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Community Analysis in Fishery Management: An Application with Northern Wisconsin Lakes

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Abstract

Decisions in fishery management usually are made on a species-by-species and site-by-site basis because most information about fishes has been collected and organized in this way. A comparative, community-level approach can contribute to the development of management strategies for large sets of lakes and fish assemblages. Here we describe an approach similar in concept to lake classification, using techniques of multivariate community analysis (ordination, classification, multiple discriminant analysis). This approach can reveal patterns among fish assemblages and relate them to the lakes' habitat characteristics. An application of the approach is illustrated by a published study on fish assemblages of 18 small lakes in northern Wisconsin. Two discrete assemblage types were distinguished and the factors believed to be responsible for their maintenance were identified. With relationships derived from those 18 lakes, predictions of the assemblage types of 11 additional lakes are made from only five habitat characteristics obtained from the literature. Analyses showed these predictions to be largely successful. We suggest that multivariate community analysis contributes to an ability to understand, predict, and manage fish assemblages.

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Fishery biology is still without a solid foundation at the community level of biological organization. Currently, management decisions are made largely on the basis of characteristics and population dynamics of individual species at single sites. Manipulations often are made without a consideration of the patterns and processes of fish-species assemblages. This approach stems in part from the historical development of fishery science in North America around population dynamics and the management of stocks for sustained yields (McHugh 1970; Larkin 1978; Regier 1978). There is growing recognition, however, of the limitations of managing fisheries, stock by stock, based on population-dynamics models (McHugh 1970; Regier and Henderson 1973; Gulland 1977; Larkin 1977, 1978; Regier 1978; Kerr 1982).

The ability to predict changes in a lake's fish assemblage brought about by a management program can be acquired by: (1) gaining a relatively complete understanding of all processes that determine the distribution and abundance of each population (and any new one proposed to be stocked); or (2) identifying repeated patterns of community structure and deriving relationships among these patterns and physical and biotic factors. Although the first approach provides valuable information, it is usually so demanding and complex that the desired level of understanding cannot be achieved.

The second, "empirical," approach (Rigler 1982) has more promise. Sites do not have to be considered on a case-by-case basis as unique entities but can be grouped or classified on the basis of their fish assemblages or habitat characteristics (Platts 1980). If lakes with similar habitats tend to have similar fish assemblages, comparisons can be made efficiently to yield relationships among them. Such relationships can be used in areas where many lakes occur to predict which assemblages or lake types would benefit from a proposed management scheme.

While there is a tradition of empiricism in aquatic science (Rigler 1982), the comparative approach has not been used extensively in fishery biology. Recent efforts have involved predictions of total fish yield or lake productivity

(Ryder et al. 1974, Melack 1976; Oglesby 1977, 1982; Hanson and Leggett 1982; Ryder 1982) and the development and use of structural indices of fish populations (Anderson 1976). The usefulness of these approaches encouraged us to compare fish assemblages in lakes using easily obtainable data and principles and methodologies from lake classification and community ecology.

Often species composition is related to attributes of the species, features of the environment, and to the complex interactions among these factors. Thus the composition of fish assemblages and the environmental, ecological, and historical characteristics of the lakes are interdependent. Patterns in fish assemblages—for example, that certain species occur together in certain types of lakes—and the importance of interactions among species and with their environment have long been recognized. However, to quantify these complex patterns and interactions, appropriate analytical methods are required.

Multivariate community analysis: (1) efficiently summarizes biological community data into a simpler form; (2) relates these simplified biological data to the environmental data; and (3) presents the results in forms that can be easily understood and used to gain further insights (Green and Vascotto 1978; Bloom 1980; Gauch 1982). The "natural experiments" of comparative community studies, in conjunction with these multivariate methods, can be used to detect patterns, generate and test hypotheses, assess mechanisms, and produce acceptable explanations for community level problems under a wide variety of conditions (Werner et al. 1978; Wiley and Cruz 1980; Rigler 1982).

In this paper we describe a multivariate community analysis that can be used to explore and define patterns of similarity and difference among fish assemblages and relate these patterns to environmental variables. To illustrate this approach, we work from a previously published example (Tonn and Magnuson 1982) to predict fish-assemblage types in other lakes.

