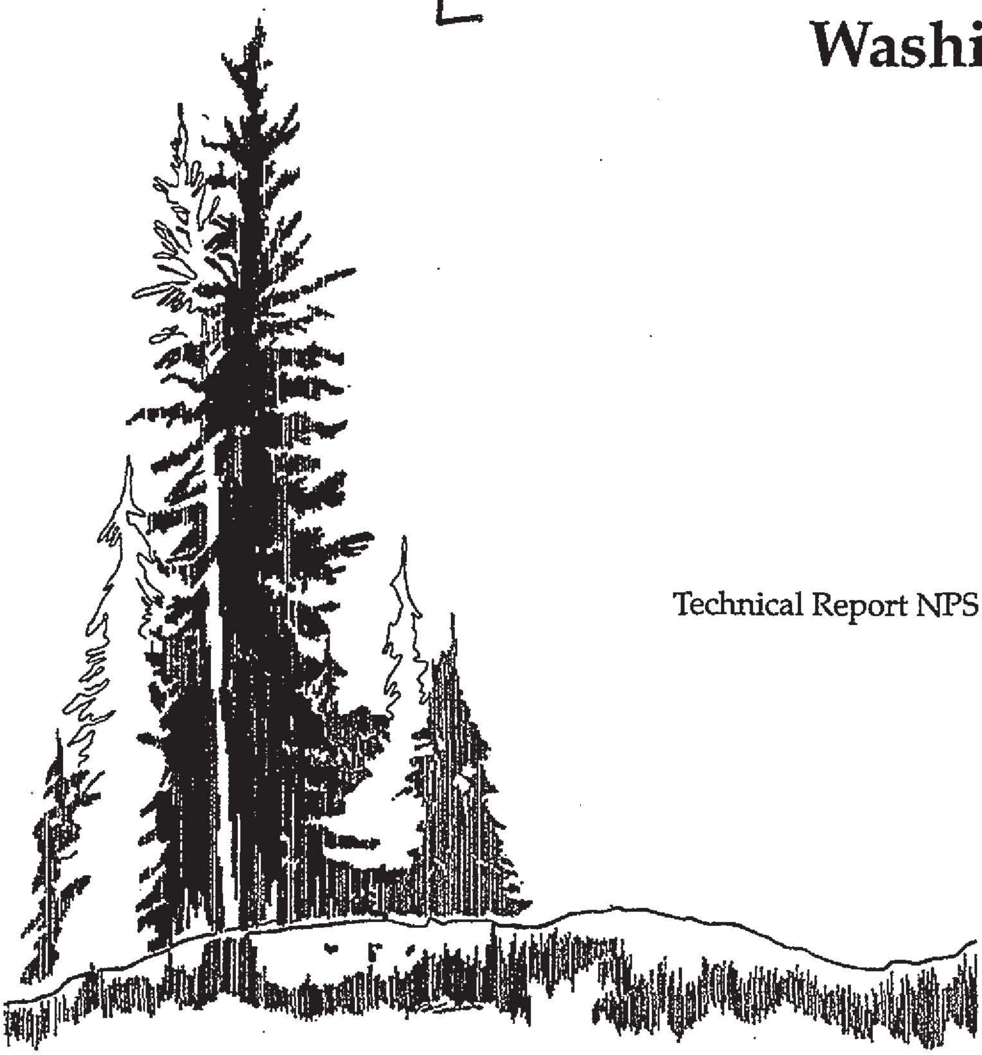
Temporal Variations of Water Quality and the Taxonomic Structures of Phytoplankton and Zooplankton Assemblages in High-Mountain Lakes, Mount Rainier National Park, Washington, USA



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April, 1998

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Memorandum

To: Contracting Officer, Columbia Cascades Support Office

From: Contracting Officer's Technical Representative, Columbia Cascades Support Office

Subject: Final Report for Subagreement No.26 to Cooperative Agreement No. CA-9000-8-0006 with Oregon State University

The final report, entitled "Temporal Variations of Water Quality and the Taxonomic Structures of Phytoplankton and Zooplankton Assemblages in High-Mountain Lakes, Mount Rainier National Park " has been reviewed and found to be acceptable. All the requirements of Subagreement No. 26 to Cooperative Agreement CA-9000-8-0006 with Oregon State University have now been met. We enclose two copies of the report for transmittal to the USDI library.

Linda Whitson
for Katherine L. Jope

cc:
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Temporal Variations of Water Quality and the Taxonomic Structures of Phytoplankton and Zooplankton Assemblages in High-Mountain Lakes, Mount Rainier National Park, Washington USA

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ABSTRACT

A synoptic inventory of physical and chemical properties and plankton assemblages of 27 high-mountain lakes was conducted at Mount Rainier National Park in 1988. Six of these lakes were resurveyed from 1990 - 1993 to determine if the lakes exhibited inter-annual changes relative to the set of characteristics surveyed in 1988. If major changes were evident, a second objective was to provide guidance to park management about the selection of park lakes and appropriate limnological characteristics for a long-term monitoring program.

Secchi-disk clarity, water temperature, and pH of the lakes in 1988 were within the range of values obtained between 1990 and 1993. Conductivities and concentrations of nutrient in some lakes were not consistent in 1990 - 93 with the values recorded in 1988. Although the dominant phytoplankton taxa in the lakes varied among years, the taxa were in closely related assemblages in ordination space, with the exception of two lakes (Clover Lake and Reflection Lake). Rotifer assemblages were fairly consistent among years, but most of the lakes exhibited dramatic changes in some years, as did crustacean zooplankton assemblages. Suggestions were made for selection of a set of lakes, which represented a range of lake characteristics and locations in the park, sampling intervals, and limnological characteristics for a long-term monitoring program to evaluate general status and lake trends.

INTRODUCTION

A level of knowledge of the range of variation of physical, chemical, and biological components of lakes is needed to judge their status and trends (Edmondson 1991). This information provides a baseline from which to judge what is "normal" and for deciphering cause and effect relationships when deviations from normal conditions are perceived. Unfortunately, many limnological studies of high-mountain lakes are limited to single samples of lakes within a region or multiple samples within a single year (e.g., Loffler 1969, Stout 1969, Larson 1973, Arvola 1986, Aizaki and others 1987, Nauwerck 1994, Larson and others 1995). Information collected from these short-term efforts is useful to assess the range of characteristics among groups of lakes or the effect of season on lake characteristics, but obviously, more extensive sampling through time is needed to describe the variation of limnological characteristics of individual or groups of lakes. The multi-year studies of high-mountain lakes that have occurred demonstrate that some characteristics vary considerably among years in some lakes, but in others, the characteristics remain relatively constant through time (Pennak 1955, Pechlaner 1966, Pechlaner 1967, Reed 1970, Anderson 1970, Anderson 1971, Anderson 1972, Strub and others 1985, Catalan 1988, Jassby and others 1995, Engle and Melack 1995, Hoffman and others 1996, Larson and others 1996, McIntire and others 1996, and Deimling and others 1997). All of these multi-year studies, however, emphasize a limited number of lake components, e.g., water quality, crustacean zooplankton assemblages, or water quality and phytoplankton assemblages. The characteristics selected in such studies often are based on presumptions about which variables might serve as indicators of future changes. The ability to document the status and trends of lakes improves, however, if studies include several components of the pelagic food web because the components may exhibit different temporal patterns and vary in sensitivity to environmental changes (Wetzel 1983; Carpenter and others 1985).

