GROWTH OF WILD RICE, *Zizania aquatica* L., IN FLOCCULENT SEDIMENTS

by

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ABSTRACT

The objectives of this research were to classify sediments from wild rice lakes, and to examine, in detail, one type of sediment that is not suitable for commercial production of wild rice.

Based on physical and chemical differences, cluster and discriminant analysis classified sediments from 39 potential and existing wild rice lakes into clay, organic, flocculent, organic-flocculent, organic-clay, and organic over clay (organic/clay) types. The major differences among the six sediment types were the percent loss on ignition, bulk density, phosphorus and cation content, and pH values. Wild rice production was best in organic, organic over clay, and organic-clay sediments. Flocculent, clay, and organic-flocculent sediments produced the lowest dry weights of individual plants.

Organic-flocculent and organic/clay sediments were examined for further physical and chemical differences, as well as seasonal nutrient trends and wild rice production. Organic-flocculent and organic/clay sediments were found to have C:N>10, and similar inorganic biogenic composition, mineral content, pH, and redox values. Major differences in nutrient values were found to exist between the sediments. Lower nutrient values (except N) in organic-flocculent sediment appear to be closely linked to the origin, type, and degree of decomposition of the organic material within the sediment. A comparison of seasonal nutrient trends between organic-flocculent and organic/clay sediments showed no nutrient depletion during the exponential growth of wild rice.

Fertilizer trials and foliar nutrient deficiency symptoms determined which nutrients were limiting production in organic-flocculent sediments. Phosphorus was found to be the main limiting nutrient; nitrogen deficiency played a secondary role. Plants grown in unfertilized organic-flocculent sediments displayed the purple leaves and slower maturation rate characteristic of phosphorus deficiency.

ACKNOWLEDGEMENTS

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Many other people, by rights, should be acknowledged by name here. However, so many people helped me in the final completion of this thesis that I have decided not to name each one individually. Instead I would like to give a general thank you to the members of my graduate committee, and the graduate students, summer students, laboratory assistants, friends, colleagues, and family who in one way or another helped me during my trials as a graduate student.

Thank you all.

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GENERAL INTRODUCTION

Wild rice (*Zizania aquatica* L.), Canada's only native cereal, may be known best as a gourmet food item (Grant, 1981). In Canada, this nutritious grain was first utilized by the native Indians (Ojibwa and Sioux) in parts of northwestern Ontario and Manitoba. The native people relied on the "manomin" or good fruit from this annual aquatic grass as a food staple, so it is not surprising that native ritual and legend surround wild rice (Cary, 1984). Today the traditional rice beds are still harvested by the native people of northwestern Ontario as a foodstuff and a cash crop. To expand wild rice production in northern Ontario both native and non-native producers have seeded new lakes using techniques similar to Lee's (1984, 1986, 1987).

Taxonomy

The taxonomy of the annual species and varieties of genus *Zizania* is still being resolved. Fassett (1924) identified one species, *Z. aquatica* and 3 varieties (vars. *brevis*, *angustifolia*, and *interior*). Dore (1969) classified 2 distinct species, each with 2 varieties: *Z. aquatica* with vars. *aquatica* and *brevis*, and *Z. palustris* with vars. *palustris* and *interior*. Recent isozyme studies by Warwick and Aiken (1986) support Dore's taxonomic split. As there is presently no concensus among the scientific community as to the correct taxonomy, all wild rice in this thesis will be referred to as *Z. aquatica*, which follows the major botanical manuals of Fassett (1957), Gleason and Cronquist (1963), and Fernald (1970).

Growth and Development

Wild rice is dispersed in a dormant state which inhibits germination. The seeds overwinter in the sediment for a period of afterripening under conditions of cold temperatures and low oxygen tensions which break dormancy for spring germination (Simpson, 1966).

Wild rice has a polymorphic life cycle with 3 distinct phenophases following germination. First, the submerged phase in which 2 to 4 submerged leaves are produced. The floating phase follows, during which 2 to 3 floating leaves are formed, and finally, the aerial phase. Atkins (1986) described the early phases and Oelke (1982) gave detailed descriptions of each phase. Anatomical characteristics of each phenophase in wild rice development were reported by Weir and Dale (1960). Hawthorn and Stewart (1970) described developmental changes in the superficial leaf anatomy.

During the growth of wild rice, changes occur in both the accumulation and allocation of nutrients. During early stages of development there is greater biomass partitioned to the roots than the shoots. After establishment, the primary allocation of nutrients is to the production of shoot biomass (Whigham and Simpson, 1977; Grava and Raisanen, 1978). Dry matter production declines with the emergence of the flowering panicle.

Flowering occurs from mid July to August when fertilization and caryopsis development occur. The structure of the caryopsis was described by Weir and Dale (1960).

Environmental Parameters

Stand establishment within newly seeded lakes has met with varied success (Lee, 1984; Lee, 1986; Lee, 1987; Lee and Stewart, 1984). Successful wild rice introductions met several environmental criteria, including:

1. Sediment suitability. This includes adequate nutrient availability, sediment

density and composition (Lee and Stewart, 1984; Lee, 1983; Lee, 1984; Lee, 1986; Lee, 1987; Garrod, 1984; Moyle, 1945).

2. Water depth. Optimal depth is between 0.3 to 1.0 m (Dore, 1969; Thomas and Stewart, 1969; Sain, 1981).

3. Plant competition. Wild rice cannot tolerate severe infestations of perennial emergents or floating leaved macrophytes (Lee, 1984; Lee, 1986; Atkins 1984; Atkins, 1985).

Although both water depth and plant competition can severly limit wild rice production, these two environmental factors can be easily checked before selecting potential wild rice lakes. Experimental management of water levels and aquatic weeds in wild rice lakes was investigated by Lee (1984). Preliminary research into slow release fertilization of aquatic sediments was conducted by Lee (1983, 1984). Stevenson and Lee (1987) found that if there were adequate nutrients, increases in water depth during any phenological stage had no adverse effects on the final biomass of wild rice.

Sediment suitability is difficult to determine because the effects of sediment characteristics (texture, nutrient availability) on wild rice production have not been completely defined. Initial attempts were made by Lee (1983, 1984, 1986, 1987) and Lee and Stewart (1984) to classify sediments in northwestern Ontario for wild rice production suitability. Garrod (1984) studied the relationships between sediment parameters and wild rice production in southern Ontario. Earlier researchers noting some habitat parameters associated with natural stands, measured water parameters, and observed that sediment type affected distribution (Moyle, 1944; Moyle, 1945; Chambliss, 1940). In general, deep organic sediments are considered to be the best (Lee, 1979), but wild rice can grow in sediments with high mineral content (Lee, 1987) and in some flocculent sediments (Lee and Stewart, 1984).

Objectives

The overall objectives of this research were:

1. to type sediments collected from a broad range of wild rice stands;
2. to determine how chemical and physical differences among two sediment types influenced wild rice production.

The thesis is presented as 3 separate but interrelated papers, each addressing rather specific questions relating to the general objectives outlined. In chapter 1, sediments from a variety of wild rice lakes in Ontario and Manitoba are classified into 6 types. Chapter 2 compares seasonal nutrient trends and biomass production between non-productive and productive wild rice lakes. Chapter 3 identifies nutrient deficiencies that occur in non-productive lakes.

The thesis itself may be summarized in 3 statements.

1. Wild rice grows in a variety of different sediments.
2. Nutrient levels varied throughout the growing season in both productive and non-productive lakes. The low nutrient levels in the non-productive lakes were detrimental to wild rice biomass production and phenological development.
3. Phosphorus was identified as the primary limiting nutrient in non-productive lakes.

Chapter 1

THE CLASSIFICATION OF SEDIMENTS FROM WILD RICE LAKES

1.1. INTRODUCTION

Wild rice has been seeded in many shallow lakes in northwestern Ontario. The success or failure of these wild rice introductions was related directly to the environment into which the seeds were sown (Lee and Stewart, 1983).

Wild rice, like other emergent macrophytes, obtains its nutrients from the bottom sediments (Trisal and Kaul, 1983). The plants grow vigorously if the nutrient supply is optimum (Lee, 1986), but, under natural conditions, nutrient availability seems to vary with the type of lake sediment. Wild rice production has been described on flocculent, organic, and clay lake sediments by Lee and Stewart (1984), and Lee (1986). The clay and flocculent sediments were reported as producing noncommercial wild rice stands, while the organic sediments were reported as good for wild rice production (Lee and Stewart, 1984; Lee, 1986).

Flocculation is a term applied to a coagulation of dispersed particles (Buckman and Brady, 1961). In lakes with flocculent sediments, the organic particles in the water column coalesce into floccules, attract suspended matter and sink to the bottom, thus leaving the water clear. These flocculent sediments are typically brown or light grey in colour and often have low nutrient values (Lee and Stewart, 1984). Organic sediments are often rich in nutrients and their firm, more consolidated consistency provides a good rooting medium for wild rice (Lee and Stewart, 1984). The clay sediments have been described as light grey in colour, low in organic material, and deficient in essential nutrients, particularly phosphorus (Lee, 1987).

Although these various types of sediments seem to influence wild rice production, the differences among these sediments have never been quantified. In this study, sediments from shallow lakes are compared in terms of their organic content, nutrient values and wild rice production. The objectives were to determine i) if it is possible to classify the various sediment types, and ii) if any differences among the sediments influence the production of wild rice.

1.2. METHODS

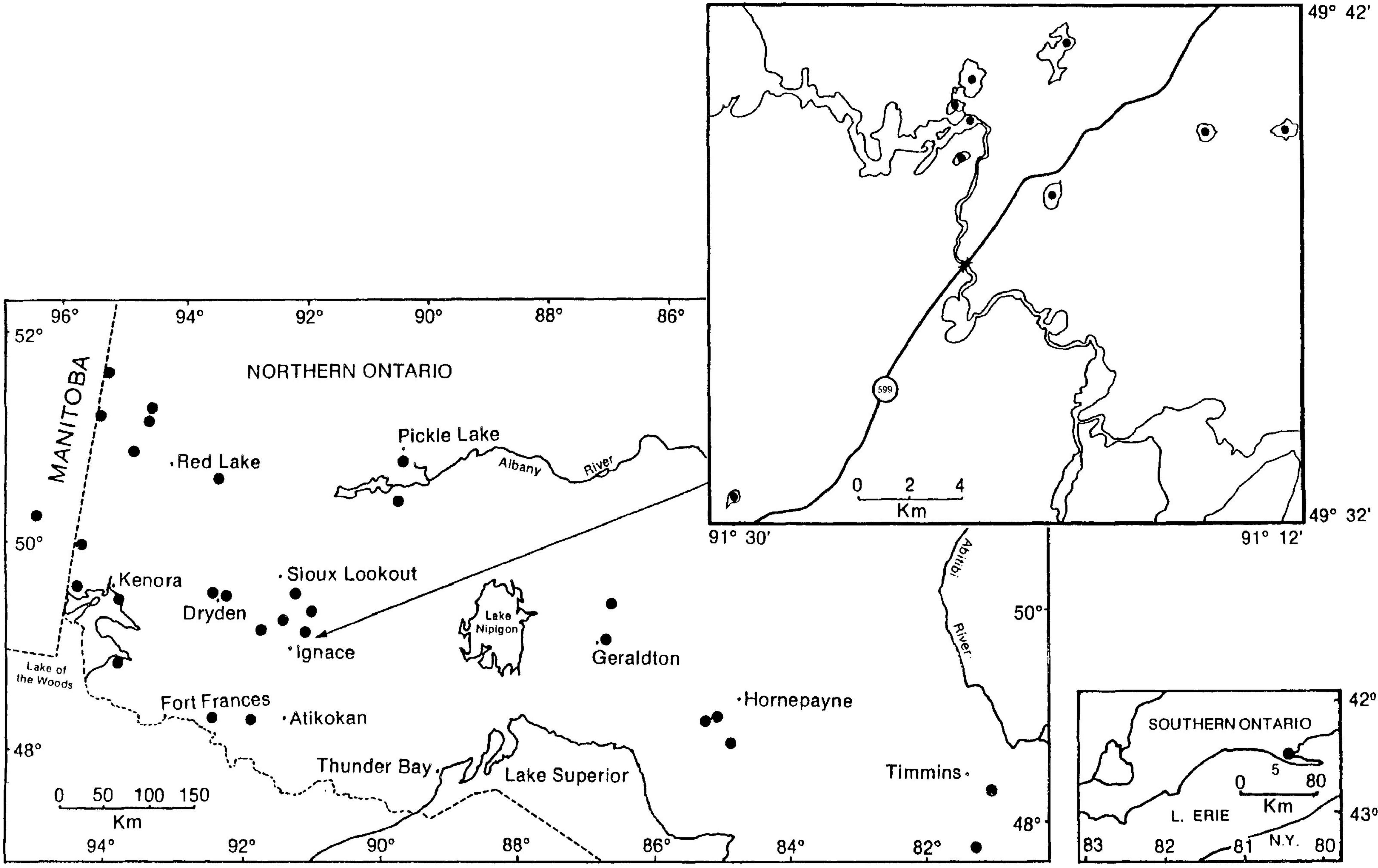
1.2.1. Sampling Sites and Field Procedures

Thirty nine lakes were sampled that either contained wild rice or had been seeded with wild rice. Thirty seven of the lakes were located in northern Ontario, 1 in Manitoba, and 1 in southern Ontario (Fig. 1.1). Sampling occurred in late August from 1983 to 1986 after the wild rice plants had achieved their maximum biomass. The lakes were randomly sampled at a rate of one quadrat (0.25 m x 0.25 m) per three hectares. A total of 801 samples were collected from the 39 different lakes. Sediment samples were collected with a core sampler from the top 20 cm of the sediment, placed into four-ply plastic bags and sealed tightly to minimize air space. Wild rice plants were removed from each quadrat, rinsed in lake water to remove any sediment, and packed in plastic bags. Both sediment and wild rice samples were refrigerated in portable coolers for transport to the laboratory. Water depth was measured in the centre of each quadrat.

1.2.2. Laboratory Procedures

The plants from each site were dried in a drying oven at 80° C until there was no change in weight for each sample. The biomass per quadrat and mean weight per plant were calculated using the plant dry weights. The sediment samples were analyzed for loss on ignition (LOI), bulk density (BD), pH, extractable nitrogen (N), phosphorus (P), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), calcium (Ca), magnesium (Mg), and potassium (K) using the methods of Lee (1986).

FIGURE 1.1. Locations (indicated by ●) of 39 lakes sampled for sediment and wild rice production characteristics. The insert details the location of 9 sites near Ignace, Ontario.


49° 42'
49° 32'
91° 30'
91° 12'
599
0 2 4
Km
NORTHERN ONTARIO
MANITOBA
96°
94°
92°
90°
88°
86°
52°
50°
48°
Pickle Lake
Red Lake
Albany
River
Kenora
Dryden
Sioux Lookout
Ignace
Lake Nipigon
Geraldton
Abitibi
River
Lake of the Woods
Fort Frances
Atikokan
Hornepayne
Thunder Bay
Lake Superior
Timmins
0 50 100 150
Km
94°
92°
90°
88°
86°
84°
82°
50°
48°
SOUTHERN ONTARIO
5
0 80
Km
L. ERIE
N.Y.
83
82
81
80
42°
43°

1.2.3. Data Analysis

A natural logarithm transformation was used to improve the normality of all the sediment variables (except pH) as recommended by Green (1971). The data were tested for normality using normal-probability plots and skewness and kurtosis statistics. Heteroscedasticity of the data was tested using Cochran's C statistic, and found to be nonsignificant ($p>0.01$) for all variables. Computer programs from the SPSSX statistical package (SPSS Inc., 1985) were used in the data analysis which proceeded in four steps.

(1) Since sediment variables are known to be highly intercorrelated (Lee, 1979), a principal components analysis was used to define a new uncorrelated set of sediment variables. The new factors produced were transformed by a "varimax" orthogonal rotation to improve interpretability.

(2) For each lake sampled, a Ward's hierarchical cluster analysis was performed using the orthogonally rotated raw factor scores to determine if different environmental regions existed within the lakes (Lee, 1986). This separated the data for those locations that had a heterogeneous character into their component homogeneous groups.

(3) Ward's hierarchical cluster analysis classified the mean factor scores of the homogeneous sediment environments into sediment types.

(4) Stepwise discriminant analysis tested the existence of the different sediment types. Wilks' lambda was used as the separating statistic among the lake types with the probability for inclusion of variables set at $P < 0.01$.

1.3. RESULTS

1.3.1. Interrelationship of Variables

Eight orthogonally rotated components were generated from the sediment data which accounted for 91 % of the variance in the original data set. The subsequent components (twelve were derived in total) accounted for only 9 % of the total variance, and were not easily interpreted.

Figure 1.2 shows the relative values of the sediment variables in the rotated factor matrix. The point of intersection for each axis on each star plot indicates the importance of that variable to the principal component.

The first component (PC1) explained 38.8 % of the environmental variation. PC1, composed primarily of the alkaline earth metals, calcium and magnesium, and the metal manganese will be referred to as the alkaline earth manganese component, or AEM.

Principal component 2 (PC2), which accounted for 15.8 % of the environmental variance, had a high positive loading of bulk density and a high negative loading of LOI, and may be interpreted as a measure of the ratio of sediment density to organic content. PC2 will be referred to as the density:organic component, or D:O.

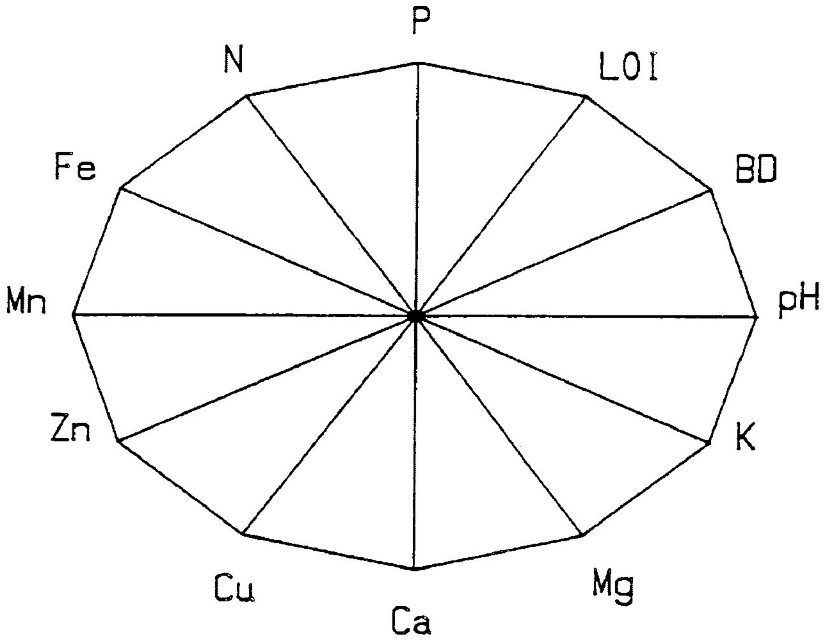
PC3, the third component, was primarily composed of zinc and copper. This component accounted for 8.2 % of the environmental variance, and will be referred to as the first metal component, or M1.

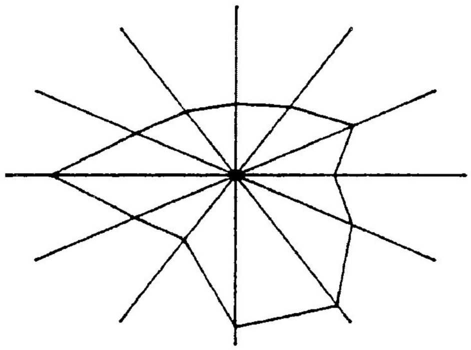
Principal component 4 (PC4) explained 8.0 % of the variation, and was primarily a function of phosphorus. This will be designated as the phosphorus component, or P.

The major variable in the fifth component (PC5) was pH. PC5 explained 7.1 % of the variation, and will be referred to as the pH component, or pH.

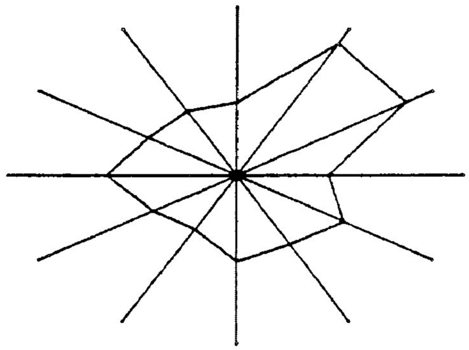
Principal component 6 (PC6) accounted for 5.1 % of the environmental

FIGURE 1.2. Star plots of eight principal components derived from the sediment variables. The point where each ray intersects each axis on each plot is proportional to the contribution of that variable to the principal component.

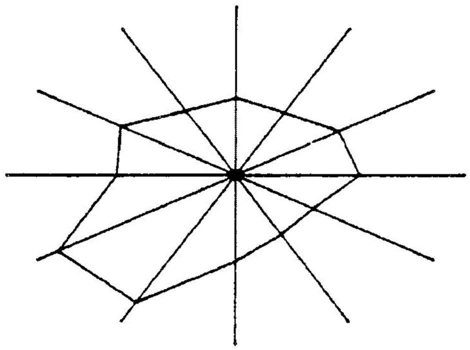




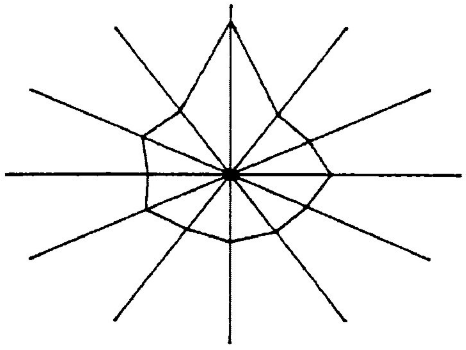
PC1 (AEM)



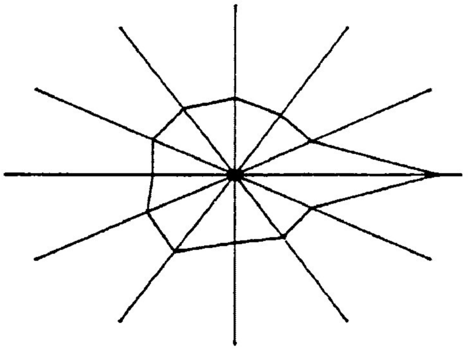
PC2 (D:O)



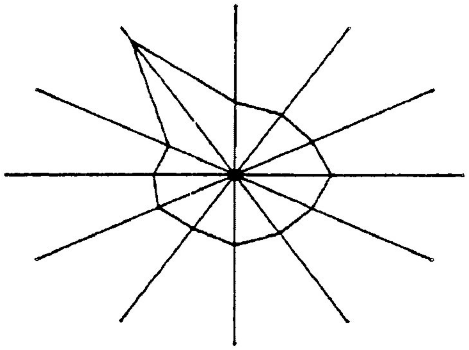
PC3 (M1)



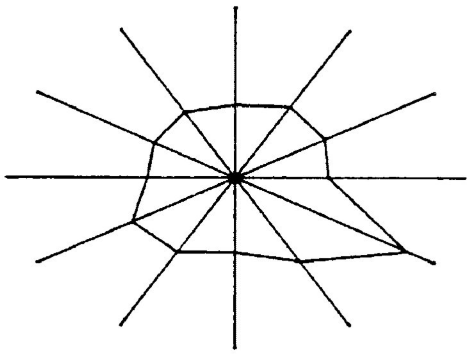
PC4 (P)



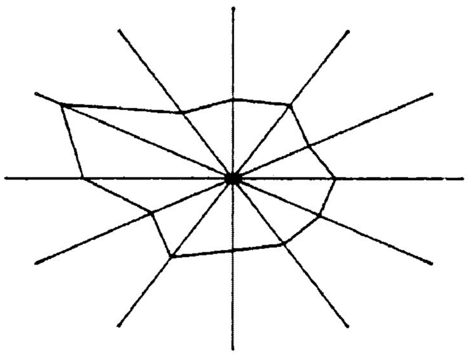
PC5 (pH)



PC6 (N)



PC7 (AAE)



PC8 (M2)

variance, and was primarily composed of nitrogen. PC6 will be referred to as the nitrogen component, or N.