Multivariate Community Analysis

Our multivariate techniques follow those of standard texts, such as Cooley and Lohnes (1971) or Srivastava and Carter (1982); application of these methods to community analysis is discussed by Green (1979), Gauch (1982), and Beals (1983). Standard computer software packages that perform the types of analyses we describe here—classification (SAS, BMPD, CEP, NT-SYS, CLUSTAN), ordination (SAS, BCORD, BMDP, CEP, SPSS), and multiple discriminant analysis (SAS, BMPD, SPSS)—are described by Nie et al. (1975), Wishart (1975), Gauch (1976), Barr et al. (1979), Dixon and Brown (1979), and Beals (in press); see also Orloci (1975). Here we present only a brief discussion of the concepts involved in multivariate community analysis and the ways these methods can be applied in fishery research.

TABLE 1.—*A lakes-by-species and a lakes-by-environment matrix appropriate for multivariate community analysis in fishery management:* s_{ij} *is the datum (for example, abundance) for the* j*th fish species in the* i*th lake;* f_{ik} *is the measurement of the* k*th environmental factor in the* i*th lake.*

	Species (s)					Environmental factors (f)				
Lake	1	2	3	· · ·	s	1	2	3	· · ·	f
1	s_{11}	s_{12}	s_{13}	· · ·	s_{1s}	f_{11}	f_{12}	f_{13}	· · ·	f_{1f}
2	s_{21}	s_{22}	s_{23}	· · ·	s_{2s}	f_{21}	f_{22}	f_{23}	· · ·	f_{2f}
3	s_{31}	s_{32}	s_{33}	· · ·	s_{3s}	f_{31}	f_{32}	f_{33}	· · ·	f_{3f}
⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮		⋮
l	s_{l1}	s_{l2}	s_{l3}	· · ·	s_{ls}	f_{l1}	f_{l2}	f_{l3}	· · ·	f_{lf}

Appropriate data for a community analysis can come from a standard fishery survey. The presence or abundances of s fish species are tallied for l lakes to form a lakes-by-species matrix (Table 1); associated with this are measurements of f environmental factors (such as area or pH) for each lake. A community analysis measures the similarities and differences ("distances") among the lakes. The lakes can be grouped by species composition or environmental factors; we focus on species composition.

The lakes-by-species matrix can be represented by plotting the l lakes as points on a graph having s axes, each being the relative abundance of an individual species (for example, Fig. 1 for 10 one-, two-, and three-species assemblages). For up to three species, an objective way to measure the similarities and differences among lakes is to directly measure the "distances" between points on the graphs. However, assemblages of more than three species can not be directly represented in this way. Multivariate analysis mathematically measures

