BIOLOGICAL, CHEMICAL AND PHYSICAL RELATIONSHIPS OF WILD RICE, *Zizania aquatica* L., IN NORTHWESTERN ONTARIO AND NORTHEASTERN MINNESOTA

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Submitted to
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Doctor of Philosophy

by
Peter Ferguson Lee
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That afternoon there was a party of tourists at the Terrace and looking down in the water among the empty beer cans and dead barracudas a woman saw a great long white spine with a huge tail at the end that lifted and swung with the tide while the east wind blew a heavy steady sea outside the entrance to the harbour.

"What's that?" she asked a waiter and pointed to the long backbone of the great fish that was now just garbage waiting to go out with the tide.

"Tiburon," the waiter said. "Eshark." He was meaning to explain what had happened.

"I didn't know sharks had such handsome, beautifully formed tails."

"I didn't either," her male companion said.

Up the road, in his shack, the old man was sleeping again. He was still sleeping on his face and the boy was sitting by him watching him. The old man was dreaming about the lions.

Ernest Hemingway
from The Old Man and the Sea

ABSTRACT

Large natural stands of wild rice, *Zizania aquatica* L., were examined in northeastern Minnesota and northwestern Ontario in terms of their biological, chemical, and physical characteristics.

The growth of wild rice during the 1976 and 1977 growing seasons was quantified at four sampling sites on the Mississippi River near the Clay Boswell Steam Electric Station at Cohasset, Minnesota. Cluster analysis was used to illustrate the intercorrelations and seasonal trends which existed among the water and sediment chemical variables. All biological, chemical, and physical variables were corrected for any time dependency and discriminant analysis isolated those factors which could separate the four sampling sites. A wild rice growth model was derived by combining (i) a time independent equation formed from a multiple regression analysis of the time corrected biological, chemical, and physical variables isolated as being significant in the discriminant analysis versus the time corrected dry weights per wild rice plant; and (ii) a time dependent equation formed by fitting a logistic equation to the overall mean weights per wild rice plant at the four sampling sites.

Seasonal changes in nutrient concentrations were monitored during 1976 and 1977 in the wild rice roots, leaves, stems, and heads at the four sampling stations near the Clay Boswell

Steam Electric Station. A time independent analysis of variance was performed on the 1976 leaf elemental concentrations to isolate those elements which were statistically different among the four sites. These isolated elements were only poorly correlated to the concentrations of the corresponding nutrients in the sediment, and the variances seemed to be a result of luxury consumption. In order to explain the similar elemental concentrations at the four sampling sites, a model was derived based on the presumption of a constant rate of absorption of the elements per unit weight. Theoretically, the model could describe the types of seasonal trends observed for many of the elements, but using actual data, good fits were obtained only after the aerial leaf stage had been reached. It was thought that the poor fits prior to this phenological stage could be due to either sampling error, differences in phenological development within each station, or absorption by the leaves as well as the roots.

The major commercial stands in the study region were examined in terms of their geographical distribution and ecological relationships. The northern limit of the rice stands was at approximately 150 growing-days. Frequency distributions were determined for seed length, number of seeds per head, density of wild rice heads per m^2, and the weight per wild rice plant. Seed lengths tended to be shorter in the more southern latitudes. Frequency distributions and cluster analysis relationships were determined for the water chemical variables, pH, iron, sulfate, conductivity, total alkalinity, magnesium, calcium and potassium; and the sediment chemical variables, pH, loss on ignition, conductivity, calcium, magnesium, phosphorus, potassium, nitrogen, iron, zinc and manganese. The frequency distributions of the leaf concentrations of iron, manganese, zinc, calcium, magnesium, and phosphorus were determined. Only poor correlations were found between the concentrations of elements in the leaf tissue and the concentrations of the corresponding element in the sediments.

Discriminant analysis was used to categorize lakes planted with wild rice in northwestern Ontario in terms of their potential to produce commercial crops. Variables included in the discriminant functions were pH and dissolved iron in the water, extinction of photosynthetically active light in the water, available calcium, zinc, and phosphorus in the sediments, and the suitability of the sediment for root anchorage. In terms of individual plant performance, photosynthetically active light was negatively correlated with head weight ratio. The role of the other variables seemed to involve deficiencies of micronutrients primarily through the formation of ferric hydroxide complexes.

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INTRODUCTION

The largest natural stands of wild rice, *Zizania aquatica* L., in North America are found in northwestern Ontario, northeastern Minnesota and eastern Manitoba. The harvest from these stands has long played an important role in this region. For hundreds of years it provided a needed source of nourishment to the native people of the region (McAndrews, 1969) and early European settlers to the area are known to have traded with the Indians for supplies of wild rice (Jenks, 1901).

Today, wild rice in these natural stands is important for its economic stimulus. In good crop years, total harvests reach as high as 4 million pounds (unprocessed) which, at 1978 prices of $2.00 per pound, inject approximately 8 million dollars into the local economy at the primary level alone. The corresponding retail value of the crop is upwards of 15 million dollars. These figures seem impressive. However, the importance of these natural stands, to the Canadian wild rice industry, is diminishing slowly as a result of the increasing development of wild rice paddy culture in Minnesota.

Paddy culture was introduced into Minnesota in the late 1960's. Primarily due to the admirable three-way communication link which existed among the American wild rice industry, the state and federal governments, and the academic community, a multi-million dollar industry has been built. Long term research requirements were early identified and the development of shatter-resistant wild rice, and control practices for diseases and insects have allowed paddy growers to achieve significant, sustainable yields. Harvests from the paddies are now in the neighbourhood of 5 million pounds annually, and although this figure changes somewhat from year to year, it does not exhibit the severe fluctuations in yields that are characteristic of the natural stands.

The impact of paddy culture on the Canadian wild rice industry has been rather severe. The American companies are now able to assure themselves of a steady supply and thus have a distinct advantage in marketing the finished product. In the past two years their efforts have been directed towards crushing the Canadian wild rice industry by paying exorbitant prices for any natural stand production, thereby cutting off the Canadian industries only supply source. It is therefore evident that if the natural stands of wild rice are to be a viable component of the Canadian wild rice industry, then management practices must be found which will allow the industry to achieve sustainable and profitable yields.

Unfortunately, the management of freshwater wetlands is still only a "state of the art" technique based on our present knowledge of these systems which is lacking in such areas as productivity, decomposition, hydrology and nutrient cycling (Wetzel, 1978). Furthermore, in managing any wetlands, consideration should be given as to how any single management technique may affect the total wetland environment (Stearn, 1978). Therefore, in terms of studying wild rice in natural waters, the approach should be an "holistic" one, which examines the interactions of all biological, chemical and physical factors affecting the growth of the plant.

The basic objective was to try and gain a better understanding of how wild rice relates to its immediate environment with the ultimate view of applying this knowledge to increasing the production of the natural stands of wild rice in Canada. It was decided to approach this overall objective by dividing the examination of interacting factors influencing the growth of wild rice into two major parts with each part in itself being subdivided once.

Firstly, the growth of wild rice was studied in detail at a site with potential extremes in growing conditions, namely a thermal power generating station. The problem of seasonal changes in environmental factors at five sampling stations near the power station was corrected for, and, using discriminant analysis - an among groups multivariate technique - the factors were isolated and used to model the growth of wild rice.

A specific problem of plant-environmental interactions was not being able to correlate the concentration of an element in plant tissue with the corresponding element in the sediment or soil. This problem arose directly out of the first study and the two hypotheses of Klopatek (1978) were assessed for their potential to explain this phenomenon. In the case of wild rice, the second hypothesis, namely that concentration of elements in plant tissue were independent of the concentrations of the same elements in the sediment or soil, appeared to offer the most likely explanation. A theoretical model was derived to offer support for the second hypothesis.

The second part of the objective examined the regional distribution of factors which influence the growth of wild rice. Specifically the biological, chemical and physical components of the environment of wild rice were investigated throughout northwestern Ontario and northeastern Minnesota in order to gain some measure of environmental ranges within existing commercial stands of wild rice.

Finally, the growth performance of wild rice plantings in various lakes, previously without wild rice, was studied with a view to deriving recommendations for the management of this resource. Based upon plant density, each lake planted with wild rice was categorized into one of three groups. Discriminant analysis was used to isolate those biological, chemical and physical factors which varied among the three groups and these isolated factors were assessed for their possible effect on the growth of wild rice.

CHAPTER 1

A STUDY OF AMONG SITE VARIANCE IN THE GROWTH OF WILD RICE, *Zizania aquatica* L., NEAR A THERMAL POWER GENERATING STATION AT COHASSET, MINNESOTA

INTRODUCTION

The growth of plants is a function of the biological, chemical and physical properties of the surrounding environment. Biological factors which may affect the growth of aquatic macrophytes are disease (Klotzli, 1970), grazing (Wetzel, 1975) and inter- and intraspecific plant competition (Hutchinson, 1975). According to the literature both disease and grazing are negligible in terms of affecting aquatic plant production. The spatial distributions of the individual species are generally attributed to the physiological requirements of the species but examples of direct plant competition have been documented between *Glyceria* spp and *Phragmites communis* (Buttery *et al*, 1965), and *Chara* spp and various rooted angiosperms (Wohlschlag, 1950). Kadlec and Wentz (1974) listed the aquatic perennials, *Eichornia crassipes*, *Trapa natans*, *Phragmites communis*, *Typha latifolia* and *Hibiscus* spp, as problem species adapted for rapid dispersal and increased competitive ability. Intraspecific competition, causing the dry weights of individual plants to decrease as plant density increases, is well known for crop plants (Milthorpe and Moorby, 1974) but has been seldom studied in aquatic macrophytes. Bernatowicz and Pieczynska (1965) observed a negative relationship between plant density and the weights of stems of *Phragmites communis*. Lind and Cottam (1969) found *Myriophyllum exalbescens* to weigh less in sampling plots with greater density.

The varying concentrations of chemical factors can influence the growth and production of macrophytes. Misra (1938), recorded that the growth of *Potamogeton perfoliatus* was dependent upon the sediment type in which it grew. Similar variations of growth rates with different sediment types were observed for *Lobelia dortmanna* and *Ruppia mortima* (Moyle, 1945), *Phragmites communis* (Pearsall and Gorham, 1956), *Myriophyllum exalbescens* (Mulligan and Barnowski, 1969), *Ceratophyllum demersum* (Denny, 1972) and *Potamogeton pectinatus* (Kollman and Wali, 1976). Some studies related the distribution and production of aquatic plants to water chemistry (Moyle, 1945; Casey and Downing, 1976), although it appeared that many aquatic plants obtain their nutrients from both water and sediment (Bristow and Whitcombe, 1971; Denny, 1972).

Physical factors known to affect the growth of aquatic macrophytes are water depths, currents, and waves (Sculthorpe, 1967; Hynes, 1972), light (Pearsall and Hewitt, 1933; Sculthorpe, 1967; Spence and Chrystal, 1970), and temperature (Sculthorpe, 1967).

In general, the majority of the above studies concentrated on only one aspect of the environment which affected the growth performance of the particular macrophyte being examined. This approach is quite simplified since in a complex natural system no one factor acts independently of other factors. An increasing number of studies are now being done, which, through the use of multivariate statistics, quantify the wetland habitat by examining a large number of environmental factors simultaneously (Walker and Coupland, 1970;

Walker and Wehrhahn, 1971; Auclair *et al*, 1976; Johnson, 1977). The multivariate approach has provided a useful, more realistic interpretation of within and among group spatial variations of the natural environment. Unfortunately many environmental factors also exhibit seasonal as well as spatial variations, which, simply as a result of changes due to time, cause the variances of these factors to become so large that multivariate methods can no longer be applied with any degree of accuracy.

During 1976 and 1977, the growth of wild rice, *Zizania aquatica* L., was quantified according to the statistical differences in the biological, chemical and physical factors at different sampling locations near a thermal power generating station. Such power plants provide ideal settings for studies of among group variations since they generally produce distinct differences in the natural environment within a relatively small area and thus allow sampling to be completed during the same time frame. The objectives of this study were; (i) to identify any seasonal trends and statistical intercorrelations of the variables thought to influence the growth of wild rice at different sampling stations, (ii) to devise a technique which would remove any seasonal time-dependency trends in the variables so that discriminant analysis, a multivariate among groups statistical technique, could be used to isolate those variables which differed among the sampling stations; and (iii) to derive a mathematical model, which included these isolated variables, for the seasonal growth of wild rice at the sampling stations.

STUDY AREA

The Clay Boswell Steam Electric Station (CBSES) is situated in the Mississippi River - Pokegama Reservoir system (Fig. 1-1), at Cohasset, Minnesota ($47^{O}14'$N, $93^{O}40'$W). The power station withdraws water for cooling and dilution purposes from the northern extension of Blackwater Lake at an elevation of 383.2 m ASL. The thermally enriched cooling water is discharged into a canal 443 m long by 15 m wide which enters an embayment area where mixing with a cooler downstream Mississippi River water occurs. The water temperatures in the discharge canal are consistently above the ambient water temperatures of the upstream river intake.

The Pokegama Dam, 8.9 km downstream from CBSES, controls the flow rate (2.5 - 79.5 m^3/sec) and water levels of this section of the river. Summer depths range from 1.8 - 6.0 m; open channel widths from 24.4 - 36.0 m; and there is just a slight elevation gradient over the 38.6 km distance of the reservoir system influenced by the Pokegama Dam.

The meteorological data of the study area was condensed from the Envirosphere (1975) impact study of CBSES. Only the mean monthly data pertinent to wild rice growth have been abstracted as follows:

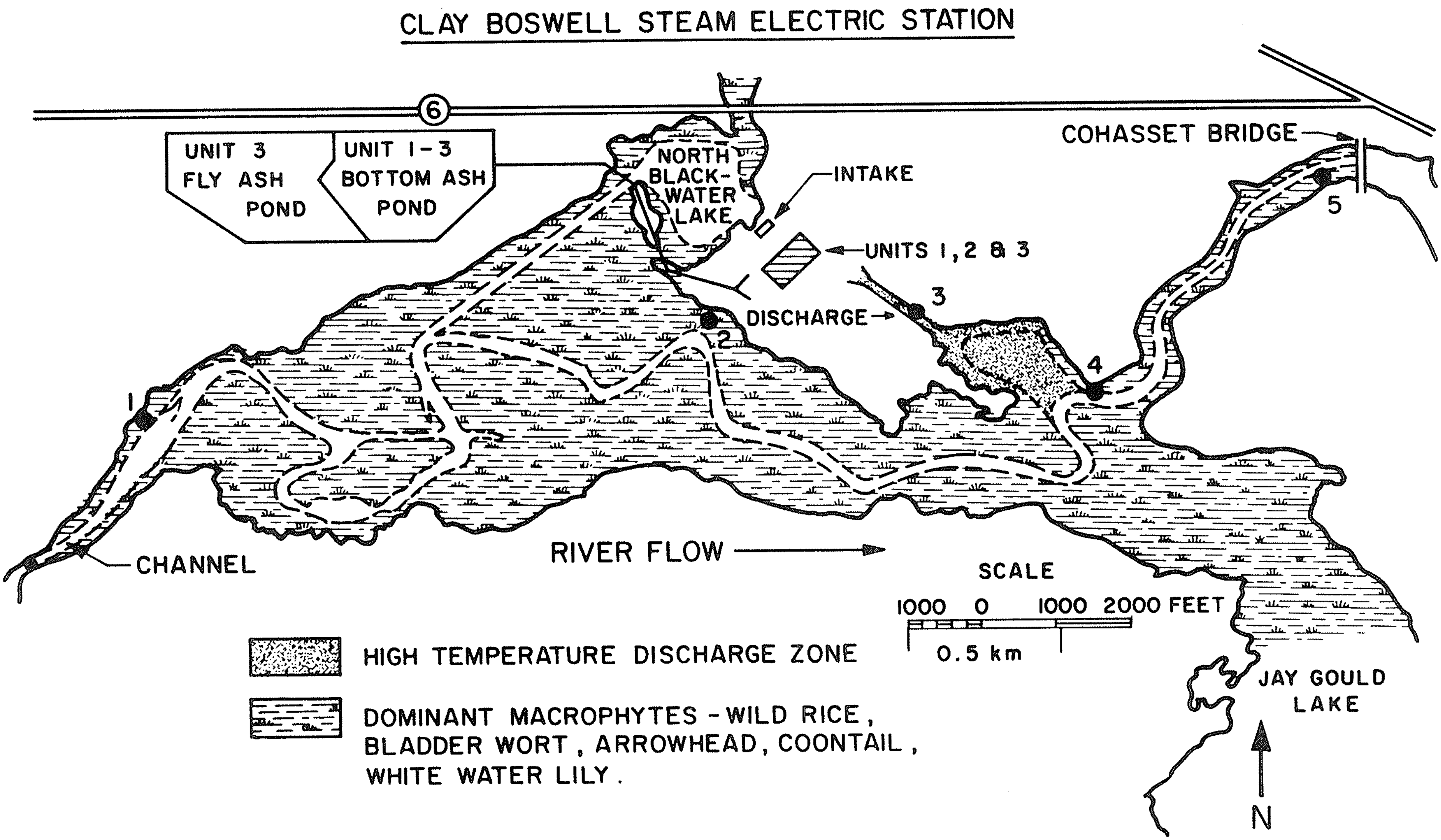


Fig.1-1. LOCATIONS OF WILD RICE SAMPLING STATIONS IN THE MISSISSIPPI RIVER DURING 1976-1977.

	April	May	June	July	August	September
Sunshine %	56	58	59	63	63	53
Air Temperature °C	3.5	10.8	15.6	18.6	17.0	12.1
Precipitation cm	4.7	7.4	9.7	9.8	9.0	7.0
Relative Humidity %	65	61	67	71	71	77
Prevailing Wind	NW	NW	SE	W	SE	SE
Wind Speed km/hr	17.0	16.3	14.0	12.9	12.6	14.3
Days of Thunderstorms	3	4	8	10	8	3

Peterson (1962) carried out a biological survey of the upper Mississippi River including the area surrounding CBSES. He identified 29 species of aquatic plants and postulated two distinct plant associations: (a) plants of the reservoir lakes and, (b) plants of the edges of the channels. Examples of such species common to both associations were *Zizania aquatica*, *Vallisneria americana*, *Nuphar variegatum* and *Potamogeton natans*.

METHODS

Sampling Stations

Five sampling stations were selected near CBSES for detailed study (Fig. 1-1). Each station contained an established stand of wild rice. The location of each sampling site was selected such that the production of wild rice could be examined in relation to any possible effects from the power plant.

Station 1 was chosen 2 km upstream from CBSES and thus represented the control site (Fig. 1-1). Water depths in the main channel were between 3 to 5 m. The area on both sides of the main channel was blanketed by dense stands of wild rice which grew in water depths ranging from 0.2 to 1.5 m. Station 1 was centered in a 3 hectare stand on the north side of the main channel. The sediment was an organically enriched silt covered by a thick layer of detritus.

Station 2 was located 50 m north of the main channel and 5 m from shore in the area just south of the main coal storage area of CBSES (Fig. 1-1). This station possessed little decaying vegetation on the sediment, perhaps a reflection of the scouring action of spring floods at the bend of the river. Water depths varied from 0.3 to 1.7 m.

Station 3 was the effluent discharge canal from the power plant to the Mississippi River (Fig. 1-1). This station was not part of the natural rice beds and had such differences from the other sampling stations that it was treated only as a monitoring site. These differences included higher water temperatures throughout the year (3° to 12°C in winter and 2° to 11°C in the summer above ambient), greater depth (up to 2.2 m), considerable current (up to 50 cm/sec), dense plant competition from *Potamogeton illinoensis* and *Typha latifolia*, and low rice density.

Station 4 was situated in the area of intermixing of the discharge canal and the Mississippi River (Fig. 1-1).

Wild rice beds extended up to 10 m from the shore on both sides and up to depths of 2.5 m.

Station 5 was located just north of the Cohasset bridge approximately 800 meters downstream from CBSES (Fig. 1-1). The thermal enrichment of this station was on the average slightly above the control site but depended to a large extent on river flow and season. Wild rice occurred on both sides of the channel with the largest beds on the south side, extending up to 30 m from the shore and up to a depth of 1.5 m.

Sampling Program

During 1976 and 1977, sampling took place at two week intervals from mid-April (105 year days from January 1) to early September (244 year days). This amounted to a total of eleven sampling periods in 1976 and ten in 1977. With the exception of site 3, this sampling period covered all the phenological stages of wild rice. Table 1-1 lists all factors examined at each sampling station during each sampling period.

TABLE 1-1. Biological, chemical, and physical factors examined for their effect on wild rice productivity at five sampling sites near CBSES during 1976 and 1977.

Biological Factors:	Intraspecific competition: density, $\bar{x}$ dry weight per plant, total biomass. Interspecific competition: total biomass of other species.
Chemical Factors:	Water Chemistry: pH, conductivity, total alkalinity, chloride, total phosphorus, sulfate, total hardness, calcium hardness*, dissolved calcium, dissolved magnesium, dissolved sodium, dissolved iron, dissolved oxygen. Sediment Chemistry: pH, conductivity, available nitrogen, phosphorus, potassium, sulfur, iron*, manganese*, zinc*, copper*, calcium* and magnesium*.
Physical Factors:	Accumulated water temperature, water depth.

*only determined during 1977

Field Procedures

In 1976, the size and number of quadrats used in estimating macrophyte production were determined according to the Braun-Blanquet concept of minimal area in homogenous stands (Kershaw, 1964). This resulted in a quadrat size of 1 m^2 and a quadrat number of 3 per site with the exception of site 3.

Quadrats were selected randomly each sampling period and all macrophytes removed. The rice plants were separated from the other macrophytes and both were then dried in a drying oven at 105°C until a constant weight was reached. Weight per wild rice plant was computed as the average of all rice plants.

In 1977 sampling was done by transects (Poole, 1974) since it enabled quadrats to be harvested across the entire station thus accounting for within site depth variance. The starting positions of 10 transects were marked on the shore of each sampling site at 10 m intervals. Each sampling period, a starting position was randomly selected without replacement and a marked floating rope was stretched from the starting position on the shore to the deep edge of the rice bed. The length of the transect varied for each station and was designed to accommodate the total width of the rice area. Six, 0.25 m^2 quadrats were then harvested at regular intervals along the transect.

In 1976 and 1977, replicate water samples were collected in 2 litre translucent polyethylene screw cap bottles from the middle of the water column of the five stations during each sampling period. The bottles were then refrigerated and transported to the laboratory for analysis. Replicate on-site measurements were made for conductivity using a portable YSI model 33 S-C-T meter and for pH using a Fisher model 150 meter.

During both sampling seasons, sediment samples were collected every sampling date from each station with an Ekman dredge (15 x 15 x 27 cm). This removed the upper 20 cm of sediment which was the main rooting depth for the wild rice plants. The sediment was poured into four-ply plastic bags and sealed tightly to minimize air space. The samples were stored in an ice cooler and transported back to the laboratory for analysis. In order to examine the spatial distribution of the sediment nutrients within each site, 15 replicate sediment samples were also collected in 1977 at stations 1, 2, 4 and 5. At each of these stations three transects were made from the shore to the edge of the river channel and the sediment samples collected at regularly spaced intervals along these transects.

Water depth was measured in the centre of each quadrat. Dissolved oxygen and temperature determinations were made in the middle of the water column in each sampling quadrat using a YSI model 54a meter.

Laboratory Procedures

Water samples collected during 1976 and 1977 were analyzed by Earl Ruble and Associates in Duluth, Minnesota according to APHA standard methods, (1971).

Total alkalinity (as $CaCO_3$) was determined by titration with sulfuric acid using phenolphthalein and methyl orange as indicators. Chloride was determined by titration with silver nitrate using potassium chromate as an indicator. For determinations of total phosphorus, the samples were initially digested following the persulfate digestion procedure and then measured turbidimetrically according to the stannous chloride procedure. Sulfate was measured turbidimetrically according to the barium chloride method. Total hardness and calcium hardness were determined titrimetrically following the EDTA method. For measurements of dissolved calcium, dissolved magnesium, dissolved sodium, and dissolved iron, the samples were initially filtered and then determined according to the atomic absorption spectrophotometric method.

In 1976 and 1977 the sediment samples were analyzed for conductivity, pH, and available nitrogen, available phosphorus, available potassium and available sulfur (1976 only) by the Soil Testing Laboratory of the Manitoba Department of Agriculture. In addition, available sulfur was measured turbidimetrically (Chesnin & Yien, 1950) from the bi-weekly sediment samples during 1977 taken along transects at sites 1, 2, 4 and 5. In 1977, extracts were made a) with 0.1 N HCl for the analysis of iron, magnesium, and zinc (Jackson, 1958), and b) with ammonium acetate solution for the analysis of calcium and magnesium (Chapman and Pratt, 1961). The concentration of these elements were measured by a Perkin-Elmer atomic absorption spectrophotometer, model 403.

Data Analysis

The data analysis proceeded in three stages:

(i) an initial cluster analysis of the chemical variables was performed in order to illustrate the intercorrelations and seasonal trends which existed among the variables;

(ii) all variables, after being corrected for time dependency, were subjected to discriminant analysis, in order to isolate those variables which could best separate the four sampling stations; and

(iii) a predictive mathematical model for wild rice growth in each of the four stations was derived from the time-independent variables identified as being statistically significant in the discriminant analysis procedure, and a time-dependent relationship between the mean weight per wild rice plant of the four stations and time.

(i) Cluster Analysis Procedure

The cluster analysis program used was an agglomerative procedure outlined by Dixon (1977) and which is contained in the BMDP (Biomed) statistical library and implemented on the IBM 370/158 at the University of Manitoba. Separate analyses were done for both the water and sediment chemical relationships. Oxygen in the water was not included in the cluster analysis procedure since the presence of oxygen influences all chemical reactions (Wetzel, 1975) but the cluster analysis procedure allows each element to be joined with only one other cluster. Interpretation of a cluster analysis including oxygen would therefore be misleading. Prior to the actual analysis, the chemical parameters were transformed logarithmically since it is thought that such chemical data is more interpretable in this form (Green, 1971).

The computer program formed groupings of variables using an index of association, derived from the correlations of the variables with each other, as the linkage criterion. Initially each element was considered a cluster. Then progressively larger groups or "clusters" of elements were added using the arithmetic average of the correlations of all possible pairings of the variables in the cluster being combined:

$$\Sigma\Sigma\ S_{ij} \setminus (IxJ)$$

where:

S_{ij} = correlation between variable i in the first cluster and variable j in the second cluster

I = number of variables in the first cluster

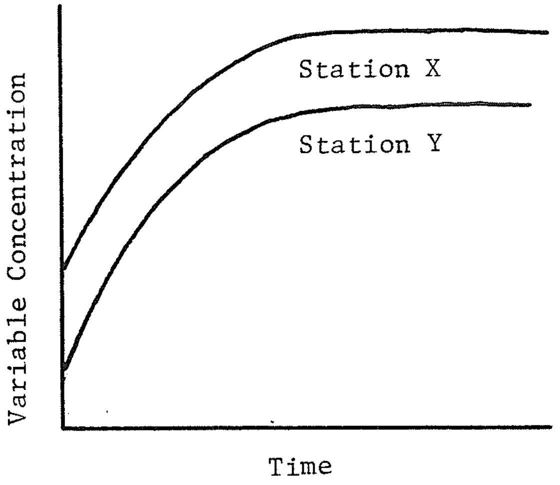
J = number of variables in the second cluster

The index of association was then evenly scaled such that values of -1 to +1 from this relationship would correspond to index of association values of 0 and 1 respectively.

The end result of this procedure was the formation of dendrograms which indicated those elements that were most highly correlated to one another. The interpretation of these dendrograms is somewhat subjective since there is no test of statistical significance which can be used to objectively separate the clusters. In this analysis, an index of similarity value of approximately 0.7 was used as the separating point. This implies that each element in a cluster had a correlation coefficient (r value) of at least 0.4, which for sample sizes considered in this study, is significant at the $P < 0.05$ level.

(ii) Discriminant Analysis Procedure

Before undertaking the discriminant analysis, initial pretreatment of the data was necessary. The major problem with much of the data was that concentrations of many of the elements changed with time even though the concentrations at each station relative to one another remained the same. The problem is visually illustrated below:



Of the two stations in the figure, Station X always has a higher concentration of the measured element at any single point in time. However, if a sample was taken from either station, without regard to time, it would not be possible to determine, with any accuracy, which station the sample was from. What is important then, is not the actual concentration at either station, but rather the concentration at one station relative to that at another.

Therefore, in order to remove the time dependency from the variables measured in this study, and to allow the relative concentrations of the four stations to still remain in effect, the data were treated as below:

(i) the mean value for each variable over all four sampling stations was calculated for every sampling period; and

(ii) for every sampling period, the value for each variable at each sampling station was transformed into a percentage of this mean value.

All biological, chemical and physical data were treated in this manner except for water temperature. In this case, accumulated water temperatures (in celsius degree - days) were first calculated for each station during each sampling period since it seems the effect of temperature on plant growth can best be expressed by an accumulative approach rather than a single reading (Wang, 1960). The accumulated water temperature values were then calculated as a percentage of the mean values as above.

The discriminant analysis procedure used was a stepwise computer program from Dixon (1977) contained in the BMDP (Biomed) statistical library as implemented on the IBM 370/158 at the University of Manitoba. The statistical assumptions for the valid use of discriminant analysis for such data are described by Green (1971).

(iii) Predictive Growth Model

Separate calculations for the growth model proceeded in the same manner described below for both 1976 and 1977.

The time independent portion of the growth model for each plant at the four main sampling stations was corrected for any time-dependency using the same method as was previously described for the biological, chemical, and physical variables. This resulted in each station mean for every sampling period being expressed as a percentage of the overall mean of the four stations at that time. For example, during the third sampling period of 1976 (16 days after germination, t = 3), the mean values of the weight per wild rice plant at stations 1, 2, 4 and 5 were 0.010 g, 0.012 g, 0.026 g, and 0.014 g respectively. The overall mean of the four stations at that time ($\overline{X}$ stn 1,2,4,5), would be 0.016 g. Using this overall mean, the time corrected value for the mean at station 1 ($\overline{X}$ stn 1), expressed in percent would be:

$$\frac{\overline{X} \text{ stn } 1}{\overline{X} \text{ stn } 1,2,4,5} \times 100\,\% \quad = \frac{.010}{.016} \times 100\,\% \quad = \quad 62.5\,\%$$

These time corrected values of percent mean weights per wild rice plant, calculated as above for each station at each sampling time, were plotted against the time corrected values of each variable isolated in the discriminant analysis. Appropriate transformations were made to produce linear relationships which were determined as the natural logarithm of the percent mean weights per wild rice plant. A multiple regression analysis was then performed using the procedure outlined by Dixon (1977) contained in the BMDP (Biomed) statistical library and implemented on the IBM 370/158 at the University of Manitoba, with the time-corrected values of percent mean weights per wild rice plant as the dependent variable.

The time-dependent portion of the model for each year was derived by iterative fitting of a logistic growth equation until the best (least sum of squares) fit was obtained for the overall mean weight per wild rice plant ($\bar{X}$ stn 1,2,4,5) for each sampling period versus time in days from germination. A similar procedure is outlined by Watt (1968).

The net result of the above procedures was the formation of two equations describing the time-independent relationship of the mean weights per wild rice plant at the four stations, and the time-dependent relationship of the overall mean weights per wild rice plant:

Time independent equation

$$\ell_n \left[\frac{\bar{X} \text{ stn 1 or 2 or 4 or 5}}{\bar{X} \text{ stn 1,2,4,5}} \times 100\% \right] = B_0 + B_1 a_1 + B_2 a_2 + \ldots B_n a_n + \Sigma_i$$

where:

$\bar{x}$ = mean weight per wild rice plant

i = sampling period

a_j (j=1...n) = time independent values of variables isolated as being significant in the discriminant analysis

B_j (j = 1...n) = regression coefficient for the contribution of variable a_j

B_0 = constant

E_i = error term (assumed independent and normally distributed with mean 0).

Time dependent equation: $$\bar{X} \text{ stn 1,2,4,5} = \frac{K}{1 + e^{c-rt}} \qquad [1.2]$$

where:

K = maximum attainable overall mean weight ($\bar{X}$ stn 1,2,4,5) per wild rice plant

c = constant

r = maximal attainable rate of biomass increase (g/day)

t = time in days from germination

For each sampling period at each sampling station, the predicted percentage of the overall mean weight per wild rice plant was calculated from equation 1.1. For each corresponding sampling period, the predicted overall mean weight per wild rice plant was also calculated from equation 1.2. The final predicted weight per wild rice plant for each of the sampling stations, for each sampling period during 1976 and 1977, was then calculated as the product of the two equations. For example, the predicted value of equation 1.1 for station 1 for the third sampling period during 1976 was $e^{4.0281} = 56.15\%$. The predicted value for the overall mean weight per wild rice plant at this time from equation 1.2 was 0.018 g. Therefore the predicted weight per wild rice plant at station 1 during this sampling period was 0.562 x 0.018 g = 0.010 g. This procedure was then repeated for the remaining sampling periods during 1976 and 1977 for stations 1, 2, 4 and 5.

RESULTS AND DISCUSSION

Biological Factors

Intraspecific Competition

During both sampling seasons, total wild rice biomass (g/m^2) followed a typical sigmoid growth curve (Fig. 1-2). Production was initially slow, then increased to a maximum after approximately 80 days, and decreased through the rest of the summer. Similar growth patterns were evidenced for wild rice in Lake Erie, Ontario (Thomas and Stewart, 1969) and in the Delaware River, New Jersey (Whigham and Simpson, 1977). Highest production was at Site 5 in 1976 (628 g/m^2) and Site 4 in 1977 (597 g/m^2). Biomass production for all four sites in 1977 ranged from 232 to 597 g/m^2 in contrast to 1976 when the range was somewhat higher (375 to 628 g/m^2). Such differences are common in natural stands and are probably a result of the unpredictability of such factors as seed dispersion, germination and spring flood conditions. All production values were within the range found by other investigators for Minnesota rice production (Rogosin, 1958; Bray *et al*, 1959), but far below production values for wild rice (2091 g/m^2) in New Jersey (McCormick, 1977).

In terms of weight per plant (Fig. 1-3), highest production in both seasons occurred at Site 4. When compared to the 1976 individual plant weights, all stations had lower production in 1977. The most noticeable factor which may

Figure 1-2

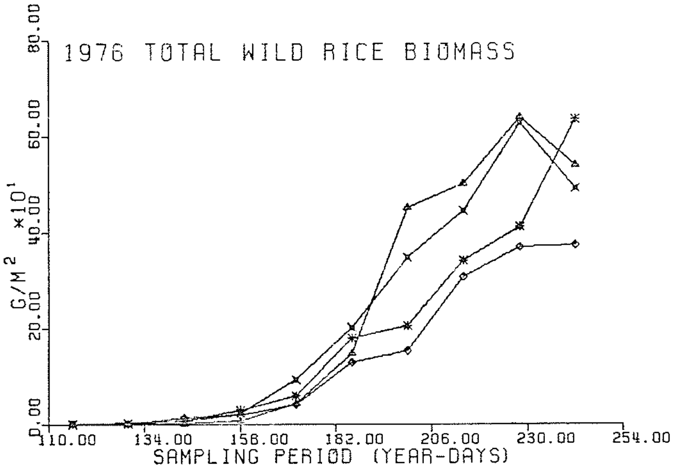
Total wild rice biomass (g/m^2) for the four stations sampled in the Mississippi River near CBSES during 1976 and 1977.

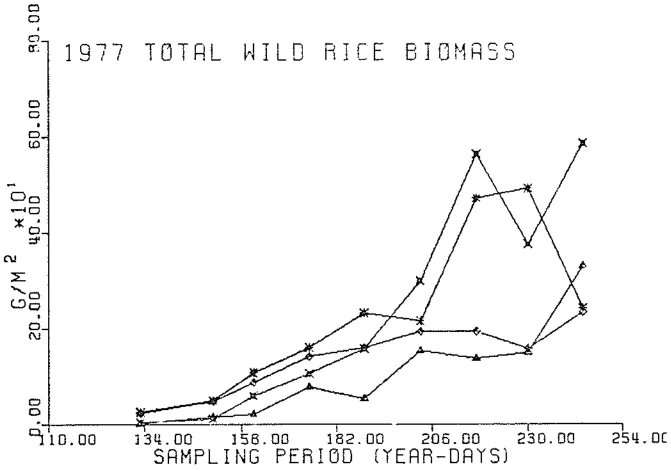
Site 1 △ Site 2 ◇ Site 4 ⌧ Site 5 ✳

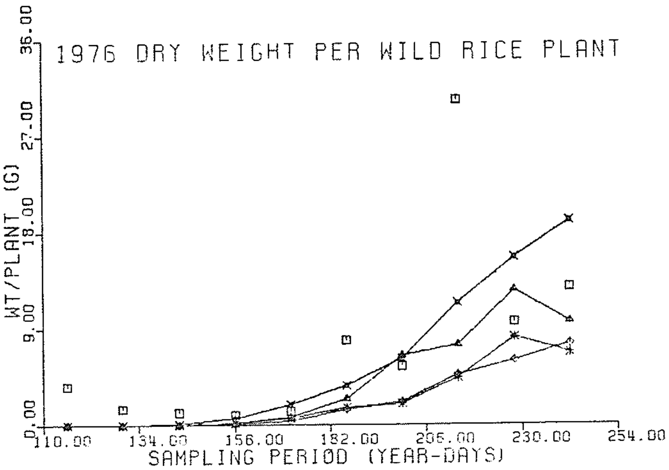
Figure 1-3

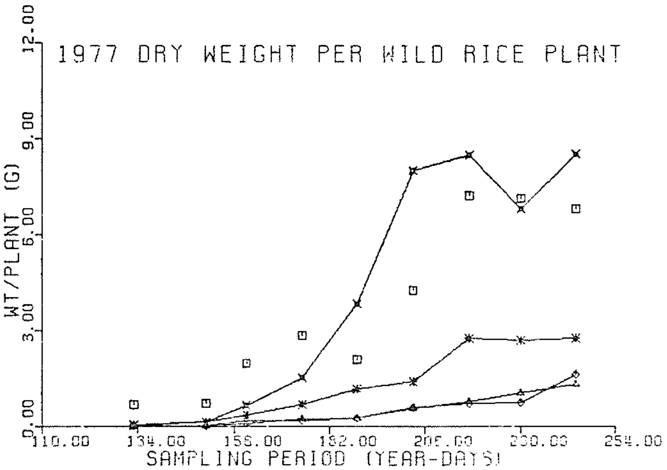
Dry weight (g) per wild rice plant for the five stations sampled in the Mississippi River near CBSES during 1976 and 1977.

Site 1 △ Site 2 ◇ Site 3 □ Site 4 ⌧ Site 5 ✳


1976 TOTAL WILD RICE BIOMASS
G/M² ×10¹
0.00
20.00
40.00
60.00
80.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


1977 TOTAL WILD RICE BIOMASS
G/M² ×10¹
0.00
20.00
40.00
60.00
80.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


1976 DRY WEIGHT PER WILD RICE PLANT
WT/PLANT (G)
0.00
9.00
18.00
27.00
36.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


1977 DRY WEIGHT PER WILD RICE PLANT
WT/PLANT (G)
0.00
3.00
6.00
9.00
12.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)

have lowered the weights in 1977 was the much higher density of wild rice plants per m^2. The use of the different sampling techniques between the two years may have also affected the weights. Transects, as used in 1977, probably give a better estimate of average weight per plant for those sites where there was considerable variance in the water depths which is known to affect wild rice production (Thomas and Stewart, 1969). These depth variances were particularly evident at Station 2 in 1976 (Fig. 1-12) and the use of simple random sampling may have at times given a biased estimate of plant weights (to the extent that depth affects wild rice production) if the use of random sampling placed all the sampling quadrats at approximately the same depth. This was also found to be the case for submerged macrophytes by Love and Robinson (1977).

