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Evidence for nutrient enrichment of high-elevation lakes in the Sierra Nevada, California

James O. Sickman[1]
Institute for Computational Earth System Science, University of California, Santa Barbara, California

John M. Melack
Institute for Computational Earth System Science and Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, California

David W. Clow
United States Geological Survey, Denver, Colorado

Abstract

Long-term measurements (1983–2001) of nutrients and seston in Emerald Lake (Sierra Nevada, California) have revealed ecologically significant patterns. Nitrate, both during spring runoff and during growing seasons, declined from 1983 through 1995. Declining snowmelt nitrate was caused primarily by changes in snow regime induced by the 1987–1992 drought: years with shallow, early melting snowpacks had lower snowmelt nitrate concentrations owing to less labile N production in catchment soils and longer plant growing seasons. However, nitrate declines during growing seasons carried through the wetter years of 1993–2000 and are likely the result of increased P loading to the lake and the release of phytoplankton from P limitation. Contemporaneous with these changes was an increase in algal biomass and a shift from P limitation toward more frequent N limitation of phytoplankton abundance. Particulate carbon concentrations in the late 1990s were two- to threefold greater than in the early 1980s. These trends were reflected in a larger set of Sierra Nevada lakes sampled as part of synoptic surveys ($n = 28$). Between 1985 and 1999, nitrate decreased and total P increased in >70% of the lakes sampled. Our data suggest that lakes throughout the Sierra Nevada are experiencing measurable eutrophication in response to the atmospheric deposition of nutrients.

The atmospheric deposition of nitrogen (N) and phosphorus (P) represents a large fraction of the nutrient inputs to high-elevation, Sierra Nevada lakes (Sickman 2001). Recent increases in nitrate concentrations in some Sierra Nevada and Rocky Mountain lakes suggest that N loading to aquatic ecosystems is intensifying (Jassby et al. 1994; Williams and Tonnessen 2000). In Lake Tahoe, the shift from colimitation of phytoplankton by N and P to persistent P limitation and the continuing decline in water clarity are due, in part, to increased loading of N from atmospheric deposition and urban sources (Goldman et al. 1993; Jassby et al. 1999). More recent data also have suggested that atmospheric P inputs are contributing to ongoing eutrophication of the lake (Liu et al. 2001). Nutrient and seston conditions in most high-elevation lakes in the Sierra Nevada indicate they are oligotrophic; thus, even small changes in the nutrient supply may impact algal productivity.

To evaluate changes within the past two decades in trophic conditions in high-elevation lakes of the Sierra Nevada, we examined nutrient and seston data from Emerald Lake, California (1983–2001) and compared synoptic surveys of wilderness lakes in national parks of California conducted during 1985 (Western Lake Survey [WLS]; Landers et al. 1987) and 1999 (Clow et al. 2002). By monitoring changes at an intensively sampled site—Emerald Lake—we were able to assess whether changes that occurred between the synoptic surveys are an indication of long-term trends or the result of natural interannual variability. Using these data, we evaluated the long-term variation in the frequency of N and P limitation of phytoplankton in Sierran lakes and explored possible causes for observed trends in lake conditions.

Methods

Site description—Emerald Lake is a small (2.7 ha), shallow (mean depth 6 m, maximum depth 10 m) cirque lake located at 2,800 m in the central Sierra Nevada (36°35′49″N, 118°40′29″W) within Sequoia National Park (Tulare County). Between 1983 and 1999, the annual hydraulic residence time of the lake varied 18–139 d, with a mean residence time of 55 d. The lake is dilute (electrical conductivity, <6 μS cm^{-1}) and poorly buffered (acid neutralizing capacity [ANC] ranges 10–50 μEq L^{-1}), and pH ranges 5.5–6.5. Em-

[1] To whom correspondence should be addressed. Present address: California Department of Water Resources, Division of Environmental Services, P.O. Box 942836 Sacramento, CA 94236-0001 (sickman@water.ca.gov).

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Table 1. Lakes sampled as part of both the 1985 and 1999 synoptic surveys. Unnamed lakes are identified with their EPA Western Lake Survey code number.

