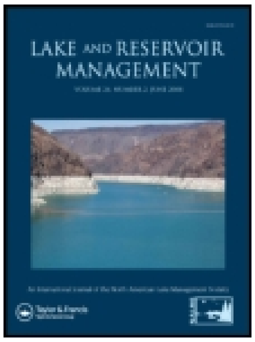

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Effects of Fisheries Management and Lakeshore Development on Water Quality in Diamond Lake, Oregon

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ABSTRACT

Eilers, J. M., C. P. Gubala, P. R. Sweets and D. Hanson. 2001. Effects of fisheries management and lakeshore development on water quality in Diamond Lake, Oregon. Lake and Reserv. Manage. 17(1):29-47.

Paleolimnological techniques were used to assess water quality changes in a heavily used recreation lake in the Oregon Cascades. Diamond Lake was fishless prior to 1910, but has been intentionally stocked with rainbow trout annually and unintentionally stocked with tui chub in the 1930s and the 1990s. The lake was converted from a mesotrophic system to an eutrophic lake as a consequence of watershed inputs of nutrients associated with shoreline development and biomanipulation in the form of fisheries management. Despite installation of a sewage collection and diversion system, Diamond Lake has increased in sediment accumulation rate and the diatom community has shown an increase in *Fragilaria crotonensis* and *Asterionella formosa*, species which are often associated with eutrophication. The two largest increases in sediment accumulation rate and alterations in the diatom community correspond most closely with the two increases in the tui chub population rather than shoreline development. Diatom-inferred (DI) pH increased from 7.95 circa 1910 to over 8.20 in the 1940s. The effects of a rotenone treatment in 1954 to eliminate the tui chub are evident in the short-term decrease in DI- pH and the response of the diatom community. The lake also experienced a major increase in zooplankton abundance in the 20th century as indicated by the remains in the sediment. The results illustrate the need to consider both external and internal sources of nutrients in lake restoration and management attempts.

Key Words: paleolimnology, Oregon, Cascades, eutrophication, biomanipulation, tui chub.

Paleolimnological approaches have become increasingly refined making it possible to consider their application as one of many routine methods for adding to our understanding of lake management. Paleolimnology has been particularly insightful for understanding water quality changes in the absence of a robust water quality record. In this particular application, there was a need to both provide a history of Diamond Lake throughout the 20th century and to resolve divergent conclusions from recent studies which would lead to different approaches for lake

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management. The two fundamental questions to address were: (1) "Has the water quality of the lake deteriorated in recent decades?" and (2) "What factors contribute to existing water quality problems in the lake?" The objective of our study was to reconstruct recent water quality history in Diamond Lake based on changes in sediment accumulation rate, changes in the diatom taxa, and changes in sediment chemistry. The changes in sediment accumulation were related to known watershed development and fisheries management activities to provide resource managers with information regarding how to better manage the resource.

Diamond Lake is a 1300 ha lake located 17 km north of Crater Lake in the Oregon Cascade Range at an elevation of 1580 m. The lake was formed by glacial activity during the Pleistocene and has a maximum depth of 15.8 m (Fig. 1). Diamond Lake is a productive lake with median chlorophyll *a* and total phosphorus values of 6.8 $\mu g \cdot L^{-1}$ and 45 $\mu g \cdot L^{-1}$ (34 $\mu g \cdot L^{-1}$ for 1992-1995; Salinas and Larson 1995, Salinas 1996), respectively (Umpqua National Forest 1998). Epilimnetic pH values in the summer occasionally exceed 9.3 (Salinas and Larson 1995) and extreme values in Secchi disk transparency ranged from 2.9 m in 1995 to 9.2 m in 1994 (Salinas and Larson 1995, Salinas 1996). A summary of relevant water quality and lake morphometry data is provided in Table 1. The algae population is dominated by diatoms, chrysophytes, and blue-green species (Salinas and Larson 1995). Stream development in this portion of the Cascades is low because of the high permeability of the volcanic terrain. Consequently, surface discharge to the lake from the watershed is relatively modest and groundwater discharge to the lake is probably substantial. The estimated hydraulic residence time is 1.6 yr (Lauer et al. 1979), although unmeasured groundwater discharge to the lake could substantially reduce this estimate.

Lake and Watershed History

Prior to 1910, Diamond Lake was fishless. However, in 1910 or 1913 the lake was stocked with rainbow trout resulting in a highly successful fishery that was renown for its productivity (Bauer 1976). The Oregon Game Commission built a fish hatchery adjacent to the lake to harvest the trout and collect eggs. In a typical year, 18,000,000 eggs were collected and 1,000,000 fry were returned to the lake with the balance being used to support trout stocking programs elsewhere around the state. The success of the fisheries attracted visitors to the lake which over the years resulted in development of a major resort, construction of 102 seasonal residences, and construction of several hundred public campsites (Fig. 2).

The success of the trout fisheries was interrupted when tui chub (*Gila bicolor*) were introduced, probably as discarded bait fish, in the 1930s and rapidly expanded in the 1940s. The chub outcompeted the trout causing the sport fisheries to collapse. In 1954, the lake was successfully treated with rotenone and was restocked in 1955 with rainbow trout (Bauer 1976). By the mid-1960s, the trout fisheries was producing up to 120 kg fish $\cdot ha^{-1}$ (Bauer 1976). However, water quality was perceived to be relatively poor as indicated by blooms of *Anabaena flos-aquae* and *A. planktonica*. In response to the perceived threat to water quality, the Forest Service constructed a sewage collection and treatment system which collected all wastes along the lake shore vicinity with the exception of the private residences on the west shore. Formerly, human wastes were discharged into septic systems and pit toilets. The homes on the west shore still rely largely on septic systems and pit toilets for waste disposal. A study by Lauer et al. (1979) conducted during and several years after implementation of the waste treatment system showed no positive water quality response in the lake. The trout fisheries began to decline rapidly in the 1990s, apparently in response to an unauthorized re-introduction of tui chub. Plans are being developed to treat the lake with rotenone and re-stock with rainbow trout (ODFW 1996).

An estimated 1500 persons visited Diamond Lake in 1921 (Umpqua National Forest 1998). Visitor use increased in the 1920s with the opening of the Diamond Lake Resort in 1922 and further expansion of existing Forest Service campgrounds. Visitor use reached a maximum in 1978 with 783,700 recreational visitor days (RVDs), declined to an average of 650,000 RVDs in the 1980s, and declined to 432,600 RVDs in 1997, largely because of the decline in the trout fishery.

The residences were constructed beginning in 1924 and the final dwelling was completed in 1955. These dwellings were built under special permits issued by the Umpqua National Forest and no further permits are anticipated. The Forest Service first constructed relatively unimproved campsites prior to 1920, followed by expansions up to 1972 when the last of the 586 campsites were installed. The most active period of both public and private expansion of the recreational development of the lakeshore occurred in the 1960s with the opening of new campgrounds, a trailer/RV park, and additional resort units. The USFS campgrounds and private facilities provide a total of 780 available units for recreational use. The expansion of the road network adjacent to the lake reflects this increased use. With the exception of the highway bypass in 1977-79, most of the subsequent road activity involved paving existing roadways.

Other noteworthy watershed activities and events include forest fires, livestock grazing, and timber harvest. The primary forest types in the watershed are lodgepole pine, representing 56% of the forest stand, and fir/mountain hemlock complex, representing 35%. The fire recurrence intervals for these forest

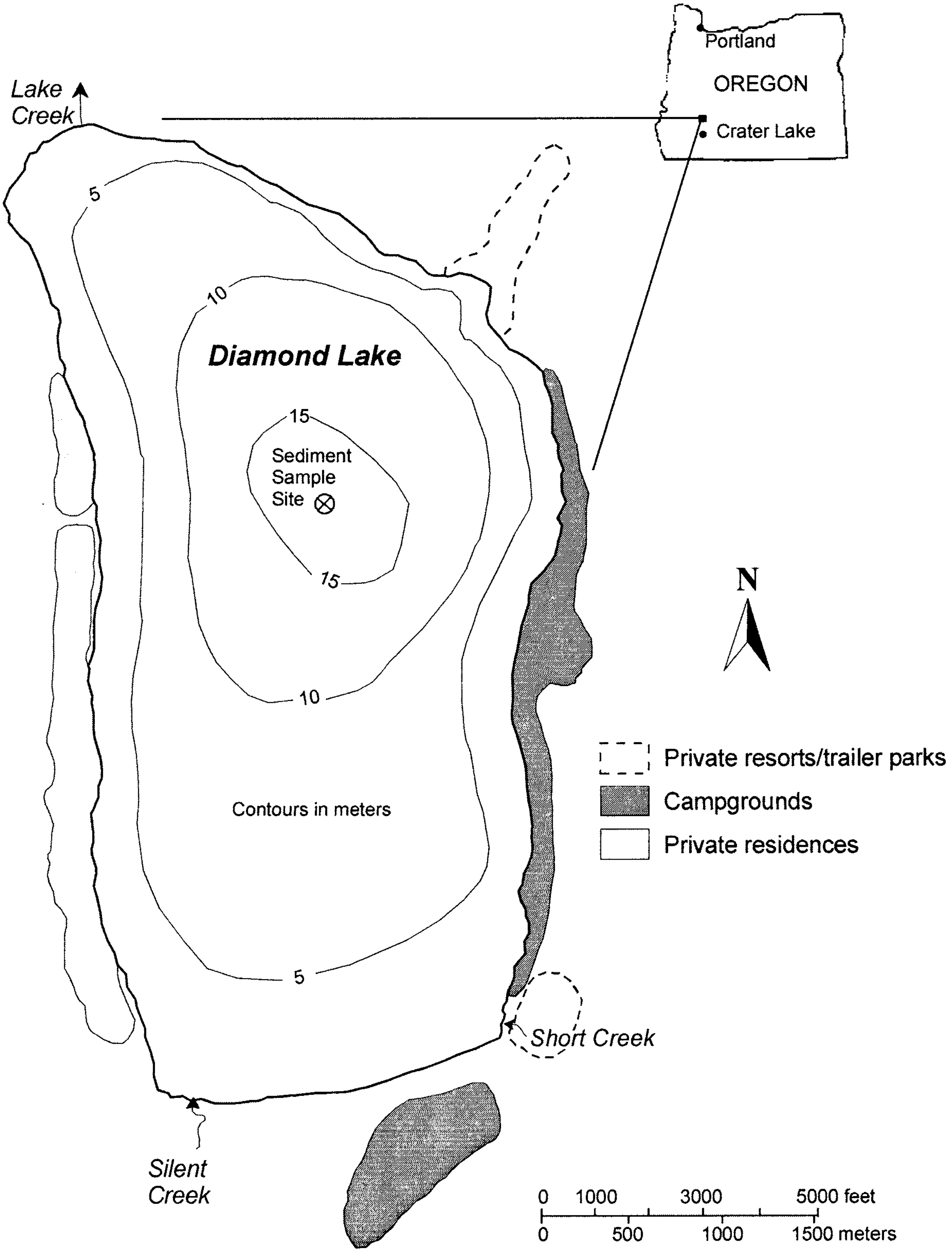

Figure 1.–Diamond Lake location, bathymetry, and development patterns. The sediment sampling site is identified in the deepest portion of the lake.