Many values are associated with lakes in units of the National Park Service (NPS), but clearly most are important components of park ecosystems, and often they are significant scenic resources. One aspect of the Organic Act (1916) that created the NPS directed the agency to conserve and preserve the natural resources of lands under its stewardship for future generations. Natural resource management is a function by which the NPS strives to understand natural processes and human-related effects, mitigate the potential and realized human-related effects, monitor for ongoing or future trends, protect existing natural ecosystem components and processes, and provide interpretation to park visitors. Inventory and monitoring tasks clearly are identified in natural resources management guidelines as a tool for management. Specific to this study, the natural resource management plan for Mount Rainier National Park (MORA) includes projects that assess park resource conditions and detection of impacts that may result from external activities and internal management decisions. Some monitoring is conducted at MORA to specifically target anthropogenic agents of change, such as air-borne pollutants from nearby metropolitan areas, but development of a program to assess the condition and trends of park lakes remains an identified, but pending need. Although a goal of park management is to inventory the 385 lakes and ponds, it is impractical to monitor all of them. Furthermore, given ongoing budgetary constraints and logistical problems associated with lake sampling in the rugged terrain of the park, park management is challenged to assign a sufficiently high priority to this task to initiate the effort. Even if a monitoring effort can be advanced as a priority, there is still the problem of selecting a subset of lakes to monitor through time, as well as selecting a subset of lake characteristics that can provide reasonable indications of lake condition and trends.

A synoptic inventory of physical and chemical properties and plankton assemblages of 27 high-mountain lakes was conducted at MORA in 1988 (Larson and others 1994). This inventory was conducted to determine if there were physical, chemical, and biological differences between subalpine and forest lakes, if a west-east climate gradient influenced the relationships within and between the lake types, and if fish predation had any detectable impacts on the zooplankton assemblages of both types of lakes. Although basic information was obtained about the characteristics of the lakes, the inventory was insufficient to evaluate inter-annual changes. From 1990 - 1993, six of these lakes were resurveyed. The first objective of this new study was to determine if the lakes exhibited inter-annual changes relative to the set of characteristics surveyed in 1988. If changes were evident, a second objective was to provide guidance to park management about the selection of park lakes and appropriate limnological characteristics for a long-term monitoring program.

STUDY AREA

Mount Rainier National Park (969 km^2) is located in south-central Washington on the western slopes of the Cascade Mountains (Figure 1). Mount Rainier, an active volcano with an elevation of 4394 m, dominates the topography of the park. The annual precipitation is about 1.5 m at the lower elevations and over 2.5 m at higher elevations. More than 75% of the precipitation falls between October and March (Richardson 1972), mostly as snow. Park lakes are capped by snow and ice for more than 7 months each year.

The study lakes were located in the south-central, northeast, and the northwest portions of the park (Figure 1). The lakes ranged from 971 m to 1,747 m in elevation, 2.4 to 7.3 ha in surface area, and 10.1 to 27.5 m in maximum depth (Table 1). The lakes were selected for study because they collectively exhibited a range of limnological characteristics typical of park lakes (Larson and others 1994). All of these naturally fishless lakes were stocked with trout several

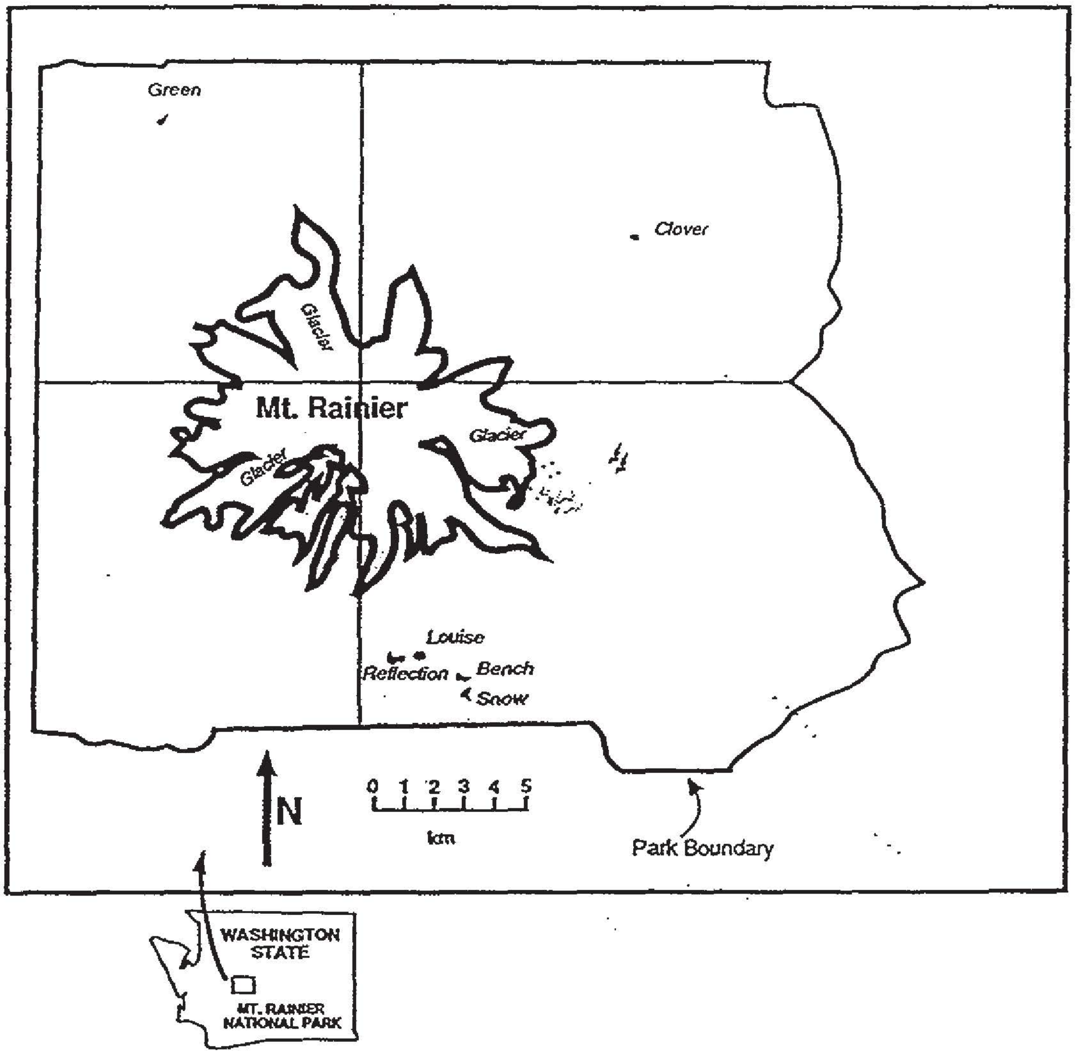

Figure 1. Geographical location of MORA in Washington State, and the location of the six study lakes.

Table 1. Surface elevations (m), surface areas (ha), and maximum depths (m) of the six MORA study lakes.

Lake	Elevation (m)	Area (ha)	Maximum Depth (m)
Bench	1384	2.9	11.0
Clover	1747	2.9	13.2
Green	971	5.0	27.5
Louise	1401	7.3	16.0
Reflection	1479	6.8	10.3
Snow	1426	2.4	10.1

decades ago and each lake was inhabited by a reproducing population of these fishes, with the possible exception of Clover Lake (Barbara Samora, Resource Management Specialist, MORA, personal communication).

METHODS

Based on the results from the 1988 study, each lake was sampled in August from 1990 to 1993 in order to minimize effects of seasonal variation. The methods employed followed those described by Larson and others (1994). In summary, sampling was conducted from an inflatable boat near the deepest point in each lake. Water samples were collected using a 1.5-L PVC Van Dorn-style bottle at a depth of 1 m below lake surfaces and about 1 m from the lake bottoms. Water temperature was taken with a hand thermometer that was inserted into the top of the water bottle. Water clarity was estimated using a standard 20-cm black and white Secchi disk. Field pH was determined using an Orion meter equipped with an automatic temperature compensation probe. Dissolved oxygen was estimated using the azide modification of the Winkler technique. Nutrient samples were collected in acid-washed polyethylene bottles. One liter samples were filtered in the field and the filtrate stored in coolers on ice packs until they could be shipped to the Cooperative Chemical Analytical Laboratory (CCAL), Forest Science Laboratory, Oregon State University. Unfiltered water samples were collected in 1-L bottles for conductivity, total Kjeldahl-N, and total phosphorus analyses. All samples arrived at CCAL 24-48 h after collection. Phytoplankton samples were collected from a depth of 1 m using the Van Dorn bottle. Each 1-liter sample was preserved with 10 ml of Lugol solution. The samples were counted using the inverted microscope method. Zooplankton samples were collected using a 20-cm-diameter net (64-μm) towed vertically from 1.5 m off the lake bottoms to the lake surfaces. Zooplankton samples were diluted to acceptable concentrations using a Folsom Plankton Splitter. The diluted samples were counted at a magnification of 40X using an inverted microscope.