Lake Name/ EPA Western Lakes Survey Code	National Park	Latitude (dd mm ss)	Longitude (ddd mm ss)	Elevation (m)
4A1-016	Sequoia	37 42 15	119 17 15	2,908
4A1-029	Sequoia	37 10 20	118 44 40	3,091
4A1-033	Sequoia	37 01 45	118 41 45	3,109
4A1-034	Sequoia	37 04 00	118 38 20	3,542
4A1-035	Sequoia	37 01 37	118 29 30	3,383
4A1-038	Sequoia	36 54 10	118 33 30	3,121
4A1-040	Sequoia	36 48 15	118 25 10	3,213
4A1-041	Sequoia	36 43 05	118 31 50	3,072
4A1-042	Sequoia	36 40 55	118 24 25	3435
4A1-043	Sequoia	36 36 25	118 38 45	3139
4A1-044	Sequoia	36 39 40	118 26 00	3206
4A1-045	Sequoia	36 37 20	118 20 45	3405
4A1-046	Sequoia	36 34 37	118 32 04	3127
4A1-047	Sequoia	36 31 37	118 18 20	3414
4A1-053	Sequoia	36 48 40	118 25 49	3171
4A1-056	Sequoia	37 08 40	118 39 50	3481
Big Five Lakes (small)	Sequoia	36 29 04	118 31 10	2975
Hockett Lakes (center)	Sequoia	36 21 29	118 39 58	2493
Horseshoe Lakes (middle)	Sequoia	36 56 37	118 34 15	3060
Swamp Lakes (western)	Sequoia	36 53 20	118 43 25	2816
Wright Lake	Sequoia	36 38 11	118 22 00	3395
4A1-006	Yosemite	38 05 12	119 42 19	2527
4A1-055	Yosemite	38 05 10	119 40 24	2563
Bingaman Lake	Yosemite	37 50 45	119 14 45	3185
Lake Vernon	Yosemite	38 00 50	119 43 22	2018
Mary Lake	Yosemite	38 08 39	119 33 40	2719
Roosevelt Lake	Yosemite	37 58 15	119 20 00	2902
Vogelsang Lake	Yosemite	37 47 12	119 20 35	2938

erald Lake is oligotrophic, with total P concentrations of <0.4 μmol L^{-1} and chlorophyll levels typically <1 μg L^{-1}. The chemical composition and trophic character of Emerald Lake are representative of small, high-elevation lakes throughout the Sierra Nevada.

Sampling of Emerald Lake—From 1983 through 1987, Emerald Lake samples were collected biweekly during the summer and autumn and monthly during the remainder of the year. From 1988 through 1999, samples were collected monthly to bimonthly (seston sampling for this study ended in 1999). Dissolved nutrient and seston samples were collected at four depths at a single station overlying the deepest part of the lake. From 500 to 1,000 ml of water were passed through an ashed Gelman A/E filter (in duplicate), stored in a petri dish, and kept frozen at -20°C until analyzed for particulate C, N, and P. Water samples for dissolved nutrient analyses (nitrate, total dissolved nitrogen [TDN], and total dissolved phosphorus [TDP]) were filtered with a 1.0-μm polycarbonate filter and stored in 125-ml polyethylene bottles.

Higher frequency nitrate samples were collected at the outflow of Emerald Lake (1983–2001), by hand and with automated samplers. Prior to 1992, samples were collected at a biweekly interval during snowmelt and monthly during other months. Beginning in the spring of 1992, outflow samples were collected every 1–2 d with an ISCO sampler during snowmelt and monthly during other months. These samples were filtered and analyzed in the same manner as the lake samples.

Synoptic lake surveys—Of the 38 Sierran lakes sampled during the 1999 lake survey, 28 were included in the original 1985 WLS (Table 1). Sample collection, timing, processing, and analytical methods used in the 1999 lake survey were similar to those used in the 1985 WLS (Kerfoot and Faber 1987; Wilde et al. 1998). In the 1999 lake survey, lakes were accessed by foot and sampled at the outlets or along the shore if the outlet was dry. Outflow chemistry (both dissolved and particulate) was not significantly different from epilimnion chemistry in 11 lakes where both types of samples were collected (Clow et al. 2002).

Filtered aliquots for nitrate, TDN, and TDP were obtained by passing water through 0.45-μm-pore size polysulfonate membrane filters. Particulate C, N, and P were obtained, in duplicate, by passing 500 ml of water through an ashed glass fiber filter (Gelman A/E). All samples were kept cool and in the dark during transport from the field and shipment to the analytical laboratory. Samples for dissolved constituents were stored at 5°C, and particulate samples were stored frozen at -20°C.

Nitrate was determined in all samples by ion chromatog-

raphy, with the exception of samples collected during 1983 and 1984, for which nitrate was determined by cadmium reduction (Strickland and Parsons 1972). TDN, TDP, and particulate P (PP) were determined by the Valderrama (1981) digestion method. Nitrate and phosphate in the digests were measured on a Latchet autoanalyzer or manually using the cadmium reduction and phosphomolybdate methods, respectively (Strickland and Parsons 1972). Particulate carbon (PC) and nitrogen (PN) were determined by combustion in an elemental analyzer. Total P (TP) and total N (TN) were computed as the sum of TDP + PP and TDN + PN, respectively.