Principal component 7 (PC7), which accounted for 4.3 % of the variation, was primarily composed of the alkali metal, potassium, and the alkaline earth metal, magnesium. This component will be referred to as the alkali-alkaline earth component, or AAE.

Iron and manganese had the largest loadings in component 8. PC8 accounted for 3.7 % of the variation, and will be referred to as the second metal component, or M2.

1.3.2. Separation of Sediment Types

Of the 39 locations sampled, eight showed a bimodal clustering which indicated that two different sediment environments were located within one lake. The data from these 47 homogeneous sediment environments were used in the cluster analysis. Six groups were derived from the cluster analysis (Fig. 1.3) that categorized the sediment into three major groups - organic (O), flocculent (F), clay (C), and three hybrid groups - organic-flocculent (OF), organic-clay (OC), and organic over clay (O/C).

The discriminant analysis of these six groupings derived five discriminant functions that statistically confirmed the results of the cluster analysis. The first three functions explained 92.33 % of the among-groups variability (Table 1.1) and were able to correctly classify 46 of the 47 sediments.

Figure 1.4 shows how discriminant functions one, two, and three separate the six sediment types. Function one (F1), which was composed primarily of AEM, M1 and pH separated sediment types based on their Ca, Mg, Cu, Zn, and Mn contents relative to pH. This function accounted for 55.40 % of among-groups variability and isolated the flocculent sediments (F) from the others.

FIGURE 1.3. Cluster analysis of sediment variables from the 47 homogeneous sediment environments. A similarity value of 11.0 was used to separate the 6 sediment types.

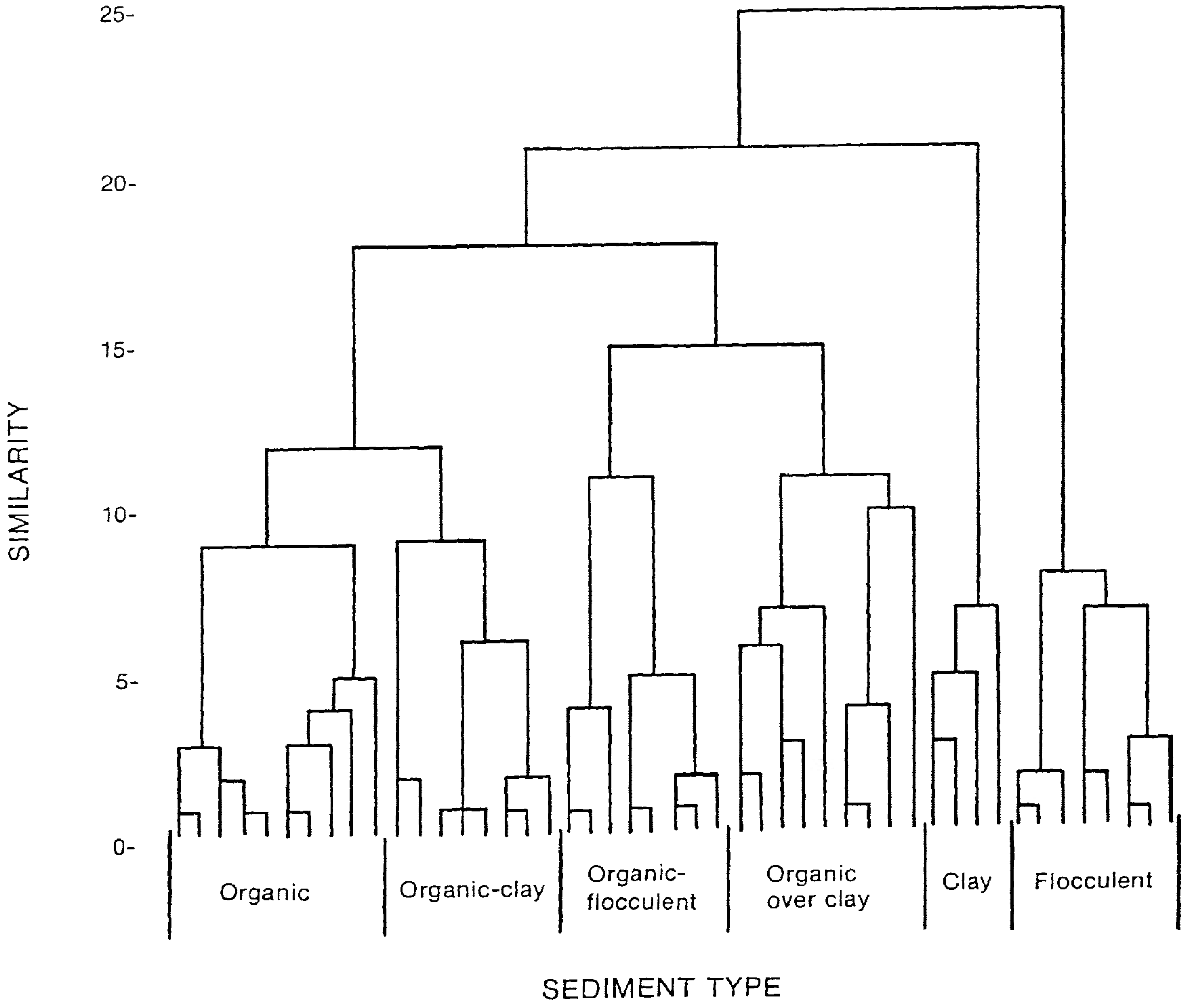
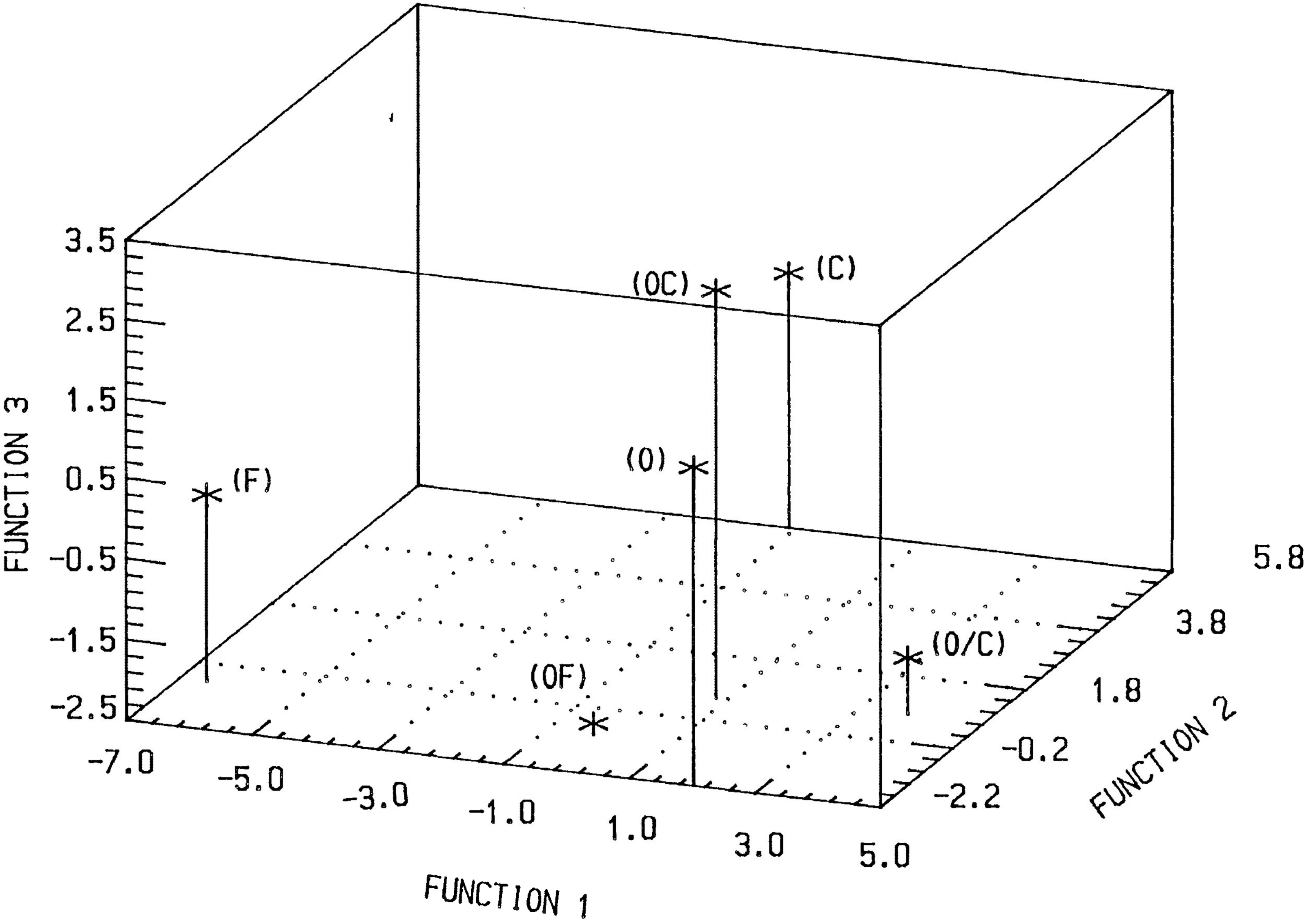

25-
20-
15-
10-
5-
0-
SIMILARITY
Organic
Organic-clay
Organic-flocculent
Organic over clay
Clay
Flocculent
SEDIMENT TYPE

TABLE 1.1. Discriminant function characteristics. The unstandardized coefficients (U) are the actual values of the variables composing the discriminant functions; the absolute values of the standardized coefficients (S) indicate the relative contribution of each variable in the discriminant functions. Coefficients in bold print indicate the largest coefficients for a function.

	Discriminant Function					
	1		2		3	
	Coefficients		Coefficients		Coefficients	
	U	S	U	S	U	S
Principal Component						
1	2.01	**0.95**	0.24	0.11	1.41	**0.66**
2	-0.18	-0.09	1.75	**0.93**	0.13	0.07
3	2.34	**1.30**	-0.15	-0.08	-0.59	-0.33
4	0.57	0.41	-0.78	-0.56	0.96	0.70
5	-1.15	**-0.77**	0.36	0.24	0.51	0.34
6	-0.67	-0.39	0.99	0.57	-0.27	-0.16
7	-0.08	-0.83	-0.66	-0.32	1.53	**0.75**
8	0.51	0.28	0.88	0.49	0.13	0.07
Constant	0.52		-0.43		0.17	
% among - group variation		55.40		20.50		16.43
cumulative percentage		55.40		75.90		92.33

FIGURE 1.4. Separation of the centroids (indicated by *) of the six sediment types according to the three derived discriminant functions.


PLOT OF SEDIMENT TYPES vs
DISCRIMINANT FUNCTIONS

Function two (F2), which explained 20.50 % of the among-groups variability, primarily used D:O to separate the sediment types. As bulk density increased, the LOI tended to decrease. As the ratio decreased the sediments became increasingly more organic, and less dense. Thus F2 separated the clay sediments from the organic, organic-flocculent, organic-clay, and organic over clay types.

Function three, which was composed primarily of AEM, P, and AAE, separated sediment types O, OF, OC, and O/C based on their P, Mg, Mn, Ca, and K values. F3 explained 16.43 % of the among-groups variance.

1.3.3. Characteristics of Sediment Types

Table 1.2 contains the nutrient, pH, LOI, bulk density, and plant weights for the major and hybrid groups. The major differences among the six sediment types were the LOI, bulk density, phosphorus, cation, and pH values. In terms of mean LOI, organic-flocculent sediments (56.04 %) > flocculent sediments (55.23 %) > organic over clay sediments (48.51 %) > organic sediments (47.57 %) > organic-clay sediments (29.42 %) > clay sediments (8.11 %). Mean bulk densities (g.cm^{-3}) in clay sediments (0.69) > organic-clay sediments (0.31) > organic over clay sediments (0.22) > organic sediments (0.21) > organic-flocculent sediments (0.18) > flocculent sediments (0.13). Mean phosphorus values (g.m^{-2}) in organic sediments (1.9) > organic-clay sediments (1.2) > organic over clay sediments (1.1) > organic-flocculent sediments (0.85) > clay sediments (0.84) > flocculent sediments (0.67). Cation values were found to follow the overall trend of organic-clay sediments > clay sediments > organic sediments > organic over clay sediments > organic-flocculent sediments > flocculent sediments. Mean pH values also differed depending upon the sediment type with flocculent sediments (6.9) > clay sediments (6.3) > organic-clay sediments (6.2) > organic over clay sediments (6.0) > organic sediments (5.9) > organic-flocculent sediments (5.8).

TABLE 1.2. Means and standard deviations of sediment variables and total wild rice dry weight for the major and hybrid sediment types.

			Lake Type			
Variable	Organic Mean ± SD	Clay Mean ± SD	Flocculent Mean ± SD	Organic-Clay Mean ± SD	Organic/Clay Mean ± SD	Organic-Flocculent Mean ± SD
N(g.m^{-2})	4.40 ± 6.86	3.19 ± 1.95	2.98 ± 0.67	2.52 ± 1.08	2.32 ± 2.09	1.97 ± 0.96
P(g.m^{-2})	1.87 ± 0.40	0.84 ± 0.70	0.67 ± 0.31	1.19 ± 0.55	1.10 ± 0.6	0.85 ± 0.30
K(g.m^{-2})	6.26 ± 3.36	10.77 ± 4.31	2.48 ± 0.30	12.69 ± 4.77	1.98 ± 1.47	2.95 ± 1.98
Fe(g.m^{-2})	84.38 ± 24.34	311.44 ± 199.32	13.95 ± 8.43	111.81 ± 36.27	69.57 ± 37.43	52.89 ± 40.83
Mn(g.m^{-2})	2.96 ± 0.91	18.04 ± 5.90	0.72 ± 0.45	6.80 ± 2.58	4.82 ± 3.98	1.25 ± 0.69
Zn(g.m^{-2})	0.84 ± 0.29	0.65 ± 0.21	0.17 ± 0.07	0.71 ± 0.52	0.83 ± 0.45	0.57 ± 0.31
Cu(g.m^{-2})	0.83 ± 0.24	0.81 ± 0.63	0.19 ± 0.05	0.66 ± 0.21	1.14 ± 0.32	1.01 ± 0.22
Ca(g.m^{-2})	232.22 ± 63.93	271.43 ± 152.05	80.32 ± 16.02	415.19 ± 75.68	329.93 ± 138.54	105.27 ± 31.17
Mg(g.m^{-2})	42.25 ± 32.03	43.01 ± 27.34	7.13 ± 2.17	76.03 ± 56.68	24.79 ± 14.93	9.16 ± 3.49
pH	5.9 ± 0.3	6.3 ± 0.3	6.9 ± 0.35	6.2 ± 0.2	6.0 ± 0.46	5.8 ± 0.3
LOI(%)	47.57 ± 10.43	8.11 ± 2.22	55.23 ± 10.55	29.42 ± 12.58	48.51 ± 19.96	56.04 ± 22.4
BD(g.cm^{-3})	0.21 ± 0.10	0.69 ± 0.11	0.13 ± 0.06	0.31 ± 0.13	0.22 ± 0.08	0.18 ± 0.11
Biomass (g.0.25m^{-}2)	93.31 ± 41.25	27.30 ± 16.93	0.00 ± 0.00	83.60 ± 61.44	100.46 ± 151.61	27.86 ± 40.77

1.4. DISCUSSION

The results (Fig. 1.3) showed that there were three major types of lake sediments - organic, clay, and flocculent, and three hybrids - organic-flocculent, organic - clay, and organic over clay. Discriminant analysis (Fig. 1.4) revealed that these sediment types differed from one another in their cation (Ca, Mg, Cu, Zn, and Mn) relative to pH values (F1), organic content (F2), and P, Mg, Mn, Ca, and K values (F3).

1.4.1. Organic sediments

The organic sediments contained a mean value of 47.57 % organic matter. This organic material was quite densely packed, with a mean bulk density of 0.21 $g.cm^{-3}$, and thus provided a rooting media for developing wild rice plants that was resistent to uprooting. In the organic group, Ca, Mg, Zn, Mn, Cu, K, and P values were higher and pH (5.9) was lower than clay (6.3) and flocculent (6.9) types. The black colour of the organic sediments was indicative of sediments rich in organic colloids capable of adsorbing cations that, under acidic conditions, are readily available to higher plants (Hansen, 1959a; Buckman and Brady, 1961). The presence of these acid humus colloids would explain the high values of Ca, Mg, Mn, K, Cu, and Zn in these sediments. Organic sediments had high values of P and N when compared to clay and flocculent sediments. This is consistent with other studies that have shown organic content to be significantly correlated to phosphorus and nitrogen within lake sediments (Trojanowski *et al*, 1985; Trisal and Kaul, 1983; Peltier and Welch, 1970; Golachowska, 1984).

1.4.2 Flocculent sediments

The flocculent sediments had a bulk density value of only 0.13 $g.cm^{-3}$ and an LOI value of 55.23 %. These characteristics made them unconsolidated and watery in nature, and would cause wild rice plants growing in these sediments to be uprooted easily by wind and wave action.

Sediments from flocculent lakes were low in cations and phosphorus, and had the least acidic pH (6.9). If only the organic content of flocculent sediments was considered, it would be expected that they would have high phosphorus values (Trojanowski *et al*, 1985; Golachowska, 1984; Trisal and Kaul, 1983; Peltier and Welch, 1970). The low phosphorus and cation values found in flocculent sediments may be due to the effects of pH and turbulent mixing. Lake bottom sediment of neutral pH was found to be low in P and cations (except Mg) due to the uptake of these ions by the surface water (Hayes, 1964; Macpherson *et al*, 1958). Mortimer (1941) found that under reduced conditions insoluble ferric complexes in the sediment surface liberated bases, including ammonia, ferrous iron, and other reduced materials adsorbed on these complexes. The release of ferrous iron, accompanied by ammonia and phosphate, in turn increases the alkalinity of bottom waters (Hayes, 1964; Mortimer, 1941). Bostrom (1984) found that phosphorus release from sediments was redox sensitive and strongly favoured by high pH values and turbulent mixing.

1.4.3. Clay sediments

Clay sediments were the most dense with a bulk density of 0.7 g.cm^{-3} and contained only 8.11 % organic material. They were also characterized by low extractable phosphorus (0.84 g.m^{-2}) values, possibly because this element is strongly adsorbed by clays (Buckman and Brady, 1961) and was not available for plant growth (Lee, 1987). Golachowska (1984) found clay minerals showed special capabilities for the adsorption and retention of phosphorus. This adsorption may be particularly pronounced under acidic conditions and results in a slow rate of decomposition of organic compounds. As is typical with clay in terrestrial environments clay sediments had high concentrations of extractable Mg, Ca, and K (Buckman and Brady, 1961).

1.4.4. Hybrid groups

The hybrid sediment types shared characteristics from both their parent types (Table 1.3).

Organic-flocculent sediments, like flocculent sediments, were low in phosphorus, cations, and bulk density, while the more acidic pH was closer to the organic sediments. The most distinctive feature of this group was the low nitrogen values.

The organic-clay sediment was high in cations, phosphorus, and nitrogen. The pH was similar to that of the clay group. The feature that was most particular to this group was the high levels of Mg, Ca, K, and other cations. This was probably due to the increased cation exchange capacity caused by the combined effects of both the clay and humus colloids.

The organic over clay sediments were very similar to the organic sediments in terms of LOI, bulk density, phosphorus and pH, but had lower cation and nitrogen values than the organic-clay sediments.

1.4.5. Sediment Types and Wild Rice Productivity

Table 1.3 shows that sediment types that produced the highest dry weights of wild rice were organic, organic-clay, and organic over clay. Flocculent, clay, and organic-flocculent types were in most cases nonproductive. Sediments with higher production were characterized by high phosphorus (1.1-1.9 $g.m^{-2}$) and cation values, medium to high nitrogen (2.3-4.4 $g.m^{-2}$) values, bulk densities ranging from 2.0-3.0 $g.m^{-2}$, LOI's ranging from 29.42-48.51 %, and a pH of 5.9-6.2. This compares to optimum levels of phosphorus of 1.0 $g.m^{-2}$, and LOI's of 40-60 % found by Lee (1986). These sediments were a mixture of clay and organic material that provided a firm nutrient rich substrate in which wild rice could grow. These findings were similar to those of Barko and Smart (1970) who found that plant biomass was greater in silt-clay sediments than in clay or sand sediments. Golachowska (1984) found that organic matter and clay minerals in bottom sediments were capable of accumulating and retaining phosphorus.

The nonproductive lakes were either clay, or flocculent and organic-flocculent. The clay lakes were very firm which made root penetration difficult, and were low in extractable phosphorus (0.84 $g.m^{-2}$) and organic material (LOI 8.11 %). Lee (1986) found that such low LOI and phosphorus values supported only poor growth of wild rice. The flocculent and organic-flocculent lakes were too unconsolidated (bulk density 0.13-0.18 $g.cm^{-3}$) to prevent uprooting and were low in extractable phosphorus (0.67-0.85 $g.m^{-2}$) and cations.

In summary, six sediment types were identified in wild rice lakes- organic, clay, flocculent, organic-clay, organic-flocculent, and organic over clay. Production was best on organic over clay, organic, and organic-clay sediments. The next chapter will look at seasonal nutrient trends, wild rice production, and chemical and physical characteristics of organic-flocculent and organic/clay sediments.