Table 1.–Water quality and lake and watershed morphometry for Diamond Lake, Oregon. Morphometric data derived from Johnson et al. (1985); Water quality data derived from Salinas and Larson (1995). Most water quality data were from samples collected in the epilimnion during the summer.

	Median	1992-1995	1967-1995
pH	8.6	7.16-9.23	7.1-9.8
chlorophyll *a* (μg·L^{-1})	6.8	2.6-8.3	1.0-39.8
total phosphorus (μg·L^{-1})	45	17-62	17-62[a]
total inorganic N (μg·L^{-1})	64	<16-88	<16-322[b]
silica (mg·L^{-1})	3.8	1.9-3.7	1.9-6.5
conductivity (μS)	39.8	38.3-40.9	
alkalinity (μeq·L^{-1})	412	396-421	
lake area (ha)	1,300		
watershed area (ha)	13,600		
max. depth (m)	15.8		
mean depth (m)	7.3		
lake volume (hm^3)	95.1		
hydraulic residence time (yr)	0.6[c]-1.6[d]		
lake elevation (m)	1,580		
max. watershed elevation (m)	2,799		

[a] excluding one observation of 140 μg·L^{-1} 1976.

[b] excluding one observation of 385 μg·L^{-1} 1967.

[c] estimated based on precipitation volume inputs for the topographic watershed.

[d] estimated based on surface discharge from the lake outlet (Johnson et al. 1985).

types were measured at 72 years (Umpqua National Forest 1998). However, due to the success of fire suppression activities, the last major fire in the watershed occurred from July 5 to the rains in September, 1910 and burned much of the watershed. Since then, only 80 ha of timber has been burned, a testament to the effectiveness of the fire suppression activities.

The advanced age of the lodgepole stands makes them more susceptible to insect damage. An infestation of mountain pine bark beetles (*Dendroctonus ponderosae*) caused damage to 64 ha of trees in the southern portion of the watershed. The harvest of this timber in 1979 constitutes the only significant logging activity since the 1910 fire. The Diamond Lake area was used for grazing by sheep beginning in the 19th century and extending into the 1940s. The flocks would graze through the summer and rotate through the mountain meadows. The only remaining livestock in the watershed is associated with a small stable used for recreational horseback riding.

The watershed assessment showed that current erosion is virtually absent with the exception of minor erosion on some unpaved roads (Umpqua National Forest 1998). We are unaware of any major erosion control efforts in the past that suggests the degree of erosion has materially changed in this century.

Methods

Diamond Lake sediments were collected on October 1, 1996 at a depth of 15.8 m in the northcentral portion of the lake (Fig. 1). A 10 cm-diameter corer, equipped with a sphincter device to close the base of the core, was slowly lowered into the sediments using a motorized winch mounted on a quadrapod attached to a coring platform. The position of the coring platform was stabilized with three anchors which allowed the core to be lowered into the sediments over a period of several minutes. The sphincter was closed prior to retrieving the sediment core. Several sediment cores were retrieved before a core of sufficient length and quality was obtained. The undisturbed 78 cm core was returned to the lakeshore where it was placed in a tripod and extruded in 1 cm sections. A 1-m length core was returned to shore, but upon further examination we judged the sidewall disturbance to be too great for a satisfactory reconstruction. Sediment samples were placed in Whirlpac® bags in a cooler and returned to Corvallis where they were refrigerated. Subsamples of the sediment (not the elutriate) were analyzed for ^{14}C, ^{210}Pb, ^{137}Cs, percent water, percent loss-on-ignition (LOI), C, N, S, P, Ca,

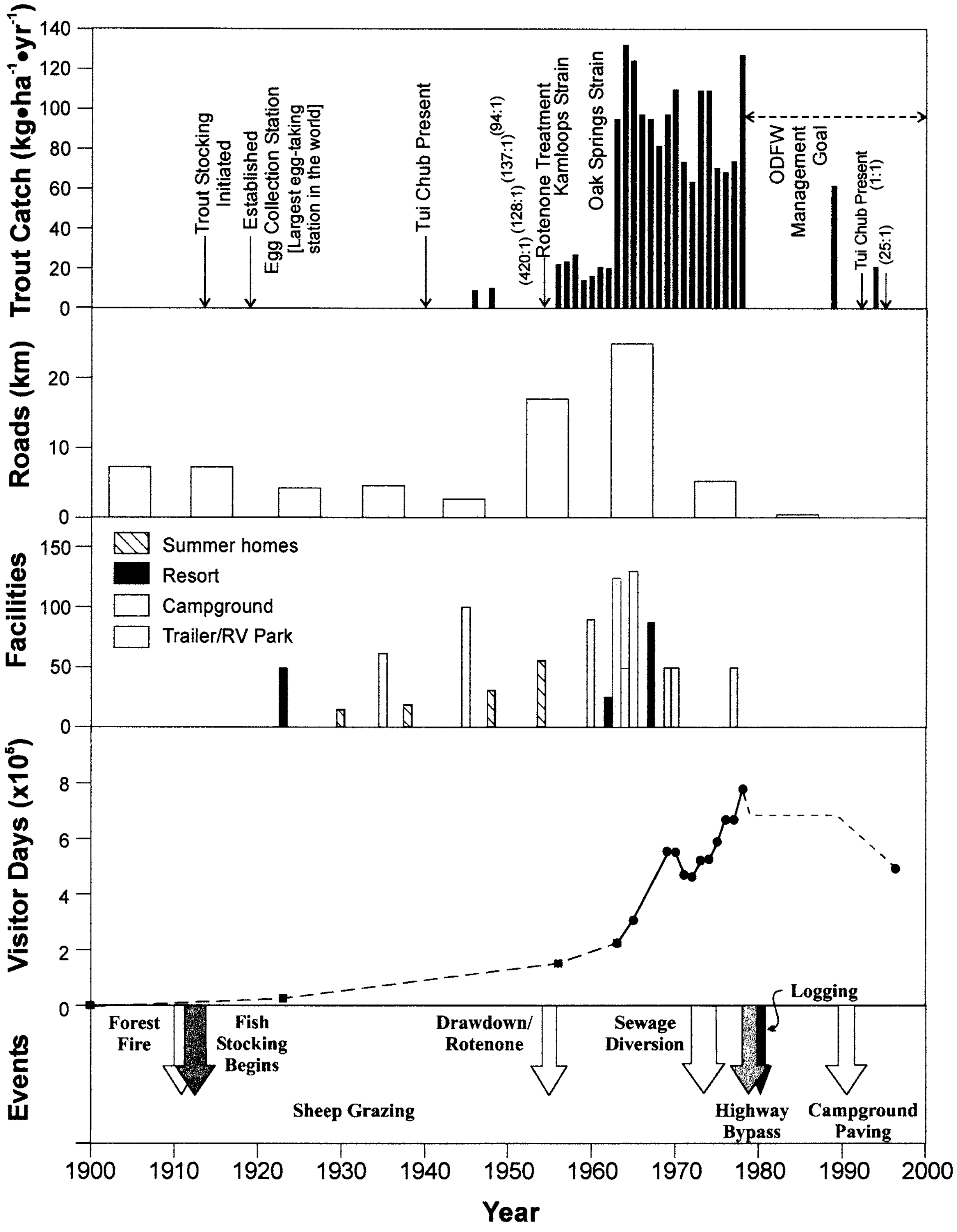

Figure 2.–Development and watershed activities for Diamond Lake in the 20th century. Chub-to-trout ratios shown in parentheses.

Mg, Na, K, Fe, Ti, Si, diatoms, and zooplankton. Carbon, nitrogen, and sulfur were analyzed using a Leco model CNS-2000 elemental analyzer. Standard Leco operating procedures were followed using sulfamethazine for standardization and a combustion temperature of 1350 °C. Other elements were analyzed with a Perkin Elmer Optima 3000 DV ICP spectrometer using the radial view. Samples were first digested in a CEM Corporation model MDS-2000 microwave digestion oven. A total digest of the sediment (CEM Corp. 1991) using HNO_3, HF, HCl, and H_3BO_4 was used for the analysis of P, Fe, Ti, and Si. The remaining cations were analyzed in a HNO_3 digest (USEPA 1994). Treatment of samples and methods of analysis are summarized in Table 2. Data were entered into SAS data files (SAS 1989) and reviewed for accuracy. Re- analyses were conducted on several sediment samples to verify that aberrant values were reproducible.

The use of a single sediment core to reconstruct lake history can yield spurious results, particularly in lakes with complex morphometry. We judged the use of a single core acceptable in this application because of the simple lake bathymetry, the sufficient lake depth to minimize wind-induced sediment resuspension, and the moderately low surface discharge and relatively stable flows of the major tributaries.

Sediment samples were dated using ^{14}C, ^{137}Cs, and ^{210}Pb isotopes. ^{14}C was analyzed using accelerator mass spectrometry (AMS) by Lawrence Livermore Nuclear Laboratory through Beta Analytic, Inc. The material was pre-treated with HCl washes to strip the sediments of carbonates. ^{137}Cs was measured using gamma spectroscopy using a counting time of 8 hrs/sample. ^{210}Pb was analyzed using alpha spectroscopy (Eakins and Morrison 1978) which involves distillation of the sample, HNO_3 digestion, and plating onto silver prior to counting. The sediment ages and accumulation rates were calculated using the constant-rate-of-supply (CRS) model of Appleby and Oldfield (1978) with old age dates using the method described by Binford (1990).