Wild rice density (Fig. 1-4), after an initial increase due to germination, declined throughout the growing season during both years. Greatest mortality at all sites seemed to occur during the submerged leaf stage when the rice plants were physically uprooted by wave action. Large numbers of the uprooted seedlings could be seen lodged against the banks at this time. A second period of density decline seemed to be the transition phase from the floating leaf stage to the aerial stage. Those plants which were able to make the transition first seemed to be favoured for survival. Competition for light is a suspected cause of this apparent selection.

Figure 1-4

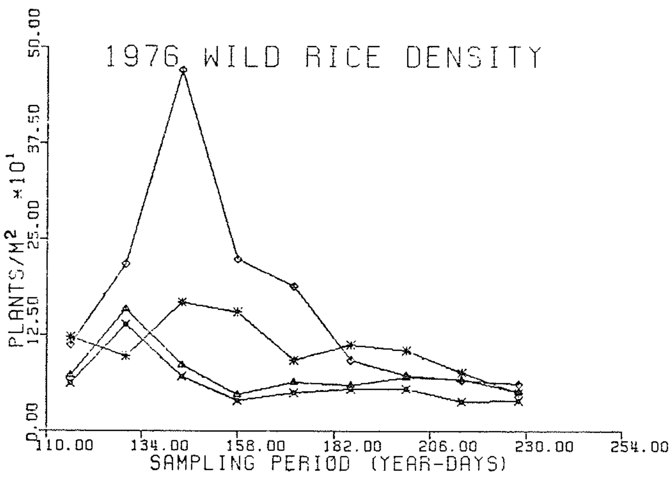
Wild rice density (plants/m^2) for the four stations sampled in the Mississippi River near CBSES during 1976 and 1977.

Site 1 △ Site 2 ◇ Site 4 ⊠ Site 5 ✳

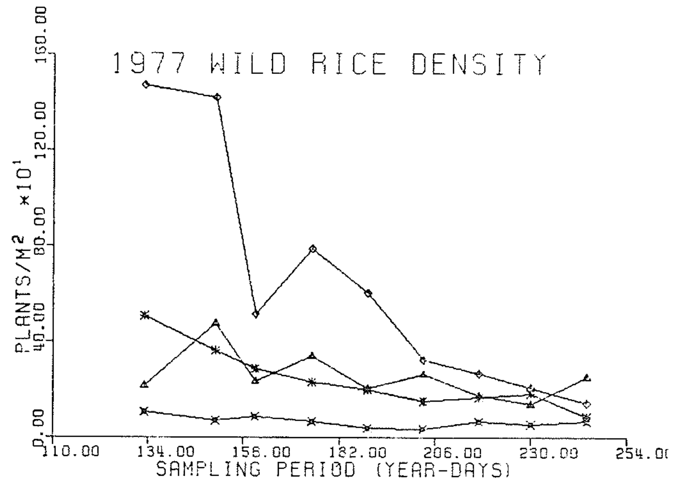
Figure 1-5

Plant competition (g/m^2) for the four stations sampled in the Mississippi River near CBSES during 1976 and 1977.

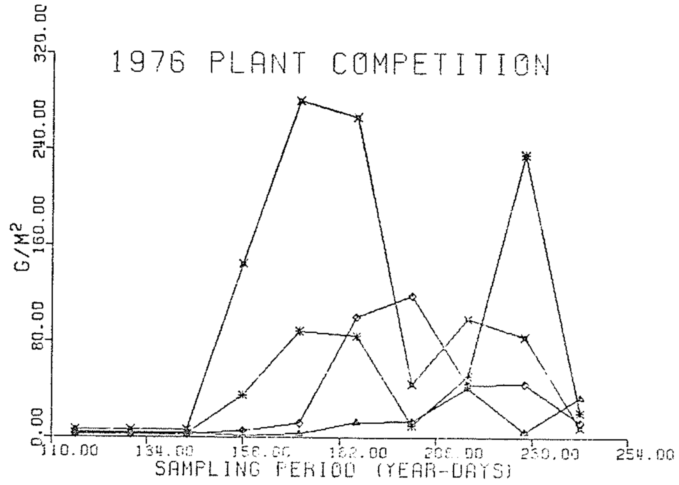
Site 1 △ Site 2 ◇ Site 4 ⊠ Site 5 ✳



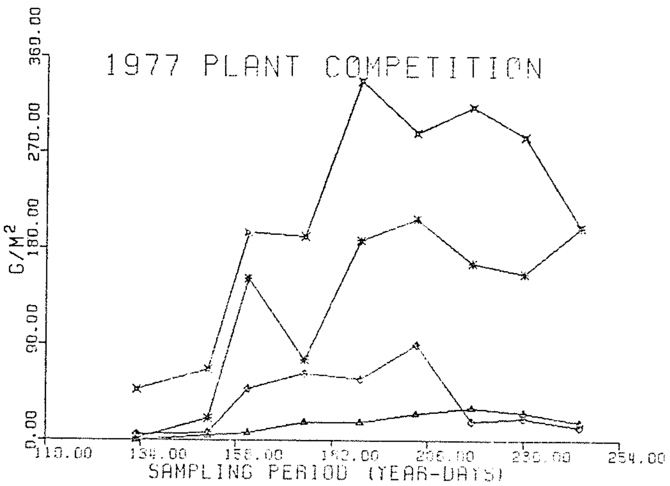
1976 WILD RICE DENSITY



1977 WILD RICE DENSITY



1976 PLANT COMPETITION



1977 PLANT COMPETITION

Interspecific Competition

Plant competition defined as the production (g/m^2) of associated aquatic macrophytes, seemed to follow irregular patterns for total seasonal production (Fig. 1-5) but could be explained by examining the production increases of the individual species. At stations 1 and 2, *Potamogeton zosteriformis* accounted for most of the seasonal behavior of plant competition during both seasons. At stations 4 and 5, bimodal peaks in plant production of other aquatics occurred during 1976 and 1977. The first production increase was attributed mainly to *Megaladonta beckii*, *Potamogeton zosteriformis*, *Ceratophyllum demersum*, *Elodea canadensis*, and *Myriophyllum* spp. The second increase was almost exclusively due to increases in production of *Sagittaria rigida*.

Chemical Factors

Water Chemistry

Figure 1-6a, Figure 1-7a contain the results for cluster analysis of the chemical variables in the water for 1976 and 1977.

In 1976, there were five clusters of variables:

Group 1 - pH, dissolved sodium

Group 2 - calcium hardness, total hardness, alkalinity, dissolved magnesium

Group 3 - chloride, sulfate, conductivity

Group 4 - total phosphorus

Group 5 - dissolved iron

Figure 1-6

a. Cluster analysis of water chemical relationships for stations 1, 2, 4 & 5, in the Mississippi River near CBSES in 1976.

b. pH values as an example of group 1 in the cluster analysis (Fig. 1-6a).

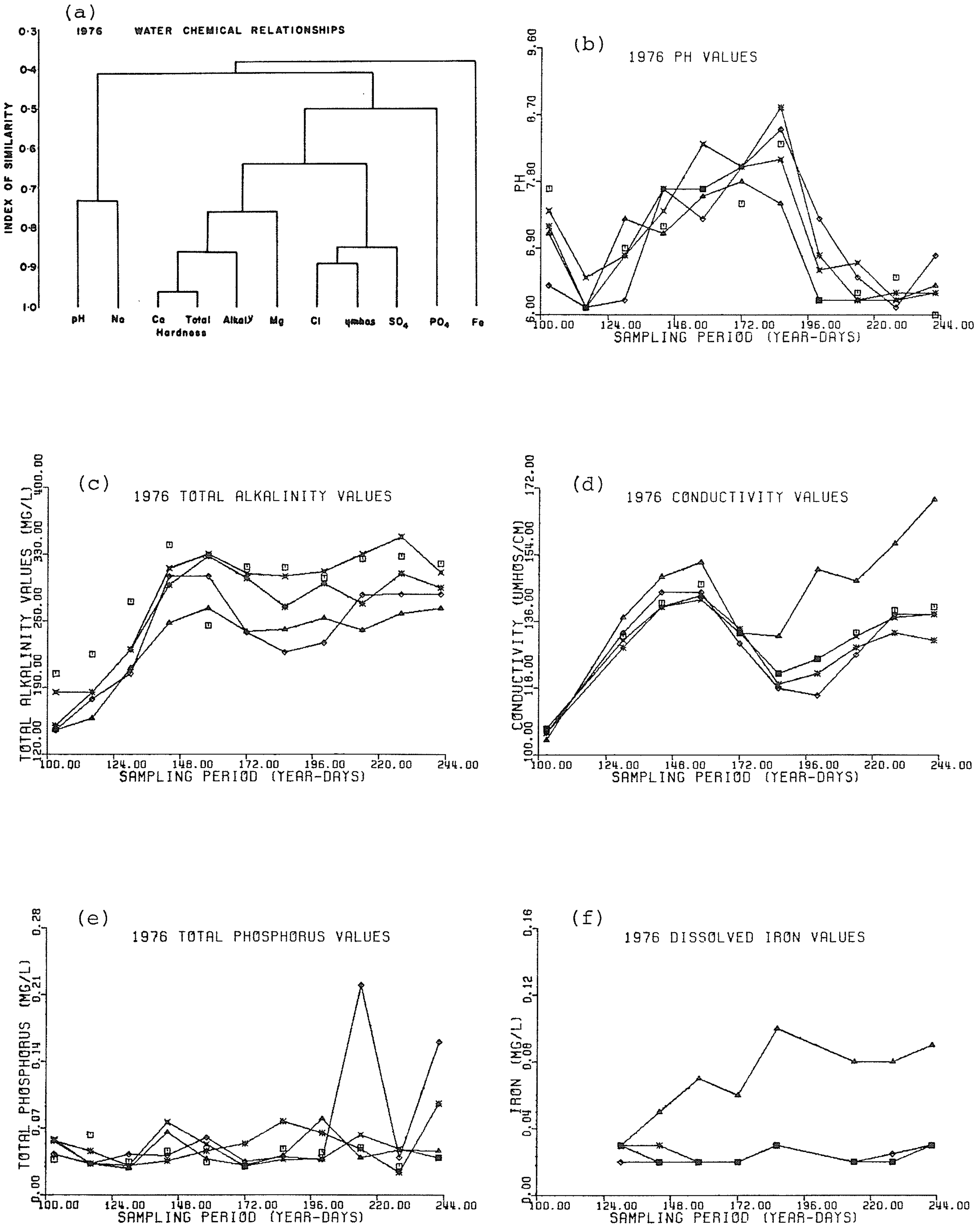
Site 1 △ Site 2 ◇ Site 3 ⊡ Site 4 ✧ Site 5 ✳

c. Alkalinity values (mg/l) as an example of group 2 in the cluster analysis (Fig. 1-6a). Symbols as of Fig. 1-6b.

d. Conductivity values (μmhos/cm) as an example of group 3 in the cluster analysis (Fig. 1-6a). Symbols as of Fig. 1-6b.

e. Total phosphorus values (mg/l) as an example of group 4 in the cluster analysis (Fig. 1-6a). Symbols as of Fig. 1-6b.

f. Dissolved iron values (mg/l) as an example of group 5 in the cluster analysis (Fig. 1-6a). Symbols as of Fig. 1-6b.


(a)
1976 WATER CHEMICAL RELATIONSHIPS
INDEX OF SIMILARITY
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
pH
Na
Ca
Total Hardness
Alkal'y
Mg
Cl
µmhos
SO_4
PO_4
Fe
(b)
1976 PH VALUES
PH
6.00
6.90
7.80
8.70
9.60
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)
(c)
1976 TOTAL ALKALINITY VALUES
TOTAL ALKALINITY VALUES (MG/L)
120.00
190.00
260.00
330.00
400.00
SAMPLING PERIOD (YEAR-DAYS)
(d)
1976 CONDUCTIVITY VALUES
CONDUCTIVITY (UMHOS/CM)
100.00
118.00
136.00
154.00
172.00
SAMPLING PERIOD (YEAR-DAYS)
(e)
1976 TOTAL PHOSPHORUS VALUES
TOTAL PHOSPHORUS (MG/L)
0.00
0.07
0.14
0.21
0.28
SAMPLING PERIOD (YEAR-DAYS)
(f)
1976 DISSOLVED IRON VALUES
IRON (MG/L)
0.00
0.04
0.08
0.12
0.16
SAMPLING PERIOD (YEAR-DAYS)

The Group 1 variables increased to a maximum level in mid-season and then decreased (Fig. 1-6b). The trends exhibited by Group 2 variables showed a bimodal distribution with maxima at approximately 150 and 230 year-days (Fig. 1-6c).

The trends in both Groups 1 and 2 were caused by the interrelationships of CO_2, pH, and H_2CO_3 shown below (Reid, 1961):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \rightleftharpoons CO_3^= + H^+$$

In early spring (up to 115 year-days) there was an influx of hydrogen ions and there was little demand for CO_2 for primary production. The hydrogen ions reacted with the carbonates at the sediment-water interface ($CaCO_3$ and $MgCO_3 + H^+$ --- $HCO_3^- + Ca^{++} + Mg^{++}$) releasing bicarbonate and causing the pH to rise, and alkalinity, calcium and magnesium to increased (Fig. 1-6b, c). This trend continued until 160 year-days, after which the demand for CO_2 for primary production increase to such an extent that concentrations of the CO_2 required to maintain equilibrium in the carbonate reactions were depleted. In order to re-establish equilibrium, the reaction shifted to the left releasing CO_2 and precipitating $CaCO_3$ and $MgCO_3$. In turn, the concentrations of bicarbonate, calcium, and magnesium decreased thereby causing alkalinity to decrease. By mid-summer (180 year-days), pH was at its highest peak while alkalinity was at its lowest mid-summer value. As the summer progressed, primary production began to decrease and so CO_2 demand also decreased. This caused the reaction to shift to the right with a corresponding decrease in acidity and increases in alkalinity, magnesium and calcium as they were again dissolved as calcium and magnesium bicarbonate. Sodium was also affected by shifts in pH and CO_2 in the same manner as calcium and magnesium.

In Group 3 (Fig. 1-6d), conductivity increased to a maximum and then levelled off. The initial increase was likely influenced by the increase in bicarbonate ions, but as the summer progressed, and with the additional release of other elements from the sediments due to decomposition, alkalinity had a less noticeable effect on conductivity. The high correlation of chloride and sulfate with conductivity was due to the influence of the power plant's effluent on sites 3, 4 and 5 which has higher concentrations of these ions than are naturally found in the Mississippi River (sites 1 and 2). Groups 4 and 5 which contain total phosphorus and dissolved iron respectively, remained relatively constant throughout the growing period (Fig. 1-63, f). This may indicate that oxygen was present at the sediment-water interface, since iron and phosphorus often form an insoluble ferric iron-phosphate complex. Such complexes under anaerobic conditions often become soluble, and release the phosphate and iron in the soluble ferrous state (Reid, 1961).

In 1977, there were five cluster groups of variables (Fig. 1-7):

Group 1 - pH, dissolved sodium
Group 2 - chloride, conductivity
Group 3 - total phosphorus
Group 4 - alkalinity, dissolved iron
Group 5 - sulfate, dissolved magnesium, calcium hardness, total hardness

Figure 1-7

a. Cluster analysis of water chemical relationships for stations 1, 2, 4 & 5 in the Mississippi River near CBSES in 1977.

b. pH values as an example of group 1 in the cluster analysis (Fig. 1-7a).

Site 1 △ Site 2 ◇ Site 3 □ Site 4 ⌧ Site 5 ✳

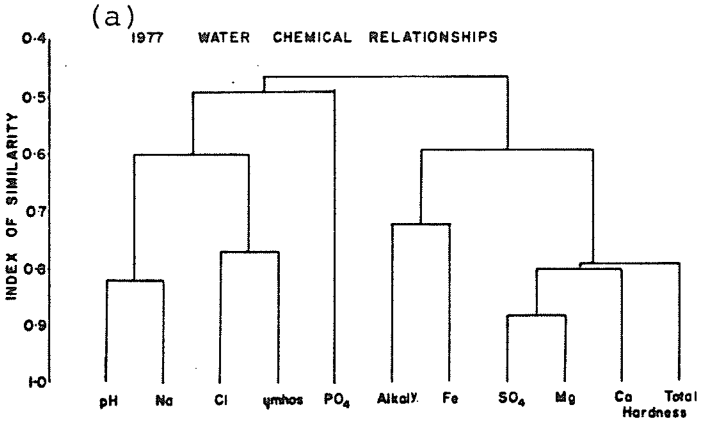
c. Chloride values (mg/l) as an example of group 2 in the cluster analysis (Fig. 1-7a). Symbols as of Fig. 1-7b.

d. Total phosphorus values (mg/l) as the only representative of group 3 in the cluster analysis (Fig. 1-7a). Symbols as of Fig. 1-7b.

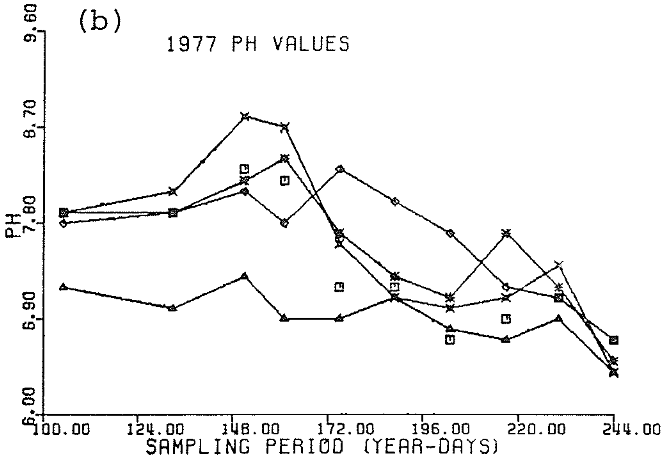
e. Alkalinity values (mg/l) as an example of group 4 in the cluster analysis (Fig. 1-7a). Symbols as of Fig. 1-7b.

f. Sulfate values (mg/l) as an example of group 5 in the cluster analysis (Fig. 1-7a). Symbols as of Fig. 1-7b.

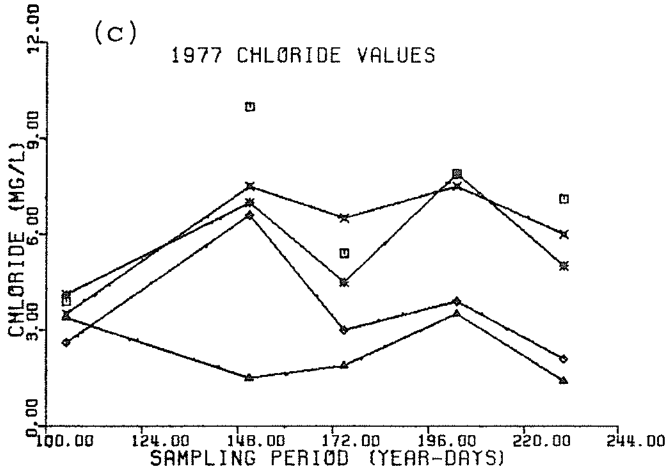
(a)


1977 WATER CHEMICAL RELATIONSHIPS
INDEX OF SIMILARITY
0·4
0·5
0·6
0·7
0·8
0·9
1·0
pH
Na
Cl
µmhos
PO4
Alkaly.
Fe
SO4
Mg
Ca
Total Hardness

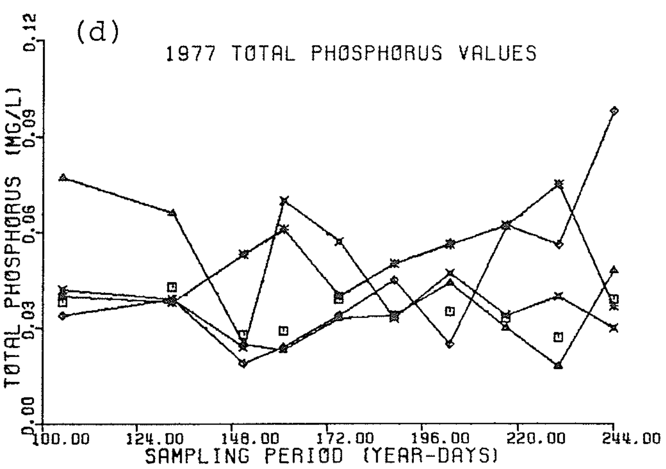
(b)


1977 PH VALUES
PH
9.60
8.70
7.80
6.90
6.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

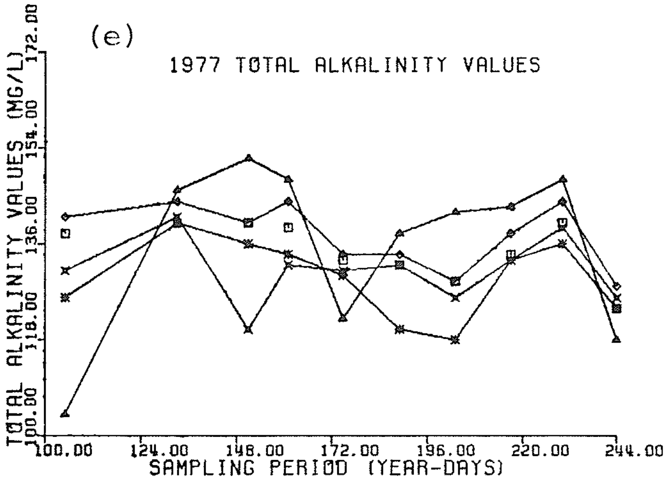
(c)


1977 CHLORIDE VALUES
CHLORIDE (MG/L)
12.00
9.00
6.00
3.00
0.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

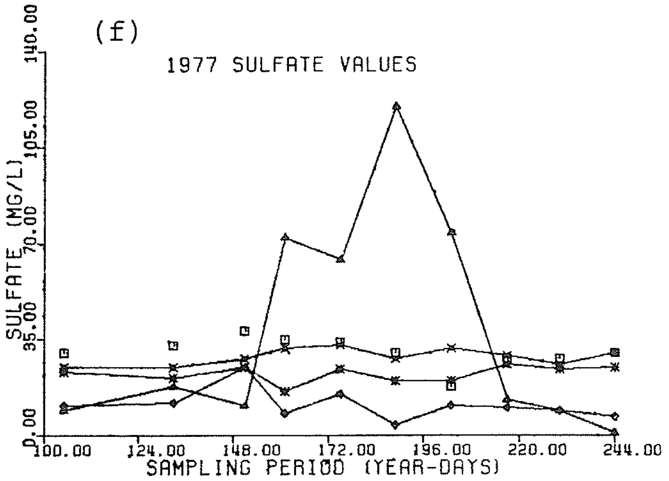
(d)


1977 TOTAL PHOSPHORUS VALUES
TOTAL PHOSPHORUS (MG/L)
0.12
0.09
0.06
0.03
0.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

(e)


1977 TOTAL ALKALINITY VALUES
TOTAL ALKALINITY VALUES (MG/L)
172.00
154.00
136.00
118.00
100.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

(f)


1977 SULFATE VALUES
SULFATE (MG/L)
140.00
105.00
70.00
35.00
0.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

In general, the seasonal patterns of Groups 1, 2 and 3 (Fig. 1-7b, 1-7c, 1-7d) in 1977 resembled those of 1976.

Group 3 which contained total phosphorus once again showed no regular pattern (Fig. 1-7d).

Group 4 variables tended to increase to a maximum, decrease, increase and finally decrease (Fig. 1-7e). The final decrease for total alkalinity differs from that of 1976, and the fact that it parallels pH indicates that the normal equilibrium reactions for the carbonate cycle were in effect.

Group 5 variables (Fig. 1-7f) followed a similar pattern to Group 3 except at Site 1 where these variables had very striking peaks at approximately 150 and 190 year-days.

Both Groups 4 and 5 were influenced by pH, CO_2 and H_2CO_3 in a similar manner to that described in 1976. Apparently calcium and magnesium carbonate were again precipitated as the demand for CO_2 by plants increased, and shifts in magnesium, calcium hardness, and total hardness coincided with those occurring in alkalinity. The main differences in 1977 were that iron exhibited seasonal fluctuations in all sites and sulfate in Site 1.

The iron shifts coincided very well with those of alkalinity. This suggests that reducing conditions existed at the sediment water interface in 1977, and that a system described by Hynes (1972) may have been in effect. The ferric ion in the sediment was reduced to the ferrous state and went into solution as ferrous bicarbonate. But with the increase in production of carbonate, the iron was precipitated as Fe_2CO_3 which is extremely insoluble (Wetzel, 1975). With the decreased demand for CO_2, and corresponding increase in hydrogen ions which reacted with the carbonates, the iron again went into solution with the bicarbonate ion.

The sudden increases in the sulfate concentration at Site 1, which correlated with those of the calcium, magnesium and total hardness values, is somewhat different and assuming it was present, may have been due to the activity of the bacterium, *Thiobacillus denitrificans*. Under alkaline conditions, it oxidizes thiosulfate by the reduction of nitrate to molecular nitrogen (Hutchinson, 1957):

$$6NO_3^- + 5S + 2CaCO_3 \longrightarrow 3SO_4^= + 2CaSO_4 + 2CO_2 + N_2$$

The fact that the high levels of sulfate release coincided with the low values of alkalinity when carbonate would be at its highest concentration, gives further support to this hypothesis.

The reasons for the differences in the water chemical relationships for 1977 as opposed to 1976 are not understood. One factor may have been that more of the wild rice plants were left to decompose in the actual rice beds during the spring of 1977. Since the spring of 1976, virtually all the rice plants at the four sites were swept by the force of the spring run-off either downstream or onto the shores. In the spring of 1977, there was a reduced spring run-off, consequently many of the plants from the previous years growth were not carried away or to shore, and instead remained *in situ* on the bottom of the rice beds. This was particularly noticeable at Site 1 which seemed to be less affected by the main channel current than the other stations. At this site large masses of the plants could be seen lying on the bottom sediment throughout the summer. Anaerobic conditions at the sediment-water interface, resulting from the low microbial activity may have released nutrients from the sediment and accounted for some of the yearly chemical differences.

Oxygen

Seasonal oxygen levels at the five stations for 1976 and 1977 are shown in Figure 1-8a,b. During both seasons, oxygen levels were at their lowest values during mid-season when decomposition activity would be the greatest. Anaerobic levels were never encountered in the middle of the water column where the sampling was done.

Sediment Chemistry

The relationships of the chemical variables in the sediment for 1976 and 1977 are shown by Figures 1-9a and 1-10a. Although distinct clusters of the variables were separated interpretation of them in terms of temporal trends is rather pointless since clearly no distinct seasonal cycles emerged (Fig. 1-9b-d and 1-10b-f). This suggested that there was a large within site variance in the concentrations of the chemical variables which is fairly common in river sediments (Hynes, 1972). Table 1-2, (p.40) which contains the results for available sulfur levels of sediment samples collected at regular intervals along transects at Stations 1, 2, 4 and 5, seems to verify this opinion. The extremely large standard

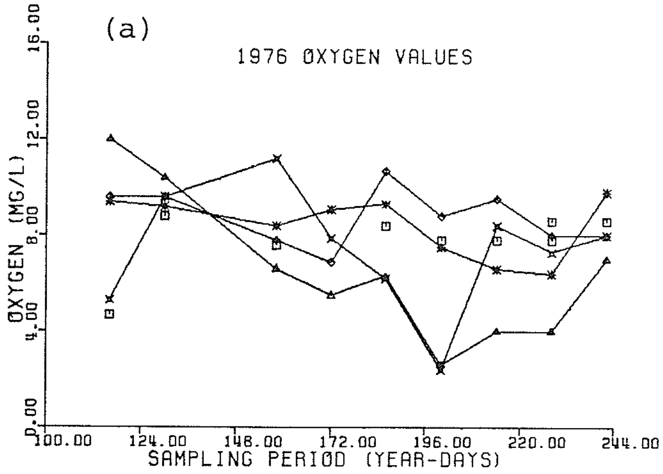
Table 1-2. Means, ranges and standard deviations for concentrations of available sulfur (ppm) collected from sediments at regular intervals along transects from the shore to the edges of the rice beds at Stations 1, 2, 4 and 5 during 1977.

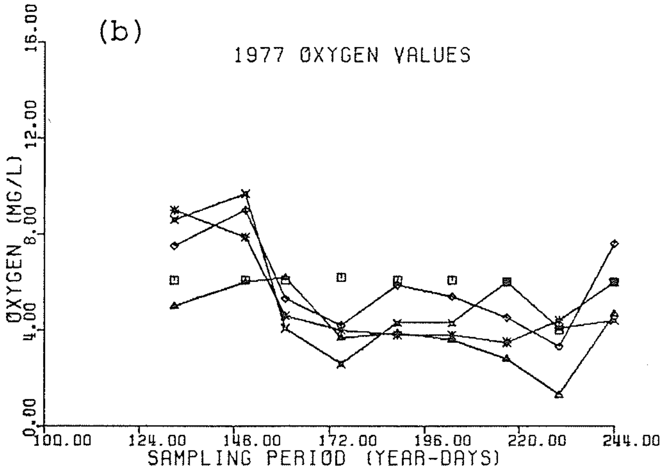
Station	Mean	Range	Standard Deviation
1	471	37 - 1111	363
2	715	93 - 1333	314
4	662	350 - 1050	196
5	770	37 - 1518	463

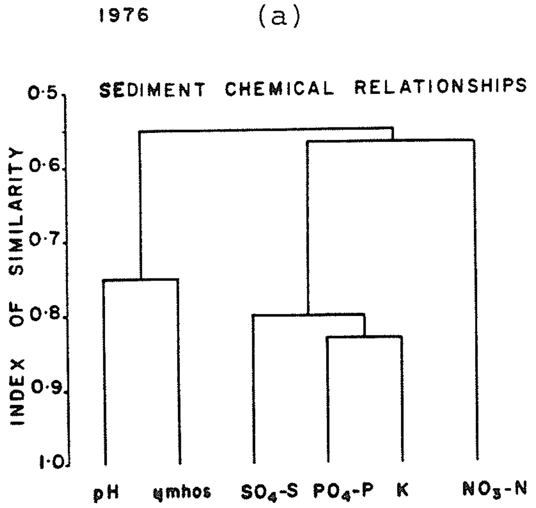
Figure 1-8.

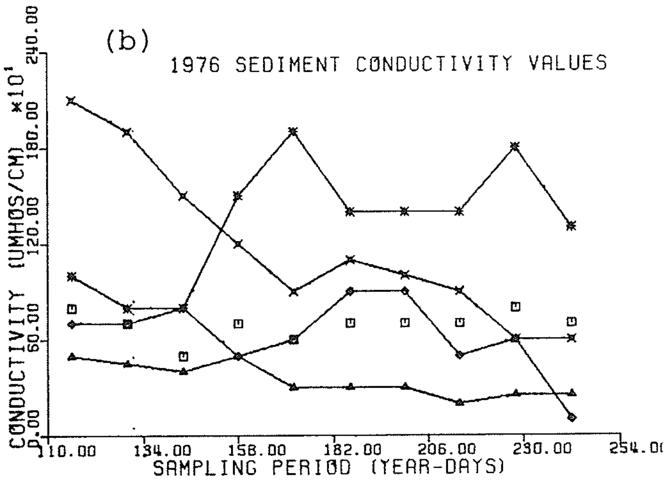
Oxygen concentrations (mg/ℓ) at 5 stations sampled near CBSES on the Mississippi River during (a) 1976 and (b) 1977.

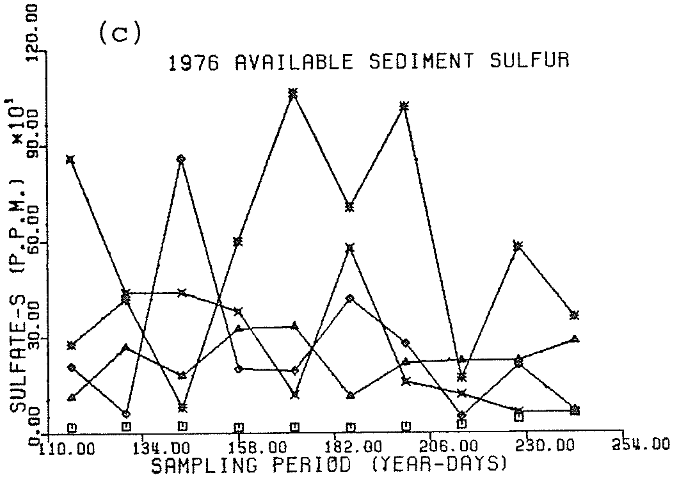
Site 1 △ Site 2 ◇ Site 3 □ Site 4 ¤ Site 5 ✳


(a)
1976 OXYGEN VALUES
OXYGEN (MG/L)
0.00
4.00
8.00
12.00
16.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(b)
1977 OXYGEN VALUES
OXYGEN (MG/L)
0.00
4.00
8.00
12.00
16.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(a)
1976
SEDIMENT CHEMICAL RELATIONSHIPS
INDEX OF SIMILARITY
0·5
0·6
0·7
0·8
0·9
1·0
pH
μmhos
SO_4-S
PO_4-P
K
NO_3-N


(b)
1976 SEDIMENT CONDUCTIVITY VALUES
CONDUCTIVITY (UMHOS/CM) ×10¹
0.00
60.00
120.00
180.00
240.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


(c)
1976 AVAILABLE SEDIMENT SULFUR
SULFATE-S (P.P.M.) ×10¹
0.00
30.00
60.00
90.00
120.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)

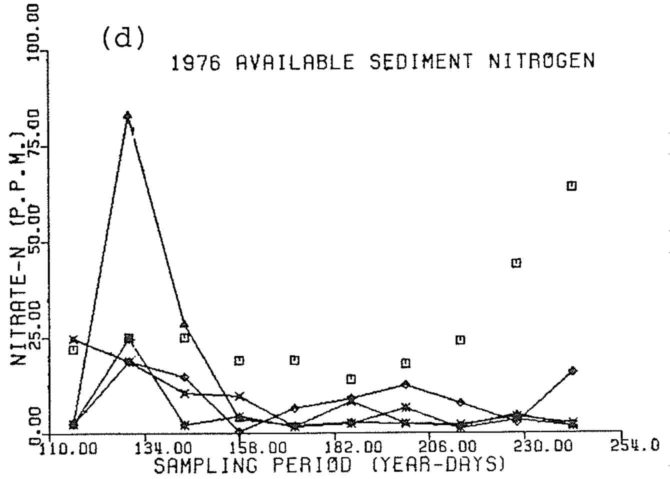

(d)
1976 AVAILABLE SEDIMENT NITROGEN
NITRATE-N (P.P.M.)
0.00
25.00
50.00
75.00
100.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)

Figure 1-10

a. Cluster analysis of sediment chemical relationships for station 1,2,3,4 & 5 in the Mississippi River near CBSES during 1977.

b. Sediment pH values as the only example of group 1 in the cluster analysis (Fig. 1-10a).

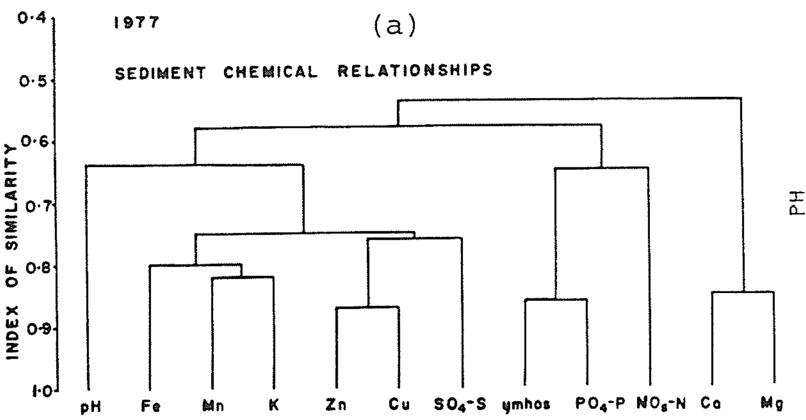
Site 1 △ Site 2 ◇ Site 3 □ Site 4 ¤ Site 5 ✳

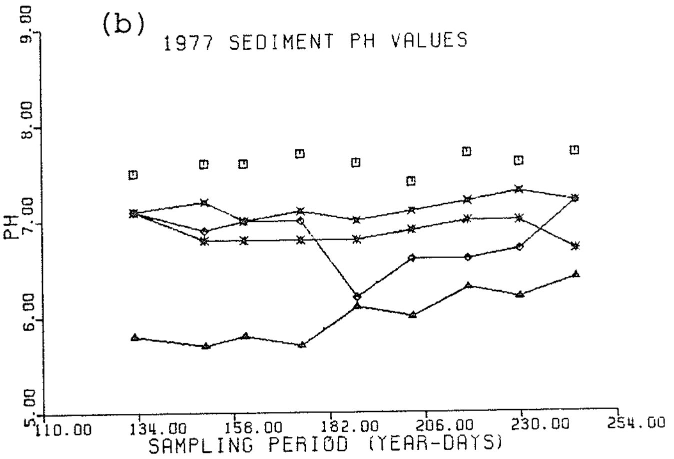
c. Available sediment sulfur (SO_4-S) ppm x 10) as an example of group 2 in the cluster analysis (Fig. 1-10a). Symbols as of Fig. 1-10b.

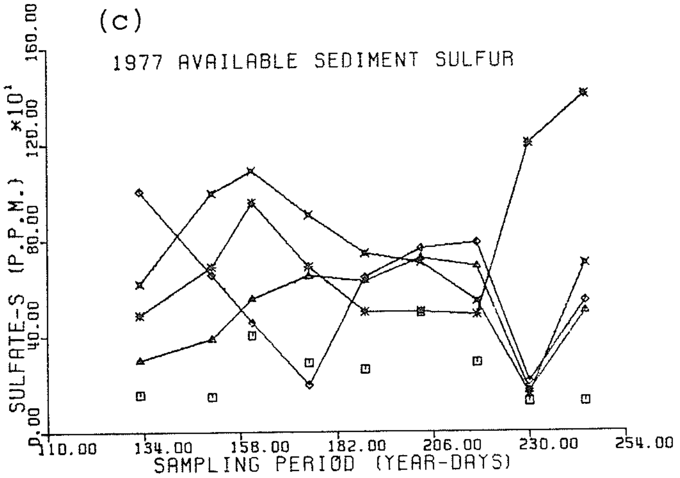
d. Available sediment phosphorus (PO_4-P ppm) as an example of group 3 in the cluster analysis (Fig. 1-10a). Symbols as of Fig. 1-10b.

