & Lomb Spectronic 20 tube containing 4.5 ml of 1% gum arabic. Approximately .05 gm of crystaline $BaCl_2$ was then added to the tube and allowed to dissolve for about five minutes. The tube was then agitated vigorously and allowed to stand for about five minutes (until all of the bubbles had risen from the measurement region of the tube). The optical density was measured with the Bausch & Lomb Spectronic 20 at 600 nm. For periods up to about one hour this method was found to be time-independent over the range of 200-2000 ppm of sulfate in the sample. Total nitrogen was determined with a Coleman Model 29A nitrogen analyzer.

The water samples were filtered and analyzed for the following cations and anions: Na, K, Ca, Mg, Li, Fe, Zn, Sn, Mn, Si, Al, chloride (Cl), sulfate (SO_4), phosphorus (P), carbonate (CO_3) and bicarbonate (HCO_3). The cation analyses were done by atomic absorption spectrophotometry, and chloride, sulfate and phosphate were determined by the same methods given for sediment analysis. The carbonate and bicarbonate alkalinity was determined by titration with 0.02 N H_2SO_4 to the phenolphthalein and methyl orange endpoints.

One gram of each of the dried plant samples was prepared for cation analysis by dry ashing in a muffle furnace at a temperature of 500°C for five hours. The percent carbon was then estimated by calculating percent weight loss on ignition. The ash was dissolved in 10 ml of 5N HCl and the solution was brought up to 50 ml volume with double distilled water. This solution was then filtered and analyzed on the atomic absorption spectrophotometer for Ca, Mg, K, Na, Li, Fe, Mn, Zn, Cu, Ni, Al, Si, and

Pb. Caloric content of the plant samples was determined using a Parr adiabatic oxygen bomb calorimeter. Nitrogen content of the plant samples was determined as with the sediments.

Data Synthesis

Various statistical techniques were used to determine the relationships of the measured variables to each other and to the productivity of _P_. _pectinatus_.

Various univariate and multivariate statistical techniques were performed on the data using the SAS (Service 1972), SPSS (Nie et al. 1970) and NT-SYS (Rohlf et al. 1972) on an IBM 370/135 computer at the University of North Dakota Computer Center.

RESULTS

Water Characteristics-Physical

The temperature of the water body in Fox Lake (Fig. 6) decreased with depth. The greatest difference between the surface temperature and the temperature at 50 cm below the surface was 5.8°C on 4 August. The greatest difference between the air temperature and the surface temperature was 3.8°C on 8 September. It is significant to note that the surface temperatures are increasing faster than are those at the lower depths from 4 July to 18 August. After 18 August the water begins to cool, as can be seen from the general shift in the curve, and the slope of the curve has changed very little from that observed for 18 August. The coldest region in the profile is no longer the sediment but the water immediately over the sediment (50 cm). By 18 September the curve has again shifted toward the colder temperatures, but the slope of the curve is also beginning to change and become more perpendicular.

The dissolved oxygen (Table 1) was generally greater at the 10 cm depth than at the 40 cm depth. On 4 July the 40 cm depth showed a higher dissolved oxygen content. In the spring (23 June) of 1973 an oxygen profile (Fig. 7) was determined. The profile indicated the same relationship as was found on 4 July, 1972. It was also determined that only the very surface layer (about 2 cm) of sediment contained any dissolved oxygen (2.13 ppm). If the oxygen probe was pushed any deeper into the sediment dissolved oxygen was absent. This strongly indicates that the sediments are composed of aerobic and anaerobic layers. Probable causes for the

Figure 6. Temperature profiles in Fox Lake, 1972.

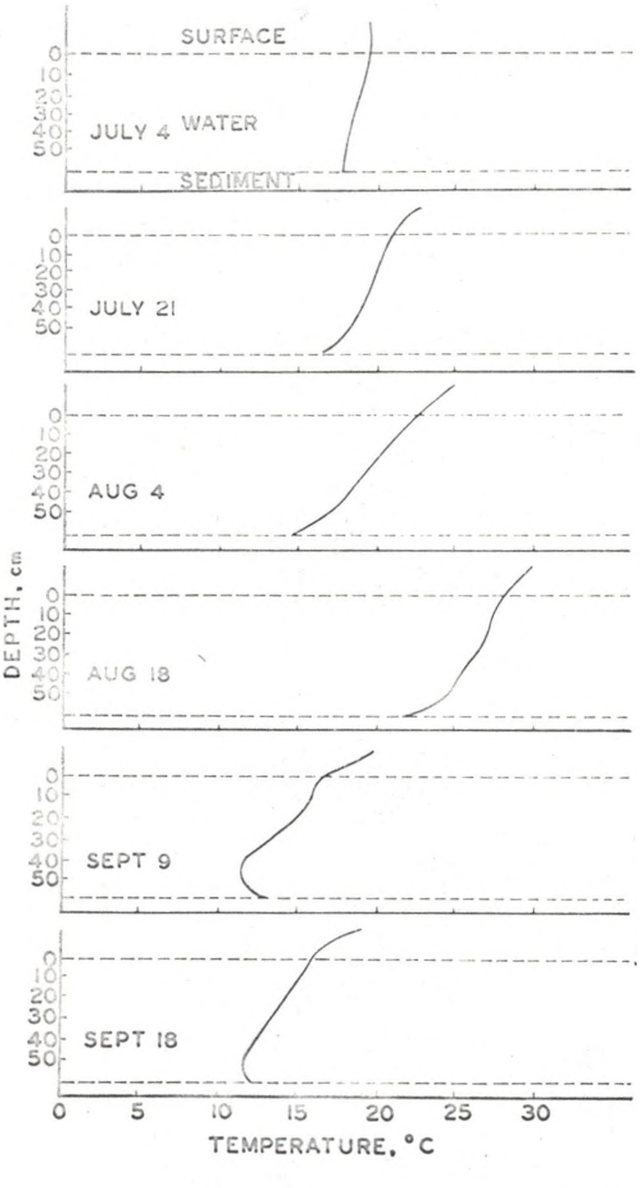

SURFACE
WATER
SEDIMENT
JULY 4
JULY 21
AUG 4
AUG 18
SEPT 9
SEPT 18
0
10
20
30
40
50
DEPTH, cm
0
5
10
15
20
25
30
TEMPERATURE, °C

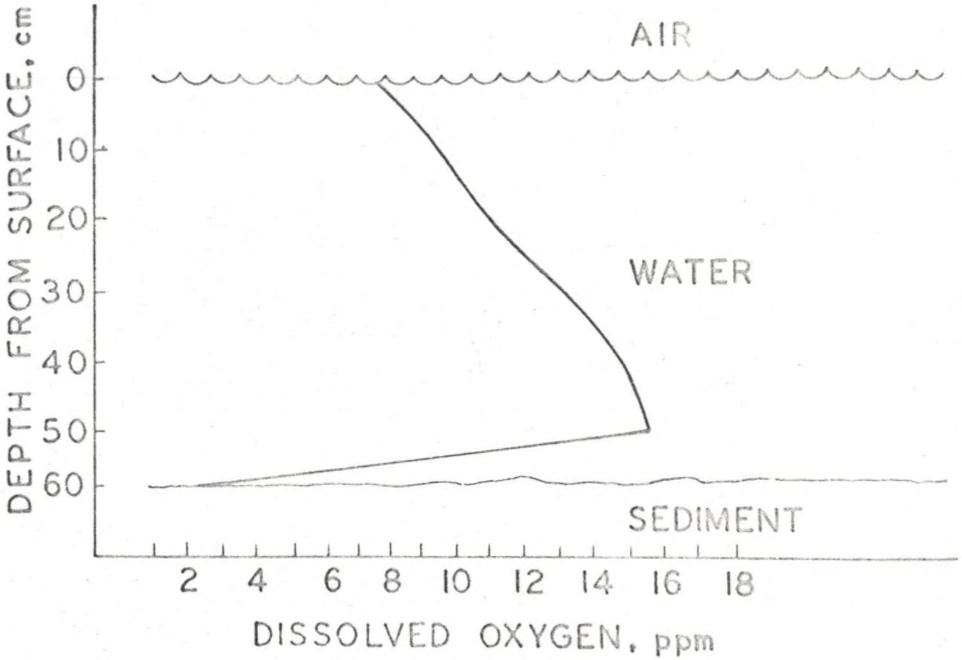
TABLE 1

MEAN DISSOLVED OXYGEN (D.O.) AT TWO DEPTHS FROM SURFACE, AND WATER DEPTH IN FOX LAKE, 1972

Dates	10 cm D.O.	40 cm D.O.	Water Depth
	------- % Saturation	-------	cm
4 July (4)[1]	105	115	75.0
21 July (5)	134	131	70.4
4 Aug. (5)	130	117	67.2
18 Aug. (4)	135	113	67.2
8 Sep. (5)	100	90	61.8
18 Sep. (5)	80	70	61.4

[1] Number in parentheses indicates sample size.

Figure 7. Dissolved oxygen profile in Fox Lake, June 23, 1973.


AIR
WATER
SEDIMENT
DEPTH FROM SURFACE, cm
0
10
20
30
40
50
60
DISSOLVED OXYGEN, ppm
2
4
6
8
10
12
14
16
18

temperature and dissolved oxygen profiles will be presented later.

The mean depth of the water in Fox Lake (Table 1) decreased from a maximum of 75 cm on 4 July to a minimum of 61.4 cm on 18 September. This decrease in depth represents a loss of approximately 36 acre-ft. from a total volume of about 400 acre-ft.

Water Characteristics-Chemical

The concentrations of 18 ions, pH, and E.C. are presented in Tables 2 and 3. A correlation matrix for these variables (Table 4) was constructed and used as a similarity matrix for construction of a phenogram by the unweighted pair-group method (Sneath and Sokal 1973). Examination of the phenogram (Fig. 8) shows that the ions form three major groups:

Group I - SO_4, Cl, Ni, CO_3, P, Li, Na, K, Mg, Sr, Ca, Fe, Mn, Cu, Zn

Group II - HCO_3, Si

Group III - Al

The temporal trends of the ions show that those in Group I (Fig. 9, 10) have a general tendency to increase through the growing season. Those in Group II (Fig. 11a) show a decrease at the beginning of the growing season and a rapid increase at the end of the growing season. Group III, aluminum (Fig. 11b), shows a constant decrease through the growing season. Although all of the elements in each group have similar trends, it is unreasonable to believe that they are all similar for the same reason. Discussion of factors affecting the behavior of individual ions is presented later.

TABLE 2

MEAN pH, ELECTRICAL CONDUCTIVITY (E.C.), MAJOR ELEMENTS AND ANIONS IN FOX LAKE WATERS, 1972

Date	pH	E.C. Mmhos/cm	Ca	Mg	K	Na	HCO_3	CO_3	SO_4	P	Cl
			meq/l				ppm				
30 May (1)[1]	8.6	11.6	5.6	8.0	0.7	24.5	154	30	5700	0.20	1310
4 Jul (1)	8.7	13.8	4.8	13.0	1.1	33.7	144	20	6450	0.17	1710
21 Jul (5)	9.5	15.8	4.8	17.7	1.8	47.5	104	34	8070	0.16	1866
4 Aug (5)	9.7	16.1	5.3	18.9	1.9	51.0	104	34	8310	0.16	1978
18 Aug (5)	9.7	16.1	4.4	14.4	1.5	40.9	98	36	7990	0.17	2018
8 Sep (5)	9.5	18.3	6.0	18.2	2.1	50.8	115	42	9830	0.20	2266
18 Sep (5)	9.2	18.3	5.9	18.3	2.0	49.8	109	34	9170	0.20	2284
6 Oct (1)	8.7	16.6	13.4	32.1	4.4	67.4	196	46	9800	0.26	1810

---

[1] Number in parentheses indicates sample size.

TABLE 3

MEAN TRACE ELEMENT CONCENTRATIONS IN FOX LAKE WATERS, 1972

Date	Al	Cu	Fe	Li	Mn	Ni	Si	Sr	Zn
	ppm								
30 May (1)[1]	2.0	0.16	0.13	0.69	0.140	0.06	10.0	2.31	0.10
4 Jul (1)	2.0	0.14	0.19	1.23	0.070	0.07	10.0	2.55	0.09
21 Jul (5)	2.3	0.17	0.24	1.72	0.074	0.13	5.4	2.87	0.12
4 Aug (5)	1.9	0.13	0.23	1.99	0.076	0.14	5.6	3.23	0.11
18 Aug (5)	0.8	0.12	0.23	1.57	0.078	0.14	4.6	2.61	0.08
8 Sep (5)	0.9	0.18	0.26	1.99	0.078	0.17	5.4	3.31	0.11
18 Sep (5)	1.6	0.15	0.26	1.94	0.086	0.16	5.2	3.20	0.09
6 Oct (1)	0.0	0.18	0.56	2.55	0.120	0.10	17.0	4.39	0.14

[1] Number in parentheses indicates sample size.