Nutrient limitation in Emerald and the survey lakes was assessed using the Redfield ratio (Redfield 1958) and the ratio of dissolved inorganic nitrogen (DIN) : TP (Morris and Lewis 1988). The DIN : TP ratio is a measure of nutrient supply to phytoplankton and has been demonstrated to be accurate in predicting limiting nutrients compared with results from bioassay experiments in high-elevation lakes (Morris and Lewis 1988; Sickman 2001). In the case of N, the largest bioavailable pool is typically DIN. Recent studies have shown that some portion of dissolved organic nitrogen (DON) may ultimately supply phytoplankton growth via microbial transformation to ammonium or urea (Berman et al. 1999; Stepanauskas et al. 2000). However, in snowmelt-dominated systems, the potential DON bioavailability is typically <30% during the summer and autumn growing periods (Stepanauskas et al. 2000). The most physiologically appropriate index of P availability is TP, because this fraction incorporates both externally available TDP (dissolved inorganic phosphorus [DIP] + dissolved organic phosphorus [DOP]) and internal reserves represented by PP. DOP is bioavailable to phytoplankton because of the excretion of alkaline and acid phosphatases that enzymatically cleave phosphate groups off organic molecules (Paerl 1982). The luxury uptake of P by phytoplankton suggests that PP represents both P available for future growth and P used in active metabolism.

A trend analysis of Emerald Lake nutrient and seston conditions was done on volume-weighted mean lake concentrations computed from chemical profiles and hypsographic information. Data were binned into ice-free periods (~June–November), and median values were computed for each year of the time series. Binning was necessary because (1) sampling intensity was lower during the 1990s than the 1980s and (2) serial correlation was evident in some cases in the regression and correlation residuals using unbinned data. Long-term changes were evaluated using time-series plots of the raw data, and the Kendall τ and t-statistic tests computed for the ice-free median values. Differences in chemistry between the 1985 and 1999 lake surveys were evaluated using the Wilcoxon signed-rank test.

Results

Nutrient and seston trends in Emerald Lake—Nitrate concentrations in Emerald Lake and outflow had an annual pattern of peak concentrations during spring snowmelt and minimum concentrations during the late summer and early autumn (Fig. 1A). In general, volume-weighted mean concentrations of nitrate in the lake closely approximated outflow chemistry; thus, the outflow data can be used to infer the hydrochemical condition in the lake at a higher frequency.

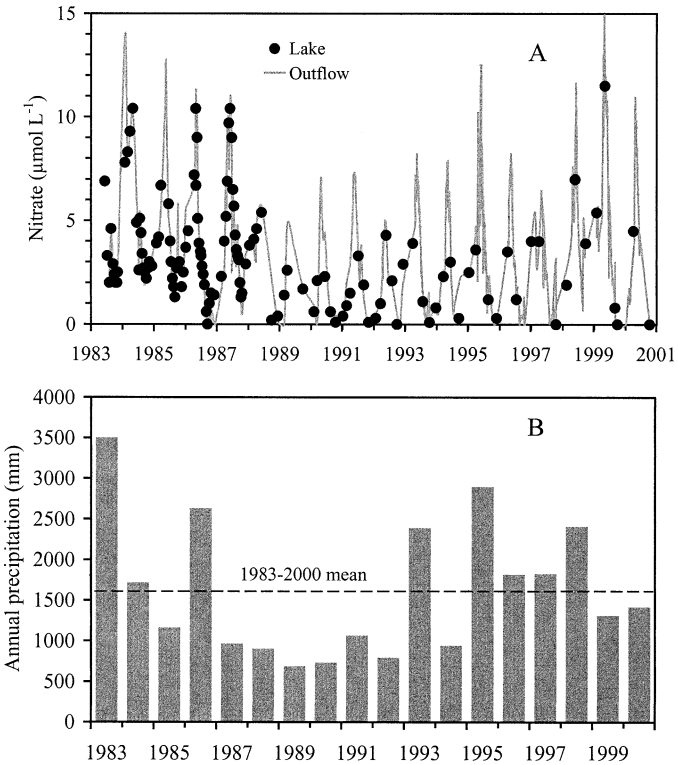

Fig. 1. Time series of (A) nitrate and (B) water-year precipitation for Emerald Lake. In panel B, the dashed line denotes the average annual precipitation at Emerald Lake during water years 1983–2000.

Intradecadal patterns in nitrate concentration were observed at Emerald Lake and its outflow. Between 1983 and 1995, nitrate concentrations decreased during both spring snowmelt (April–July) and the growing season (August–October) (Fig. 1A). Prior to 1988, nitrate concentrations in early spring were >10 μmol L^{-1} and nearly always remained above the detection limit (0.05 μmol L^{-1}) throughout the summer and autumn. Beginning in 1988, spring nitrate concentrations decreased by ~50%, and levels fell to below the detection limit during late summer and autumn in both the lake and outflow. During 1987–1992, California experienced a severe drought and precipitation at Emerald Lake was only 40%–70% of the average from 1983–2000 (Fig. 1B). Peak nitrate concentrations in the spring were generally higher during 1995–2001 than during the 1988–1992 drought. In all but one of these years, 1999, Emerald Lake experienced near- or above-average precipitation, and growing season nitrate concentrations nearly always declined to near the detection limit. The one exception was 1998; the nitrate concentration fell to 0.8 μmol L^{-1} by early September, but unusually large and N rich rains during September caused nitrate levels in the lake to increase.