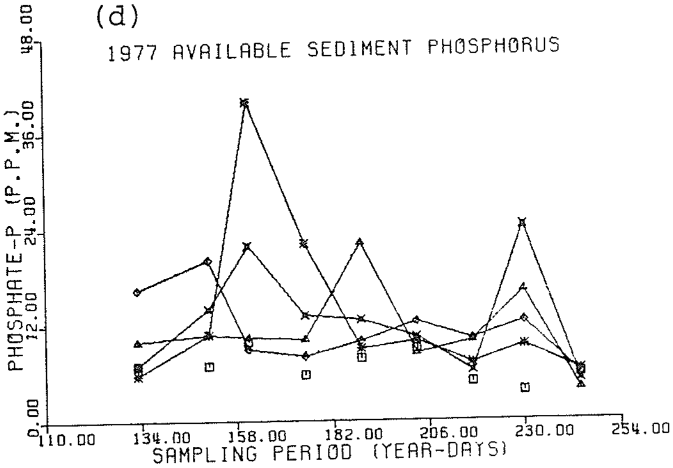
e. Available sediment nitrogen (NO_3-N ppm) as the only example of group 4 in the cluster analysis (Fig. 1-10a). Symbols as of Fig. 1-10a.

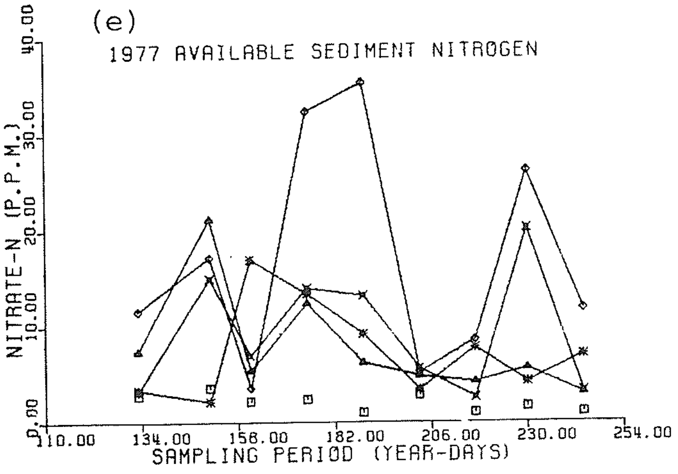
f. Available sediment calcium (ppm x 10^2) as an example of group 5 in the cluster analysis (Fig. 1-10a). Symbols as of Fig. 1-10a.


(a)
1977
SEDIMENT CHEMICAL RELATIONSHIPS
INDEX OF SIMILARITY
0·4
0·5
0·6
0·7
0·8
0·9
1·0
pH
Fe
Mn
K
Zn
Cu
SO4-S
ymhos
PO4-P
NO3-N
Ca
Mg


(b)
1977 SEDIMENT PH VALUES
PH
5.00
6.00
7.00
8.00
9.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


(c)
1977 AVAILABLE SEDIMENT SULFUR
SULFATE-S (P.P.M.) ×10¹
0.00
40.00
80.00
120.00
160.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


(d)
1977 AVAILABLE SEDIMENT PHOSPHORUS
PHOSPHATE-P (P.P.M.)
0.00
12.00
24.00
36.00
48.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)


(e)
1977 AVAILABLE SEDIMENT NITROGEN
NITRATE-N (P.P.M.)
0.00
10.00
20.00
30.00
40.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)

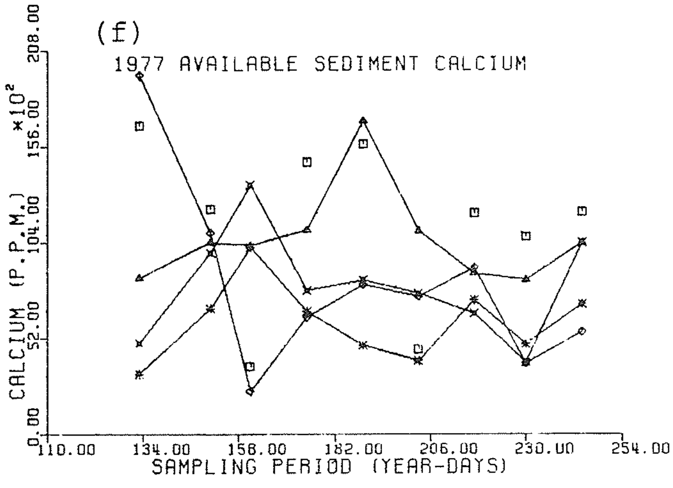

(f)
1977 AVAILABLE SEDIMENT CALCIUM
CALCIUM (P.P.M.) ×10²
0.00
52.00
104.00
156.00
208.00
110.00
134.00
158.00
182.00
206.00
230.00
254.00
SAMPLING PERIOD (YEAR-DAYS)

Table 1-2. Means, ranges and standard deviations for concentrations of available sulfur (ppm) collected from sediments at regular intervals along transects from the shore to the edges of the rice beds at Stations 1, 2, 4 and 5 during 1977.

Station	Mean	Range	Standard Deviation
1	471	37 - 1111	363
2	715	93 - 1333	314
4	662	350 - 1050	196
5	770	37 - 1518	463

deviations indicate that little significance could be attached to within site means of available sulfur. Although other elements were not analyzed at the same time, the close correlation of available sulfur (similarity index 0.7) with other variables (Fig. 1-9a, 1-10a) indicates that similar variations for these elements would occur. Clearly then, any possible temporal chemical trends which existed in the sediments would be evident only if sampling had been done consistently at the same area within the site. Since this was not the case, further interpretation of the results will be concerned only with the relative associations of the elements with each other at any point in time.

In 1976, there were three cluster groups of variables (Fig. 1-9a).

Group 1 - pH, conductivity
Group 2 - available sulfur, available phosphorus, available potassium
Group 3 - available nitrogen

The association of pH with conductivity in Group 1 is similar to that reported by Ponnamperuma (1965) under flooded conditions. He attributed this association primarily to concentrations of calcium and magnesium which increase under alkaline conditions and decrease under acidic conditions.

The Group 2 associations (Fig. 1-9a) are consistent with their similar chemical behaviour under reducing conditions when high concentrations of available potassium and phosphorus are generally present (Ponnamperuma, 1965; Mortimer, 1941, 1942). The fact that available sulfur was also associated with these two elements suggests that it was mainly present in the sulfide form, its normal state under such reducing conditions (Ponnamperuma, 1965).

Group 3 (Fig. 1-9a) consisted solely of available nitrogen which indicates that reactions for this variable were not following the same pattern as the other variables. This seems reasonable when it is considered that nitrogen is the first element to undergo reduction under anaerobic conditions (Ponnamperuma, 1965).

In 1977, there were five groups of variables (Fig. 1-10a):

Group 1 - pH
Group 2 - available iron, available manganese, available potassium, available zinc, available copper, available sulfur
Group 3 - conductivity, available phosphorus
Group 4 - available nitrogen
Group 5 - available calcium, available magnesium

pH was isolated in Group 1 since at the locations sampled in 1977 there was little fluctuation in the pH values (Fig. 1-10b) and therefore no correlations with other variables would be detected.

It is quite predictable that the five cations--iron, manganese, potassium, zinc, and copper, would be associated with available sulfur and form Group 2 (Fig. 1-10a) due to the formation of metallic sulfides (Higgins and Burns, 1975). It is noteworthy that within this group, the subgroup of iron, manganese, and potassium should occur.

This same relationship was found by Ponnamperuma (1965) who found that concentrations of available potassium increased with the content of available iron and manganese.

The association of conductivity with available phosphorus forming Group 3 (Fig. 1-10a) seems unexpected and may only be a spurious relationship. The fact that conductivity occurred in this group (as opposed, for example to Group 2 or 4) indicates that in these sediments the ionic conductivity was being influenced by ions from all groups and was not dominated by any single group.

Available nitrogen was isolated into a separate cluster, as in 1976, and formed Group 4 (Fig. 1-10a) again probably due to its tendency to be reduced at higher redox potentials than the other variables (Ponnamperuma, 1965).

The association of calcium and magnesium in Group 5 (Fig. 1-10a) was expected since these elements generally exhibit similar chemical behavior in the soil (Donahue et al, 1977).

Physical Factors

Water temperatures for 1976 and 1977 are shown by Figure 1-11. Higher temperatures were present during the early portion of the growing season at Sites 4 and 5 clearly due to the thermal effluent from the power plant. But by 170 year-days, the effect of air temperatures had caused the water temperatures at all sites to be relatively uniform.

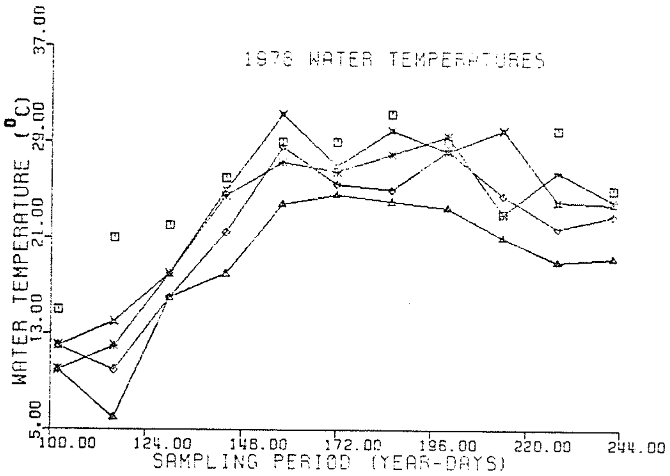
Figure 1-11.

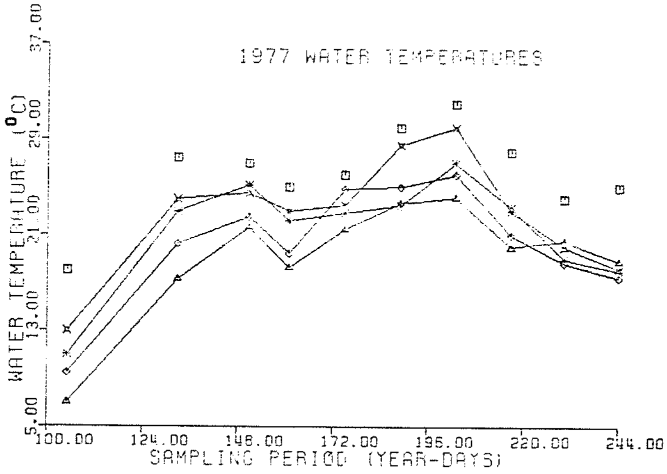
Water temperatures (°C) at stations 1,2,3,4 & 5 sampled in the Mississippi River near CBSES during 1976 and 1977.

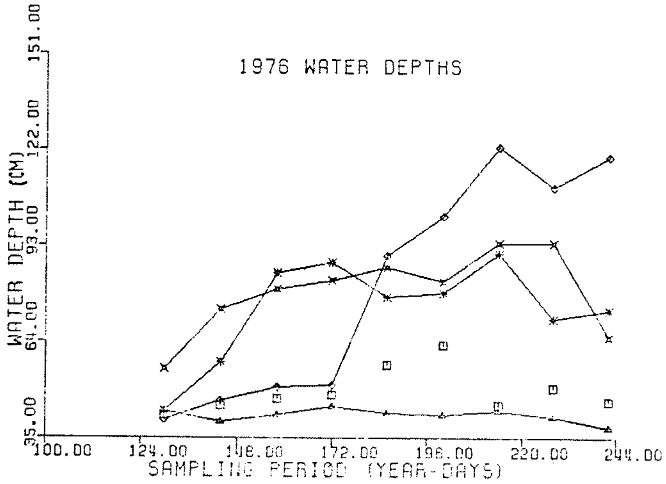
Site 1 △ Site 2 ◇ Site 3 ⊞ Site 4 ⌧ Site 5 ✳

Figure 1-12.

Water depths (cm) at station 1,2,3,4, & 5 sampled in the Mississippi River near CBSES during 1976 and 1977. Symbols as of Fig. 1-11.


1976 WATER TEMPERATURES
WATER TEMPERATURE (°C)
5.00
13.00
21.00
29.00
37.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


1977 WATER TEMPERATURES
WATER TEMPERATURE (°C)
5.00
13.00
21.00
29.00
37.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


1976 WATER DEPTHS
WATER DEPTH (CM)
35.00
64.00
93.00
122.00
151.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

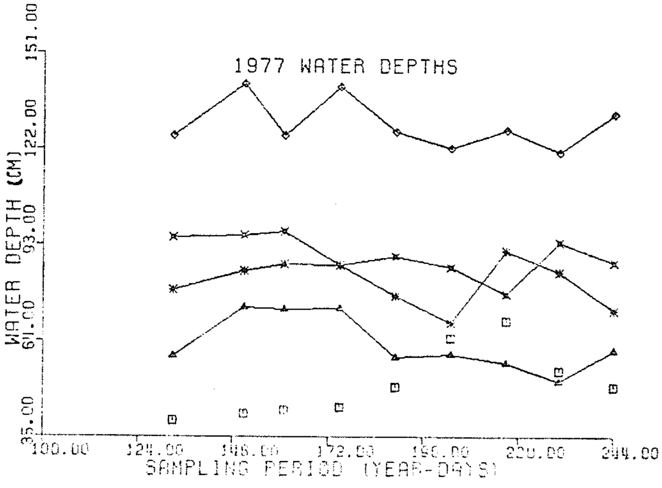

1977 WATER DEPTHS
WATER DEPTH (CM)
35.00
64.00
93.00
122.00
151.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

Figure 1-12 shows the mean sampling depths of the five stations during 1976 and 1977. It is noteworthy that there is much less fluctuation in the depths during 1977, particularly at station 2, illustrating how the use of transects, as opposed to random sampling, was able to reduce within site variation for this parameter.

Discriminant Analysis

Table 1-3 contains the F statistics for a one-way analysis of variance for all variables considered in 1976 and 1977. In 1976, statistically significant differences occurred among the sampling sites for the following factors: (a) biological-wild rice density and plant competition, (b) water-, pH, conductivity, total alkalinity, sulfate, calcium hardness, dissolved magnesium, dissolved iron, (c) sediment-pH, conductivity, and available sulfur, and (d) physical-accumulated water temperature and water depth. In 1977 similar results occurred except that concentrations of chloride in the water, total hardness in the water, sodium in the water, and available sediment nitrogen were also statistically different but available sediment sulfur was not. Additionally, available sediment iron, available sediment manganese, available sediment zinc, available sediment copper, available sediment calcium, and available sediment magnesium, which were not measured in 1976, were found to be statistically significant.

Table 1-3. One way analysis of variance for environmental variables examined at the four sampling sites on the Mississippi River (all variables corrected for time dependency, df= 3,36 (1976); 3,32 (1977)).

Environmental Factor	F Value 1976	 1977
Biological		
Wild rice density	* 11.496	* 32.366
Plant competition	* 5.499	* 7.087
Chemical		
Water		
pH	* 6.948	* 12.262
Conductivity	* 22.427	* 10.026
Total alkalinity	* 3.193	* 6.423
Chloride	1.731	* 83.756
Total phosphorus	1.703	2.088
Sulfate	* 33.334	* 3.456
Total hardness	1.418	* 4.769
Dissolved Calcium (1976) Calcium hardness (1977)	* 21.519	* 4.375
Dissolved magnesium	* 33.790	* 2.997
Dissolved sodium	1.290	* 10.196
Dissolved iron	* 5.171	* 4.445
Dissolved oxygen	* 3.930	* 4.496
Sediment		
pH	*103.252	* 57.254
conductivity	* 22.164	* 8.986
Available nitrogen	2.039	* 5.068
Available phosphorus	2.486	0.101
Available potassium	1.677	0.191
Available sulfur	* 3.001	1.713
Available iron		* 6.389
Available manganese		* 6.389
Available zinc		* 20.116
Available copper		* 33.608
Available calcium		* 3.930
Available magnesium		* 22.912
Physical		
Accumulated water temperature	* 289.838	* 112.526
Water depth	* 15.684	* 229.177

---

* Statistically significant at the 0.05 level

The results of the discriminant analysis for 1976 and 1977 are contained in Tables 1-4 and 1-5. In 1976 and 1977 the first two of the three derived discriminant functions accounted for the majority of the variance in the sampling observations.

These discriminant functions were very effective in classifying the sampling observations into their respective sampling stations. In both years, all sampling observations were correctly predicted. Figures 1-13 shows the definite clustering of the sampling observations for their respective sampling stations during each year according to the discriminant functions.

The absolute values of the standardized coefficients in Tables 1-4 and 1-5 indicate the relative significance of the variables comprising the functions.

In 1976 the first function was mainly influenced by accumulated water temperature, magnesium, and sediment pH; the second function by wild rice density, depth, pH and magnesium; and the third function by sediment pH and conductivity.

In 1977 the first function was mainly influenced by accumulated water temperature, chloride, and wild rice density; the second function by depth; and the third function by wild rice density and calcium hardness.

Although there seems to be a discrepancy between the factors discriminating between the two years, this is not necessarily the case. In the discriminant analysis procedure, any ecological parameters that are highly correlated to other ecological parameters will be eliminated in the formation of

Table 1-4. 1976 Discriminant Function Characteristics

	Discriminant Functions					
	1		2		3	
Relative Percentage of Sampling Variance Explained	86.800		11.906		1.294	
Cumulative Percentage	86.800		98.706		100.000	
	Coefficients		Coefficients		Coefficients	
Environmental Variables	Unstandardized	Standardized	Unstandardized	Standardized	Unstandardized	Standardized
Magnesium	-.041	-.705	.037	.636	-.016	-.275
pH	.027	.113	.206	.861	.085	.355
Sediment pH	-.276	-.537	-.077	-.150	.264	.514
Sediment conductivity	-.004	-.148	.011	.407	-.017	-.628
Depth	.010	.206	-.047	-.967	-.012	-.247
Accumulated water temperature	-.449	-.973	-.014	-.030	-.002	-.004
Wild rice density	.003	.094	-.046	-1.444	-.008	-.251
Constant	72.966		-7.123		-29.346	

Percent Correct Classification of Sampling Observations -100

Table 1-5. 1977 Discriminant Function Characteristics.

	Discriminant Functions 1		2		3	
Relative Percentage of Sampling Variance Explained	80.436		19.314		.250	
Cumulative Percentage	80.436		99.750		100.000	
	Coefficients		Coefficients		Coefficients	
Environmental Variables	Unstandardized	Standardized	Unstandardized	Standardized	Unstandardized	Standardized
Chloride	-.101	-1.499	.008	.119	-.020	-.297
Calcium hardness	.048	.651	.013	.176	.034	.461
Depth	-.092	- .560	-.149	-.906	.041	.249
Accumulated water temperature	-.400	-1.189	.082	.244	.001	.003
Wild rice density	.029	.988	-.011	-.375	-.020	-.681
Constant	51.729		5.711		-3.621	

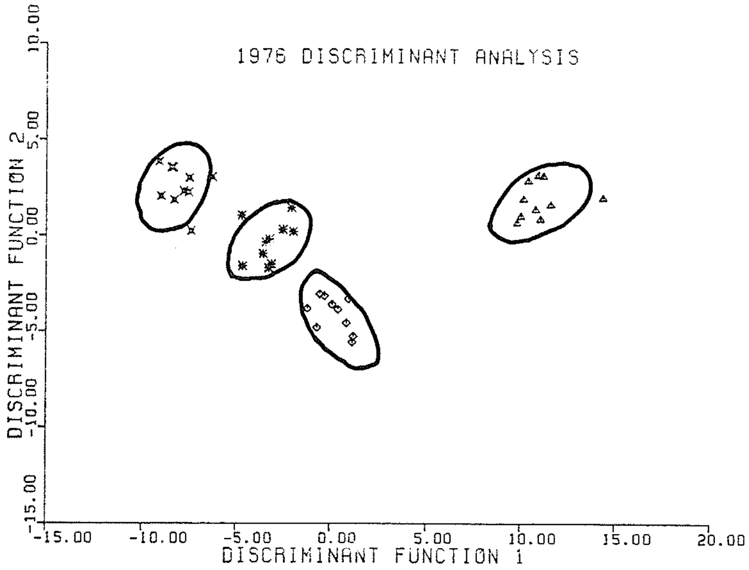
Percent Correct Classification of Sampling Observations -100

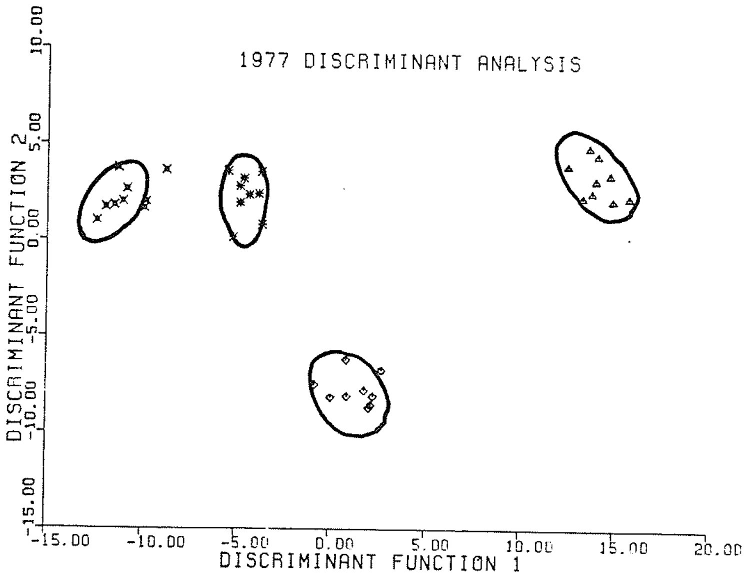
Figure 1-13

Clustering of the sampling observations for station 1, 2, 4 & 5 according to the discriminant functions during 1976 and 1977.

Site 1 △ Site 2 ◇ Site 4 ¤ Site 5 ✳

(the ellipses indicate the bivariate normal probabilities of including 90 percent of the obervations at each sampling site)


1976 DISCRIMINANT ANALYSIS
DISCRIMINANT FUNCTION 2
10.00
5.00
0.00
-5.00
-10.00
-15.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
DISCRIMINANT FUNCTION 1


1977 DISCRIMINANT ANALYSIS
DISCRIMINANT FUNCTION 2
10.00
5.00
0.00
-5.00
-10.00
-15.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
DISCRIMINANT FUNCTION 1

the discriminant functions (Green, 1971). As the cluster analysis for the water and sediment variables illustrated, such intercorrelations existed in this instance. Therefore, in order to test the hypothesis that the variables which seemed to be important in 1976 were not in 1977 (and vice-versa), since they were highly intercorrelated with each other, two additional discriminant analyses were performed:

(a) only those variables determined as being significant in 1977 were allowed to discriminate the 1976 data; and

(b) only those variables determined as being significant in 1976 were allowed to discriminate the 1977 data.

Using the 1977 variables, 97.5 percent of the 1976 sampling observations were correctly classified in their appropriate sampling station. Those variables included in these new discriminant functions were accumulated water temperature, wild rice density, water depth and chloride.

Using the 1976 variables, 100 percent separation of the 1977 sampling observations were correctly classified in their appropriate sampling stations. Those variables included in these new discriminant functions were accumulated water temperature, depth and wild rice density. In this case, although the inclusion of the other variables in the 1977 discriminant functions reduced the variance of the predictor functions, correct classification of the observations could have been achieved using only the above three variables.

Finally, in order to determine if the discriminant analysis technique was not only isolating the same variables in both years in forming the discriminant functions, but was also isolating a stable relative contribution of these variables to the discriminant functions, two additional analyses were done:

(a) the 1977 discriminant functions were used to discriminate the 1976 data; and

(b) the 1976 discriminant functions were used to discriminate the 1977 data.

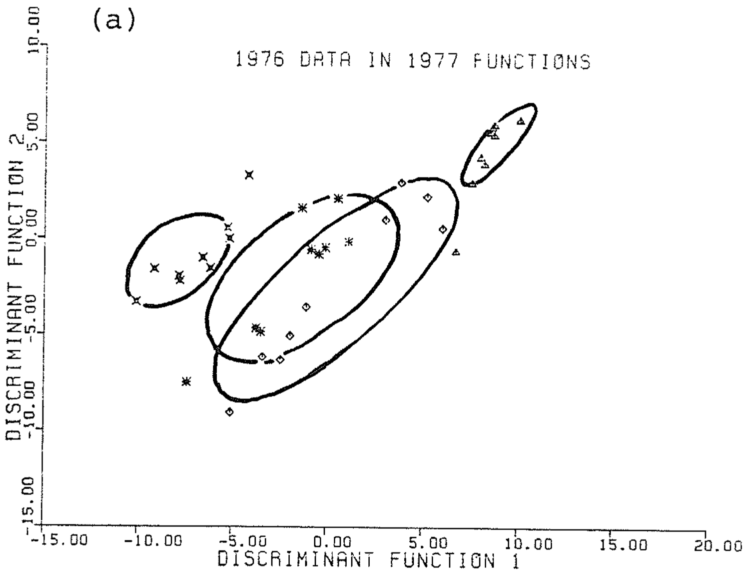
In the separation of the 1976 data with the 1977 discriminant functions (Fig. 1- 14a) there were a few misclassifications for stations 2 and 5. This is probably a result of the change in the sampling program between the two years. As previously mentioned, the use of transects in 1977 reduced within-site depth variance, causing a higher loading for this variable in the discriminant functions in 1977 than in 1976 (Tables 1-4, 1-5), and thus affected the separation of the 1976 data. The separation of the 1977 data in the 1976 functions was very good (Fig.1-14b), indicating that the factors causing among-site differences in 1976 would also result in among-site differences in 1977. Therefore, in general, the discriminant functions did seem to exert a stable separating effect on the four stations during both years and this gives further evidence that the factors, isolated by the discriminant analysis technique would result in among-site differences and would in turn cause differences in wild rice growth at the four sites.

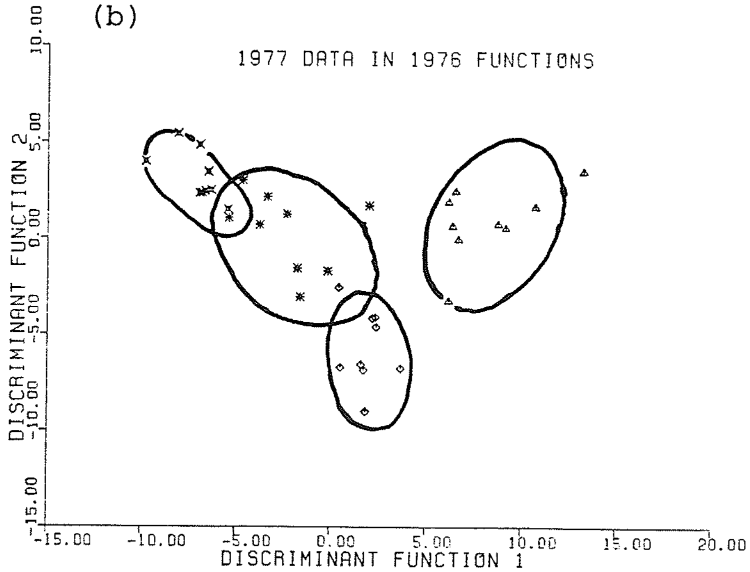
Figure 1-14

(a) Separation of the 1976 data using the 1977 discriminant functions.

Site 1 ⚠ Site 2 ◈ Site 4 ⌘ Site 5 ✳

(b) Separation of the 1977 data using the 1976 discriminant functions. Symbols as in Fig. 1-14a. (the elipses indicate the bivariate normal probabilities of including 90 percent of the observations at each sampling site)


(a)
1976 DATA IN 1977 FUNCTIONS
DISCRIMINANT FUNCTION 2
10.00
5.00
0.00
-5.00
-10.00
-15.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
DISCRIMINANT FUNCTION 1


(b)
1977 DATA IN 1976 FUNCTIONS
DISCRIMINANT FUNCTION 2
10.00
5.00
0.00
-5.00
-10.00
-15.00
-15.00
-10.00
-5.00
0.00
5.00
10.00
15.00
20.00
DISCRIMINANT FUNCTION 1

Growth Model

The time-corrected values of the biological, chemical and physical variables isolated by the discriminant analysis during 1976 and 1977 were plotted against the time-corrected values of the percent mean dry weights per wild rice plant. These generally revealed curvilinear responses which were made linear by taking the natural logarithm of the plant weights.

The 1976 and 1977 results of the multiple regression analysis of these transformed variables versus the time-corrected dry weights per wild rice plant were as follows:

1976

$$\ln \left(\frac{\bar{x} \text{ stn 1 or 2 or 4 or 5}}{\bar{x} \text{ stn,1, 2, 4, 5}} \right) \text{X } 100\% = -5.223 - 0.002 \text{ mg} + 0.056 \text{ pH} + 0.042 \text{ sediment pH} - 0.001 \text{ sediment } \mu\text{mhos} - 0.004 \text{ depth} - 0.005 \text{ wild rice density} + 0.012 \text{ accumulated water temp.}$$

1977

$$\ln \left(\frac{\bar{x} \text{ stn 1 or 2 or 4 or 5}}{\bar{x} \text{ stn 1, 2, 4, 5}} \right) \text{X } 100\% = 2.212 + 0.011 \text{ Cl} - 0.005 \text{ Ca hardness} - 0.003 \text{ depth} - 0.005 \text{ wild rice density} + 0.021 \text{ accumulated temp.}$$

In both years, suitable fits were obtained as determined by the regression (R) coefficients of 0.92 (1976) and 0.93 (1977) explaining 85 and 86 percent of the variance in the weights per plant for both years.

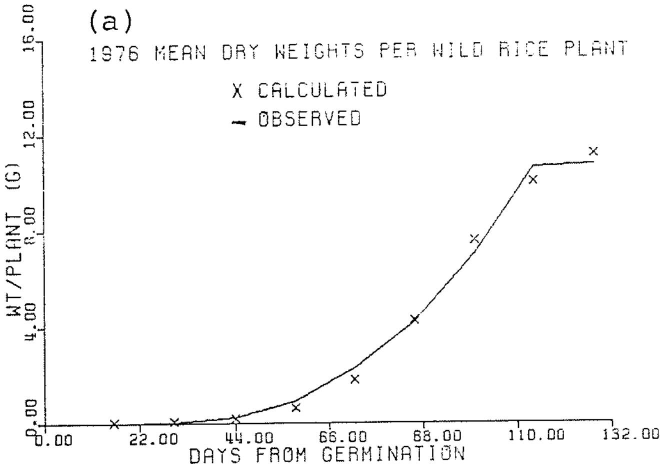
The results of using a logistic model to explain the mean dry weights per wild rice plant in the time dependent portion of the growth models of 1976 and 1977 are contained in Fig. 1-19a, b. In both years the predicted values approximated very closely the measured values. It should be realized

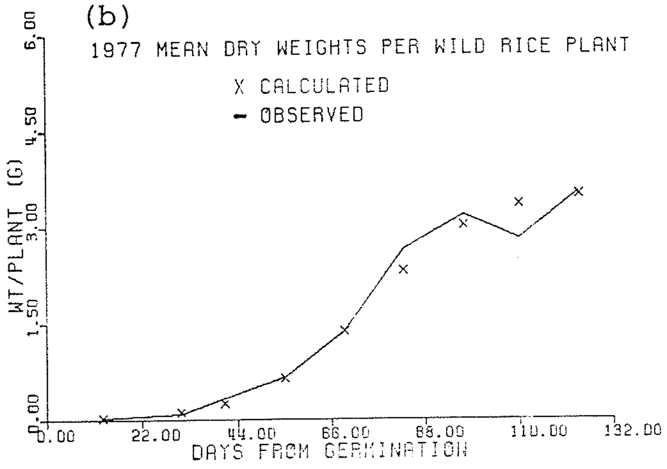
Figure 1-15

Mean dry weights per wild rice plant in the time dependent portion of the growth models for

(a) 1976, $\bar{x}$ stn 1, 2, 4, 5 = $\dfrac{11.8}{1 + e^{7.674 - 0.083t}}$

(b) 1977, $\bar{x}$ stn 1, 2, 4, 5 = $\dfrac{3.6}{1 + e^{5.712 - 0.076t}}$


(a)
1976 MEAN DRY WEIGHTS PER WILD RICE PLANT
X CALCULATED
— OBSERVED
WT/PLANT (G)
0.00
4.00
8.00
12.00
16.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION

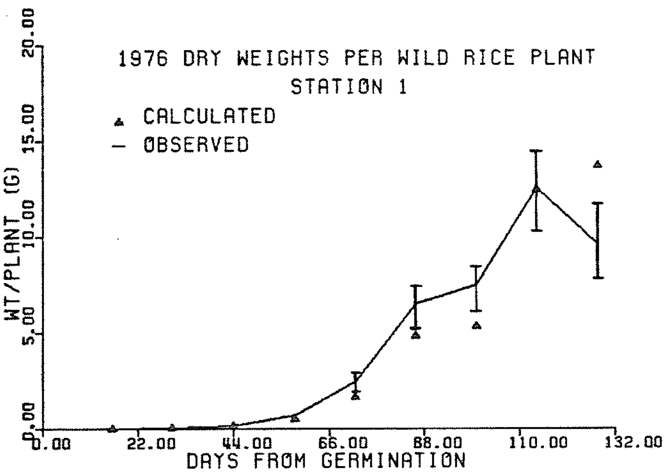

(b)
1977 MEAN DRY WEIGHTS PER WILD RICE PLANT
X CALCULATED
— OBSERVED
WT/PLANT (G)
0.00
1.50
3.00
4.50
6.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION

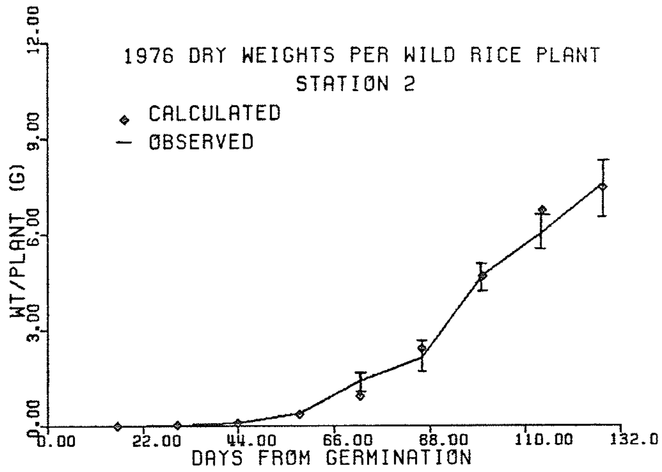
that this may not always be the case. Apparently the values for the weights per plant at the four sites averaged out to give a smooth logistic curve. If fewer sites had been used, or if the among site variance in wild rice plant weights had fluctuated more, a less accurate fit may have resulted.

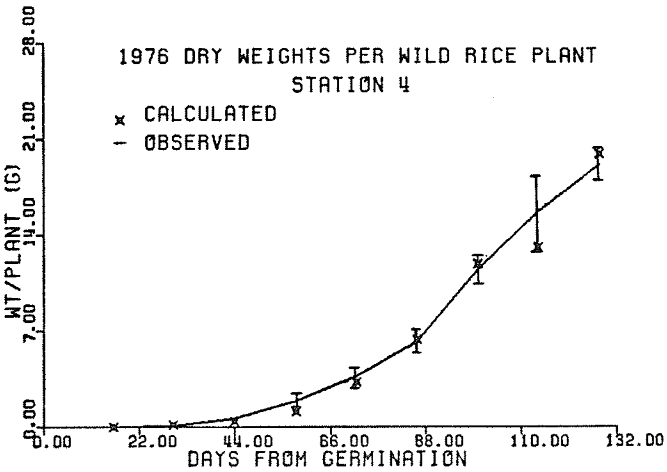
By combining the time independent portion of the model with the time dependent portion, the final weight predictions for the wild rice plants are obtained (Fig. 1-16, 1-17). Predictions for all stations in 1976 and 1977 were very close to the actual measured values, being in nearly every case within one standard deviation of the measured means, and thus clearly illustrating the accuracy of this "relative approach" for predicting the growth of plants. The approach is much simpler than the derivation of theoretical growth models employing complex mathematical relationships based on absolute environmental measurements which often do not vary to any significant amount among sampling areas. This relative approach concentrates only on environmental differences which occur among sampling areas, assuming that any similarities are irrelevant and that any growth response fluctuations among sites will be due to these differences.

Figure 1-16

The final weight predictions for the wild rice plants in 1976 obtained by combining the time independent portion of the model with the time dependent portion for stations 1, 2, 4 and 5.


1976 DRY WEIGHTS PER WILD RICE PLANT
STATION 1
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
5.00
10.00
15.00
20.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION


1976 DRY WEIGHTS PER WILD RICE PLANT
STATION 2
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
3.00
6.00
9.00
12.00
0.00
22.00
44.00
66.00
88.00
110.00
132.0
DAYS FROM GERMINATION


1976 DRY WEIGHTS PER WILD RICE PLANT
STATION 4
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
7.00
14.00
21.00
28.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION

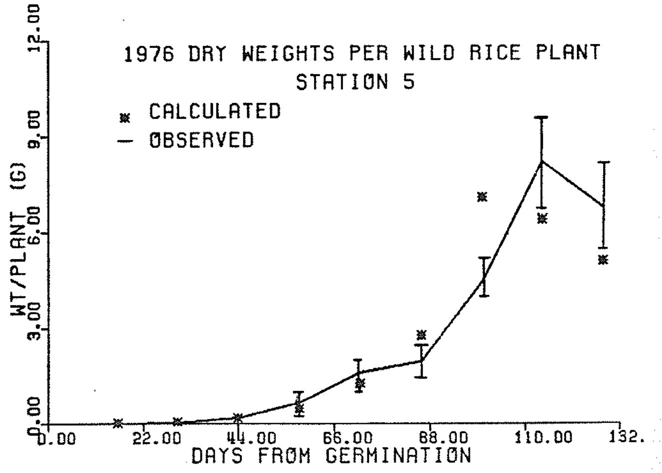
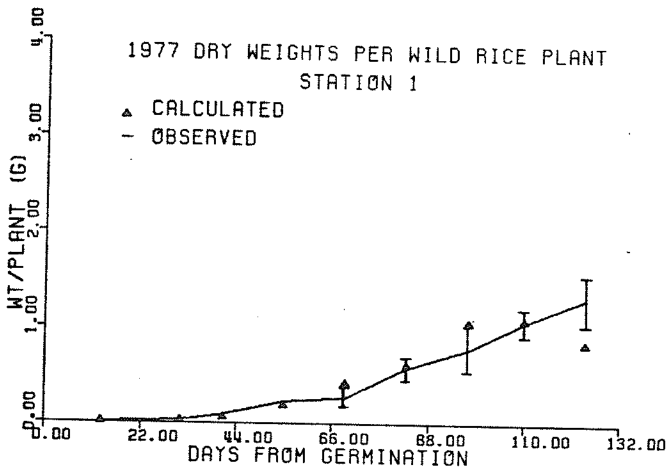
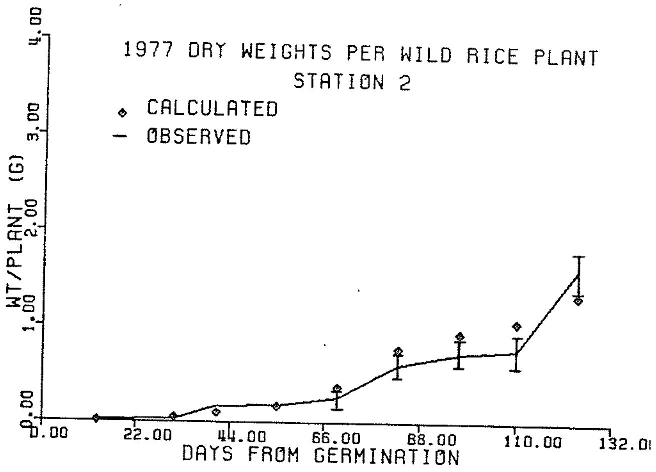
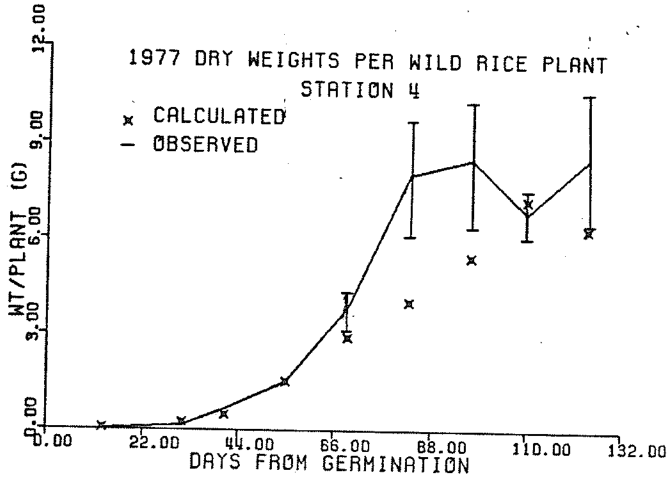

1976 DRY WEIGHTS PER WILD RICE PLANT
STATION 5
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
3.00
6.00
9.00
12.00
0.00
22.00
44.00
66.00
88.00
110.00
132.
DAYS FROM GERMINATION

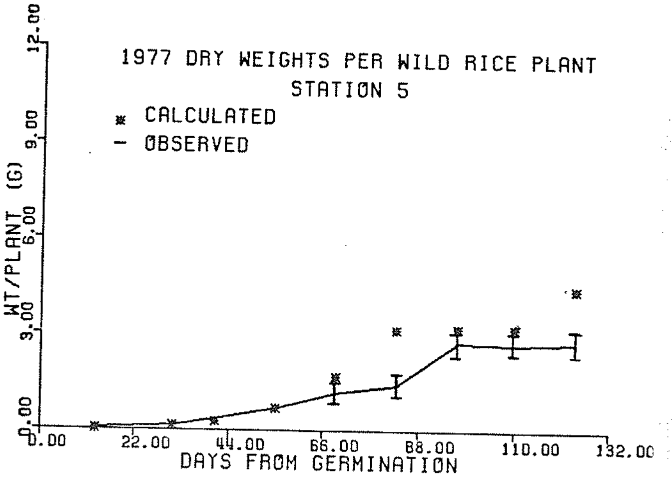
Figure 1-17

The final weight predictions for the wild rice plants in 1977 obtained by combining the time independent portion of the model with the time-dependent portion for stations 1, 2, 4 and 5.