Chapter 2

THE EFFECTS OF PHYSICAL, CHEMICAL, AND SEASONAL SEDIMENT CHARACTERISTICS ON WILD RICE PRODUCTION IN ORGANIC-FLOCCULENT AND ORGANIC/CLAY SEDIMENTS

2.1. INTRODUCTION

In chapter 1, sediments from wild rice lakes were classified into three major types - organic, clay, and flocculent, and three hybrid types - organic over clay (organic/clay), organic-clay, and organic-flocculent. These divisions were based on variations in the organic content, bulk densities, and nutrient values.

Wild rice production also varied in the six sediment types. Organic, organic-clay, and organic/clay sediments were good producers of wild rice, while flocculent and organic-flocculent sediments were poor producers. The flocculent sediments were characterized by low phosphorus (< 1.0 g.m^{-2}), bulk density (< 0.2 g.cm^{-3}), and cation values. The reason for these low nutrient values is not known. Other studies have shown that redox, pH, turbulent mixing, rate of decomposition, and physical composition influence nutrient values in sediments (Bostrom, 1984; Sain, 1984; Twilley *et al*, 1985; Jordana, 1983; Twinch and Ashton, 1983; Zicker *et al*, 1956; Hayes, 1964; Mortimer, 1941; Macpherson *et al*, 1958). The type of organic matter can also affect nutrient levels. Swain (1963) found lower nutrient levels in gyttja (neutral humus) versus dy (acid humus). Hansen (1961) classified dy and gyttja sediments on the basis of the carbon to nitrogen ratio, and the amounts of organic, minerogenic, and inorganic biogenic matter.

Previous research revealed that such physical and chemical variations in the sediment greatly influence wild rice growth and development (Lee and Stewart, 1984; Lee, 1986; Lee, 1987). The low nutrient levels detected in flocculent sediments seem to be in limiting concentrations and would be expected to be detrimental to normal wild rice growth. However, it is not known if these low levels occur throughout the growing season, or if wild rice, like other macrophytes depletes the reserves by nutrient uptake (Trisal and Kaul, 1983).

In the present study, unproductive organic-flocculent sediments are compared to a productive organic/clay sediment. The specific objectives of the study were (i) to determine whether the physical and chemical characteristics of organic-flocculent sediments differed from organic/clay sediment; and (ii) to determine whether seasonal nutrient trends and wild rice production differed between organic-flocculent versus organic/clay sediments.

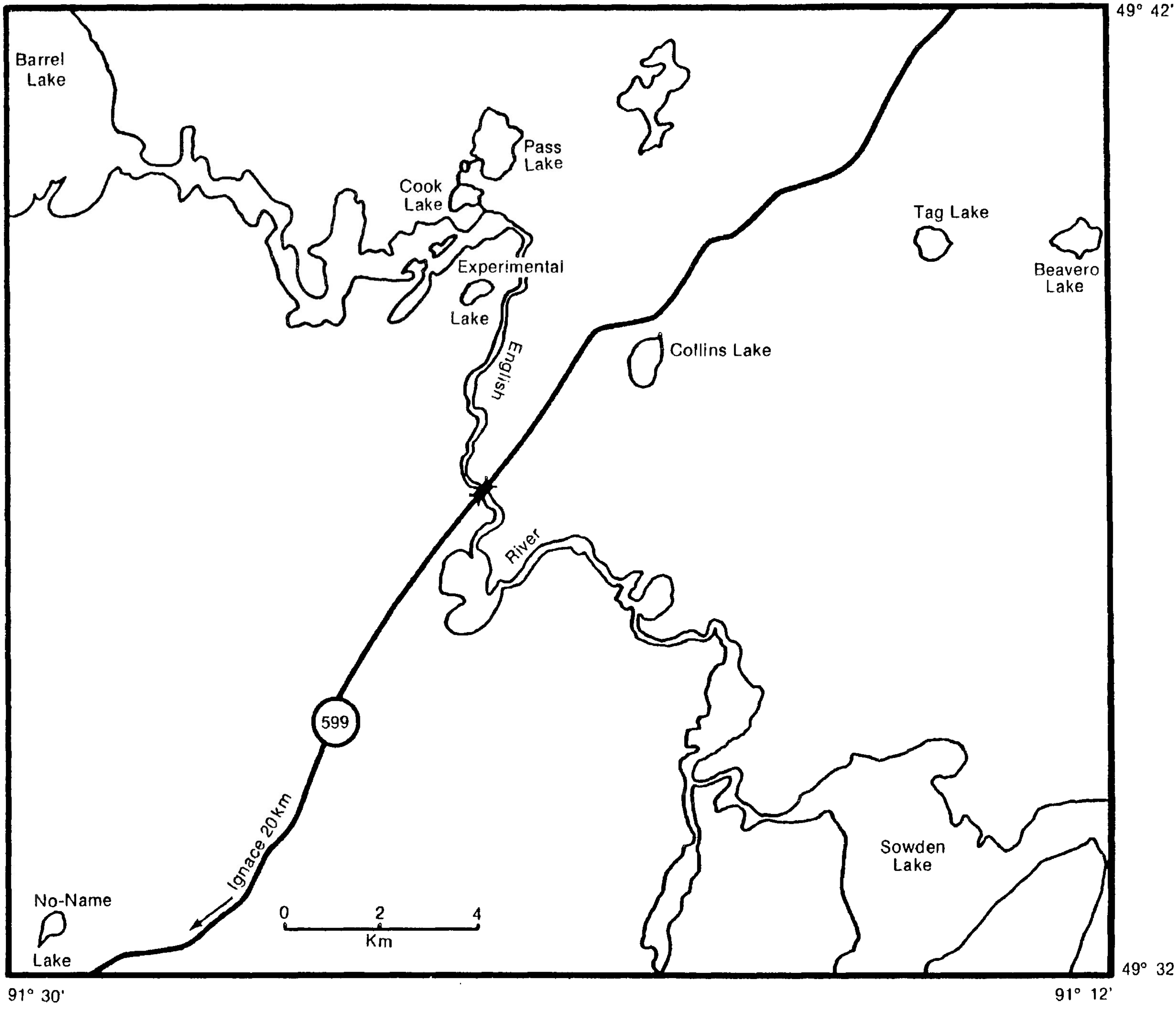
2.2. METHODS

2.2.1. Field Procedures

In the spring of 1985, 0.25 h plots (50 m x 50 m) were seeded with wild rice in 3 lakes, Collins, Tag, and No-Name which have organic-flocculent sediments and Beavero Lake, which has organic/clay sediment. All lakes are shallow (< 1.0 m in depth) and are located near Ignace, Ontario, Canada (Fig. 2.1). The wild rice seed was from Beavero Lake. The plots were sampled biweekly from June 3 to August 27 using transects 50 m in length. The starting position of the transect was randomly determined. At 5 m intervals along the transect, 10, 0.25 m x 0.25 m quadrats were sampled each sampling period. At each quadrat wild rice plants were harvested, the top 20 cm of the sediment was sampled, and the depth was measured in the centre of the quadrat. The plant and sediment samples were packaged and stored in portable coolers for transport to the laboratory.

In early September, *in situ* redox measurements were made with a Fisher Accumet Portable pH/mV meter (Model 640) and an Orion redox electrode at random intervals throughout the lakes at a rate of 1 per 3 hectares. The electrode was placed in a protective submersible housing, which allowed the platinum tip to be

FIGURE 2.1. The locations of the three lakes with organic-flocculent sediment (Tag, Collins, and No-Name) and the lake with organic/clay sediment (Beavero). The town of Ignace, Ont. is approximately 20 km to the south.


49° 42'
Barrel Lake
Pass Lake
Cook Lake
Experimental Lake
Tag Lake
Beavero Lake
Collins Lake
English River
599
Ignace 20 km
Sowden Lake
No-Name Lake
0
2
4
Km
49° 32'
91° 30'
91° 12'

lowered into the sediment. A sediment sample was also collected at each location.

2.2.2. Laboratory Procedures

The seasonal sediment samples collected along the transects were analyzed for loss on ignition (LOI), bulk density (BD), pH, and extractable nitrogen (N), phosphorus (P), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), calcium (Ca), magnesium (Mg), and potassium (K) using the methods of Lee (1986).

Using the samples collected at the end of the season, the carbon to nitrogen ratio (C:N), inorganic biogenic component, and the mineral component were determined. C:N ratios were calculated using a Model 240-XA elemental analyzer (Control Equipment Corp.). Inorganic biogenic material was determined by visually inspecting the sediments under a light microscope. X-ray diffraction (Philips X-ray Diffractometer) was used to determine the mineral composition of the sediments (Whittig, 1965).

2.2.3. Data Analysis

A three step analysis of the seasonal sediment data determined which characteristics differed among the lakes: (1) The data were transformed into time independent values following the method of Lee and Stewart (1981). (2) Since sediment variables are highly intercorrelated (Lee, 1979), principal components analysis defined a new uncorrelated set of time independent sediment data (SPSS Inc., 1985). A "varimax" orthogonal transformation was used to improve the interpretability of the factors produced. (3) Stepwise discriminant analysis (SPSS Inc., 1985) separated the sediments from the 4 lakes based on the new set of uncorrelated time independent sediment data. Wilks' lambda was used as the separating statistic with the probability for inclusion of variables set at $P<0.01$.

2.3. RESULTS

2.3.1. Sediment Characteristics

Mean values for sediment variables and the type of minerals present are contained in Table 2.1. The organic/clay sediments had higher extractable P, Fe, Mn, Ca, and Mg values than the organic-flocculent sediments. Values for extractable N and K were higher in organic-flocculent sediments. LOI (organic content) was higher in organic- flocculent sediments while BD was generally lower.

The organic matter in Beavero sediments appeared to be more decomposed than organic matter in the organic-flocculent sediments (Fig. 2.2). A larger portion of both orgainc-flocculent and organic/clay sediment types were composed of diatom frustules (Fig. 2.3), and quartz and feldspar (Appendix 1). All sediments were reduced with redox levels ranging from -149 to -201 mV. Mean pH values ranged from 6.0 to 6.4. All sediments had C:N > 10 which indicates that they were acid humus (Hansen, 1959).

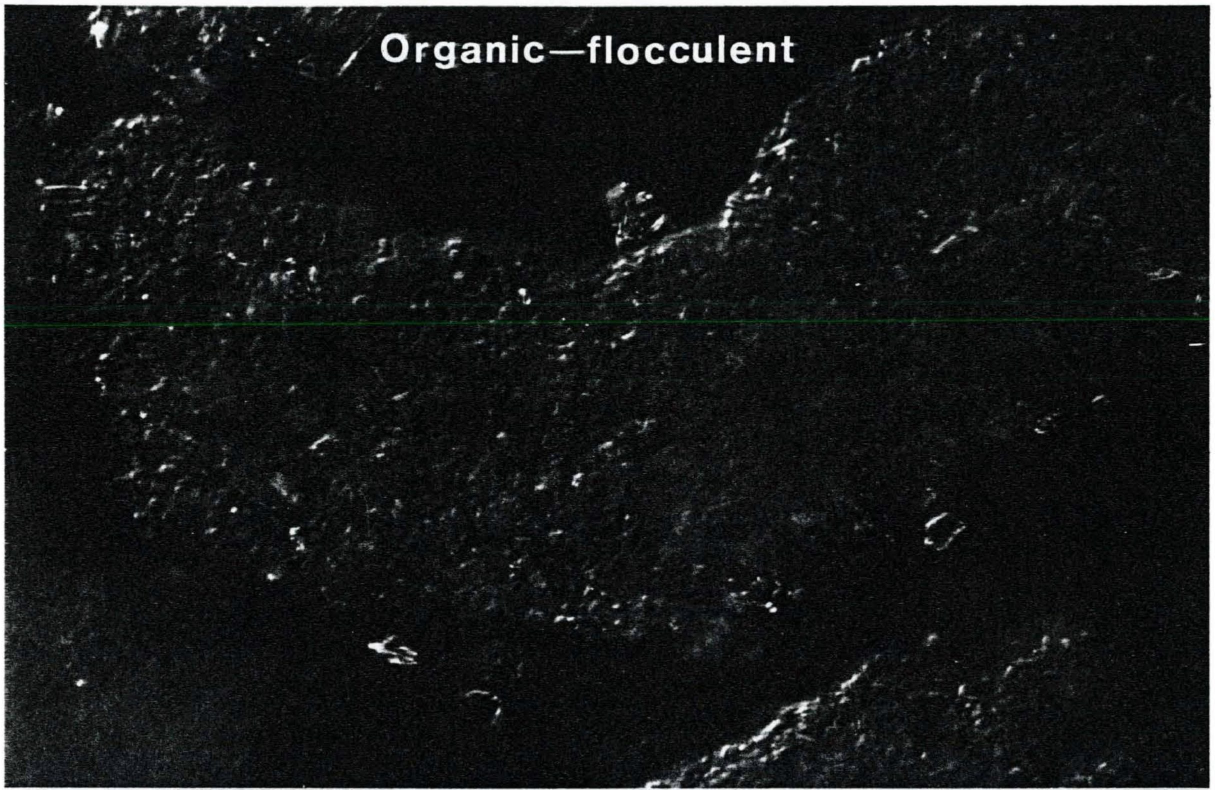
2.3.2. Interrelationship of Sediment Variables

A total of eleven uncorrelated orthogonally rotated principal components were generated from the time independent sediment data. The first seven principal components accounted for 97.1 % of the variation within the original data set (Table 2.2). The first principal component (PC1), which explained 47.2 % of the variance, could be interpreted as a mineral component and had high positive loadings for BD, P, Mn, Mg, and Ca which were all highly correlated with each other. Principal component 2 (PC2) explained 18.4 % of the variance, and had high positive loadings of LOI and N, and high negative loadings of P and BD. This component could be interpreted as the ratio of organic and N content to the mineral and P content. The third principal component (PC3) was primarily composed of pH and accounted for 11.9 % of the variance. Principal component 4 (PC4) explained 9.8 % of the variance

TABLE 2.1. Means and standard deviations of sediment variables, carbon to nitrogen ratios (C:N), and minerals present for Beavero, Collins, Tag, and No-Name Lakes.

Lake	Beavero	Collins	Tag	No-Name
Bulk density ($g.m^{-3}$)	0.15±0.04	0.11±0.06	0.04±0.03	0.10±0.03
Loss on ignition (%)	41.01±10.00	52.98±15.81	82.04±5.96	68.18±6.36
pH	6.1±0.3	6.4±0.3	6.0±0.4	6.2±0.4
Nitrogen ($g.m^{-2}$)	0.49±0.35	1.13±0.88	1.88±1.32	0.85±0.58
Phosphorus ($g.m^{-2}$)	1.27±0.33	0.89±0.30	0.37±0.22	0.82±0.21
Potassium ($g.m^{-2}$)	2.37±0.33	4.18±7.26	5.67±10.75	5.40±8.15
Iron ($g.m^{-2}$)	96.71±20.25	28.18±23.28	47.03±25.22	96.14±31.56
Manganese ($g.m^{-2}$)	4.51±1.67	0.38±0.18	0.60±0.54	0.94±0.45
Zinc ($g.m^{-2}$)	0.30±0.13	0.26±0.11	0.27±0.25	0.49±0.21
Copper ($g.m^{-2}$)	0.93±0.44	0.96±0.48	0.92±0.28	1.10±0.36
Calcium ($g.m^{-2}$)	200.64±46.34	154.58±75.78	115.07±86.94	166.63±149.86
Magnesium ($g.m^{-2}$)	17.49±5.67	11.26±6.55	9.51±9.30	7.19±4.26
Redox (mV)	-190.25±38.47	-200.63±57.91	-149.83±40.73	-168.31±36.75
C:N	13:1	11:1	12:1	11:1
Mineral content	quartz feldspar	quartz feldspar	quartz feldspar	quartz feldspar

FIGURE 2.2. Comparison of the organic material in organic-flocculent and organic/clay sediments. Organic/clay sediments were composed of more strongly decomposed organic material (magnification 450X).


Organic—flocculent

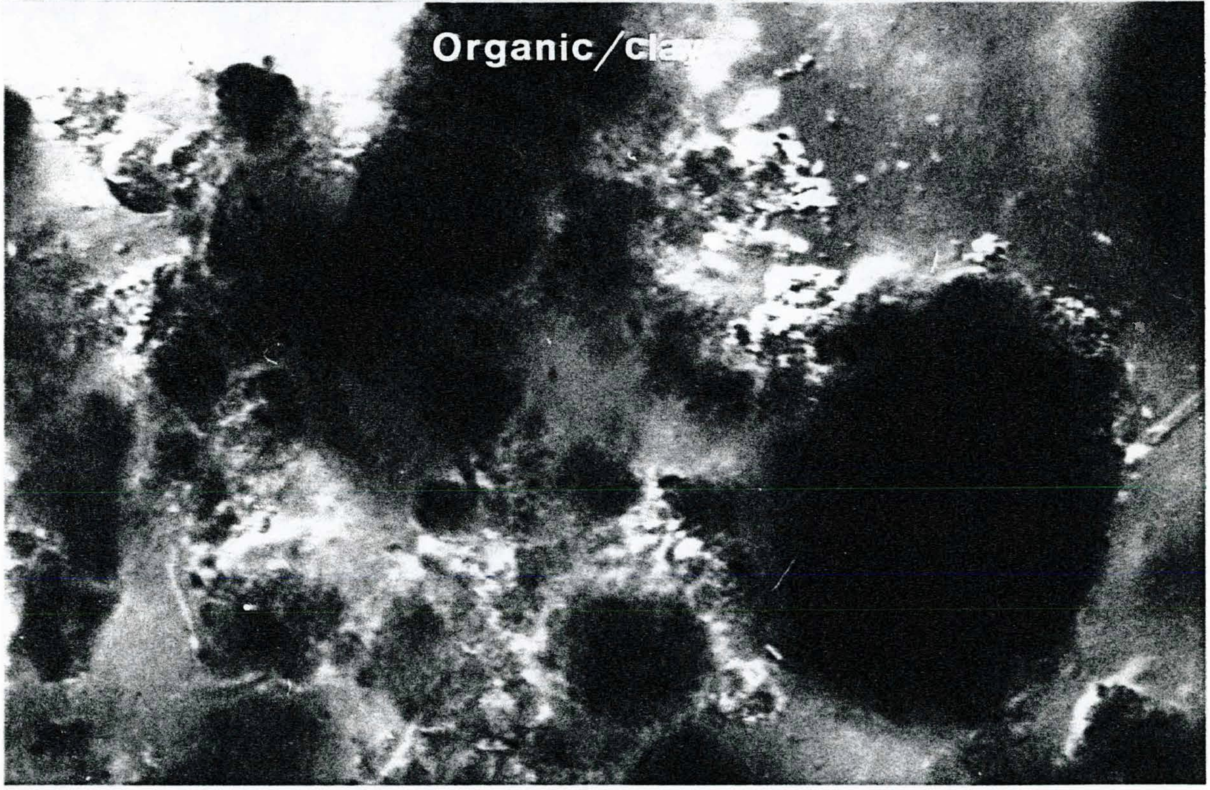

Organic/clay

FIGURE 2.3. Diatom frustules which contributed a large portion of the inorganic biogenic component in organic/clay and organic-flocculent sediments (magnification 450X).

TABLE 2.2. Coefficients of the total factor matrix and the variance explained for the first seven principal components of the time independant sediment data. Bold print indicates the largest coefficient(s) for a variable.

	Principal Component						
	1	2	3	4	5	6	7
Loss on ignition	-.147	**-.927**	-.101	-.103	-.134	-.182	-.191
Bulk density ($g.cm^{-3}$)	**.700**	**.597**	.136	.121	.094	-.005	.097
pH	.023	.123	**.982**	.043	.060	.069	-.096
Phosphorus ($g.m^{-2}$)	.573	**.774**	.040	.077	-.130	.015	-.028
Nitrogen ($g.m^{-2}$)	-.488	**-.791**	-.076	-.114	-.006	-.148	-.162
Iron ($g.m^{-2}$)	.300	.359	-.252	.297	.088	.341	**.707**
Manganese ($g.m^{-2}$)	**.786**	.355	-.270	-.020	-.106	-.042	.308
Zinc ($g.m^{-2}$)	-.114	.173	.089	.097	.284	**.916**	.139
Copper ($g.m^{-2}$)	-.052	.046	.061	-.057	**.964**	.240	.035
Calcium ($g.m^{-2}$)	**.750**	.396	.267	-.106	.107	.021	.215
Magnesium ($g.m^{-2}$)	**.934**	.168	-.006	-.237	-.093	-.124	-.020
Potassium ($g.m^{-2}$)	-.154	.139	.046	**.965**	-.058	.086	.110
Percent of variance	47.2	18.4	11.9	9.8	4.2	3.7	1.9

and was primarily a function of K. The fifth, sixth, and seventh principal components were primarily composed of Cu, Zn, and Fe respectively, and in total, accounted for only 9.8 % of the total variance.

Utilizing these 7 principal components, discriminant analysis derived 3 discriminant functions that gave 100 % separation of the 4 lakes (Fig. 2.4). The first 2 functions accounted for 92.43 % of the among group variability and were primarily responsible for separating the 4 lakes (Table 2.3). PC1, PC2, and PC7 were the major components of discriminant function 1. All values of the variables composing these principal components, except N, were higher in the organic/clay sediment of Beavero Lake (Table 2.1). Function 2 primarily used PC3 (pH) to separate the lakes. From low to high mean sediment pH of the lakes were in the order of Tag (6.0), Beavero (6.1), No-Name (6.2), and Collins (6.4).

2.3.3. Seasonal Nutrient Trends

The seasonal values for the sediment variables that were important in separating the organic-flocculent sediments of Tag, Collins, and No-Name lakes from the organic/clay sediment of Beavero Lake, are shown in Figure 2.5. Appendix 2 contains the complete set of seasonal sediment variables. These trends were similar for the organic-flocculent and organic/clay sediments. Nitrogen values increased until mid August and then decreased. Phosphorus, manganese, and LOI values were fairly constant throughout the growing season. Following peak levels in the spring Mg and Ca decreased in value until early August and then increased to spring concentrations. Iron values decreased from June to July and the increased in August. Bulk density and pH increased in value in the spring, then decreased during June and July before again increasing in August.

FIGURE 2.4. Separation of Tag (T), Collins (C), No-Name (N), and Beavero (B) sediments according to discriminant functions 1 and 2. The ellipses describe the bivariate distributions that contain 90 % of the sampling observations within each lake.