Correspondence analysis without detrending (CA) provided ordinations of the six lakes relative to the taxonomic composition of the phytoplankton assemblages, rotifer assemblages, and crustacean zooplankton assemblages in the 30 samples. For each analysis, cell densities (phytoplankton) or densities of individual organisms (rotifers and crustaceans) were relativized and expressed as a proportion of the total density in each sample. This transformation gave samples equal weight. In each analysis, the axes of the lake (sample) ordinations were scaled to approximate chi-square distances (Jongman and others 1987). Therefore, with this scaling, lakes represented by sample points in close approximation to one another had similar species compositions, whereas lakes with greater distances in ordination space were less similar in taxonomic composition. CA also produced species ordinations that had maximum correspondence to the configuration exhibited by the lake ordinations. Consequently, relationships between the species and lakes were revealed by examining corresponding positions in the lake and species ordination graphs. For example, species with points in the lower left of the rotifer species ordination graph were prominent in lakes located in the same position in the sample ordination graph; species represented by points in intermediate positions were more evenly distributed among the lakes.

RESULTS

Secchi Disk Clarity and Water Quality

Secchi disk clarity readings in 1988 were consistent with readings obtained between 1990 and 1993 (Table 2). The pH values of the study lakes in the 1990's were similar to pH values in 1988, with the exception of low values in Reflection Lake and Snow Lake in 1993 (Table 3). Conductivities generally were slightly higher in the 1990's as compared to those in 1988

Table 2. A comparison of Secchi disk clarity readings in 1988 with those recorded between 1990 and 1993 for the six MORA study lakes.

	Secchi-disk clarity (m)	
Lake	1988	1990-93
Bench	6.8[1]	7.6-9.0 (8.4)[2]
Clover	btm[3]	btm
Green	16.0-19.5	15.5-16.2 (15.9)
Louise	13.8	11.5-13.7 (12.8)
Reflection	9.3	8.7-9.0 (8.9)
Snow	btm	btm

[1]September 13 reading; none taken in August
[2]Minimum-maximum (average)
[3]Disk visible on lake bottom

Table 3. A comparison of near-surface and near-bottom pH and conductivity measurements of the six MORA study lakes between 1988 and 1990 to 1993.

Lake	Sample depth[1]	pH		Conductivity	
		1988	1990-93	1988	1990-93
Bench	T	6.4	6.1-6.9[2]	4.3	2.0-6.6[2]
	B	–	5.8-6.1	5.6	5.0-13.9
Clover	T	7.2	7.1-7.4	12.9	14.0-15.7
	B	–	6.3-6.8	14.3	22.3-23.0
Green	T	7.1	6.9-7.0	19.7	25.2-30.0
	B	6.4	6.4-6.5	34.1	47.6-53.6
Louise	T	6.8	6.7-6.9	7.3	5.0-9.1
	B	6.0	6.9	7.2	7.0-14.0
Reflection	T	6.9	6.0-7.0	8.3	9.9-12.8
	B	6.2	5.7-6.3	9.9	14.3-22.0
Snow	T	7.1	5.9-7.3	10.3	11.0-12.4
	B	6.2	6.6-7.3	11.2	14.3-16.0

[1] sample depth: T = near surface; B = near-bottom
[2] minimum-maximum

Table 4. A comparison of near-surface and near-bottom water temperatures, TKN, NH3-N, NO3-N, TP and OP, and near-bottom DO between 1988 and 1990 to 1993 for the six MORA study lakes.

Lake	Sample Depth[1]	Temp °C		TKN $\mu g/L$		NH_3-N $\mu g/L$		NO_3-N $\mu g/L$		TP $\mu g/L$		OP $\mu g/L$		DO mg/L	
		1988	1990-93	1988	1990-93	1988	1990-93	1988	1990-93	1988	1990-93	1988	1990-93	1988	1990-93
Bench	T	19.5	18.7-21.5[2]	81	80-94	1	3-8	1	0-1	12	3-7	6	1-2	–	–
	B	10.0	8.0-10.2	69	60-100	1	2-9	0	0-1	15	4-8	–	0-4	–	6.0-8.0
Clover	T	15.0	14.4-17.1	39	45-60	2	1-16	0	0-1	3	3-5	1	0-1	–	–
	B	9.0	10.0-12.8	41	60-110	3	1-9	0	0-1	7	5-6	–	1-2	8.4	7.5-9.0
Green	T	12.7	10.5-18.2	13	17-20	6	4-6	10	8-33	5	4-7	1	0-2	–	–
	B	5.0	5.1 - 6.0	98	50-194	62	24-152	77	50-77	8	6	–	0-1	1.4-3.3	1.6-3.8
Louise	T	17.5	8.9-16.2	24	15-30	2	4-18	0	0-1	8	3-9	1	0-2	–	–
	B	7.5	6.0-15.5	35	30-80	2	4-13	0	0-1	15	5-12	–	0-3	6.4	4.4-7.0
Reflection	T	16.0	16.0-20.5	37	30-77	2	2-6	0	0-1	13	5-9	1	0-1	–	–
	B	11.0	7.0 - 9.2	43	40-107	2	4-14	0	1-2	10	6-10	–	0-1	8.2	3.6-7.9
Snow	T	11.0	8.8-13.5	12	15-20	5	0-5	19	0-8	9	4-13	0	0-1	–	–
	B	8.0	7.3-11.7	10	10-20	3	0-13	16	4-11	13	3-14	0	1	10.2	8.0-10.9

[1]Sample depth: T = near-surface; B = near-bottom
[2]minimum-maximum

(Table 3), whereas water temperatures were fairly consistent between the two studies (Table 4). Relative to nutrient concentrations measured in 1988, near-surface TKN increased in Clover Lake, Green Lake, and Snow Lake, NH_3-N increased in Bench Lake, Clover Lake, and Louise Lake, NO_3-N decreased in Snow Lake, TP decreased in Bench Lake and Reflection Lake, and OP decreased in Bench Lake (Table 4). For near-bottom samples, TKN decreased in Clover Lake, NO_3-N decreased in Snow Lake, and TP decreased in Bench Lake. In other cases, near-surface and near-bottom concentrations of nutrients and near-bottom concentrations of dissolved oxygen were within the range of concentrations observed in 1988 (Table 4).

Phytoplankton Assemblages

Fifty-nine taxa were observed in the 30 samples from the six lakes (Table 5). These taxa included 25 chrysophytes (Chrysophyceae), 12 chlorophytes (Chlorophyta), 8 cyanobacteria (Cyanophyta), 7 diatoms (Bacillariophyceae), 4 dinoflagellates (Pyrrhophyta), and 3 cryptomonads (Cryptophyta). The corresponding relative abundances of these groups of taxa were 42.4% (chlorophytes), 20.3% (chrysophytes), 13.6% (cyanobacteria), 11.8% (diatoms), 6.8% (dinoflagellates), and 5.1% (cryptomonads). *Chrysocapsa planctonia* was the most ubiquitous taxon and was found in 24 samples. *Diogenes* sp. and *Ochromonas silvarum* were found in 22 samples each. The other taxa were found in 8 or fewer samples.

CA sample (lake) ordinations determined by the relative abundance of phytoplankton species (Figure 2) indicated that the locations of Snow Lake, Louise Lake, Green Lake, and Bench Lake were fairly consistent in ordination space (Figure 3). Snow Lake and Louise Lake (except for 1992) occupied similar ordination space (Figure 3), whereas Reflection Lake and Clover Lake exhibited considerable changes in location. The position of Louise Lake in ordination space in 1992 was due to the presence of *Oocystis parva* (18%) and *Chroococcus*

Table 5. List of taxa (>10% relative abundance) found in 30 phytoplankton samples collected from 6 MORA study lakes in 1988 and 1990 - 1993. The table also includes an acronym for each taxon.