Table 4. Correlation matrix of the water variables.
n=28; ** $p \leq .01$, * $.05 \geq P > .01$

Ca																			
.825**	Mg																		
.890**	.970**	K																	
.734**	.934**	.934**	Na																
.645**	.938**	.888**	.950**	Li															
.795**	.883**	.864**	.869**	.881**	Sr														
.858**	.873**	.914**	.778**	.756**	.752**	Fe													
.563**	.385*	.469**	.378*	.294	.417*	.436**	Mn												
.347*	.508**	.473**	.494**	.461**	.413*	.368*	.155	Zn											
.014	.191	.256	.423**	.378*	.207	.077	.028	.023	Ni										
.213	.330*	.310	.324	.316	.241	.208	.033	.884	.094	Cu									
.544**	.219	.248	-.004	-.084	.144	.313	.223	.162	-.565**	.093	Si								
-.231	-.068	-.202	-.125	-.073	-.041	-.354*	-.245	.320	-.089	.266	.104	Al							
.128	.211	.287	.422*	.402*	.331*	.130	.141	-.029	.868**	.144	-.518**	-.177	C						
.474**	.540**	.632**	.708**	.610**	.531**	.476**	.152	.229	.813**	.261	.231	-.204	.789**	SO_4					
.626**	.472**	.524**	.378*	.391*	.484**	.551**	.252	.229	.299	.258	.352*	-.055	.372*	.512**	PO_4				
.513**	.151	.205	-.068	-.124	.077	.277	.125	.018	-.537**	.057	.884**	-.062	-.395*	-.142	.352*	HCO_3			
.344*	.445**	.474**	.479**	.505**	.470**	.380*	.066	.047	.400*	.082	-.295	-.233	.476**	.625**	.228	-.131	CO_3		
-.249	.046	.040	.215	.266	.103	-.053	-.010	.006	.509**	-.092	-.804**	-.150	.384*	.295	-.280	-.807**	.544**	pH	
.302	.398*	.478**	.575**	.532**	.440**	.353*	.183	.100	.842**	.198	-.447**	-.259	.922**	.907**	-.485**	-.294	.587**	.361*	CON

Figure 8. Phenogram of the water variables.

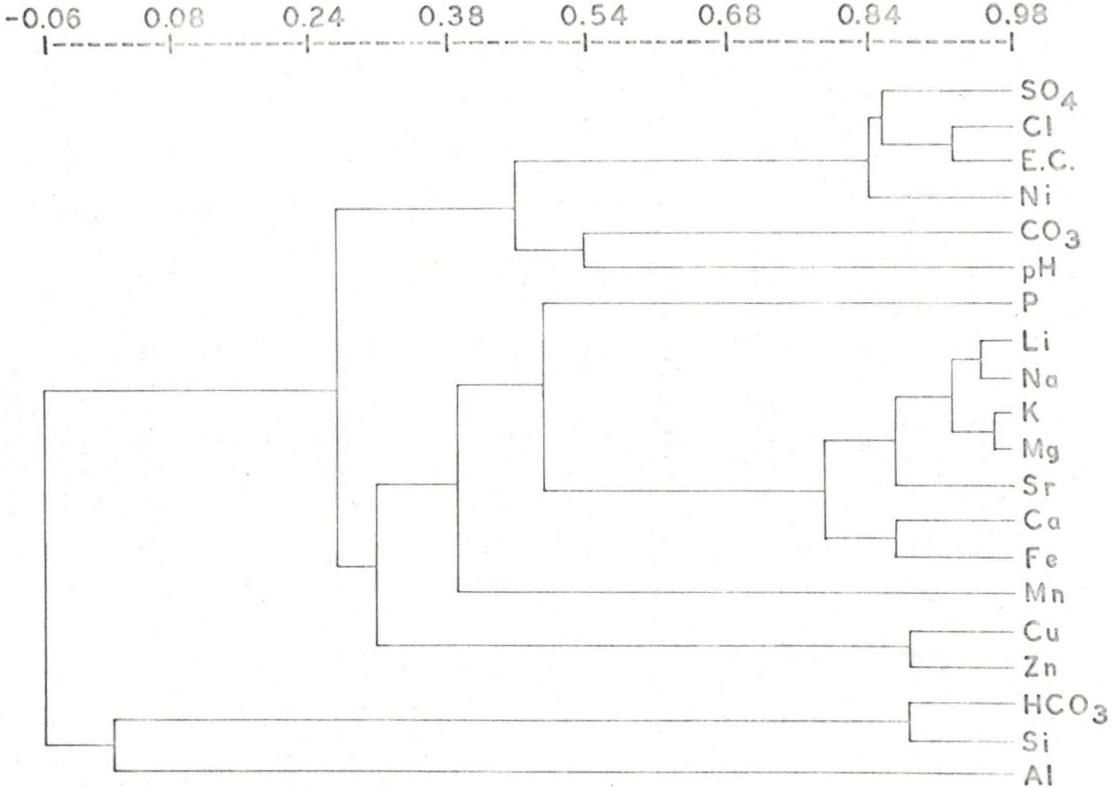

-0.06
0.08
0.24
0.38
0.54
0.68
0.84
0.98
SO_4
Cl
E.C.
Ni
CO_3
pH
P
Li
Na
K
Mg
Sr
Ca
Fe
Mn
Cu
Zn
HCO_3
Si
Al

Figure 9. The temporal trends of water variables in Group I.

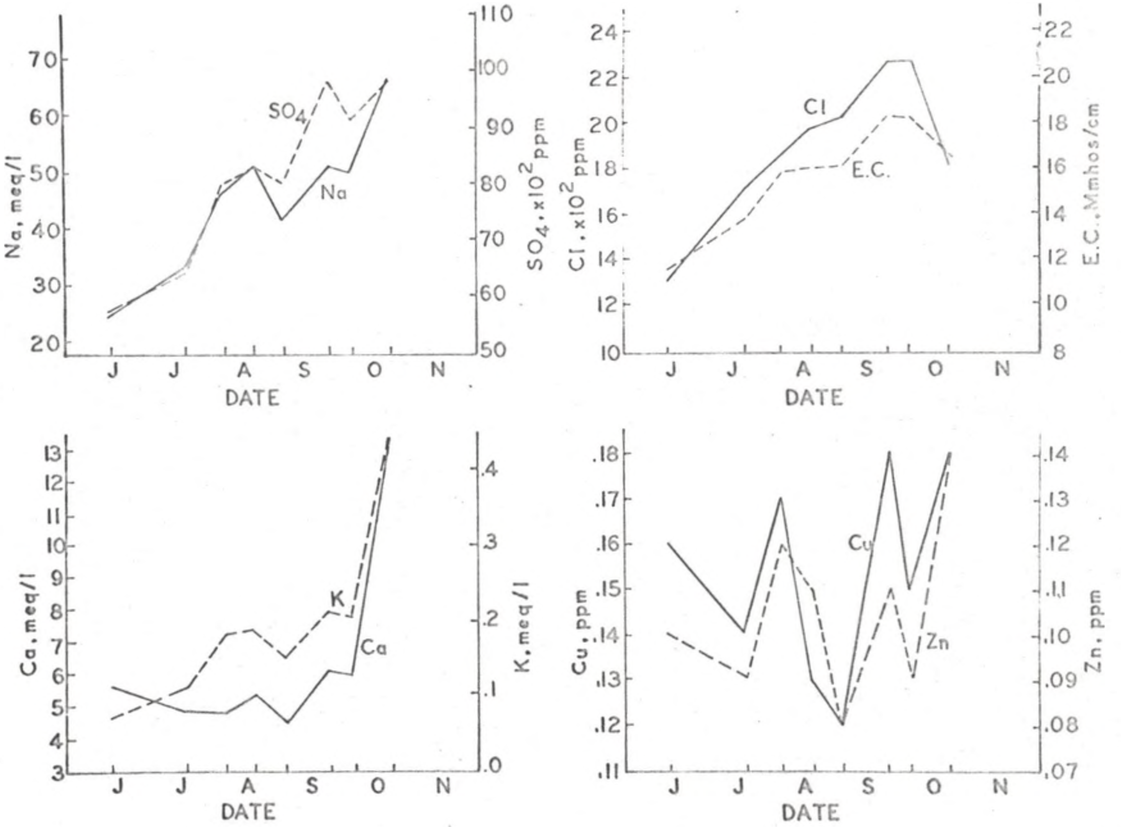
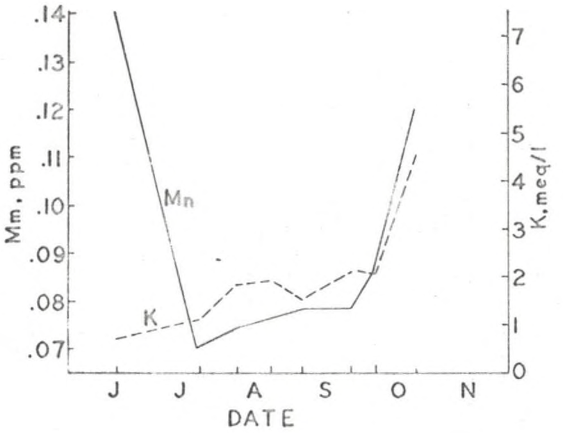
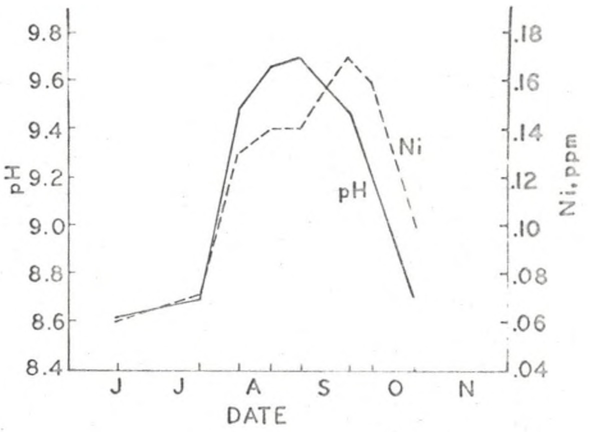

Na, meq/l
70
60
50
40
30
20
SO4
Na
110
100
90
80
70
60
50
SO4 . x10² ppm
J J A S O N
DATE
Cl . x10² ppm
24
22
20
18
16
14
12
10
Cl
E.C.
22
20
18
16
14
12
10
8
E.C., Mmhos/cm
J J A S O N
DATE
Ca, meq/l
13
12
11
10
9
8
7
6
5
4
3
K
Ca
.4
.3
.2
.1
.0
K, meq/l
J J A S O N
DATE
Cu, ppm
.18
.17
.16
.15
.14
.13
.12
.11
Cu
Zn
.14
.13
.12
.11
.10
.09
.08
.07
Zn, ppm
J J A S O N
DATE

Figure 10. The temporal trends for water variables.


Mm, ppm
.14
.13
.12
.11
.10
.09
.08
.07
Mn
K
7
6
5
4
3
2
1
0
K, meq/l
J
J
A
S
O
N
DATE


pH
9.8
9.6
9.4
9.2
9.0
8.8
8.6
8.4
Ni
pH
.18
.16
.14
.12
.10
.08
.06
.04
Ni, ppm
J
J
A
S
O
N
DATE

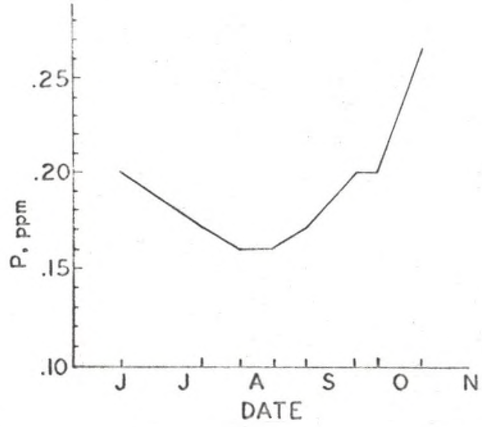
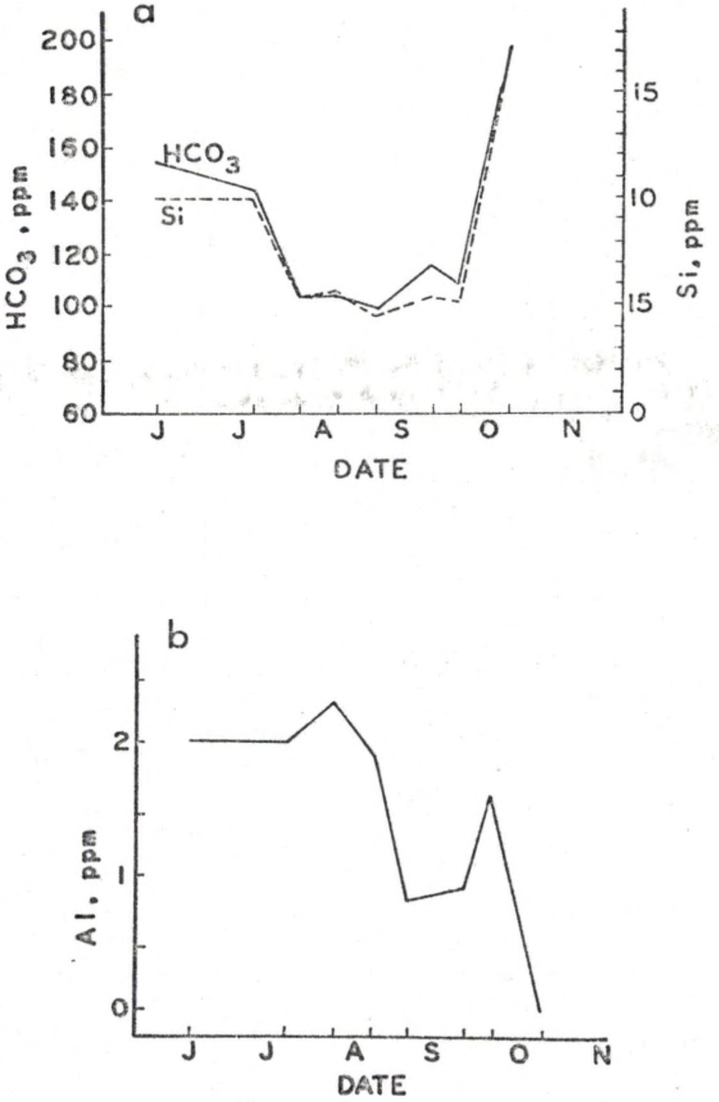

P, ppm
.25
.20
.15
.10
J
J
A
S
O
N
DATE

Figure 11. The temporal trends of (a) two elements in Group II and (b) aluminum (Group III) in the water.


a
200
180
160
140
120
100
80
60
HCO$_3$, ppm
HCO$_3$
Si
15
10
5
0
Si, ppm
J
J
A
S
O
N
DATE
b
2
1
0
Al, ppm
J
J
A
S
O
N
DATE

Sediment Characteristics-Physical

The mean sand, silt, clay, and organic matter of each of the sample plots is given in Table 5. The grand means ($\bar{\bar{X}}$) show percentages of 44.5 for sand, 30.6 for silt, 25.1 for clay and 4.0 for organic matter. The sediments have a thin aerobic layer and very dark anaerobic lower layers. They seem to have a lower temperature than the water directly above them during most of the growing season, in the fall when the waters have begun to cool the sediments show a higher temperature than the deeper waters.

