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The Effects of Glacial Silt
On Primary Production, Through
Altered Light Regimes and
Phosphorus Levels, In Alaska Lakes[1]

by
Jim A. Edmundson and
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Don W. Collinsworth
Commissioner

Stanley A. Moberly
Director

P. O. Box 3-2000
Juneau, Alaska 99802

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ABSTRACT

Suspended silt derived from glacier meltwater has been found to dominate the phosphorus cycle and determine light regimes in glacially influenced lakes. Both parameters are important determinants of autochthonous primary production.

An immediate result of glacier meltwater intrusion is an increase in turbidity, a function of varying particle concentrations as well as size distributions. Turbidity levels were found to be inversely related to the light-compensation depth, thereby defining the extent of the euphotic zone. Accordingly, the euphotic volume (as a percent of the total lake volume) is significantly less in glacial systems, compared to the nonturbid systems we examined. Of equal significance to the productivity of glacial lakes is the composition of the silt particles. Fractionation studies have shown that the phosphorus (and iron) contained within the particulate inorganic fraction dominates the cycling of these elements in glacial lakes.

The effects of glacial silt were evident both on primary productivity (carbon uptake rates) and on primary production (chlorophyll *a*). That is, volumetric measurements of carbon uptake decreased with an increase in glacier-melt influence. Moreover, when productivity rates were integrated over the euphotic zone, areal productivity was considerably reduced, especially at the height of glacial meltwater influence. We also observed that summer chlorophyll *a* levels were significantly less than those predicted using phosphorus-chlorophyll response (P-C) models derived from clear-water lakes. The discrepancies in P-C models were found to be partially explained by the dominance of inorganic particulate phosphorus (IPP) on the total phosphorus (TP) cycle. When only biologically available phosphorus was used as the criterion in P-C models, much of the variation was reduced. Finally, a consideration of the ratio of euphotic volume to total volume also proved to be an important factor in P-C expressions

and in providing a more meaningful P-C model for use in glacial systems. Thus the magnitude of glacier meltwater intrusion through its effects on nutrient cycles and light regimes results in decreased autochthonous production and the increased oligotrophy of glacial lakes.

KEY WORDS: glacial silt, nephelometric turbidity, euphotic zone depth, primary productivity, phosphorus, iron, chlorophyll a.

INTRODUCTION

Autochthonous primary production has been linked to solar radiation (Brylinsky and Mann 1973) and an adequate nutrient supply (Shindler 1978). Brylinsky and Mann (1973) associate productivity more closely with energy-related parameters, including latitude, temperature, and light penetration. That is, energy variables are correlated more strongly with productivity than with nutrient concentrations. However, phosphorus has also been shown to be an important factor in controlling productivity (Smith 1979) and, as evidenced by the various phosphorus-chlorophyll relationships proposed by Sakamoto (1966), Dillon and Rigler (1974), Jones and Bachman (1976), Vollenweider (1976), and others. These factors considered, we observed an increased oligotrophy of glacial systems, compared to the clear-water lakes with similar morphometric features, climatic conditions, and nutrient ratios. That is, increases in total phosphorus levels were not accompanied by increased chlorophyll concentrations. Thus we hypothesized that the presence of suspended glacial particles could account for this discrepancy through its effects on both light regimes (energy) and phosphorus (nutrient) supply.

Previous studies have suggested that nonalgal particles affect aquatic production by alteration of light regimes or nutrient concentrations (Hoyer and Jones 1983). Further, Goldman (1960,

1961) indicates that productivity occurring on bright days in near-surface layers decreases because of the effects of light inhibition; in turn, he indicates that the presence of turbidity lessens this effect and also tends to decrease areal production because of a decreased euphotic zone. Tizler et al. (1976) also found that turbidity, in association with suspended sediments, lessens the effect of light inhibition near the surface. More importantly, he found that, although sediment loading into Lake Tahoe causes turbidity plumes, productivity within these plumes may increase as a result of sediment-induced nutrients. Similarly, Verduin (1954) observed increased production within turbid plumes in western Lake Erie, but Rawson (1953) and Oglesby (1977) found decreased production within turbid lakes, compared to clear-water systems, as a consequence of climatic features or light limitation.

In order to account for chlorophyll levels at given phosphorus concentrations that are an order of magnitude less than those found for less turbid systems, we have considered herein the effects of glacial particles (turbidity) on both the phosphorus economy and light regimes of glacial lakes. Our approach centers on comparing turbidity-determining particles (size and concentration) in clear-water and glacial lakes and determining the phosphorus levels associated with inorganic particles that may not be readily metabolized by phytoplankton.

METHODS AND MATERIALS

Turbidity, euphotic-zone depth (EZD), phosphorus, iron, chlorophyll <u>a</u> (chl <u>a</u>), and mean lake depth were compiled from limnological data collected through the efforts of the Alaska Department of Fish and Game (limnology program). The field and laboratory methods and techniques are described in detail in Koenings et al. (1985); therefore, the materials and methods are discussed here in only general terms.