1977 DRY WEIGHTS PER WILD RICE PLANT
STATION 1
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
1.00
2.00
3.00
4.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION


1977 DRY WEIGHTS PER WILD RICE PLANT
STATION 2
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
1.00
2.00
3.00
4.00
0.00
22.00
44.00
66.00
88.00
110.00
132.0
DAYS FROM GERMINATION


1977 DRY WEIGHTS PER WILD RICE PLANT
STATION 4
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
3.00
6.00
9.00
12.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION


1977 DRY WEIGHTS PER WILD RICE PLANT
STATION 5
CALCULATED
OBSERVED
WT/PLANT (G)
0.00
3.00
6.00
9.00
12.00
0.00
22.00
44.00
66.00
88.00
110.00
132.00
DAYS FROM GERMINATION

Conclusions:

This study of among-site variance of the biological, chemical and physical factors which affect the growth of wild rice has demonstrated the following:

i. cluster analysis was able to distinguish the seasonal trends and intercorrelations of the water chemical variables. It was not able to identify definite seasonal trends in the sediment chemical variables, but the association of these variables with each other at any point in time could generally be explained according to the chemical relationships known to occur in anaerobic sediments.

ii. the use of relative rather than absolute values of the biological, chemical and physical variables removed any time dependency and allowed the variables to be used in a discriminant analysis procedure. This discriminant analysis identified those variables which separated the four sampling stations and also showed that the response to these variables remained relatively stable over both years.

iii. the wild rice growth model which included a time dependent and time independent portion was shown to be an effective method of predicting the growth of the wild rice plants at the four sampling stations.

CHAPTER 2

SEASONAL NUTRIENT RELATIONSHIPS OF WILD RICE, *Zizania aquatica* L., NEAR A THERMAL POWER GENERATING STATION AT COHASSET, MINNESOTA

INTRODUCTION

In a previous paper (Lee and Stewart, 1980a) the growth of wild rice, *Zizania aquatica* L., was quantified at four sampling stations near a thermal power generating station according to differences in the biological, chemical and physical factors. In conjunction with this study, it was found that the concentrations of nutrients in the sediments varied among, as well as within sites; the within-site variation being attributed to the effect of river currents.

Many studies have tried to relate the concentrations of elements within aquatic plants to the amounts of nutrients in the surrounding water and sediment (Reimer and Toth, 1968; Anderson *et al*, 1972; Cowgill, 1974a, 1974b; Casey and Downing, 1976; Kollman and Wali, 1976; Carpenter and Adams, 1977). These investigations have produced relatively poor correlations. This phenomenon was recently reviewed for emergent aquatics by Klopatek (1978). He hypothesized that these poor associations could be due to two factors:

(1) the nutrient concentration of emergent macrophytes depends on their phenotypic stage, and

(2) given that a species of emergent macrophyte occurs in a location, its elemental constitution may be expected to fall within definite limits for the major essential elements, regardless of their concentration in the environment.

In the present study, these two hypotheses were examined as they relate to wild rice. The objectives were: (1) to determine if wild rice at the four sampling stations exhibited seasonal trends in its inorganic nutrient levels. If this was the case, to correct for any time dependencies in order to determine which elements differed in concentration among the sites and if these differences could be related to the concentrations in the sediment; and (2) if differences in plant inorganic nutrient levels did not occur, to explain how this could happen even though concentrations of the same nutrients varied both among and within sites.

MATERIALS AND METHODS

The plant components, roots, leaves, stems and heads, used for chemical analyses, were randomly selected from quadrats harvested at four sampling stations (Stations 1, 2, 4 and 5) and one monitoring station (Station 3) situated in the Mississippi River near the Clay-Boswell Steam Electric Station (CBSES), Cohasset, Minnesota. Details of the sampling stations and program were previously outlined by Lee and Stewart (1980a). These samples were rinsed with distilled water to remove extraneous surface material and dried in a drying oven at 105°C. The tissue was then ground in a Wiley mill (0.5 mm mesh size).

For iron, manganese, zinc, copper, calcium, magnesium and potassium determinations, 0.25 g of the plant tissue was ashed overnight in a muffle furnace at 600°C. Extracts were made of the residue using 3N $HC\ell$ and appropriately diluted for determinations with a Perkin-Elmer atomic absorption spectrophotometer model 403 (Perkin-Elmer, 1973). A portion of this extract was also used for determinations of phosphorus following the ammonium vanadate method of Chapman & Pratt (1961).

For sulfur determinations, 0.25 g of the plant tissue was ashed overnight in a muffle furnace at 450°C.

Extracts were made using Morgan's solution and analyzed with a Bausch and Lomb Spectrophotometer Model 20 following the procedure of Chesnin and Yien (1950).

Data Analysis

The data analysis proceeded in three steps:

(i) the 1976 and 1977 seasonal trends of the mineral elements in the tissue of the wild rice plants were isolated using a cluster analysis program contained in the BMDP (Biomed) statistical library (Dixon, 1977) as implemented on the IBM 360/158 at the University of Manitoba. An index of similarity value of 0.7 was always used as the division point for the formation of groups of elements having similar seasonal behavior. Additional details of the procedure were previously described by Lee and Stewart (1980a).

(ii) Klopatek's first hypothesis was examined using the 1977 elemental concentrations in the plant tissue as an example, since the concentrations of the corresponding nutrients in the sediment were known for that year. The elemental concentrations in the plant tissue were first corrected for any time dependency as described by Lee and Stewart (1980a) and an analysis of variance was computed for the time-independent values of each of the elements. Then, in order to assess the effect of the sediment concentrations on the leaf tissue concentrations, correlations were calculated between the time independent values of the elements, isolated as being significantly different among the four stations, and the time independent values of the corresponding element in the sediment.

(iii) Klopatek's second hypothesis was examined by deriving a theoretical model which could explain how a species in a varying chemical environment could contain relatively uniform concentrations of the elements. The modelwas tested against the leaf magnesium concentrations at the four sampling stations in 1976 by iterative fitting until the best (least sum of squares) estimate of the absorption constant in the equation was obtained. Logistic growth equations were calculated for leaf weight using data obtained during a previous (Lee and Stewart, 1980a) study at the four stations following the procedure of Poole (1974). These estimates and the absorption estimate previously calculated were used to test the fit of the model for explaining trends of leaf magnesium concentrations at each of the four stations.

Results

Seasonal Nutrient Trends

Seasonal trends of the elemental concentrations found to exist in wild rice. Table 2-1 illustrates the wide variations which occurred throughout the growing season. The seasonal behavior of the elements in each of the plant components in 1976 and 1977 are described in detail below.

It should be kept in mind that in 1977 the analysis program began two weeks earlier than in 1976. At this time the phenological stage of the plants at Sites 1 and 2 was not as advanced as at Sites 4 and 5 which were affected by the thermal effluent from the power plant. Therefore the nutrient trends at Sites 1 and 2 are initially somewhat out of phase with those of Sites 4 and 5.

Table 2-1. Concentration ranges of selected nutrients found in plant tissue components from sampling sites examined in the Mississippi River near the CBSES during 1976 and 1977.

	Ranges of Plant Component Concentrations			
	Root	Leaf	Stem	Head
Iron (ppm)	3200-4700	110-5300	69-3000	60-250
Manganese (ppm)	160-3200	66-6100	68-3000	44-180
Zinc (ppm)	7-1000	2-580	2-520	3-190
Copper (ppm)	7-640	2-620	2-520	1-200
Calcium (%)	0.24-3.20	0.17-4.00	0.05-2.40	0.05-0.64
Magnesium (%)	0.18-0.51	0.06-0.86	0.03-0.47	0.01-0.21
Potassium (%)	0.09-5.10	0.08-6.00	0.10-8.50	0.17-2.48
Phosphorus (%)	0.03-0.95	0.03-0.50	0.03-0.82	0.05-0.46
Sulfur (%)	0.20-1.50	0.02-0.64	0.04-0.91	0.03-0.36

Roots

Figures 2-1a contain the results of the cluster analysis for root nutrient relationships for 1976.

In 1976, four distinct groups of elements were found (Fig. 2-1a):

Group 1 - iron, potassium, phosphorus
Group 2 - manganese, zinc, copper
Group 3 - calcium, magnesium
Group 4 - sulfur

The general seasonal trends of these groups are shown by Figure 2-1b-e.

Group 1 elements (Fig. 2-1b) had maximum concentrations during the late submerged stage (145 year-days) and then tended to decrease throughout the rest of the growing season, with only slight increases during the emergent and flowering stages.

Group 2 elements (Fig. 2-1c) exhibited a bimodal tendency, with relatively high concentrations before the start of the aerial leaf stage (155 year-days), which gradually decreased until just prior to the start of flowering (190 year-days) at which point an increase in concentrations again commenced. This increase continued until grain formation was initiated (200 year-days) after which point the levels again fell.

Calcium and magnesium, which formed Group 3 (Fig. 2-1d), increased in concentration during the floating leaf stage (145-155 year-days). After this period, the elemental con-

Figure 2-1

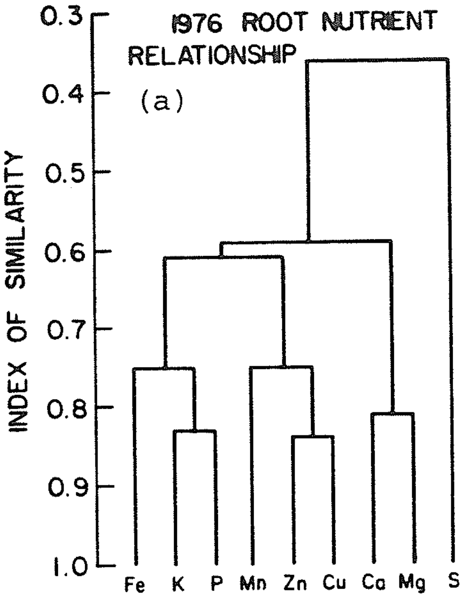
a. Cluster analysis of the 1976 root nutrient relationships for Stations 1, 2, 4 and 5 in the Mississippi River near CBSES.

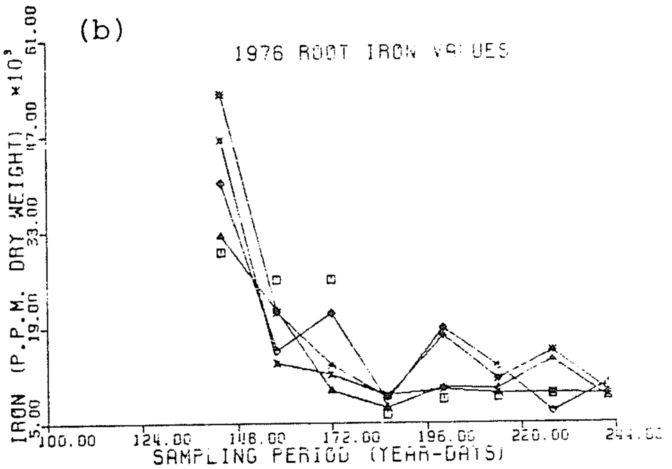
b. Iron values (ppm dry weight) as an example of Group 1 in the cluster analysis (Fig. 2-1a).
Site 1 △ , Site 2 ◇ , Site 3 □ , Site 4 ¤ , Site 5 ✳ .

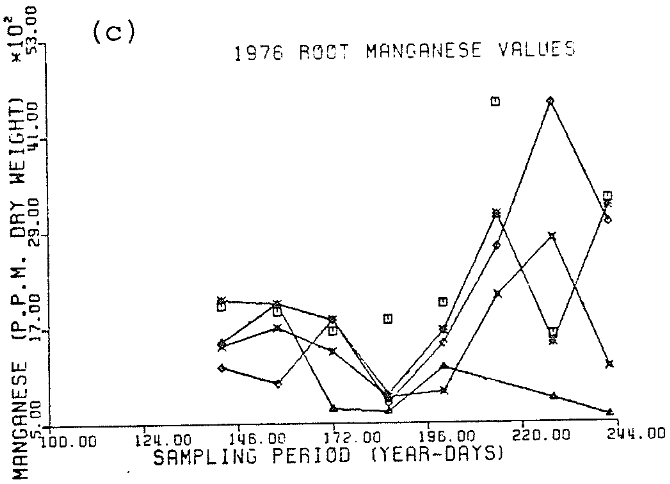
c. Manganese values (ppm dry weight) as an example of Group 2 in the cluster analysis (Fig. 2-1a).
Symbols as of Fig. 2-1b.

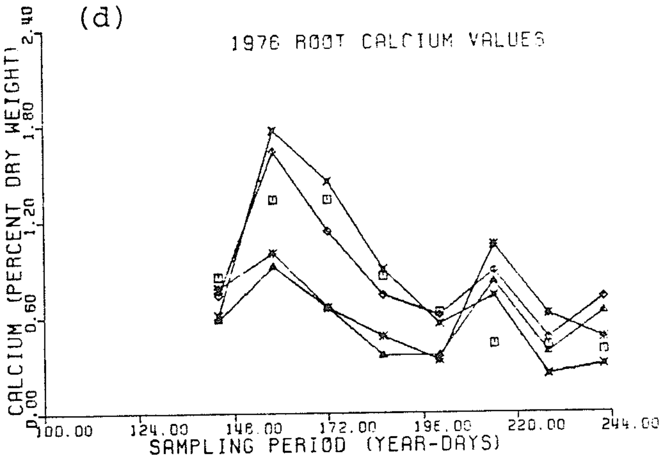
d. Calcium values (% dry weight) as an example of Group 3 in the cluster analysis (Fig. 2-1a). Symbols as of Fig. 2-1b.

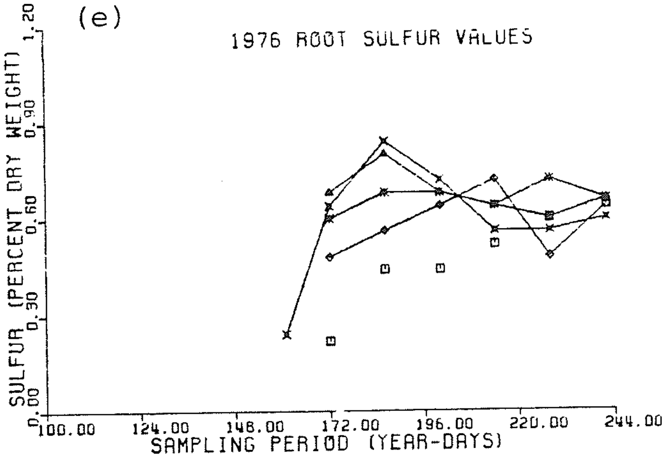
e. Sulfur values (% dry weight) as an example of Group 4 in the cluster analysis (Fig. 2-1a). Symbols as of Fig. 2-1b.


(a)
1976 ROOT NUTRIENT RELATIONSHIP
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Fe
K
P
Mn
Zn
Cu
Ca
Mg
S


(b)
1976 ROOT IRON VALUES
IRON (P.P.M. DRY WEIGHT) ×10³
5.00
19.00
33.00
47.00
61.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(c)
1976 ROOT MANGANESE VALUES
MANGANESE (P.P.M. DRY WEIGHT) ×10²
5.00
17.00
29.00
41.00
53.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(d)
1976 ROOT CALCIUM VALUES
CALCIUM (PERCENT DRY WEIGHT)
0.00
0.60
1.20
1.80
2.40
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(e)
1976 ROOT SULFUR VALUES
SULFUR (PERCENT DRY WEIGHT)
0.00
0.30
0.60
0.90
1.20
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

centrations decreased until the initiation of flowering (200-210 year-days) when a smaller peak in concentrations occurred. As grain formation continued, the levels again decreased.

Group 4 (Fig. 2-1e), consisting only of sulfur, tended to increase in concentration during the late submerged and the floating leaf growth phases, and then decreased throughout the rest of the growing season.

In 1977, there were four groups of elements (Fig. 2-2a):

Group 1 - sulfur
Group 2 - calcium, magnesium, potassium
Group 3 - iron, manganese, copper, zinc
Group 4 - phosphorus

In general, the elements in these groups behaved similarly to those of 1976.

Sulfur again comprised a separate group and tended to decrease throughout the summer (Fig. 2-2b). The increase in the late submerged and floating leaf stages, which was evident in 1976, is shown only by Station 1 in 1977. This may be because the first sulfur determination in 1977 occurred only after this stage had been past at Stations 4 and 5, and insufficient sample was available for determinations at Station 2.

Figures 2-2

a. Cluster analysis of the 1977 root nutrient relationships for stations 1, 2, 4 and 5 in the Mississippi River near CBSES.

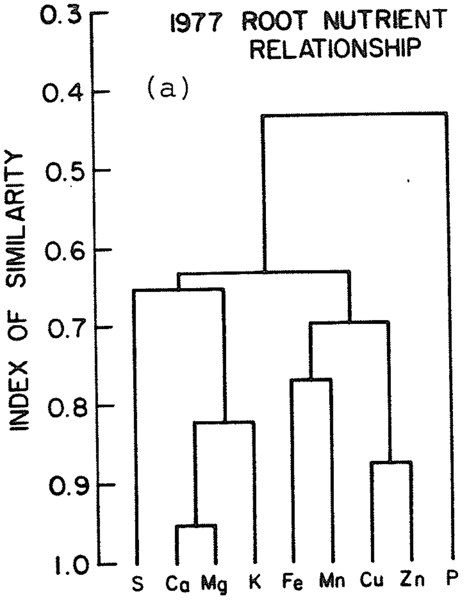
b. Sulfur values (% dry weight) as an example of Group 1. in the cluster analysis (Fig. 2-2a).

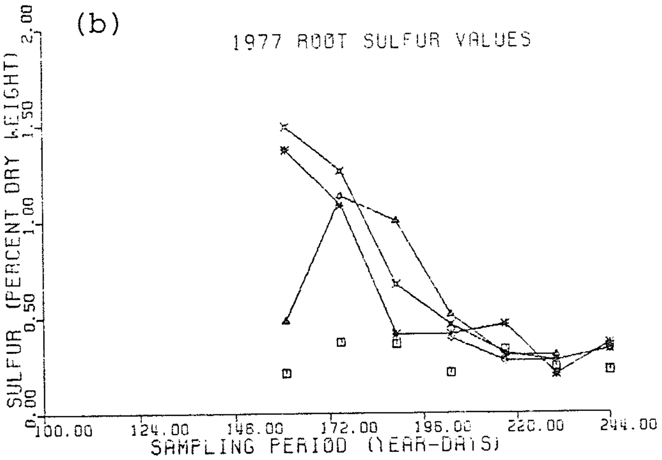
Site 1 △ , Site 2 ◇ , Site 3 □ , Site 4 ⌧ , Site 5 ✳ .

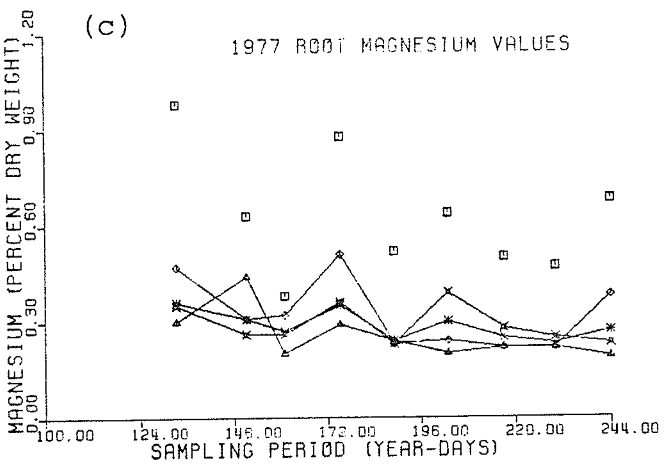
c. Magnesium values (% dry weight) as an example of Group 2 in the cluster analysis (Fig. 2-2a). Symbols as of Fig. 2-2b.

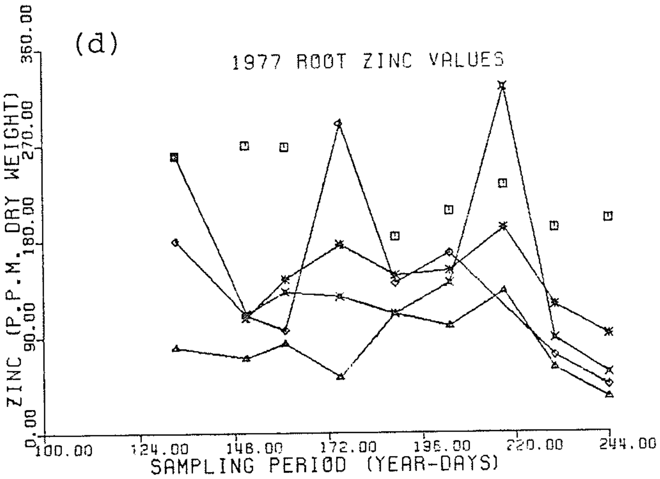
d. Zinc values (ppm dry weight) as an example of Group 3 in the cluster analysis (Fig. 2-2a). Symbols as of Fig. 2-2b.

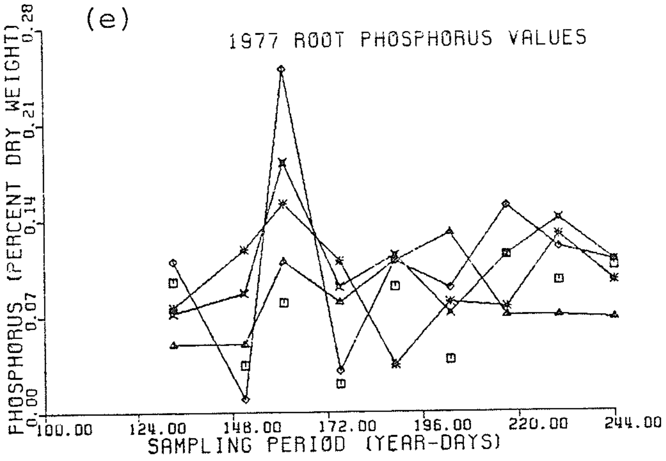
e. Phosphorus values (% dry weight) as an example of Group 4 in the cluster analysis (Fig. 2-2a). Symbols as of Fig. 2-2b.


1977 ROOT NUTRIENT RELATIONSHIP
(a)
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
S
Ca
Mg
K
Fe
Mn
Cu
Zn
P


(b)
1977 ROOT SULFUR VALUES
SULFUR (PERCENT DRY WEIGHT)
0.00
0.50
1.00
1.50
2.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(c)
1977 ROOT MAGNESIUM VALUES
MAGNESIUM (PERCENT DRY WEIGHT)
0.00
0.30
0.60
0.90
1.20
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(d)
1977 ROOT ZINC VALUES
ZINC (P.P.M. DRY WEIGHT)
0.00
90.00
180.00
270.00
360.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


(e)
1977 ROOT PHOSPHORUS VALUES
PHOSPHORUS (PERCENT DRY WEIGHT)
0.00
0.07
0.14
0.21
0.28
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

Although in 1976 (Fig. 2-1d) calcium and magnesium exhibited an initial increase in concentration during the submerged leaf stages (130-150 year days), a slight decline was observed in 1977 (Fig. 2-2c). Behaviour throughout the rest of the growing season was essentially the same as in 1976. There may be a possibility of a second smaller increase in accumulation of these elements during the final grain filling period (215-225 year days) as evidenced by the small peak during this time in 1977. The fact that the final decline in concentration of the Group 2 elements after this peak was not present in 1976 may have been because the plants were slightly further developed at this time in 1977. Potassium trends resembled those of 1976 except for the initial decline during the floating leaf stage which were not apparent the first year possibly because of the later sampling determinations.

Manganese and zinc in Group 3 (Fig. 2-2d) had similar seasonal patterns to 1976. There was an initial high concentration of these elements at the floating leaf stage which declined until the initiation of flowering (190 year-days) at which point levels again increased. This was followed by a final decrease as grain formation proceeded. Iron concentrations in 1977 generally declined during the growing season as they did in 1976 with only slight increases at the start of the flower and grain formation stages. There was one difference which was evident in 1977 in the trends of manganese, zinc and iron at Sites 1 and 2 which were less advanced in plant development early in the growing season than sites 4 and 5. These two sites indicated that in all three of the above elements, there appeared to be initial increases in concentrations during the early stages of the submerged growth phase. Copper trends in 1977 exhibited an initial decline in concentration from the submerged phase and an increase in concentration in the floating leaf phase which were not evident in 1976 possibly due to the later sampling in that year. Otherwise the levels behaved as they did in 1976.

Phosphorus, comprising Group 5 (Fig. 2-2e), resembled the 1976 trend except for an initial increase in concentration during the submerged and floating leaf stages not detected in 1976 because no analyses were done at this stage.

Leaves

Figures 2-3 and 2-4 contain the results of the cluster analysis for the nutrient relationships for 1976 and 1977 and the seasonal trends exhibited by the major groups.

Two major groups were formed in 1976 (Fig. 2-3a):

Group 1 - iron, magnesium, manganese, calcium

Group 2 - zinc, potassium, phosphorus, sulfur, copper

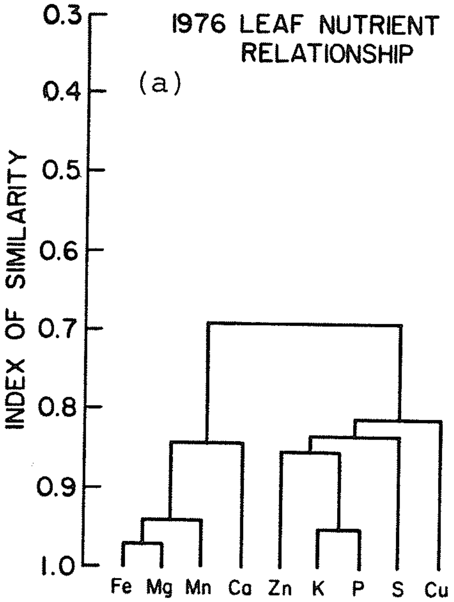
The Group 1 elements (Fig. 2-3b) increased in concentration during the floating leaf stage, and then decreased until the initiation of flowering at which point their concentrations again increased.

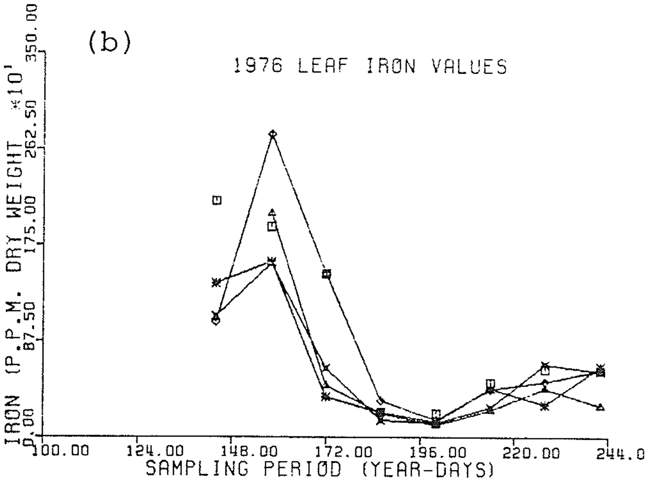
Figure 2-3

a. Cluster analysis of the 1976 leaf nutrient relationships for stations 1, 2, 4 and 5 in the Mississippi river near CBSES.

b. Iron values (ppm dry weight) as an example of Group 1 in cluster analysis (Fig. 2-3a).
Site 1 △ , Site 2 ◇ , Site 3 ⊡ , Site 4 ⌘ , Site 5 ✳ .

c. Copper values (ppm dry weight) as an example of Group 2 in cluster analysis (Fig. 2-3a). Symbols as of Fig. 2-3b.


1976 LEAF NUTRIENT RELATIONSHIP
(a)
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Fe
Mg
Mn
Ca
Zn
K
P
S
Cu


(b)
1976 LEAF IRON VALUES
IRON (P.P.M. DRY WEIGHT ×10¹)
0.00
87.50
175.00
262.50
350.00
100.00
124.00
148.00
172.00
196.00
220.00
244.0
SAMPLING PERIOD (YEAR-DAYS)

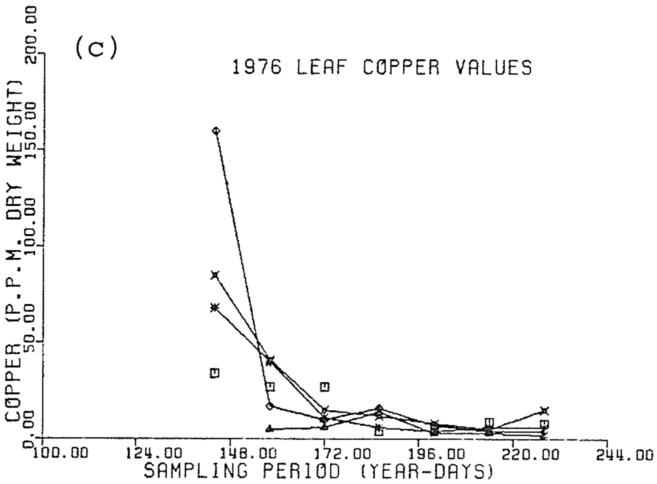

(c)
1976 LEAF COPPER VALUES
COPPER (P.P.M. DRY WEIGHT)
0.00
50.00
100.00
150.00
200.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

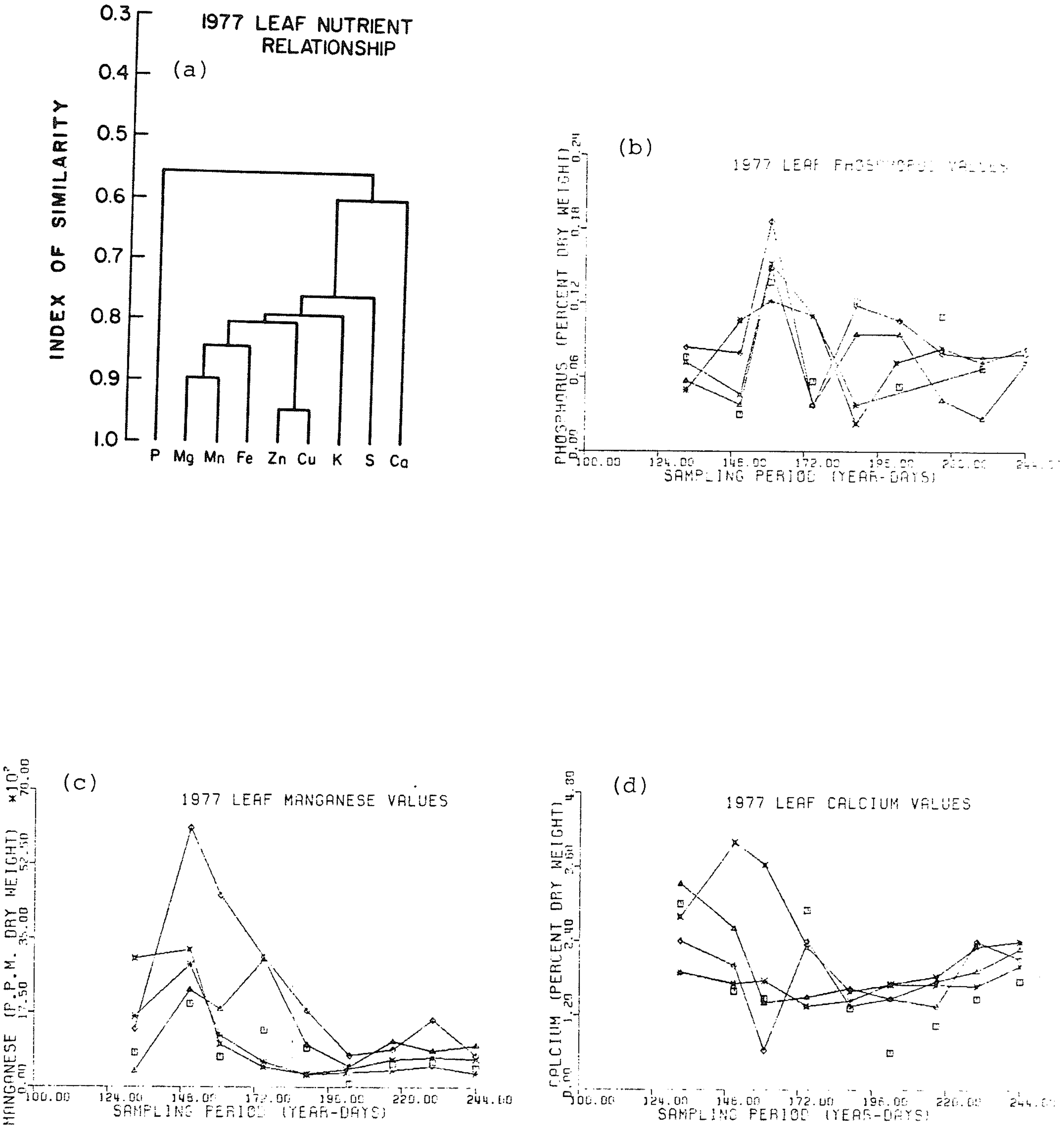
Figure 2-4

a. Cluster analysis of the 1977 leaf nutrient relationships for stations 1, 2, 4 and 5 in the Mississippi river near CBSES.

b. Phosphorus values (% dry weight) as an example of Group 1 in the cluster analysis (Fig. 2-4a).
Site 1 ⟁ , Site 2 ◇ , Site 3 ⊡ , Site 4 ¤ , Site 5 ✳ .

c. Manganese values (ppm dry weight) as an example of Group 2 in the cluster analysis (Fig. 2-4a).
Symbols as of Fig. 2-4b.

d. Calcium values (% dry weight) as an example of Group 3 in the cluster analysis (Fig. 2-4a).
Symbols as of Fig. 2-4b.


(a)
1977 LEAF NUTRIENT RELATIONSHIP
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
P
Mg
Mn
Fe
Zn
Cu
K
S
Ca
(b)
1977 LEAF PHOSPHORUS VALUES
PHOSPHORUS (PERCENT DRY WEIGHT)
0.00
0.06
0.12
0.18
0.24
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)
(c)
1977 LEAF MANGANESE VALUES
MANGANESE (P.P.M. DRY WEIGHT) ×10²
0.00
17.50
35.00
52.50
70.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)
(d)
1977 LEAF CALCIUM VALUES
CALCIUM (PERCENT DRY WEIGHT)
0.00
1.20
2.40
3.60
4.80
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

The Group 2 elements (Fig. 2-3c) had initially high concentrations during the submerged and floating leaf stages, after which they decreased in concentration and remained relatively stable at low levels during the rest of the growing season.

In 1977, three groups of elements were found (Fig. 2-4a):

Group 1 - phosphorus

Group 2 - magnesium, manganese, iron, zinc, copper, potassium, sulfur

Group 3 - calcium

Phosphorus, in Group 1 (Fig. 2-4b) showed an initial tendency to decrease in concentration during the submerged leaf stage and then increase in concentration in the floating leaf stage. Seasonal behaviour after that resembled 1976.

Group 2 elements (Fig. 2-4c) generally tended to decrease throughout the growing season, but examination of some of the subclusters can give further details of their behaviour. Manganese and magnesium, which were very closely correlated had seasonal trends similar to 1976, except for an initial increase during the submerged leaf stage. Iron trends in 1976 were identical to those of 1977. Zinc, copper, potassium and sulfur decreased in concentration during the submerged leaf stage, then increased in concentration during the floating leaf stage. With the start of the emergent stage, these levels again fell, but were characterized by a small peak which occurred as flowering commenced; later falling with the continuance of grain formation.

Calcium, as the sole representative of Group 3 (Fig. 2-4d), had similar seasonal fluctuations to calcium in 1976 except for an initial decrease in concentration during the submerged leaf stage again possibly due to the later sampling date in 1976.

Stems

In both 1976 and 1977 the seasonal trends of all the elements were similar, and therefore all highly associated in the cluster analysis (Fig. 2-5a, 2-6a).

In 1976 (Fig. 2-5b), maximum concentrations occurred in the floating leaf stage and began to decrease as the plant entered the emergent stage. Later, with the start of flowering, a slight increase in concentration again occurred, which declined with the continued development of the grain.

In 1977 (Fig. 2-6b) concentrations of all elements, manganese, phosphorus and potassium, were again at high levels in early spring during the submerged and floating leaf stages and decreased throughout the summer. Differences in manganese, phosphorus and potassium were perhaps attributable to the earlier sampling in 1977. Phosphorus and potassium exhibited an initial decrease during the submerged leaf stage followed by an increase in concentration during the floating leaf stage. Manganese concentrations generally increased in the submerged leaf stage, and then decreased as in 1976 (Fig. 2-6b).

Figure 2-5

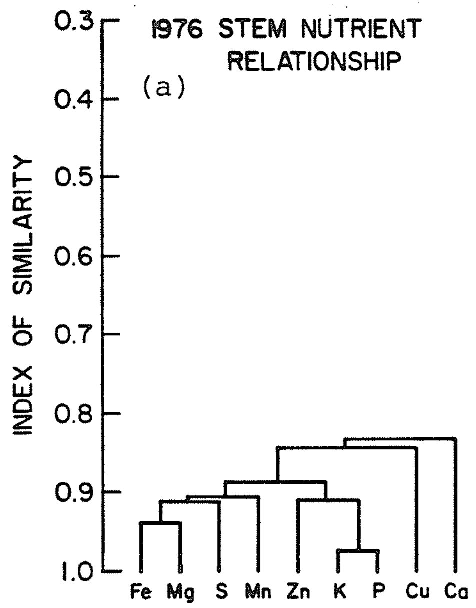
a. Cluster analysis of the 1976 stem nutrient relationship for station 1, 2, 4 and 5 in the Mississippi river near CBSES.