Sediment Characteristics-Chemical

The mean concentrations for 19 ions, pH, E.C. (electrical conductivity), and percent organic matter are shown in Table 6 and 7. Comparisons of the mean replaceable (ammonium acetate extractable) and chelated-complexed (EDTA-extractable) Li, Sr, and Mn are shown in Table 8. The replaceable ions are subscripted 1 (Mn_1, Li_1, Sr_1) and the chelated complexed ions 2 (Mn_2, Li_2, Sr_2), respectively. The lithium values from the two extraction techniques showed a correlation of 0.971, strontium showed a correlation of 0.815, and manganese showed a correlation of 0.718, all were found to be highly significant ($P \leq 0.01$).

A correlation matrix of the sediment variables (Table 9) was constructed and this matrix was then used as a similarity matrix to construct a phenogram by the unweighted pair group method (Sneath and Sokal 1973). The phenogram depicts similar ion behavior (Fig. 12). It can be seen that the elements fall into four groups:

Group I - Na, Cl, Mg, K, Li, P, SO_4

Group II - Ca, Sr

Group III - Fe, Mn_1, Mn_2, Zn, Al, Ni, Pb, Cu

TABLE 5

MEAN PERCENT SAND, SILT, CLAY AND ORGANIC MATTER (O.M.) OF FOX LAKE SEDIMENTS, 1972

Areas	Sand	Silt	Clay	O.M.
	%			
11 (6)[1]	45.7	31.4	22.9	3.2
22 (6)	47.4	29.7	23.0	4.3
33 (6)	41.3	29.1	29.6	4.4
44 (6)	45.2	31.8	23.1	3.9
55 (6)	43.1	31.3	27.1	4.3
$\bar{\bar{X}}$	44.5	30.6	25.1	4.0

[1] Number in parentheses indicates sample size.

TABLE 6

MEAN pH, ELECTRICAL CONDUCTIVITY (E.C.), ORGANIC MATTER (O.M.), AND MAJOR IONS IN THE SEDIMENTS OF <u>POTAMOGETON PECTINATUS</u>, 1972

Date	pH	E.C. Mmhos/cm	O.M. %	Ca	Mg	K	Na	N[1] %	P	SO_4	Cl
				meq/100gm					ppm		
4 July (5)[2]	7.59	8.08	3.85	40.6	16.1	3.1	24.6	0.21	9.20	20300	1140
21 July (5)	7.68	7.97	3.56	40.9	15.8	3.3	24.9	0.17	9.60	18400	1230
4 Aug. (5)	7.78	8.55	4.05	33.6	16.5	3.5	26.1	0.24	8.20	17500	1310
18 Aug. (5)	7.85	9.28	4.35	33.4	18.2	3.7	30.3	0.27	9.40	17100	1590
8 Sep. (5)	7.88	9.63	4.39	29.8	18.3	3.7	30.8	0.26	9.10	14400	1725
18 Sep. (5)	7.89	14.19	4.00	37.0	21.7	4.4	44.1	0.25	13.50	28100	2330

[1] Total nitrogen, sample size is 1

[2] Number in parentheses indicates sample size.

TABLE 7

MEAN TRACE ELEMENT CONCENTRATIONS IN THE SEDIMENTS OF *POTAMOGETON PECTINATUS*, 1972

Date	Al	Cu	Fe	Li	Mn_1	Mn_2	Ni	Pb	Si	Sr	Zn
	ppm										
4 July (5)[1]	2.50	5.42	66.6	2.22	11.90	74.40	2.65	4.68	77.8	35.42	2.28
21 July (5)	1.00	5.01	61.6	2.24	10.47	69.55	2.47	4.15	76.0	36.76	2.12
4 Aug. (5)	1.50	5.14	60.5	2.32	10.82	72.35	2.54	4.15	77.5	34.73	2.14
18 Aug. (5)	2.19	5.00	77.0	2.71	11.57	85.82	2.63	4.62	74.2	33.06	2.39
8 Sep. (5)	2.00	4.92	85.7	2.67	11.70	81.30	2.68	4.88	68.6	31.49	2.69
18 Sep. (5)	0.00	5.59	88.9	3.50	11.17	68.60	2.70	4.38	64.0	37.31	2.22

[1] Number in parentheses indicates sample size.

TABLE 8

COMPARISON OF MEAN NH$_4$OAC-(AMMONIUM ACETATE) AND EDTA-(ETHYLENEDIAMINE TETRAACETATE) EXTRACTABLE MANGANESE, STRONTIUM AND LITHIUM IN FOX LAKE SEDIMENTS

Dates	Mn$_1$ NH$_4$OAC	Mn$_2$ EDTA	Sr$_1$ NH$_4$OAC	Sr$_2$ EDTA	Li$_1$ NH$_4$OAC	Li$_2$ EDTA
4 July (5)[1]	11.9	74.4	35.4	13.6	2.22	1.38
21 July (5)	10.5	69.6	36.8	13.6	2.24	1.38
4 Aug. (5)	10.8	72.4	34.7	13.8	2.32	1.44
18 Aug. (5)	11.6	85.8	33.0	12.5	2.71	1.70
8 Sep. (5)	11.7	81.3	31.5	12.7	2.67	1.66
18 Sep. (5)	11.2	68.6	37.3	15.0	3.50	2.23

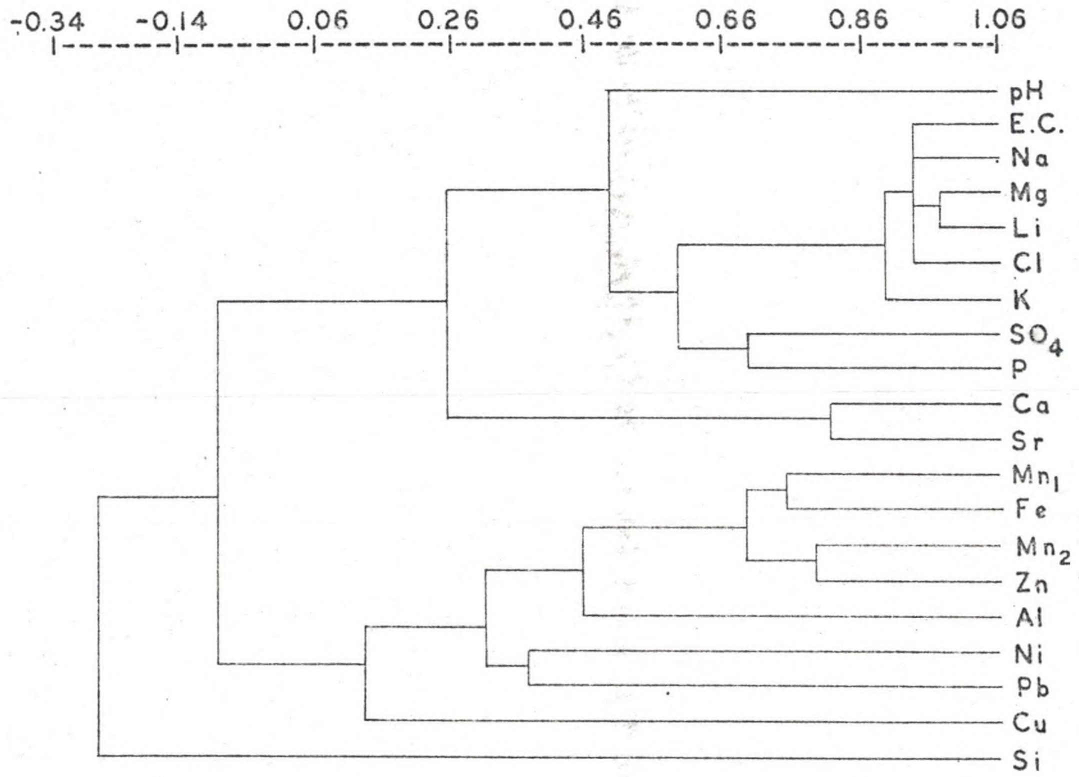
[1] Number in parentheses indicates sample size.

[2] These variables were deleted from the statistical data set.

Table 9. Correlation matrix of sediment variables of the *Potamogeton pectinatus* community.
n=25; ** $p \leq .01$, * $.05 \geq p > .01$

pH																		
0.385**	E.C.																	
0.504*	0.936**	Na																
0.559**	0.902**	0.903**	K															
-0.206	0.094	0.180	0.117	Ca														
0.558**	0.913**	0.936**	0.881**	0.031	Mg													
0.042	0.402*	0.435*	0.412*	0.815**	0.206	Sr												
-0.131	-0.170	-0.225	-0.303	-0.590**	-0.148	-0.551**	Mn_1											
0.100	-0.201	-0.187	-0.140	-0.501*	-0.080	-0.497*	0.719**	Mn_2										
0.579**	0.953**	0.961**	0.925**	0.118	0.974**	0.378	-0.228	-0.147	Li									
0.232	0.185	0.090	0.079	-0.616**	0.261	-0.342**	0.757**	0.640**	0.158	Fe								
-0.050	0.136	0.006	0.186	-0.076	0.101	-0.090	0.161	0.036	0.090	0.387	Cu							
0.198	0.331	0.359	0.342	-0.184	0.401*	0.008	0.315	0.307	0.344	0.372	0.274	Ni						
0.203	0.188	0.249	0.220	-0.013	0.254	-0.020	0.171	0.463**	0.238	0.159	-0.119	0.390	Pb					
-0.065	-0.315	-0.313	-0.320	-0.482*	-0.327	-0.325	0.475*	0.574**	-0.371	0.255	-0.037	0.323	0.329	Al				
-0.349	-0.548**	-0.510**	-0.460*	0.270	-0.620**	0.127	-0.074	0.041	-0.552**	-0.471*	-0.086	0.039	-0.101	0.222	Si			
0.272	0.651**	0.627**	0.461*	0.428*	0.603**	0.556**	-0.281	-0.375	0.589**	-0.072	-0.041	0.032	0.228	-0.306	-0.444*	SO_4		
0.033	-0.037	-0.054	0.023	-0.557**	0.061	-0.471*	0.688**	0.803**	-0.035	0.760**	0.286	0.358	0.378	0.500*	-0.286	-0.280	Zn	
0.338	0.635**	0.625**	0.543**	0.512**	0.615**	0.491*	-0.347	-0.329	0.653**	-0.066	0.134	-0.061	0.035	-0.560**	-0.422*	0.701**	-0.224	P
0.645**	0.931**	0.943**	0.864**	-0.016	0.945**	0.246	-0.186	-0.132	0.951**	0.189	-0.034	0.347	0.266	-0.293	-0.591**	0.608**	-0.021	0.593**

Figure 12. Phenogram of the P. *pectinatus* sediment variables.


-0.34
-0.14
0.06
0.26
0.46
0.66
0.86
1.06
pH
E.C.
Na
Mg
Li
Cl
K
SO_4
P
Ca
Sr
Mn_1
Fe
Mn_2
Zn
Al
Ni
Pb
Cu
Si

Group IV - Si

These same groups can be observed in the mean temporal trends of the elements (Figs. 13-16). It will also be noted that copper is a member of Group III and SO_4 and P are members of Group I but their temporal trends are more similar to that of calcium and strontium, the Group II elements.

The temporal trends for Groups II and III are nearly mirror images of each other as are the trends for Groups I and IV.

It has been shown that the elements can be grouped by statistical methods by construction of a phenogram using the unweighted pair group method, and that in most cases this objective method gives the same groups as would be constructed by comparisons of the mean temporal trends.

Analysis of these data by principal components analysis (Table 10) showed many of the same groups but they were not nearly so distinct as those shown by the above methods. The Group I elements had high positive loadings Factor 1 and Si and Al showed the highest negative loadings for the same factor. Calcium and Sr (Group II) showed high positive loadings on Factor 2 and, as would be expected, the Group III elements, except copper, showed high negative loadings. Group II (Ca and Sr) and Ni, Pb, Al, and Si from Group III showed high negative loadings on Factor 3. Copper was the only element to load highly on Factor 4. This was the only high loading for Cu.

Characteristics of the Barren Sediments

The chemical characteristics of the barren sediments are presented in Tables 11 and 12. Electrical conductivity, organic matter, K, Na, Cl, Fe, Si and Zn are higher in the barren areas, and Ca, P, and SO_4 are higher in the *P. pectinatus* community. The phenogram based on the correlations

Figure 13. The temporal trends of P. pectinatus sediment variables in Group I.