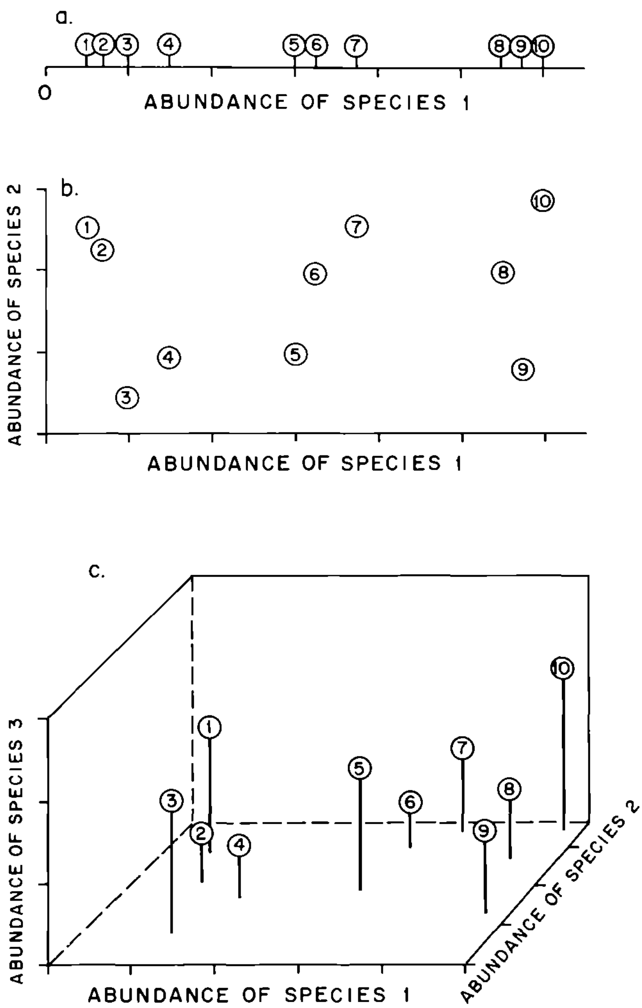

FIGURE 1.—*Illustrations of "direct" ordinations: abundance plots of (a) one, (b) two, and (c) three species in 10 lakes. The number of axes equals the number of species.*

the "distances" among lakes, thus providing a relatively objective and simplified summary of complex, multispecies systems.

Two basic strategies of multivariate community analysis can be used to summarize and reveal patterns in the lakes-by-species matrix. Hierarchical classification groups similar lakes into clusters and arranges the clusters into a hierarchical dendrogram analogous to a taxonomic family tree. Ordination arranges the lakes in a one- to three-dimensional graph such that similar assemblages are close together and dissimilar ones are far apart; these ordination graphs are similar in appearance to Fig. 1, but use mathematically derived axes rather than the species abundances directly. Hierarchical classification and ordination complement each other; using both strategies, one often can determine the extent to which clusters of distinct community types exist or if the fish assemblages occur along a continuum.

The relationships of fish-assemblage groups to environmental variables can be evaluated by several methods, for example, by plotting the groups on maps to examine geographic patterns, by uni- and multivariate analyses of variance, and by canonical correlation analysis (Green and Vascotto 1978; Green 1979; Golden 1981). Here we use multiple discriminant analysis. Multiple discriminant analysis evaluates the extent to which groups of lakes, distinguished by classification–ordination analysis of the fish assemblages (or by any other method), are environmentally different. The derived axes of the discriminant analysis represent mathematical combinations of the environmental variables that maximize the differences among lake groups relative to those within groups.

Application

To illustrate our approach, we use our published community analysis of 18 small lakes in northern Wisconsin (Tonn and Magnuson 1982) to predict species assemblages in 11 additional lakes from the same region. The 18 original lakes were chosen to represent a gradient of winter dissolved-oxygen concentrations; roughly half of the lakes were known or suspected to have suffered from periodic winterkill. In addition, gradients among lakes of productivity, surface area, and water source (seepage or drainage) were known. We examined patterns in the species composition and richness and seasonal dynamics of the fish assemblages to assess factors and mechanisms that appeared important in the ecological maintenance of assemblage structure.

In winter (January–March) and summer (June–August) 1978, we sampled fishes using minnow traps, fyke nets, and trammel nets to provide a matrix of presence or absence of each species in the 18 lakes. We also measured several limnological variables and habitat characteristics (Table 2). Of the 23 fish species caught, 18 were present in the winter sampling, 22 in the summer (Table 2).

We initially ran Bray–Curtis ordination and association analysis (a classification procedure) on both the summer and winter data sets separately. There was close correspondence between ordination and classification of the summer data, and several relatively distinct groups were revealed. No clear patterns were found with the winter data, as classification and ordination showed little agreement with each other or with the summer patterns. When seasonal data were combined, we distinguished two groups using the first two axes of the ordination (Fig. 2). We called these two groups "*Umbra*–cyprinid assemblages" and "centrarchid–*Esox* assemblages" after their common and characteristic species.