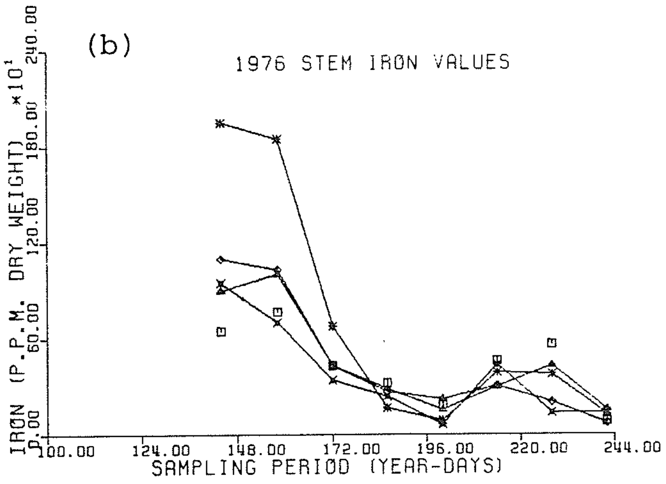
b. Iron values (ppm dry weight) as an example of group 1 in the cluster analysis (Fig. 2-5a).
Site 1 △ , Site 2 ◇ , Site 3 □ , Site 4 ⊠ , Site 5 ✳ .

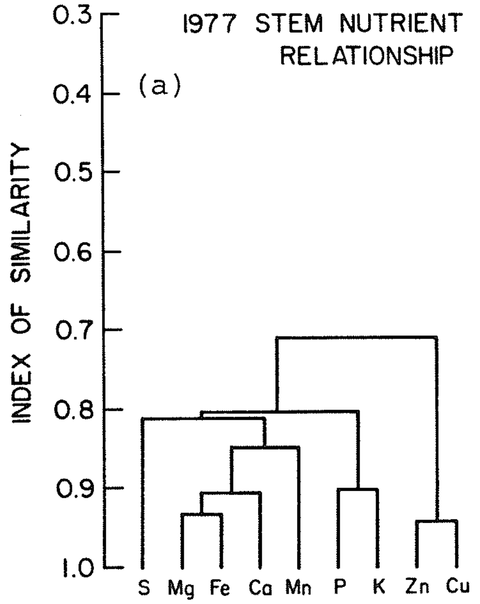
Figure 2-6

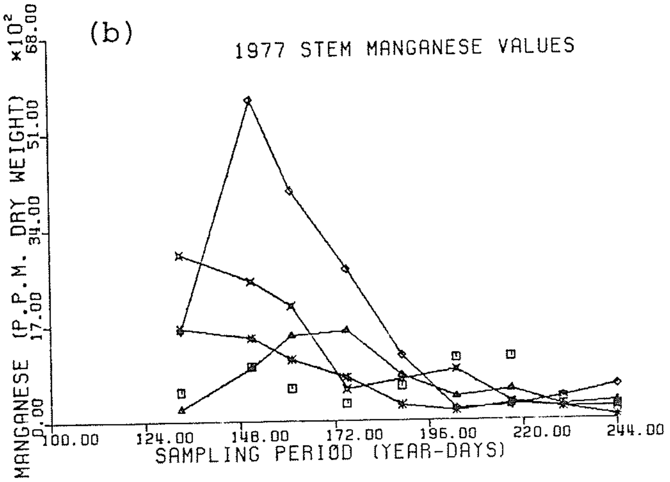
a. Cluster analysis of the 1977 stem nutrient relationship for station 1, 2, 4 and 5 in the Mississippi river near CBSES.

b. Manganese values (ppm dry weight) as an example of group 1 to the cluster analysis (Fig. 2-6a).
Symbols as of Fig. 2-5b.


1976 STEM NUTRIENT RELATIONSHIP
(a)
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Fe
Mg
S
Mn
Zn
K
P
Cu
Ca


(b)
1976 STEM IRON VALUES
IRON (P.P.M. DRY WEIGHT) ×10¹
0.00
60.00
120.00
180.00
240.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)


1977 STEM NUTRIENT RELATIONSHIP
(a)
INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
S
Mg
Fe
Ca
Mn
P
K
Zn
Cu


(b)
1977 STEM MANGANESE VALUES
MANGANESE (P.P.M. DRY WEIGHT) ×10²
0.00
17.00
34.00
51.00
68.00
100.00
124.00
148.00
172.00
196.00
220.00
244.00
SAMPLING PERIOD (YEAR-DAYS)

Heads

Only four sampling observations were possible for the nutrient analysis of the heads, making it difficult to attach much significance to the type of association analysis used for the roots, leaves and stems. Problems were also suspected in the accuracy of the head samples since the entire panicles were ground for use in the chemical analysis . Temporal variation in the relative proportions of vegetative and flowering parts may have caused some inconsistencies in the data. In spite of this problem, by examining the 1976 and 1977 concentrations it is possible to divide the elements into three groups based on their general seasonal trends:

Group 1 - manganese, calcium
Group 2 - zinc, phosphorus, potassium
Group 3 - iron, magnesium, copper, sulfur

Elements in Group 1 generally increased in concentration in the heads. Those elements in Group 2 tended to decrease, while Group 3 elements remained at a relatively constant concentration throughout the remainder of the growing season.

Discussion

Relationships between the elemental concentrations in the plant tissue with the corresponding element in the sediment were assessed in terms of Klopatek's two hypotheses. The first hypothesis was examined using the 1977 leaf tissue and sediment concentrations as an example. The second hypothesis was examined by deriving a theoretical model which could explain the observed seasonal trends and testing this model with the 1976 data on concentrations of magnesium in leaves as an example.

Hypothesis 1: Lack of Plant Tissue-Sediment Correlations due to Seasonal Trends

A time-independent analysis of variance for all elements revealed that magnesium, manganese, iron, zinc and copper exhibited statistically significant differences in concentrations in the leaves during 1977. Such differences in the elemental concentrations in the plant tissue among the various sites could occur either due to (i) differences in sediment concentrations or (ii) luxury consumption, where the element is present in the plant in excess of that required for normal growth. Examination of the data reveals that the latter is probably the case.

Concentrations of all the above elements were higher in the plant tissue at Stations 1 and 2 than Stations 4 and 5. Assuming that nutrient concentrations in the sediment caused these differences, there should be positive correlations between the time independent sediment and tissue concentrations of the corresponding element. But examination of Table 2-2 reveals that no significant correlations occurred between the leaf and sediment concentrations for magnesium, manganese, and zinc, and negative correlations actually existed for iron and copper. Therefore sediment concentrations did not cause these differences. Figure 2-7 shows the relationships of time independent concentrations of magnesium, manganese, iron, zinc and copper in the leaves versus time independent weights per wild rice plant. The figure illustrates that as the concentrations of the mineral elements in the plant tissue decreased, the weights per wild rice plant increased to approximately the average mean weight (100 percent). Thereafter concentrations in the plant tissue remained relatively constant, indicating that the supply of nutrients was always present in sufficient quantities to compensate for any increases in growth, and that luxury consumption was probably occurring. One other interpretation which could be made from the figure is that at the higher levels the mineral elements were present in toxic quantities which were limiting the growth of the rice plants. However, in the first part of this study (Lee and Stewart, 1980a), the growth of wild rice at the four stations was modelled using other factors extracted in a discriminant analysis procedure, none of which were the above mineral elements.

In terms of Klopatek's first hypothesis, although seasonal trends do exist in the tissue concentrations of wild rice which could alter the significance of any correlation

Table 2-2. Correlation coefficients between time-independent mineral concentrations in leaf tissue versus time-independent concentrations in the sediment. n = 36.

Element in Leaf	Correlation (r value) between Tissue Concentration and Sediment Concentration
magnesium	.077
manganese	.066
iron	-.457*
zinc	-.257
copper	-.333*

---

*statistically significant at the P=.05 level

Figure 2-7

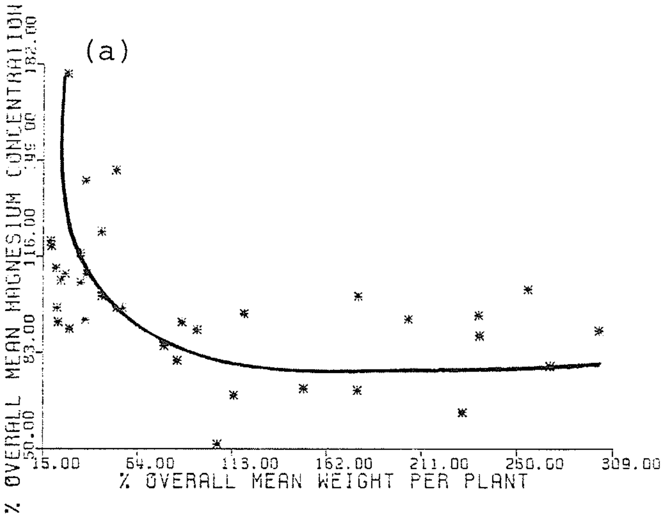
a. Relationship between time-independent overall mean magnesium concentrations (% ppm dry weight) in leaves from stations 1, 2, 4 and 5 and the overall mean weight per plant (% g dry weight).

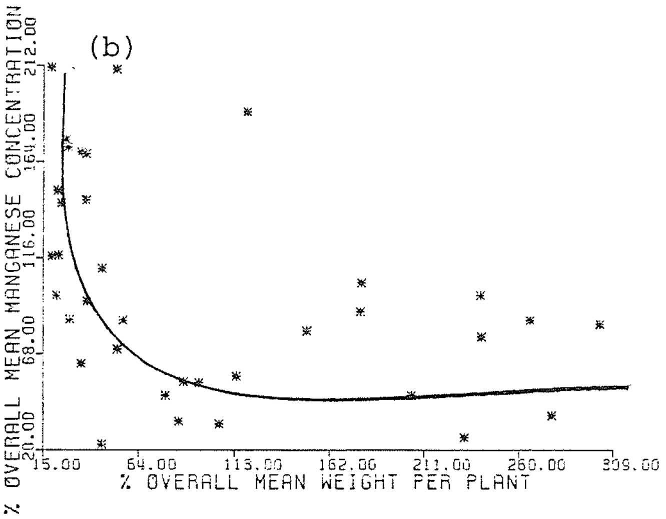
b. Relationship between the time-independent overall mean manganese concentration (% ppm dry weight) in leaves from stations 1, 2, 4 and 5 and the overall mean weight per plant (% g dry weight).

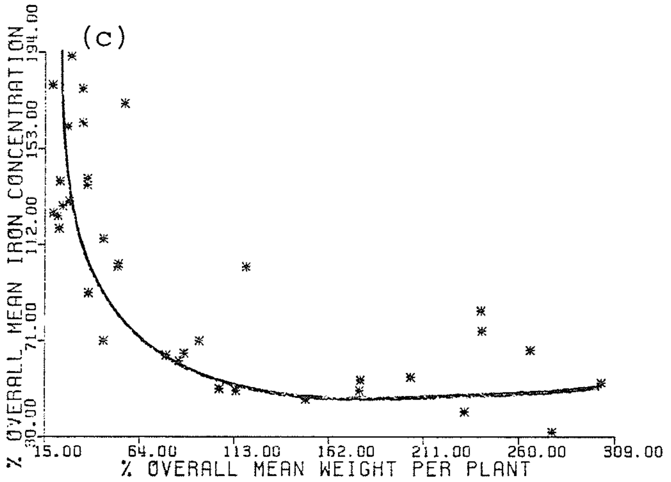
c. Relationship between the time-independent overall mean iron concentration (% ppm dry weight) in leaves from stations 1, 2, 4 and 5 and the overall mean weight per plant (% g dry weight).

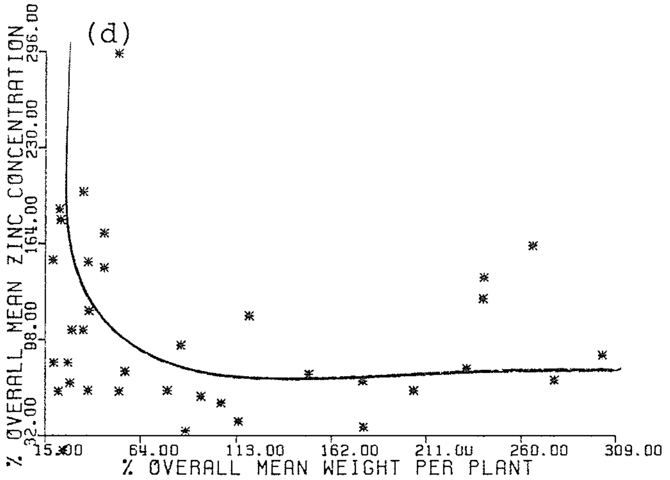
d. Relationship between the time-independent overall mean zinc concentration (% ppm dry weight) in leaves from stations 1, 2, 4 and 5 and the overall mean weight per plant (% g dry weight).

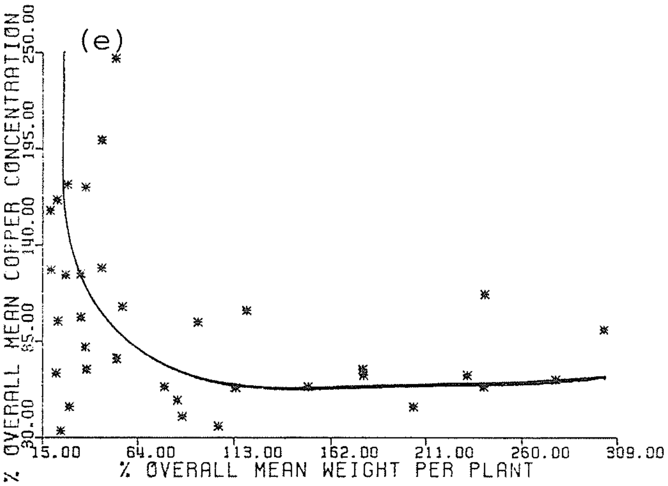
e. Relationship between the time-independent overall mean copper concentration (% ppm dry weight) in leaves from stations 1, 2, 4 and 5 and the overall mean weight per plant (% g dry weight).


(a)
% OVERALL MEAN MAGNESIUM CONCENTRATION
50.00
83.00
116.00
149.00
182.00
15.00
64.00
113.00
162.00
211.00
260.00
309.00
% OVERALL MEAN WEIGHT PER PLANT


(b)
% OVERALL MEAN MANGANESE CONCENTRATION
20.00
68.00
116.00
164.00
212.00
15.00
64.00
113.00
162.00
211.00
260.00
309.00
% OVERALL MEAN WEIGHT PER PLANT


(c)
% OVERALL MEAN IRON CONCENTRATION
30.00
71.00
112.00
153.00
194.00
15.00
64.00
113.00
162.00
211.00
260.00
309.00
% OVERALL MEAN WEIGHT PER PLANT


(d)
% OVERALL MEAN ZINC CONCENTRATION
32.00
98.00
164.00
230.00
296.00
15.00
64.00
113.00
162.00
211.00
260.00
309.00
% OVERALL MEAN WEIGHT PER PLANT


(e)
% OVERALL MEAN COPPER CONCENTRATION
30.00
85.00
140.00
195.00
250.00
15.00
64.00
113.00
162.00
211.00
260.00
309.00
% OVERALL MEAN WEIGHT PER PLANT

with the sediment, even when they are corrected for time-dependency, a correlation still does not exist. In the present instance, any differences which did occur were attributed to luxury consumption and therefore Klopatek's first hypothesis could not explain the lack of plant tissue-sediment correlations in this instance.

Hypothesis 2: Lack of Plant Tissue-Sediment Correlations due to Relatively Constant Tissue Concentrations.

Although the concentrations of the nutrients varied considerably both among and within sites, the seasonal trends for the elemental concentrations in the plant tissue indicated that at any one time the concentrations were relatively constant at the four stations. Thus no correlation between the plant tissue and sediment would be expected and this seems to verify Klopatek's second hypothesis. How this phenomen could occur is not fully understood. One clue to the mechanism may be gained by relating the concentrations in the plant tissue to the weights of the wild rice plants.

It was known from a previous study (Lee and Stewart, 1980a) that the weights per wild rice plant were considerably different at the four stations for each year. However, since the elemental tissue concentrations at any one time were the same (even though the weights per plant were different), this suggests that the elements were absorbed from the sediment in equal proportions per unit weight and at the same rate per unit time. Such a concept is essentially an extension of the "carrier" theory for the active uptake of ions introduced by Epstein and Hagen (1952) and reviewed by Epstein (1972). Epstein determined that ion uptake can be described by enzyme kinetics based on the Michaelis-Menten equation. According to this theory, the rate of absorption of an ion increases with increasing external concentrations of the ion, but at progressively higher concentrations, each increment of concentration adds less of an increment in absorption rate until a concentration is reached beyond which the absorption rate becomes independent of the external concentration (Epstein, 1972).

Applying this theory to the uptake of nutrients in emergent macrophytes, a model can be derived which assumes concentrations of the ions in the sediment are such that the maximum rate of absorption has been reached.

The concentration of an element in the plant at time $t + \Delta t$ is :

$$C_{t + \Delta t} = \frac{A_{t + \Delta t}}{W_{t + \Delta t}} \qquad [2.1]$$

where:

$C_{t + \Delta t}$ = concentration of the element in the plant tissue (% (g/100g)), (ppm (mg/kg)) at time $t + \Delta t$

$A_{t + \Delta t}$ = accumulation of the element (mg,g) present in the plant at time $t + \Delta t$

$W_{t + \Delta t}$ = weight of the plant (g) at time $t + \Delta t$

The accumulation of an element at any time is equivalent to the integral of absorption of the element from the initiation of growth ($t = t_o$). Substituting this integral for $A_{t + \Delta t}$, equation [2.1] becomes:

$$C_{t + \Delta t} = \frac{\int_{t_o}^{t + \Delta t} a\, W(u)\, du}{W_{t + \Delta t}} \qquad [2.2]$$

where:

a = absorption rate of the element (mg/kg/time; g/100g/time)

W(u) = weight of the plant at time t = u

Considering the accumulation of the element after any fixed point in time, t, equation [2.2] can be re-written as:

$$C_{t + \Delta t} = \frac{\int_{t_o}^{t} a\, W(u)\, du + \int_{t}^{t + \Delta t} a\, W(u)\, du}{W_{t + \Delta t}} \qquad [2.3]$$

The first integral in equation [2.3] is the accumulation up to time t ($=C_tW_t$). Making this substitution, equation [2.3] becomes:

$$C_{t + \Delta t} = \frac{C_tW_t + \int_{t}^{t + \Delta t} a\, W(u)\, du}{W_{t + \Delta t}} \qquad [2.4]$$

Since a is a constant, equation [2.4] can be further simplified to:

$$C_{t + \Delta t} = \frac{C_t W_t + a\int_t^{t + \Delta t} W(u)\, du}{W_{t + \Delta t}} \qquad [2.5]$$

Equation [2.5] is the general form of the concentration model for any plant assuming a constant rate of absorption.

For the specific case of wild rice the weight at any time W(t) can be described by a logistic equation as below:

$$W(t) = \frac{K}{1 + e^{c - rt}} \qquad [2.6]$$

The definite integral for equation [2.6] is as below:

$$\int_t^{t + \Delta t} W(u)\, du = F(t + \Delta t) - F(t) \qquad [2.7]$$

where:

$$F(t) = K[t + (1/r)\log_e(1 + e^{c - rt})]$$

The result from equation [2.7] can then be substituted into equation [2.5] to yield the concentration of the particular element at any time, $t + \Delta t$, after time t, given the observed concentration at time t (C_t), the absorption rate (a), and the parameters of the logistic weight-growth curve (K, c and r).

In order to determine if this model could be used to describe the type of seasonal nutrient trends found in a wild rice plant, a theoretical example was initially tried using the calculated overall mean values for the weights per wild rice plant for 1976 from a logistic model used in describing the growth of wild rice in a previous paper (Lee and Stewart, 1980a). Figure 2-8 shows the results for this. An initial concentration was arbitrarily assumed to be 0.5. By increasing the absorption rate (a=0.004, Fig. 2-8) or decreasing the absorption (a=0.002, Fig. 2-8), the calculated curves are shown to very closely resemble the type observed for the elemental seasonal concentrations in the wild rice plants.

The next step was to test the model against the actual data found in the rice plant to calculate the absorption rate, a. Leaf magnesium concentrations in 1976 were used as an example. There was no particular reason for selecting magnesium, but the model does assume active uptake, and so leaf or stem tissue should give a better estimate of absorption rate than root tissue where passive absorption occurs to some extent (Epstein, 1972). The observed and expected magnesium concentrations, calculated from the logistic growth equation parameters (K,c and r) and the best fit (least sum of squares) for a, are shown by Figure 2-9. Good fits were obtained for stations 1 and 4 throughout most of the growing season, but stations 2 and 5 had good fits only after approximately 90 days. The poor fits at these two stations could possibly be attributed to one or more of the following factors:

Figure 2-8

Theoretical relationships between seasonal concentrations (% dry weight) and days from germination.

absorption rate = 0.004 g/100 g/day ---------

absorption rate = 0.002 g/100 g/day ————

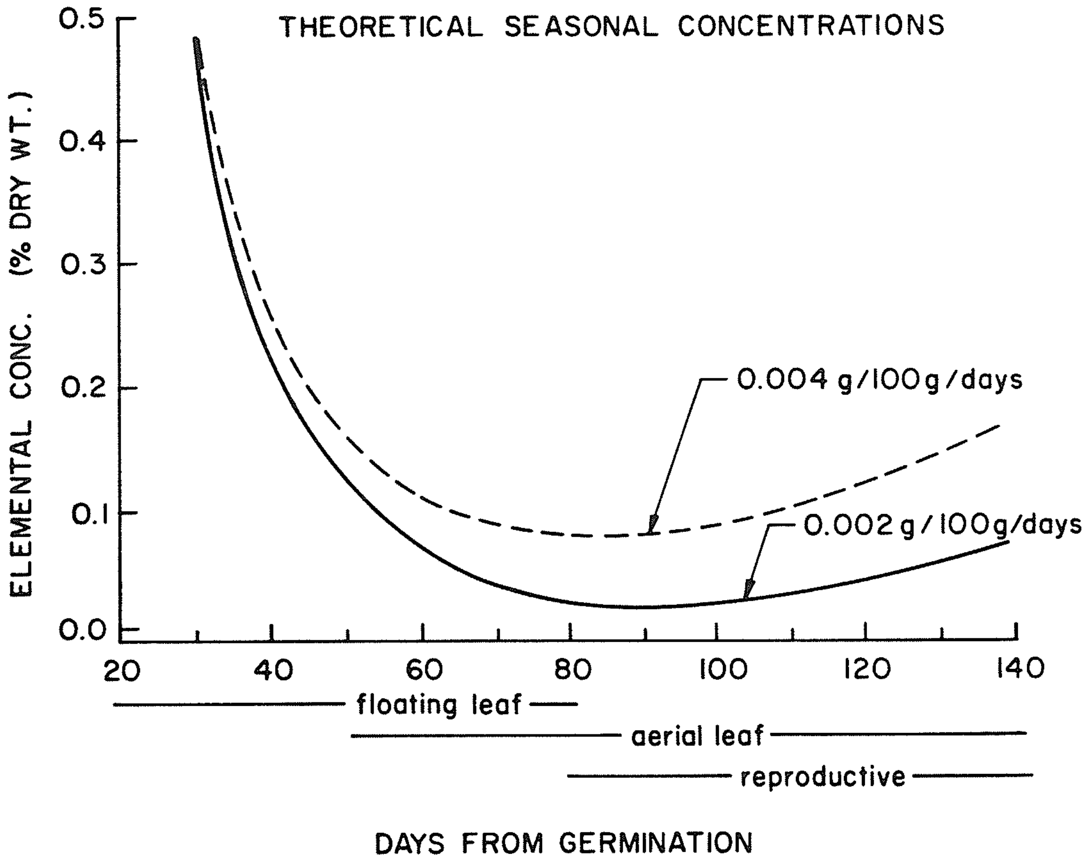
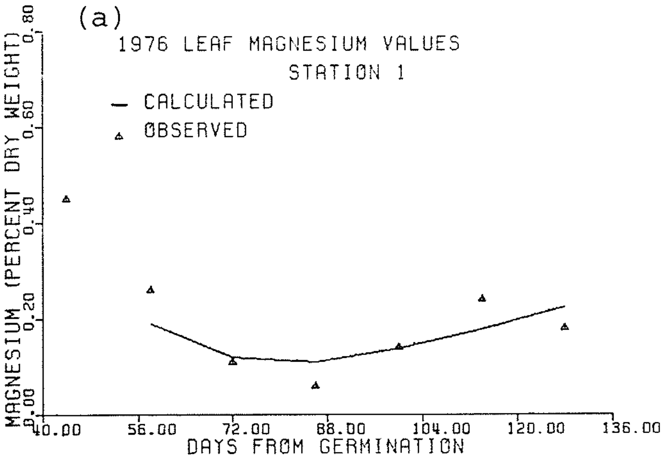

THEORETICAL SEASONAL CONCENTRATIONS
ELEMENTAL CONC. (% DRY WT.)
0.5
0.4
0.3
0.2
0.1
0.0
0.004 g/100g/days
0.002 g/100g/days
20
40
60
80
100
120
140
floating leaf
aerial leaf
reproductive
DAYS FROM GERMINATION

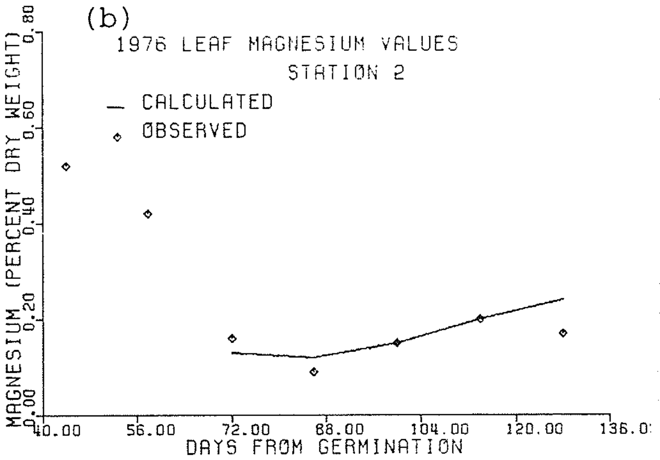
Figure 2-9

1976 observed leaf magnesium concentrations and concentrations calculated using the fitted logistic leaf growth data and a constant rate of absorption of 0.0036 g of Mg/100g/day at (a) Station 1 (c=6.388, r=0.086, K=1.330) (b) Station 2 (c=6.269, r=0.087, K=0.690) (c) Station 4 (c=5.767, r=0.079, K=1.820) (d) Station 5 (c=5.187, r=0.072, K=0.760)

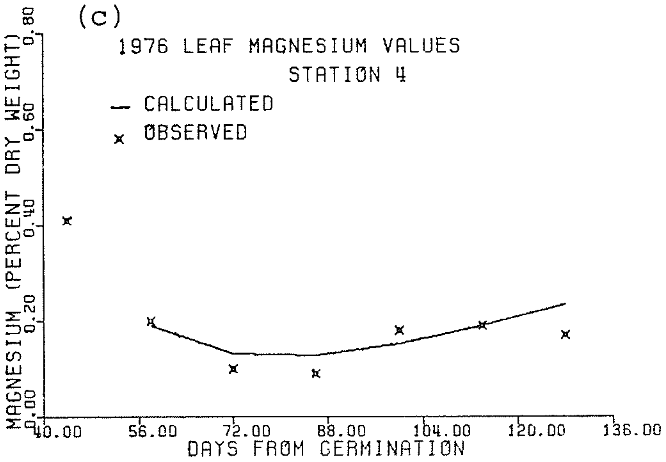
(a)


1976 LEAF MAGNESIUM VALUES
STATION 1
CALCULATED
OBSERVED
MAGNESIUM (PERCENT DRY WEIGHT)
0.00
0.20
0.40
0.60
0.80
40.00
56.00
72.00
88.00
104.00
120.00
136.00
DAYS FROM GERMINATION

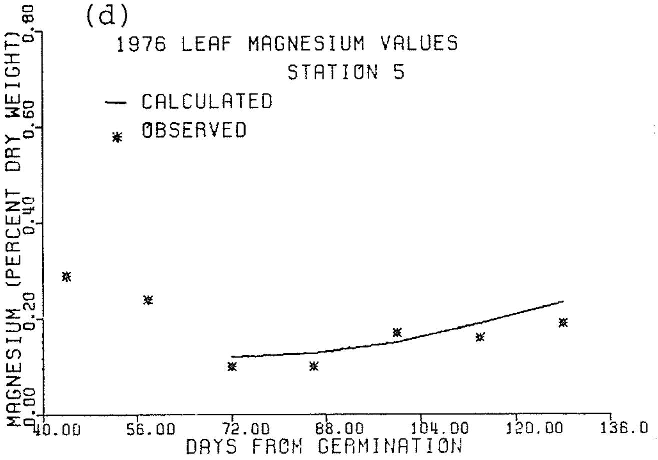
(b)


1976 LEAF MAGNESIUM VALUES
STATION 2
CALCULATED
OBSERVED
MAGNESIUM (PERCENT DRY WEIGHT)
0.00
0.20
0.40
0.60
0.80
40.00
56.00
72.00
88.00
104.00
120.00
136.0
DAYS FROM GERMINATION

(c)


1976 LEAF MAGNESIUM VALUES
STATION 4
CALCULATED
OBSERVED
MAGNESIUM (PERCENT DRY WEIGHT)
0.00
0.20
0.40
0.60
0.80
40.00
56.00
72.00
88.00
104.00
120.00
136.00
DAYS FROM GERMINATION

(d)


1976 LEAF MAGNESIUM VALUES
STATION 5
CALCULATED
OBSERVED
MAGNESIUM (PERCENT DRY WEIGHT)
0.00
0.20
0.40
0.60
0.80
40.00
56.00
72.00
88.00
104.00
120.00
136.0
DAYS FROM GERMINATION

(i) the model assumes that weights of the plant at any time were reasonably accurate and increase according to a deterministic logistic equation. But during the submerged and floating leaf stages, the plant grows very slowly between sampling periods and so the weight change is small. The accuracy of the measurement of leaf weight per wild rice plant at this time may not have been sufficient to account for such small weight changes.

(ii) the model assumes that all the plants are at the same phenological stage of development. This requirement is fairly well met after 60 days from germination, but prior to this there is some variation in phenology within each site as a result of within site depth variation.

(iii) the model assumes active uptake from the root. During the early stages of wild rice development, this may not be entirely true since submerged species are known to absorb some nutrients through their leaves (Sculthorpe, 1967). Additionally, the plant may be relying on nutrient reserves in the seed during its earlier stages of development.

The model does seem to fit the type of nutrient trends observed in wild rice at least after the emergent stage of phenological development is reached. Controlled experiments would be required to examine the influence of the assumptions required by the model. This model, like Epstein's enzyme kinetic model, does not account for luxury consumption such as described previously in the discussion of Hypothesis 1. Other factors (temperature, oxygen, inhibitors, light) are also known to influence active uptake (Epstein, 1972) and will require further investigations to examine their specific roles in mineral uptake in emergent aquatics.

Conclusions

Over a two year period, wild rice was shown to exhibit seasonal trends in the concentrations of mineral elements in the roots, leaves and stems. By correcting for time dependency, it was found that magnesium, manganese, iron, zinc and copper had statistically significant differences in concentrations among the four sampling stations in 1977. Those differences could not be accounted for by correlating to the time-independent concentrations of the corresponding element in the sediment, but appeared to result from luxury consumption. Therefore Klopatek's first hypothesis could not be used, in this instance, to explain the generally observed poor correlations between elements in plant tissue and sediment.

The observed seasonal trends for many of the elements in the plant tissue resulted in similar concentrations at the four sampling stations. Since it was known that the sediment concentrations varied both within and among sites, this seemed to verify Klopatek's second hypothesis as a reason for the generally observed poor plant tissue-sediment correlations. Based on the observation that plants at the four stations varied greatly in their weights, but still had similar elemental concentrations in their tissue, a model based on the assumption of constant absorption was derived. Theoretically the model could describe the type of seasonal trends observed in the elements in the plant tissue, but further investigations will be required to test its explanation for actual observed data.

CHAPTER 3

A SURVEY OF COMMERCIAL WILD RICE STANDS IN NORTHWESTERN ONTARIO AND NORTHEASTERN MINNESOTA

INTRODUCTION

In North America, wild rice, *Zizania aquatica* L., grows from northern Saskatchewan to the eastern sea board and south to the Gulf of Mexico. Some wild rice introductions also have been reported from Alaska, California, British Columbia and Alberta (pers. comms.). By far the largest natural stands of wild rice are found in northeastern Minnesota, eastern Manitoba and northwestern Ontario, where its harvest forms an important part of the local economy. Details of wild rice distribution are described by Fyles (1920), Fassett (1924), Chambliss (1940), Moyle (1944) and Dore (1969).

Recently wild rice paddy culture has advanced in the United States to the point where it is diminishing the economic importance of the natural stands to the wild rice industry (Northprint, 1973). If the economics of harvesting wild rice from natural stands is to compare with the efficiency of paddy culture, then methods of stabilizing production and increasing the yield from natural wild rice stands must be pursued. Such methods are possible only if their ecological relationships are understood in terms of their biological, chemical and physical requirements (Lee and Stewart, 1980a).

Previous studies have described both the historical aspects and the future economic potential of these natural stands (Jenks, 1901; Steeves, 1952; McAndrews, 1969; Edman, 1969; Lee, 1975). Very few published accounts exist on the ecological relationships of wild rice (Moyle, 1944, 1945; Rogosin, 1958).

The purpose of the present study was to expand on earlier research in order to gain a better understanding of the growth requirements of wild rice in these natural stands. A regional survey was undertaken which would provide preliminary information on (i) the distribution of the commercial wild rice stands; and (ii) the biological, chemical and physical characteristics associated with these stands.

MATERIALS AND METHODS

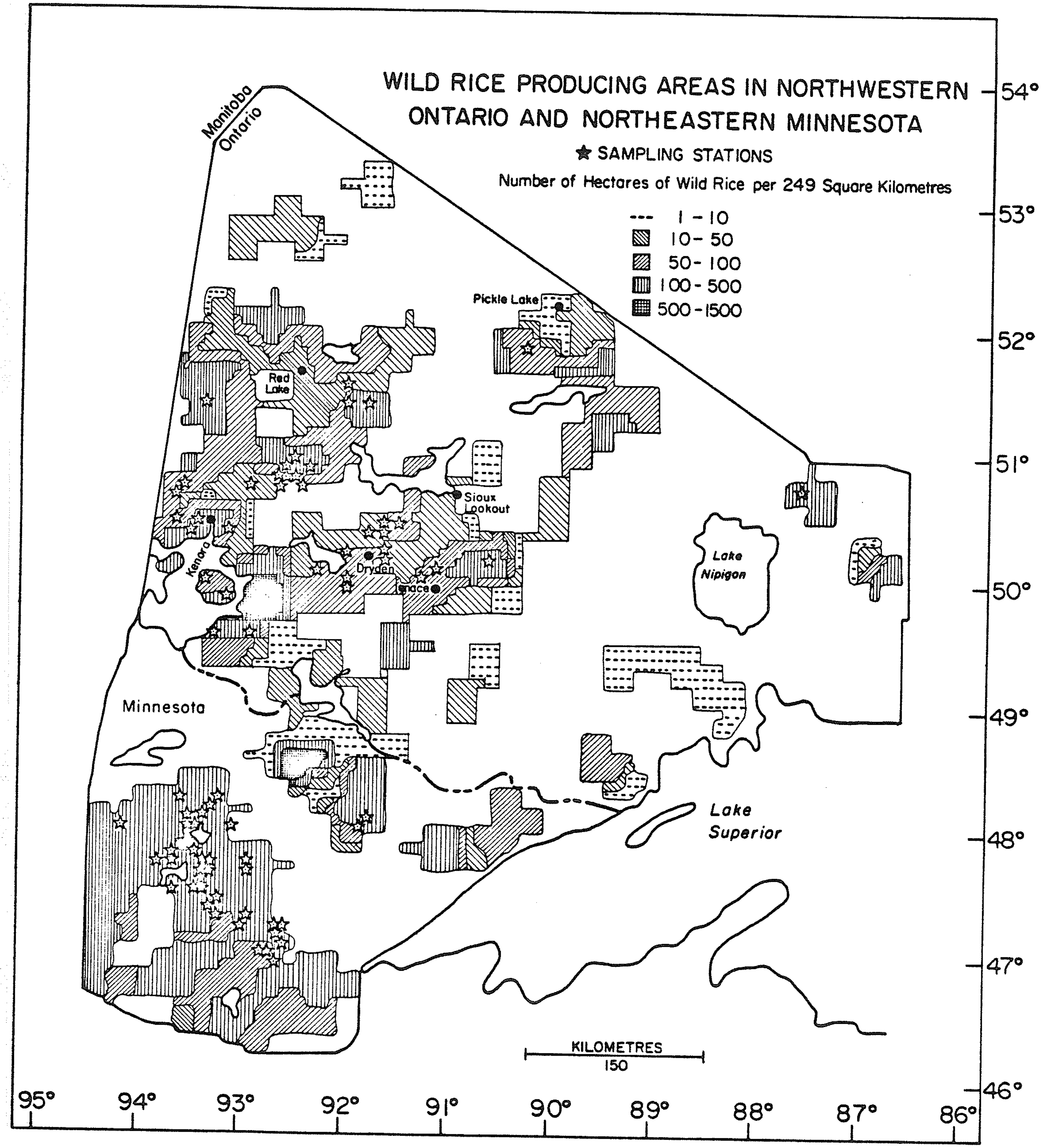
Study Area

The study area (Fig. 3-1) encompassed over 420,000 square kilometres, stretching from the Ontario-Manitoba border in the west (95°30'W) to Geraldton, Ontario in the east (87°00'W). The northern boundary occurred near North Spirit Lake, Ontario (52°30'N) and the southern boundary near Bemidji, Minnesota (47°30'N).

Glacial actions greatly modified the soil characteristics and surficial features of the region. Retreat of the glacial lakes, Agassiz and Ojibway-Barlow, left deposits of clay and silt in Minnesota, south of Lake of the Woods to Red Lake, west to the border with North Dakota and east to Nett Lake; and in Ontario, west of Fort Frances, northwest of Dryden and near Thunder Bay and Lake Nipigon. Large areas of exposed bedrock are found along the Manitoba-Ontario and Minnesota-Ontario borders, and along the shores of Lake Superior and Lake Nipigon. Sand and gravel deposits are quite common, with extensive deposits near Ignace and northeast of Lake St. Joseph where large eskers are found. Ground moraines, consisting of rocks and gravel with little clay, formed by deposits of drift left at the ice edge during pauses in the retreat of the ice front, are the most common surficial type and comprises the remainder of the study area. The topography

Figure 3-1

The wild rice producing areas in northwestern Ontario and northeastern Minnesota delineating the number of hectares of wild rice per 249 km^2 by means of an extrapolation procedure (SYMAP).