Taxon	Acronym
Division Chlorophyta	
Chlamydomonas sp.	CHLA
Diogenes sp.	DIOG
Oocystis parva West and West	OOPA
Crucigenia fenestrata Schmidle	CRFE
Oocystis pusilla Hasgirg	OOPU
Ankistrodesmus braunii (Naeg.) Brunnthaler	ANBR
Selenastrum sp.	SELE
Chlorella sp.	CHLL
Elakatothrix gelatinosa Wille	ELGE
Cosmarium tumidum Lund	COTU
Crucigenia tetrapedia (Kirch.) West and West	CRUC
Euastrum sp.	EUAS
Division Chrysopyhta	
Class Bacillariophyceae	
Synedra radians Kutz.	SYRA
Melosira distan var. *Pfaffiana* (Reinsch) Grun.	MEDI
Navicula sp.	NAVI
Melosira italica (Ehr.) Kutz	MEIT
Achnathes clevei var. *rostrata* Hust.	ACCL
Cyclotella stilligera Cl. u. Grun.	CYST
Achnanthes sp.	ACHA
Class Chrysophyceae	
Ochromonas minuscula Conrad	OCMI
Ochromonas silvarum Dofl.	OCSI
Ochromonas nana Dofl.	OCNA
Chromulina pseudonebulosa Pasher	CHPS
Ochromonas sphagnalis Conrad	OCSP
Chrysocapsa planctonia (W. and G. S. West) Pascher	CHPL
Dinobryon bavaricum Imhof	DIBA
Chromulina sphaeridia Schiller	CRSP
Chromulina minuta Dofl.	CHMI
Ochromonas elegans Dofl.	OCEL

Arthrodesmus incus (Ehr.) Hasr.	ARIN
Chrysapsis sp.	CHRY
Ochromonas tenera H. Meyer	OCTE
Epipyxis sp. 1	EPIP
Mallomonas sp.	MALL
Diceras phaseolus Fott	DIPH
Chrysococcocystis elegans Dofl.	CHEL
Epipyxis sp. 2	EPYX
Dinobryon sertularia (Ehr.)	DISE
Synura sp.	SYNU
Gloeobotrys limneticus (G. M. Smith) Pascher	GLLI
Uroglena sp.	UROG
Chrysoikos sp. [cyst]	CHKO
Bicoeca sp. Imhof	BICO
Dinobryon divergens	DIDI
Division Cryptophyta	
Chroomonas acuta Utermohl	CHRO
Cryptomonas erosa (Ehr.)	CRER
Rhodomonas sp.	RHOD
Division Cyanophyta	
Synechocystis sp.	SYNE
Anabaena affinis Lemmermann	ANAF
Chroococcus dispersus var. *minor* G. M. Smith	CRDI
Aphanocapsa delicatissima West and West	APDE
Chroococcus sp.	CHOO
Aphanocapsa elachista var. *conferta* West and West	APEL
Anabaena sp.	ANBA
Merismopedia minima Beck	MEMI
Division Pyrrhophyta	
Gymnodinium sp. 1	GYMN
Gymnodinium sp. 2	GYMO
Amphidinium sp.	AMPH
Peridinium pusillum (Penard) Lemm.	PERI

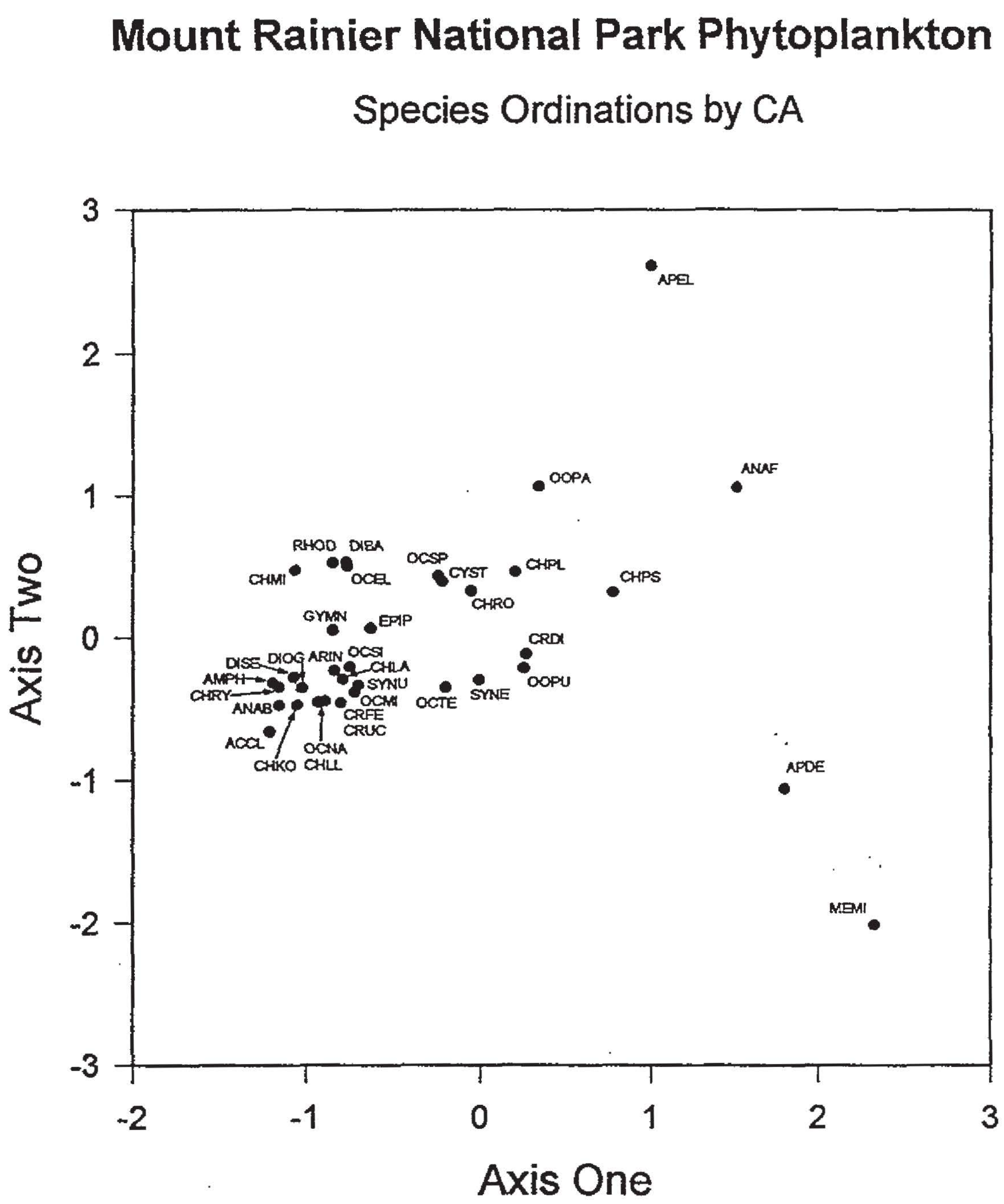

Figure 2. Ordination of the phytoplankton species in 30 samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993.