Table 2.–Analytical methods used to analyze sediments associated with Diamond Lake sediment.

Analyte	Method Description	Reference	Laboratory
Physical			
Percent Water	@ 95 °C	–	OSU-Soil Science
Loss-on-Ignition	@ 550 °C	Dean (1974)	OSU-Soil Science
Dating			
^{14}C	Accelerator Mass Spectrometry (AMS)	cf Taylor (1987)	Beta Analytic (Lawrence Livermore National Labotatory)
^{210}Pb	Alpha spectroscopy	Eakins and Morrison (1978)	
^{137}Cs	Gamma spectroscopy	Pennington et al. (1973)	Flett Laboratories University of Louisville
Chemistry			
C	CNS Analyzer	Leco model CNS-2000 elemental analyzer; sulfamethazine standardization; combustion temp @ 1350 °C	OSU-Soil Science
N	CNS Analyzer		OSU-Soil Science
S	CNS Analyzer		OSU-Soil Science
Ca	ICP; HNO_3 digest	EPA 3051 (Rev. 0, 9/94)	OSU-Soil Science
Mg	ICP; HNO_3 digest	EPA 3051 (Rev. 0, 9/94)	OSU-Soil Science
Na	ICP; HNO_3 digest	EPA 3051 (Rev. 0, 9/94)	OSU-Soil Science
K	ICP; HNO_3 digest	EPA 3051 (Rev. 0, 9/94	OSU-Soil Science
P	ICP; HNO_3 + HF + HCl + H_3BO_4	CEM Corp. (1991)	OSU-Soil Science
Fe	ICP; HNO_3 + HF + HCl + H_3BO_4	CEM Corp. (1991)	OSU-Soil Science
Ti	ICP; HNO_3 + HF + HCl + H_3BO_4	CEM Corp. (1991)	OSU-Soil Science
Si	ICP; HNO_3 + HF + HCl + H_3BO_4	CEM Corp. (1991)	OSU-Soil Science

Diatoms were analyzed according to protocols developed for the Paleoecological Investigation of Recent Lake Acidification (PIRLA) program (Charles et al. 1990). Sediment samples were digested and mounted on slides, and 300 diatoms were counted per slide. Four additional slides of sediment from Diamond Lake were obtained from an earlier paleolimnological study (Meyerhoff 1977). These slides were analyzed by Roger Sweets by identifying and counting 100 individual diatoms per slide. The purpose of re-analyzing these slides was to provide an additional independent check on the age of the sediments from the current study. This was accomplished by conducting a test of statistical similarity of the diatom communities in the current study with the diatom communities in Meyerhoff's slides. Similarity of diatom sediment intervals was measured using an average linkage cluster analysis (SAS 1989) for all species present.

The diatom-inferred changes in lake chemistry were based on a collection set of 48 lakes in the Oregon and Washington Cascades (Eilers et al. 1998). The calibration equations were generated using weighted averaging regression (Birks et al. 1990) with the WACALIB program (Line and Birks 1990). The approach is based on computing a weighted average value that represents the optimum environmental condition for that taxon.

Zooplankton remains were viewed through a binocular microscope at 100 power by scanning multiple chambers per slide. The sample was prepared by suspending 2 gm of sediment in 250 ml water solution and scanning up to 100 ml of material to achieve a target of 200 individual organisms. The remains were identified to species, but because of minor uncertainties the results are reported here to genus. The quantities were expressed as organisms per dry gram of sediment.

Results

Sediment Age

The sediment dating using ^{210}Pb shows that the unsupported ^{210}Pb is contained within the upper 40 cm of sediment. The CRS model results indicate that the top 20 cm of sediment represent the last 40 years and the subsequent 20 cm represent the next ~80 years of accumulation (Fig. 3). The sediment dating makes it possible to compute changes in the sediment accumulation rate (SAR) which increased from ~0.01 g · cm^{-2} · yr^{-1} near the beginning of the century to a high of ~0.03 g·cm^{-2}·yr^{-1} from the 1950s-1960s and again in the 1990s (Fig. 4). In the mid-1970s, the SAR decreased to values ~0.02 g·cm^{-2}·yr^{-1}.

The accuracy of the ^{210}Pb dating for the 1950s-1960s period was assessed by measuring the ^{137}Cs peak which is expected to correspond to the year 1963 (Pennington et al. 1973). The ^{137}Cs results indicate a peak at 19 cm which corresponds to a ^{210}Pb date of 1956. The accuracy of the pre-development SAR computed with ^{210}Pb was assessed using measurements for the base of the core. The sediment interval 76-78 cm yielded a radiocarbon age of 720 ± 50 years before present (YBP). The computed SAR for the lower portion of the core (40-78 cm) was 0.0075 g·cm^{-2}·yr^{-1} using ^{14}C compared to an extrapolated rate of 0.009 g·cm^{-2}·yr^{-1} using ^{210}Pb dating.

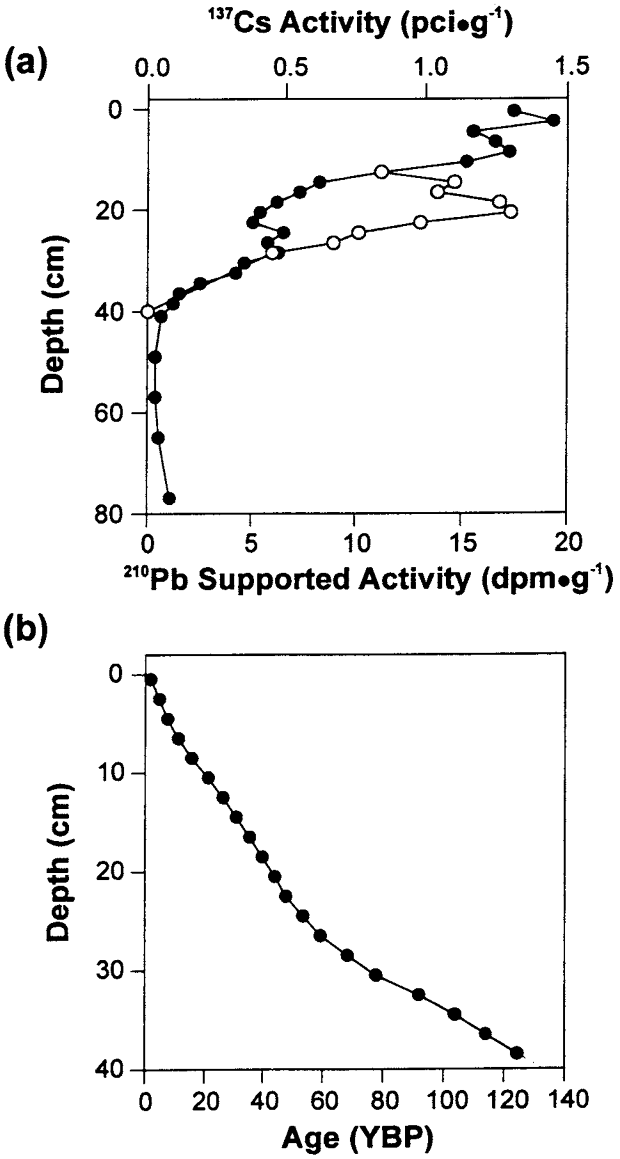

Figure 3.–Sediment dating results for Diamond Lake. (a) ^{210}Pb (•) and ^{137}Cs (o) activity; and (b) age of sediments based on ^{210}Pb dating.

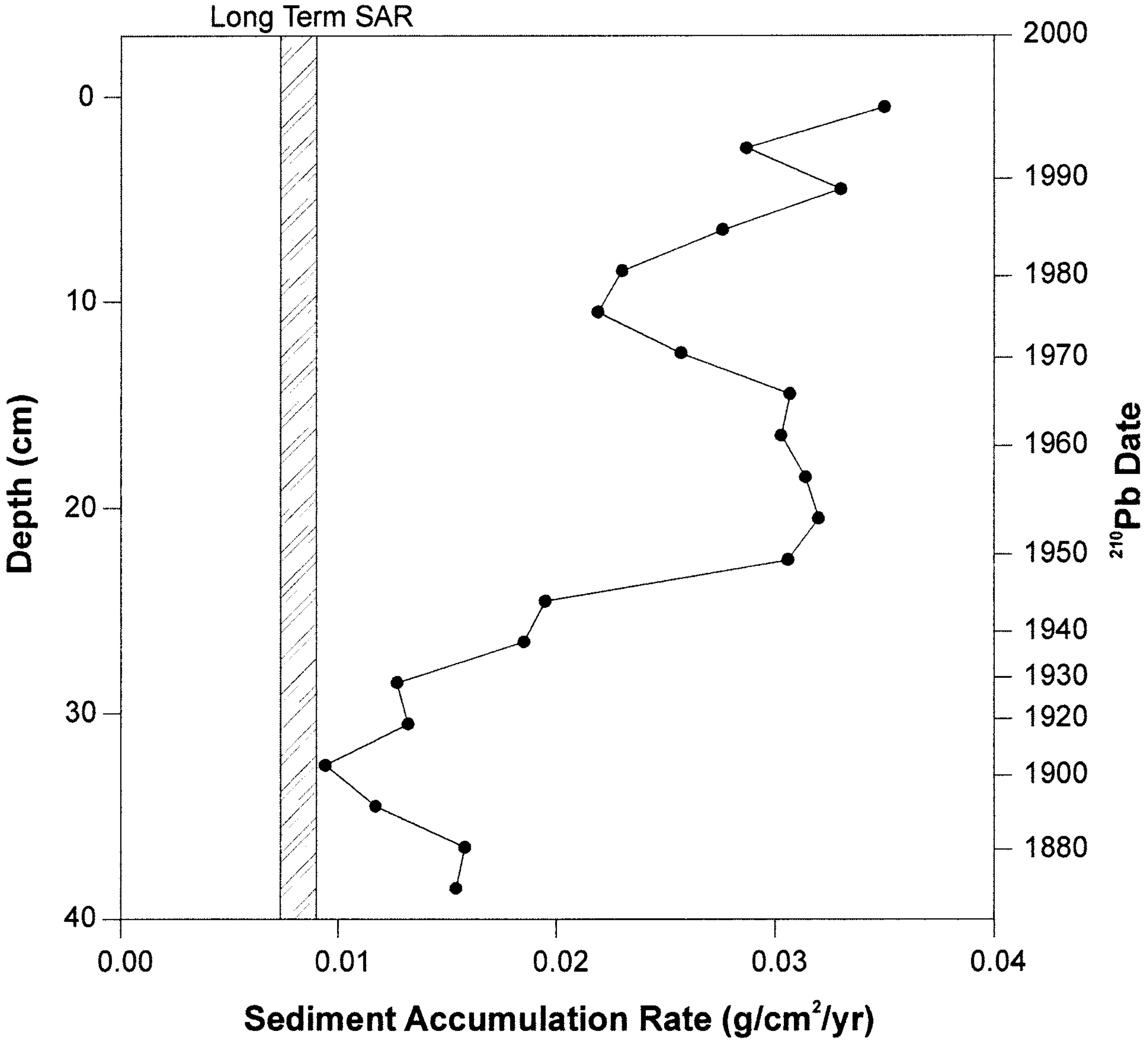

Figure 4.–Sediment accumulation rates (SAR) for Diamond Lake sediments computed using the CRS model of Appleby and Oldfield (1978) as modified by Binford (1990) for old age dates. The estimated long-term SAR range prior to development, based on ^{14}C dating, is shown as a vertical bar.