Concomitant with these patterns in nitrate concentrations was an increase in PC in Emerald Lake; the trend is evident

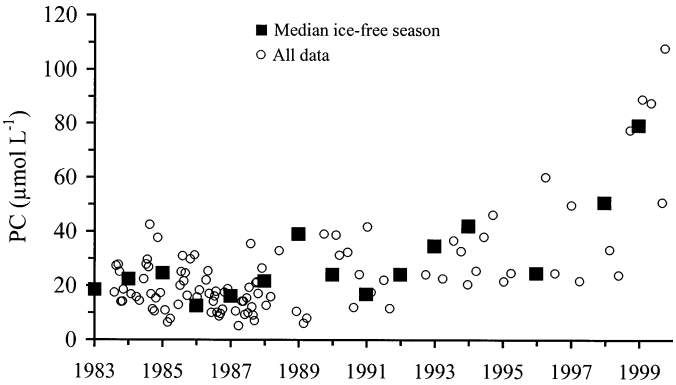

Fig. 2. Time series of PC in Emerald Lake.

in both the raw data and in the ice-free median values (Fig. 2). The trend was statistically significant (Kendall τ: $r = 0.56$, $p = 0.003$; Table 2), and the slope of the equation was significantly different from 0 as based on the t-statistic (3.9, $p = 0.002$). Bioassay experiments (Sickman 2001) and nutrient limitation indices based on dissolved and particulate constituents suggested that phytoplankton growth during the early 1980s was limited by P supply and that, as time progressed, there was a trend toward more frequent reciprocal or colimitation by N+P and N limitation (Fig. 3). The trend in the nutrient supply index (Fig. 3A) suggests more frequent N limitation during the late 1990s, but neither the Kendall τ or linear regression tests were significant at the 0.05 level. The trend in the N : P ratio of seston was stronger (Fig. 3B) and statistically significant (Kendall τ: $r = -0.57$, $p = 0.002$; t-statistic: -3.9, $p = 0.002$) (Table 2).

Regional changes—Nitrate, TP, and DIN : TP ratios in Sierra Nevada lakes sampled during the 1985 and 1999 synoptic surveys were compared (Fig. 4). From 1985 to 1999, nitrate concentrations decreased in 71% of the survey lakes (Wilcoxon signed-rank test: $p = 0.017$), paralleling the nitrate decline observed at Emerald Lake (Fig. 4A). All but six lakes had an increase in TP from 1985 to 1999 (Fig. 4B), and TP concentrations in 1999 were significantly greater than those in 1985 ($p = 0.001$). Changes in nitrate and TP resulted in an overall decrease in the DIN : TP ratio ($p = 0.036$, Fig. 4C), indicating that there were more N-limited lakes in the autumn of 1999 than in 1985, which is consistent with the shifts observed at Emerald Lake during the same period.

Discussion

Long-term variations in N and P supply to Emerald Lake—Sickman et al. (2001) found that interannual variations in spring nitrate concentrations are controlled partially by the timing of runoff. In years with shallow snowpacks and earlier snowmelt, nitrate pulses are smaller and catchment retention of N is higher than in years with normal to above-normal precipitation. In dry years, there may be less microbial mineralization of N in catchment soils, and, when combined with a longer plant growing season, nitrate pulses are muted. Thus, lower spring nitrate peaks observed in Em-

Table 2. Results from statistical trend analysis on the long-term data set from Emerald Lake (1983–1999). Data used in the analyses are the median values from ice-free seasons (~June–November).

Parameter	Kendall Tau	p	t-statistic	p
DIN : TP	−0.28	0.15	−1.4	0.19
PN : PP	−0.57	0.002	−3.9	0.002
PC	0.56	0.003	3.9	0.002
TN	0.03	0.88	0.9	0.37
TDN	0.07	0.72	0.8	0.44
PN	0.10	0.62	1.8	0.10
TP	0.35	0.067	1.9	0.09
TDP	−0.31	0.10	−1.7	0.10
PP	0.67	0.001	4.7	<0.001

DIN: dissolved inorganic nitrogen, PC: particulate carbon, PN: particulate nitrogen, PP, particulate phosphorus, TDN: total dissolved nitrogen, TDP: total dissolved phosphorus, TN: total nitrogen, TP: total phosphorus.