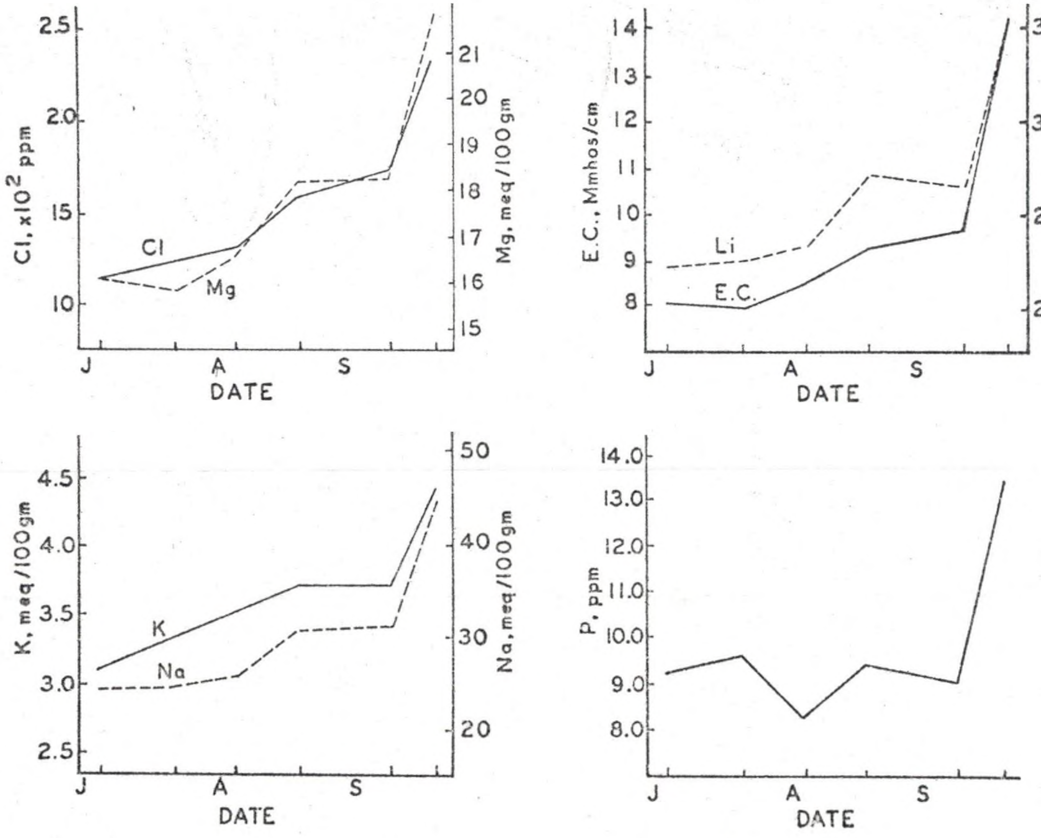
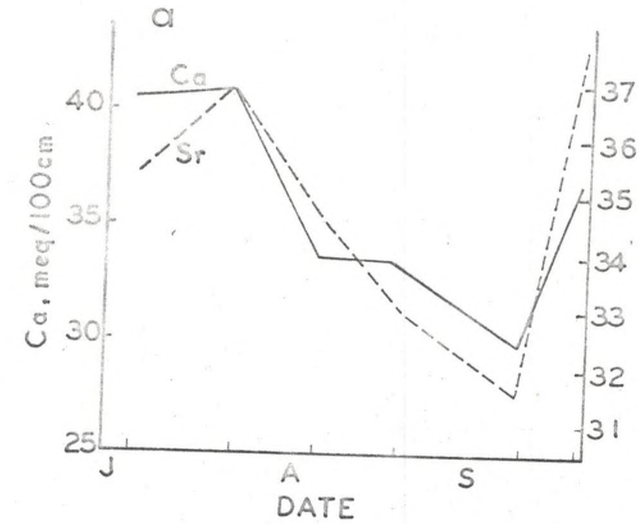

Cl, x10^2 ppm
2.5
2.0
15
10
Cl
Mg
21
20
19
18
17
16
15
Mg, meq/100gm
J
A
S
DATE
E.C., Mmhos/cm
14
13
12
11
10
9
8
Li
E.C.
3.5
3.0
2.5
2.0
Li, ppm
J
A
S
DATE
K, meq/100gm
4.5
4.0
3.5
3.0
2.5
K
Na
50
40
30
20
Na, meq/100gm
J
A
S
DATE
P, ppm
14.0
13.0
12.0
11.0
10.0
9.0
8.0
J
A
S
DATE

Figure 14. The temporal trends of P. pectinatus sediment variables in (a) Group II and (b) Groups I and III.


a
Ca
Sr
Ca, meq/100cm
40
35
30
25
37
36
35
34
33
32
31
Sr, ppm
J
A
S
DATE

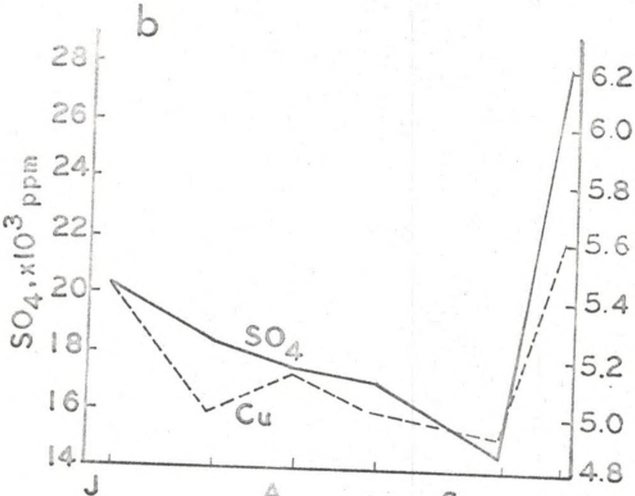
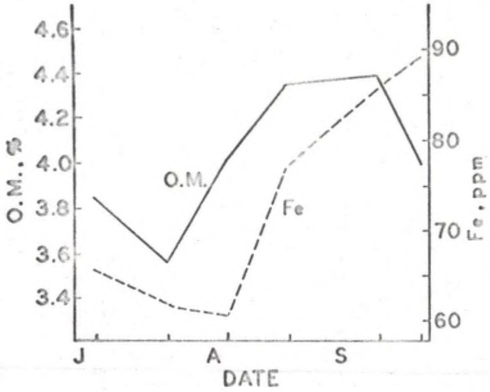
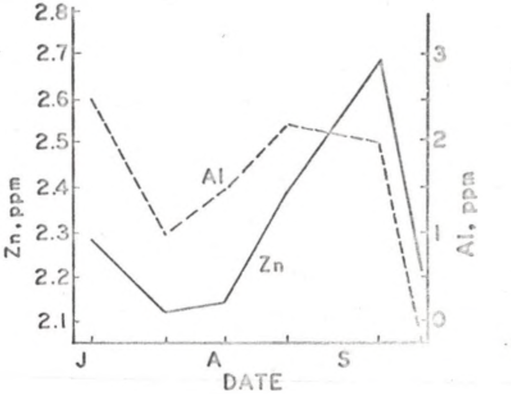
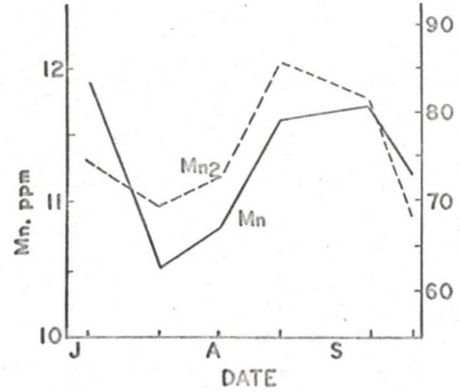

b
SO$_4$
Cu
SO$_4$, x10^3 ppm
28
26
24
22
20
18
16
14
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
Cu, ppm
J
A
S
DATE

Figure 15. The temporal trends of seven elements and organic matter (O.M.) in the *P. pectinatus* sediments. All are members of Group III.


O.M., %
4.6
4.4
4.2
4.0
3.8
3.6
3.4
O.M.
Fe
90
80
70
60
Fe, ppm
J
A
S
DATE


Zn, ppm
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
Al
Zn
3
2
1
0
Al, ppm
J
A
S
DATE


Mn, ppm
12
11
10
Mn2
Mn
90
80
70
60
Mn_2, ppm
J
A
S
DATE

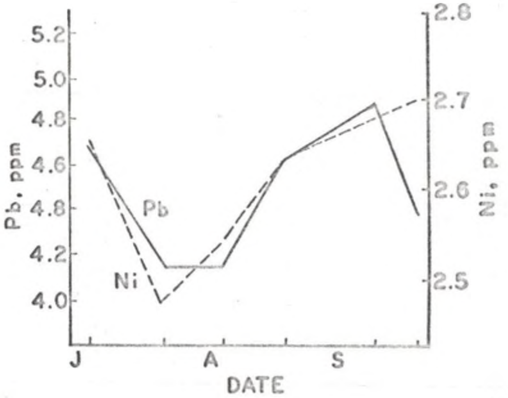

Pb, ppm
5.2
5.0
4.8
4.6
4.8
4.2
4.0
Pb
Ni
2.8
2.7
2.6
2.5
Ni, ppm
J
A
S
DATE

Figure 16. The temporal trends of silicon (Group IV), nitrogen (Group III) and pH in the *P. pectinatus* sediments.

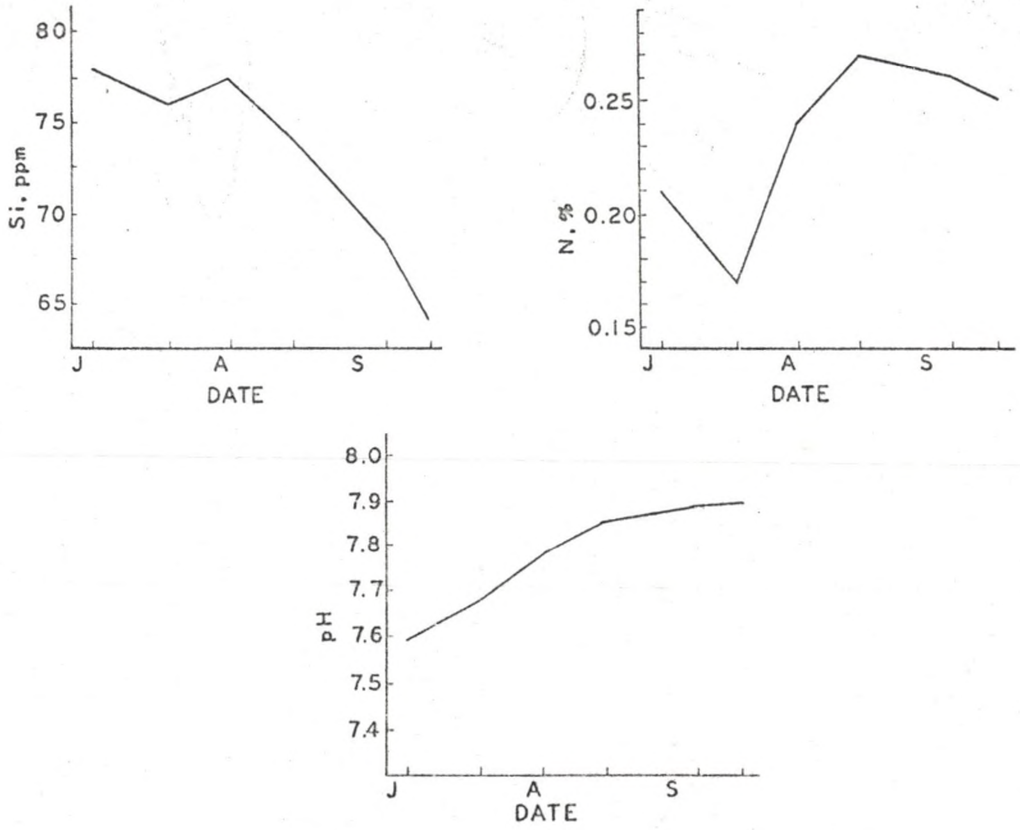

80
75
70
65
Si, ppm
J
A
S
DATE
0.25
0.20
0.15
N, %
J
A
S
DATE
8.0
7.9
7.8
7.7
7.6
7.5
7.4
pH
J
A
S
DATE

TABLE 10

FACTOR LOADINGS ON THE *POTAMOGETON PECTINATUS* SEDIMENT VARIABLES AND THE VARIANCE ACCOUNTED FOR BY EACH FACTOR.

	Factors					
	1	2	3	4	5	6
pH	0.569	-0.298	0.019	-0.395	0.243	0.421
E.C.	0.947	-0.185	0.023	0.054	0.096	-0.066
Na	0.948	-0.137	-0.101	-0.030	0.064	0.120
K	0.898	-0.160	-0.056	0.052	0.233	0.116
Ca	0.286	0.781	-0.318	0.322	-0.274	0.140
Mg	0.931	-0.278	0.022	-0.017	0.048	-0.067
Sr	0.514	0.588	-0.395	0.243	-0.071	-0.023
Mn_1	-0.370	-0.755	0.039	0.151	-0.211	-0.209
Mn_2	-0.319	-0.786	-0.261	-0.036	-0.173	0.287
Li	0.961	-0.182	-0.011	-0.017	0.096	-0.001
Fe	0.021	-0.881	0.292	0.172	-0.142	-0.012
Cu	0.068	-0.258	0.281	0.814	0.179	0.183
Ni	0.242	-0.536	-0.476	0.329	0.361	-0.230

TABLE 10-Continued

	Factors					
	1	2	3	4	5	6
Pb	0.192	-0.419	-0.656	-0.141	-0.338	0.150
Al	-0.467	-0.507	-0.457	-0.101	0.054	-0.175
Si	-0.553	0.376	-0.503	0.177	0.335	0.145
SO_4	0.738	0.180	-0.085	0.027	-0.444	-0.232
Zn	-0.175	-0.860	-0.034	0.163	-0.200	0.131
P	0.764	0.216	0.140	0.184	-0.353	0.217
Cl	0.929	-0.243	0.004	-0.192	0.093	-0.080
% Variance Accounted For	39.74	24.79	8.26	6.55	5.38	3.24

TABLE 11

THE pH, ELECTRICAL CONDUCTIVITY (E.C.), ORGANIC MATTER (O.M.), MAJOR ELEMENTS AND ANION VARIABLES FOR SEDIMENTS IN BARREN AREAS.[1]

Date	pH	E.C. Mmhos/cm	O.M. %	Ca	Mg	K	Na	P	SO_4	Cl
				meq/100gm				ppm		
30 May	7.6	9.5	5.1	23.7	18.1	4.4	53.7	9.1	28600	2500
4 July	8.0	9.7	5.7	27.3	16.7	4.1	29.8	5.0	15400	1450
21 July	7.8	10.8	4.8	34.1	16.0	4.3	33.6	8.5	16900	1750
18 Aug.	8.0	11.7	5.3	32.7	20.0	4.8	41.4	8.0	19600	2000
8 Sep.	8.1	4.5	4.5	16.5	17.0	2.8	46.1	7.7	16550	1950
18 Sep.	8.3	11.6	4.8	26.5	18.3	3.6	34.3	8.0	16400	1925
6 Oct.	7.8	6.1	2.1	19.9	12.6	1.5	17.8	6.5	9600	900

[1] n=1, for each date

TABLE 12

THE TRACE ELEMENT CONCENTRATIONS FOR SEDIMENTS IN BARREN AREAS.[1]

Date	Al	Cu	Fe	Li	Mn_1	Mn_2	Ni	Pb	Si	Sr	Zn
						ppm					
30 May	6.3	2.8	42.5	2.0	8.1	95.5	6.5	4.7	70.0	32.4	2.4
4 Jul	0.0	4.5	74.0	2.2	13.7	106.0	2.7	4.3	85.0	34.0	3.1
21 Jul	0.0	5.4	64.5	2.3	10.1	71.3	2.4	4.0	80.0	36.6	2.4
18 Aug	3.0	5.1	76.5	3.3	13.0	81.3	2.6	4.8	81.0	36.7	2.5
8 Sep	5.0	5.1	126.0	1.9	7.0	69.8	4.2	4.8	60.0	32.0	2.2
18 Sep	2.5	6.1	157.0	3.1	20.0	86.3	2.6	4.0	72.5	31.0	3.0
6 Oct	0.0	4.0	158.0	1.5	35.0	94.0	2.4	2.9	67.5	18.2	2.2

[1] n=1, for each date

of the barren sediment variables (Fig. 17) is quite different from that of the *P. pectinatus* community variables. Fewer observations (7) of the barren communities, however, may not show the true relationship between these areas in the lake.