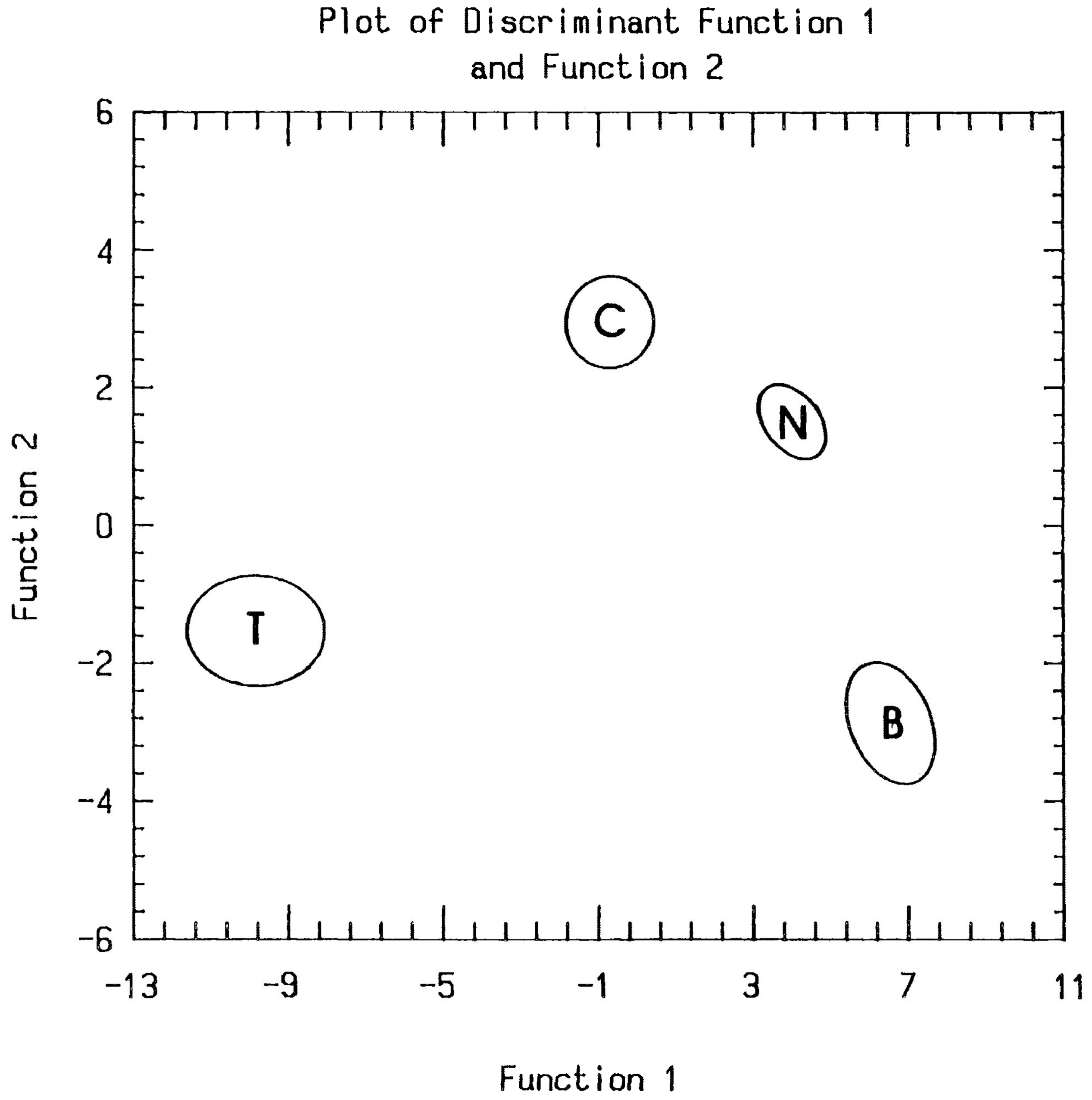
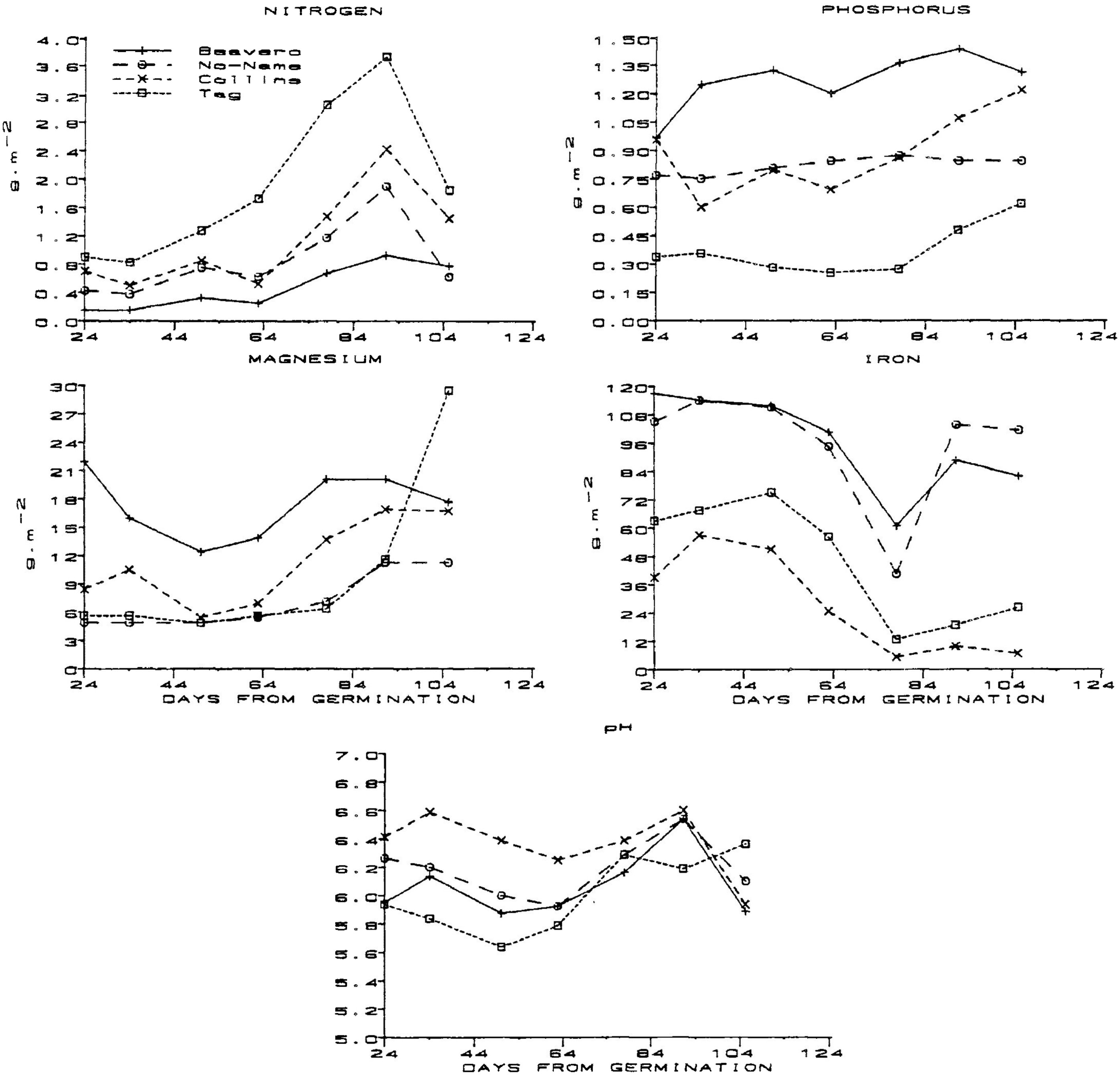

Plot of Discriminant Function 1
and Function 2
6
4
2
0
-2
-4
-6
-13
-9
-5
-1
3
7
11
Function 2
Function 1
C
N
T
B

TABLE 2.3. Discriminant function characteristics for organic-flocculent and organic/clay sediments. The unstandardized coefficients are the actual values of the variables composing the discriminant functions. Coefficients in bold print indicate the largest coefficients for a function.

	Discriminant Function			
	1		2	
	Coefficients		Coefficients	
	Unstandardized	Standardized	Unstandardized	Standardized
Principle Component				
1	2.501	**1.656**	-1.544	-1.020
2	5.502	**2.651**	0.721	0.348
3	0.356	0.298	1.503	**1.260**
4	1.167	1.176	0.142	0.143
5	0.730	0.722	0.522	0.516
6	1.085	0.944	0.112	0.097
7	1.348	**1.187**	-0.980	-0.863
Constant	$0.327x10^{-2}$		$-0.235x10^{-2}$	
% among group variation		81.35		11.08
Cumulative percentage		81.35		92.43

FIGURE 2.5. Seasonal levels of nitrogen, phosphorus, magnesium, iron, and pH from organic-flocculent lakes (No-Name, Collins, Tag) and the organic/clay lake (Beavero).


NITROGEN
Beavero
No-Name
Collins
Tag
g.m^{-2}
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
24
44
64
84
104
124
PHOSPHORUS
g.m^{-2}
1.50
1.35
1.20
1.05
0.90
0.75
0.60
0.45
0.30
0.15
0.00
24
44
64
84
104
124
MAGNESIUM
g.m^{-2}
30
27
24
21
18
15
12
9
6
3
0
24
44
64
84
104
124
DAYS FROM GERMINATION
IRON
g.m^{-2}
120
108
96
84
72
60
48
36
24
12
0
24
44
64
84
104
124
DAYS FROM GERMINATION
pH
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
24
44
64
84
104
124
DAYS FROM GERMINATION

2.3.4. Wild Rice Production

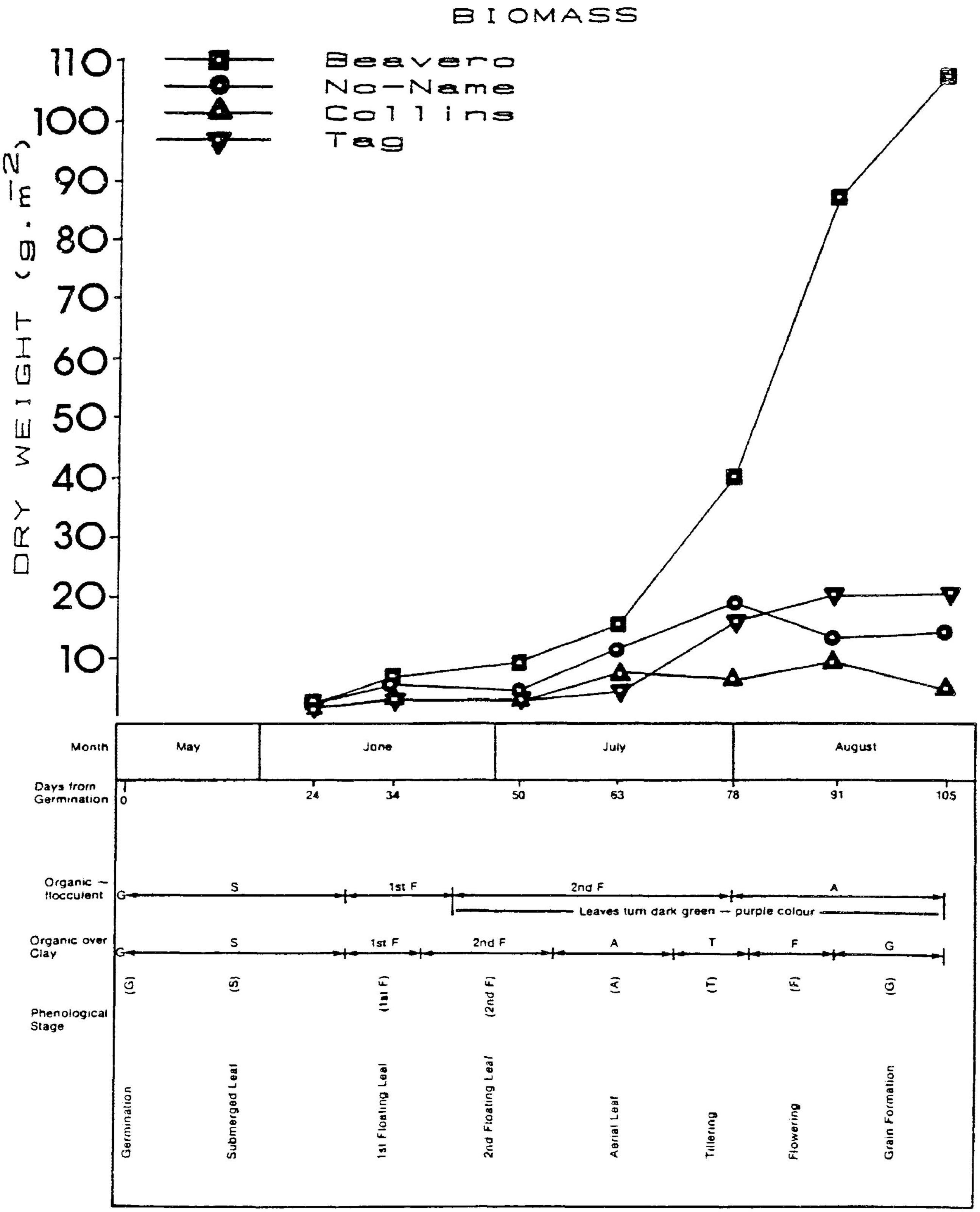
Figure 2.6 show the mean seasonal biomass ($g.m^{-2}$) and the phenological development of wild rice in organic-flocculent and organic/clay sediments. By August the organic/clay sediment produced a dense stand of large mature plants (biomass > 100 $g.m^{-2}$), while the organic-flocculent sediments produced small plants (biomass < 22 $g.m^{-2}$) that entered the aerial stage but produced no grain. The leaves of the wild rice plants grown in the organic-flocculent sediments were initially green, but by the floating leaf stage many leaves had turned purple.

2.4. DISCUSSION

2.4.1. Sediment Relationships

Organic/clay and organic-flocculent sediments shared many similarities. This included similar inorganic biogenic composition, mineral content, and redox values (Table 2.1). Many chemical relationships were also the same in the two types of sediments. PC1 indicated that extractable phosphorus, manganese, magnesium, and calcium were highly correlated in both the organic-flocculent and the organic/clay sediments. Other studies have also shown P to be correlated to Mn and Ca in lake sediments (Trojanowski *et al*, 1985; Golachowska, 1984; Williams *et al*, 1971; Delfino *et al*, 1969; Swain, 1963). This implies that phosphorus in these sediments may be in the form of calcium, magnesium, and manganese phosphate compounds. However, X-ray diffraction did not reveal any mineral compounds which would contain extractable P. It is therefore more probable that P, Mn, Mg, and Ca were associated with organic matter, likely humic acids, which are known to complex with these elements (Challa and Roman, 1984; Swain, 1963). The correlation of nitrogen with LOI in PC2 also implicates the presence of organic complexes. This concurs with other studies that have shown sediment N increased with increasing organic content

FIGURE 2.6. Comparison of biomass production and phenological development of wild rice in organic-flocculent and organic/clay lakes.


BIOMASS
Beavero
No-Name
Collins
Tag
DRY WEIGHT (g.m⁻²)
110
100
90
80
70
60
50
40
30
20
10
Month
May
June
July
August
Days from Germination
0
24
34
50
63
78
91
105
Organic — flocculent
G
S
1st F
2nd F
A
Leaves turn dark green — purple colour
Organic over Clay
G
S
1st F
2nd F
A
T
F
G
Phenological Stage
(G) Germination
(S) Submerged Leaf
(1st F) 1st Floating Leaf
(2nd F) 2nd Floating Leaf
(A) Aerial Leaf
(T) Tillering
(F) Flowering
(G) Grain Formation

(Trojanowski *et al*, 1985; Golachowska, 1984; Trisal and Kaul, 1983; Peltier and Welch, 1970).

Although there were several similarities between the organic-flocculent and the organic/clay sediments, there were also important differences which might ultimately affect wild rice production. The discriminant analysis (Table 2.3) showed that PC1 and PC2 were the most important factors in separating the two types of sediments. These components were comprised of organic content (correlated directly with LOI and inversely with BD) and the nutrients P, Mn, Ca, Mg, and N. The nutrient and bulk density values were higher in the organic/clay sediment than the organic-flocculent sediments, while LOI was lower.

The variation in the nutrient content between the two sediment types may reflect the origin of the organic material. Detrital material within sediments acts as a sink for nutrients (Hayes and Philips, 1958; Swain, 1963; Johannes, 1968). Nutrients within sediments tend to increase with microbial decomposition, adsorption, deposition, and subsequent partial mineralization of large quantities of organic detritus (Trisal and Kaul, 1983). Much of the organic matter within organic-flocculent sediments is believed to be peat detritus derived from the surrounding peat bogs and may be classified as sedimentary peat (Swain, 1963). Sediments derived from peats tend to be resistant to decay and have low bacterial and nutrient content (Jordana, 1983; Swain, 1963). Macrophytes, algae, and straw, on the other hand, decompose at a faster rate than peat (Sain, 1984; Trisal and Kaul, 1983; Johannes, 1968; Swain, 1963; Hayes and Phillips, 1958). Thus the decomposing wild rice straw within Beavero would be a major source of nutrients and could account for the higher nutrient values. The lower values of N in Beavero sediments was likely the result of cumulative nutrient depletion caused by years of wild rice cropping. Similar results were found by Keenan and Lee (1987) in another commercially harvested wild rice lake in northwestern Ontario.

Sediment density may also be affecting the release of phosphorus and other nutrients from the sediments and account for some of the nutrient variations between the two types of sediment. The principal components analysis (Table 2.2) showed that bulk density was correlated with the concentrations of several nutrients in PC1 and PC2. Research has shown that turbulent mixing of sediments increases the rate of phosphorus loss to overlying water (Bostrom, 1984; Zicker *et al*, 1956). In shallow lakes the density of the sediments directly determines the severity of the turbulent mixing, with less dense sediments being more susceptible. Thus lower phosphorus values, and possibly other nutrients, may have resulted from greater turbulent mixing within the organic-flocculent sediments.

2.4.2. Seasonal Nutrient Trends

Most seasonal nutrient data for the four sediments studied showed no nutrient depletion during the period of exponential wild rice growth (July 17 to August 27). This was contrary to the results of Trisal and Kaul (1983) who showed that reductions in nutrient concentrations corresponded to the exponential growth of macrophytes. Fe and N showed reductions during the latter half of the growing season in both organic/clay and organic-flocculent sediments. The lack of obvious reductions in P and most other nutrients implies that mechanisms for nutrient replenishment exist within the lake-sediment environment (Hayes and Philips, 1958; Johannes, 1968).

The seasonal nutrient trends also showed that for each nutrient, fluctuations were similar throughout the growing season and that organic/clay sediments, with the exception of N, had higher nutrient values. The lower nutrient values within the organic-flocculent sediments apparently affected wild rice production, since wild rice biomasses were much lower in these sediments (Fig. 2.6).

2.4.3. Wild Rice Development

During the initial part of the vegetative growth phase, (germination to the floating leaf stage) wild rice plants (Fig. 2.6) matured at about the same rate, regardless of the sediment type, and accumulated about 2 % of their total dry weight per quadrat. Nitrogen, potassium, and phosphorus uptake would be about 7.5 %, 5.0 %, and 3.8 % respectively, of the total amounts accumulated by maturity (Grava, 1982). Therefore, during this early growth phase, nutrient requirements were minimal and were adequately provided by the seed, nutrient translocation, and the sediment.

From the second floating leaf stage to maturity, wild rice produces 98 % of its biomass, and takes up most of the required (P 96.2 %, K 95.0 %, and N 92.5 %) nutrients (Grava, 1982). In organic-flocculent sediments maturation rates slowed during the second floating leaf stage and growth stopped during the aerial leaf stage (Fig. 2.6). In organic/clay sediments wild rice tillered, flowered, formed seed, and reached maturity (Fig. 2.6). In other plants during this part of their life cycle, N, K, and P accumulate in the most actively growing parts, while Mg, Ca, and Fe accumulations are associated with older plant tissue (Malsner and Nihlgard, 1980). Certainly wild rice requires adequate concentrations of nutrients at maturity, since wild rice seeds contain high concentrations of P, K, Mg, and Ca, as well as some Zn and Fe (Anderson, 1976). Deficiencies in N, P, K, or any other required nutrient could explain the slow rate of growth and small plant size of wild rice grown in organic-flocculent sediments.

Visual symptoms also suggested nutrient deficiencies in the organic-flocculent sediments. No unusual colour changes were observed in the plants from Beavero Lake, while the leaves and stalks of plants grown in the organic-flocculent sediments turned purple during the floating leaf stage. In other plants this may indicate phosphorus, nitrogen, or micronutrient deficiencies (Chapman, 1966). Visual nutrient deficiency symptoms for wild rice have not been determined so it is not possible to state with any certainty which specific element is limiting in this case.

In conclusion, major differences in nutrient values existed between organic/clay and organic-flocculent sediments. Lower nutrient values in organic-flocculent sediment were closely linked to the organic material and likely resulted from i) the origin, type, and degree of decomposition of the organic material, ii) slower nutrient mineralization and recycling of required nutrients, and iii) lower density and a high degree of turbulent mixing. A comparison of the seasonal trends between organic-flocculent and organic/clay sediments showed no nutrient depletion during the exponential growth of wild rice. Throughout the growing season organic/clay sediments had higher nutrient values with the exception of N. The maturation of wild rice grown in organic-flocculent sediments was retarded by nutrient deficiencies, while rice grown in the organic/clay sediment reached maturity. The next chapter will concentrate on the identification of the nutrient(s) limiting wild rice production in organic-flocculent sediments.

Chapter 3

THE IDENTIFICATION OF GROWTH LIMITING NUTRIENTS IN ORGANIC-FLOCCULENT SEDIMENTS

3.1. INTRODUCTION

The sediments of wild rice lakes can be classified as organic, clay, flocculent, organic/clay, organic-clay, or organic-flocculent (chapter 1). Wild rice production and seasonal nutrient trends in lakes containing organic-flocculent or organic/clay sediments were described in chapter 2. Plants from the organic-flocculent sediments were smaller, took longer to mature, and had purple foliage. It was suggested that nutrient deficiencies (phosphorus, metals, or micronutrients) were causing low production in these sediments (Lee and Stewart, 1984). In this study, this hypothesis is examined by the application of fertilizer under natural and controlled conditions. The objective of the study was to determine which nutrients were limiting wild rice production in organic-flocculent sediments.

3.2. METHODS

3.2.1. Fertilizer Trials

Fertilizer trials were conducted with wild rice cultivation rafts described by Stevenson and Lee (1987). Tubs containing sediment from 3 organic-flocculent lakes were suspended at a depth of 45 cm. The sediment sources were Tag, Collins, and No-Name lakes, located near Ignace, Ontario, Canada and previously described in chapter 2.

The experimental procedure essentially followed Lee (1987). Three cultivation rafts, one for each sediment source, were used in a randomized block experimental design with two replicates of nine fertilizer treatments in each raft. Slow release fertilizers manufactured by the Sierra Chemical Company, Milpitas, California were added in high (H) and low (L) concentrations in all but the control treatment.