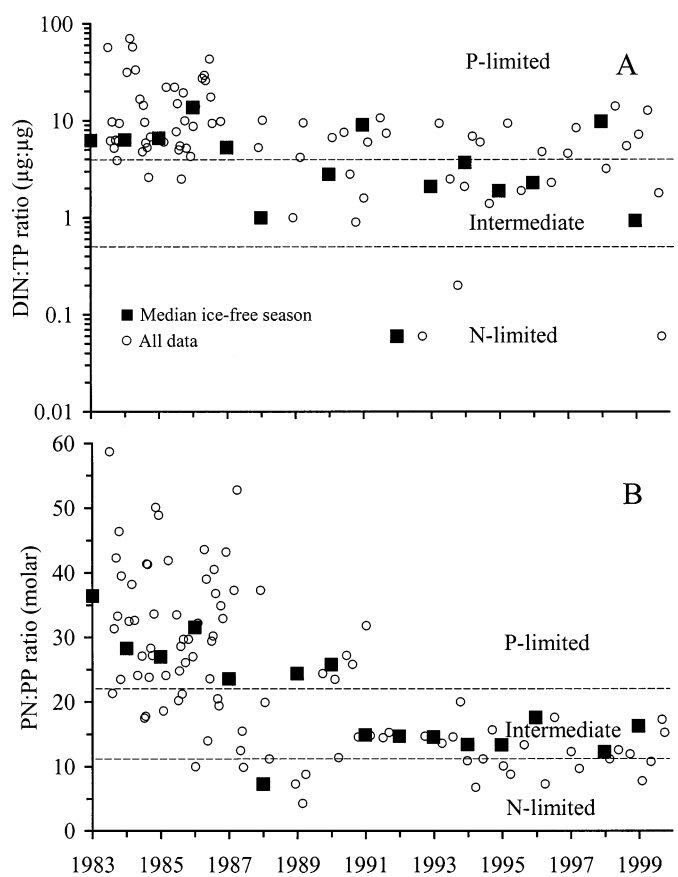

Fig. 3. Time series of (A) DIN : TP and (B) PN : PP ratios in Emerald Lake. Zones of nutrient limitation for the DIN : TP and PN : PP ratios are from Redfield (1958) and Morris and Lewis (1988), respectively.

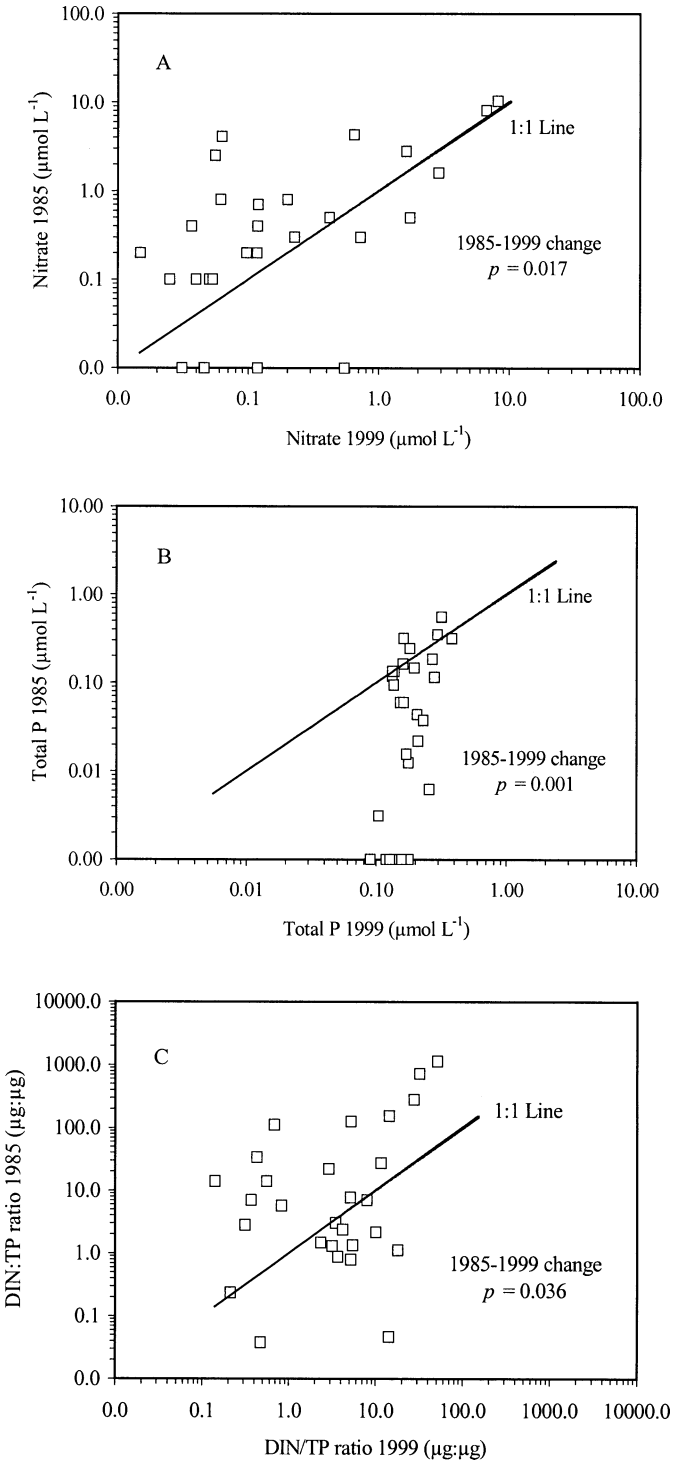

Fig. 4. Comparison of (A) nitrate, (B) TP, and (C) the DIN : TP ratio in lakes sampled during the 1985 and 1999 synoptic surveys. Significance values are from Wilcoxon signed-rank tests and are used to evaluate whether constituent values changed between 1985 and 1999.