Characteristics of Aerobic and Anaerobic Sediments

The oxidized and reduced (aerobic and anaerobic) layers of sediments are compared in Tables 13 and 14 for Fox Lake and the areas along the North Dakota transect. Of the eight, the number of sites in which the results for individual elements agree with those found by Gorham and Swaine (1965) are: Fe (7); Ni, Mn (6); P, Sr, Li (5); Zn (2); Pb, Na, K (1); Cu (0). The areas are quite different from one another, yet they often show some similar characteristics of ionic content in the oxidized and reduced layers. Copper and nickel were generally higher in the reduced layer, as was pH. Sodium, K, Ca, Mg, Mn, Li, Fe, Pb, Si, SO_4, and Zn were generally higher in the oxidized layers, accounting for a higher E.C. in these layers. Three ions, Cl, Sr and Al, showed no real trend.

Plant Characteristics-Productivity

The mean production of *P. pectinatus* in Fox Lake is summarized in Table 15. The first macrophyte growth was observed on 30 June and the entire community was dead on 6 October, a growing season of 129 days. Maximum production was observed after 80 days (Fig. 18a). The maximum rate of production (5.2 $gm/m^2/day$) was observed during the first 30 days of growth. The mean production rate from germination to the maximum was 3.7 $gm/m^2/day$.

The maximum caloric content per gram of tissue (Fig. 18b) was found to be 3397 cal on 21 July, and the minimum was 2587 cal on 4 July. The

Figure 17. Phenogram of barren sediment variables.

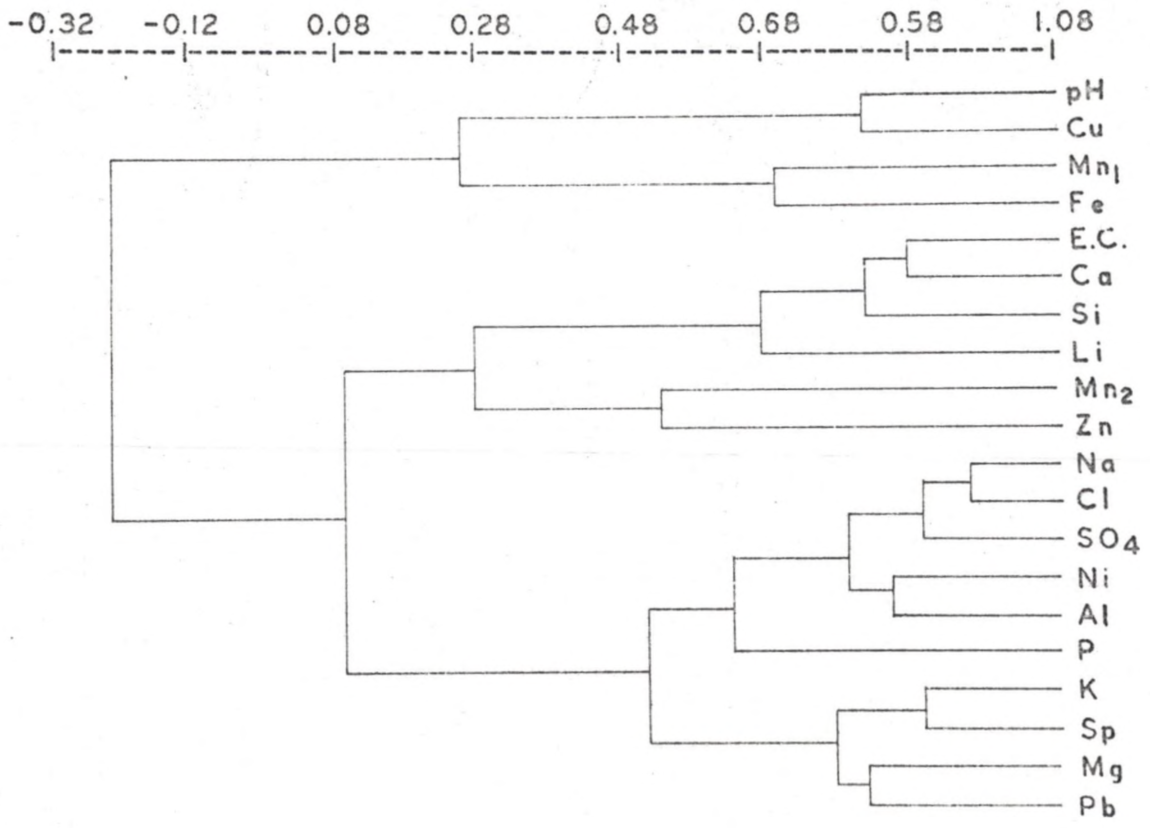

-0.32
-0.12
0.08
0.28
0.48
0.68
0.58
1.08
pH
Cu
Mn_1
Fe
E.C.
Ca
Si
Li
Mn_2
Zn
Na
Cl
SO_4
Ni
Al
P
K
Sp
Mg
Pb

TABLE 13

COMPARISON OF OXIDIZED AND REDUCED LAYERS FOR pH, ELECTRICAL CONDUCTIVITY (E.C.), MAJOR ELEMENTS AND ANIONS IN FOX LAKE AND ALONG THE NORTH DAKOTA TRANSECT.

Site	pH	E.C.	Ca	Mg	K	Na	SO_4	Cl	P
		Mmhos/cm	meq/100gm						ppm
FOX LAKE									
Oxidized (5)[1]	7.7	9.3	20.2	18.2	3.4	30.8	25.0	9.7	8.6
Reduced (5)	7.9	9.3	39.9	18.3	3.8	30.1	41.5	8.4	9.8
HARWOOD SLOUGH									
Oxidized (1)	7.5	2.1	10.4	19.2	2.2	2.2	6.5	10.2	47.0
Reduced (1)	7.6	1.1	9.9	16.7	2.2	1.3	3.6	9.3	39.0
LAKE ASHTABULA									
Oxidized (1)	7.7	1.2	8.3	4.4	0.7	1.2	4.5	2.8	1.1
Reduced (1)	7.8	0.9	5.4	6.4	0.6	3.2	3.5	3.7	0.4
ARROWWOOD LAKE									
Oxidized (1)	7.5	1.3	6.4	5.9	0.8	3.0	4.4	3.7	1.0
Reduced (1)	7.6	1.0	6.1	4.8	0.6	1.0	4.3	3.7	0.6
MT. MORIAH POND									
Oxidized (1)	7.9	1.1	3.8	6.5	0.6	1.2	2.5	3.7	10.3
Reduced (1)	7.5	1.4	4.7	3.5	0.3	0.7	3.6	2.8	1.2
WING POND									
Oxidized (1)	7.6	3.3	7.1	24.6	2.5	7.2	10.4	4.6	0.8
Reduced (1)	7.8	1.9	5.0	15.4	2.3	4.5	6.1	2.8	1.3
DICKINSON STREAM									
Oxidized (1)	7.7	2.7	6.7	17.1	1.0	6.6	7.7	3.7	0.9
Reduced (1)	7.7	2.0	6.7	7.6	0.6	1.5	10.4	3.7	0.6

TABLE 13–Continued

Site	pH	E.C. Mmhos/cm	Ca	Mg	K	Na	SO$_4$	Cl	P ppm
			-------	-------	-------	meq/100gm	-------	-------	
GOLVA STREAM									
Oxidized (1)	7.4	3.3	8.0	23.8	1.2	4.4	12.3	3.7	0.2
Reduced (1)	8.0	0.6	5.7	7.8	0.8	1.8	1.7	3.7	0.5

[1] Number in parentheses indicates sample size.

TABLE 14

COMPARISON OF OXIDIZED AND REDUCED LAYERS FOR TRACE ELEMENT CONCENTRATION IN FOX LAKE AND ALONG THE NORTH DAKOTA TRANSECT.

Site	Al	Cu	Fe	Li	Mn_1	Mn_2	Ni	Pb	Si	Sr	Zn
	ppm										
FOX LAKE											
Oxidized (5)[1]	3.6	3.8	91.4	20.6	13.2	113.5	2.8	5.1	84.7	25.1	9.7
Reduced (5)	1.5	5.6	69.8	22.6	10.7	72.0	2.6	4.4	69.0	37.0	8.4
HARWOOD SLOUGH											
Oxidized (1)	15.0	6.5	94.0	0.5	50.0	381.3	4.8	11.3	67.5	15.9	6.3
Reduced (1)	15.0	9.4	134.0	0.5	75.0	386.3	6.0	11.6	62.5	16.1	8.3
LAKE ASHTABULA											
Oxidized (1)	10.0	2.7	53.0	0.1	30.0	336.3	2.3	6.1	42.5	8.0	5.1
Reduced (1)	12.5	3.5	47.0	0.2	30.0	198.8	3.0	4.5	40.0	10.4	4.7
ARROWWOOD LAKE											
Oxidized (1)	10.0	1.3	97.0	0.2	18.0	280.0	1.3	4.1	65.0	9.2	7.8
Reduced (1)	17.5	2.8	54.0	0.1	5.7	132.5	1.8	2.6	55.0	7.8	3.0
MT. MORIAH POND											
Oxidized (1)	15.0	0.7	75.0	0.3	10.6	97.5	0.5	2.0	82.5	7.8	2.1
Reduced (1)	12.5	1.6	58.0	0.2	6.8	36.3	4.3	1.7	35.0	6.3	2.9
WING POND											
Oxidized (1)	15.0	0.9	175.0	1.3	25.0	642.5	3.0	9.8	60.0	21.9	6.9
Reduced (1)	15.0	6.0	58.0	0.8	15.3	562.5	0.8	8.5	67.5	20.0	4.1
DICKINSON STREAM											
Oxidized (1)	15.0	2.4	164.0	0.3	35.0	292.5	3.0	6.8	50.0	31.6	7.1
Reduced (1)	15.0	7.7	99.0	0.2	40.0	236.3	4.0	5.0	32.5	23.8	6.2

TABLE 14–Continued

Site	Al	Cu	Fe	Li	Mn_1	Mn_2	Ni	Pb	Si	Sr	Zn
						ppm					
GOLVA STREAM											
Oxidized (1)	15.0	1.3	233.0	0.6	16.3	141.3	2.3	8.5	55.0	24.6	6.8
Reduced (1)	17.5	7.8	104.0	0.3	7.3	131.3	2.5	6.9	35.0	16.9	4.0

---

[1] Number in parentheses indicates sample size.