Sediment Composition

The sediments were light brown, largely homogeneous appearing material with a gelatinous non-cohesive consistency. Chironomids were present to a depth of 40 cm in the core. The sediment cores were difficult to collect, largely because of the high water content of the sediment. The surface sediments were 97% water and declined to 91% water at 38 cm, reaching a minimum of 87% at 78 cm, the base of the core (Fig. 5a).

LOI values in the surface sediments approached 30% and declined to values near 15% at 40 cm, reaching a minimum of ~11% near the base of the core (Fig. 5b). The general trend for a decline in LOI proceeding downcore was interrupted by a slight increase in LOI from 20 to 30 cm and abrupt changes in the slope of the LOI at 20 cm, 30 cm, and 40 cm.

The carbon, nitrogen, and phosphorus concentrations all decreased by a factor of two to three from the surface sediments to 40 cm (Figs. 5c,d,e). Total phosphorus concentrations exhibited a slight increase from 40 cm upwards to 16 cm. From 16 cm to the surface, the phosphorus values increased three-fold from 0.06% to 0.18%. Sulfur exhibited a 31% decrease from 0 to 21 cm, but the value at 40 cm was only 7% less than the surface sediments (Fig. 5f).

Titanium and iron concentrations were low throughout the sediments. Titanium showed two periods of increased concentrations, at 33 cm and from 23 to 15 cm (Fig. 5g). Titanium concentrations de-

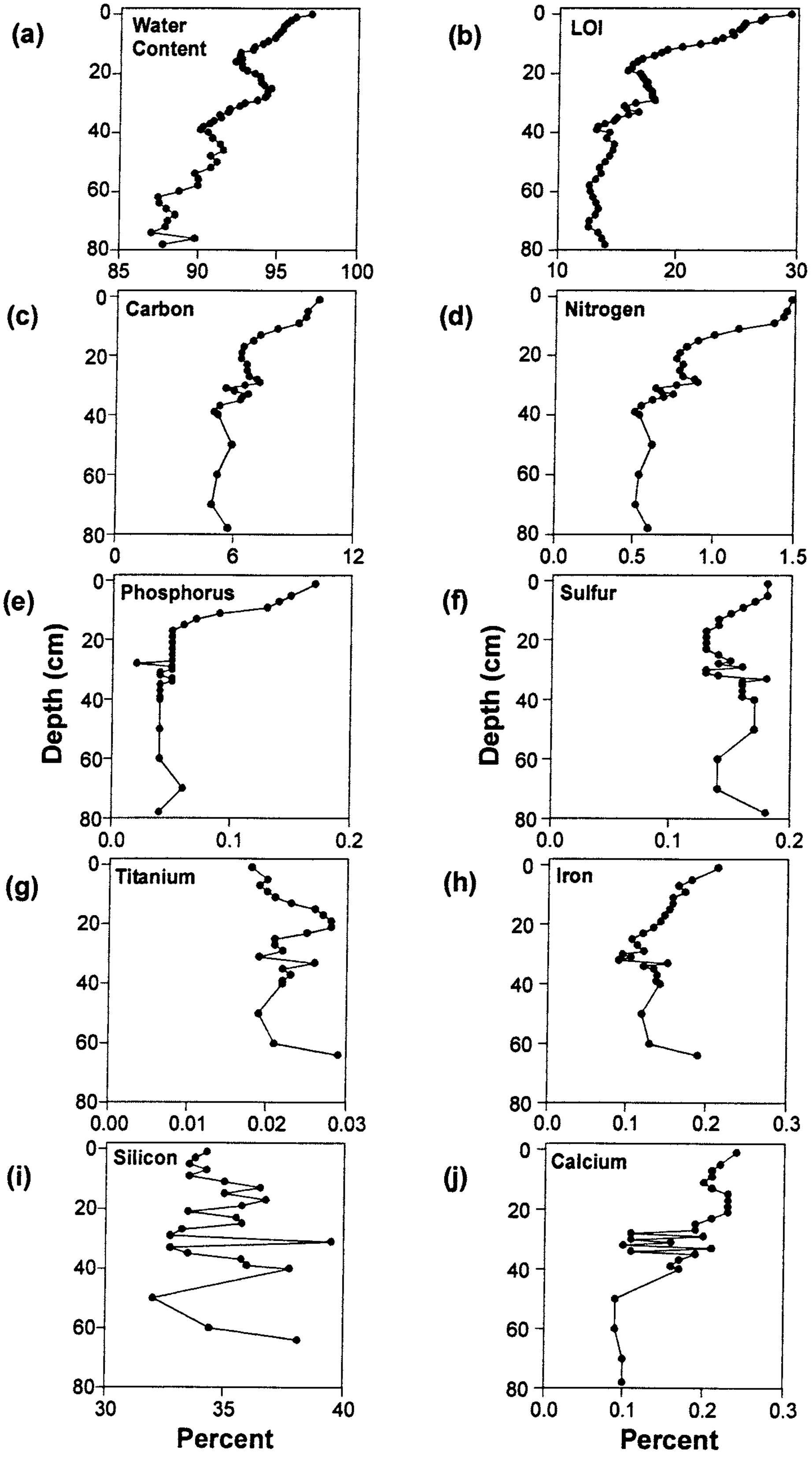

Figure 5.–Composition of sediment in Diamond Lake expressed as a percent of dry weight: (a) water content; (b) loss-on-ignition (LOI); (c) carbon; (d) nitrogen; (e) phosphorus; (f) sulfur; (g) titanium; (h) iron; (i) silicon; (j) calcium;

creased by 36% from a high of 0.28% at 21 cm and 19 cm to a low of 0.18% at the surface. The pattern for Fe in the sediments was considerably different than observed for Ti. The Fe values from 39 to 33 cm were constant at 0.14%, decreased at 31 cm to 0.11%, and increased up to a maximum of 0.21% at the surface (Fig. 5h).

Silicon concentrations decreased by about 15% from the base of the core (40 cm) to a low at 30 cm (Fig. 5i). Silicon increased during the mid-20th century and decreased again in the top sediments. All base cations exhibited similar changes in which the lowest concentrations were observed from 40 to about 31 cm (Fig. 5j; only Ca shown). Peak values generally occurred from 21 cm to 15 cm and intermediate values were measured at the surface. Discontinuities were observed for Ca, Mg, and K from depths of about 26 to 34 cm. Variations in concentrations of Na in the sediments were not distinguishable given the analytical methods.

Diatoms

The diatom community in Diamond Lake was moderately rich with a total of 121 taxa identified in the upper 40 cm. The dominant taxon was *Fragilaria crotonensis* which represented over 50% of the frustules at 28 cm. Other major taxa (defined as taxa with >25 individuals in any sample) included three subspecies of *Fragilaria pinnata, Fragilaria construens, Fragilaria brevistriata, Stephanodiscus minutulus, S. niagarae,* and *Asterionella formosa* (Fig. 6). These taxa are generally indicative of eutrophic waters.

A cluster analysis (average linkage, SAS 1989) including all diatom taxa present defined three major clusters of sediment intervals, a Recent (I) cluster (20 cm → 0 cm), a Mid-Century (II) cluster (30 cm → 18 cm), and a Pre-Development (III) cluster (40 cm → 32 cm; Fig. 7). The only overlap in diatom-sediment clusters was the 20 cm interval which classified into the Recent cluster and the 18 cm interval which classified into the Mid-Century cluster. Although the cluster analysis indicates that the Recent diatom taxa are statistically more similar to Pre- Development taxa than the Mid-Century taxa, the analysis of the diatom community does not reflect possible changes in absolute abundance of diatoms or changes in other taxonomic groups such as cyanobacteria which aren't sufficiently preserved in the sediments to identify species. The Mid-Century cluster is most different from other diatom community groups in the sediment reconstruction. The taxa most responsible for distinguishing the Mid-Century cluster from the Pre-