WILD RICE PRODUCING AREAS IN NORTHWESTERN ONTARIO AND NORTHEASTERN MINNESOTA
★ SAMPLING STATIONS
Number of Hectares of Wild Rice per 249 Square Kilometres
1 - 10
10 - 50
50 - 100
100 - 500
500 - 1500
Manitoba
Ontario
Pickle Lake
Red Lake
Sioux Lookout
Kenora
Dryden
Ignace
Lake Nipigon
Minnesota
Lake Superior
KILOMETRES
150
54°
53°
52°
51°
50°
49°
48°
47°
46°
95°
94°
93°
92°
91°
90°
89°
88°
87°
86°

of the area could be described as gently rolling with some areas of strongly broken relief near Lake Superior and Lake Nipigon.

There are four major watersheds in the study area. The southern boundary of the arctic watershed is described by a line stretching from just north of Lake Nipigon to the Manitoba border at approximately 53° latitude. Below the arctic watershed are found the Lake Superior watershed in the east and the Winnipeg River watershed in the west. South of the Winnipeg River drainage area is the Mississippi River watershed, with its headwaters near Bemidji, Minnesota. Within these watersheds, the area is completely dominated by over 150,000 lakes (Zoltai, 1961, 1965, 1967; Zumberge, 1952).

The continental climate of the region has been modified by the presence of Lake Superior. Mean daily temperatures across the study area range from -21°C - 3°C during January and 18°C - 19°C during July. Mean annual precipitation varies from 56 cm to 91 cm, and the growing season from 150 days to 190 days (Chapman and Thomas, 1968).

Identification of Wild Rice Producing Areas

The locations of the commercial wild rice stands were determined from government records (Ontario Ministry of Natural Resources; Minnesota Department of Natural Resources, personal communications), interviews with individuals concerned with the wild rice industry, and personal reconnaissance

Field Procedures

The sampling program was designed to maximize variance in space, and minimize variance in time. In order to do this, as many separate commercial stands as possible were sampled from late July to early August, 1977, when the wild rice plants had reached their maximum biomass. Most of the rice stands in northwestern Ontario are accessible only by aircraft and in order to minimize expense, the rice stands examined were generally in close proximity to the major centres where facilities are available for floatplanes (Fig. 3-1). In Minnesota, the commercial stands examined were those which were easily accessible by road (Fig. 3-1).

In northwestern Ontario, the procedure was to anchor the aircraft in a representative portion of the rice stand (not at the deep or shallow edge of the stand). All sampling was done at this location. Ten wild rice plants and specimens of all other aquatic plants in the immediate vicinity were collected, and placed in a large plastic bag. Water samples were collected in a 2 litre translucent polyethylene screw cap bottles from the middle of the water column. Both plants and bottles were stored in an ice cooler for transport to the laboratory. Measurements in the field were made for conductivity using a portable YSl model 33 S-C-T meter and for pH using a Fisher model 150 meter. Sediment samples were collected with an Ekman dredge (15 x 15 x 27 cm), poured into four-ply plastic bags and sealed tightly to minimize air space. The samples were then stored in an ice cooler for transport to the laboratory. Water depth was also measured.

In Minnesota, the same procedure was used except that quadrats were used to count the number of heads/m^2, other aquatics were not collected, and depth was not measured.

Laboratory Procedures

In the laboratory, counts were made from the collected rice plants of the number of grains per head, and the length of ten of the grains from each plant. The plants were then divided into roots, leaves, stems and heads and dried to a constant weight in a drying oven at 105°C. The mean dry weight per plant from each site was calculated as the sum of the mean plant component weights. The leaves from each sampling site were ground in a Wiley mill (0.5mm aperture sieve size) and 0.25 g of the powder was ashed overnight in a muffle furnace at 600°C. Using 3.0 N $HC\ell$ extracts were made from these samples for the analysis of iron, manganese, zinc, calcium, magnesium and potassium using a Perkin-Elmer atomic absorption spectrophotometer, model 403, (Perkin-Elmer, 1973) and for phosphorus according to the ammonium vanadate method of Chapman and Pratt (1961).

The water samples were filtered and measured for dissolved iron, dissolved calcium, dissolved magnesium and dissolved potassium with a Perkin-Elmer atomic absorption spectrophotometer, model 403 (Perkin-Elmer, 1973).

The sediment samples were analyzed for pH, conductivity, and available nitrogen and phosphorus by the Soil Testing Laboratory of the Manitoba Department of Agriculture. Extracts were made for the analysis of iron, manganese and zinc using 0.1 N HCℓ (Jackson, 1958) and for calcium, magnesium and potassium using ammonium acetate solution (Chapman and Pratt, 1961). The concentrations of these elements were measured by the same atomic absorption spectrophotometer as used in the leaf tissue and water samples. Loss of dry weight on ignition, as an estimate of percent organic matter of the sediments, was determined by ashing 1.0 g of the sediment samples overnight in a muffle furnace at 500°C.

Data Analysis

The distributions of the major concentrations of wild rice were quantified using a contour extrapolation procedure contained in the Symap library (Dougenik and Sheehan, 1977) and implemented in the IBM 370/158 at the University of Manitoba. A map of the study area was initially gridded into blocks corresponding to areas of 249 km^2. The number of hectares of wild rice in each of these blocks, determined from government records, were then categorized into one of five concentration ranges (Fig. 3-1). The search radius of this computer procedure was progressively reduced until the extrapolated contours only included those areas known to contain wild rice.

The statistical relationships which existed among the water and sediment variables were determined by entering their respective correlation matrices into a cluster analysis program for variables, contained in the BMDP (Biomed) library (Dixon, 1977), and implemented on the 370/158 at the University of Manitoba. An index of similarity value of 0.7 was always used to separate the groups. This corresponds to a correlation coefficient value (r value) of 0.4 which for sample sizes considered in this study would be significant at the $P \leq 0.05$ level.

RESULTS AND DISCUSSION

Distribution of Commercial Wild Rice Stands

Figure 3-1 shows the locations of the commercial wild rice stands in the study area. The most northern locale occurred near North Spirit Lake (52°30'N) and the northern limit then sloped southward following very closely the 150 growing day contour as defined by Chapman and Thomas (1968). The greatest concentrations are found near Grand Rapids and Bemidji, Minnesota, and around Lake of the Woods in Ontario.

The combined area of these commercial wild rice stands is greater than 24,000 hectares, but drastic fluctuations occur in water levels with corresponding fluctuations in the size of the rice stands from year to year (Ontario Ministry of Natural Resources, 1974). For example, the number of hectares of rice on Lake of the Woods during 1977 under low water level conditions (April - September $\overline{X}$ = 1057.3 A.S.L.) was 5490 hectares, but in 1978, under high water level conditions (April - September $\overline{X}$ = 1060.0 A.S.L.), this fell to only 128 hectares (Ontario Ministry of Natural Resources, pers. comm.).

Characteristics of Wild Rice in the Commercial Stands

Biological Characteristics

Phenotypic Appearance

There seemed to be two distinct phenotypic populations of rice plants whose separation into their appropriate taxa is difficult because of the confusion from various classifications of this plant by different authors (Fassett, 1924; Fassett, 1957; Hitchcock, 1935; Dore, 1969). The taxa which seem to best describe the two populations are *Zizania aquatica* var *interior* (Fassett) and *Zizania aquatica* var *angustifolia* (Hitchc.). *Interior* was the more common of the two varieties and generally had wider leaves, and shorter but more grains per panicle. Variety *angustifolia* was confined to the more severe climatic areas and seemed to be able to tolerate deeper waters. Large stands of *angustifolia* occur near Ignace, west of Lac Seul on the Whitemud River, on the Manitoba-Ontario border near Irregular Lake, and in the Pickle Lake - Lake St. Joseph area (Fig. 3-1). However, separation of the rice stands into these two varieties is difficult since many intermediate forms seem to exist and the phenotypic appearances may in some cases be related to environmental differences between sites rather than distinct genetic differences.

Seed Length, Seeds per Head, Weight per Plant, Density of Heads per m^2

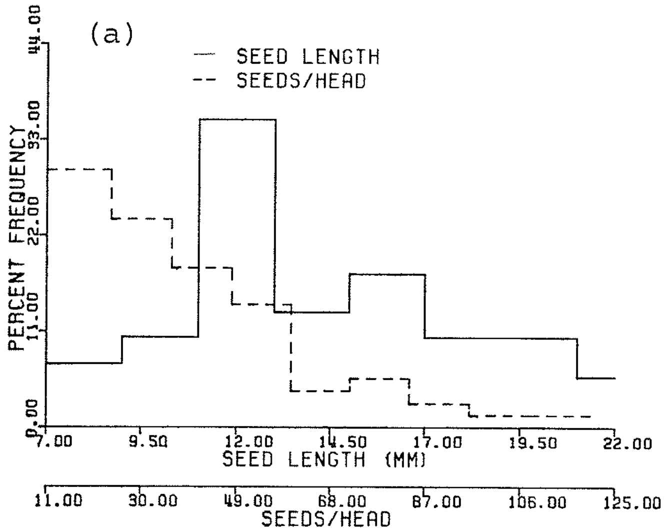
Seed length (Fig. 3-2a) varied from 7.0-22.0 mm with a mean value of 13.9 mm. The two peaks at 13.0 mm and 17.0 mm correspond with the seed lengths of Minnesota and Ontario plants respectively. This difference in length was statistically significant ($T = 7.05$, $P < 0.01$), but the reason for the natural selection of the two lengths is not understood. Assuming a seed length - seed weight relationship exists, it is possible that this length variance is related to climatic differences. The more severe climate in Ontario may require that the seedlings have a readily available source of nutrition to begin growing after germination. Rorison (1969) commented on this fact that individuals grown from large seeds often have a better chance of survival than from smaller seeds due to their greater nutritional reserves.

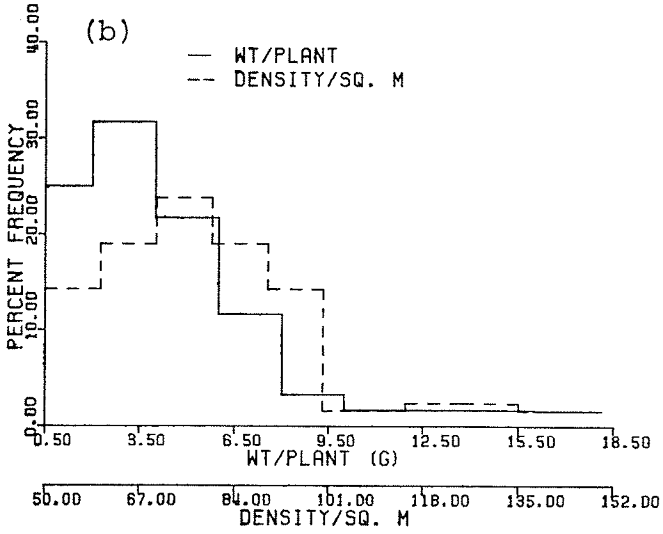
The number of seeds per head ranged from 11 - 120, with a mean value of 40. Seventy-five percent of the sites had 50 seeds or less per head (Fig. 3-2a). This differs from the findings of Moyle (1945) who found only 34 percent of the sites he examined had 50 seeds or less per head. This discrepency is largely due to the high frequency of Ontario sites with a low number of grains per head.

Figure 3-2

(a) Percent frequency of occurrence of different seed lengths (mm) ($n=71$, $\bar{x} = 13.9$, range = 7.0 - 22.0, $s = 3.4$) and numbers of seeds per head ($n=71$, $\bar{x} = 40$, range = 11 - 120, $s = 23$) of wild rice throughout the sampled areas in northeastern Minnesota and northwestern Ontario.

(b) Percent frequency of occurrence of different dry weights per plant (g) ($n=60$, $\bar{x} = 4.4$, range = 0.5 - 17.2, $s = 3.3$) and density of heads per m^2 ($n=41$, $\bar{x} = 83$, range = 48 - 150, $s = 20$) of wild rice throughout the sampled areas in northeastern Minnesota and northwestern Ontario.


(a)
— SEED LENGTH
-- SEEDS/HEAD
PERCENT FREQUENCY
0.00
11.00
22.00
33.00
44.00
7.00
9.50
12.00
14.50
17.00
19.50
22.00
SEED LENGTH (MM)
11.00
30.00
49.00
68.00
87.00
106.00
125.00
SEEDS/HEAD


(b)
— WT/PLANT
-- DENSITY/SQ. M
PERCENT FREQUENCY
0.00
10.00
20.00
30.00
40.00
0.50
3.50
6.50
9.50
12.50
15.50
18.50
WT/PLANT (G)
50.00
67.00
84.00
101.00
118.00
135.00
152.00
DENSITY/SQ. M

The dry weight per wild rice plant ranged from 0.5 - 17.2 g with an overall mean of 4.4 g (Fig. 3-2b). These weights seem quite low. Under conditions of low intraspecific competition and presumably adequate levels of physical and chemical requirements, wild rice plants in one experimental planting of a lake achieved a dry weight of 125 g (Lee and Stewart, 1980d).

The density of heads per m^2 in Minnesota ranged from 48-150 with a mean value of 83 (Fig.3-2b). Counts were not made of the heads per m^2 in northwestern Ontario in this study, but other field observations recently done in this area have found ranges of 59 - 250 (Ontario Ministry of Natural Resources, pers. comm.).

Associated Aquatics

Table 3-1 lists the species commonly found in the wild rice beds in northwestern Ontario. A zonation of these aquatics often seemed to occur in the rice beds. Near the shore, emergents such as *Sium suave*, *Sagittaria* spp., *Equisetum fluviatile* were present. Within the dense rice bed itself, the most commonly encountered species had finely dissected leaves such as *Myriophyllum* sp., *Ceratophyllum* sp., and *Megaladonta beckii*. Since these finely dissected leaves have a greater surface area (Sculthorpe, 1967) their presence in the rice bed may be an adaptation to reduced light conditions. On the deeper edges of the rice beds, the floating leaf species, *Nymphaea* spp., *Nuphar variegatum*, and *Potamogeton natans*, and the emergent species, *Scirpus acutus*, were often encountered.

Table 3-1. Aquatic species commonly associated with wild rice in northwestern Ontario.

Species
Ceratophyllum demersum L.
Equisetum fluviatile L.
Fontinalis duriaei Schimp.
Lemna trisulca L.
Megaladonta beckii (Torr.) Greene
Myriophyllum alterniflorum DC.
Myriophyllum exalbescens Fern.
Nuphar variegatum Engelm.
Nymphaea odorata Ait.
Nymphaea tuberosa Paine
Potamogeton amplifolius Tuck.
Potamogeton gramineus L.
Potamogeton natans L.
Potamogeton praelongus Wulfen
Potamogeton richardsonii (Benn.) Rydb.
Potamogeton robbinsii Oakes
Potamogeton zosteriforimis Fern.
Ranunculus longirostris Godr.
Sagittaria latifolia Willd.
Sagittaria rigida Pursh
Scirpus acutus Muhl.
Sium suave Walt.
Sparganium angustifolium Michx.
Spirodela polyrhiza (L.) Schleid.
Utricularia americana Gray
Utricularia vulgaris L.
Vallisneria americana Michx.

Commonly bordering these species in still deeper waters were *Potamogeton praelongus* and *Potamogeton amplifolius*.

Chemical Characteristics

Water Chemistry

Figure 3-3 shows the concentration frequencies found in the chemical components of the waters examined in this study.

Alkalinity (Fig. 3-3a) exhibited bimodal peaks also occurred for calcium (Fig. 3-3b); magnesium (Fig. 3-3b); and conductivity (Fig. 3-3d) which is consistent with their intercorrelated behavior in the $CaCO_3$-CO_2-H_2O system (Reid, 1961) and described specifically for a wild rice stand by Lee and Stewart (1980a).

Values for sulfate (Fig. 3-3a) ranged from 1-59 mg/l with a mean of 9 mg/l. The majority of the water (83%) had values less than 10 mg/l.

Dissolved iron concentrations (Fig. 3-3c) ranged from 0.01 mg/l to 0.67 mg/l, with a mean of 0.10 mg/l. Seventy-five percent of the waters examined had concentrations less than 0.12 mg/l.

Dissolved potassium concentrations (Fig. 3-3c) with a range of 0.3 - 4.1 mg/l tended to be concentrated around the

Figure 3-3

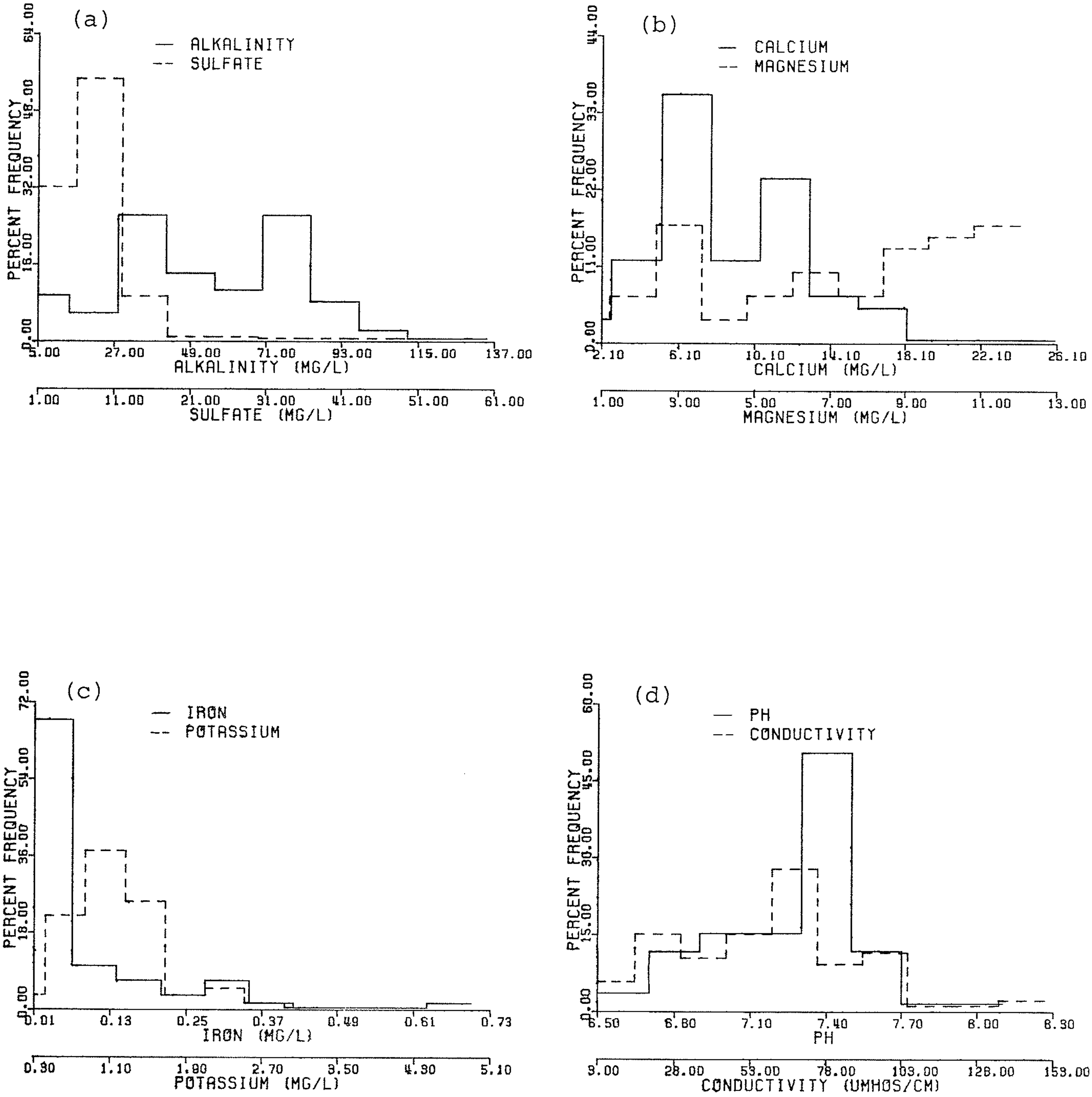
Percent frequency of occurrence of concentrations of water chemical variables from wild rice stands sampled in northeastern Minnesota and northwestern Ontario.

(a) total alkalinity (mg/ℓ $CaCO_3$), n = 84, $\bar{x}$ = 57, range = 5 - 132, s = 26; and sulfate (mg/ℓ), n = 53, $\bar{x}$ = 9, range = 1 - 59, s = 8.

(b) dissolved calcium (mg/ℓ), n = 59, $\bar{x}$ = 9.0, range = 2.1 - 25.4, s = 4.3; and dissolved magnesium (mg/ℓ), n = 59, $\bar{x}$ = 7.1, range = 1.0 - 12.0, s = 3.4.

(c) dissolved iron (mg/ℓ), n = 59, $\bar{x}$ = 0.10, range = 0.01 - 0.67, s = 0.15; and dissolved potassium (mg/ℓ), n = 59, $\bar{x}$ = 1.2, range = 0.3 - 4.1, s = 0.6.

(d) pH, n = 85, $\bar{x}$ = 7.3, range = 6.5 - 8.1, s = 0.1; and conductivity (μmhos/cm), n = 86, $\bar{x}$ = 62, range = 3 - 150, s = 3.1.


(a)
— ALKALINITY
-- SULFATE
PERCENT FREQUENCY
0.00
16.00
32.00
48.00
64.00
5.00
27.00
49.00
71.00
93.00
115.00
137.00
ALKALINITY (MG/L)
1.00
11.00
21.00
31.00
41.00
51.00
61.00
SULFATE (MG/L)
(b)
— CALCIUM
-- MAGNESIUM
PERCENT FREQUENCY
0.00
11.00
22.00
33.00
44.00
2.10
6.10
10.10
14.10
18.10
22.10
26.10
CALCIUM (MG/L)
1.00
3.00
5.00
7.00
9.00
11.00
13.00
MAGNESIUM (MG/L)
(c)
— IRON
-- POTASSIUM
PERCENT FREQUENCY
0.00
18.00
36.00
54.00
72.00
0.01
0.13
0.25
0.37
0.49
0.61
0.73
IRON (MG/L)
0.30
1.10
1.90
2.70
3.50
4.30
5.10
POTASSIUM (MG/L)
(d)
— PH
-- CONDUCTIVITY
PERCENT FREQUENCY
0.00
15.00
30.00
45.00
60.00
6.50
6.80
7.10
7.40
7.70
8.00
8.30
PH
3.00
28.00
53.00
78.00
103.00
128.00
153.00
CONDUCTIVITY (UMHOS/CM)

mean of 1.2 mg/l.

The peak in frequency of alkalinity concentrations in this study at approximately 40 mg/l and the lower peak in pH readings correspond roughly to Moyle's (1944) Group 1, the soft water flora which he described as having a total alkalinity less than 40 mg/l, a pH between 6.8 and 7.5, and a sulfate concentration of less than 5 mg/l. The second frequency peak for alkalinity at approximately 80 mg/l, and the peak at the higher pH values correspond to Moyle's Group II, the hardwater flora, described by Moyle as having a total alkalinity of 90 - 150 mg/l, a pH of 8.0 - 8.8, and a sulfate concentration of 5 - 40 mg/l. One very evident difference between the findings of Moyle and those of this study, is that Moyle did not include wild rice in his Group 1, but it was found to be extremely common under similar chemical ranges in the present study.

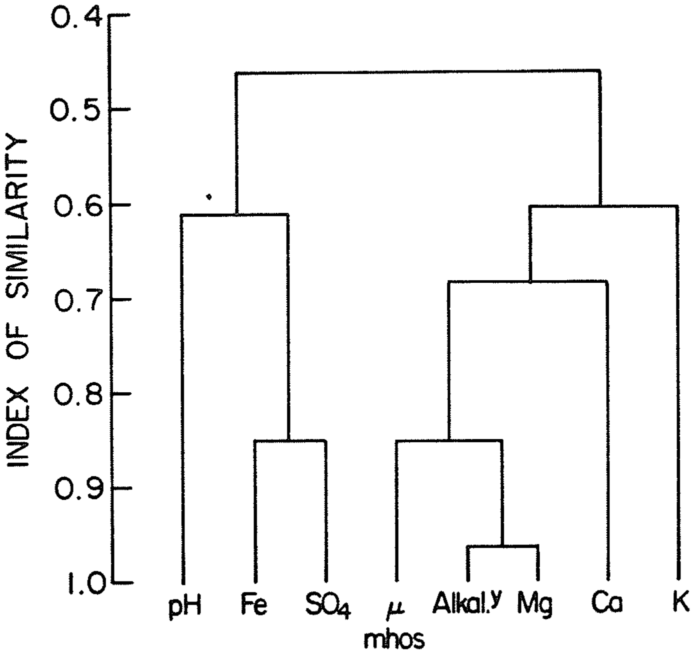
Figure 3-4 shows the intercorrelations which existed among the chemical constituents measured in the water. Four groups of variables were found:

Group 1 - pH
Group 2 - dissolved Fe, SO_4
Group 3 - conductivity, total alkalinity, dissolved Mg
dissolved Ca
Group 4 - dissolved K

The fact that pH was isolated in Group 1, and not associated with the elements in Group 3, may indicate that at this time of the year in many of the waters examined there was a high carbon dioxide demand for primary production which would cause calcium and magnesium carbonate to be

Figure 3-4

Cluster analysis of water chemical variables from wild rice stands sampled in northeastern Minnesota and northwestern Ontario.


0.4
0.5
0.6
0.7
0.8
0.9
1.0
INDEX OF SIMILARITY
pH
Fe
SO_4
μ mhos
Alkal.y
Mg
Ca
K

precipitated. This would result in alkalinity, conductivity, magnesium and calcium concentrations being lower with the higher pH levels and therefore no statistical correlation would occur.

The association of dissolved iron with sulfate in Group 1 may be a result of the oxidation of pyrite, dissolved from the surrounding lake basin, to iron sulfate (Wetzel, 1975), or it may simply be a statistical association.

The Group 3 variables were associated with each other because of their interrelationships in the $CaCO_3$-CO_2-H_2O system as was previously mentioned when describing their similar bimodal frequencies.

Dissolved potassium was isolated in Group 4. This monovalent cation generally exhibits very little seasonal variation in its concentrations (Wetzel, 1975), and this may explain why it would not be associated with the other variables previously described which do have such variations.

Sediment Chemistry

Figure 3-5 contains the results for the frequencies of concentrations for the variables analyzed in the sediments.

The metals, iron and manganese (Fig. 3-5a), and zinc (Fig.3-5c) were generally present in concentrations in the order: Fe > Mn > Zn, which is common to most lake sediments (Wetzel, 1975). Ranges of iron concentrations (6 - 2700 ppm), manganese (5 - 420 ppm) and zinc (1 - 190 ppm) were comparable

Figure 3-5

Percent frequency of occurrence of concentrations of sediment chemical variables from wild rice stands sampled in northeastern Minnesota and northwestern Ontario.

(a) available iron (ppm), $n = 56$, $\bar{x} = 690$, range = 6 - 2700, $s = 580$; and available manganese (ppm), $n = 56$, $\bar{x} = 135$, range = 5 - 420, $s = 110$.

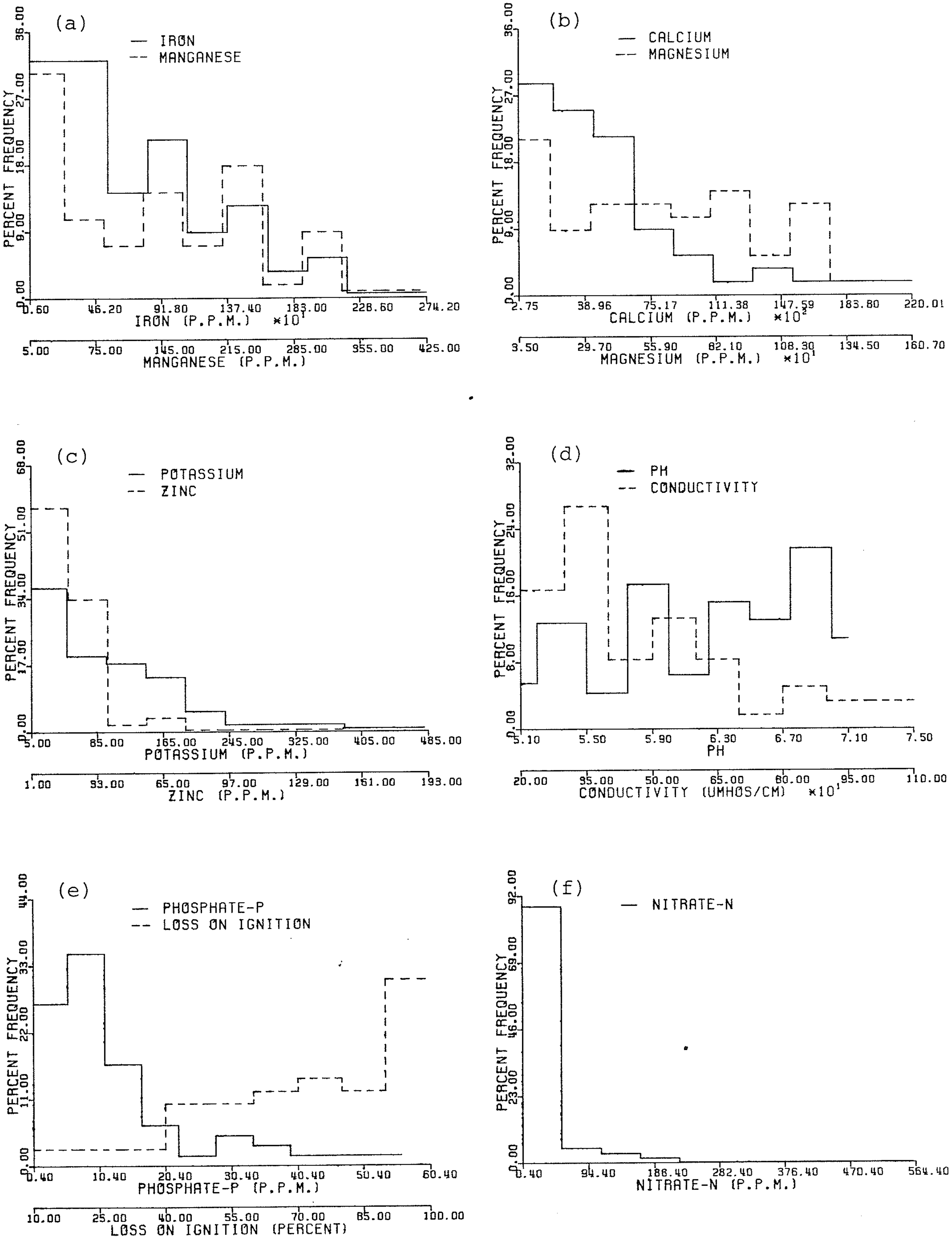
(b) available calcium (ppm), $n = 57$, $\bar{x} = 5200$, range = 280 - 22000, $s = 4900$; and available magnesium (ppm), $n = 57$, $\bar{x} = 590$, range = 35 - 1600, $s = 4.22$.

(c) available potassium (ppm), $n = 57$, $\bar{x} = 110$, range = 5 - 480, $s = 95$; and available zinc (ppm), $n = 56$, $\bar{x} = 23$, range = 1 - 190, $s = 32$.

(d) pH, $n = 50$, $\bar{x} = 6.2$, range = 5.1 - 7.1, $s = 0.6$; and conductivity (μmhos/cm), $n = 50$, $\bar{x} = 520$, range = 200 - 1100, $s = 260$.

(e) available phosphorus (ppm), $n = 60$, $\bar{x} = 13.0$, range = 0.4 - 56.0, $s = 12.0$; and loss on ignition (%), $n = 49$, $\bar{x} = 72$, range = 10 - 99, $s = 23$.

(f) available nitrogen (ppm), $n = 60$, $\bar{x} = 31.0$, range = 0.4 - 560.0, $s = 79.0$.


(a)
— IRON
-- MANGANESE
PERCENT FREQUENCY
0.00
9.00
18.00
27.00
36.00
0.60
46.20
91.80
137.40
183.00
228.60
274.20
IRON (P.P.M.) ×10¹
5.00
75.00
145.00
215.00
285.00
355.00
425.00
MANGANESE (P.P.M.)
(b)
— CALCIUM
-- MAGNESIUM
PERCENT FREQUENCY
0.00
9.00
18.00
27.00
36.00
2.75
38.96
75.17
111.38
147.59
183.80
220.01
CALCIUM (P.P.M.) ×10²
3.50
29.70
55.90
82.10
108.30
134.50
160.70
MAGNESIUM (P.P.M.) ×10¹
(c)
— POTASSIUM
-- ZINC
PERCENT FREQUENCY
0.00
17.00
34.00
51.00
68.00
5.00
85.00
165.00
245.00
325.00
405.00
485.00
POTASSIUM (P.P.M.)
1.00
33.00
65.00
97.00
129.00
161.00
193.00
ZINC (P.P.M.)
(d)
— PH
-- CONDUCTIVITY
PERCENT FREQUENCY
0.00
8.00
16.00
24.00
32.00
5.10
5.50
5.90
6.30
6.70
7.10
7.50
PH
20.00
35.00
50.00
65.00
80.00
95.00
110.00
CONDUCTIVITY (UMHOS/CM) ×10¹
(e)
— PHOSPHATE-P
-- LOSS ON IGNITION
PERCENT FREQUENCY
0.00
11.00
22.00
33.00
44.00
0.40
10.40
20.40
30.40
40.40
50.40
60.40
PHOSPHATE-P (P.P.M.)
10.00
25.00
40.00
55.00
70.00
85.00
100.00
LOSS ON IGNITION (PERCENT)
(f)
— NITRATE-N
PERCENT FREQUENCY
0.00
23.00
46.00
69.00
92.00
0.40
94.40
188.40
282.40
376.40
470.40
564.40
NITRATE-N (P.P.M.)

to those found in other studies of lake sediments in the precambrian shield (Pazetta and Iskandan, 1975; Wagemann *et al*, 1977). The iron and manganese concentrations exceeded the toxic levels of 100 ppm for iron and 50 ppm for manganese as reported by Donahue *et al* (1977) for the cultivation of terrestrial plants under greenhouse conditions. However, the high concentrations of these elements commonly found in lake sediments and aquatic macrophyte tissue (Hutchinson, 1975) suggest that these toxic levels do not apply to the aquatic environment.

Calcium and magnesium (Fig. 3-5b) and potassium (Fig. 3-5c) were present in concentrations in the order Ca > Mg > K, which is again the common result in most lake sediments (Wetzel, 1975). Concentration ranges for calcium (280 - 22,000 ppm), magnesium (35 - 1600 ppm) and potassium (5 - 480 ppm) were also comparable to those found in the sediments of freshwater wetlands (Klopatek, 1978).

Sediment pH values (Figure 3-5d) were generally acidic, ranging from 5.1 - 7.1. Such acidic conditions are a common characteristic of the marsh environment, caused primarily by the decomposition of organic matter (Auclair *et al*, 1976).

Percent loss on ignition values of sediment weights (Fig. 3-5e), as an estimate or organic matter content, were generally high, ranging up to 99 percent, with the majority being over 50 percent. In another study on lake sediments in northwestern Ontario (Brunskill and Schindler 1971), loss on ignition values were found to range from 18 - 62 percent with a mean value of 44 percent.

Sediment conductivity (Fig. 3-5d) exhibited values ranging from 200 - 1100 μmhos/cm, which are typical for flooded, moderately acidic soils (Ponnamperuma, 1965).

Concentrations of available phosphorus (Fig. 3-5e) ranged from 0.4 - 56.0 p.p.m. with a mean value of 13.0 p.p.m. Available nitrogen (Fig. 3-5f) concentrations ranged from 0.4 to 560.0 p.p.m. with a mean value of 31.0 p.p.m. Those concentrations compare to 20-60 p.p.m. for phosphorus and 20-40 p.p.m. for nitrogen recommended for cultivation of terrestrial plants (Donahue *et al*, 1977). These low values for nitrogen and phsophorus seem to be typical of most lake sediments and they are the most likely of the elements to be limiting primary production (Hutchinson, 1975).

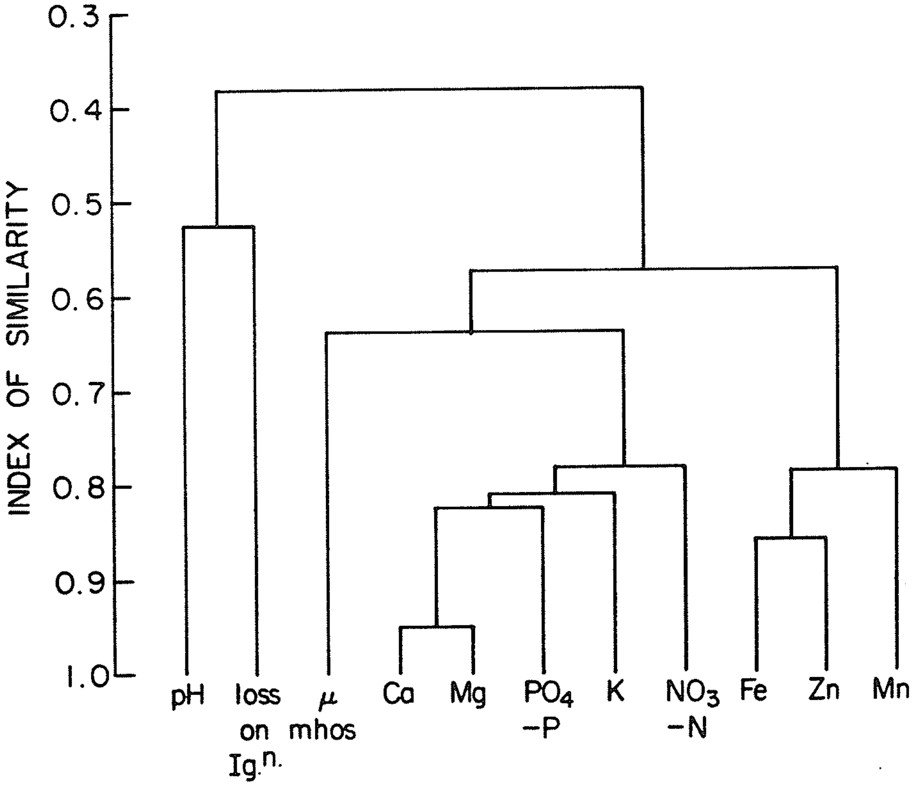
The relationships among the five main groups of variables in the sediments are shown by Figure 3-6.

Group 1 - pH
Group 2 - loss on ignition
Group 3 - conductivity
Group 4 - Ca, Mg, PO_4-P, K, NO_3-N
Group 5 - Fe, Mn, Zn

pH was the sole constituent of Group 1. The isolation of pH from other variables reflects the buffering capacity of these acid soils, rich in iron and other metals, which are regulated by the equilibrium reactions of the $Fe(OH)_2 - CO_2 - H_2O$ system (Ponnamperuma, 1965). According to this system, hydroxyl ions which are released as the cation concentrations

Figure 3-6

Cluster analysis of sediment chemical variables from wild rice stands sampled in northeastern Minnesota and northwestern Ontario.


INDEX OF SIMILARITY
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
pH
loss on Ig.n.
μ mhos
Ca
Mg
PO4 -P
K
NO3 -N
Fe
Zn
Mn

increase, react with the iron and other metals. In this manner, increases in cation concentrations in the sediments under acidic conditions would not be expected to be correlated with pH, and the metals, which are lowered in concentrations as pH increases, would be expected to be negatively correlated with pH. These were the observed trends in this study.