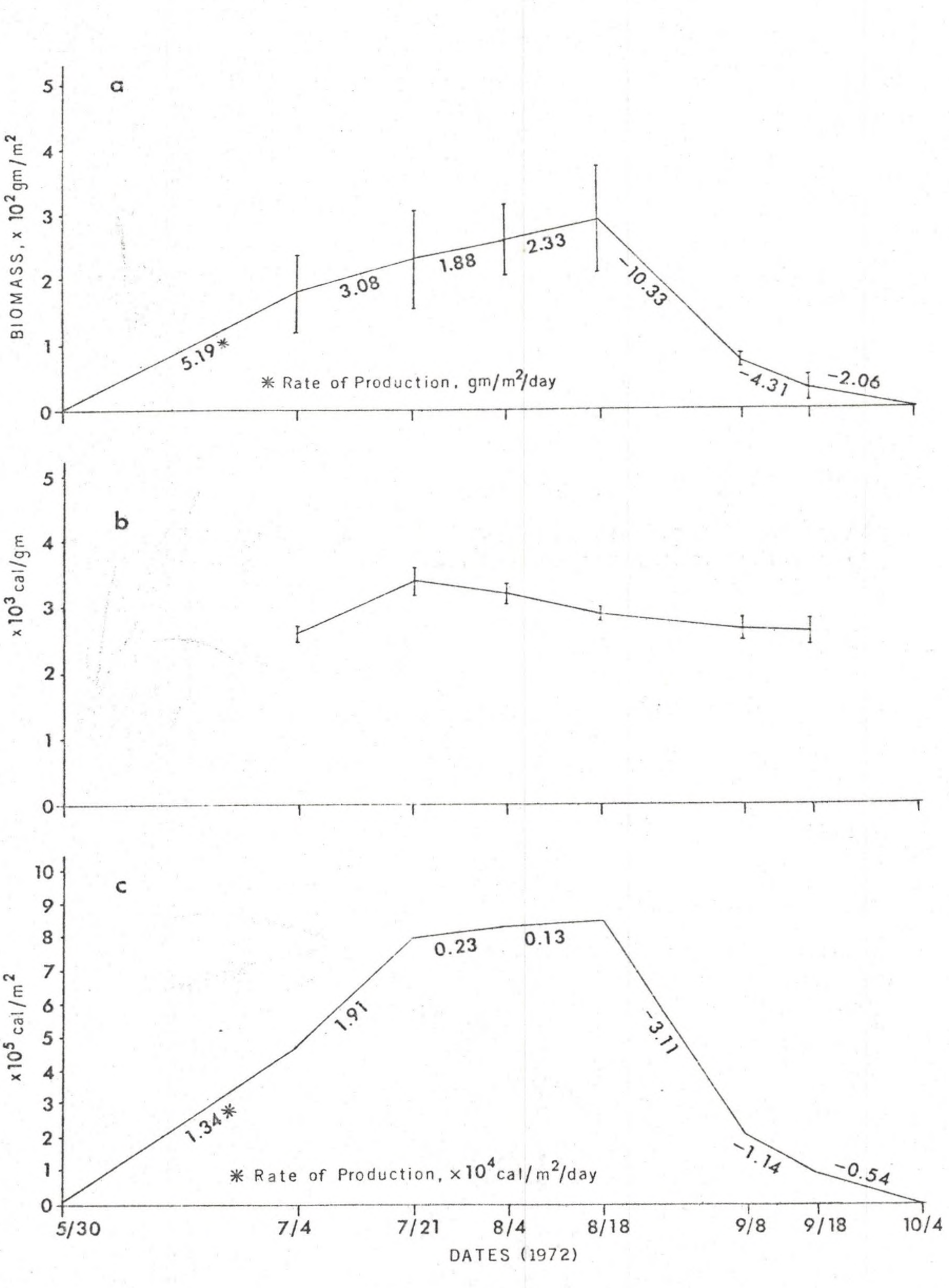
TABLE 15

MEAN BIOMASS PRODUCTION, CALORIC CONTENT, AND PRODUCTION RATE OF POTAMOGETON PECTINATUS IN FOX LAKE, 1972

Dates	Production gm/m^2	Caloric Content cal/gm	Production Rate $gm/m^2/day$
4 July (5)[1]	181.6	2587.7	5.2
21 July (5)	234.0	3397.0	3.1
4 Aug. (5)	260.3	3179.7	1.9
18 Aug. (5)	292.9	2888.0	2.3
8 Sep. (5)	76.0	2628.6	-
18 Sep. (5)	32.9	2602.5	-

[1] Number in parentheses indicates sample size.

Figure 18. Intraseasonal variation in (a) biomass production, (b) caloric content per gram and (c) total energy production in Fox Lake, 1972.


a
BIOMASS, x 10² gm/m²
5
4
3
2
1
0
5.19*
3.08
1.88
2.33
-10.33
-4.31
-2.06
* Rate of Production, gm/m²/day
b
x 10³ cal/gm
5
4
3
2
1
0
c
x 10⁵ cal/m²
10
9
8
7
6
5
4
3
2
1
0
1.34*
1.91
0.23
0.13
-3.11
-1.14
-0.54
* Rate of Production, x 10⁴ cal/m²/day
5/30
7/4
7/21
8/4
8/18
9/8
9/18
10/4
DATES (1972)

mean caloric content for the entire growing season was 2972.5 cal/gm.

Plant Characteristics-Chemical

The plant chemical characteristics (Tables 16 and 17) were determined on dry ashed plant samples. The ash was dissolved in 1N HCl for all analyses.

Mean ash content had a range of 56.0 to 35.4 percent. Westlake (1965) reports that *P. pectinatus* has an ash content of 19%. This compares to a mean ash content of 45.7% for *P. pectinatus* in Fox Lake, but the sample by Westlake was taken in June before maximum marl production. A correlation matrix (Table 18) was constructed using percent carbon, biomass and the 13 elements that were measured. A phenogram (Fig. 19) was again constructed using the unweighted pair-group method. The second level in the phenogram has broken the elements into four similar groups:

Group I - C, Na, K
Group II - Mg, Fe
Group III - Li, Cu, Sr, Al, Ni, Zn, Ca, Si
Group IV - Mn

If we again look at the temporal trends (Figs. 20, 21) of the elements in each group, we find that the trends are similar. The elements in Group III show three subgroups:

Group III A - Cu, Li
Group III B - Sr, Al, Ni, Zn
Group III C - Ca, Si

The trends in these three subgroups aren't as different as one might

TABLE 16

MEAN CARBON (C), NITROGEN (N), AND MAJOR ELEMENT CONCENTRATION IN *POTAMOGETON PECTINATUS* IN FOX LAKE, 1972

Date	C[1]	Ca	Mg	K	Na	N[2]
	%	-----meq/100gm-----				%
4 July (5)[3]	44.0	984.8	198.8	30.6	93.9	1.08
21 July (5)	64.6	579.8	247.9	40.2	143.7	1.43
4 Aug. (5)	61.9	836.2	403.8	37.8	199.6	1.66
18 Aug. (5)	54.1	1146.0	504.6	20.0	115.4	1.41
8 Sep. (5)	46.7	899.2	443.8	14.5	108.3	1.64
18 Sep. (5)	46.8	750.8	377.9	15.9	117.6	1.75
6 Oct. (1)	62.3	93.0	158.3	36.3	135.7	1.35

[1] Loss of weight on ignition
[2] Sample size is 1
[3] Number in parentheses indicates sample size.

TABLE 17

MEAN TRACE ELEMENT CONTENT OF *POTAMOGETON PECTINATUS* IN FOX LAKE, 1972

Date	Al	Cu	Fe	Li	Mn	Ni	Si	Sr	Zn
	ppm								
4 July (5)[1]	1816	11.4	3370	15.4	960	19.5	8370	545.0	20.4
21 July (5)	556	9.9	38105	13.8	560	13.3	4910	205.6	19.0
4 Aug. (5)	422	12.0	21865	15.6	625	10.7	7280	141.7	17.3
18 Aug. (5)	730	9.4	31605	11.9	520	11.5	9860	268.3	15.6
8 Sep. (5)	1048	13.3	50120	23.5	815	17.8	10550	402.2	17.4
18 Sep. (5)	1440	14.1	13205	21.4	785	20.8	10400	397.5	20.4
6 Oct. (1)	950	8.5	1940	12.5	3100	9.0	4550	128.0	12.5

[1] Number in parentheses indicates sample size.

Table 18. Correlation matrix of *Potamogeton pectinatus* variables.
$n=31$; ** $P < .01$, * $.05 \geq P > .01$

C														
0.562**	Na													
0.630**	0.671**	K												
0.059	0.179	-0.369*	Mg											
-0.319	-0.039	-0.278	-0.011	Li										
-0.392*	-0.064	-0.278	0.148	-0.097	Ca									
-0.875**	-0.572**	-0.416*	-0.408*	0.253	0.352*	Sr								
0.201	-0.019	-0.201	0.415*	-0.016	-0.043	-0.206	Fe							
-0.227	-0.068	0.078	-0.496**	0.024	-0.069	0.301	-0.322	Mn						
-0.431**	-0.158	0.015	-0.536**	0.187	0.047	0.534**	-0.243	0.012	Zn					
-0.543**	-0.126	-0.521**	0.194	0.429**	0.547**	0.427**	-0.142	-0.002	-0.041	Si				
-0.812**	-0.532**	-0.326*	-0.357*	0.347*	0.069	0.744**	-0.413*	0.309	0.558**	0.287	Al			
-0.746**	-0.436**	-0.376*	-0.352*	0.564**	0.118	0.763**	-0.208	0.167	0.615**	0.402*	0.796**	Ni		
-0.355*	-0.079	-0.294	-0.071	0.749**	-0.137	0.289	-0.077	-0.070	0.342*	0.230	0.401*	0.617**	Cu	
0.374*	0.124	0.283	0.128	-0.574**	0.185	-0.202	0.136	-0.368*	-0.314	0.103	-0.496**	-0.489**	-0.589**	Biomass

Figure 19. Phenogram of the plant variables.

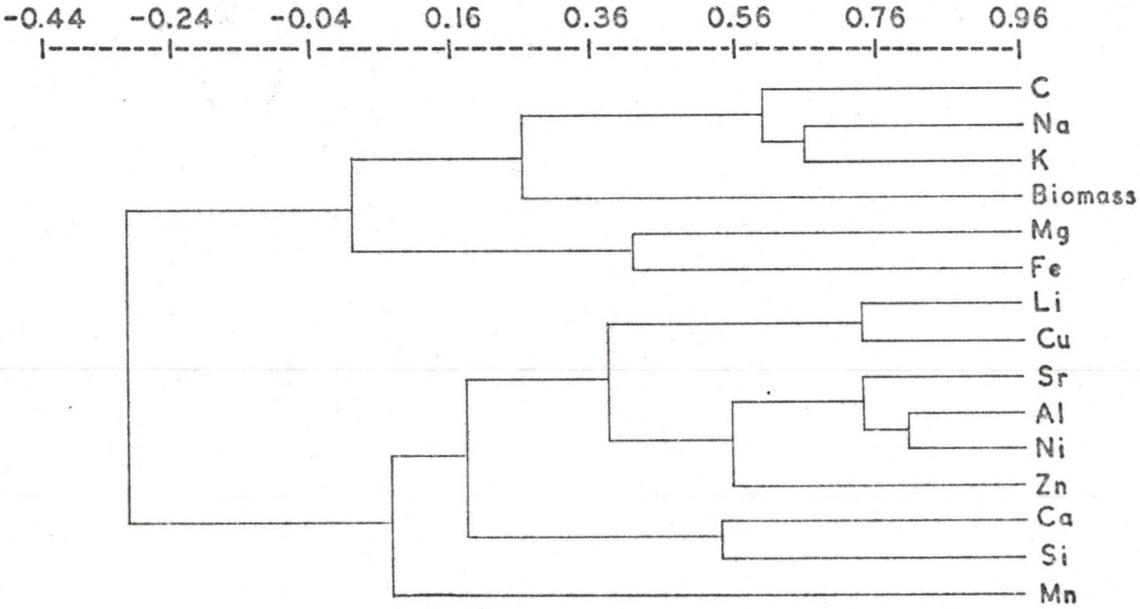

-0.44
-0.24
-0.04
0.16
0.36
0.56
0.76
0.96
C
Na
K
Biomass
Mg
Fe
Li
Cu
Sr
Al
Ni
Zn
Ca
Si
Mn

Figure 20. Temporal trends of the plant variables in (a) Group I, (b) Group II and (c, d) Group III B.

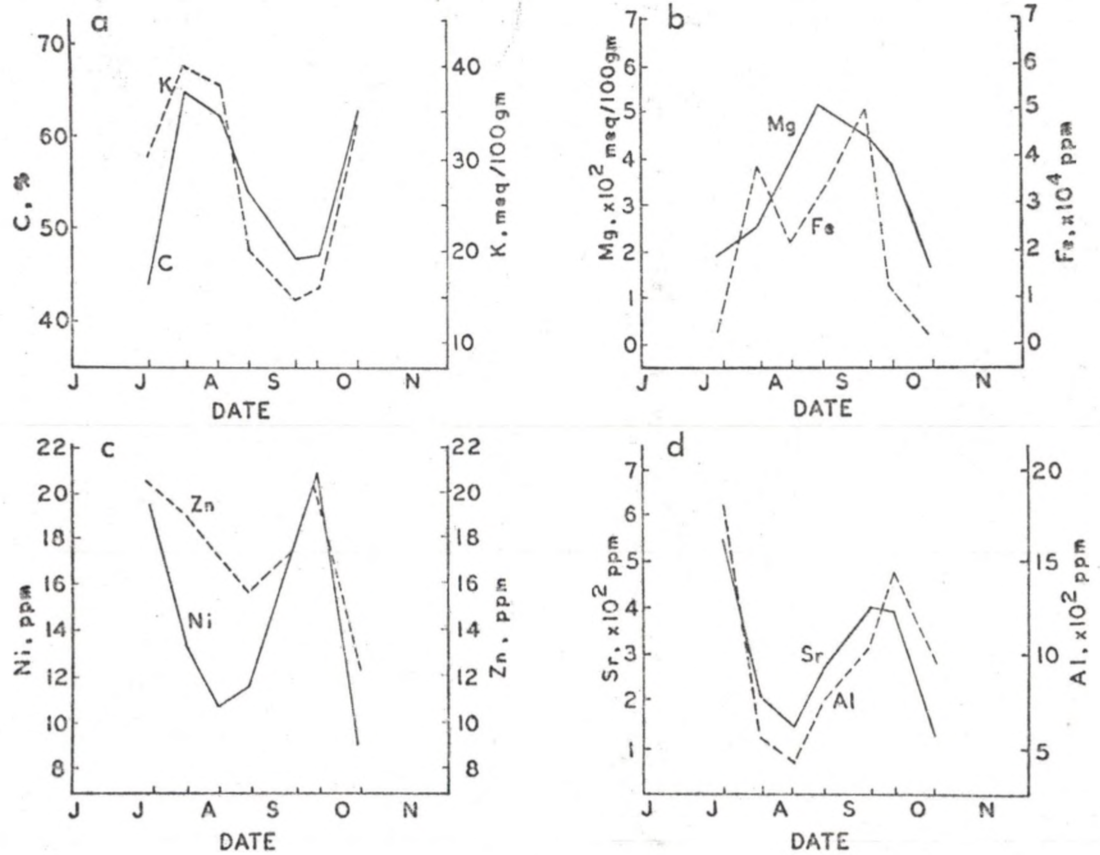
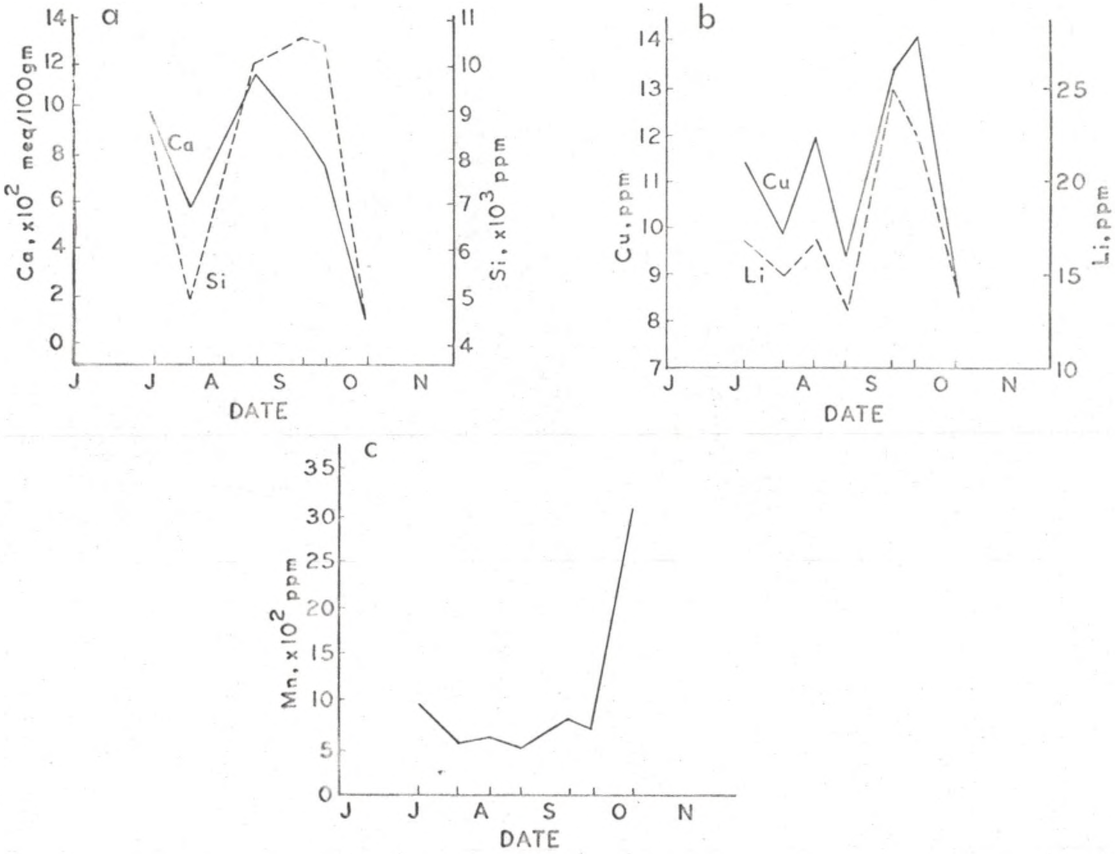