Treatments consisted of the following: control (C, no fertilizer), +P, H (120 $kg.h^{-1}$ P) and +P, L (30 $kg.h^{-1}$ P) of 0-4-0; +NPK, H (800 $kg.h^{-1}$ N) and +NPK, L (200 $kg.h^{-1}$ N) of 18-6-12; +N, H (800 $kg.h^{-1}$ N) and +N, L (200 $kg.h^{-1}$ N) of 40-0-0; +M, H (200 $kg.h^{-1}$) and +M, L (100 $kg.h^{-1}$) of a micronutrient mixture (12 % Fe, 2.5 % Mn, 1.0 % Zn, 0.5 % Cu, 0.1 % Bo, 0.05 % Mo, and 15.0 % S).

Five seedlings were planted in each tub and grown until mature. The plants were then removed, soil was rinsed from the roots, and the height, dry weight, and number of seeds determined for each plant. Rafts were designed to accomodate 24 tubs; therefore six additional control tubs were used on each raft to ensure that each tub in the experiment was bracketed on at least 2 sides by other tubs containing wild rice. This created equal shade for all plants in the experiment. The plants within these six additional tubs were not used in the analysis.

Skewness and kurtosis statistics were calculated for the nine fertilizer treatments. The normality of the variables was improved with a square root transformation. Analyses of variance (SPSS Inc., 1985) of the transformed variables were then used to detect statistical differences among the nine fertilizer treatments in wild rice height, dry weight, and number of seeds per plant.

3.2.2. Foliar Mineral Deficiency Symptoms

Wild rice plants were initially grown to the aerial leaf stage in a greenhouse using culture tanks (Lee, 1984). A 16 hour photoperiod was used for the entire experiment. Day temperatures were kept at 23° C, while night temperatures were maintained at 15° C. To ensure that the plants had adequate nutrients, 10 g of slow release Osmocote 18-6-12 fertilizer (Sierra Chemical Company, Milpitas, Califoria) was mixed into the organic soil.

Once the plants reached the aerial leaf stage, they were removed from their pots and the soil was gently washed from the roots. The roots were kept wet at all times prior to transfer to the test solutions.

Modified Hoagland solutions (Hoagland and Arnon, 1950) were used in the experiment. N, P, K, Ca, and Mg were mixed at half strength (50 % Hoaglands); micronutrients and Fe were 2.5 times normal strength to approximate sediment values (Lee, 1983). A complete solution (control) and solutions lacking N, P, K, Ca, Mg, Fe, and micronutrients (Bo, Mn, Zn, Cu, and Mo) were prepared for a total of 8 treatments. The pH range of the solutions (5.5-6.5) was similar to that found in productive lake sediments (chapter 1).

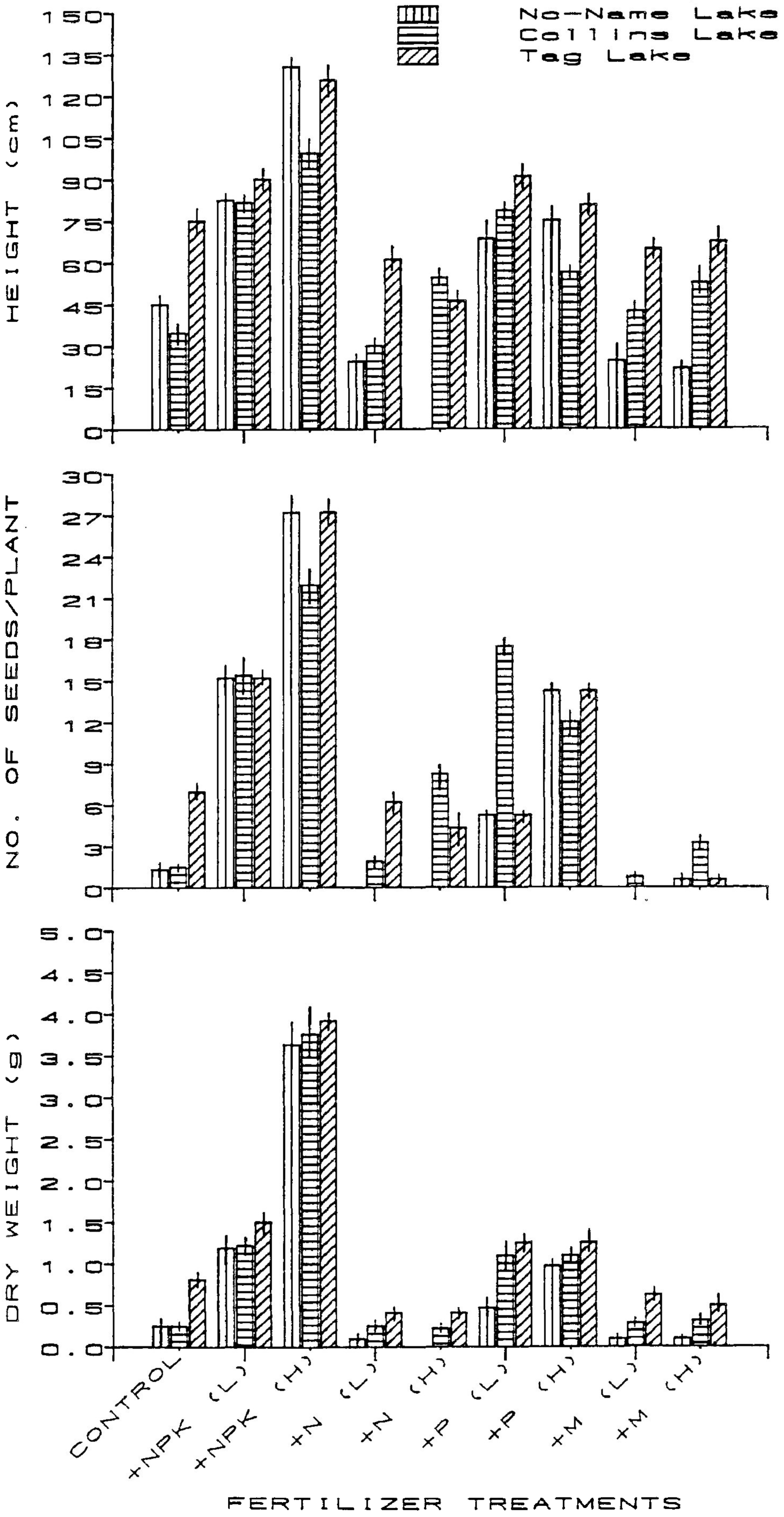
Five wild rice plants were used for each of the eight different treatments. Individual plants were placed in 2 L glass jars that had been washed with double distilled water. The jars were filled with the appropriate nutrient solution and placed in culture tanks. Nutrient solutions were replenished daily. Aeration of the media was not required since wild rice grows in reduced sediment conditions. In order to impede light penetration and prevent algal growth, the tanks were covered with two layers of black plastic. The leaves of the plants were left uncovered, and the stems were supported with clamps to prevent the plants from falling. The plants were monitored daily for a 30 day period and visual foliar symptoms were recorded.

3.3. RESULTS

3.3.1. Raft Experiments

Wild rice production in the three different lake sediments responded similarly to the fertilization. Analyses of variance showed that differences among treatments were statistically significant (wt/plant $F=_{(8,16)}17.0$, $p<0.01$; ht/plant $F=_{(8,16)}14.0$, $p<0.01$; seeds/plant $F=_{(8,16)}87.1$, $p<0.01$). Differences among the rafts were not significant. Figure 3.1 shows the mean production values (weight, height, and number of seeds per plant) for each treatment in each of the three lake sediments.

FIGURE 3.1. Mean height, mean number of seeds per plant, and mean dry weight response of wild rice plants grown in sediment from Collins, Tag, and No-Name lakes to the nine fertilizer treatments. Error bars indicate one standard deviation from the mean.


No-Name Lake
Collins Lake
Tag Lake
HEIGHT (cm)
150
135
120
105
90
75
60
45
30
15
0
NO. OF SEEDS/PLANT
30
27
24
21
18
15
12
9
6
3
0
DRY WEIGHT (g)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
CONTROL
+NPK (L)
+NPK (H)
+N (L)
+N (H)
+P (L)
+P (H)
+M (L)
+M (H)
FERTILIZER TREATMENTS

Production values were highest in NPK and P treatments. N and micronutrient treatments did not significantly increase dry weight or plant height relative to the control. Similar results were obtained for seeds per plant, except in the Collins lake sediment where high nitrogen and micronutrient treatments resulted in greater seed numbers than the control.

Figure 3.2 shows the results obtained for Collins Lake sediment. In the treatments containing phosphorus, plant growth and seed production were noticeably better than the treatments in which phosphorus was absent. Phenological development was also affected. Wild rice in the NPK and P treatments were well advanced into the aerial leaf stage, while plants in the N, micronutrients, and control treatments were still in floating leaf and early aerial leaf stages.

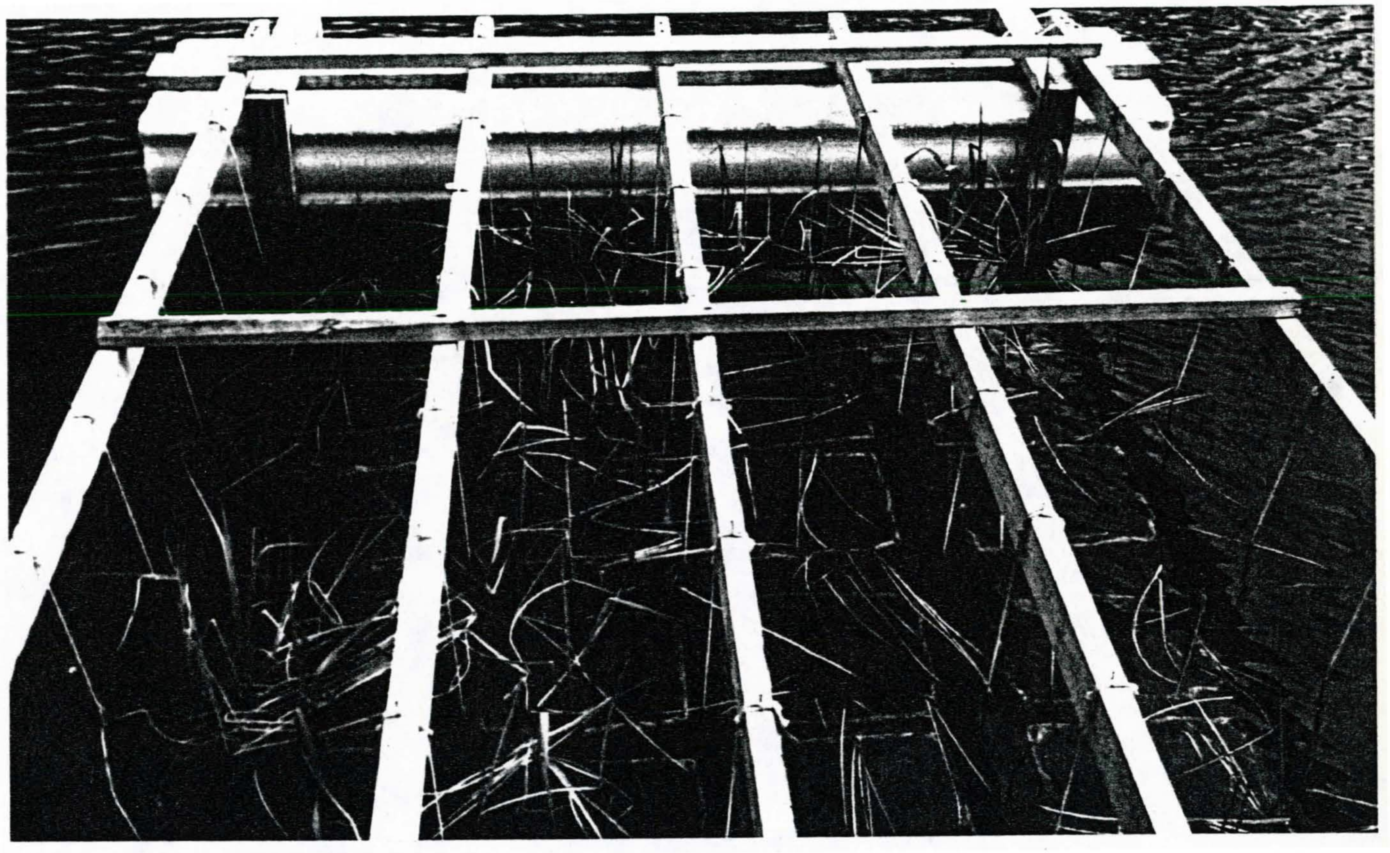
3.3.2. Nutrient Deficiency Symptoms

The leaves of some of the plants in the complete and deficient solutions displayed chlorosis when first transplanted into the nutrient solutions. These chlorotic leaves were removed since these symptoms were believed to be the result of transplant shock. After this the plants in the complete solution remained green and healthy for the duration of the experiment.

Figure 3.3 compares the visual deficiency symptoms of wild rice grown in complete and deficient nutrient solutions with the appearance of wild rice grown in organic-flocculent sediments. The first visible symptoms were recorded at day 10 of the experiment. As time progressed, the symptoms became more severe, affecting more leaf area and often the stalks.

The appearance of wild rice grown in organic-flocculent sediment (field) most closely resembled the plants grown in the phosphorus deficient (-P) solution. These plants displayed purple colouration along the margins, interveinally, and on the stalks of the more recently affected leaves, while older leaves were necrotic.

FIGURE 3.2. The randomized block experimental design with 2 replicates of 9 fertilizer treatments used for the Collins Lake sediment. High (H) and low (L) treatments were used for each fertilizer. The wild rice growing in the +NPK and +P treatments matured faster (shown in the aerial leaf stage) than did the +N, +M, and control (C) treatments (shown in the floating leaf stage).



LEGEND

C	+P(H)	+P(L)	+NPK(H)
+M(H)		+N(L)	
+N(L)	+P(L)		C
	+NPK(L)	+M(L)	+M(L)
+NPK(H)	+P(H)		+N(H)
+M(H)		+N(H)	+NPK(L)

FIGURE 3.3. Comparison of the visual nutrient deficiency symptoms displayed by wild rice grown in the field (organic-flocculent sediments) to wild rice grown in complete solution and in solutions deficient in nitrogen (-N), phosphorus(-P), potassium(-K), iron(-Fe), magnesium(-Mg), calcium(-Ca), and micronutrients (-micro).


Field
Complete
−N
−P
−K
−Fe
−Mg
−Ca
−micro

Similarly, the plants in the phosphorus deficient treatment initially turned dark green, and then later purple along the leaf margins, interveinally, and on the stems.

In the nitrogen deficient (-N) treatments, chlorosis first appeared at the tips and margins of the older leaves, and then progressed towards the base. Potassium deficient (-K) plants were scorched at the tips and margins of the most recently matured leaves. The iron deficient (-Fe) plants displayed interveinal chlorosis in the younger leaves. The visual symptom of wild rice in magnesium deficient (-Mg) and calcium deficient (-Ca) treatments was interveinal chlorosis in the older leaves. After 10 days, the plants grown in the micronutrient deficient (-micro) solution, displayed marginal and interveinal chlorosis and a slight purple colour along the margins and sheaths of the older leaves. These leaves later turned an orange-brown colour, and became necrotic after 20 days. After a 30 day period, all the above symptoms still prevailed for the respective treatments. Many of the earlier leaves that were affected became necrotic.

3.4. DISCUSSION

Evidence from the fertilizer trials and the nutrient deficiency results points to phosphorus as the limiting nutrient in organic-flocculent lakes. The plants from organic-flocculent lakes (Fig. 3.3) most closely resembled the phosphorus deficient treatment. Phosphorus deficient plants were characterized by purple colouration of the leaves, and a slower maturation rate. These same symptoms have been observed in other plants that are phosphorus deficient and occur as a result of anthocyanin pigment formation (Chapman, 1966).

Plants subject to fertilizer regimes that included phosphorus were characterized by early maturation, good production and no chlorosis. By contrast, wild rice plants resulting from micronutrient, nitrogen, and control treatments (ie. lacking P) displayed both slow maturation and purple foliage. These findings were similar to those of Enyi (1963) who found that phosphate fertilization of rice (*Oryza sativa* L.) increased plant weight and maturation rate. The high and low phosphorus treatments did result in some chlorosis in the mature leaves, symptoms that indicate nitrogen deficiency. A secondary deficiency of nitrogen may have resulted in the lower production values for the P treatments as compared to the NPK treatmeants.

Phosphorus deficiency in these sediments seems reasonable when their composition is considered. Although past studies have indicated that high organic content is correlated to high phosphorus values within lake sediments (Trojanowski *et al*, 1985; Golachowski, 1984; Trisal and Kaul, 1983; Peltier and Welch, 1970), in chapter 1 and 2 the reverse was found to be true in organic-flocculent and flocculent sediments These sediments were characterized by high organic content (% LOI > 50) but low phosphorus values. This discrepancy may be due to the degree of decomposition of organic matter which influences the release of nutrients (Twilley *et al*, 1985; Sain, 1984; Jordana, 1983; Twinch and Ashton, 1983; Malsner and Nihlgard, 1980). Assuming there is a positive linear correlation between bulk density and the degree of decomposition, as determined for northern peats by Silc and Stanek (1977), the organic matter in organic-flocculent sediments would be undecomposed to moderately decomposed while organic sediments would be more completely decomposed and, therefore, more likely to have higher phosphorus values.

Turbulent mixing of sediments is known to accelerate phosphorus release (Bostrom, 1984; Zicker *et al*, 1956) and this could also explain the lower phosphorus values in the organic-flocculent and flocculent sediments. Certainly the low bulk density of these sediments would allow them to be easily disturbed by wave and wind action, and in turn increase phosphorus release.

Lee and Stewart (1984) suggest that in addition to deficiencies in phosphorus, flocculent lake sediments might be deficient in some metals and micronutrients. Szalay (1974) found that Mn and Cu were deficient in plants grown in peat soils. However, the fertilizer study (Fig. 3.1) showed that additions of micronutrients had no affect on wild rice.

In conclusion, wild rice production in organic-flocculent sediments was limited by phosphorus, with nitrogen acting as a secondary nutrient deficiency. Phosphorus deficiency in wild rice is characterized by slow maturation and anthocyanin pigment formation. Phosphorus deficiency may be related directly to the type of sediment. Organic-flocculent sediments contained a high percentage of poorly decomposed organic material which tends to be nutrient poor. Their low bulk densities makes these sediments susceptible to turbulent mixing which releases nutrients to the water column.

SUMMARY AND CONCLUSIONS

Six sediment types were classified using statistical techniques. These included the following major and hybrid sediment types- organic, clay, flocculent, organic-clay, organic-flocculent, and organic/clay. Of the six sediments, only organic, organic/clay, and organic-clay produced plant dry weights that were commercially suitable. The sediment characteristics of flocculent and organic-flocculent sediments included high organic content (LOI), low bulk density (BD), poor consolidation, and low cation and P values.

Many similarities were found between the sediment characteristics of organic-flocculent and organic/clay sediments including inorganic biogenic composition, mineral content, acid humus, pH, and redox values. P, Mn, Mg, Ca, and N were believed to be associated with humus in organic complexes rather than in mineral complexes within these sediment types.

Major differences in nutrient values existed between organic/clay and organic-flocculent sediments. Lower nutrient values in organic-flocculent sediment were closely linked to the organic material and likely result from the following 4 factors;

1) the origin, type, rate, and degree of decompositon of the organic material.
2) slow nutrient mineralization and recycling of P and N.
3) lower density and higher degree of turbulent mixing of the sediments.
4) lower availability of required nutrients.

A comparison of the seasonal trends between organic-flocculent and organic/clay sediments showed no nutrient depletion during the exponential growth of wild rice. Throughout the growing season, with the exception of N, organic/clay lakes had higher nutrient values with the exception of N. The growth of wild rice within organic-flocculent sediments was often retarded while normal development occurred in the organic/clay sediments.

Fertilizer experiments showed that the symptoms displayed by the wild rice grown in organic-flocculent sediments (slow maturation and purple leaves) resulted primarily from a deficiency of P with N as a possible secondary deficiency.

The results from these experimental and field studies have several implications for wild rice production. These have been discussed in the individual chapters, but to conclude this thesis, the more important points are summarized below.

1. Lake sediments from wild rice stands can be classified into specific types. Wild rice production can be predicted for these various types.

2. Nutrients required for wild rice production vary throughout the growing season. Inadequate amounts of these nutrients impedes normal wild rice development.

3. Unproductive sediments that can be classified as flocculent are primarily deficient in phosphorus. Addition of fertilizer can correct this problem and result in normal wild rice growth.

REFERENCES

Anderson, R.A. 1976. Wild rice: Nutritional review. Cereal Chem. 53:949.

Atkins, T.A. 1984. Continuing investigations of the ecological relationships of wild rice at Lake of the Woods. *In*: Lee, P.F. (ed.) The aquaculture of wild rice: Progress year 3. Dept. Bio. Lakehead Univ. Thunder Bay, Ont.

Atkins, T.A. 1985. An inventory of macrophytes competing with wild rice at Lake of the Woods and the impact of competition on wild rice productivity: interim report. *In*: Lee, P.F. (ed.) The aquaculture of wild rice: Progress year 4. Dept. Bio. Lakehead Univ. Thunder Bay, Ont.

Atkins, T.A. 1986. Ecology and early life history tactics of wild rice: seed bank dynamics, germination, and submerged leaf phenophase growth. Ph.D. Thesis. University of Manitoba, Winnipeg.

Barko, J.W. and R.M. Smart. 1978. The growth and biomass distribution of two emergent freshwater plants, *Cyperus esculentus* and *Scirpus validus*, on different sediments. Aquat. Bot. 5: 109-117.

Bostrom, B. 1984. Potential mobility of phosphorus in different types of lake sediments. Int. Revue Ges. Hydrobiol. 69:457-479.

Buckman, H.O. and N.C. Brady. 1961. The Nature and Properties of Soils. Macmillan. New York.

Cary, B. 1984. The ritual of the rice. Canoe. 12:44-49.

Challa, O. and K.V. Raman. 1984. Organic matter and metal ion complexes-Stability studies under different pH and thermal conditions. J. Indian Soc. Soil Sci. 32:230-234.

Chambliss, C.E. 1940. The botany and history of *Zizania aquatica* L. ("Wild rice"). J. Wash. Acad. Sci. 30:185-205.

Chapman, H.D. (Ed.) 1966. Diagnostic Criteria for Plants and Soils. Univ. of Calif. Div. of Agri. Sci., Berkeley, Calif.

Delfino, J.J., G.C. Bortleson, and G.F. Lee. 1969. Distribution of Mn, Fe, P, Mg, K, Na, and Ca in the surface sediments of lake Mendota, Wisconsin. Environ. Sci. Technol. 3:1189-1192.

Dore, W.G. 1969. Wild Rice. Can. Dept. of Agric. Pub. No. 1393, Ottawa.