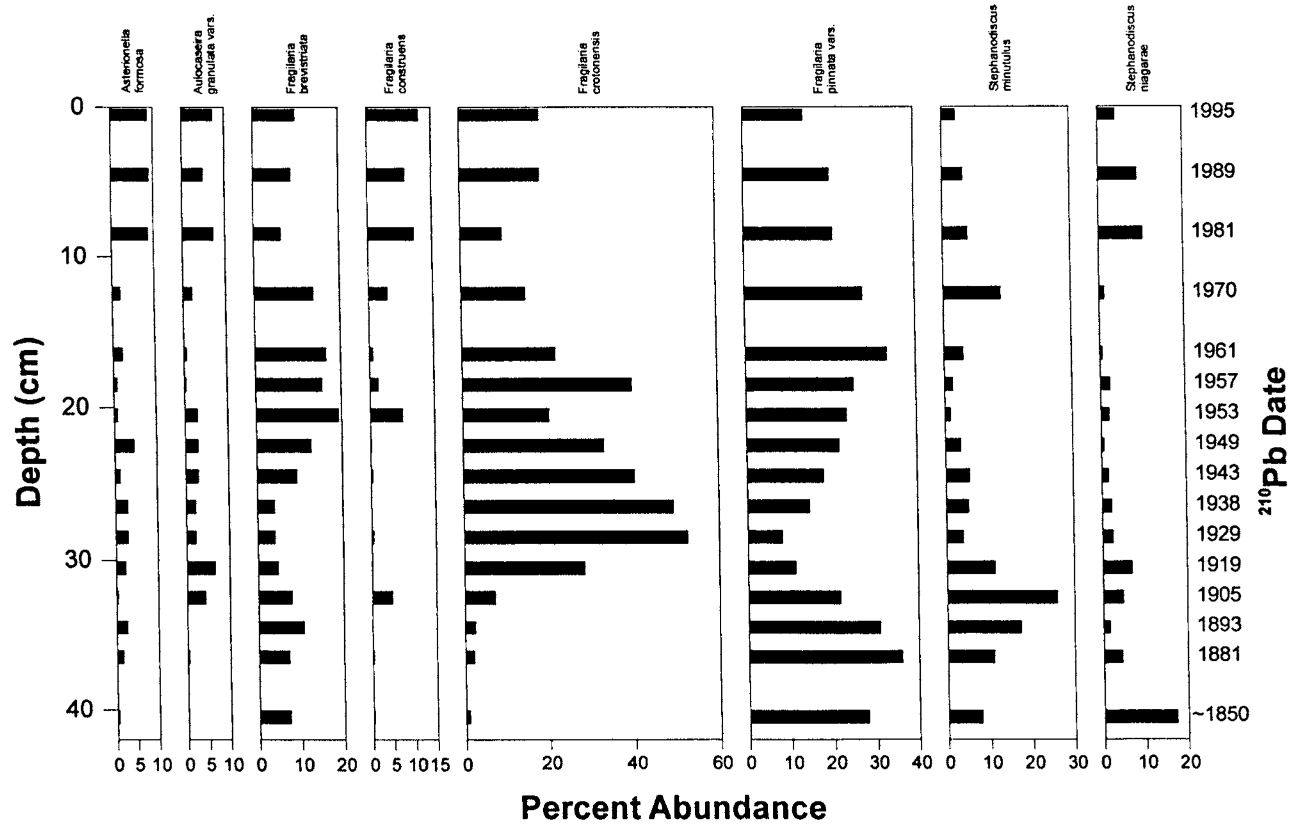

Figure 6.–Percent abundance of the eight most abundant diatom taxa in Diamond Lake sediments.

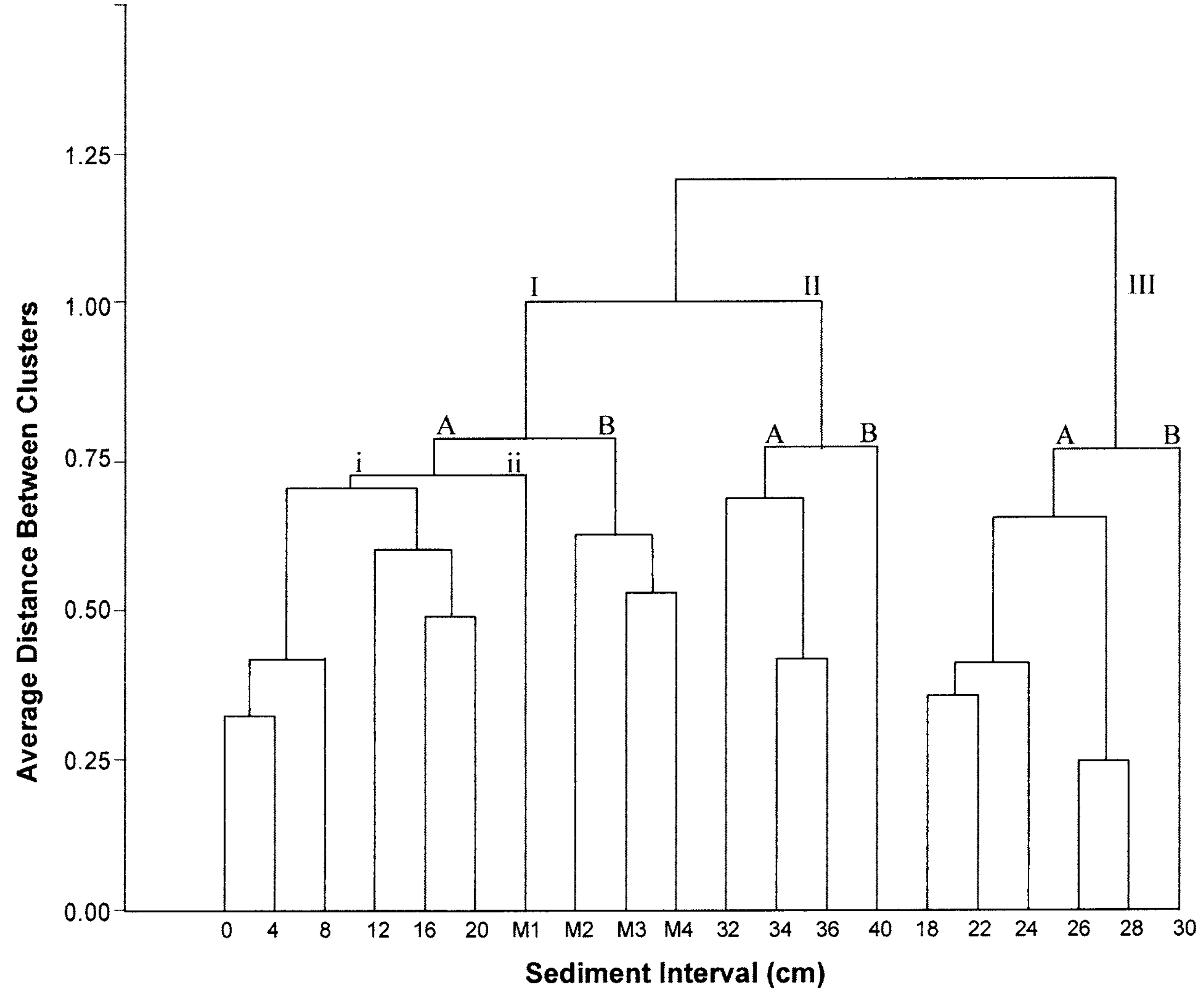

Figure 7.–Dendogram produced from an average linkage cluster analysis of all diatom taxa present in sediments of Diamond Lake. Numbers on the base of the plot identify sediment intervals (cm). Intervals preceded with an "M" represent sediment samples collected by Meyerhoff (1977). Major clusters are identified with Roman numerals and letter designations. Diatom assemblages that are most similar from clusters at lower values on the dissimilarity scale shown on the y-axis.

Development cluster are increases in *Fragilaria crotonensis* and decreases in *S. minutulus* and *S. niagarae*. Differences between the Mid-Century cluster and the Recent cluster are attributed largely to recent decreases in *Fragilaria crotonensis*, and increases in *Asterionella formosa, Fragilaria construens*, and *S. niagarae*.

The Recent cluster (I) was divided into two principal groups, A(i) comprised of the 0 to 20 cm samples (excluding sample 18 which grouped into Cluster III) and A(ii) plus B which consisted of the four samples (M1, M2, M3, and M4) collected by Meyerhoff (1977). These four samples represented surface sediment samples (0.5, 1.0. 1.5, and 2.0 cm depths) collected in 1974 or 1975 and were recounted by P.R. Sweets. Meyerhoff's surface samples show the greatest agreement with the current core depths of 12.5 cm and 18.5 cm (Eilers et al. 1997). These correspond with ^{210}Pb dates on the current core of 1970 and 1957, respectively.

The diatoms can be classified into four groups on the basis of their habitat types (Fig. 8). The three principal groups (attached, tychoplankton, plankton) had similar abundances at the base of the core (40 cm). However, by 32 cm (circa 1905), the planktonic diatoms (esp. *Fragilaria crotonensis*) became abundant with a corresponding decrease in attached taxa such as *Navicula spp.* and *Nitzschia spp.* Planktonic taxa peaked in the period 1929-1943, declined abruptly from 1943-1953 and increased to about 50% of the individuals in subsequent years. The tychoplankton (e.g., *Fragilaria construens, Fragilaria pinnata*) exhibited trends that were generally opposite those of the euplanktonic species. The tychoplankton currently

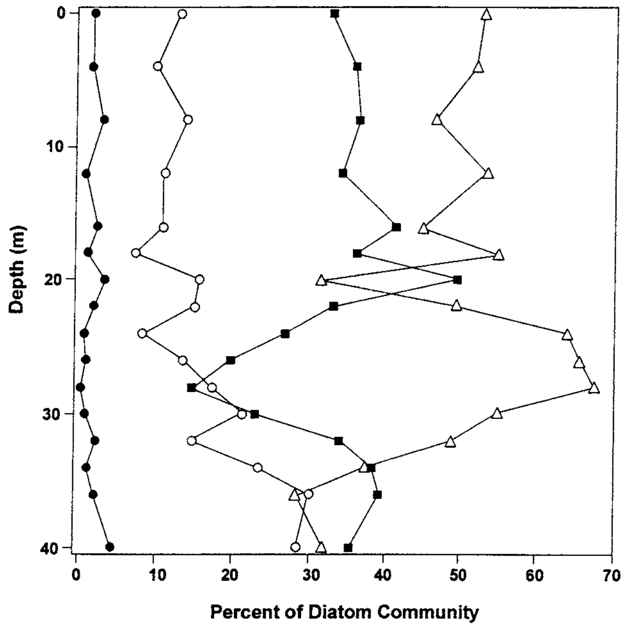

Figure 8.–The proportion of diatom community classified in Diamond Lake plotted against depth in sediment (cm). The groups of diatoms are epiphytes (•), attached (O), planktonic (Δ), and tychoplanktonic (•).

represent about 35% of the diatom taxa, similar to their proportion of the community at the base of the core (40 cm). In summary, the diatom community showed a substantial change in the early to mid 20th century as planktonic species became dominant. Planktonic species remain the most important group of diatoms in the upper sediments and the attached taxa represent about 10% of the population.