Lakes with each fish-assemblage type appeared to be environmentally distinct. By discriminant analysis, watershed size (related to whether a lake was a seepage lake or a drainage lake with an inlet and outlet), lake area, and maximum depth (highly correlated with winter oxygen concentrations) combined to distinctly separate the two groups of lakes. We concluded that the type of assemblage present in our lakes was related to winter oxygen concentrations interacting with the availability of refuges from low oxygen or large piscivores. Centrarchid–*Esox* assemblages occurred in lakes with high winter oxygen concentrations, and in lakes with low winter oxygen if access to a refuge was provided by an inlet or outlet stream or connecting lake. Low-winter-oxygen lakes without refuges lacked piscivorous fishes but contained *Umbra*–cyprinid assemblages (Tonn and Magnuson 1982).

Prediction

Frank J. Rahel (1982, and personal communication) has compiled fish-assemblage and environmental data for a diverse set of northern Wisconsin lakes, based on his own sampling and recent surveys conducted by personnel of the Wisconsin Department of Natural Resources. From his lake set, we found 11 lakes that fell within the ranges exhibited by our 18 lakes for four habitat characteristics that usually are important to fish: lake area, maximum depth, pH (Table 2), and substrate type (all lakes were predominantly soft-bottomed, with silt, organic muck, or both).

First, we conducted a new discriminant analysis of our 18 lakes using a reduced set of five environmental variables that are easily measured or available from lake files or the literature: lake area, maximum depth, pH, watershed size, and conductivity. Separation of the two lake types was preserved (Fig. 3). We also divided the 18 lakes into three separate groups: "mudminnow" (same as *Umbra*–cyprinid), "pike," and "bass"—the latter two being divisions of the centrarchid–*Esox* type, based on our judgement as to which species was the dominant piscivore. A clear separation of these three groups also was produced (Fig. 4).

We were then able to predict which fish-assemblage type was present in each of the 11

TABLE 2.—*Environmental factors and fish assemblages for 18 original study lakes in northern Wisconsin (data from Tonn and Magnuson 1982) and 13 new lakes from the same area (data from Rahel 1982) used to test predictions of extant fish assemblages.*

Lake	Area (hectares)	Maximum depth (m)	pH	Watershed size[a] (km²)	Conductivity (μmhos/cm at 20 C)	Fish assemblage[b,c] (*summer only; **winter only)
				18 original lakes		
1. Apeekwa	76.1	3.0	7.2	117.8	107	1**, 2*, 11*, 12*, 13, 18*, 19, 20*, 22, 23*
2. Aurora	38.0	1.2	6.8	35.7	130	1*, 2*, 6*, 10*, 13*, 14*, 20, 23*
3. Blueberry	4.9	8.2	5.8	0.5	36.5	14, 17*, 19, 22
4. Camp Two	5.7	1.5	5.9	0.5	58	1, 3, 6, 22
5. Gateway	3.2	2.4	7.5	0.3	141	1, 4*, 5, 6*, 8, 16
6. Grassy	42.9	1.2	7.0	10.1	112.5	1, 3, 4*, 6, 8, 10, 12*, 13*, 16*, 22, 23*
7. Johnson	9.7	3.6	7.2	185.2	92	1**, 2*, 6*, 12*, 13, 17*, 18*, 19, 20*, 21*, 22*, 24**
8. Landing	89.0	3.3	7.5	22.0	130.5	7, 9*, 12*, 13, 20, 21
9. Little Rice	23.9	2.1	7.0	255.1	157	2*, 12*, 13*, 17*, 22*
10. Maple	19.0	4.3	6.0	33.0	43	2*, 12*, 14*, 17*, 19*, 20*, 22
11. Mill	53.0	1.2	8.0	38.6	209	1**, 2*, 6*, 7*, 12*, 13*, 20*, 22*
12. Mystery	8.1	2.1	7.1	8.3	67	1, 4, 5, 10, 12**, 13, 22*, 23
13. Nixon	44.5	1.5	7.0	197.6	92	2*, 12*, 13*, 14*, 18*, 19*, 21*, 22*
14. Spruce	6.1	4.9	6.2	1.3	40	12, 17, 22
15. Whitney	89.8	2.4	7.3	339.3	76	2*, 6**, 12*, 13, 17**, 18*, 20*, 22*
16. Whynot	3.2	5.8	5.2	0.3	37.5	1**, 13**, 17*, 19
17. 33-6	2.4	3.3	5.1	2.6	53	1, 22
18. 33-13	2.8	3.0	6.0	2.6	47.5	1
				11 new lakes		
19. Benedict	10.5	5.0	6.1	0.8	8	1, 2, 6, 17, 20, 22
20. Black Tern	0.4	1.5	5.5	0.3	39	1, 16
21. Bug	7.7	3.4	6.5	0.5	11.5	1, 5, 6, 10
22. Himley	60.3	4.6	6.8	17.6	108	2, 6, 12, 15, 19, 20, 22
23. Richardson	19.0	3.6	8.9	16.3	150	2, 6, 12, 15, 17, 19, 20, 21, 22
24. Shoe	68.4	2.1	8.5	10.9	157	2, 6, 12, 15, 20, 22
25. Weber	4.4	4.0	6.2	0.5	18.5	6, 14, 22
26. 6-7	2.0	2.0	5.2	0.3	8	1
27. 8-9	0.8	3.0	6.1	1.3	11.5	1, 4, 16
28. 23-12	6.1	6.0	5.3	2.6	7	17, 19, 22
29. 25-14	1.6	3.2	5.9	0.5	13	1, 4, 5, 13