Loss on ignition, which formed Group 2, had the expected trend of increasing in concentration as the concentrations of the mineral elements decreased, and thus was not associated with any of the analyzed elements.

Conductivity formed Group 3 and was not significantly associated with any of the elements. Apparently, in the sediments examined, increases in concentrations of those elements forming Group 4 were accompanied by corresponding decreases in the elements of Group 5. These two simultaneous trends tended to negate any significant relationships between conductivity and the mineral elements.

The associations of calcium, magnesium, phosphorus, potassium, and nitrogen in Group 4, and iron, zinc, and manganese in Group 5 were a result of the similar behaviour of the elements comprising the two groups under acidic conditions. In pH ranges of 5 - 7, concentrations of all elements in Group 4 increase as pH increases and decrease as pH decreases. The reverse is true for the Group 5 elements which decrease as pH rises and increase as pH decreases (Brady, 1974).

Plant Tissue Chemistry

Figure 3-7 illustrates the frequencies of elemental concentrations found in the leaves of the rice plants. Calcium and magnesium (Fig. 3-7a) tended to have concentrations centered around their means of 1.20% and 0.18% respectively. In terms of comparisons with the concentrations found in other aquatic plants, the mean value for calcium corresponds quite well to the means of 1.17% and 1.06% for calcium found in the floating leaves of *Potamogeton amplifolius* and *Potamogeton gramineus* by Ophel and Fraser (1970). The mean value for magnesium compares to the mean value of 0.19% in the leaves of *Nuphar advena*, 0.12% in *Nymphaea odorata* and 0.14% in *Nymphaea tuberosa* reported by Reimer and Toth (1968).

Potassium (Fig. 3-7b) was present in the highest concentration of any of the elements examined with peaks in concentration frequencies occurring at approximately 2.3% and 4.0%. Phosphorus concentrations (Fig. 3-7b) ranged from 0.02 to 0.16% with peaks in frequency at approximately 0.05 and 0.10% The potassium mean value of 2.23% compares extremely well to the mean of 2.26% for 18 aquatic species in South Carolina (Boyd, 1970), 2.92% for 37 aquatic species in New Jersey (Reimer and Toth, 1968), and 2.30% for six species in Connecticut (Cowgill, 1974a). The mean value for phosphorus of 0.08% was low, with only 19% of the sites having values for phosphorus above the concentration of 0.13% recommended by Gerloff and Krombholz (1966) for aquatic plants. Ranges of phosphorus from other studies on aquatic plants are 0.18 -

Figure 3-7.

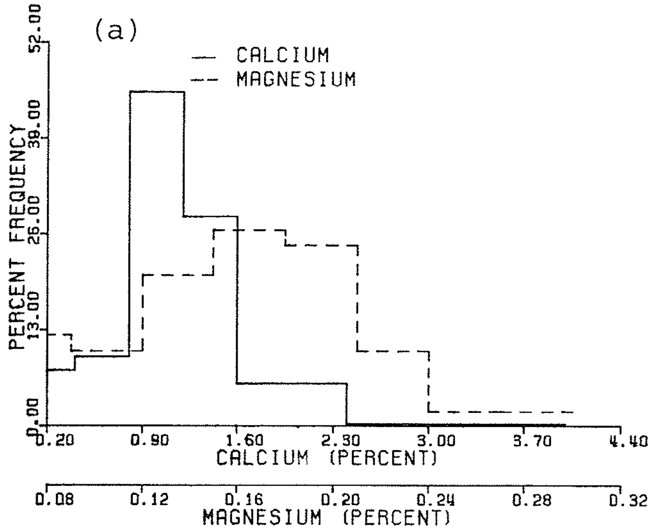
Percent frequency of occurrence of elemental concentrations found in the leaves of wild rice plants from stands sampled in northeastern Minnesota and northwestern Ontario.

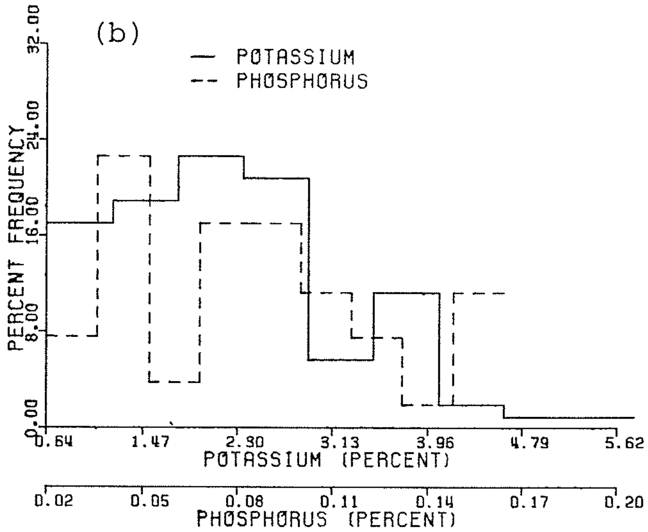
(a) calcium (% dry weight), n = 53, $\bar{x}$ = 1.2, range = 0.2 - 3.7, s = 0.3; and magnesium (% dry weight), n = 53, $\bar{x}$ = 0.18, range = 0.08 - 0.29, s = 0.05.

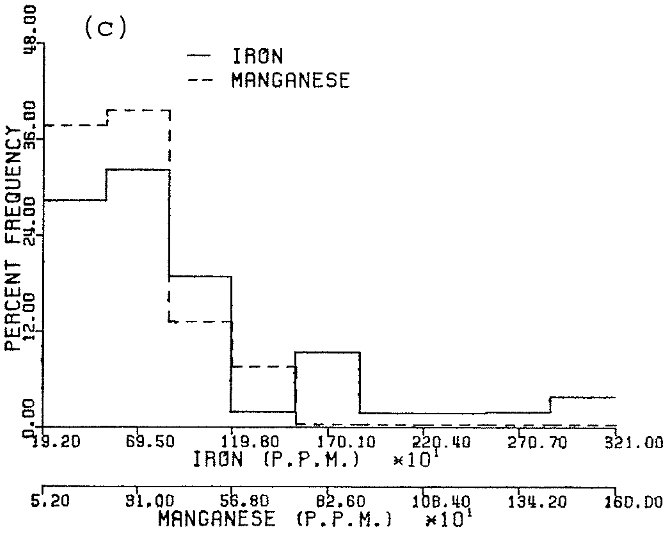
(b) potassium (% dry weight), n = 53, $\bar{x}$ = 2.2, range = 0.6 - 5.8, g = 1.1; and phosphorus (% dry weight), n = 53, $\bar{x}$ = 0.08, range = 0.02 - 0.16, s = 0.04.

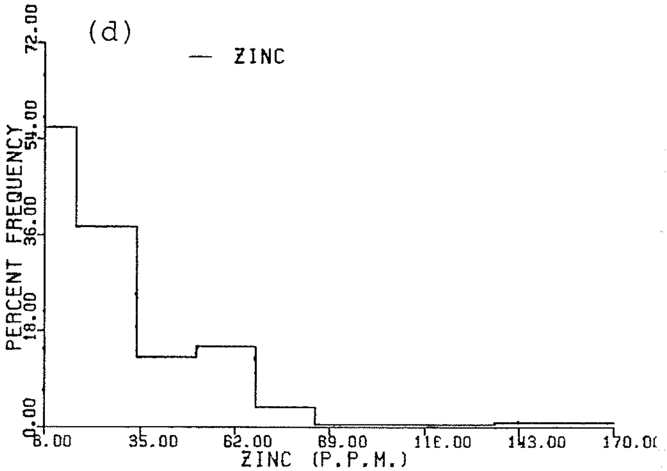
(c) iron (ppm dry weight), n = 53, $\bar{x}$ = 950, range = 190 - 3200, s = 660; and manganese (ppm dry weight), n = 53, $\bar{x}$ = 310, range = 50-1600, s = 240.

(d) zinc (ppm dry weight), n = 53, $\bar{x}$ = 36, range = 8 - 160, s = 30.


(a)
CALCIUM
MAGNESIUM
PERCENT FREQUENCY
0.00
13.00
26.00
39.00
52.00
0.20
0.90
1.60
2.30
3.00
3.70
4.40
CALCIUM (PERCENT)
0.08
0.12
0.16
0.20
0.24
0.28
0.32
MAGNESIUM (PERCENT)


(b)
POTASSIUM
PHOSPHORUS
PERCENT FREQUENCY
0.00
8.00
16.00
24.00
32.00
0.64
1.47
2.30
3.13
3.96
4.79
5.62
POTASSIUM (PERCENT)
0.02
0.05
0.08
0.11
0.14
0.17
0.20
PHOSPHORUS (PERCENT)


(c)
IRON
MANGANESE
PERCENT FREQUENCY
0.00
12.00
24.00
36.00
48.00
19.20
69.50
119.80
170.10
220.40
270.70
321.00
IRON (P.P.M.) $\times 10^{1}$
5.20
31.00
56.80
82.60
108.40
134.20
160.00
MANGANESE (P.P.M.) $\times 10^{1}$


(d)
ZINC
PERCENT FREQUENCY
0.00
18.00
36.00
54.00
72.00
8.00
35.00
62.00
89.00
116.00
143.00
170.0
ZINC (P.P.M.)

1.95% (Reimer and Toth, 1968), 0.01 - 0.61% (Bernatowicz, 1969), 0.28 - 1.36% (Casey and Downing, 1976), and 0.08 - 0.50% (Carpenter and Adams, 1977).

The majority of the iron concentrations (Fig. 3-7c) were concentrated around 700 ppm and, to a lesser extent, 2000 ppm. Manganese concentrations (Fig. 3-7c) were primarily in the range of 50 - 800 ppm, with only incidental occurrences at higher concentrations. The mean tissue concentrations for iron of 950 ppm and for manganese of 310 ppm were high relative to values commonly found in terrestrial plants of 100 ppm for iron and 50 ppm for manganese (Epstein, 1972). The high concentrations of these elements found in aquatic plants in general may be a result of their great availability in the reduced lake sediments (Hutchinson, 1975). The values in the rice plants of these two elements compare well to the means from other studies of aquatic plants of 920 for iron and 320 for manganese (Boyd, 1970) and 560 for iron and 414 for manganese (seasonal averages) (Carpenter and Adams, 1977), but well below the 7170 ppm for iron and 2280 ppm for manganese found by Reimer and Toth (1968), and the ranges of approximately 200 - 50,000 ppm for iron and 500 - 3200 ppm for manganese by Kollman and Wali (1976). The discrepancy with the higher values is probably due to the fact that the majority of the above studies determined whole plant concentrations rather than just leaf values. The concentrations of iron and manganese are much higher in the roots of wild rice plants (Lee and Stewart, 1980b), and if these root values were averaged with those from other plant parts, the concentrations would therefore rise.

Zinc concentrations (Fig. 3-7d) ranged from 8 - 160 ppm, but 90% of the values were less than 65 ppm. The mean from this study (36 ppm) is considerably lower than the mean from whole plant analysis of 143 as reviewed by Hutchinson (1975).

Plant Tissue-Sediment Relationships

Table 3-2 contains the correlation coefficients for each element in the plant tissue versus the corresponding element in the sediment. The only element which was statistically significant was potassium with a correlation coefficient of .37, accounting for only 13.7% of the variation in the concentrations of potassium in the plant tissue according to the concentrations of potassium in the sediments. Such poor correlations between tissue concentrations and sediment concentrations seem to be a common occurrence in the aquatic habitat and have been reported in other studies (Anderson *et al*, 1966, Casey and Downing, 1976). This weak association is probably due to the great variances in the biological, physical and chemical conditions which exist between sites in the natural environment as was reviewed by Rorison (1969).

Physical Characteristics

Water Depth

The mean of water depths in the wild rice stands examined in northwestern Ontario (n = 17) was 0.70 m and ranged from 0.42 m - 1.20 m. Maximum depths of occurrence of wild rice

Table 3-2. Correlation coefficients between mineral elements in the tissue of wild rice leaves versus the corresponding element in the lake sediment.

Mineral Element	Correlation Coefficient
Iron	.23
Manganese	-.06
Zinc	-.00
Calcium	-.13
Magnesium	-.06
Potassium	.37*
Phosphorus	.04

*Statistically significant at the P = .05 level.

were not determined in this study, but previous personal observations in this area have found this to range from approximately 0.4 to 2.0 m. This large depth variance seems to be dependent on the availability of light, with the clearer waters having rice stands in deeper waters. Since increasing depth has been previously reported as an important factor in decreasing the production of wild rice (Moyle, 1944; Rogosin, 1958; Thomas and Stewart, 1969), it would seem reasonable that in future these maximum depths be standardized according to the amount of photosynthetically active light present as was done by Lee and Stewart (1980d), rather than taking a simple depth measurement.

CONCLUSIONS

This study has shown the distribution of wild rice in northeastern Minnesota and northwestern Ontario and has provided a preliminary analysis of the ecological characteristics of wild rice in this region. More detailed studies will be required to quantify specific spatial and temporal variances in these characteristics, but based on the findings of this initial survey, some conclusions can be made.

Wild rice distribution is confined to climatic zones with greater than 150 growing days per year. Within this region, two phenotypic populations occur, best described by *Zizania aquatica* var. *angustrifolia* Hitchc. and *Zizania aquatica* var. *interior* Fassett, and which exhibit a south-north gradient of increasing seed length.

Chemical characteristics indicated that wild rice occurs in lakes and rivers with either a soft or a moderately hard water type and with an anerobic, moderately acid sediments. The elemental concentrations in the leaves of the wild rice plants are generally similar to those found in other aquatic plants except for phosphorus which is mostly below normal. These tissue concentrations are only poorly correlated to the concentrations of the corresponding elements in the sediment.

Wild rice occurred in water depths ranging from 0.42 to 1.2 m. Changes in water depths from year to year are thought to be largely responsible for the drastic fluctuations in the size of the commercial stands in this region.

CHAPTER 4

DISCRIMINANT ANALYSIS AS A METHOD OF CATEGORIZING POTENTIAL WILD RICE LAKES

INTRODUCTION

Extensive natural stands of wild rice, *Zizania aquatica* L., grow in many of the lakes and rivers of northwestern Ontario where the harvest of wild rice can form an important part of the local economy. Unfortunately, the major wild rice areas are located on watersheds which are not controlled for wild rice commercial production. In years when there are high water levels, the size of the wild rice harvest decreases, thus preventing the sustainable yields needed for ensuring a viable wild rice industry (Lee and Stewart, 1979c). To partially alleviate the problem of variable yields from natural stands of wild rice, a program was initiated in 1974 to determine if the range of wild rice could be extended commercially by experimentally seeding a number of lakes in northwestern Ontario (Lee, 1974).

During 1975 and 1976, the wild rice plantings were visited and considerable variation in the growth performances of wild rice plants observed. Since the viability of the seed was known and no grazers of the sown seed or seedlings were observed, it was assumed that variations in wild rice growth were a result of differences in the environmental properties among the planted lakes. Because these plantings could be categorized *a priori*, it was reasonable to assume that discriminant analysis, a multivariate among-groups statistical technique, would assist in the isolation of the key environmental factors responsible for the variations in wild rice performance among the different lakes.

As a technique, discriminant analysis was used as early as 1898 for separating plants between two populations with genetic differences (Kendall, 1972). Its development for classifying individuals into one of the several populations was outlined by Rao (1948). Its use in ecological studies has been confined to niche analysis (Green, 1971; Shugart and Patten, 1972), since it provides a useful method for modelling Hutchinson's (1957) definition of a niche as a 'N-dimensional hypervolume'. More recently, this technique has been used by plant ecologists to describe the distribution and production of plant species (Anderson, 1978; Lee and Stewart, 1979a).

The objectives of this study were, (i) to test the effectiveness of discriminant analysis for isolating the measured environmental factors which could separate the planted lakes into their observed categories, and (ii) to assess these isolated factors in terms of their effects on the growth performance of wild rice.

METHODS AND MATERIALS

Seeding Program

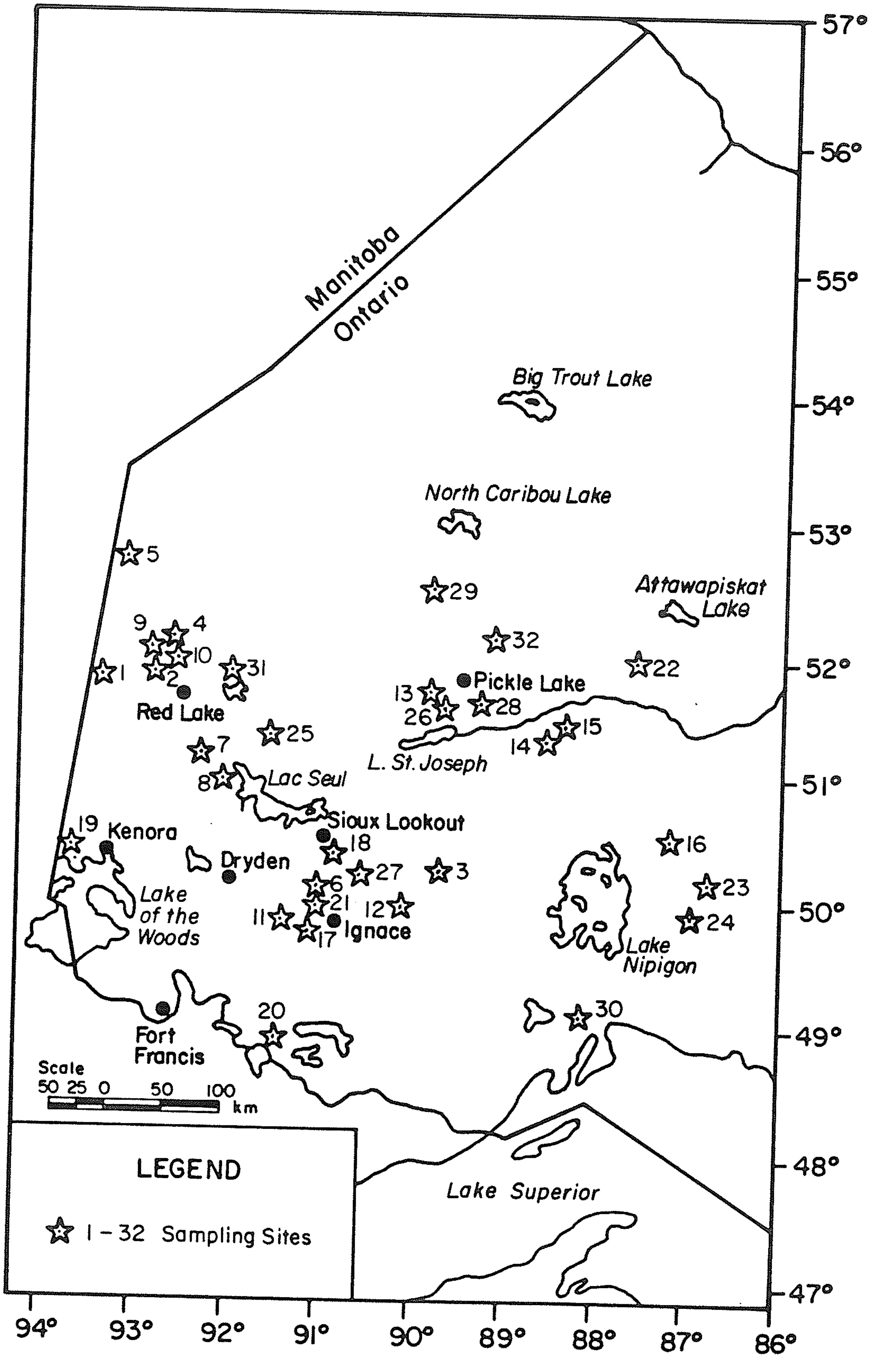
Figure 4-1 shows the locations of the lakes which were seeded with wild rice. These lakes were selected for planting following aerial surveys of the region and had the common characteristic of being shallow (less than 1.5 m) for an area of at least 50 hectares.

In each lake approximately 28 kg of wild rice seeds, collected from the same locale, were sown. Generally, aerial seeding was used by releasing the rice through a chute in the drop-hatch of a De-Haviland Beaver aircraft from an altitude of 60 m at an air speed of approximately 160 kph. This method gave an even spread of seed over an area approximately 142 m long by 10 m wide. In those cases where seeding was done by hand, the same seeding density was used.

Random samples of the seed used for the plantings were kept damp and refrigerated for 120 days. In order to determine the viability of the seeds, samples of 50 seeds each were placed in glass beakers filled with distilled water at room temperature. As the seeds germinated, they were removed. After approximately one month, germination had ceased and the test was stopped. This procedure was replicated ten times and it was found that the viability of the seeds varied from 30 percent to 45 percent.

Figure 4-1

Sites planted with wild rice in northwestern Ontario during 1974 and 1975.


57°
56°
55°
54°
53°
52°
51°
50°
49°
48°
47°
94°
93°
92°
91°
90°
89°
88°
87°
86°
Manitoba
Ontario
Big Trout Lake
North Caribou Lake
Attawapiskat Lake
Pickle Lake
Red Lake
L. St. Joseph
Lac Seul
Sioux Lookout
Kenora
Dryden
Ignace
Lake of the Woods
Lake Nipigon
Fort Francis
Lake Superior
5
29
32
22
9
4
10
1
2
31
13
26
28
15
14
25
7
8
19
18
27
3
16
6
21
12
23
24
11
17
20
30
Scale
50 25 0 50 100
km
LEGEND
1 – 32 Sampling Sites

Sampling Program

Field Procedures

Because of the large area, the inaccessability of the majority of the sites to road vehicles, and the desirability of sampling all sites within a short time period, sampling was done by aircraft during August, 1976. Sampling for all parameters, except photosynthetically active light, was confined to the same 1 m^2 quadrat in a representative portion of the planting if it was successful. If it was not successful, sampling was done from the area in the lake where the seed was sown. Photosynthetically active light was measured in the open water immediately bordering the planted area.

The numbers of wild rice individual plants per m^2 were recorded, then harvested and placed in large plastic bags and stored in an ice cooler for transport to the laboratory.

Water samples were collected in 2 litre translucent polyethylene screw cap bottles from the middle of the water column and transported to the laboratory in an ice cooler. Measurments were made for conductivity using a portable YSl model 33 S-C-T meter and for pH using a Fisher model 150 meter.

Sediment samples were collected with an Ekman dredge (15 x 15 x 27 cm), poured into four-ply plastic bags and sealed tightly to minimize air space. The samples were stored in an ice cooler for transport to the laboratory. One noticeable factor which was thought to play an important role in affecting wild rice growth was the relative firmness of the sediments. Extremely "loose" or "hard" sediments seemed to impede the development of the wild rice plants by not allowing the roots to anchor the plants. Since no quantitative criteria could be found to describe this factor, the following firmness classes were devised and recorded in the field:

1. Substrate unconsolidated, particles actually appearing to be still in suspension. Generally, sediment of this nature was light brown to grey in colour. In many cases, the plant, *Potamogeton amplifolius* was associated with this type of sediment and was the only species present. The sediment before drying appeared "gel-like".

2. Appearing in colour the same as 1, but the particles seemed to have settled. In texture, this sediment was also "gel-like" before drying.

3. Sediment firm compared to 1 and 2 but still offering little resistance to penetration by an external object such as a paddle. These sediments were dark brown or black in colour, the typical soft "muck" associated with most marshes.

4. Sediment very firm, unable to be penetrated by a paddle, consisting mostly of sand and gravel or sandy loam.

Photosynthetically active radiation of the light penetrating the water was measured at 10 cm intervals from the surface of the water to the underlying bottom sediment with a Li-Cor quantum light meter, model 185, manufactured by Lambda Instruments Ltd. Water depth was measured in the centre of each quadrat.

Laboratory Procedures

In the laboratory, counts were made from the collected rice plants of the number of grains per head and the number of tillers per plant. The plants from each site were then divided into roots, leaves, stems and heads and dried to constant weight in a drying oven at 105°C. The mean dry weight per plant from each site was calculated as the sum of the mean plant component weights. Root weight ratios, leaf weight ratios, stem weight ratios and head weight ratios were also calculated. The plant components for each site were then ground separately in a Wiley mill (0.5 mm aperture sieve size) and 0.25 g of the powder from each component per site was ashed overnight in a muffle furnace at 600°C. Using 3.0 N HCl, extracts were made from these samples for the analysis of iron, manganese, zinc and copper using a Perkin-Elmer atomic absorption spectrophotometer model 403.

From the water samples, sulfate concentrations were determined according to the turbidimetric method of the American Public Health Association (1971). For measurements of dissolved magnesium and dissolved potassium, the water samples were initially filtered prior to being measured with a Perkin-Elmer atomic absorption spectrophotometer model 403.

The sediment samples were analyzed for pH, conductivity, and available nitrogen and phosphorus by the Soil Testing Laboratory of the Manitoba Department of Agriculture. Extracts were made for the analysis of iron, manganese and zinc using

0.1 N HCℓ (Jackson, 1958) and for calcium, magnesium and potassium using ammonium acetate solution (Chapman and Pratt, 1961). The concentrations of these elements were measured using the same atomic absorption spectrophotometer as for plant tissue and water samples.

Data Analysis

The data analysis proceeded in three steps:

1. The lake plantings were categorized into one of three groups, based on the number of wild rice heads per square metre.

2. Discriminant analysis was used to determine the combination of measured environmental factors which could best separate the plantings into these groups.

3. The factors isolated by the discriminant analysis procedure as being statistically significant in separating the plantings were assessed for their real biological contribution by examining their intercorrelations and relating them to an indicator of wild rice growth performance.

Initial pre-treatment of some of the data was necessary.

From the values for photosynthetically active light, the extinction coefficients were calculated following the method for the extinction coefficient of total light described by Cole (1975). Total extinction of photosynthetically active light was then calculated as the product of water depth and the extinction coefficient of photosynthetically active light.

For use in the discriminant analysis, all water and sediment chemical variables (except pH) were transformed logarithmically since it is thought such variables are better interpreted in this form (Green, 1971).

A sediment suitability index for normal anchorage by the wild rice roots, containing three distinct values, was derived from the soil firmness values. Values 1 and 4 from the firmness index became 1 in the suitability index since both values had the same effect on wild rice of hindering the anchorage of the plants. Values 2 and 3 from the firmness index remained the same. This therefore resulted in a scale from 1-3 of increasing suitability for normal anchorage of the rice plants. The inclusion of somewhat qualitative data may be questionable, but the use of distinct categories, as in this case, has been previously shown to be very successful in quantitative studies of plant communities (Lambert and Dale, 1964; Strahler, 1978).

All the above data were then used in a discriminant analysis program contained in the SPSS statistical library (Nie *et al*, 1975) and implemented on the IBM 370/158 at the University of Manitoba. The statistical assumptions for the valid use of discriminant analysis for data, such as used in this study, are contained in Green (1971). Following Tatsuoka (1971), the within group variance and covariance of the discriminant scores of the lakes were used to calculate the bivariate normal distribution associated with each *a priori* planting group which would include 90 percent ($X^2 = 4.605$) of the within-group observations.

A cluster analysis program contained in the BMDP (Biomed) statistical library (Dixon, 1977) and implemented on the IBM 370/158 at the University of Manitoba was used to determine the intercorrelations among all included variables in the discriminant analysis procedure. An index of similarity value of 0.7 was used as the separating point for the clusters. This implies that each element in a cluster had a correlation coefficient (r value) of at least 0.4, which for sample sizes considered in this study is significant at the $P<0.05$ level.

All additional univariate analyses of variance and regression analysis were done using programs contained in the BMDP statistical library.

RESULTS AND DISCUSSION

Discriminant Categories

Examination of the planted lakes revealed that they could be divided into three groups:

1. Sites capable of producing commercial wild rice stands with a density greater than 75 wild rice heads/m^2 (Figure 4-2a,b).
2. Sites capable of producing marginal commercial stands with a density of 30-75 wild rice heads/m^2 (Figure 4-2c,d).
3. Sites incapable of producing commercial stands of wild rice with either densities less than 30 wild rice heads/m^2, or no growth whatsoever.

These discriminant categories were derived based on the following assumptions:

a. a density of 75 heads/m^2 would be required for commercial production. The selection of this lower limit for commercial production was based on personal observations and consultation with personnel in the wild rice industry (Shoal Lake Wild Rice Ltd., personal communication). Its selection was somewhat subjective but it does compare well to the mean of 83 heads/m^2 found in a survey of commercial wild rice stands in this region

Fig. 4-2a. Aerial view of discriminant category 2 (Site 9).

Fig. 4-2b. Surface view of discriminant category 2 (Site 9).

Fig. 4-2c. Aerial view of discriminant category I (Site 10).

Fig. 4-2d. Surface view of discriminant category I (Site 10).

(Lee and Stewart, 1979c), and the recommendation from Minnesota paddy research over a six year period concerning the optimum depth for paddy production which found an average of 72 heads/m^2 under optimum depth conditions (Oelke, 1978).

b. the seeding density was approximately 100 seed/m^2. This was determined by counting the seeds on the ice following aerial winter plantings. The lowest germination percentage was 30. Therefore a density of at least 30 heads/m^2 should be present in all plantings and provided the lower limit for Group 2. If less than 30 heads/m^2 were present, it was assumed that the population of the plants was being depleted for environmental reasons.

The classification of the planted lakes according to their discriminant categories is contained in Table 4-1. These classifications were based on 1976 observations only. Table 4-1 also includes the mean weights per wild rice plant, the mean root, stem, leaf and head weight ratios of the rice plants, and the F values of an analysis of variance for these variables among the three groups. Statistically significant differences occurred among the groups for the mean weight per wild rice plant and the head weight ratio, thus suggesting that these variables are good indicators of wild rice plant performance. In this particular instance, head weight ratio is probably the better of the two indicators due to variances between the two years of wild rice growth in those lakes which

Table 4-1. Classification of planted lakes into discriminant categories, mean weights per wild rice plant, and mean root, stem, leaf and head weight ratios for the discriminant groups.

	Group 1	Group 2	Group 3
Lakes Included	1 - 6	7 - 18	19 - 32
Mean Weight per wild rice plant (F=3.87) *	35.28 ± 18.86	6.22 ± 0.87	1.67 ± 0.39
Mean Root Weight Ratio (F=0.49)	.164 ± .018	.150 ± .026	.108 ± .029
Mean Stem Weight Ratio (F=2.93)	.566 ± .028	.638 ± .024	.681 ± .055
Mean Leaf Weight Ratio (F=1.86)	.130 ± .023	.095 ± .013	.144 ± .041
Mean Head Weight Ratio (F=7.12) *	.140 ± .008	.117 ± .009	.065 ± .015

* Statistically significant at the P=.05 level.

were planted in 1974. During the first year these plantings had a relatively low density of wild rice plants per square metre. This low intraspecific competition often resulted in intense tillering causing high weights per plant. In the second year, natural seeding from the first year's crop increased the density of plants per square metre, thereby increasing intraspecific competition and lowering the weight per plant. Therefore a simple weight per plant value as a measure of plant performance would bias the success of the plantings in their first year of production.

Discriminant Variables and Derived Functions

The means, ranges, and F values for a univariate analysis of variance for the variables included in the discriminant analysis are contained in Table 4-2. Variables which exhibited statistical significant differences among the three groups were conductivity of water, available calcium concentration of the sediment, and suitability of the sediment for normal anchorage by the wild rice roots.

Two discriminant functions were derived from the analysis which significantly separated the three categories of plantings (Table 4-3). The standardized discriminant functions in Table 4-3 indicate the relative significance of the variables comprising the two functions. The first function, which explained 71.5 percent of the separation of the groups, was comprised mostly of the suitability of the sediment for the rice roots and the available phosphorus concentration of the sediment. The second function which explained 28.5

Table 4-2. Means, ranges, and univariate F statistics for variables included in the discriminant analysis.

Variable		Group 1	Group 2	Group 3	F Value
pH-water	mean	6.5	6.5	6.5	0.88
	range	6.4 - 6.6	6.3 - 6.7	6.3 - 6.7	
conductivity-water (μmhos/cm)	mean	33	60	75	3.57*
	range	20 - 48	18 - 114	20 - 152	
Fe-water (mg/l)	mean	0.22	0.08	0.03	3.02
	range	0.01-0.92	0.01-0.32	0.01-0.19	
Mn-water (mg/l)	mean	-	-	-	0.05
	range	0.01-0.03	0.01-0.03	0.01-0.02	
Ca-water (mg/l)	mean	4.0	10.7	11.5	2.47
	range	2.2 - 7.0	2.9 - 22.0	2.6 - 28.0	
Mg-water (mg/l)	mean	1.50	2.76	3.28	2.41
	range	0.68-3.25	0.76-6.83	0.94- 6.38	
K-water (mg/l)	mean	0.65	0.93	0.60	0.77
	range	0.49-0.99	0.30-4.08	0.11- 1.15	
$SO_4^{=}$-water (mg/l)	mean	6.3	5.3	10.0	0.33
	range	1.0 -17.0	2.0 -11.0	1.0 - 85.0	
Light extinction (μeinsteins)	mean	0.360	0.685	0.587	2.21
	range	0.225-0.510	0.140-1.240	0.110-1.260	
K-sediment (ppm)	mean	262	132	116	1.79
	range	35 - 900	48 - 320	17 - 260	
Ca-sediment (ppm)	mean	2900	4040	6110	4.79*
	range	1630-4200	1930-7250	1650-13300	
Mg-sediment (ppm)	mean	383	402	440	0.14
	range	150-925	150-725	75-825	
Fe-sediment (ppm)	mean	1860	1490	1190	1.47
	range	615-3140	300-2900	317-2350	
Mn-sediment (ppm)	mean	152	130	103	0.36
	range	46-550	44-403	23-305	
Zn-sediment (ppm)	mean	27.5	34.8	37.3	0.39
	range	15.0-35.0	7.5 - 79.0	6.3 - 73.0	
NO_3-N-sediment (ppm)	mean	10.2	16.5	28.2	0.70
	range	2.8 - 37.8	2.8 - 84.0	2.8 - 120.0	
PO_4-P-sediment (ppm)	mean	29.1	17.4	13.0	1.67
	range	9.0 - 60.0	1.8 - 60.0	1.0 - 32.4	
Suitability of sediment for root anchorage (1-3)	mean	3	3	2	13.25*
	range	2-3	2-3	1-3	

*Statistically significant at the P = 0.05 level.

Table 4-3. Values of discriminant functions derived for the separation of wild rice waters into production groups.

Discriminant Function	Relative Percentage Explained	Cumulative Percentage
1	71.5	71.5
2	28.5	100.0

DISCRIMINANT FUNCTION COEFFICIENTS

Variable	Function 1		Function 2	
	Standardized	Unstandardized	Standardized	Unstandardized
pH-water	0.117	1.066	0.731	6.681
Fe-water	-0.257	-1.434	0.485	2.700
Light Extinction	0.269	0.828	-0.522	-1.605
Ca-Sediment	0.307	0.592	0.167	0.322
Zn-Sediment	0.292	0.404	-0.551	-0.761
Sediment Suitability for Root Anchorage	-0.575	-0.692	-0.667	-0.802
PO_4P-Sediment	-0.495	-0.478	0.554	0.536
Constant		-10.679		-42.128

MEANS OF GROUP CENTROIDS

Group	Function 1	Function 2
1	-1.225	0.780
2	-0.209	-0.749
3	0.921	0.495

percent of the group separations was comprised mostly of the pH in the water, the iron concentration of the water, the suitability of the sediment for the rice roots, and the available zinc and available phosphorus concentrations of the sediment.

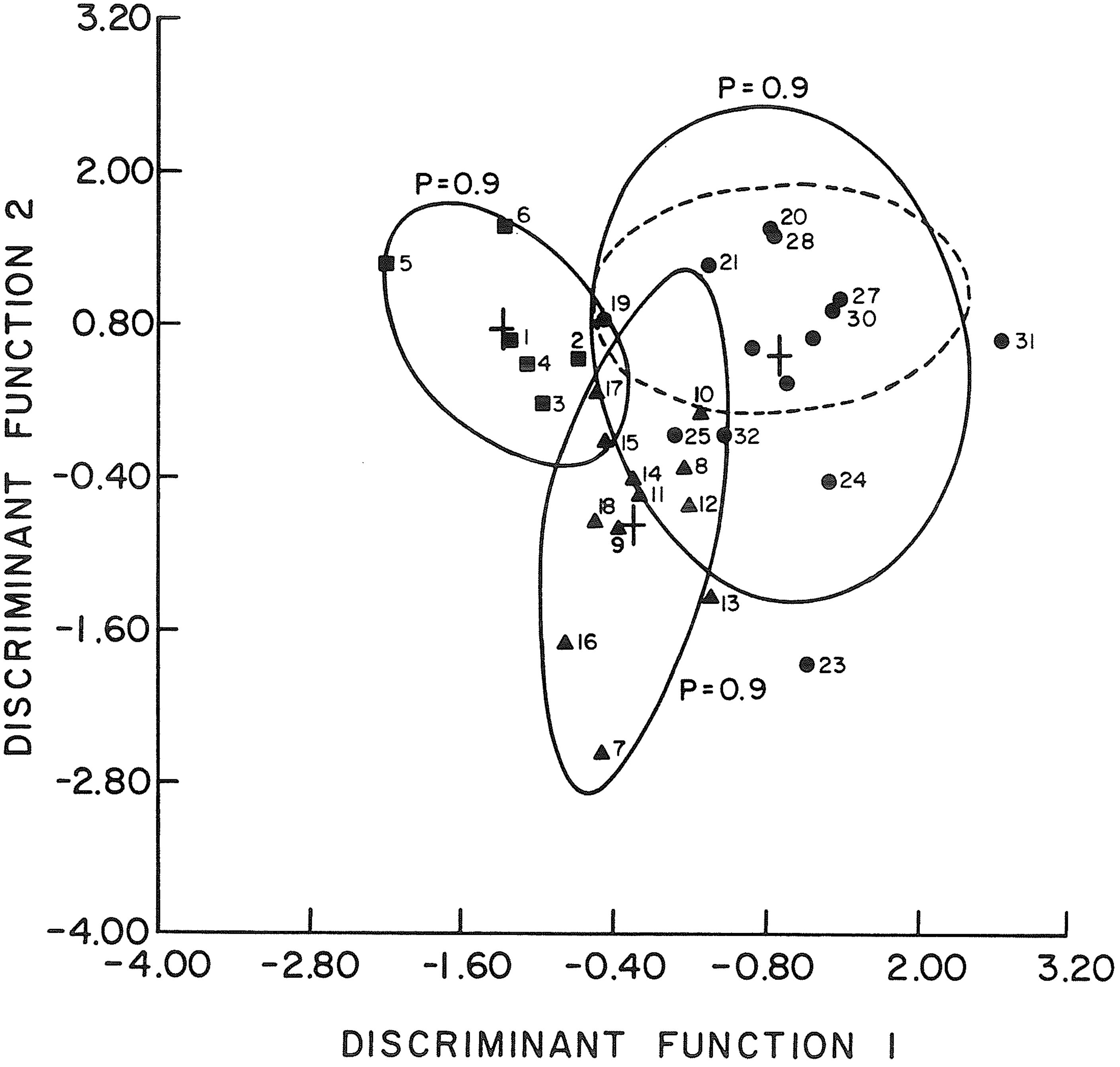
Effectiveness of the Discriminant Analysis

Figure 4-3 illustrates the separation of the planted lakes with respect to their discriminant scores. The three elipses describe the bivariate normal distributions of the discriminant scores for each of the sampling groups which would include 90 percent of the lakes in their *a priori* discriminant categories. The larger the within group variance, the larger the elipse. Therefore, if there are any samples which deviate considerably from the group mean, this will cause the bivariate normal distribution associated with the group to be disproportionately large. This is the case for group 3 where lake 19 had discriminant scores not typical of the group and this caused the group 3 bivariate normal distribution to be stretched resulting in considerable overlap with group 2. The dotted elipse shows that by not including lake 19 in the calculations for group 3, the variance and the region of overlap were considerably reduced.