a
C, %
70
60
50
40
K
C
K, meq/100gm
40
30
20
10
J
J
A
S
O
N
DATE
b
Mg, x10^2 meq/100gm
7
6
5
4
3
2
1
0
Mg
Fe
Fe, x10^4 ppm
J
J
A
S
O
N
DATE
c
Ni, ppm
22
20
18
16
14
12
10
8
Zn
Ni
Zn, ppm
J
J
A
S
O
N
DATE
d
Sr, x10^2 ppm
7
6
5
4
3
2
1
Sr
Al
Al, x10^2 ppm
20
15
10
5
J
J
A
S
O
N
DATE

Figure 21. Temporal trends of the plant variables in (a) Group III C, (b) Group III A and (c) Group IV.


a
Ca, x10² meq/100gm
14
12
10
8
6
4
2
0
Si, x10³ ppm
11
10
9
8
7
6
5
4
Ca
Si
J
J
A
S
O
N
DATE
b
Cu, ppm
14
13
12
11
10
9
8
7
Li, ppm
25
20
15
10
Cu
Li
J
J
A
S
O
N
DATE
c
Mn, x10² ppm
35
30
25
20
15
10
5
0
J
J
A
S
O
N
DATE

expect (Figs. 20c, d, 21a, b). It can be seen that subgroup A differs from B on only one date, 21 July and from C on 4 August. Subgroup B differs from subgroup C in that the curve has shifted slightly. It should also be noted that the Group I and Group III elements are nearly perfect mirror images of one another and that the Group II and IV elements show no similarities to one another or to the other groups or subgroups.

DISCUSSION AND CONCLUSIONS

It has been shown that temporal trends can be grouped by several methods based on the correlation matrix, as well as by examination of the plots of the trends. The greatest information content is probably found in the plots of the trends, but variations in the trend on a single date can cause the trends to appear quite different when in reality they are very similar. This was the case with the elements in Plant Group III (Figs. 20, 21). This points out the need for dependable objective methods to form groups and subgroups based on some measure of similarity. The two methods used here are the construction of phenograms and principal components analysis. Phenograms are better for showing the groups and subgroups that are present. The information content of the phenograms is nearly as great as that of the plotted trends. Principal components analysis shows dissimilarities in groups as efficiently as it shows similarities, this is its only advantage over the phenograms. The greatest usefulness for both of these methods is that they will form trend similarity groups in data that are not as obviously similar as the data in this study. This would be especially true when several different ecosystems are studied. In such a study the means of the individual variables are not as informative due to the great variability that might be encountered within the data.

In general, the factors affecting the nutrient dynamics in the Fox Lake *P. pectinatus* community can be grouped into four major categories: abiotic factors, ion interaction factors, primary productivity factors and decompositional factors. Each of these factors has several important subfactors: it is the interaction of these subfactors that caused the trends that were observed.

The temperature and dissolved gases in Fox Lake are very closely tied to the productivity of P. pectinatus. Even though the lake is very shallow it shows a temperature regime similar to a dimictic lake, in that a definite thermal gradient is set up in the summer, density flows occur in the fall and the lake undergoes two periods of mixing. The macrophytes shade the lower waters and tend to concentrate the heat in the surface water. They also hamper the mixing action by wind and convection currents that would normally cause uniform temperatures in a lake so shallow. In the fall when the surface waters cool they are again kept more or less in place by the dense mat of macrophytes at the surface. When they cool enough, they tend to sink to the bottom due to their higher density. This causes the situation observed in Fox Lake in which the water above the sediment was the coolest region in the profile. This also causes early fall mixing even before the macrophytes have died and wind action causes complete mixing of the water column. Moss (1969) and Happey (1970a) found that the same thing was true of a small English lake which had a dense cover of Ceratophyllum demersum.

Anderson (1958) found that the bottom water in a small saline pond was higher in density due to dissolved salts. This is a plausible explanation of cooler temperatures at an intermediate depth than directly above the sediment.

Early in the growing season it was observed that the dissolved oxygen was higher in the lower than in the surface waters. This is probably due to the fact that the macrophytes were very short and growing rapidly. The oxygen liberated was absorbed by these lower waters. By mid-July the macrophyte growth had reached the surface and dissolved oxygen was greater there at that time and for the rest of the growing season. Again the effect of the macrophyte in decreasing turbulence is a factor that influences this relationship. Another factor is oxygen depletion in the lower waters due to absorption by sediments.

Dissolved carbon dioxide may be very low in Fox Lake due to the high pH. Bicarbonate is probably the dominant photosynthetic carbon source in brackish, alkaline waters such as Fox Lake (Steemann Nielsen 1954, Wetzel 1970). This usage of bicarbonate causes marl (carbonates) to form on the leaf surfaces of the macrophytes.

Wetzel (1970) and Otsuki and Wetzel (1972, 1973) refer to the consequences of this carbonate formation in the adsorption of dissolved organic matter from the water, coprecipitation of phosphate, and chelation of trace elements by adsorbed dissolved organic matter. This is a good example of an ion interaction effect. Burstrom (1963) and Stumm and Morgan (1970) point out that cobalt or high quantities of calcium or magnesium can force ferrous iron from chelation complexes. The effect of this process is to force ferrous iron into a dissolved ionic state. It has been shown by Saunders (1957), Schelski (1962) and Schindler (1972) that unless metals like iron and manganese are in a chelated form they are unavailable to the plants, probably because ferrous (Fe^{+2}) or manganous (Mn^{+2}) ions react with hydroxide in the presence of oxygen to form insoluble ferric (Fe^{+3}) or manganic (Mn^{+4}) hydroxides (Mortimer 1941, Stumm and Morgan 1970).

Decomposition of organic materials, both in the water and in the sediments, may occur as a result of microbial action or a direct chemical reaction with dissolved oxygen. The end result of this decomposition is the formation of carbon dioxide, the depletion of dissolved oxygen and the occurrence of reducing conditions (Siever et al. 1965, Mortimer 1971, Weiler 1973). Release of Fe, Mn, Si, P and other elements may be due to reduction of these ions to more soluble forms or changes in pH or both. Stumm and Morgan (1970) arrange the most easily reduced components to the least easily reduced in the oxidation of organic matter as follows: O_2, NO_3, NO_2, Mn^{+4} Oxide, Fe^{+3} Oxide, SO_4, CO_2. Since the odor of hydrogen sulfide is easily detectable in Fox Lake, it is an indication that SO_4 has been reduced and would therefore suggest that N, Mn, and Fe are available in the sediments. It has been shown that PO_4, NH_4 and Si O_2 are available in hypolimnetic (anaerobic) waters and become available after the spring and fall overturns (Happey 1970b, Mortimer 1971). The reduction of sulfate has another effect in that insoluble sulfides may be formed with ions like Cu^{+1}, Zn^{+2}, and Pb^{+2} (Stumm and Morgan 1970) it should also be possible for insoluble iron sulfides to form under these conditions.

In the following sections the trends of individual elements and groups of elements in the water, sediments, and plants will be discussed in terms of these processes.

Nutrient Trends in the Water

In any discussion of plant nutrients and nutrient transfer, the medium of exchange, water, is of paramount importance. It is therefore logical to approach the nutrient dynamics of an aquatic system with analysis of nutrient trends in the water. It must be kept in mind that the system is dynamic, that there is constant flux in the nutrient concentrations between the components of the ecosystem and that at all times there is a tendency toward homeostatis in the system (Lerman and Brunskill 1971). Also, prior to the onset of plant growth the system is probably at or near this homeostatic condition, and during the majority of the growing season changes in the equilibrium are relatively slow and constant due to the gradual uptake by the primary producers, and the time immediately after plant death (the end of the growing season) is the time of the greatest stress on the equilibrium.

The temporal trends of the ion concentrations in the water follow several general patterns during the growing season.

I. A constant increase in concentration throughout the season

II. A constant increase in concentration until the time of plant death followed by a very rapid increase

III. A constant increase in concentration until the time of plant death followed by a decrease

IV. A constant decrease in concentration throughout the growing season

V. A decrease at the beginning of the growing season and a rapid increase at the time of plant death.

All of the ions that were measured in Fox Lake water samples follow one of these trends. The reasons for the behavior of individual ions may be quite different although their trends may be very similar.

TREND I - Constant Increase

The ions that followed this trend are sulfate, sodium, magnesium, lithium, carbonate, copper and zinc. Typical examples of this trend are sulfate and sodium (Fig. 9). Except for carbonate, all of the ions in this group probably show this trend because of evaporation and, therefore, increasing concentration. The carbonate increase is probably due to breakdown of bicarbonate by *P. pectinatus* and algae that are present. This breakdown of bicarbonate yields carbonate, water and carbon dioxide by the following reactions:

$$\textit{P. pectinatus}\text{--}Ca^{++} + 2HCO_3^- \longrightarrow CaCO_3 + H_2O + CO_2$$

$$\text{algae--}2Na^+ + 2HCO_3^- \longrightarrow 2Na^+ + CO_3^= + H_2O + CO_2$$

The carbon dioxide that is liberated is in close association with the plant tissues and is a direct source of carbon for fixation. Steemann Nielsen (1951) and Lowenhaupt (1956) believe that there is passive absorption of HCO_3^- and an associated cation into the plant tissues followed by a breakdown of the bicarbonate to form a hydroxide radical and carbon dioxide. The hydroxide and associated cation are then moved to the upper surface of the leaf by active transport involving some photochemical process. When these ions diffuse through the leaf a very alkaline microzone, as reported by Otsuki and Wetzel (1973), is created on the leaf surface. This very alkaline environment would then cause precipitation of calcium carbonate (marl).

Copper and Zn also seem to follow this trend although there seem to be great fluctuations in their concentration. The trend is still generally toward higher concentration (Fig. 9). It is unknown whether the fluctuations are responses to some factor of productivity such as various algal blooms or whether they are only random fluctuations caused by measurement error, sample contamination, etc. The similarity of the fluctuations would tend to indicate the former. It may also be tied to marl formation and adsorption of organics and their chelated metal ions by the marl.

TREND II - Constant Increase, Rapid Increase

Calcium, potassium, iron and strontium follow this trend. Calcium and potassium are the most typical of the trend although probably for different reasons (Fig. 9). All of the ions in this group show the constant increase for the same reason as those elements in Trend I, e.g. evaporation. For potassium and iron the rapid increase at the end of the growing season is probably due to evaporation plus a very rapid leaching out of these elements from the dead plant material (Boyd 1970). Calcium and, probably, strontium show the rapid increase because the marl that coated the leaves and stems of P. pectinatus begins to fall off when the plants die and begin to decompose. During this decomposition carbon dioxide is released which effectively decreases the pH (Misra 1938). This decrease in pH causes some of the insoluble calcium and strontium carbonates that form the marl to become soluble bicarbonates. Therefore, the soluble calcium and strontium concentrations increase very rapidly.