[a] For drainage lakes, these values also include the watershed areas of the next adjacent lake, both upstream and downstream.
[b] Fish assemblages in the 11 new lakes were determined only during the summer.
[c] Species codes:

1. central mudminnow *Umbra limi*
2. northern pike *Esox lucius*
3. pearl dace *Semotilus margarita*
4. northern redbelly dace *Phoxinus eos*
5. finescale dace *Phoxinus neogaeus*
6. golden shiner *Notemigonus crysoleucas*
7. bluntnose minnow *Pimephales notatus*
8. fathead minnow *Pimephales promelas*
9. common shiner *Notropis cornutus*
10. blacknose shiner *Notropis heterolepis*
11. redhorse *Moxostoma* sp.
12. white sucker *Catostomus commersoni*
13. black bullhead *Ictalurus melas*
14. yellow bullhead *Ictalurus natalis*
15. brown bullhead *Ictalurus nebulosus*
16. brook stickleback *Culaea inconstans*
17. largemouth bass *Micropterus salmoides*
18. rock bass *Ambloplites rupestris*
19. bluegill *Lepomis macrochirus*
20. pumpkinseed *Lepomis gibbosus*
21. black crappie *Pomoxis nigromaculatus*
22. yellow perch *Perca flavescens*
23. Iowa darter *Etheostoma exile*
24. mottled sculpin *Cottus bairdi*

new lakes, using the discriminant function equations provided by the analyses. Of the 11 new lakes, seven were predicted to have *Umbra*–cyprinid assemblages and four to have centrarchid–*Esox* in the two-group analysis (Fig. 3). In the three-group analysis, we predicted that six lakes would have mudminnow, two would have bass, and three would have pike assemblages (Fig. 4).

To examine these predictions of fish-assemblage types for the 11 new lakes, we performed discriminant analyses of summer assemblages

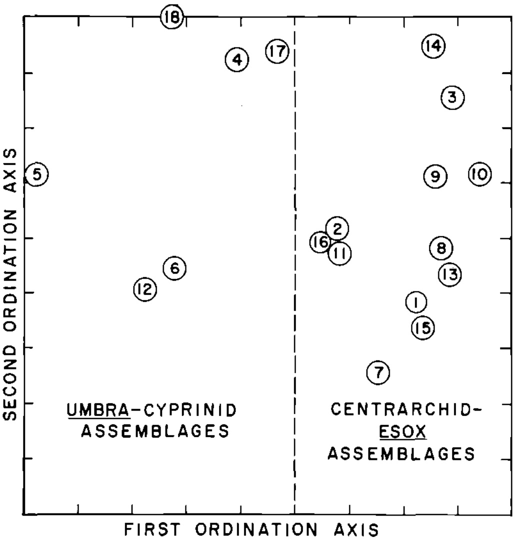

FIGURE 2.—*Bray–Curtis ordination of combined summer and winter fish assemblages for 18 northern Wisconsin lakes, modified from Fig. 2 of Tonn and Magnuson (1982). Two assemblage types were identified. Lakes are numbered as in Table 2.*

in the 29 lakes combined. All species of the assemblage groups were included in the evaluations (Fig. 5).