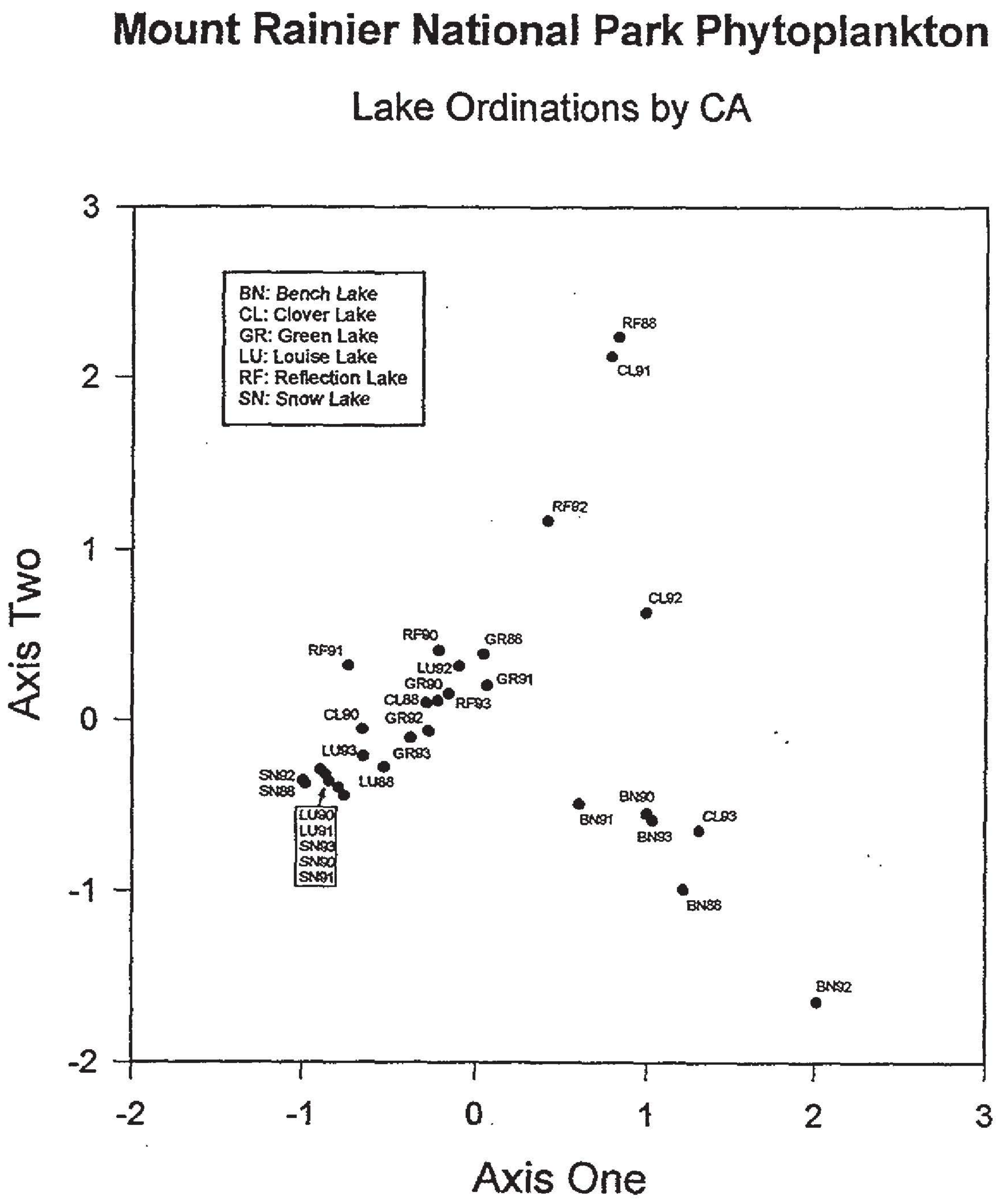

Figure 3. Ordination of 30 phytoplankton samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993. Numbers indicate year of sample.

dispersus (16%). Reflection Lake and Green Lake were located typically near this region of the ordination. However, Reflection Lake was located in the upper portion of the ordination in 1992 and 1988. In 1992 the lake was co-dominated by the *Chrysocapsa planctonia* (48%) and *Aphanocapsa elachista* (33%), whereas in 1988 it was dominated by the *A. elachista* (80%). Clover Lake exhibited dramatic changes in position on the lake CA ordination. In 1988 the dominant taxa were *Chrysocapsa planctonia* (20%) and *Oocystis parva* (10%). In 1990 the dominant taxa were *Dinobryon sertularia* (21%) and *Ochromonas nana* (10%), whereas *Aphanocapsa elachista* (78%) was the dominant taxon in 1991, *Aphanocapsa delicatissima* (29%) and *A. elachista* (25%) co-dominated in 1992, and *A. delicatissima* (73%) was the dominant in 1993. Bench Lake was dominated or co-dominated by *A. delicatissima.*

Zooplankton: Rotifer Assemblages

Ten rotifer taxa were observed in the 30 samples (Table 6). *Conochilus unicornis* was the most ubiquitous taxon because it occurred in 25 samples. *Kellicottia longispina* was found in 15 samples, *Keratella taurocephala* in 14 samples, and *Polyarthra vulgaris* in 11 samples. The other taxa were found in 4 or fewer lakes. In fact, *Keratella quadrata* and *Trichotria* sp. were found only in Snow Lake in 1988. For the purposes of the CA analysis, these taxa were deleted from the data set. Since *K. quadrata* and *trichotria* sp. were the only rotifer taxa in Snow Lake in 1988, the 1988 data were not used in the CA sample (lake) ordination.

CA sample (lake) ordinations based on the relative abundances of rotifer species (Figure 4) indicated considerable differences in the rotifer assemblages among the lakes (Figure 5). Bench Lake was dominated by *K. taurocephala)*, except in 1991 when it dominated by *C. unicornis* (84%). Snow Lake also was dominated by *K. taurocehpala* or *P. vulgaris*, with the exception of 1991 when it was dominated by *K. longispina.* Green Lake was dominated by

Table 6. Rotifer and crustacean zooplankton taxa obtained in 30 samples from the six study lakes in 1988 and 1990 to 1993. Acronyms for each species are shown in the parentheses.

Rotifers	Crustaceans
Conochilus unicornis (COUN)	*Holopedium gibberum* (HOLO)
Keratella hiemalis (KEHI)	*Daphnia rosea* (DARO)
Keratella taurocephala (KETA)	*Daphnia pulex* (DAPU)
Polyarthra vulgaris (POLY)	*Bosmina coregoni* (BOCO)
Kellicottia longispina (KELL)	*Diaptomus kenai* (DIKE)
Lecane sp. (LECA)	*Diaptomus arcticus* (DIAR)
Asplanchna priodonta (ASPR)	*Diaptomus franciscanus* (DIFR)
Gastropus sp. (GAST)	*Diaptomus* sp. (DIAP)
Keratella quadrata (KERA)	*Macrocyclops albidus* (MCAL)
Trichotria sp. (TRIC)	*Macrocyclops fuscus*(MCFR)