Diatom-inferred (DI) changes in lake pH were generated for Diamond Lake using the calibration equations described in Eilers et al. (1998). The DI changes in pH indicate that although the historical DI-pH was high, Diamond Lake showed an increase in pH in the early 20th century (Fig. 9). DI-pH decreased to a minima circa 1953 which is consistent with the rotenone treatment in 1954. DI-pH has since increased and then decreased to the current value of 7.9. The variations in lake pH most likely reflect changes in primary productivity where pH would show a positive relationship with productivity. Although the DI-pH values are consistent with some of the other measured changes in the sediments, the standard error of the regression is high (0.31) relative to the inferred changes in DI-pH.

Zooplankton

The zooplankton results illustrate dramatic shifts in the abundance of zooplankton remains present in the sediment (Fig. 10). Prior to the 20th century, zooplankton abundance appeared to be low. Only *Daphnia* and *Eubosmina* were generally present. However, at interval 24-25 cm, the zooplankton abundance increased by three to four orders of magnitude. Ninety-five percent of the individuals were *Eubosmina* and *Bosmina*. The remaining taxa, *Daphnia, Ilyocryptus, Alona,* and *Eurycercus,* also showed major increases but still represented only one to two percent of the individuals. In the upper sediments, 0 to 10 cm, the organisms experienced a major decline, but remained far more abundant than during pre-development conditions. *Eubosmina* and *Bosmina* continued to be the dominant taxa preserved in the sediments. The only other taxa found in the upper sediments was *Daphnia* (2-3 cm).

Discussion

LOI, Percent Water, Carbon

The sediment appeared nearly uniform in color and the consistency of the sediment increased only slightly downcore. However, there appears to be three relatively distinct regions of the sediment based on the relationship between water content and the loss-on-ignition (Fig. 11). The upper sediments (<20 cm) exhibit a steep drop in LOI relative to the loss in water content, whereas the intermediate sediments (20 to 60 cm) exhibit a decrease in LOI only one-half as great as the upper sediments over the same percentage loss in water content. The bottom sediments (>60 cm) show no pattern which may indicate that diagenetic reactions are relatively stable.

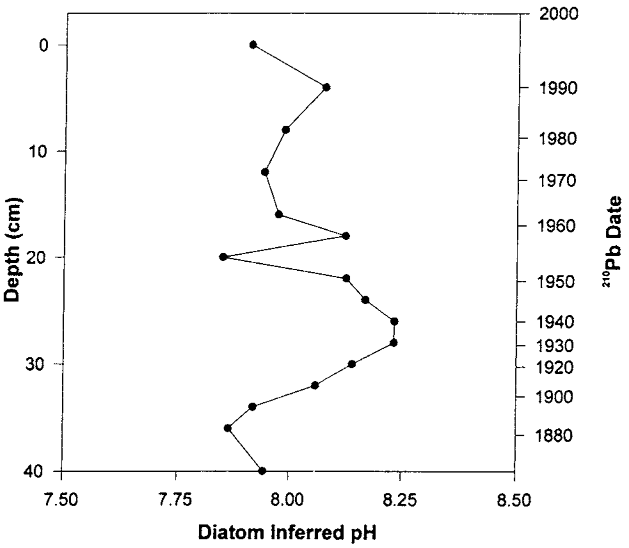

Figure 9.–Diatom-inferred changes in pH for Diamond Lake. The regression statistics for the equation used to generate the DI-pH are: r^2=0.804; se=0.402.

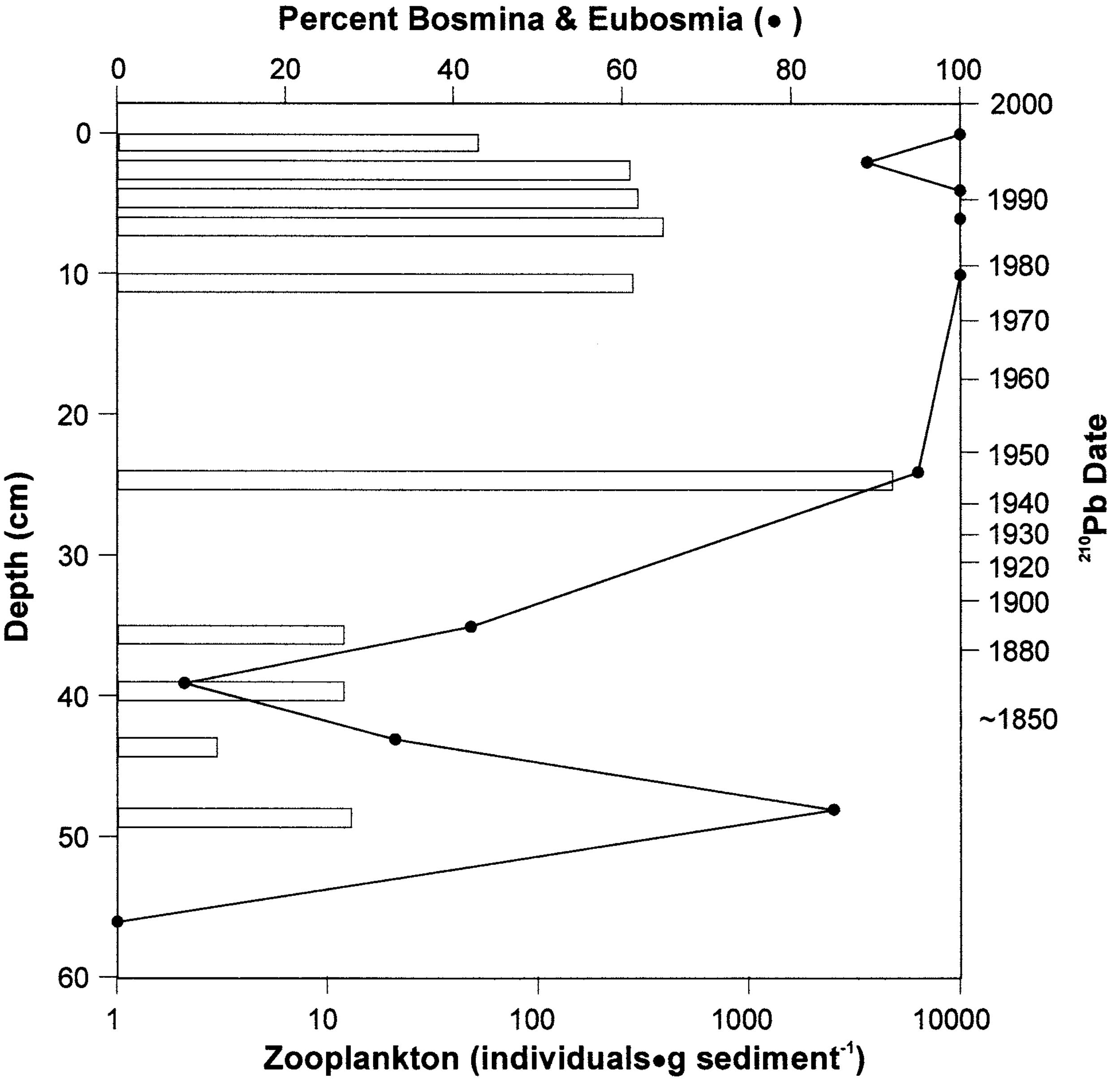

Figure 10.–Abundance of zooplankton remains and the ratio of dominant taxa in selected sediment intervals of Diamond Lake.

Loss-on-ignition is operationally defined as the reduction in mass of dried sediment by ignition at 550 °C. Although most of the loss of mass is often assumed to relate to organic matter, other compounds (e.g. carbonates) can be lost that potentially complicate its interpretation. However in Diamond Lake sediments, LOI is highly correlated with carbon content (Fig. 12a).

Age of Sediments and SAR

The sediment dating results are relatively consistent among the three methods used to compute the age of the sediments. The ^{210}Pb CRS dates show that the upper 40 cm contain all the measurable unsupported ^{210}Pb with an estimated age of 124 yrs at 38.5 cm (interval center). The ^{210}Pb date at 19 cm is 1956 compared to an inferred ^{137}Cs date of 1963. Binford (1990) estimated the uncertainty in ^{210}Pb dates for sediments of this age to be approximately 2 to 3 yrs. Because Cs can exhibit considerable post-depositional mobility (Sholkovitz 1985), we believe that it is more likely that the ^{137}Cs peak could have been displaced relative to the ^{210}Pb profile. Post-depositional mobility in Diamond Lake sediments could be particularly great given the high water content of the sediments. The SAR values computed using ^{210}Pb for the sediments from 30 to 40 cm range from 0.009 to

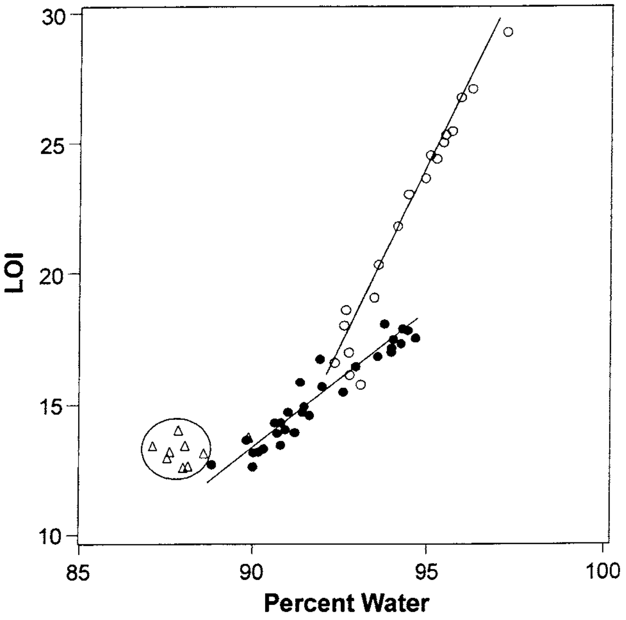

Figure 11.–Loss-on-ignition (LOI, %) versus water content (%) for Diamond Lake sediments coded by sediment depth: (O) <20 cm; (•) 20-60 cm; Δ >60 cm.