The classification of the lakes (based on the distance to the nearest group centroid mean) into their *a priori* groups was good, with 84.4 percent of the lakes being correctly

Figure 4-3

Separation of the planted lakes according to their discriminant scores. The three ellipses describe the bivariate normal distributions of the discriminant scores for each of the sampling groups which include 90 percent of the lakes in their *a priori* discriminant categories (+ indicates the mean for each discriminant group). The dotted ellipse (- - -) described the bivariate normal distribution with Site 19 removed.


3.20
2.00
0.80
-0.40
-1.60
-2.80
-4.00
-4.00
-2.80
-1.60
-0.40
-0.80
2.00
3.20
DISCRIMINANT FUNCTION 2
DISCRIMINANT FUNCTION I
P=0.9
P=0.9
P=0.9
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
23
24
25
27
28
30
31
32

classified. One lake from group 2 (lake 17) and one lake from group 3 (lake 19) were incorrectly classified as group 1. One lake from group 2 (lake 10) was incorrectly classified into Group 3, and two lakes from group 3 (lakes 23, 25) were incorrectly classified into group 2. No lakes from group 1 were incorrectly classified. These misclassifications generally occurred in those overlapping regions of the bivariate normal distributions not unique for each group.

It is interesting to examine further the two lakes placed incorrectly in group 1. Lake 17 was severely influenced by plant competition which is not a variable used in the discriminant analysis. Lake 19 was initially planted in 1974. When it was examined in 1975, the growth performance was very poor it was thought that this may have been due to high water levels in the early spring, and the lake was reseeded the same year. In 1976 the result was the same poor growth performance, suggesting that some variable not accounted for by the discriminant functions was affecting the growth of wild rice in this lake.

Utilization of the Discriminant Functions as a Selection Criterion

It seems possible that the method for categorizing the success of the wild rice plantings could be used as a selection criterion for predicting potential wild rice producing lakes. However, the limitations of doing this should be clearly pointed out:

a. the selection criterion would be valid only to the extent of the number of environmental variables examined. Other factors not considered in the study could very well play an important role in specific lakes. An obvious limitation is plant competition. The majority of the lakes planted in the study had been pre-selected to have no effect from other aquatics and therefore using the discriminant procedure for categorizing lakes which had considerable plant competition could result in incorrect growth performance predictions.

b. the selection criterion would be valid only within the geographical region in which it was devised. It would be incorrect to assume the criterion would be valid outside of northwestern Ontario without first testing the validity of the criterion in the specific region being considered. This is because there may be important influential variables affecting wild rice growth, which, while not measured in this study, could be considered either more or less constant, or highly correlated with the measured variables. In another area (or in this area at another time) this may not be true, giving erroneous results from this criterion.

c. the criterion itself would only be an empirical criterion for discriminating between potential wild rice waters and would not necessarily explain the real factors influencing wild rice growth. These real influencing factors could only be determined with any degree of certainty under controlled conditions. However, by examining the intercorrelations of the variables comprising the discriminant functions and their relationships with the growth performance of the wild rice plants, some further insight into the possibility that they may be exerting some real effect on the rice plants may be gained.

Validity of Discriminant Function Components

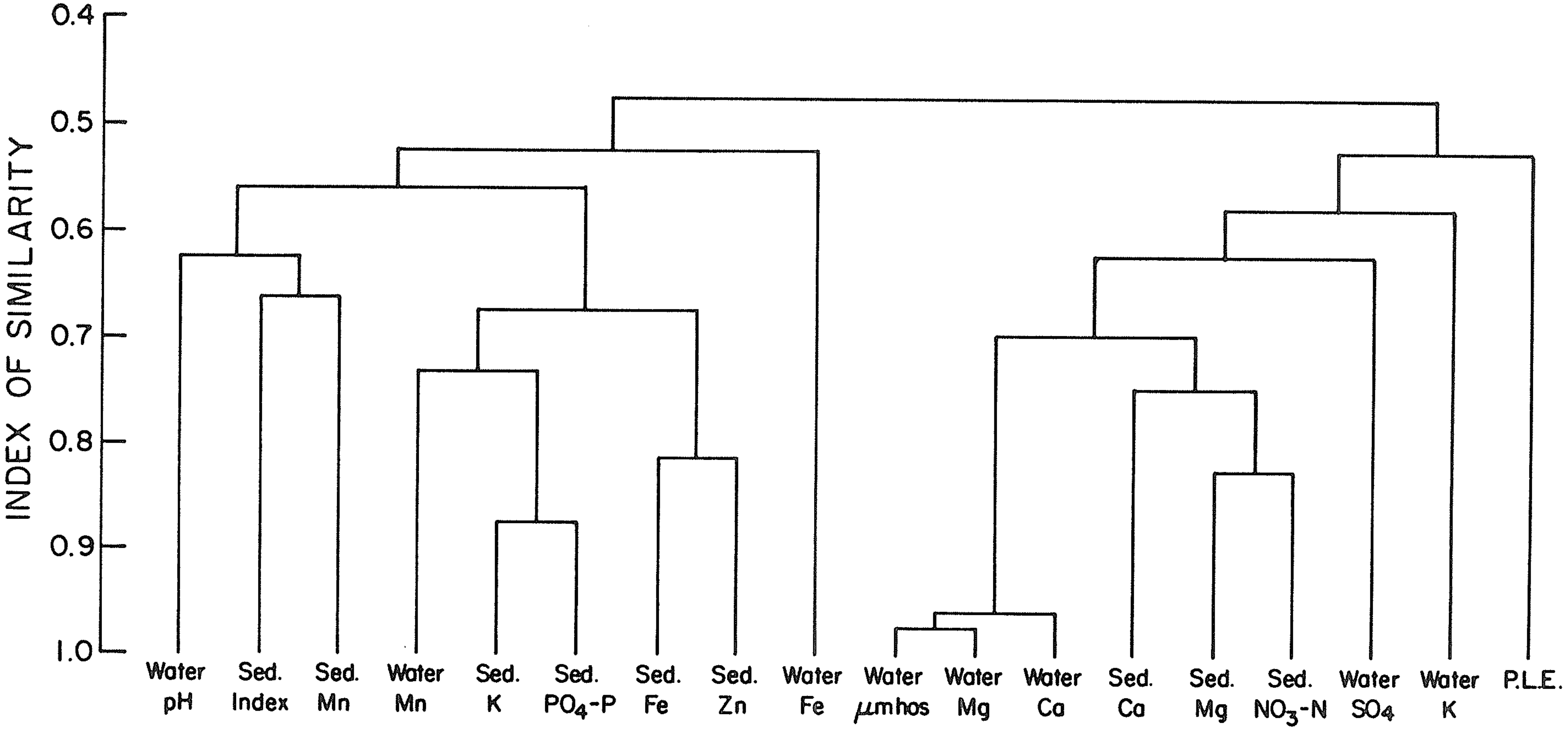
Intercorrelations of Variables

In the formation of the discriminant functions, a variable which is highly correlated to another variable already in the discriminant function will be excluded (Green, 1971). Therefore it is incorrect to assume that the variables isolated as being significant in the discriminant functions are acting independently, but rather they may be simply correlated to other variables which are influencing the growth of wild rice.

Figure 4-4 shows the intercorrelations which existed among the variables used in this analysis. There were ten main groups:

Figure 4-4

Intercorrelations of variables used in the discriminant analysis as determined by the cluster analysis of variables.


INDEX OF SIMILARITY
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Water pH
Sed. Index
Sed. Mn
Water Mn
Sed. K
Sed. PO_4-P
Sed. Fe
Sed. Zn
Water Fe
Water µmhos
Water Mg
Water Ca
Sed. Ca
Sed. Mg
Sed. NO_3-N
Water SO_4
Water K
P.L.E.

Group 1 - pH

Group 2 - suitability of sediment for anchorage by wild rice roots

Group 3 - Mn-sediment

Group 4 - Mn-water, K-sediment, available P-sediment

Group 5 - available Fe-sediment, available Zn-sediment

Group 6 - Fe-water

Group 7 - water conductivity, Mg-water, Ca-water, available Ca-sediment, available Mg-sediment, available N-sediment

Group 8 - SO_4-water

Group 9 - K-water

Group 10 - photosynthetically active light extinction

Of the seven variables isolated in the discriminant analysis, four of these, the pH of the water, the suitability of the sediment for the normal anchorage by the wild rice roots, the iron concentration of the water, and the extinction of photosynthetically active light, formed their own separate group. The other three isolated variables, available calcium, available zinc, and available phosphorus concentrations in the sediment, were all highly correlated with other variables. In order to illustrate that variables which occurred in the same group as the above elements (and were therefore intercorrelated with them) could also be influencing the separation of the planted waters, additional discriminant analyses were performed substituting one, two and finally all three of the original variables with correlated variables. In all cases the classifications of the lakes predicted using the substituted variables differed only marginally from those predicted with the original discriminant functions. Therefore, the specific variables isolated in the discriminant analysis were not necessarily the cause of the differences in the results of the wild rice plantings, but were merely indicative of more general factors acting on the rice plants. Some indication as to how these factors affected the growth of the rice plants can be assessed by relating the isolated variables to some measure of wild rice growth performance for the water which did support wild rice growth.

Growth Performance Relationships

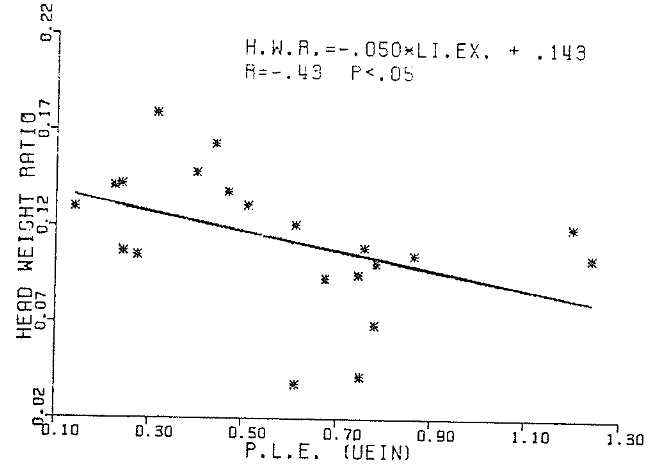
As previously discussed, head weight ratio was thought to be a better indicator of wild rice growth performance than weight per plant since some of the waters had been growing rice for two years and some for only one year. In examining the relationships between the head weight ratios in the planted lakes and the environmental variables extracted from the discriminant analysis, it should be realized that there is a very fundamental difference between the performance of the plantings according to the head weight ratio and that according to the three groups used in the discriminant analysis. The development of relationships between the head weight ratios and the environmental variables will be concerned strictly with the biological performance of the plants on an individual basis. In the discriminant analysis, the concern was solely in selecting wild rice waters for their potential ability to produce commercial crops. There was no concern with individual plant performance, although since the head weight ratios were significantly different between the groups, it can be generally assumed that there was a strong association of head weight ratio with the different groups. However, exceptions could and did occur. For example, lake 17, which was influenced by plant competition, was classified as less than optimum for commercial production (i.e. not group 1) simply because the density of heads per square metre was not high enough, even though individual plants which did survive were actually quite productive.

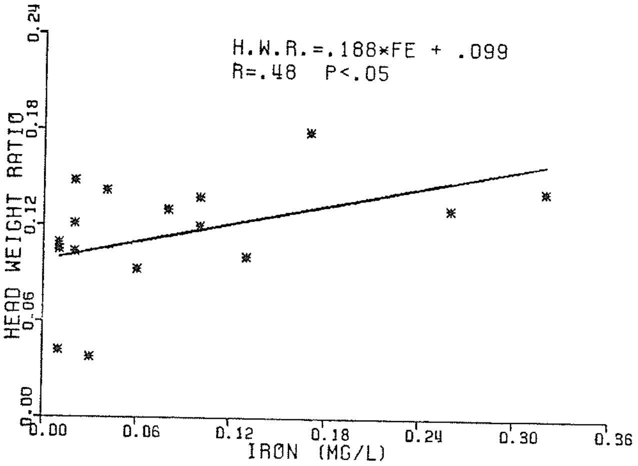
Regression analysis revealed that statistically significant ($P<0.05$) trends existed between head weight ratio and extinction of photosynthetically active light (Fig. 4-5a), and head weight ratio and the iron concentration of the water (Fig. 4-5b). Positive trends existed for head weight ratio with sediment zinc concentrations and the suitability of the sediment for the wild rice roots. A negative trend existed between head weight ratio and the calcium concentration of the sediment. No apparent trends existed between head weight ratio and the pH of the water or sediment phosphorus concentration.

The effect of decreases in photosynthetically active light resulting in decreases in the growth performance of the wild rice plants was to be expected. Most existing wild rice stands are found in shallow, clear waters (Lee and Stewart, 1980c) apparently because wild rice requires a fairly high

Figure 4-5

Relationship of (a) extinction of photosynthetically active light and (b) iron concentrations of the water with head weight ratio.


H.W.R.=-.050*LI.EX. + .143
R=-.43 P<.05
HEAD WEIGHT RATIO
0.02
0.07
0.12
0.17
0.22
0.10
0.30
0.50
0.70
0.90
1.10
1.30
P.L.E. (UEIN)


H.W.R.=.188*FE + .099
R=.48 P<.05
HEAD WEIGHT RATIO
0.00
0.06
0.12
0.18
0.24
0.00
0.06
0.12
0.18
0.24
0.30
0.36
IRON (MG/L)

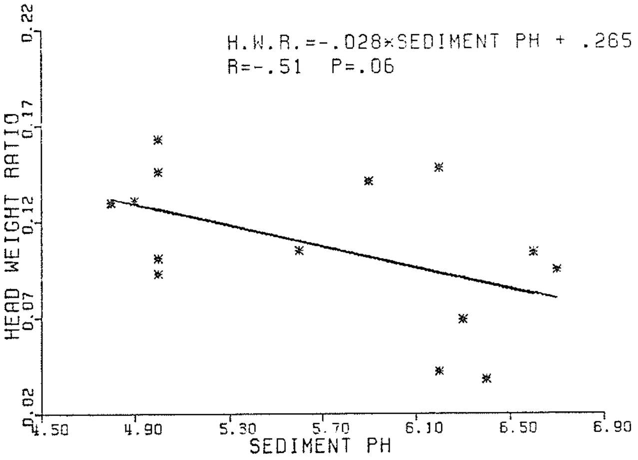
intensity of light for adequate photosynthesis during its early stages of development. In this study, the maximum extinction value at which wild rice survived was 1.24 μeinsteins. If the mean for photosynthetically active light extinction for group 1 from this study is considered optimum, best production occurs at a value of approximately 0.36 μeinsteins.

It is unlikely that the iron concentration in the water has any direct effect on wild rice growth performance, but rather is correlated to some other factor(s) which influence the plants. One such intercorrelated variable which may well have considerable effect, both directly and indirectly on the wild rice plants, is the available sediment iron concentration (Fig. 4-4 does not show an association between iron in the water and iron in the sediment since sediment iron is more closely correlated with sediment zinc). Wild rice does accumulate high concentrations of iron especially in the roots (Lee and Stewart, 1979b) and it is possible that it could be limiting in some cases. But Table 4-2 indicates that sediment iron was present in high concentrations. However, the 0.1N HCℓ extraction solution removes ferric as well as ferrous ions. When wild rice is cultured using ferric chloride as an iron source it exhibits general chlorosis, extremely weak stems which generally do not allow the plants to survive the transition from the floating leaf stage to the emergent stage, and in those cases where emergent leaves are produced, the classical iron deficiency symptom of the green of the leaf veins setting off the chlorotic area of the rest of the leaf is very noticeable. These symptoms can be remedied by substituting a chelated iron (pers. obs.). Therefore it is not important what the total concentration of ferrous and ferric iron is, but only the concentration of ferrous iron. The concentration of the ferrous form in the sediments increases with lower redox and pH values (Hem and Cropper, 1960) and lower calcium concentrations (Oborn, 1960). It is in this sense that the isolated factors in the discriminant analysis may be related.

Increasing calcium concentrations in the sediments would result in a decreased amount of ferrous and associated metals due to higher pH values (Hem, 1960). In order to determine if the pH of the sediments also differed between the planted groups, the pH of several of the lake sediments from each group was measured and it was found that there was a trend for pH values to increase from Group 1 to Group 3. When head weight ratio was regressed against the pH sediment values a statistically significant negative trend (P=0.06) was found to exist (Fig. 4-6), suggesting that even in some of the waters which did produce wild rice there is some evidence that metal deficiencies associated with higher pH values could exist. There is an extremely rapid decrease in ferrous iron for even slight increases in pH (Ponnamperuma, 1965), but over the range of pH values found in this study, there still should be adequate ferrous iron in the usually low redox levels commonly found in lake sediments. Therefore, if deficiencies of iron or other metals were occurring, it should be because the redox levels in the sediments were so high

Figure 4-6

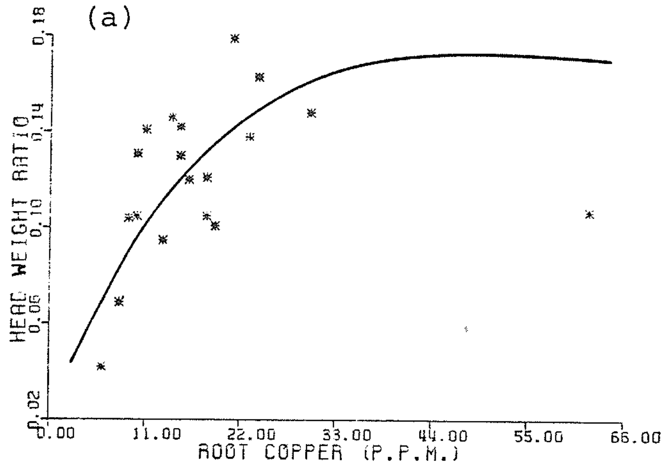
Relationship between head weight ratio and the pH of the sediments of lakes seeded with wild rice.

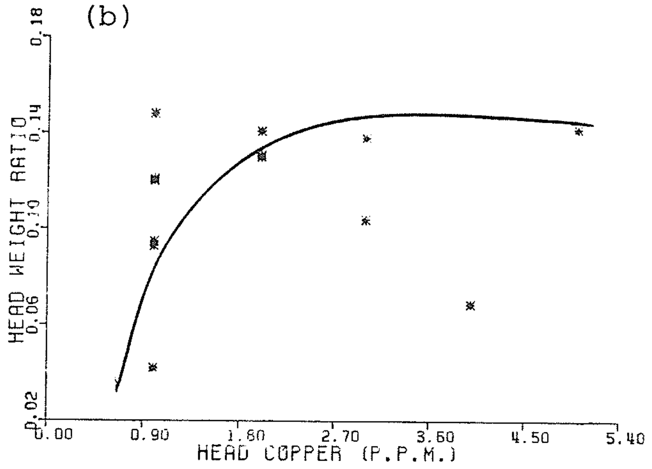

H.W.R.=-.028×SEDIMENT PH + .265
R=-.51 P=.06
HEAD WEIGHT RATIO
0.02
0.07
0.12
0.17
0.22
4.50
4.90
5.30
5.70
6.10
6.50
6.90
SEDIMENT PH

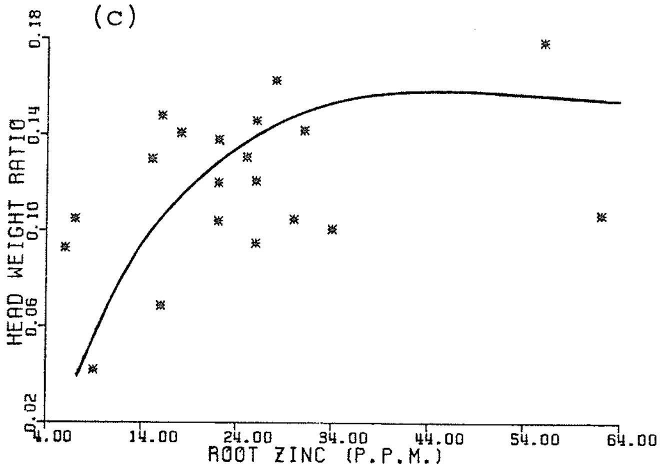
that the reduction of the metals was impeded. Such deficiencies can be detected by plotting the tissue concentrations of the elements versus the head weight ratios. If a plot similar to that described by Gerloff and Krombholz (1966) occurs, whereby there is an increase in head weight ratios with increases in tissue concentrations until a maximum head weight ratio is achieved and is not affected by further tissue concentration increases, then this will indicate that some of the plantings may have been affected by deficiencies of the concerned element. When this was done for the metal concentrations in the roots, leaves, stems and heads, it was found that such a general pattern occurred for zinc and copper in the roots and heads and iron in the leaves and heads, although there was considerable scatter (Fig. 4-7). This suggests that copper and zinc are decreased in availability under much the same conditions as iron, possibly as a result of the tendency for copper and other metals to be co-precipitated with ferric hydroxide complexes (Hem and Skougstad, 1960) and rendering them not readily available to the wild rice plants. One interesting point from the copper and iron concentrations in the heads (Fig. 4-7b, 4-7f) is that several of the plantings which had high head weight ratios had what appeared to be limiting tissue concentrations. Apparently there were sufficient quantities of these elements present to achieve a certain weight, and after that may have limited further weight increases. It is also possible, even in those waters which did not exhibit deficiencies of these elements, that after

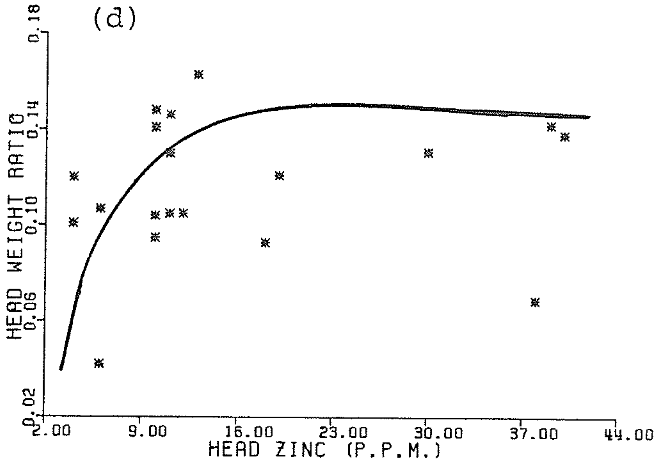
Figure 4-7

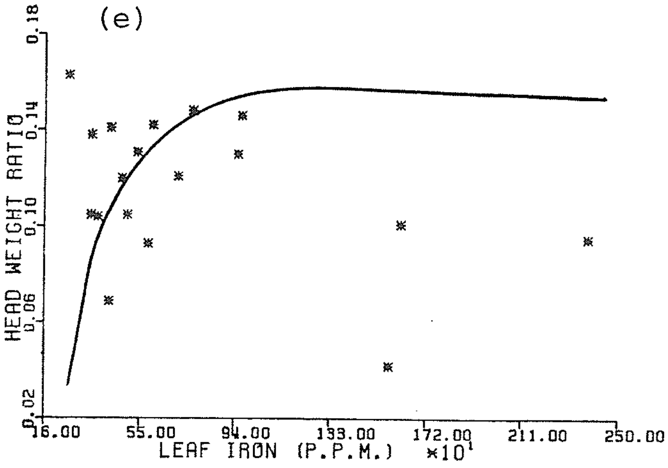
Relationship between head weight ratio and tissue concentrations of (a) root copper (b) head copper (c) root zinc (d) head zinc (e) leaf iron and (f) head iron.

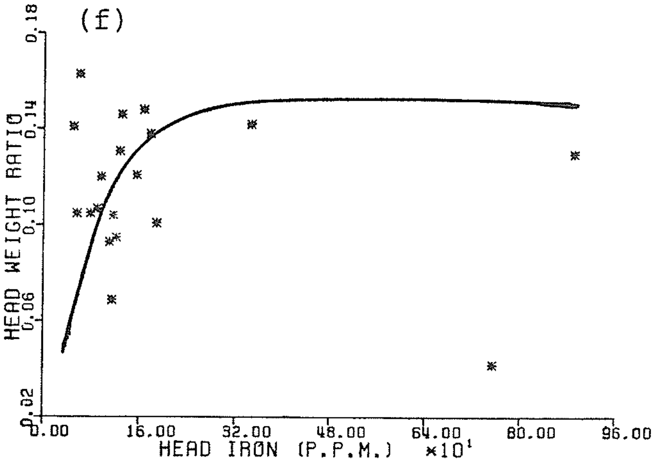

(a)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
0.00
11.00
22.00
33.00
44.00
55.00
66.00
ROOT COPPER (P.P.M.)


(b)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
0.00
0.90
1.80
2.70
3.60
4.50
5.40
HEAD COPPER (P.P.M.)


(c)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
4.00
14.00
24.00
34.00
44.00
54.00
64.00
ROOT ZINC (P.P.M.)


(d)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
2.00
9.00
16.00
23.00
30.00
37.00
44.00
HEAD ZINC (P.P.M.)


(e)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
16.00
55.00
94.00
133.00
172.00
211.00
250.00
LEAF IRON (P.P.M.) ×10¹


(f)
HEAD WEIGHT RATIO
0.02
0.06
0.10
0.14
0.18
0.00
16.00
32.00
48.00
64.00
80.00
96.00
HEAD IRON (P.P.M.) ×10¹

several years of continued production, deficiency symptoms could occur if the metal reserves were being depleted.

The above problem was probably compounded in those shallow lakes which did not grow any rice and which were characterized by the flocculent nature of their sediments. In these lakes, wind action could make the sediments aerobic at least to the rooting depth of wild rice, and, combined with the generally higher pH levels, this would encourage the formation of ferric rather than ferrous iron. In fact it seems quite possible that these loose flocculent sediments are composed largely of ferric hydroxide complexes. Ferric salts are commonly added as coagulants in the treatment of public and industrial water supplies. These salts form a bulky gelatinous floc which is capable of attracting and co-precipitating suspended clay particles, organic colloids and micro-organisms (Hem and Skougstad, 1960). This could explain the extremely clear waters of these lakes (Fig. 4-8). These ferric hydroxide precipitates also attract other trace metals (Hem and Skougstad, 1960) and phosphates (Oburn, 1960) which were also isolated in the discriminant analysis. The problem of these lakes therefore becomes analogous to that of marl lakes. In marl lakes, iron and manganese can limit primary production because of their unavailability at the high pH levels found in these lakes (Schelske, 1962; Wetzel, 1966). In the above "ferric hydroxide lakes" iron is unavailable for primary production because of the generally high redox potentials in the sediments.

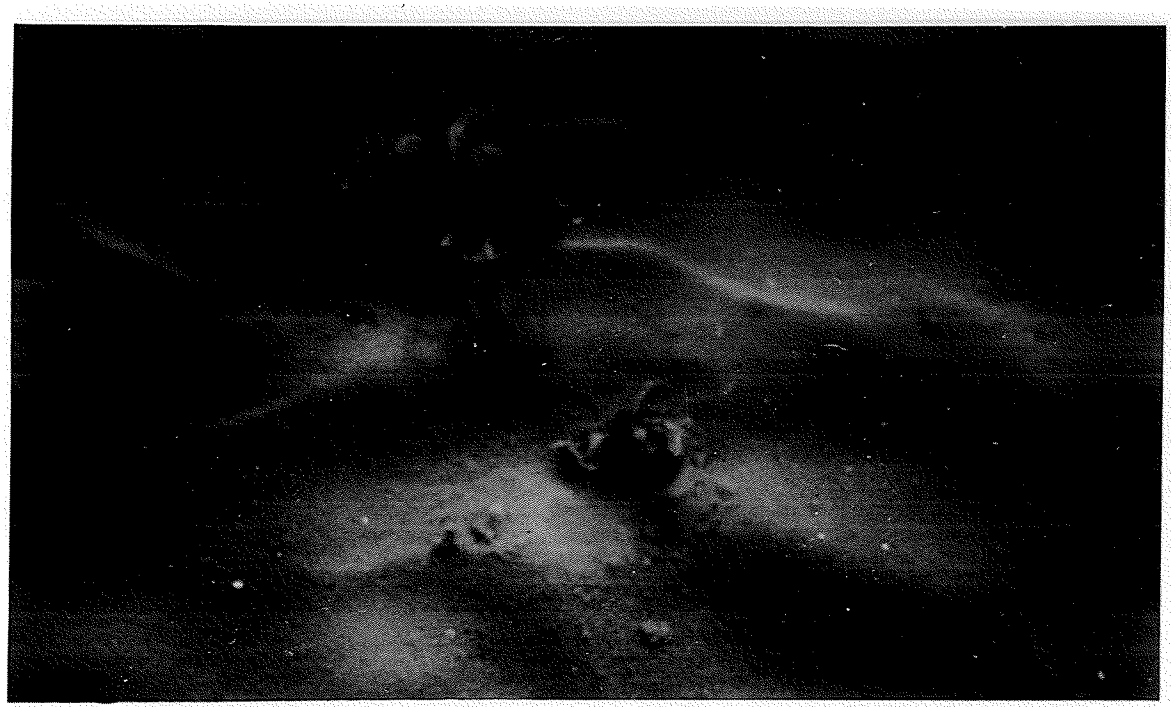


Fig. 4-8. Shallow clear water associated with flocculent sediments of waters unsuitable for wild rice.

CONCLUSIONS

In the present study, discriminant analysis was able to isolate the planted lakes into their respective *a priori* categories with 85 percent accuracy. Variables included in the discriminant functions were pH and dissolved iron in the water, extinction of photosynthetically active light in the water, available calcium, zinc, and phosphorus in the sediments, and the suitability of the sediment for root anchorage.

Photosynthetically active light extinction of the water was negatively correlated with head weight ratio, possibly as a result of a requirement for high light intensity during the plant's early stages of development. The role of the other variables seemed to involve the availability of micronutrients. Non-reducing conditions and higher calcium and pH levels may have occurred at several of the plantings, resulting in deficiencies of iron zinc, and copper. Under such aerobic conditions, ferric hydroxide complexes could have formed, precipitating other metals, and inorganic and organic matter, resulting in the extremely clear waters and flocculent sediments observed at several of the unproductive lakes.

GENERAL CONCLUSIONS

Any general conclusions from this study should be based on the overall basic objective of gaining a better understanding of wild rice in terms of its biological, chemical, and physical environment, and the application of this knowledge for improving yields in the natural stands. At the same time, consideration should be given to specific areas of concern which are not fully understood and will require further research.

The most significant contribution of the first paper was the derivation of a "relative approach", involving time-corrected data, which could be used to model the growth of wild rice. The model was based on the premise that differences in environmental variables among sampling sites could account for the differences which occurred in the growth of wild rice at the same sites. Presumably seasonal trends of environmental variables exist in all wild rice stands, and a similar procedure could be used to quantify variances in wild rice plant performance at these stands. Discriminant analysis was used as part of this procedure, and shown to be a useful method for determining those factors which could cause among-site variances in wild rice growth. Unfortunately, there is a basic limitation of the method in that it relies on the mean values of the environmental variables in forming the discriminant functions even though many of these variables often fluctuate greatly from this mean. This, however, is a weakness not just of discriminant analysis, but of statistics in general. Statistics is merely a stop-gap measure and, in future, more deterministic methods should be used to derive models for wild rice growth which are based on differences among environmental variables and which can account for individual, not just mean results.

The second paper suggested that the reason for poor correlations between the concentrations of elements in plant tissue and the concentrations in the sediment may be due to excess quantities of nutrients which are present in the sediment and absorbed at a constant maximum rate per unit weight of the plant. This concept has considerable importance for properly managing the natural stands of wild rice. Assuming these maximum concentrations could be determined, any rice stand could be sampled and zones where nutrient deficiencies occur could be corrected. More detailed studies on nutrient uptake in general should be done. Immediate attention should be directed at whether or not wild rice absorbs any nutrients through its leaves during its early stages of development. Another area of concern should be to develop better analytical techniques for measuring the nutrient concentrations in the sediment. The present methods require the sediment sample be dry, thus completely altering them from their natural state. The results may therefore be only gross approximations of what may be true under flooded conditions.

The third paper illustrated that on a regional basis, wild rice seems to have a fairly wide range of environmental tolerance for many variables. Future research should be done which could determine the minimum, optimum, and maximum levels of these variables. Areas of immediate management concern are intraspecific competition, and concentrations of nitrogen and phosphorus in the sediments. The plant itself also exhibited considerable phenotypic variation. Grain size is of particular interest since different lengths are required for different commercial markets and it would be highly desirable to have seed sources for this purpose. Plant breeding, for improving natural stands, seems to have raised little interest in Canada. A breeding program to produce seed sources which could provide better yields would seem to be a definite priority for the present Canadian wild rice industry.

The final paper was able to separate the majority of the planted lakes into their appropriate groupings according to factors isolated by discriminant analysis. Of the variables used in the formation of the discriminant functions, photosynthetically active light is probably the most universally important in influencing rice production in natural stands. Future research may determine that there is a relatively constant minimum value for this variable beyond which rice does not survive. Maximum expected depths of occurrence could then be calculated by dividing this constant by the extinction coefficient of photosynthetically active light of the particular rice stand. The other variables isolated in the discriminant analysis seemed to be mainly involved in micronutrient deficiencies. In the majority of rice lakes, this may be of minor importance, but in some potential rice lakes with aerobic sediments, additions of chelated metals could be tried as a corrective measure. Considerably more research in general should be done on these lakes which exhibit aerobic sediments. There are no descriptions of this type of lake in the literature, and yet they are not uncommon in northwestern Ontario, some of them being as large as 700 hectares.

Therefore, it can be stated that some progress has been made in better understanding the growth of wild rice, but certainly a great deal of time may pass before all the requirements can be quantified exactly. However, as long as the basic approach is to try to understand the ecology of the plant, not merely manipulate it, this will someday be possible. There is a reason for everything in nature, and as long as we never deviate from this fact, we will eventually win at this great game of science. As Einstein put it "God does not play dice with the world."

APPENDIX 1-1

Macrophytes in Association with Wild Rice

A total of 40 macrophytic species or species groups were identified during the 1976 and 1977 growing seasons at the 5 sampling sites (Figure 1-1). Identification and nomenclature follow Scoggan (1957), Fassett (1960), Gleason (1968) and Hotchkiss (1972).

No.	Scientific Name	Common Name
1	*Bidens cernua*	Beggar Tick
2	*Calamogrostis canadensis*	Blue-joint
3	*Carex spp.*	Sedge
4	*Ceratophyllum demersum*	Coon Tail
5	*Elocharis palustris*	Spike Rush
6	*Elodea canadensis*	Canada Waterweed
7	*Equisetum fluviatile*	River Horsetail
8	*Glyceria spp.*	Manna Grass
9	*Hippuris vulgaris*	Mares Tail
10	*Lemna trisulca*	Star Duckweed
11	*Megalodontia Beckii*	Water Marigold
12	*Myriophyllum exalbescens*	Water Milfoil
13	*Myriophyllum heterophyllum*	Water Milfoil
14	*Najas spp*	
15	*Nuphar variegatum*	Yellow Waterlily
16	*Nymphaea odorata*	White Waterlily
17	*Phragmites communis*	Reed
18	*Polygonum natans*	Floatingleaf Smartweed
19	*Potamogeton illinoensis*	Variable Pondweed (Site 3 only)
20	*Potamogeton natans*	Floating leaf Pondweed
21	*Potamogeton pectinatus*	Sago Pondweed
22	*Potamogeton Richardsonii*	
23	*Potamogeton Robbinsii*	
24	*Potamogeton strictifolius*	Narrowleaf Pondweed
25	*Potamogeton vaginatus*	Bigsheath Pondweed
26	*Potamogeton zosteriformis*	Flatstem Pondweed
27	*Ranunculus aquatilis*	White Water Buttercup
28	*Sagittaria latifolia*	Arrowhead
29	*Sagittaria rigida*	Wapato
30	*Scirpus acutus*	Hardstem Bulrush
31	*Scirpus atrocinctus*	Wood Grass
32	*Scirpus fluviatilis*	River Bulrush
33	*Scirpus validus*	Softstem Bulrush
34	*Sparganium eurycarpum*	Burreed
35	*Spirodela polyrhiza*	Greater Duckweed
36	*Typha latifolia*	Cattail
37	*Utricularia intermedia*	Flatleaf Bladderwort
38	*Utricularia vulgaris*	Common Bladderwort
39	*Vallisneria americana*	
40	*Zizania aquatica var interior*	Wild Rice

Appendix 1-2

Interspecific Competition with Wild Rice

Interspecific competition during both 1976 and 1977 growing seasons is tabled below in terms of total biomass of other species (d (dry weight g/m^2) present in sample quadrats at sites 1,2,4 and 5. Note that sites 4 and 5 data have consistently higher biomas values, perhaps a reflection of the stimulatory effects of mixing of the Mississippi River water with the thermally enriched effluent discharge.

Interspecific Plant Competition 1976 (dry weight g/m^2)

	Site 1 Time (year - Days)							Site 2 Time (Year - Days)							Site 4 Time (Year - Days)							Site 5 Time (Year - Days)						
Species or Species Groups	158	172	186	200	214	228	242	158	172	186	200	214	228	242	158	172	186	200	214	228	242	158	172	186	200	214	228	242
1. *Carex* spp																						0.3						
2. *Ceratophyllum demersum*			3.4		1.0					3.0	4.0	9.1	9.1	1.4	3.9			1.2	68.6	3.6	4.0	4.8		2.6			12.5	
3. *Elodea canadensis*										2.1	3.6	4.5	3.4		0.3	0.1	0.1		6.6	0.6	0.2	0.4		14.4		1.5	2.4	
4. *Lemna trisulca*		0.5																				0.1						
5. *Megalodontia beckii*				0.3	0.6	0.4				0.2	11.4	5.8	2.3	4.8	93.8	14.1	195.5	19.7	7.6	1.1	4.4	21.3	2.0	14.1		1.6	4.6	13.2
6. *Myriophyllum* spp							0.3			0.1					0.2				2.6			0.3				1.7		
7. *Najas* spp											0.1																	
8. *Nuphar variegatum*		1.9			36.8		29.7					0.3										4.3	10.5	0.1			5.8	
9. *Potamogeton natans*																		1.9						0.5				
10. *Potamogeton pectinatus*															0.7				0.3									
11. *Potamogeton richardsonii*																2.16			0.2									
12. *Potamogeton robbinsii*															1.8													
13. *Potamogeton zosteriformis*		1.0	5.8	7.3	1.7	3.4		1.2	11.6	92.7	54.7	10.6	30.5	6.6	44.6	264.2	32.0	23.5	3.6	2.3	0.5	2.8	2.5	35.9	0.6	1.5	5.8	
14. *Ranunculus aquatilis*										0.3																		
15. *Sagittaria* spp			3.7	5.7				1.9		2.3							39.7			76.4			38.5	9.5		42.5	204.6	7.8
16. *Sparganium eurycarpum*	1.8	0.3						2.7														0.1	2.5					
17. *Utricularia* spp					1.4	0.8	3.8															2.3	10.5	4.5	7.8	2.2		

APPENDIX

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