Enyi, B.A.C. 1963. Influence of varying phosphorus and water supply on the growth and yield of swamp rice variety (*Oryza sativa* L.). Journal of Agricultural Science. 61:227-231.

Fassett, N.C. 1924. A study of the genus *Zizania*. Rhodora. 26:153-160.

Fassett, N.C. 1957. A Manual of Aquatic Plants. U. of Wisconsin Press, Madison Wis. USA.

Fernald, M.L. 1970. Gray's Manual of Botany. 8th. Ed. D. Van Nostrand Co., Toronto.

Garrod, R.C. 1984. Ecology of Wild rice (*Zizania palustris* L.): Fruit production and habitat relationships. M.Sc. Thesis University of Manitoba, Winnipeg.

Gleason, H.A. and A. Cronquist. 1963. Manual of Vascular Plants of the Northeastern United States and Adjacent Canada. PWS Publishers, Boston, Mass.

Golachowska, J. 1984. Phosphorus in bottom sediments of some lakes of the world. Polish Archives of Hydrobiology. 31:175-206.

Grant, B.S. 1981. Protein-rich wild rice, our only native cereal. Canadian Geographic. 101:51-61.

Grava, J. 1982. Soil fertility. *In*: Wild Rice Production in Minnesota, Extension Bulletin 464, Agricultural Extention Service, University of Minnesota, St. Paul, Minnesota. p.18-21.

Grava, J. and K.A. Raisanen. 1978. Growth and nutrient accumulation and distribution in wild rice. Argon. J. 70:1077-1081.

Green, R.H. 1971. Multivariate statistical approach to the Hutchinsonian niche: bivalve molluscs of central Canada. Ecol. 52:543-556.

Hansen, K. 1959a. The terms gyttja and dy. Hydrobiologica. 13:309-315.

Hansen, K. 1959b. Sediments from Danish lakes. Journal of Sedimentary Petrology. 29(1):38-46.

Hansen, K. 1961. Lake types and lake sediments. Verh. Internat. Verein. Limnol. 14:285-290.

Hawthorn, W.R. and J.M. Stewart. 1970. Epicuticular wax forms on the leaf surfaces of *Zizania aquatica*. Can. J. Bot. 48:201-205.

Hayes, F.R. 1964. The mud-water interface. Oceanogr. Mar. Biol. Ann. Rev. 2:121-145.

Hayes, F.R. and J.E. Phillips. 1958. Lake water and sediment. IV. Radiophosphorus equilibrium with mud, plants, and bacteria under oxidized and reduced conditions. Limnol. Oceanogr. 3:459-475.

Hoagland, D.R. and D.I. Arnon. 1950. The water-culture method for growing plants without soil. Calif. Exp. Sta. Circ. pp. 347.

Johannes, R.E. 1968. Nutrient regeneration in lakes and oceans. Adv. Microbiol. Sea. 1:203-212.

Jordana, J.C.C. 1983. Physical, chemical, and metabolic characteristics of a peat bog in the depression of Padul (Granada, Spain). Acth. Hydrobiol. 25:253-266.

Keenan, T.J. and P.F. Lee. 1987. Ecological relationships of wild rice, *Zizania aquatica* L. 7. Sediment nutrient depletion following introduction of wild rice to a shallow Boreal lake. Can. J. Bot. (in press).

Lee, P.F. 1979. Biological, chemical, and physical relationships of wild rice, *Zizania aquatica*, in northwestern Ontario and northeastern Minnesota. Ph.D. thesis, University of Manitoba, Winnipeg, Man.

Lee, P.F. (ed.). 1983. The aquaculture of wild rice. Progress year 2. Dept. Bio. Lakehead Univ. Thunder Bay, Ont.

Lee, P.F. (ed.). 1984. The aquaculture of wild rice. Progress year 3. Dept. Bio. Lakehead Univ., Thunder Bay, Ont.

Lee, P.F. 1986. Ecological relationships of wild rice, *Zizania aquatica*. 4. Environmental regions within a wild rice lake. Can. J. Bot. 64:2037-2044.

Lee, P.F. 1987. Ecological relationships of wild rice, *Zizania aquatica*. 5. Enhancement of wild rice production by *Potamogeton robbinsii*. Can. J. Bot. 65:1433-1438.

Lee, P.F. and J.M. Stewart. 1981. Ecological relationships of wild rice, *Zizania aquatica*. 1. A model for among-site growth. Can. J. Bot. 59:2140-2151.

Lee, P.F. and J.M. Stewart. 1983. Ecological relationships of wild rice, *Zizania aquatica*. 2. Sediment plant tissue nutrient relationships. Can. J. Bot. 61:1775-1784.

Lee, P.F. and J.M. Stewart. 1984. Ecological relationships of wild rice, *Zizania aquatica*. 3. Factors affecting seeding success. Can. J. Bot. 62:1608-1615.

Macpherson, L.B., N.R. Sinclair, and F.R. Hayes. 1958. Lake water and sediment. III. The effect of pH on the partition of inorganic phosphorus between water and oxidized mud or its ash. Limnol. Oceanogr. 3:318-326.

Malsner, N. and B. Nihlgard. Supply and transport of mineral nutrients in a subarctic mire. *In*: Ecology of a Subartic Mire. Ecol. Bull. (Stockholm) 30:63-95.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29:280-329.

Moyle, J.B. 1944. Wild Rice in Minnesota. J. Wildl. Man. 8:177-184.

Molye, J.B. 1945. Some chemical factors influencing the distribution of aquatic plants in Minnesota. Amer. Midl. Nature. 34: 402-420.

Oelke, E.A. 1982. The wild rice plant. *In*: Wild Rice Production in Minnesota, Extension Bulletin 464, Agricultural Extention Service, U. of Minnesota, St. Paul. pp. 6-9.

Peltier, W.H. and E.B. Welch. 1970. Factors affecting growth of rooted plants in a reservoir. Weed Science. 18:7-9.

Sain, P. 1984. Decomposition of wild rice (*Zizania aquatica* L.) straw in two natural lakes in northwestern Ontario. Can. J. Bot. 62:1352-1356.

Silc, T. and W. Stanek. 1977. Bulk density estimations of several peats in norther Ontario using the von Post humification scale. Can. J. Soil Sci. 57:75.

Simpson, G.M. 1966. A study of germination in the seed of wild rice (*Zizania aquatica*). Can. J. Bot. 44:1-9.

SPSS Inc. 1985. SPSSx User's Guide. 2ed. McGraw-Hill. Montreal.

Stevenson, S. and P.F. Lee. 1987. Ecological relationships of wild rice, *Zizania aquatica.* 6. The effects of increases in water depth on vegetative and reproductive production. Can. J. Bot. 65:2128-2132.

Swain, F.M. 1963. Geochemistry of humus. In: Organic Geochemistry. Ed. Ingerson, E., and I. Breger. Pergamon Pree, New York. p. 87-147.

Trisal, C.L. and S. Kaul. 1983. Sediment composition, mud-water interchange and the role of macrophytes in Dal Lake, Kashmir. Int. Revue ges. Hydrobiol. 68:671-682.

Thomas, A.G. and J.M. Stewart. 1969. The effects of different water depths on the growth of wild rice. Can. J. Bot. 47:1525-1531.

Trojanowski, J., C. Trojanowska, and H. Ratajczyk. 1985. Chemical characteristics of the bottom sediment top layer in Szcytno Male Lake (Poland). Polish Archives of Hydrobiology. 32:99-112.

Twilley, R.R., L.R. Brinson, and J.D. Davis. 1985. Biomass production and nutrient cycling in aquatic macrophyte communities of the Chawen River, North Carolina (U.S.A.). Aquatic Botany. 22:231-252.

Twinch, A.J. and P.J. Ashton. 1983. Wetlands as accreting systems: nutrient cycling in wetlands. J. Limnol. Soc. Sth. Afr. 9:104-109.

Warwick, S.I. and S.G. Aiken. 1986. Electrophoretic evidence for the recognition of two species in annual wild rice (*Zizania*, Poaceae). Systematic Bot. 11:464-473.

Weir, C.M. and H.M. Dale. 1960. A developmental study of wild rice, *Zizania aquatica* L. Can. J. Bot. 38:719-739.

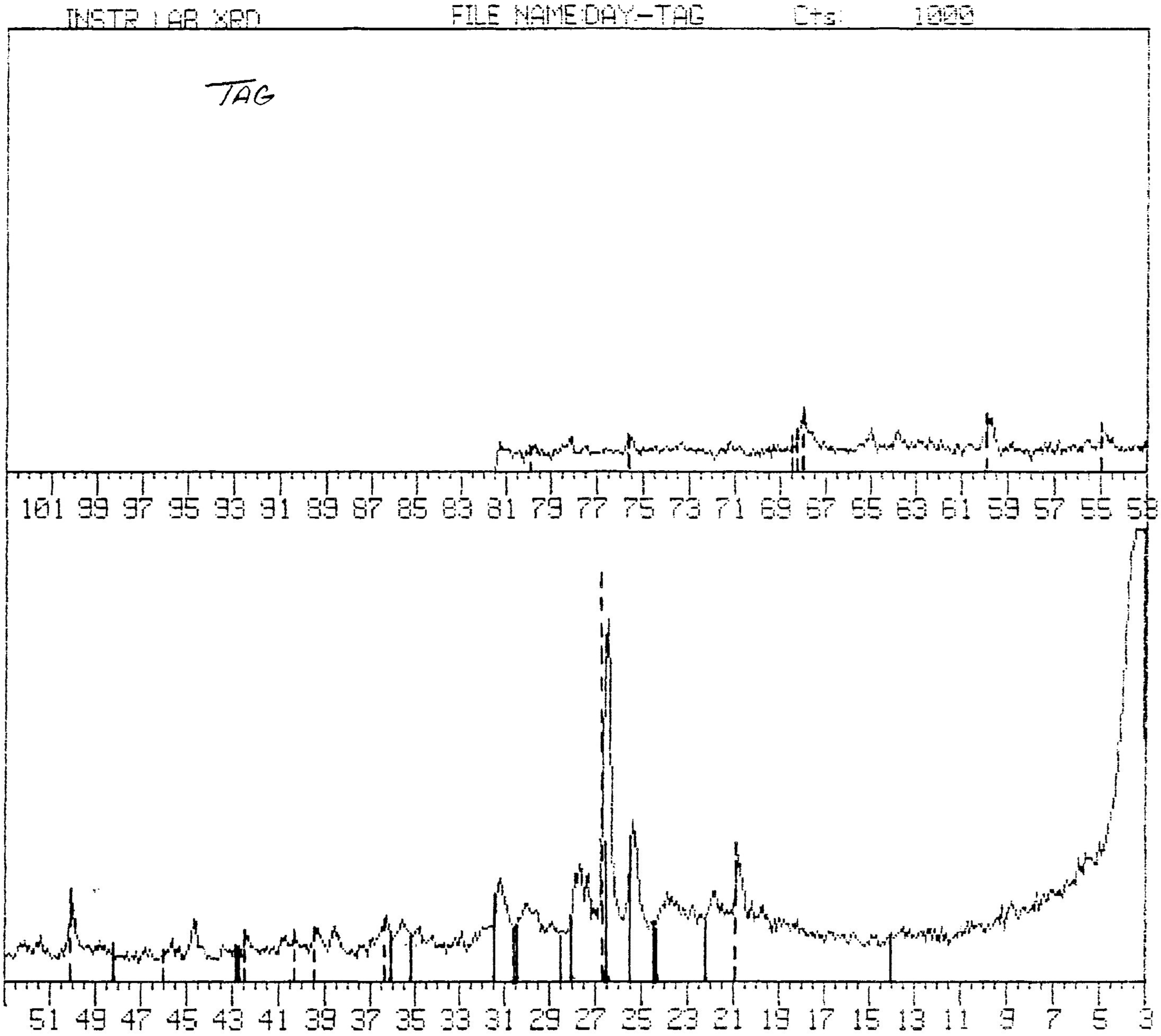
Whigham, D. and R. Simpson. 1977. Growth, mortality, and biomass partitioning in freshwater tidal wetland populations of wild rice (*Zizania aquatica* var. *aquatica*). Bull. Torrey Bot. Club. 104:345-351.

Whittig, L.D. 1965. X-ray diffraction techniques for mineral identification and minerological composition. Agronomy. 9:671-698.

Williams, J.D.H., J.K. Syres, S.S. Shakla, R.F. Harris, and D.E. Armstrong. 1971. Levels of inorganic and total phosphorus in lake sediments as related to other sediment parameters. Environ. Sci. Tech. 5:1113-1120.

Zicker, E.L., K.C. Berger, and A.D. Hasler. 1956. Phosphorus release from bog lake muds. Limnology Oceanogr. 1:296-303.

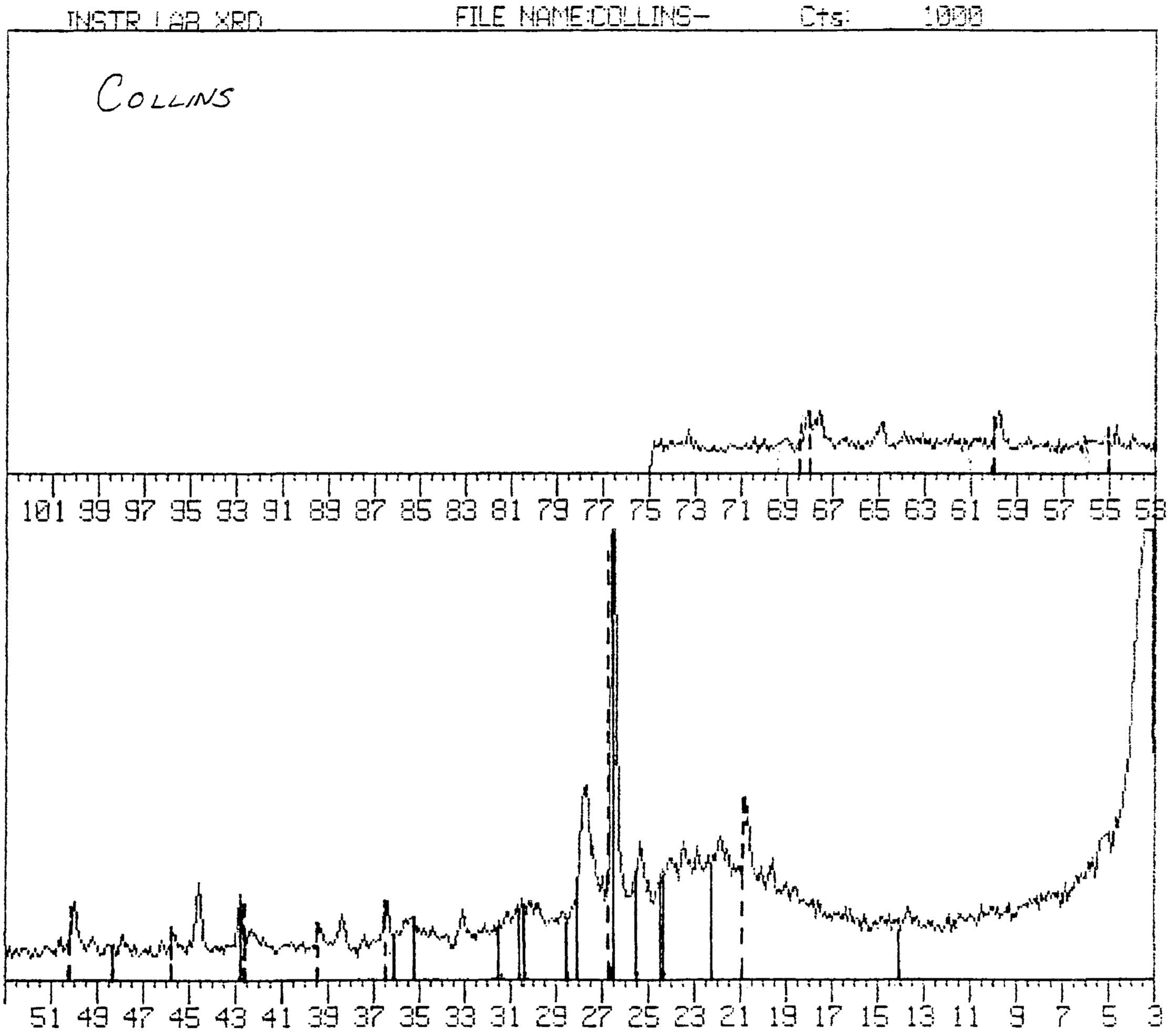
APPENDIX 1. X-ray diffraction results for Tag, Collins, No-Name, and Beavero sediments.