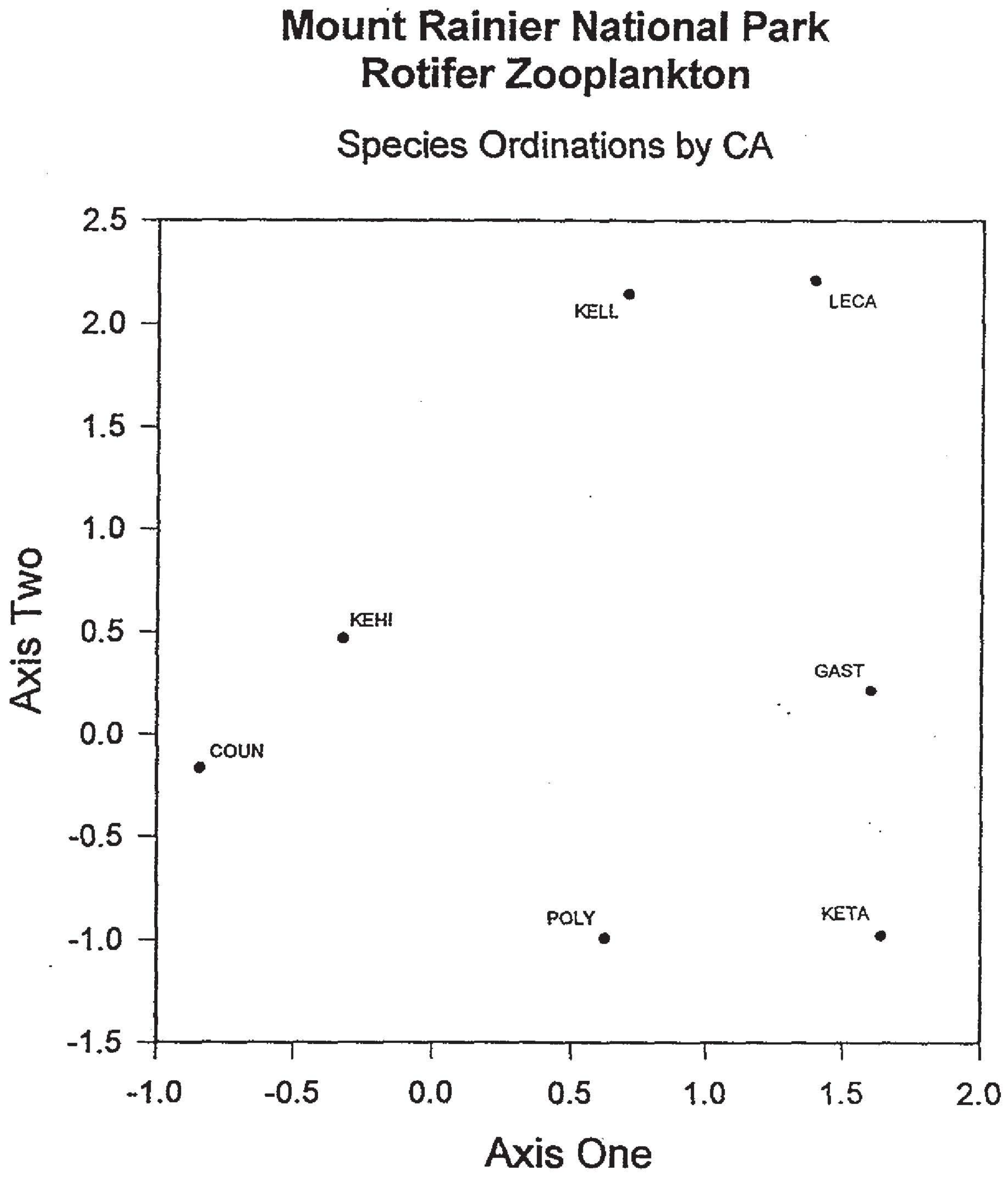

Figure 4. Ordination of the rotifer species in 29 samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993.

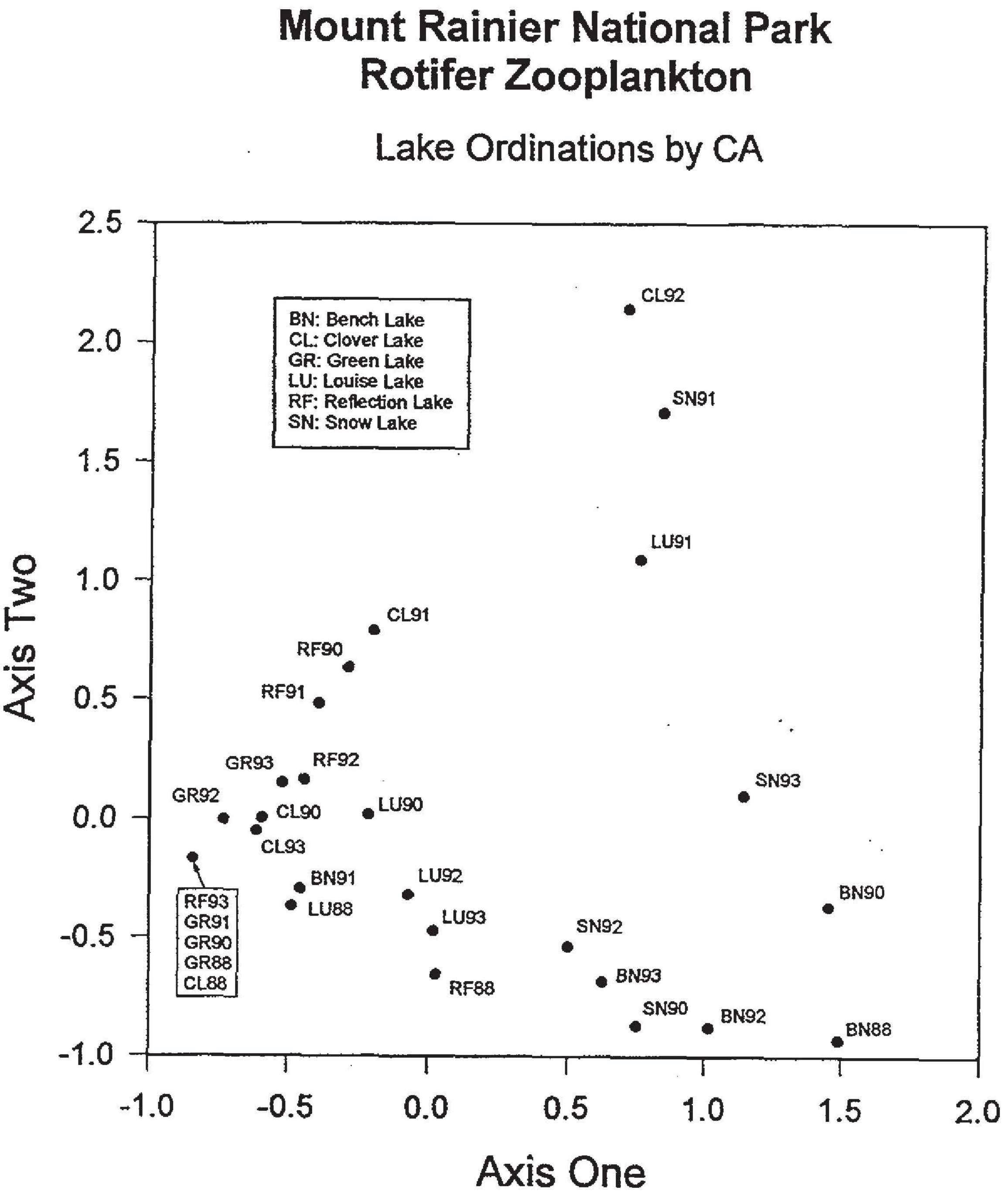

Figure 5. Ordination of 29 rotifer samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993. Numbers indicate year of sample.

C. unicornis, as was Clover Lake, Reflection Lake, and Louise Lake, with some exceptions. *K. longispina* (100%) dominated Clover Lake in 1992, and *K. longispina* (33%) and *Lecane* sp. (23%) co-dominated Lake Louise in 1991. Reflection Lake in 1988 was co-dominated by *P. vulgaris* (59%) and *C. unicornis* (41%).

Zooplankton: Crustacean Assemblages

Ten crustacean taxa were recorded from the 30 samples (Table 6). *Holopedium gibberum* was the most ubiquitous taxon and was found in 21 samples. *Daphnia rosea* was present in 16 samples and *Diaptomus kenai* in 9 samples. All of the other taxa were found in fewer than 7 samples.

CA sample (lake) ordinations based on the species ordinations (Figure 6) demonstrated that the dominant crustacean taxa in some lakes were consistent throughout the study, whereas substantial temporal changes in taxonomic composition occurred in other study lakes (Figure 7). Snow Lake was dominated by *D. kenai* each year, although *H. gibberum* (40%) was a co-dominate in 1992. Louise Lake was dominated by *H. gibberum* each year. The taxonomic composition of crustacean zooplankton in Reflection Lake, Clover Lake, and Bench Lake were variable, shifting between the lower and upper portions of the left side of the graph. Reflection Lake was dominated by *H. gibberum*, except in 1992 when it was dominated by *D. rosea* (50%). The dominant taxon in Clover Lake in 1988 was *D. franciscanus* (71%), whereas *D. rosea* (81%) dominated in 1992 and *H. gibberum* dominated in other years. At Bench Lake, *H. gibberum* (44%) and *D. rosea* (43%) were co-dominants in 1988, but the lake was dominated by *M. fuscus* (63%) in 1991, *D. rosea* (92%) in 1992, and *H. gibberum* in 1990 (70%) and 1993 (50%). The taxonomic composition of the dominant crustacean zooplankton in Green Lake shifted among *D. kenai* (69%) in 1988 and 1991 (68%), *D. rosea* in 1990 (70%) and 1993 (52%), and *Daphnia*