erald Lake after 1987 are likely the result of interactions among climate, soil microbial populations, and plants. Growing-season nitrate concentrations also declined during 1988–1992, and they remained low even after precipitation and spring nitrate peaks increased in the mid- to late 1990s. We hypothesize that growing-season nitrate levels are more likely to be controlled by phytoplankton dynamics and atmospheric deposition (e.g., N-rich rainstorms during September 1998).

Decreased loading of N and increased loading of P were investigated as possible explanations for the long-term changes in seston and growing-season nitrate conditions detected in Emerald Lake. We observed no long-term changes in N deposition to the watershed and, in fact, N deposition during both the winter and nonwinter periods of 1995–2000 was greater than average owing to above-normal precipitation and higher snowpack DIN concentrations (i.e., 1999 and 2000; Sickman et al. 2001). In Emerald Lake, no monotonic trend was evident in any N fraction (PN, TDN, and TN); levels of these constituents tended to be lower during the drought than during the preceding and following wet periods (Table 2 and Fig. 5A–C). Thus, increased P loading is the most likely explanation for the trophic changes observed at Emerald Lake.

There was a weak downward trend in TDP in Emerald Lake, but PP levels increased more than threefold (Table 2; Fig. 5D,E). The PP increase was not simply a net transfer from dissolved to particulate P fractions, because TP concentrations doubled from 1983 to 1999 (Table 2; Fig. 5F). The lack of P accumulation in dissolved fractions is not surprising, given the extent of P limitation observed during the 1980s (Fig. 3) and the oligotrophic nature of the lake; additional P inputs would likely be taken up by phytoplankton and held in the seston. Stratigraphic analysis of organic P in recent lake sediments shows that organic P values increased by threefold between ~1980 and 1999 (Sickman and Melack, unpub. data).

We suggest that increased P loading to Emerald Lake reduced the incidence of P limitation, allowing phytoplankton to utilize excess N supply to the lake, hence the near-zero summer and autumn nitrate levels observed from 1988–2000. PC levels measured in Emerald Lake in the autumn of 1999 were fourfold greater than the average concentration from 1983–1998 and, coupled with the increasing trend in TP, demonstrate that measurable eutrophication has occurred in the lake.

The long-term data record at Emerald Lake and the synoptic surveys indicate that nutrient and seston changes at Emerald Lake may be part of a regional trend. We propose that P loading has increased to most Sierra Nevada lakes, resulting in decreased nitrate levels, higher TP concentrations, and a greater incidence of N limitation. The close correspondence between site-specific and regional trends suggests that large numbers of Sierra Nevada lakes may be experiencing mild eutrophication, although we lack the necessary phytoplankton biomass data to fully test this inference.

Causes of increased P loading to Sierra Nevada lakes—Because increased P concentrations were detected through-