0.016 g·cm^{-2}·yr^{-1}. Using the ^{14}C date for the base of the core and the cumulative mass of sediment, the SAR for the period ~1250 to ~1870 yields values from 0.0075 to 0.0081 g·cm^{-2}·yr^{-1}. These values are similar to the SAR value of 0.009 computed for circa 1905. We conclude from these results that the sediment dates derived from the ^{210}Pb are reasonably constrained for both recent and older dates and thus provide a realistic assessment of the age of the sediments. The age of the sediments presented in the remainder of the manuscript is based on the ^{210}Pb dates. For ease of presentation, the dates are presented for the sediment interval without any qualification of the uncertainty associated with those dates. The uncertainty in the ^{210}Pb dates according to Binford (1990) typically ranges from about 1 to 2 years at 10 years of age and 10 to 20 years at 100 years (expressed as 95% confidence intervals using Monte Carlo simulations). Error analysis for sediment ^{210}Pb dates older than 130 years was considered unreliable.

The SAR results for Diamond Lake show that the current SAR values are elevated approximately four-fold over long term baseline SAR values and at least two-fold over values measured in the early part of the century. The ^{210}Pb SAR values show an increase from 1905, first peaking in 1953. SAR values remained high through 1966, declined to a minimum in 1975, and reached a new maximum in the top sediments. The pattern in SAR values corresponds with some lake and watershed activities that suggest a possible causal relationship. The increase in SAR during the first half of the century (esp. 1930 to 1950) corresponds to some degree with the history of the development of the lake during this period. SAR values were maintained at a high rate during the 1950s and 1960s when development and disturbance activities were high. In the 1970s and early 1980s, development activity decreased and the sewage treatment plant became operational, presumably reducing nutrient input to the lake. However, in the 1990s the SAR increased despite a cessation of development. The only major disturbance activity occurring in the watershed during this period is believed to be associated with pavement of campground roads which was implemented to reduce erosion.

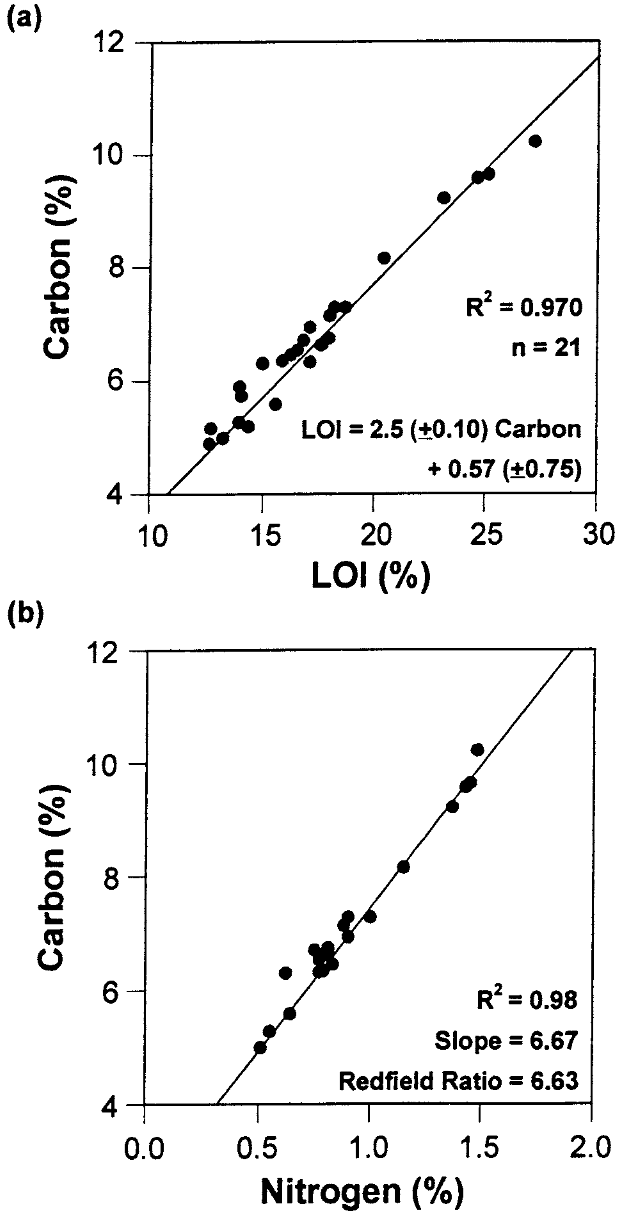

Figure 12.–Carbon versus (a) loss-on-ignition (LOI) and (b) nitrogen (N) for Diamond Lake sediments.

The disproportionately smaller increase in Ti from 1942 to 1953 compared to SAR also suggests that the autochthonous sources were largely responsible for the major increase in SAR at that time. A substantial increase in SAR did not begin until 1930 or possibly as late as 1945, depending on which SAR value is judged to be significantly different from the preceding datum. The greatest increase in Ti occurred from circa 1942 to 1953 when the Ti content of the sediments increased 33% and SAR increased 68%. However, since circa 1957, Ti concentrations have decreased 38%, whereas SAR has both decreased (by 29% from 1965 to 1975) and increased (by 59% from 1975 to 1995). This decoupling of the Ti and SAR in the upper 20 cm of sediments indicates that autochthonous sources of sediment are largely responsible for much of the current sediment accumulation.

Sediment Stoichiometry

The patterns of carbon, nitrogen, and phosphorus in the sediments lend insight into the nature of productivity in Diamond Lake. As indicated earlier, LOI and C are highly correlated in these sediments. Similarly, C is also highly correlated with N concentrations (Fig. 12b). However, a closer examination of the C:N atomic ratio (Fig. 13) indicates that the surface sediments have a C:N ratio near 8, considerably greater than the Redfield ratio for C:N of 6.6 (Redfield et al. 1963). The C:N ratio increases steadily downcore reaching a stable ratio of about 11 in the sediments deeper than 37 cm.

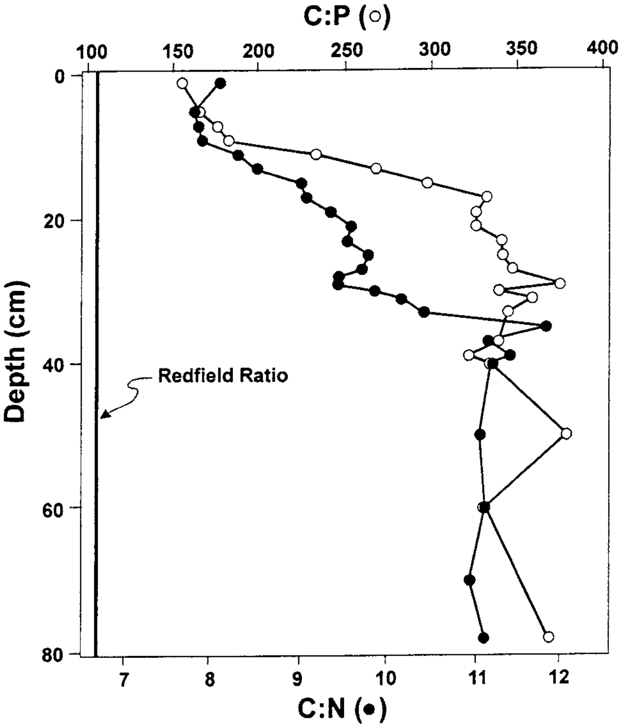

Figure 13.–Molar ratios of carbon:nitrogen (•) and carbon:phosphorus (O) for Diamond Lake sediments. The values are compared to the Redfield ratio for the respective elements.

The pattern for C:P is somewhat similar to C:N in that both ratios are greater than the Redfield ratio, exhibit the lowest values at the sediment surface, decrease downcore, show an anomaly at 35 cm, and then stabilize in the deeper sediments at high ratios. However, the rate of increase in the C:P ratio downcore is much greater than observed for C:N. If the C:N:P ratio of the algae forming much of the mass of the accumulated sediments has remained constant, then the nutrient ratios suggest that both N and P are being recycled from the sediments into the water column. The more rapid loss of P from the sediments to the lake water relative to N suggests that P may be more limiting to primary production than N. Although the differences in N and P ratios in the sediments can be attributed to a variety of diagenetic and redox reactions, the disparity in average concentrations of dissolved P in tributary inputs of 50 ug·L^{-1} to only 1 ug·L^{-1} in the lake measured in 1998 (Salinas 1999) demonstrates the high demand for P in Diamond Lake that appears to be satisfied, in part, by recycling from the sediments.

Diatoms

The taxonomic shifts in diatom species indicate that substantial changes in water quality have occurred in Diamond Lake. The rapid increase in *Fragilaria crotonensis* circa 1920 and high abundance through the 1950s is evidence of a considerable enrichment of the lake. *Fragilaria crotonensis* is a superior competitor for available P and thrives in waters with high N:P ratio (Thompson and Rhee 1994). *Asterionella formosa*, which like *Fragilaria crotonensis* was virtually absent at the base of the core, showed only minor increases in abundance prior to 1981 when its relative abundance approached 10%. *Asterionella formosa* also competes well in high N:P environments, except that P enrichment alone can be inhibitory for this species (Hough and Thompson 1996). *Asterionella formosa* competes well in waters with high Si:P ratios (Thompson and Rhee 1994). This is in contrast with *Stephanodiscus minutulus* which competes most effectively in low Si:P environments (Thompson and Rhee 1994). *Stephanodiscus minutulus* was generally most abundant in Diamond Lake prior to development. However, given the modest changes in *Asterionella formosa and Stephanodiscus minutulus*, it is difficult to assess the significance of their changes in relative abundance in this study.

The shifts in individual taxa towards diatoms more indicative of eutrophic waters is mirrored by shifts in diatom taxa grouped by their habitat types. The attached, planktonic, and tychoplanktonic taxa were nearly equal prior to the 20th century. By the 1930s, attached taxa were declining whereas the proportion of planktonic taxa increased dramatically. Such a shift would be consistent with a decrease in transparency causing attached forms to be outcompeted by planktonic diatoms.

The diatom-inferred (DI) changes in pH illustrate that the lake had been productive prior to development with a pre-development DI-pH averaging 7.9 (±0.31). Because of the relatively large standard error of prediction, most of the inferred changes in pH were statistically insignificant ($P \leq 0.05$). Nevertheless, the results suggest that pH has increased during the 20th century which is consistent with the measured increase in SAR and the taxonomic shifts in diatom taxa.