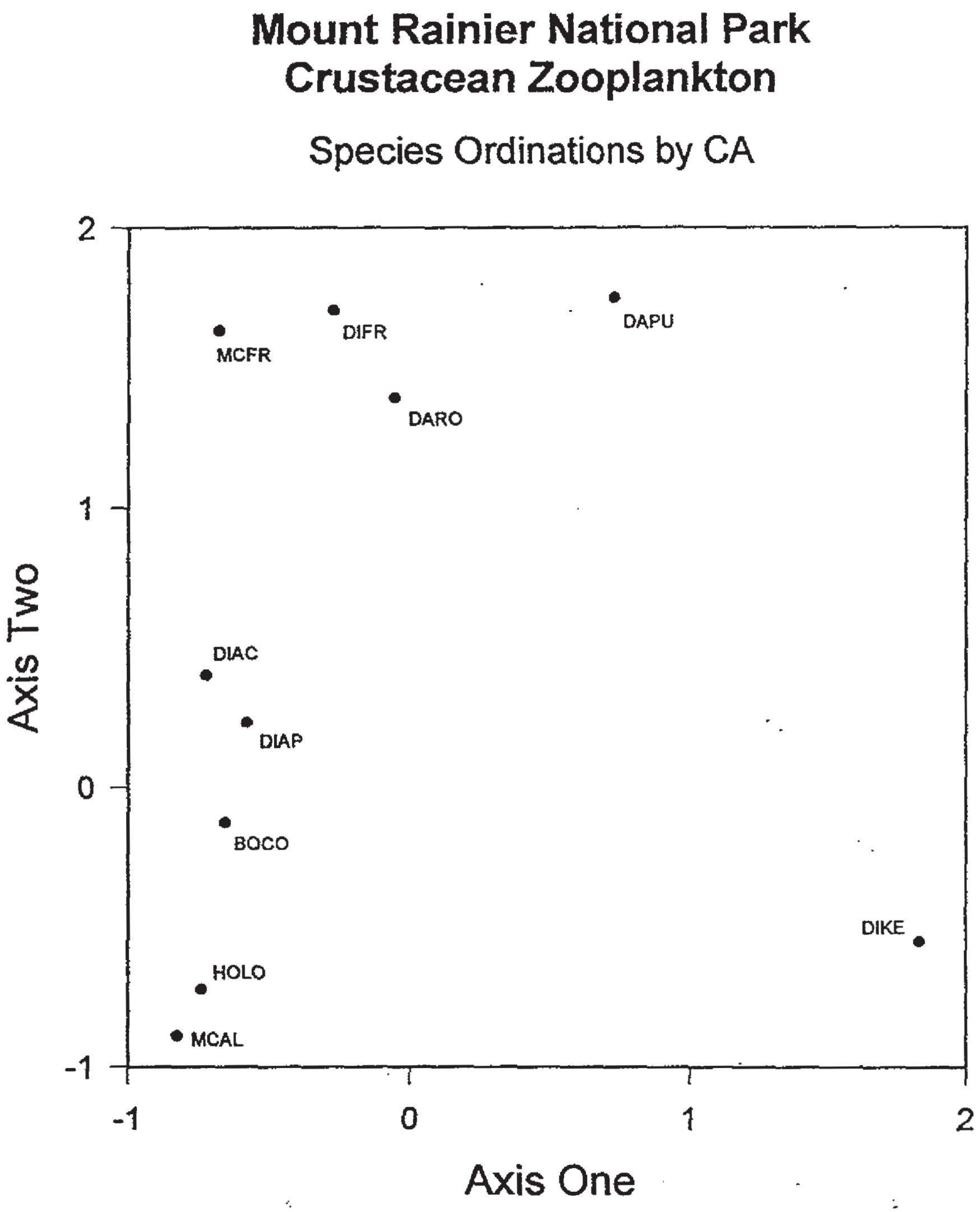

Figure 6. Ordination of the crustacean zooplankton species in 30 samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993.

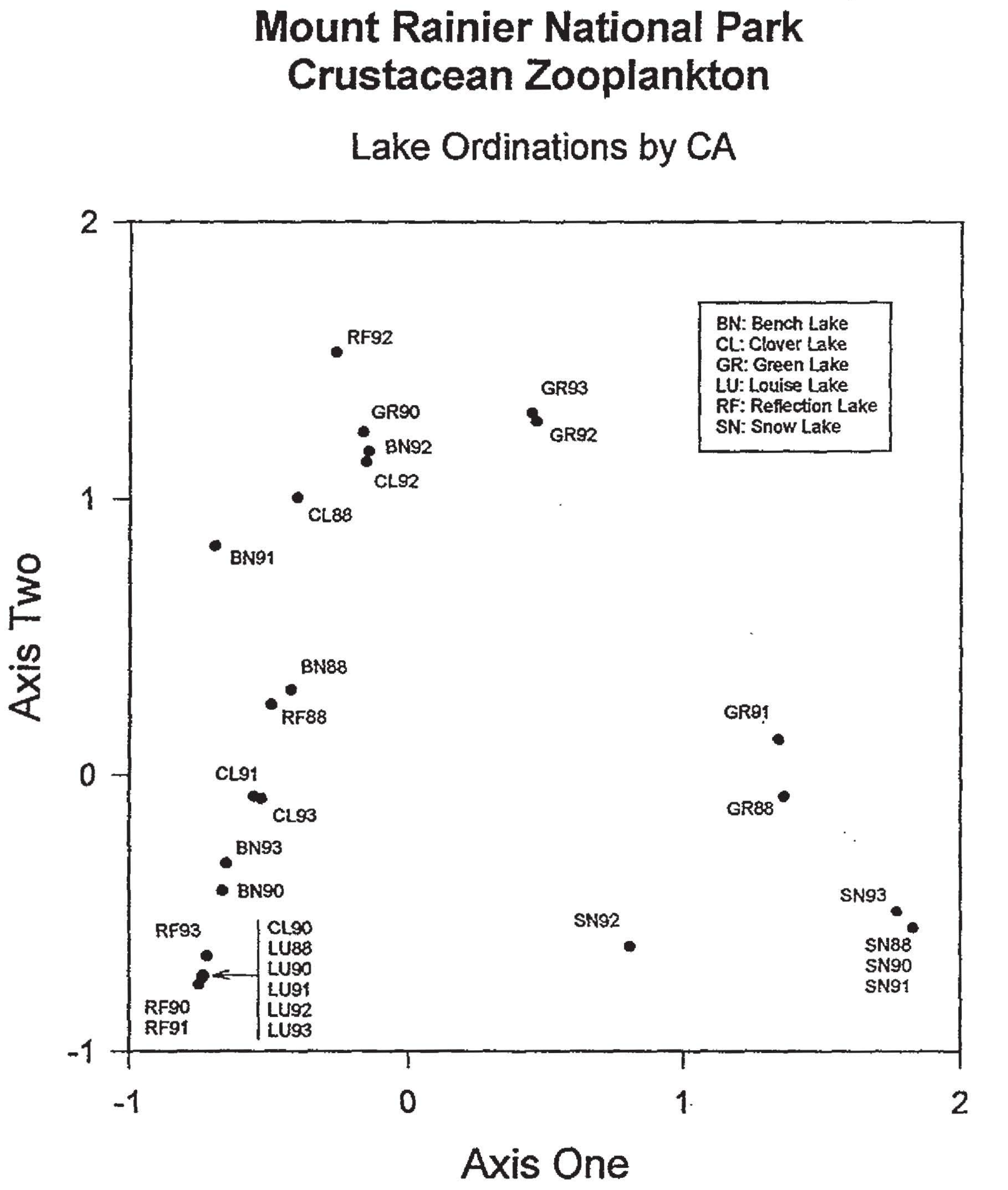

Figure 7. Ordination of 30 crustacean zooplankton samples from six MORA lakes by correspondence analysis (CA). Samples were obtained in August of 1988 and 1990 - 1993. Numbers indicate year of sample.

pulicaria (34%), *D. rosea* (25%), and *D. franciscanus* (25%) in 1992.