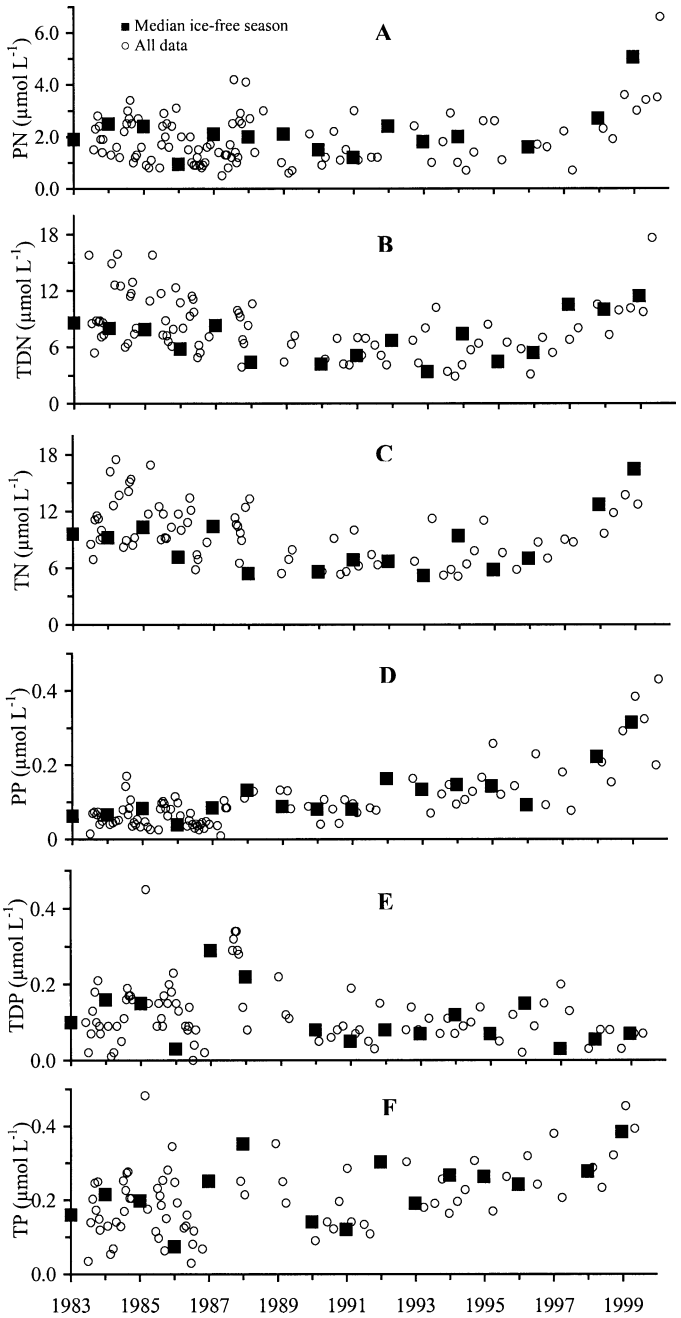

Fig. 5. Time series of (A) PN, (B) TDN, (C) TN, (D) PP, (E) TDP, and (F) TP in Emerald Lake, 1983–1999.

out the Sierra Nevada, site-specific P sources (i.e., urban or agricultural runoff) are unlikely causes of the observed trends. To assess potential P sources to Emerald Lake, we made a first approximation of the major P fluxes to and P pools within the watershed (Table 3). Atmospheric deposition (7.9 kg as P) and catchment export (8.8 kg) are in approximate balance and are about an order of magnitude greater than the amount of P held within the lake water column (0.97 kg). The lake sediments (3,000 kg) and catchment soils (2,100 kg) are the largest reservoirs of P in the Emerald Lake basin. Atmospheric deposition and accelerated internal

Table 3. Comparison of yearly P fluxes and pools in the Emerald Lake watershed (area = 120 ha).

Component	Catchment flux (kg P)	Catchment pool (kg P)
Atmospheric Deposition	7.9*	
Catchment Export	8.8†	
Lake Water		0.97‡
Lake Sediments		3,000§
Catchment Soil		2,000‖
Organo-P Pesticide Deposition	0.011¶	

* Sum of TDP in rain and snow plus additional 50% from estimated dry deposition. Data are the average from 1985–1999.
† Includes TDP and PP. Data are the average from 1985–1999.
‡ Includes TDP and PP. Data are the average from 1983–1999.
§ Includes both organic and inorganic P forms. Assumes sediment area of 27,000 m^2, mean sediment depth of 1 m, mean bulk density of 0.085 g cc^{-1}, and sediment P-content of 1.3 mg g^{-1} (J.O. Sickman and J.M. Melack, unpubl. data).
‖ Assumes soil N : P ratio of 8.75 : 1 by weight and catchment N-storage in soil of 150 kg ha^{-1} (Williams et al. 1995).
¶ Based on chlorpyrifos deposition estimate of 0.0002 kg ha^{-1} yr^{-1} in Sequoia National Park from McConnell et al. (1998) plus the following assumptions: Chlorpyrifos (formula weight = 350 g $mole^{-1}$) is 9% P by weight, and chlorpyrifos deposition composes 19% of all organophosphate deposition (this estimate is based on the ratio of chlorpyrifos : total organo-P chemical application in the San Joaquin Valley; Kegley et al. 2000; Sickman 2001).

cycling of P caused by climate change (either in the watershed or lake) are processes that could act over large areas of the Sierra Nevada and may be the most likely sources of increased P loading to Sierra Nevada lakes.

It is difficult to assess whether internal P cycling rates have changed in the Sierra Nevada over the past few decades. Recent climate change has altered the timing of snowmelt (Johnson 1998) and river runoff patterns (Dettinger and Cayan 1995), but further process-level investigations are needed to understand the linkages between snow regimes and P cycling in high-elevation watersheds. We would note, however, that our long-term monitoring program has detected no increasing trend in base cations or silica, which would be indicative of increased weathering of P-bearing minerals such as apatite. The lack of change in inorganic P in lake sediments suggests that mineral weathering rates have been relatively stable over the past 150 yr (Sickman and Melack unpubl. data). In addition, bimonthly chemical profiles in Emerald Lake do not show an increasing incidence of hypolimnetic hypoxia or higher sulfate concentrations, both of which might lead to a greater flux of P from sediments (Caraco et al. 1989).