LEGEND

FELDSPAR /Na/Al/Albite - low ————————

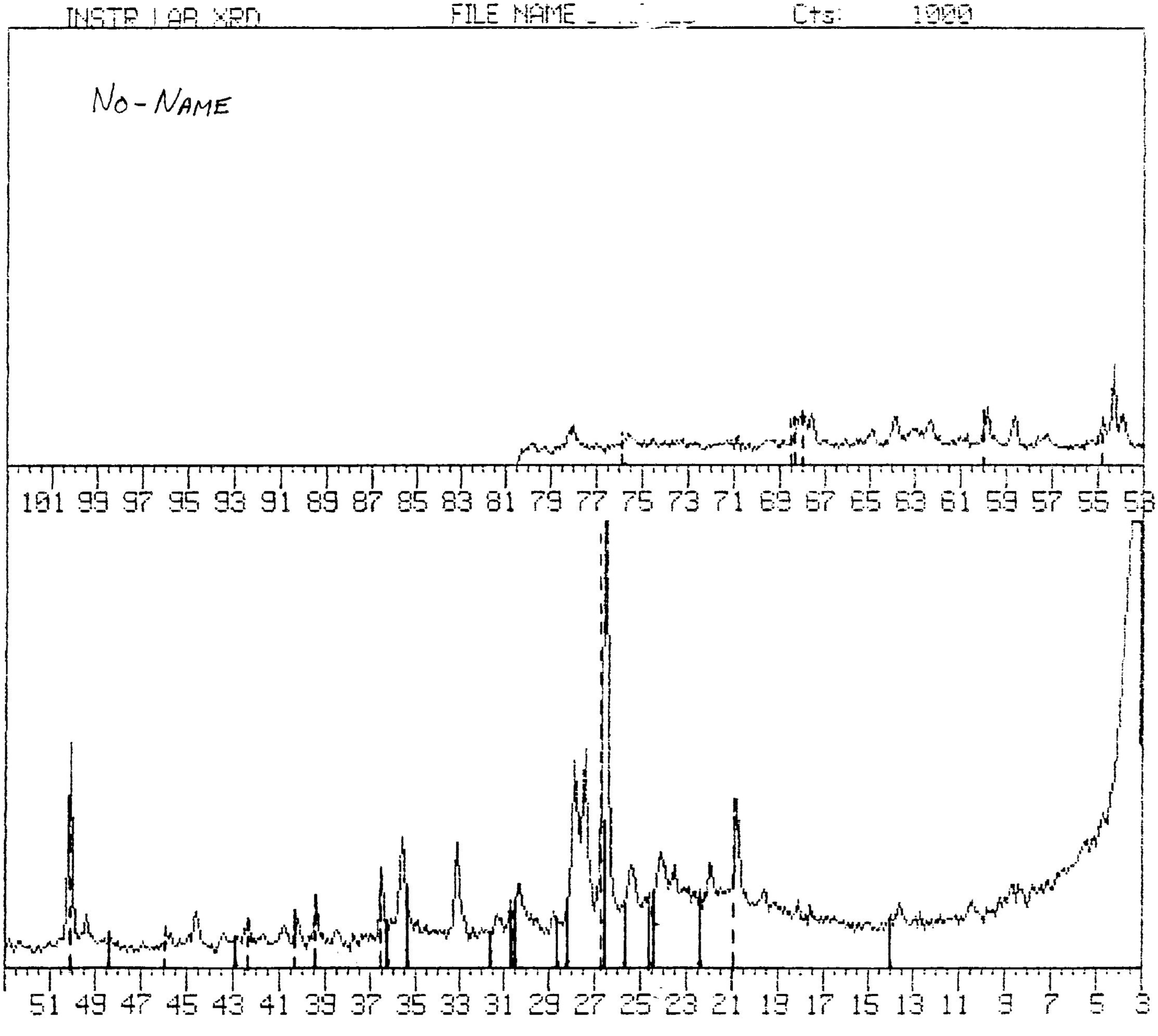
QUARTZ - low — — — — — — — —



LEGEND

FELDSPAR /Na/Al/Albite - low ———

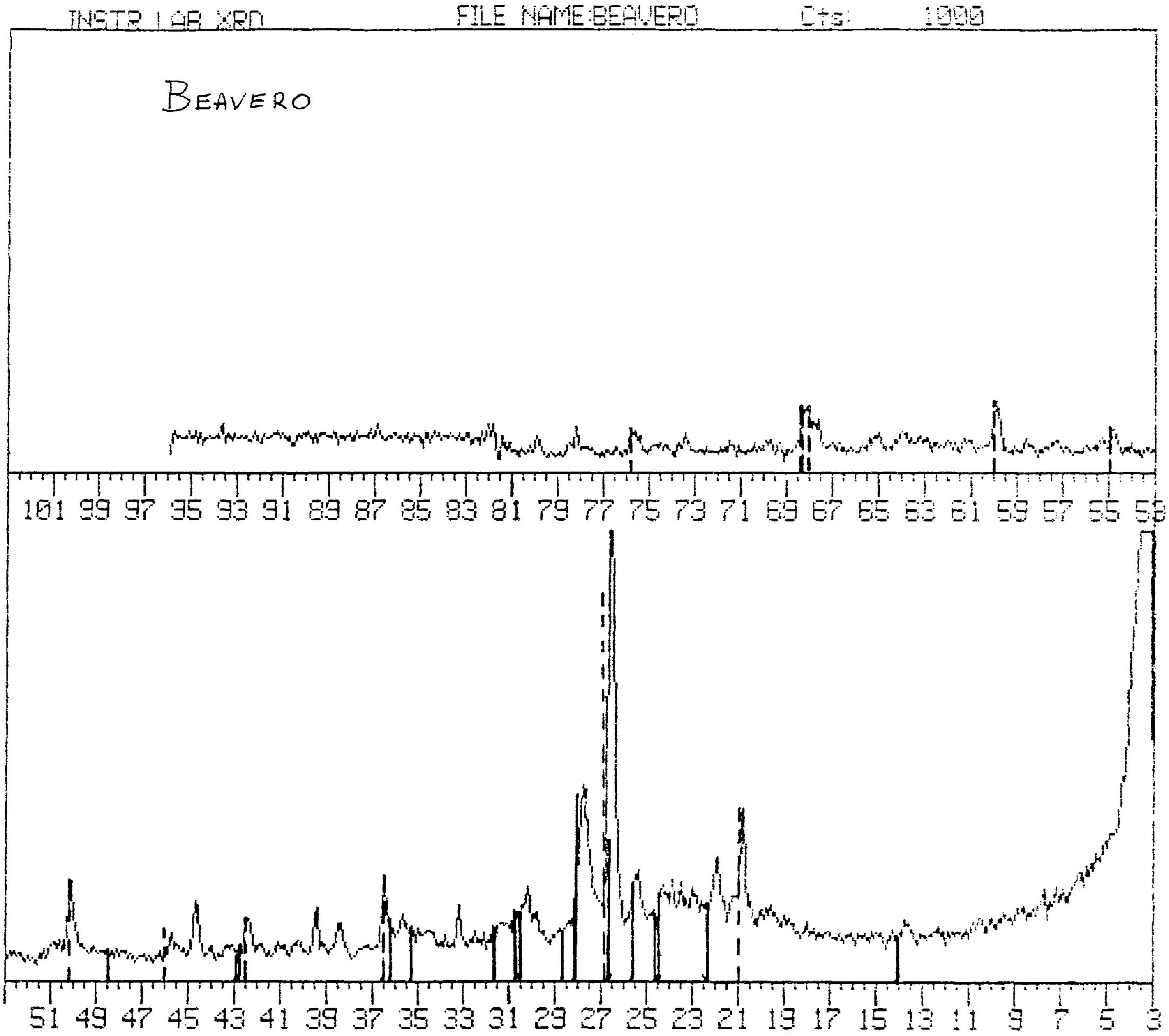
QUARTZ - low – – – – – –



LEGEND

FELDSPAR /Na/Al /Albite - low ————

QUARTZ - low – – – – – – –



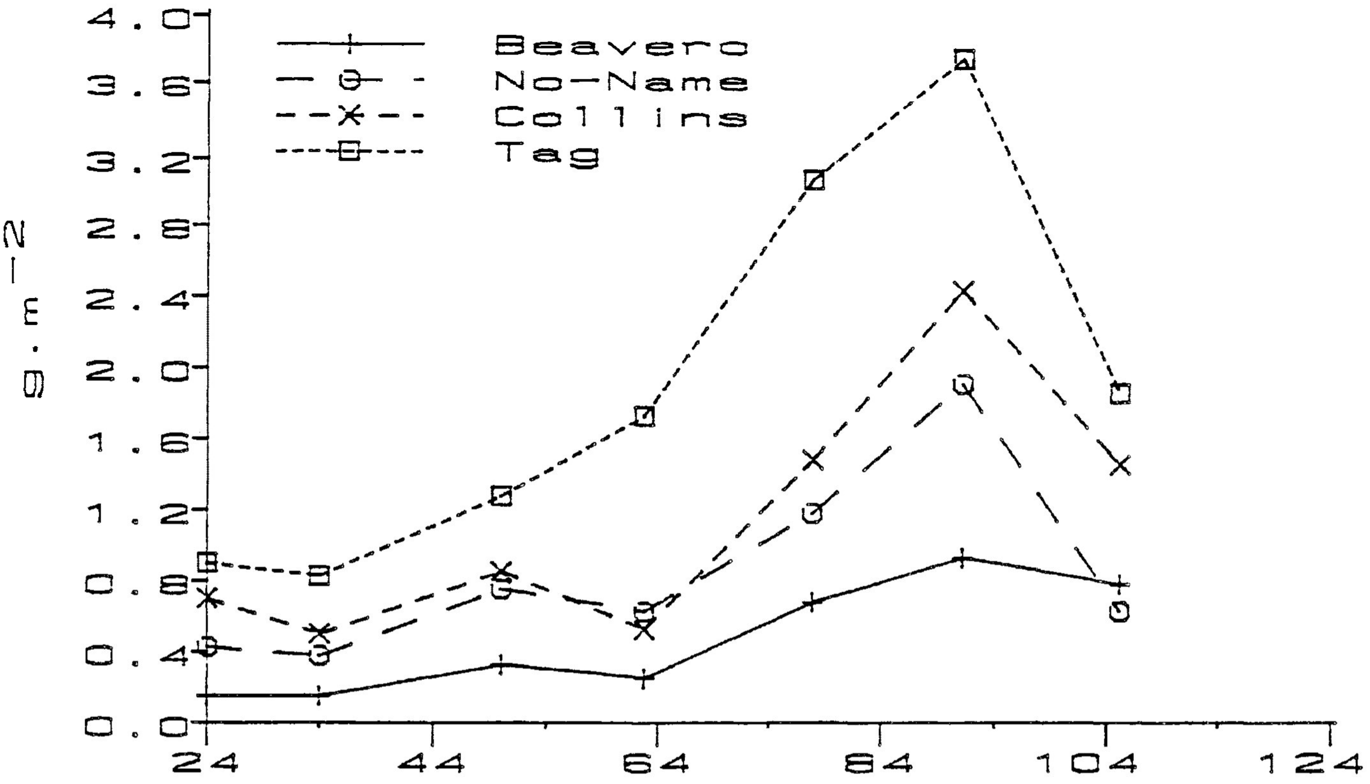
LEGEND

FELDSPAR / Na / Al / Albite - low ————

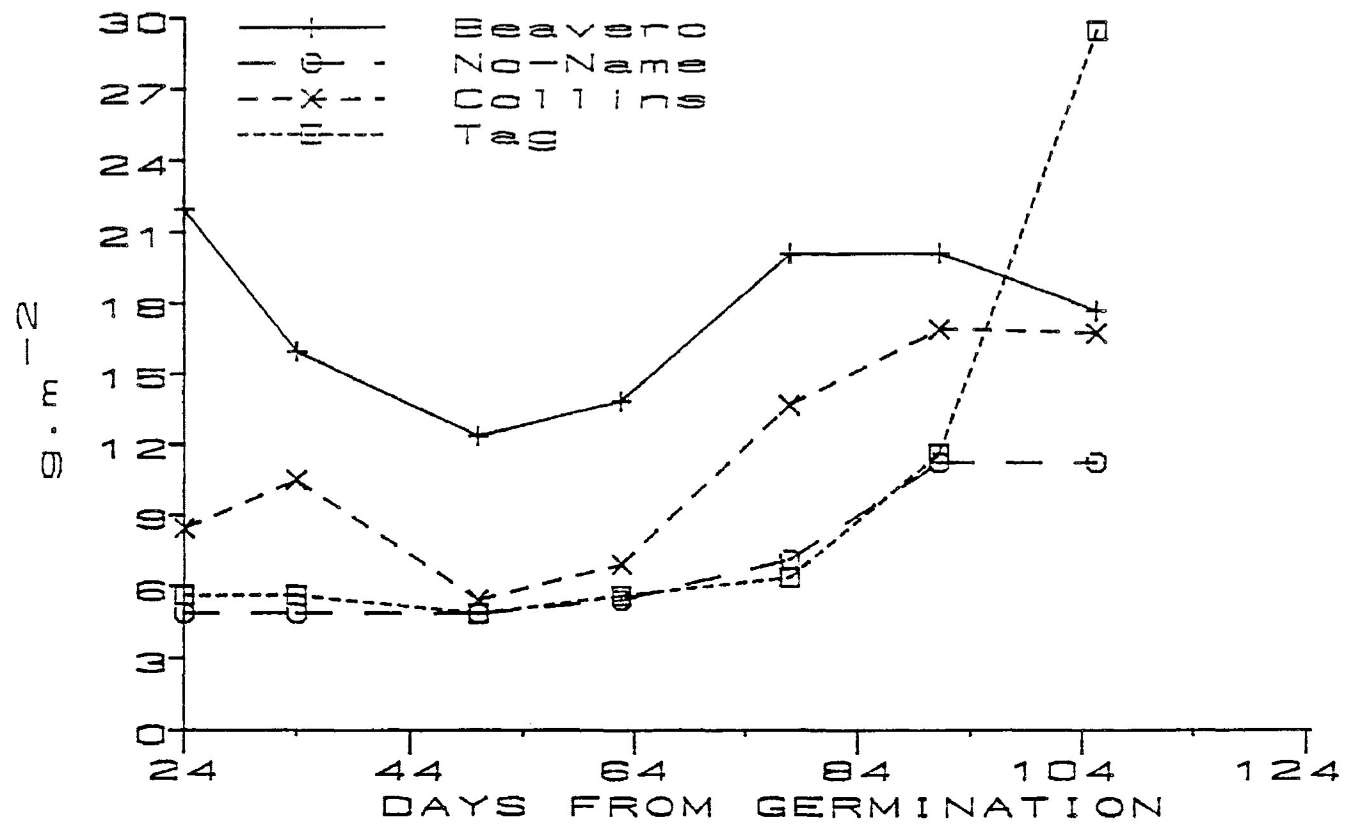
QUARTZ - low — — — — — —

APPENDIX 2. The seasonal sediment values of nitrogen (N), magnesium (Mg), phosphorus (P), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), calcium (Ca), potassium (K), loss on ignition (LOI), bulk density (BD), and pH for Beavero, No-Name, Collins, and Tag sediments.