In the results of the two-group predictions, none of the 11 new lakes were misclassified by the discriminant analysis (Fig. 5). Although not misclassified by this analysis, two lakes predicted to have *Umbra*–cyprinid assemblages (numbers 19 and 25) do not have strong similarities with other *Umbra*–cyprinid assemblages (Table 2). For the three-group predictions, none of the new lakes were misclassified by the analysis; again, number 25 does not appear to fit well with any group, having neither mudminnows, bass, or pike. Based on the presence–absence data, we cannot say whether bass or pike is dominant in the new lakes that have both species (numbers 19 and 23). However, the analysis showed that the total compositions of the assemblages for these two lakes were not inconsistent with our predictions.

Thus, our community analyses not only revealed interpretable patterns for the fish assemblages and environments of our original 18 study lakes, but were robust enough to correctly predict the fish-assemblage types present in nearly all of the 11 additional lakes. These predictions were based on only five environmental variables that are easily available in survey reports.

For the final form of our discriminant model, we re-ran the five-variable, three-group environmental analysis using data from all 29 lakes (Table 2). This final model can be used for additional predictions of fish-assemblage type for other lakes in the same district that have the same substrate type and that fall within the ranges of our 29 lakes for the five environmental factors (all factors except pH are transformed by $\log_{10}$; the dependent variables are dimensionless):

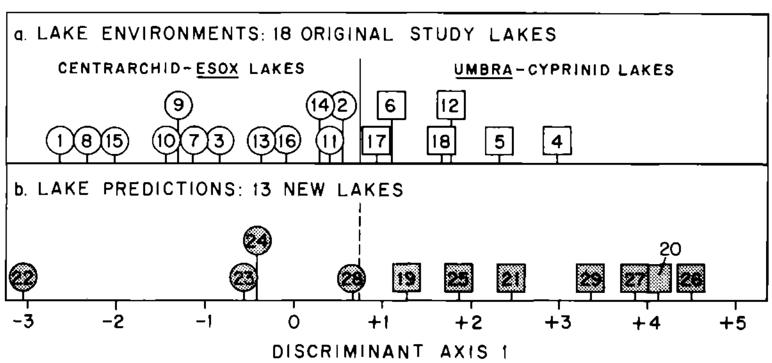

FIGURE 3.—*(a) A discriminant analysis of 18 northern Wisconsin lakes based on* $\log_{10}$(area + 1), $\log_{10}$(maximum depth), *pH*, $\log_{10}$(watershed size + 1), *and* $\log_{10}$(conductivity). *Lakes were divided into the same two groups* (Umbra*–cyprinid and centrarchid–*Esox) *as in Fig. 2. (b) Fish assemblages predicted for 11 additional lakes from the discriminant equation provided by the analysis in (a). Lakes are numbered as in Table 2.*