An analysis of sediment intervals for akinete remains provides additional support for the eutrophication of Diamond Lake. Akinetes are spore-like vegetative cells found in some algae and cyanobacteria that can germinate after periods of years. The results for sediment intervals from pre-development levels (38 to 39 cm, circa 1860) and recent levels (3 to 4 cm, 1990) show that the relative abundance of cyanobacterial akinetes increased 1.7-fold on an absolute basis and 7- fold relative to pollen counts or when adjusted for the change in SAR (Table 3).

Zooplankton

The zooplankton results for sediments, although decidedly incomplete relative to taxa sampled in the water column (cf Vogel 1999), illustrate additional changes in Diamond Lake that appear to be related to fisheries management activities. Prior to the 20th century, the zooplankton populations in Diamond Lake were low (Fig. 10). Sometime immediately before the rotenone treatment, or possibly as a consequence of the rotenone (assuming the uncertainty in the ^{210}Pb dating encompasses this sediment interval), the zooplankton remains increased dramatically. The imperfect preservation of the zooplankton taxa (relative to diatoms) makes the interpretation somewhat more tenuous. However, the magnitude of the changes in overall population abundance illustrates that prior to fish introduction, the zooplankton abundance was much lower than present levels. Presumably, the algal population to support the zooplankton was lower at this time as well.

Table 3.–Cyanobacterial akinetes in pre-development and recent sediments of Diamond Lake expressed as number per gram of dry sediment.

Cyanobacterial Akinetes	Pre-development (38-39 cm)	Recent (3-4 cm)
Measured	30,100	81,500
Adjusted for Pollen	-	248,000
Adjusted for SAR[a]	-	244,000

[a]Assuming 3-fold increase in SAR.

Reconciling Watershed Development, Fisheries Changes, and Sediment History

Watershed development often leads to increased erosion and nutrient export resulting in higher lake productivity. However, when we examine the nature, extent, and timing of the development history of Diamond Lake, there is often poor correspondence between the increases in SAR and watershed development. The two most rapid increases in SAR occurred during the 1930s to 1950s and again from 1985 to 1995. However, the development prior to 1950 was relatively modest, most of it occurring in the 1960s and 1970s when SAR was high but stable or declining. Since 1975 there has probably been a substantial reduction in nutrient loading from the watershed to Diamond Lake as a consequence of installation of a sewage collection/treatment system, rerouting of the highway away from the shoreline, and paving of all Forest Service campground areas. Lauer et al. (1979) estimated that the sewage collection system reduced P loading by 14% and N loading by 18%. Despite these efforts, SAR has shown a marked increase in recent years.

The two periods of accelerated SAR in Diamond Lake also correspond to periods of above-normal annual air temperatures for western Oregon. For the 16 years of complete air temperature data from 1931 to 1951 at Crater Lake, all but two years were above average. Eight of the 11 years from 1986 to 1996 also were above average temperature. Elevated temperatures would certainly contribute to more favorable conditions for phytoplankton growth during these periods, perhaps accounting for some of the observed changes in SAR. However, had the elevated SAR been attributed solely to cyclic temperature variations, we would have expected the SAR values to return to circa background rates during cooler periods. Instead, SAR values have shown a dramatic and, so far, irreversible increase during the 20th century indicating that the changes are not solely attributed to cyclic weather-related phenomena. Other problems with attributing the increase in SAR to climate changes is that increased water temperature would be expected to lead to increased phytoplankton productivity, but not necessarily an increase in production which presumably would still remain nutrient-limited.

Another check on the independence of the changes in Diamond Lake from climatic shifts was derived from an analysis of sediments in a nearby lake. Maidu Lake, located in the Mt. Thielsen Wilderness about 15 km northeast of Diamond Lake, exhibits a relatively stable diatom community composition (Eilers, unpublished data). If Diamond Lake had responded in a major way to climate-related factors, we would have expected to observe a similar change in the neighboring lake.

Another issue that is relevant to the SAR is the sediment composition and what that means with respect to the source of sediment. The titanium concentrations increased only 33% during the 1940s whereas SAR values increased by 68% during the same period. Ti values decreased by 38% after the mid-1950s, whereas SAR decreased by 29% from 1965 to 1975 and increased by 54% from 1975 to 1995. The lack of a strong relationship between SAR and Ti suggests a decoupling between erosional watershed inputs and lake response. The evidence for only modest erosional inputs into Diamond Lake is supported by several physical attributes of the watershed. Despite the mountainous terrain, the stream drainage network for the watershed is low relative to the annual precipitation (~1.5 m), indicating a high rate of groundwater infiltration. Some stream courses disappear prior to reaching the lake and the two principal tributaries have a combined length of only 8.1 km. Short Creek, the second largest tributary to Diamond Lake based on stream discharge, is only 150 m in length. Streambank erosion is not evident and the tributaries are generally clear. Lakeshore erosion appears to be the most likely contributing source of erosion to the lake.

Analysis of the andesite basalt composition in this portion of the Cascades indicates TiO_2 values of 0.7 to 1.3% (0.42 to 0.78% as Ti) by weight (Sherrod 1986). This compares to Ti concentrations of about 0.02% in the lake sediments. Based on the ratio of Ti in the watershed to lake sediments, erosional inputs from the watershed account for only about 3% to 5% of the accumulated sediments. The vast majority of the sediments are derived from autochthonous sources. Although erosional sources as indicated by Ti in the sediments don't explain the increases in SAR, we cannot exclude the possibility that dissolved contributions of N and P from the watershed could stimulate primary production independent of particulate forms of N and P from surface inputs.

The lack of substantial erosional inputs to Diamond Lake does not preclude an influx of groundwater as an important watershed source of nutrients (cf. Lauer et al. 1979). However, if watershed inputs of nutrients from groundwater were the primary source for the increased lake productivity, the minimal watershed development prior to 1930 appears inadequate to account for the precipitous rise in SAR from 1930 to 1950.

An alternate hypothesis for the pattern in SAR in Diamond Lake is that most of the nutrients are derived from autochthonous sources and that internal cycling of nutrients has been altered by fish management activities. The "biomanipulation" concept as first proffered by Shapiro et al. (1975) continues to be advanced and better understood as an important mechanism to explain changes in trophic status (Sanni and Waervågen 1990; Sarnelle 1992, 1993; Nicholls et al. 1996; Drenner et al. 1996; Proulx et al. 1996). Under the biomanipulation concept, multiple aspects of lake productivity can be altered by changes in the predator/prey relationships at the top trophic levels. These changes typically involve the introduction of planktivorous fish. The cropping of the large zooplankton species results in increased algal biomass through a reduction in phytoplankton grazing. However, some investigators report the reduction in algal biomass can occur independent of changes in zooplankton as a result of a decrease in fish-mediated internal loading (Horppila et al. 1998). In addition, the benthic community can be greatly affected by the presence of benthivorous fish (Wong et al. 1998). In the case of Diamond Lake, the formerly fishless lake was first stocked with rainbow trout in 1910 or 1913 (Bauer 1976), and trout fingerlings were subsequently stocked annually. The trout fishery collapsed in the 1940s when an unintentional introduction of tui chub outcompeted both fingerlings and adult trout for zooplankton and benthic resources. The lake was treated with rotenone in 1954 to kill the chub population and was restocked in 1955 with rainbow trout. The trout population returned to a high level of productivity in 1963 with the introduction of another strain of rainbow trout and remained high until the late 1980s. Tui chub were documented in the lake again in 1992 and trout production continues to decline (ODFW 1996).

Of particular interest is the strong correlation of the tui chub population with the SAR values in the 1940s to 1950s and 1980s to 1990s. Tui chub population increased to a level of 120 $kg \cdot ha^{-1}$ in 1954 at the time of the rotenone application (Bauer 1976) and judging from the increasing chub:trout ratio of 25:1 in

1996 and ~2000:1 by 1999 (David Loomis, Oregon Dept. Fish. Wildlife, pers. comm. 2000), the chub are once again dominant. In contrast, the annual trout harvest was 125 $kg \cdot ha^{-1}$ in 1978, yet the SAR was near its post-1950s minimum of 0.023 $g \cdot cm^{-2} \cdot yr^{-1}$. The specific role of the tui chub in affecting Diamond Lake zooplankton and its subsequent effect on the phytoplankton populations appears to be evident in changes in the zooplankton community. Recent monitoring of Diamond Lake has shown that the formerly common large daphnids have greatly declined in the last several years with corresponding increases in the rotifers, *Keratella* spp., *Kellicottia longispina*, and *Polyarthra doliochoptera* (Vogel 1999). Vogel attributes these changes to cropping of the larger zooplankton taxa by the increasing chub population.

Previous studies present a variety of interpretations regarding the current conditions and relative importance of various processes in Diamond Lake. Based on an undated sediment core, Meyerhoff (1977) concluded that Diamond Lake had responded to increased watershed loading of nutrients by becoming eutrophic. This conclusion was supported by changes in the diatom community composition and sediment chemistry. The nutrient monitoring by Lauer et al. (1979) led the authors to conclude that the lake was historically eutrophic and that natural watershed loading of nutrients was sufficient to maintain the present lake status. In a more recent monitoring program and data review effort, Salinas and Larson (1995) concluded that Diamond Lake had become enriched by watershed sources of nutrients to such a degree that the present trophic status could never be reversed. The divergence of opinions among these investigators regarding the evaluation of current status and projected future trends makes it difficult for management agencies to effectively respond to lake problems or determine whether a problem even exists.

In our view, the value of a paleolimnological approach such as this study is that it documents historical conditions, identifies inconsistencies in watershed/lake interactions, and provides information on future trajectories either independently or in conjunction with watershed modeling approaches. Our paleolimnological analysis confirmed that the lake prior to development was less productive based on changes in the diatom composition, that the SAR increased greatly in the 20th century, and that most of this increase was not associated with erosional inputs from the watershed. The timing of the increases in SAR was most consistent with increases in the tui chub, not the trout, leading us to conclude that the tui chub were more effective than trout in altering the zooplankton and subsequently the phytoplankton community. The lowered SAR in the 1970s and early 1980s provides support for continued efforts to reduce watershed sources of nutrients, but important controls on algal biomass in Diamond Lake appear to be associated with internal mechanisms, especially the tui chub population.

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