TREND III - Constant Increase, Then Decrease

Only two ions, chloride and nickel, follow this pattern. It seems unlikely that the decrease at the end of the growing season would be a direct result of the death of the plants; an increase due to leaching would be expected. It must be a response that is related to one or more factors that are direct results of plant death. The decrease in nickel concentrations may be a response to the decreasing pH (Fig. 10). It is also possible that insoluble sulfides are formed from reduction of sulfate during this period. The decrease in chloride is probably not due to pH but to some other factor that isn't evident. It is interesting to note that the chloride trend very closely parallels the trend in specific conductivity (Fig. 9). If there is a cause and effect relationship in these two parameters it is probably that the decrease in conductivity is a result of the chloride decrease rather than a cause for it.

TREND IV - Constant Decrease

Only aluminum (Fig. 11b) follows this trend, probably due to the precipitation of aluminum hydroxide or phosphate due to the high pH, and the added effect of plant uptake in the early part of the growing season and complexing by dissolved organic matter after plant death.

TREND V - Decrease, Constancy, Increase

This trend is shown by silicon and bicarbonate (Fig. 11a). These two elements follow such a similar pattern through the growing season that it might be postulated that their behavior is a direct response to a single factor, plant productivity. Silicon is used directly by the diatoms in the formation of their frustules and, as was explained in the discussion of carbonate in Trend I, the bicarbonate is broken down as a source of carbon dioxide, this causes an increase in pH. Diatom frustules are insoluble at high pH accounting for the lower concentration at this time. Phosphorus also appears to follow this trend (Fig. 10), although the decrease is not as rapid. This is probably because the concentration is low (0.2 ppm) to begin with. Therefore, the time necessary for a significant decrease due to plant uptake is longer (due to mass action effects). Another possible cause for the increase at the end of the growing season is secretion of phosphate by the macrophyte as McRoy (1972) found for a related species, Zostera marina. Manganese (Fig. 10) may also follow this trend, but the pattern is not very similar to the others (Fig. 11a). The initial rapid decrease may be due to precipitation of manganic hydroxides in the presence of dissolved oxygen and high pH. The trend from this point on is very similar to that for the Trend I elements (Fig. 10) indicating that evaporation and probably release of manganous ions from the sediments due to the reducing conditions later in the growing season are responsible for the trend. This trend indicates that bicarbonate may limit the productivity of both the algae and the macrophytes. Limitation of production due to carbon dioxide or bicarbonate concentration has been shown by Wetzel (1965, 1970) and Hartman and Brown (1966).

Nutrient Trends in the Sediments

It was shown earlier that the sediment ions form four general groups based on correlation analysis. The trends in the sediment ions, pH, E.C. and organic matter group in the same manner. The trends can be stated as follows:

Trend I - constant increase through the growing season

Trend II - a decrease followed by a rapid increase on plant death

Trend III - a decrease early in the growing season followed by a slow increase

Trend IV - a constant decrease.

The trends of the individual ions may be discussed in terms of the factors that are responsible for their behavior.

Trend I - Constant Increase

As in the case of the water variables in Trends I and II, this trend is probably a result of evaporation of the lake water and reduction of insoluble sediment complexes. The concentrations of the ions that follow this trend (Na, Cl, Mg, K, Li, P) are also increasing in the water (Fig. 13). This would suggest that the increase in the sediment is due to increased concentration in the interstitial water. The breakdown of organic materials in the sediments may be partially responsible, especially in the case of phosphorus.

Trend II - Continuous Decrease, Rapid Increase

The trends for calcium and strontium (Fig. 14a) are probably due to the marl forming nature of *P. pectinatus* and direct uptake and incorporation in plant tissues. During the growing season the plant is continually forming marl on the stems and leaf surfaces by incorporation of calcium in the water. This will cause equilibrium shifts from the water to the sediments. The trend for sulfate (Fig. 14b) may be partially due to the factors discussed for calcium and strontium plus the fact that in anaerobic sediments sulfate may be broken down by bacteria as a source of respiratory energy (Mortimer 1971, and Weiler 1973). The result of the breakdown is hydrogen sulfide gas which gives the sediments their characteristic odor. The rapid rise at the time of plant death may be a result of two factors acting nearly simultaneously. These factors may be the large quantities of decomposing organic matter and the density flows in the water due to temperature. The effect of the density flow is to bring oxygen rich upper waters down to the sediments. This will cause a more rapid oxidation of the organic matter and insoluble metal sulfides in the sediments to form soluble sulfates. The trend in copper concentration (Fig. 14b) is probably a result of the same process. Copper sulfides may form through the growing season, it then shows a rapid increase in concentration at the same time as the sulfides are oxidized to sulfate.

Trend III - Early Decrease, Slow Increase

The trends of the elements in this group are probably related to the quantities of organic matter that are present. All of these elements except iron and nickel (Fig. 15) follow a trend that is very similar to the concentration of organic matter. There may be several reasons for this similarity. It has been shown that ions may be chelated and/or complexed by organic matter (Groth 1971, Schlindler 1972, and Wali et al. 1972). This may be the case in Fox Lake sediments. A second possibility is that the organic matter trend (Fig. 15) and the trend of the elements in this group (Fig. 15) are responses to some other factor. It has been shown, for example, that the dissolved oxygen content of the deeper waters is greater during the spring than later in the year. This relatively high dissolved oxygen could cause the initial decrease in organic matter. The consumption of the dissolved oxygen during decomposition would cause oxygen depletion in these lower waters. This would allow for a slow build up of organic matter in the sediments, accounting for the slow increase observed. Late in the fall when the surface waters cool and move downward with their relatively high dissolved oxygen, the organic matter is again rapidly decomposed causing the decrease observed. Another influence of this decomposition is the oxidation of the sulfides that are formed during the period of low oxygen content. These factors acting singularly or together may result in the trends that were observed.

Trend IV - Constant Decrease

This trend is shown only by Si and is probably due to the fact that silicate is released from the sediments under reducing conditions and is recycled as diatom frustules. Since the pH shows a relatively constant increase, the frustules would tend to remain in an insoluble form.

Composition of the Plants

To interpret the nutrient trends in the plants it is necessary to look at the events that are occurring during the growth cycle of *P. pectinatus*.

The growth cycle from germination until no living members are observed can be divided into four periods:

I. The establishment period begins about the first of June and ends before the first of July. During this period the macrophytes have either germinated from the seed or from the tubers in sediment. They show a relatively slow growth rate and a small standing biomass, although the rhizomes are probably well developed.

II. The rapid growth period begins before the first of July and ends at about mid July to early August. By the end of this period the plants have attained about 80 percent of their maximum biomass.

III. The reproductive period begins about late July or early August and continues until about late August or early September. During this period flowering and fruiting occurs and the tubers are forming on the rhizomes.

IV. The decline period begins in late August or early September and continues until no living plants are observed in early October.

Marl formation occurs through periods II and III. During period IV many of the macrophytes are uprooted by waterfowl in search of tubers, a major food source (Metcalf 1931). Those not uprooted are dead or dying and the marl which has coated the leaves and stems begins to flake off. The marl was included as part of the plant samples when present. Those samples containing excessive marl may not give an accurate representation of the actual tissue concentrations, since the sample would contain a proportionately smaller amount of organic material than those containing no marl.

The trends in plant chemical composition can be grouped into four major categories:

Trend I - The elements in this trend, sodium, potassium and carbon (Fig. 20a), show a rise during the rapid growth period, a decline through the reproductive period and a rise in the decline period. The trend in the carbon content is probably a result of the quantity of marl present. Early in the growing season marl isn't evident on the tissues, nor is there excessive marl on the tissues during the decline period when the plants are beginning to decompose. It will be noted that these periods correspond with the periods of maximum carbon content, and that there is a steady decrease in percent carbon content during the marl forming period. Westlake (1965) reports there is very little change in ash free percent carbon over the growing season.

Since sodium and potassium form very few insoluble salts they probably are not predominent constituents of the marl. The marl would then tend to dilute them in the plant samples as well. There may also be some transport of these elements to the rhizomes during tuber formation, this would also cause a decline during the reproductive period.

Trend II - The elements in this group, iron and magnesium (Fig. 20b), show their maximum concentration at the end of the reproductive period. Magnesium is an essential component of the chlorophyll molecule. Since the chlorophyll content is probably increasing prior to this time and decreasing after fruiting, it is reasonable that magnesium behaves similarly. Iron may also be functioning in pigment formation or in fruit formation. Neel, et al. (1973) found iron to be concentrated in the lower 1/3 of P. pectinatus during the fruiting period. Mayer and Gorham (1951) have observed concentration of Fe and Mn in plants growing on organic and anaerobic muds.

Trend III - The elements in this group (Fig. 20c, d, 21a, b) all show an increase during fruiting then a decrease afterward. The increase may reflect a greater uptake during fruit formation and leaching out upon plant death. The trend may also be caused by incorporation of these elements as insoluble or chelated components in association with the marl, with a decrease occurring when the marl flakes off during the decline period. It is more probable, however, that the trend is a combination of these two factors. Especially significant is the trend of calcium which is due primarily to marl formation.

Trend IV - Only manganese (Fig. 21c) follows this trend in which the concentration is relatively constant until only a few living plants remain, then there is a rapid rise. This may be due to the ability of decomposing organic material to chelate cations like manganese which form stable complexes.

The complexity of ecosystems and their numerous interacting variables makes it almost impossible to attribute the distribution, abundance and productivity rate of an organism to any single factor. Relationships of nutrients, for example, are based on physiological uptake in relation to growth and hence should not be expected to bear a direct correlation to the concentrations of nutrients either in the water or sediments, especially in eutrophic lakes or other nutrient rich ecosystems. Consequently a correlation approach relating several operating parameters must be devised that can explain the organismal or community growth and distribution.

Likewise, due to the same complexity of interaction, it is unreasonable to expect that the factor complexes that have a great influence on a species in one ecosystem have an equivalent influence in all other ecosystems in which the species exists. An effort must be made to determine if there are some common denominators between the different ecosystems and factor complexes that are operative in each. If no such common denominator can be found it is then necessary to treat each ecosystem as a unique situation until all of the factors that can influence the species are discovered.

With this in mind it is appropriate to ask three questions about the Fox Lake ecosystem.

1. Is Fox Lake an optimum or near optimum environment for the productivity of _P. pectinatus_?
2. Why does _P. pectinatus_ grow in Fox Lake?
3. Why is the _P. pectinatus_ community monotypic?

Russian workers (Gaevskya 1969) have reported more than three times the productivity for this species and productivity of about two and one half times that of Fox Lake was observed in one site in this study (Site 8).

This points out that Fox Lake is not an optimum environment for the species production. Several possibilities could account for this decreased production: (1) some nutrient is in short supply and is limiting, (2) some element is in excess to such an extent that it is toxic, (3) the macrophyte must expend some of the energy that it has fixed or that it could fix as production in maintaining itself in a non-optimum environment. It has been shown by Steemann Nielsen (1951) that there is an active transport mechanism involved in the assimilation of HCO_3^- by certain macrophytes. According to him the utilization of bicarbonate is light dependent due to a photochemical enzyme process. In a highly alkaline system such as Fox Lake the availability of carbon dioxide would be minimal, this would force the submerged macrophytes living there to be dependent upon the utilization of HCO_3^- as a carbon source. The macrophytes then must expend some energy in active transport in order to fix energy as organic material, hence production is decreased. The quantity of carbon that is fixed is also dependent on the rate of this photochemical active transport mechanism and the rates at which the bicarbonate can diffuse into the leaf and the rate of hydroxide and cation diffusion out of the leaf.

It has been shown that P. pectinatus exists in waters with greater quantities of electrolytes than those in Fox Lake (Martin and Uhler 1939, Stewart and Kantrud 1972), and that other common macrophytes that are able to utilize HCO_3^- as a carbon source, such as Ceratophyllum demersum and Elodea canadensis (Steemann Nielsen 1954), haven't been reported from waters with such high electrical conductivity (Martin and Uhler 1939 and Moyle 1945). Species, such as Ruppia maritima, that are able to withstand the salinity haven't been shown to be able to utilize HCO_3^-. Moyle (1945) has reported that Ruppia grown in cultures with high alkalinity does not survive. It is probable then that P. pectinatus exists in Fox Lake because it is able to withstand the osmotic stress of the saline environment as well as utilize bicarbonate as a carbon source.

The community may be monotypic because other species that are native to the region are unable to perform at least one of these functions. Another causal factor for the occurrence of P. pectinatus in a dense monotypic stand observed in Fox Lake, may be the postulation by Boyd and Hess (1969) and Goulder and Boatman (1971) that some species are able to absorb and store particular nutrients early in the growing season making these nutrients limiting for other species.

There have been no comprehensive studies of the environmental concentrations at which most nutrients become limiting or toxic to P. pectinatus. It is therefore impossible to entirely discount the possibility that there are nutrients in a shortage or excess that are limiting the productivity.

Further studies are necessary on P. pectinatus to determine if the rate of the photochemical reaction in bicarbonate utilization is the limiting factor, if the usage of energy in this process is causing the decreased production, or if it is a combination of these and/or other factors.

APPENDICES

APPENDIX A

Locations of the Study Areas

Site 1. Fox Lake, Ramsey County, Sec. 24 T.155N. R.62W.

Site 2. Harwood Slough, Cass County, 4 miles W., 2 miles N. of Fargo, N.D.

Site 3. Lake Ashtabula, Barnes County, East Ashtabula Crossing.

Site 4. Arrowwood Lake, Stutsman County, National Wildlife Refuge Headquarters.

Site 5. Mount Moriah Pond, Stutsman County, Sec. 28 T.144N. R.67W., 14 miles west of Edmunds, N.D.

Site 6. Wing Pond, Burleigh County, 1/2 mile east of Wing, N.D.

Site 7. Dickinson Stream, Stark County, along Interstate 94, 9 1/2 miles west of Dickinson, N.D.

Site 8. Golva Stream, Golden Valley County, along county road 4 miles south of Golva, N.D.

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