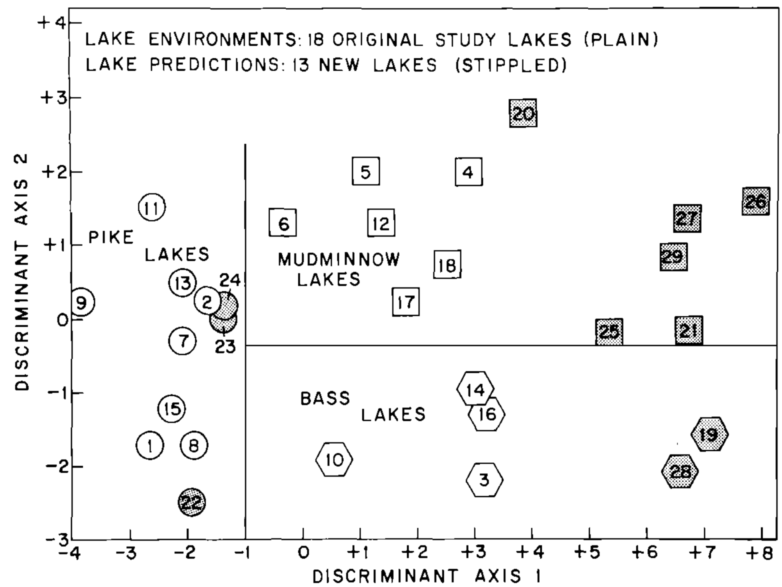

FIGURE 4.—*A discriminant analysis of 18 northern Wisconsin lakes (plain figures) based on the environmental variables of Fig. 3. Lakes were divided into "mudminnow," "bass," and "pike" lakes based on previous analyses. Fish assemblages were predicted for the 11 new lakes (stippled figures) from the equations provided by the discriminant analysis. Lakes are numbered as in Table 2.*

$$X = 7.96 - 1.18(area + 1) - 1.44(maximum\ depth) - 0.52(pH) - 1.49(watershed + 1) - 0.67(conductivity);$$

$$Y = -0.09 - 1.76(area + 1) - 5.74(maximum\ depth) + 0.73(pH) + 0.11(watershed + 1) - 0.17(conductivity).$$

If $X \leq -1.18$: pike lakes.
If $X > -1.18$ and $Y > -0.86$: mudminnow lakes.
If $X > -1.18$ and $Y \leq -0.86$: bass lakes.

As an example of how this kind of analysis can be reduced to a practical field tool, we have constructed a dichotomous key summarizing the above model. We again emphasize that strict application of this key should be limited to other lakes in the same district having the same range of environmental variables (including soft-bottomed substrate). Otherwise, predictive success will fall off rapidly (James Schneider, personal communication; William Tonn, personal observation).

1a. Lakes with total watershed size 0.3–10.1 km² and surface area 0.4–43 hectares 2
1b. Lakes with total watershed size 10.2–339.3 km² or surface area 43.1–90 hectares 3
2a. Lakes with maximum depth 1.2–4.0 m .... mudminnow lakes
2b. Lakes with maximum depth 4.1–8.2 m .... bass lakes
3a. Lakes with pH 5.2–6.5 or conductivity 7–50 μmhos/cm .... bass lakes
3b. Lakes with pH 6.6–8.9 or conductivity 51–209 μmhos/cm .... pike lakes

Although the discriminant-model equations and lake classification key are strictly empirical and do not necessarily have any biological meaning, they do identify and separate what we feel are ecologically distinct fish-assemblage types that result from specific deterministic mechanisms (Tonn and Magnuson 1982). However, our major point here is that multivariate community analysis can be used in management planning for different sets of lakes or other fish habitats.