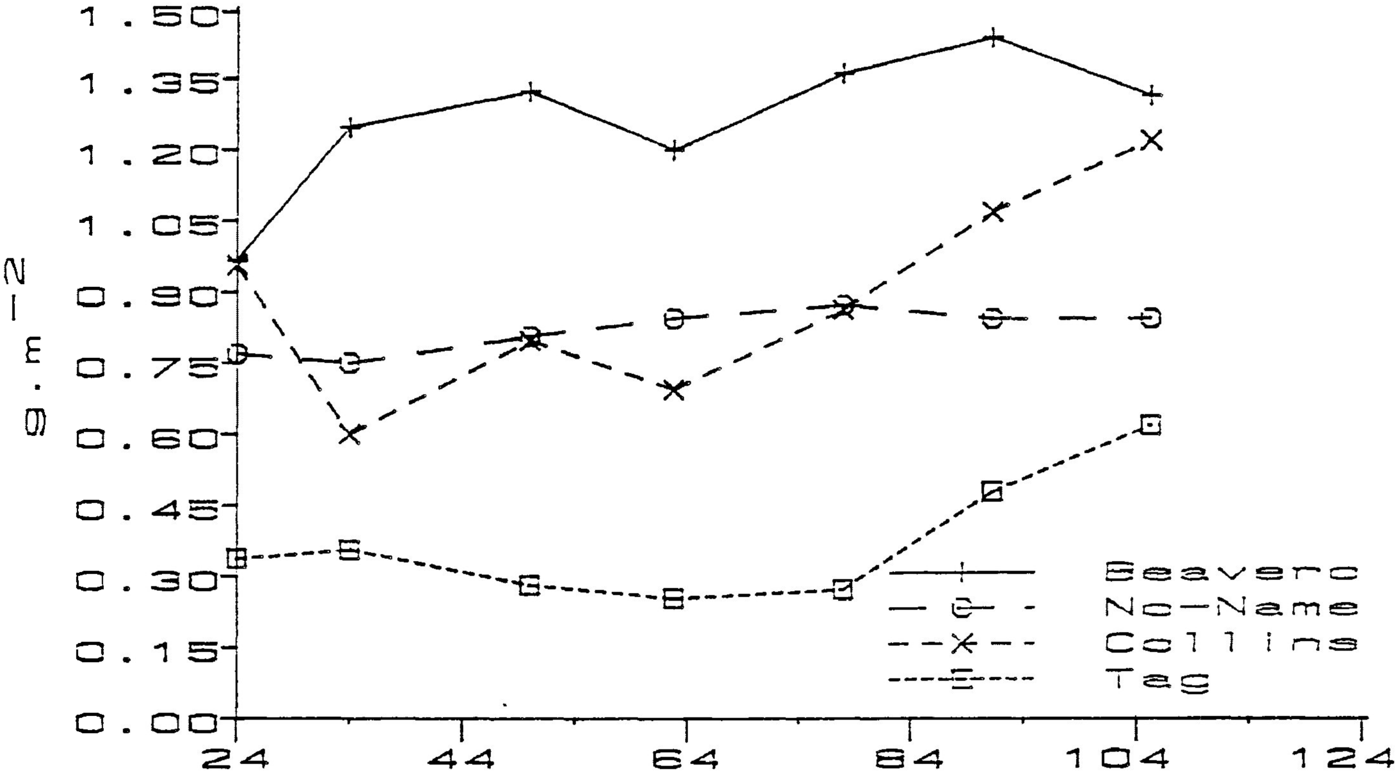
NITROGEN



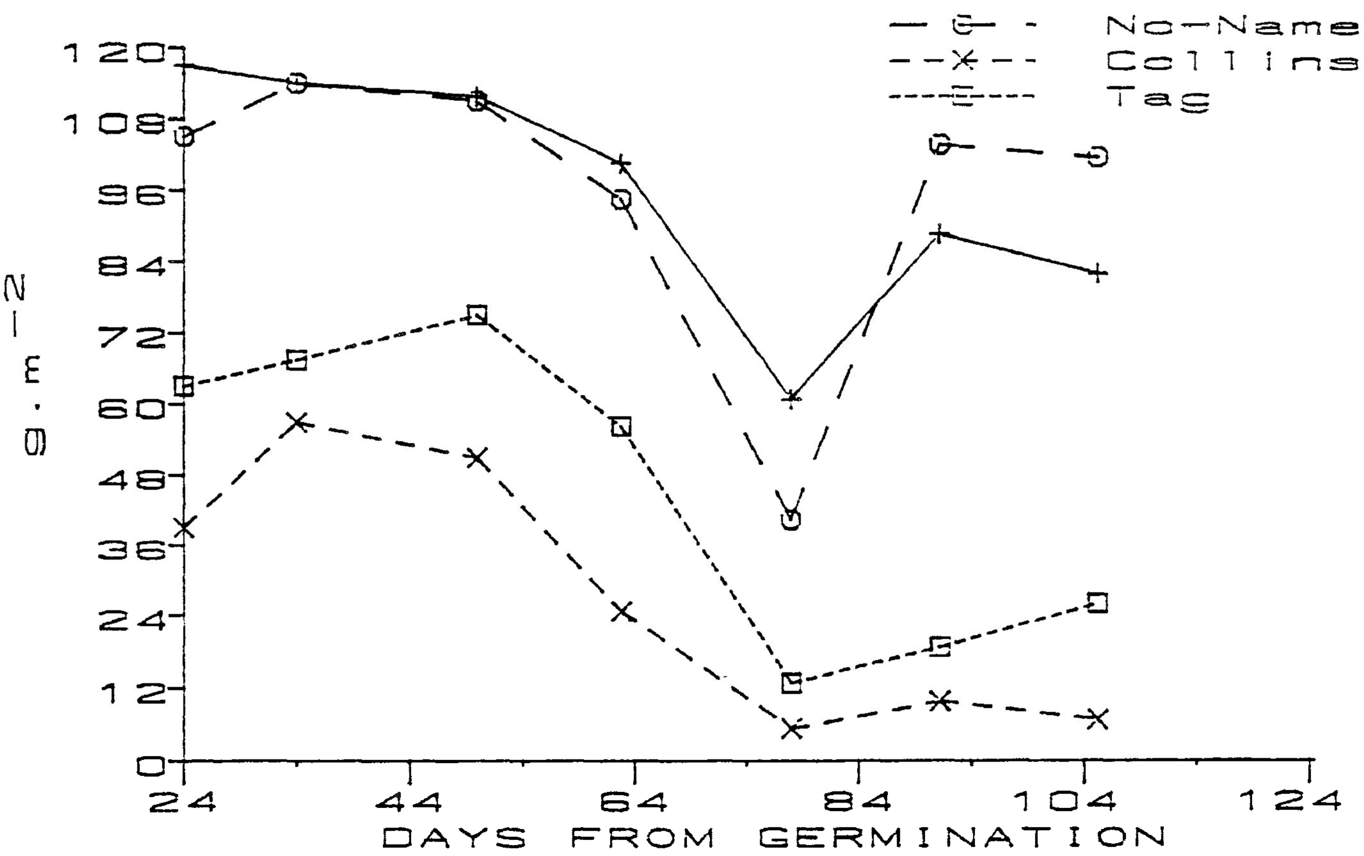
MAGNESIUM

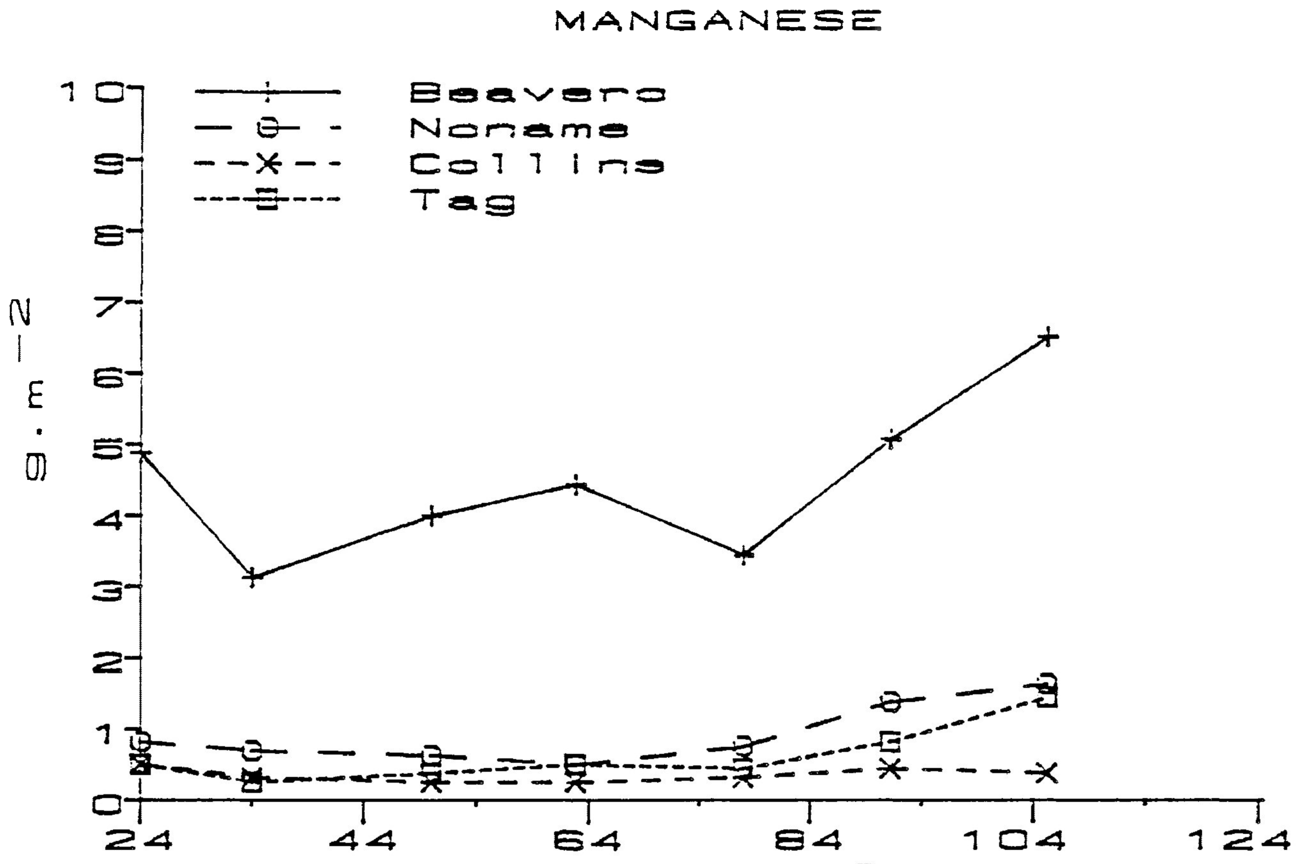


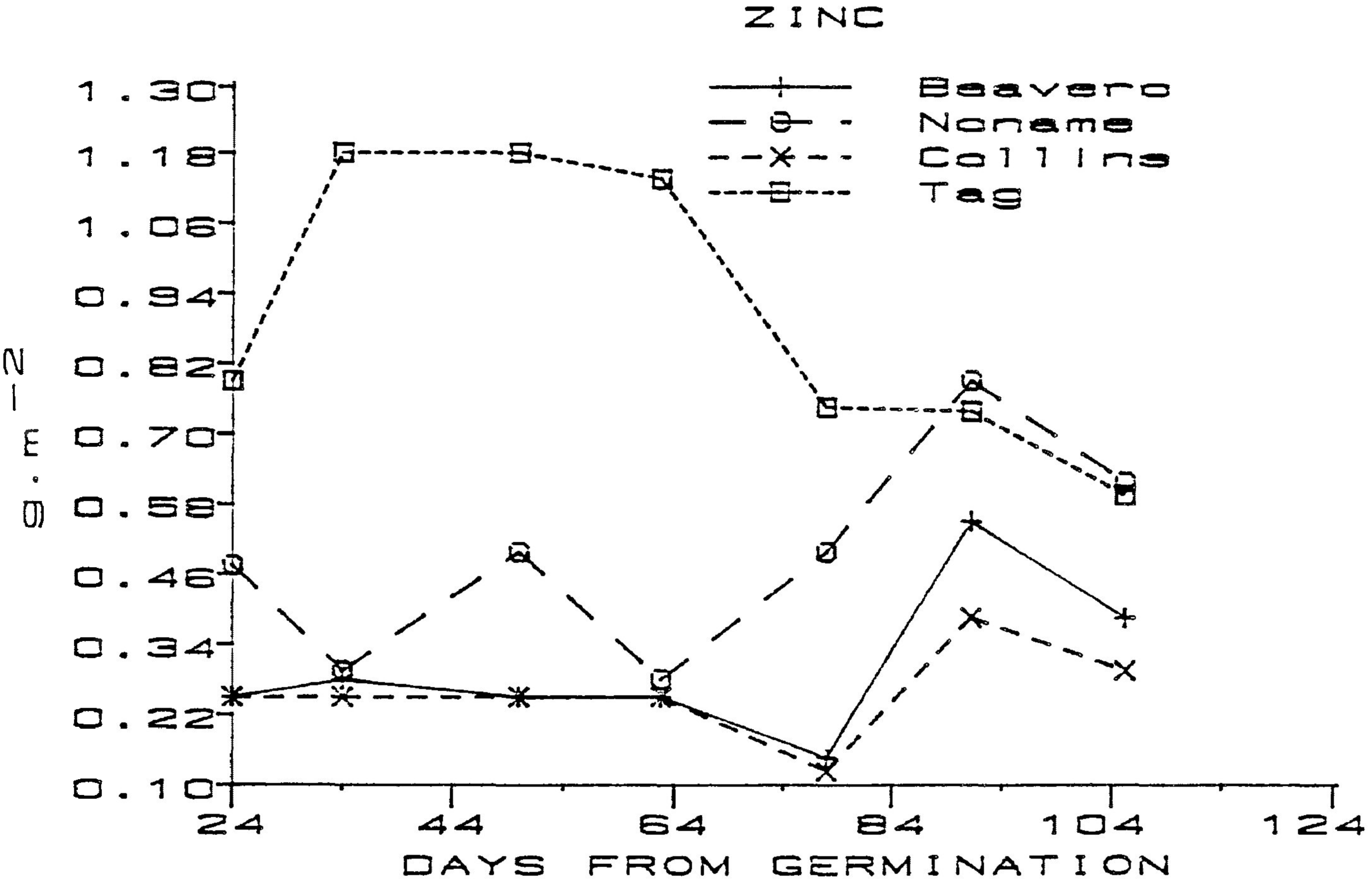
PHOSPHORUS



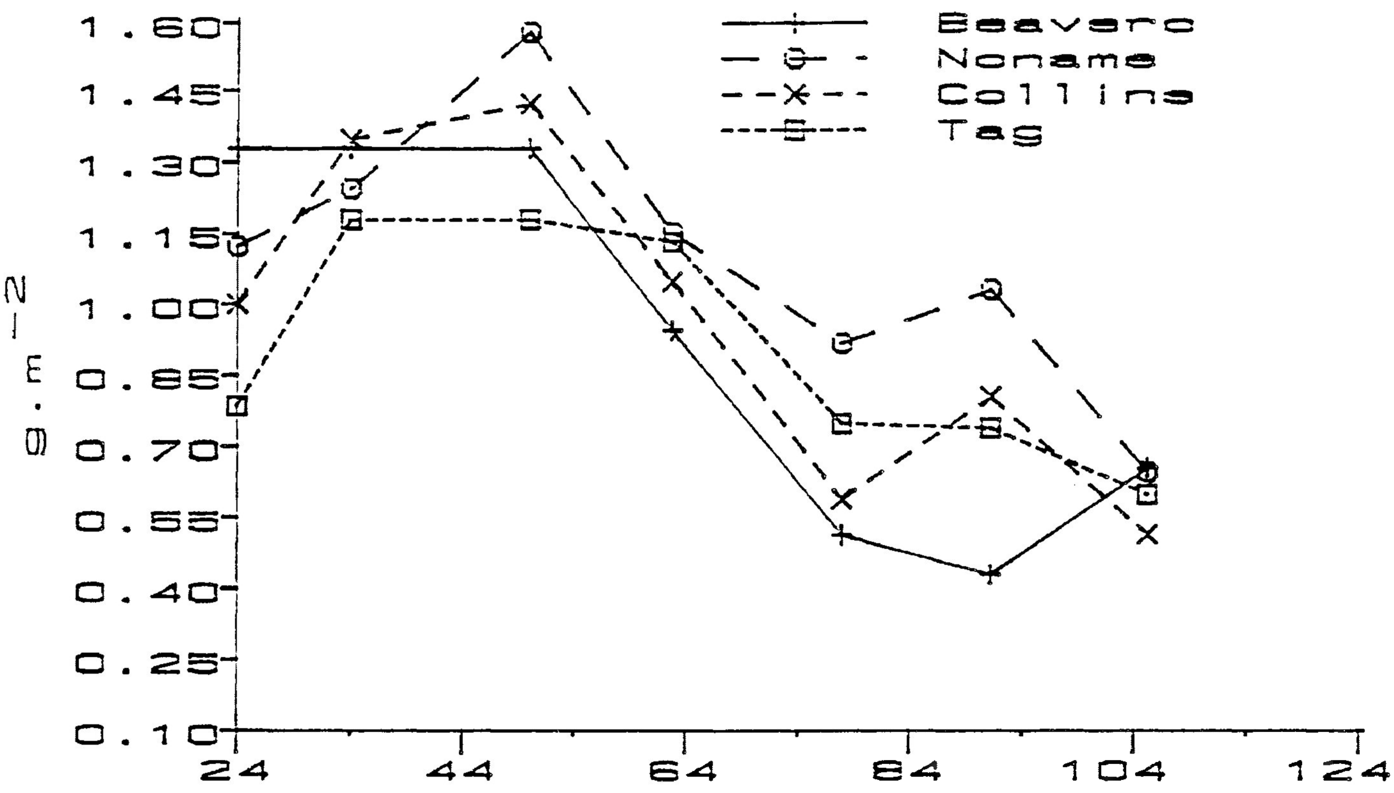
IRON



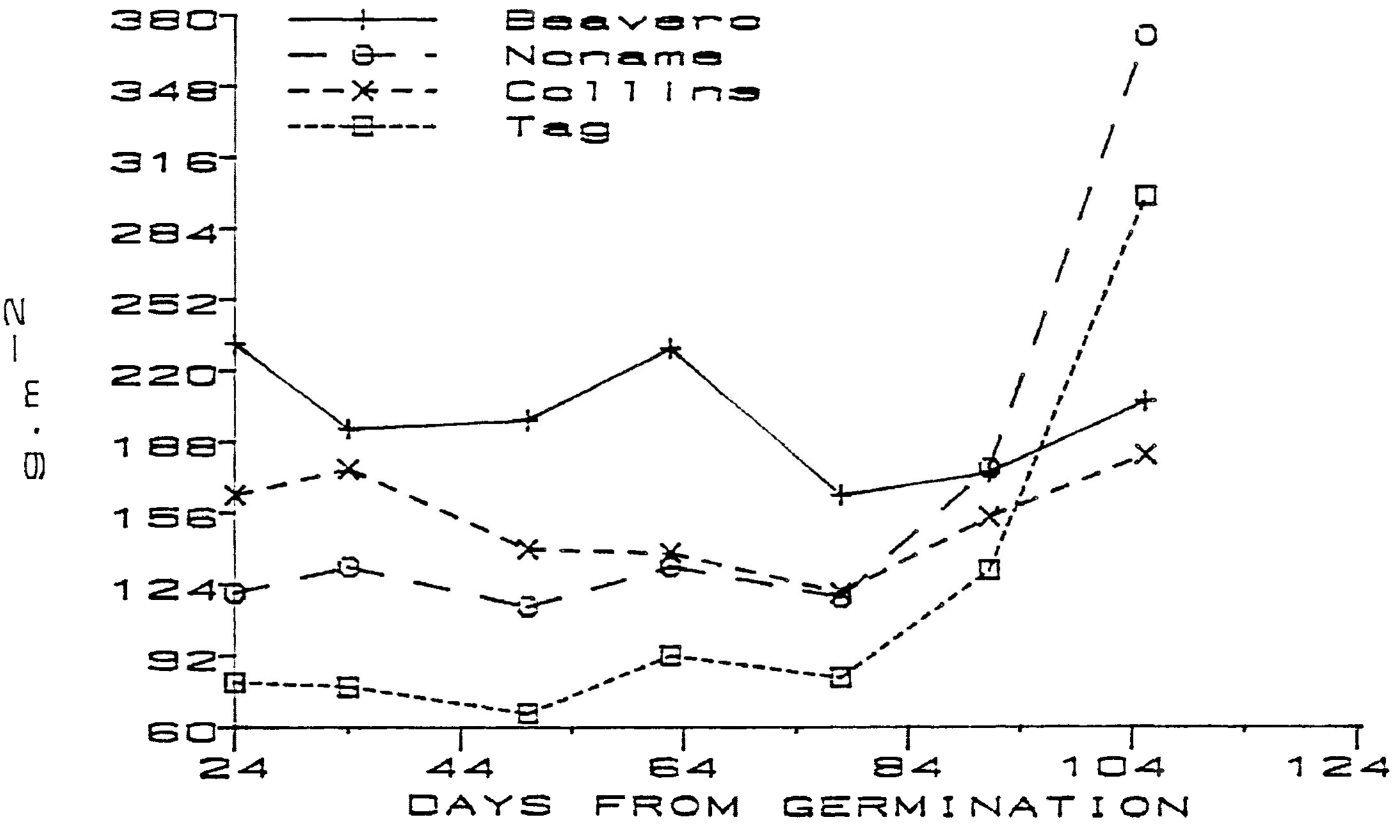

MANGANESE
Beavers
Noname
Collins
Tag
g.m^{-2}
10
9
8
7
6
5
4
3
2
1
0
24
44
64
84
104
124

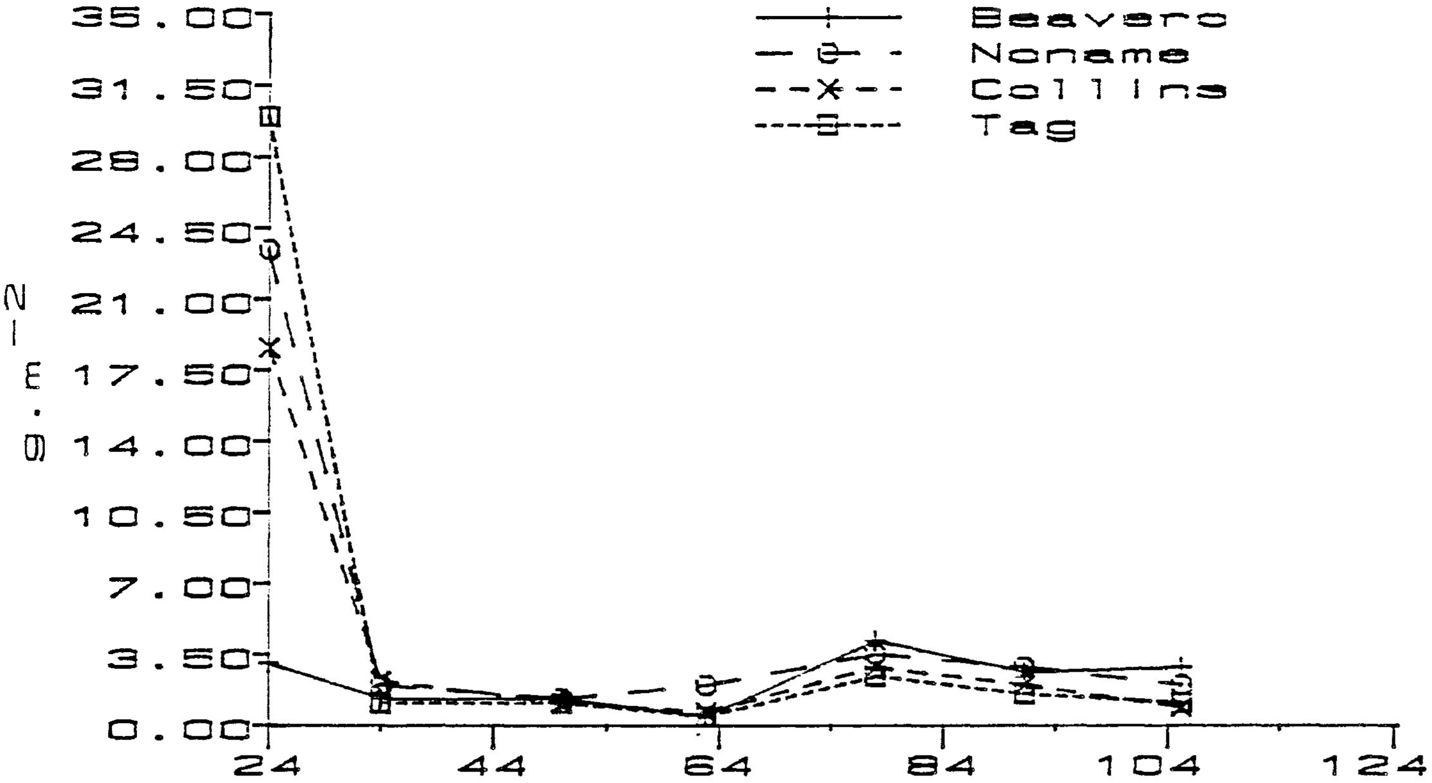

ZINC
Beavers
Noname
Collins
Tag
g.m^{-2}
1.30
1.18
1.06
0.94
0.82
0.70
0.58
0.46
0.34
0.22
0.10
24
44
64
84
104
124
DAYS FROM GERMINATION

COPPER

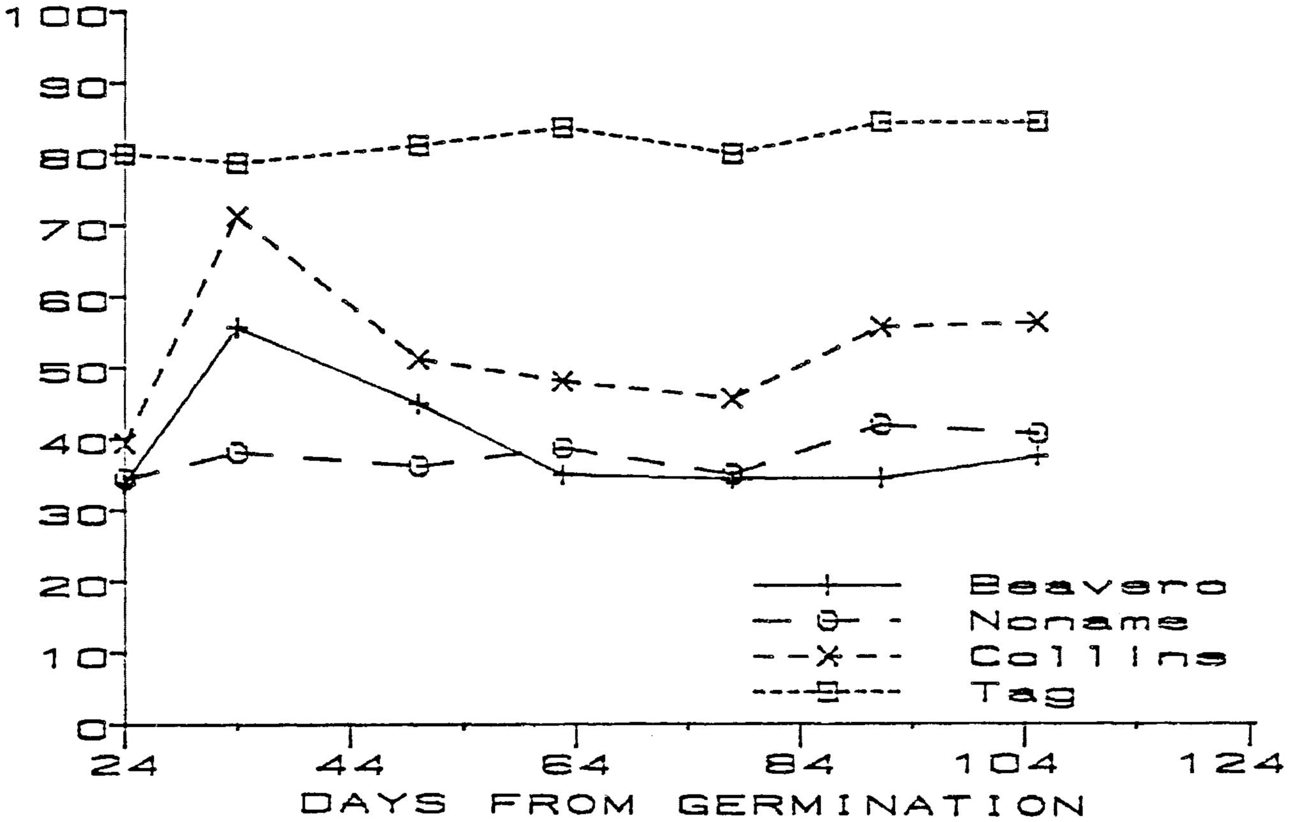


CALCIUM

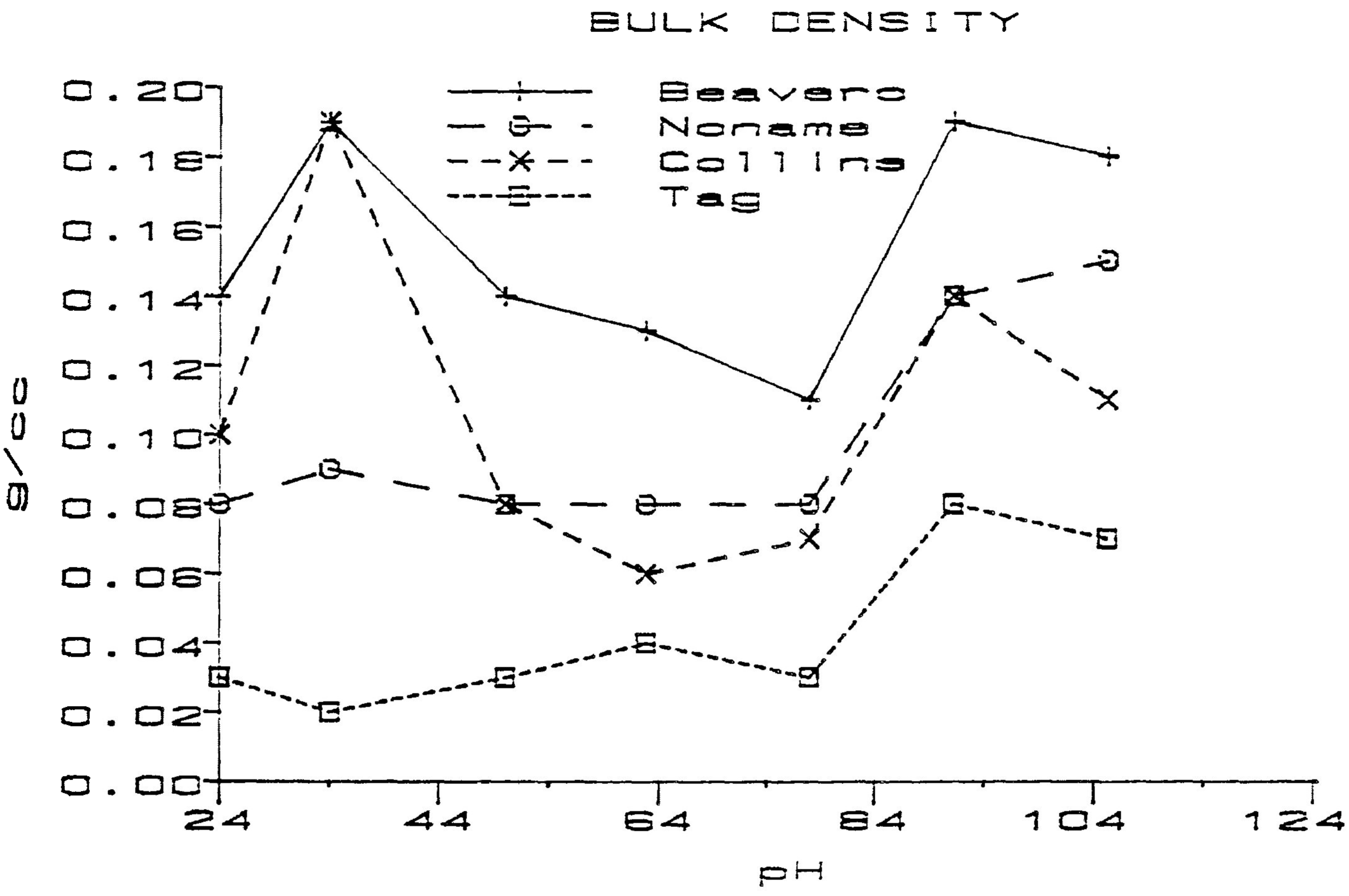


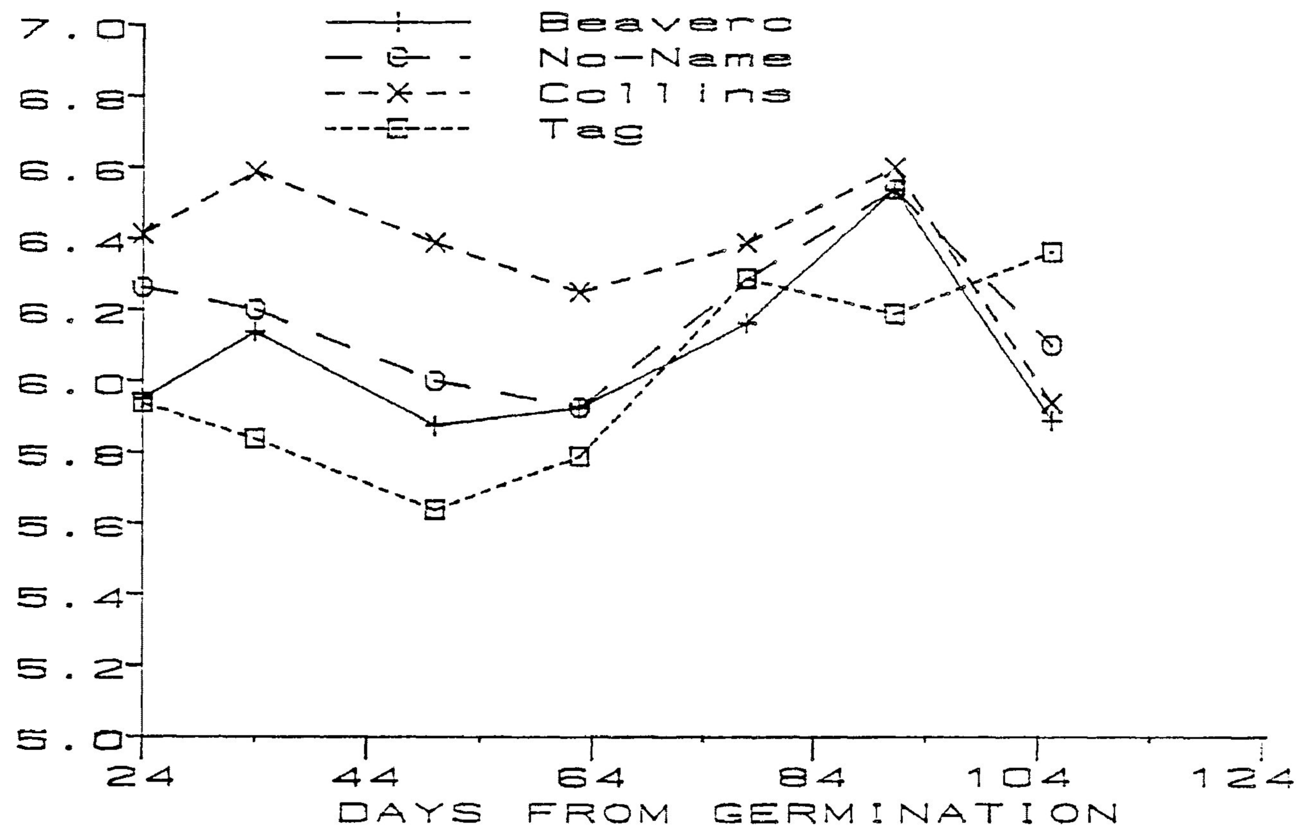


POTASSIUM



% LOSS ON IGNITION


BULK DENSITY
Beaverc
Noname
Collins
Tag
g/cc
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
24
44
64
84
104
124
pH


Beaverc
No-Name
Collins
Tag
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
24
44
64
84
104
124
DAYS FROM GERMINATION