DISCUSSION

The results of this study demonstrated that some of the physical and chemical characteristics of the study lakes in 1988 were within the range of values obtained between 1990 and 1993; others were not consistent through time. The dominant phytoplankton taxa in the individual lakes were in closely related assemblages, with the exception of the taxa found in Clover Lake and Reflection Lake. Rotifer assemblages were consistent among years in Green Lake and Reflection Lake. Although the other lakes exhibited fairly consistent rotifer assemblages, the assemblages exhibited marked changes in some years. The crustacean zooplankton assemblages in Louise Lake and Snow Lake were consistent through time, whereas those in the other lakes exhibited considerable change.

Clearly none of the lakes exhibited consistency through time for all limnological characteristics. Assuming that the results of this study are applicable to the other park lakes sampled in 1988, this lack of persistence among components limits the utility of this single-year study to serve as a baseline for judgements about future conditions. Quite simply, baseline conditions must be based on multiple years of sampling. Although this conclusion is not surprising given the complexity of lake systems, it does fit well with the general attitude that long-term monitoring must be conducted as an iterative process with frequent evaluations of the results and program redirection as necessary. It is not enough, however, to simply conclude studies such as this one by directing managers that more monitoring is needed. There are recommendations that can emerge from these studies that can provide some direction in the development of additional monitoring.

Therefore, we offer the following recommendations. Lake monitoring at MORA should continue to focus on annual samplings (see below) of water quality, phytoplankton assemblages, and zooplankton (rotifer and crustacean) assemblages. Although some researchers have concluded that long-term monitoring should emphasize biological indicators rather than water quality (Karr 1991), many high-mountain lakes are susceptible to impacts from atmospheric deposition (Melack and others 1985, Eilers and others 1988, and Jassby and others 1995). The inclusion of water quality monitoring at MORA is essential given the potential contamination of park lakes from air-borne pollutants from nearby metropolitan areas. Furthermore, adopting an iterative process is essential because the extended data base may provide sufficient evidence of consistent patterns of variation in water quality and the taxonomic structures of phytoplankton and zooplankton assemblages in some lakes to support a change from annual sampling to less frequent sampling. As part of this iterative process, park management is encouraged to include historic park data from other lentic systems, as well from surveys of the remaining unsampled park lakes, ponds, and wetlands. In fact, a long-term goal of park management should be to develop a data base (elevation, surface area, maximum depth, and at least one sample for water clarity, water quality, phytoplankton, and zooplankton) for all park lakes and ponds. Such a data base would provide the park with at least some measure of the diversity of the characteristics of lentic systems at the landscape level, as well as providing some information from which to evaluate future characteristics.

Lake monitoring will require a long-term commitment by park management. This effort should include samplings just after ice-out, again in August, and a third time in September to document seasonal changes in the lakes (Larson and others 1994; Larson and others 1995). This sampling procedure provides a better window of observation than just August sampling as in this study because seasonal changes can not be expected to be consistent each year (Strub and others

1985).

As mentioned earlier, logistical and budgetary issues constrain field studies in the park. Thus, park management will need to carefully select a lake or lakes for long-term monitoring. If park management selects only one lake for long-term monitoring, we recommend Louise Lake because its limnological characteristics are relatively consistent through time. This lake provides the best opportunity to document "normal" conditions from which to assess its status and trends. If additional lakes are selected, the results of this study and the 1988 inventory, plus recent investigations by park staff, suggest five lakes that provide a range of lake types in the park: Snow Lake, Bench Lake, Green Lake, Eunice Lake, and Mowich Lake. Bench Lake and Snow Lake provide examples of warm lakes and cold lakes in the park, respectively. From a logistical standpoint, selection of these lakes make sense because they are located near Louise Lake. Green lake, Eunice Lake, and Mowich Lake are located in the northwest corner of the park where they are vulnerable to potential deposition of air-borne pollution from nearby metropolitan areas. Green Lake exhibits relatively high concentrations of nitrogen and in near-bottom samples, low concentrations of dissolved oxygen as compared to the characteristics of other lakes. For this reason, sampling should continue to fully characterize the condition and trends in this lake. Mowich Lake is recommended because it is representative of the two large park lakes. It is the largest (45.9 ha) and deepest (58.6 m) lake in the park, it is extremely clear and unproductive (Larson 1973), and it has a small granitic watershed. Similarly, Eunice Lake has a small granite watershed and it is extremely clear and unproductive, but is small in size (5.3 ha) and shallow (11.5 m) relative to Mowich Lake, which is located nearby. Priority should be given to these lakes, but if funding is available, two additional lakes are recommended for long-term monitoring for a better geographical distribution of lakes in the park. These include Shriner Lake

(1.7 ha, maximum depth of 2.9 m) and Lake George (13.9 ha, maximum depth of 38.3), the second largest lake in the park. These lakes are found in the southeast and southwest quadrants of the park, respectively.

The initiation of a long-term lake monitoring program is a decision for park management. It is clear, however, that the 1988 synoptic lake inventory will not provide a sound basis for evaluating the status and trends of the lakes in the event of future environmental changes. Thus, management will need to assess the value of lake monitoring relative to other, perhaps more urgent short-term needs that are addressed in the MORA natural resource management plan. Since this may not be an easy decision given the daily political pressures on park managers to address natural resource management problems, a brief review as to why a limnological research and monitoring was established at Crater Lake, Crater Lake National Park, may serve as an example of the need to initiate a lake monitoring program at MORA.

Independent research at Crater Lake between 1978 and 1982 suggested that the clarity of this extremely clear and deep-blue lake had diminished relative to measurements made in 1937 and 1969 (D. Larson 1984). These results prompted the National Park Service to convene several peer review panels in 1982 to review the lake data base. Although there was a suspicion that lake clarity had diminished, the panels were not able to substantiate the claim because the data base was sparse and fragmented. As a result, Congress passed Public Law 97-250 in the fall of 1982 that directed the Secretary of the Interior to evaluate the limnological characteristics of the lake for 10-years. At the end of the study the researchers concluded that the lake was pristine, except for the consequences of introduced fishes (Larson and others 1993). They also concluded that the decreased clarity of the lake during the period from 1978 to 1982 was a natural feature of the lake system. This conclusion was substantiated in 1995 and 1997 when the clarity of the lake was equal or better than the measurements made in 1937 and 1969 (Larson and others 1996; Larson 1997; unpublished 1997 park data).

The long-term limnological monitoring project at Crater Lake provides additional evidence that historical data based on short-term and infrequent studies may provide inaccurate information to assess the status and trends of lake systems. We conclude, therefore, that long-term lake monitoring at MORA is essential to reduce the uncertainty. Such information would be particularly important to park management owing the potential external threats from atmospheric pollution and the impacts from future global climate changes (Schneider 1989).

A long-term monitoring program on selected park lakes needs to include an iterative process, as mentioned earlier, from which to frequently evaluate the results of the program. Key to this ongoing assessment will be the documentation of changing conditions cause by natural phenomena and those from human-related activities. This will not be an easy task because our study suggests that considerable variational ready exists for many components of the lakes. Although some evidence of the impacts of atmospheric deposition is available for zooplankton assemblages (Engle and Melack 1995) and introduced trout on native salamander populations (Tyler and others 1998) in high-mountain lakes in the west, managers must realize that in general, little is known about how these lake systems respond to environmental changes (Frissell and Bayles 1996). Low-level disturbances from human-related activities may be masked by natural variability. Managers need to look for changes in trajectories of lake components through time. The change in phytoplankton assemblages from 1988 to 1993 in Clover Lake is a good example. The observed inter-annual shifts between dominant zooplankton taxa, for example *Holopedium* and *Daphnia* or *Daphnia* and *D. kenai*, in some of the lakes are additional examples. But whether these changes reflect natural features of the lake systems or responses to environmental changes is unknown. Managers need to be patient and understand that subtle effects on lake systems should not be de-emphasized or ignored in their management programs (Frissell and Bayles 1996). Natural areas, such as MORA, represent the best remaining places to evaluate these effects because their landscapes are relatively undisturbed. Such information will be extremely useful for developing restorative ecosystem management on disturbed landscapes.

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