Although P is not commonly measured in atmospheric deposition, data exist with which to assess trends in atmospheric transport of P in California. The deposition of organophosphate (OP) pesticides has been measured in Sequoia National Park (Zabik and Seiber 1993; Datta et al. 1998) and has been implicated in amphibian declines in aquatic ecosystems throughout the Sierra Nevada (LeNoir et al. 1999). OP use in the San Joaquin Valley and Tulare County increased markedly during the 1990s until a peak in 1995 (Kegley et al. 2000; Fig. 6). There is no comprehensive

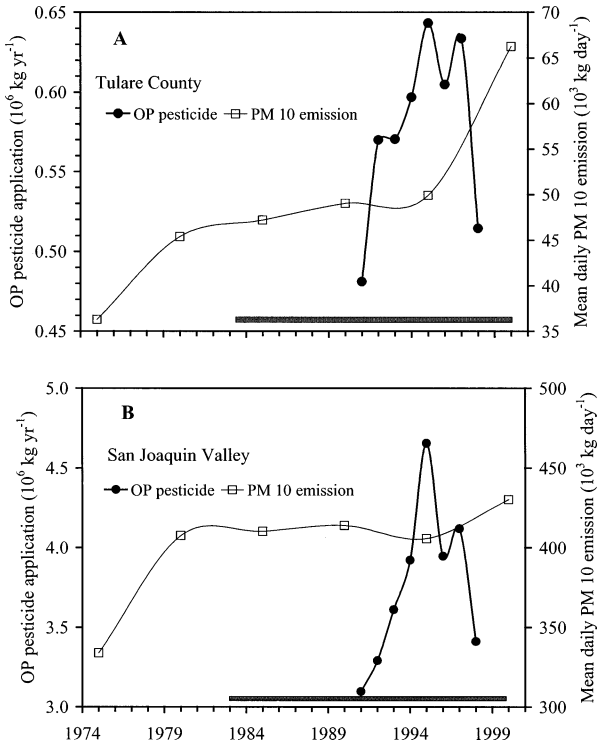

Fig. 6. Time series of OP pesticide applications and PM 10 emissions in (A) Tulare County and (B) the San Joaquin Valley of California. Pesticide application rates are kg of active ingredient and are from Kegley et al. (2000). PM 10 data are from Alexis et al. (2001). The shaded horizontal bar denotes the time period of the Emerald Lake dataset.

database for pesticide applications prior to 1991, but the use of these compounds accelerated after their introduction in the 1960s (Kegley pers. comm.). Using published data on OP deposition in Sequoia National Park (McConnell et al. 1998) and current-use pesticide data for the San Joaquin Valley (i.e., 1991–1998), we estimate that total OP P deposition to the Emerald Lake watershed is 0.011 kg, or 0.13% of total atmospheric deposition of P (Table 3).

Aeolian transport of soils and dust from the San Joaquin Valley to the high Sierra Nevada may be a significant source of atmospheric P, as based on studies from a variety of ecosystems (Bergametti et al. 1992; Lesack and Melack 1996; Jickells et al. 1998), including other mountain ranges (Lewis et al. 1985; Schwikowski et al. 1995; Psenner 1999). Preliminary data for the Lake Tahoe basin suggests that 26% of the annual phosphorus external inputs are derived from atmospheric dry deposition. Liu et al. (2001) found that much of this P-bearing dust was 0.5–1 μm in diameter, suggesting that it could be transported from sources outside of the Tahoe Basin. Potential surrogates for dust transport include PM 10 emissions in upwind regions of the Central Valley of California. PM 10 particles have a mean aerodynamic diameter of $\leq$10 μ and can be transported over large distances in the air. The particles originate from widespread sources in the San Joaquin Valley such as fugitive dust (e.g., plowing and unpaved roads), biomass burning (agricultural and forest fires), and diesel engines (Alexis et al. 2001). On the basis of published records, particulate emissions increased by 82% in Tulare County and 29% in the San Joaquin Valley over the past quarter century, suggesting that deposition of particulate-borne P could be increasing in the Sierra Nevada (Fig. 6A,B; Alexis et al. 2001).

Our analyses of high-elevation Sierra Nevada lakes support findings from long-term studies of Lake Tahoe. The nutrient enrichment of lakes has likely occurred throughout the Sierra Nevada, possibly because of increasing levels of atmospheric N and P from regional and perhaps global sources (Wilkening et al. 2000). These findings illustrate the sensitivity of high-elevation lakes to global change and suggest that a regional alteration of aquatic ecosystems is taking place. The continued long-term study of Lake Tahoe and other wilderness lakes such as Emerald Lake will be required to fully understand and monitor the impact of changes in climate and nutrient inputs on aquatic ecosystems in the Sierra Nevada.

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