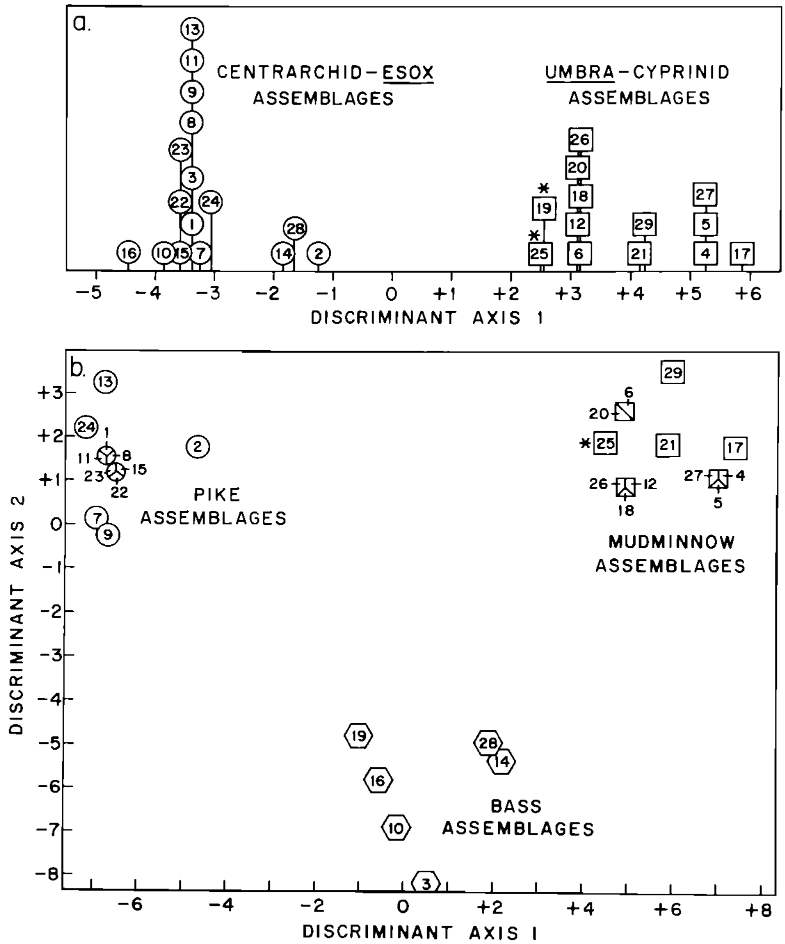

FIGURE 5.—*Discriminant analyses of fish assemblages in 29 northern Wisconsin lakes. Lakes are numbered as in Table 2. The analyses are based on the summer presence or absence of all species. (a) The assemblages were divided into two groups based on the analyses and predictions of Fig. 3. (b) Assemblages were divided into three groups based on the analyses and predictions of Fig. 4. Asterisks denote assemblages that were not misclassified by the analyses but that showed low similarity to other assemblages in their group.*

Discussion

We believe that application of multivariate community analysis to fishery management would involve two general phases. In the first or planning phase, one would identify or evaluate real or potential fishery uses and values for the lakes of a region. A community analysis, similar to the one presented above, would be performed. The analysis would attempt to make explicit those environmental factors that determine (or are related to) the fish-assemblage types in particular lakes.

Other fish-community analyses, involving various forms and combinations of classification, ordination, discriminant analysis, and other techniques, include those of Haedrich et al. (1975), Echelle and Rose (1976), Johnson et al. (1977), Harvey (1978, 1981), Gladfelter et al. (1980), Rose and Echelle (1981), Schneider (1981), Finger (1982), and Rahel (1982). For example, Johnson et al. (1977) classified 2,496 Ontario lakes on the basis of the combinations of walleye *Stizostedion vitreum,* northern pike, lake trout *Salvelinus namaycush,* and smallmouth bass *Micropterus dolomieui* present in each lake and found that seven limnological characteristics adequately defined the lake type in which each species combination was found. Schneider (1981) performed community analyses on groups of 126–221 Michigan lakes to determine which lakes had the most similar fish assemblages, groups of species being identified by abundance correlations and relationships among distributions and abundances of fish species and five environmental variables. In conjunction with the community analysis, a fishery-yield assessment, based on a morphoedaphic or other index, could be performed on the lakes at this time.

In the second or transfer phase, the results of the community analysis and yield assessment would be converted to a form useful in daily management activities. Such activities for which a community analysis could be helpful include: (1) providing advice on the fishery values and limitations of particular lakes to landowners, potential landowners, and other users; (2) avoiding inappropriate or wasteful management measures; (3) formulating regional lake-management plans based on an assessment of the available resources, such as the number of lakes of each classification type present; (4) using the regional view of the resources and the identification of the important environmental factors that structure the fish assemblages to explain to the public why some lakes are suitable for certain management procedures (such as stocking) and why others are not; (5) classifying or predicting the type of fish assemblage present in other lakes of the region not included in the original analysis (restricted to those lakes falling within the ranges of the environmental variables used in the original analysis); and (6) identifying rare or unique fish assemblages or habitat types for state scientific or natural-areas programs.

Community analysis can assist and improve informal classification systems developed by experienced field workers. Of course, computer programs and graphs are not substitutes for experience and insight; there should be continuous interaction among these elements. Progress in fishery biology, as in community ecology in general, is typically a process of successive refinement (Gauch 1982). We think the ability to understand, predict, and manage fish community structure through the use of multivariate community analysis will contribute to the advancement of fishery biology and management.

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