Turbidity levels, given in nephelometric turbidity units (NTU), were measured using a model-DRT-100 (H.F. Instruments) turbidimeter. Representative samples were analyzed for particle-size distribution by Marco-Scientific, Ltd., Sunnyvale, California, using a model-715 granulometer. Particle numbers were determined visually at X1000 magnification using a Zeiss model-14 compound microscope. Using a Levy-Hausser counting chamber, replicate counts of five 2.5- x 10^{-3}-mm^2 grids were made and the particle number calculated per cubic meter. Individual samples were systematically diluted (x1.5, 3, and 6), recounted, and measured for turbidity. Values for euphotic-zone depth were determined from photosynthetically available radiation measurements obtained using a Protomatic submarine photometer.

The composition of suspended glacial-silt particles was determined through fractionation studies. Six lakes representing various lake types (i.e., clear water, organically stained, semiglacial [less turbid], and glacial) were chosen for detailed phosphorus and iron analyses. Using a Van Dorn sampler, water samples were collected every 3 weeks from a depth of 1 meter and the midhypolimnetic zone. Samples were filtered through a Whatman 4.5-cm GF/F filter, and a subsample of the filtrate was passed through (ultrafiltered) a Millipore CX-10 (10000 MWCO) immersible filter having a nominal pore size of .05 μm. The various fractions (i.e., unfiltered, filtered, and ultrafiltered) were stored frozen until analyzed.

In general, filterable and dissolved reactive-phosphorus analyses were determined using the molybdenum-blue method, as modified by Eisenreich et al. (1975); following acid-persulfate digestion, total phosphorus analysis utilized the same method. The inorganic and organic particulate phosphorus (OPP) fractions were analyzed directly on a seston sample obtained by filtering a known volume (0.5-1.0 liter) of lake water through a Whatman 4.5-cm GF/F filter. IPP was extracted using acidified ammonium fluoride and analyzed using the filterable reactive-phosphorus method of

Strickland and Parsons (1972). The remaining OPP fraction was analyzed using the total phosphorus method after Eisenreich et al. (1975). Values for both colloidal (unreactive and reactive) and dissolved unreactive phosphorus were obtained by difference. Finally, each of the sized fractions were also analyzed for total, total filterable, and dissolved iron (DFe) (Koenings et al. 1985).

The effects of glacial silt on autochthonous primary productivity were examined using various algal-transfer and silt-addition experiments with carbon-14 radioisotopes (^{14}C). The method utilized the light-dark bottle technique after Saunders et al. (1962). Replicate clear and lightproof bottles containing 100 ml of lake water were labeled with 5.2 μc of $NaH^{14}CO_3$ and incubated in situ 4-6 hours. Samples were fixed with Lugol's acetate solution and filtered through a Whatman 2.5-cm GF/F filter. Filters were stored frozen in 20-ml polyethylene vials. Prior to analysis, filters were thawed, acidified, and then dissolved in a toluene-based scintillation cocktail. Algal carbon incorporation was quantified using a Packard model-3255 scintillation spectrometer. Volumetric uptake rates (mg C/m^3) were calculated after Saunders et al. (1962), and day-rate estimates (mg C/m^3/day) were determined using the cumulative percent/time productivity curve after Vollenweider (1965).

A total of six separate samples were collected at various depths from Hidden Lake and Bear Lake (two clear-water systems located in the Kenai River drainage basin) and labeled with ^{14}C. The 8-liter bulk samples were then transferred to either Upper Trail Lake or Skilak Lake (glacially influenced systems located in the same area), and subsamples were incubated under reduced light levels that were comparable to the depths from which the samples were collected. As a control, replicate sets of bottles of each sample were also incubated in the clear lakes. Because of the proximity of the lakes to one another, transportation times were minimal, and the actual addition of the isotope occurred only after arrival at the transfer site. Similar algal-uptake (^{14}C) experiments were conducted using glacial lake water from Tustumena Lake, Upper Trail Lake, and Skilak Lake, which had varying turbidity levels; samples were incubated under conditions of increased light levels found at comparable depths in the clear-water systems. As temperature regimes differ at equivalent depths in clear and turbid lakes, all incubations took place during the spring-summer turnover period when the lakes had equal temperatures throughout the euphotic zone.

To examine the effect of turbidity on productivity as a result of altered light conditions, glacial silt was incrementally added to clear-water samples. Glacial silt used in these experiments was extracted by boiling glacial meltwater and then centrifuging it. The supernatant was decanted, the remaining concentrated silt removed by pipet, and then silt added to clear-water lake samples to reproduce the effect of turbidity. Following the treatment, the samples were labeled with ^{14}C and incubated either at near-surface levels in situ or under laboratory conditions. Laboratory incubation conditions consisted of a constant temperature (15°C) water bath illuminated by two Sylvania Gro-Lux lamps that provided a maximal illumination of 30 foot candles.

Chl a values used in our P-C regression models were determined by direct analysis using the fluorometric method by Strickland and Parsons (1972) and the modification of dilute-acid addition after Reimann (1978). P-C regression analysis was facilitated using STATPRO on an IBM PC-XT.

RESULTS

The Nature of Turbidity and Its Effects on Light Regimes

As shown in Figure 1(A), mean particle size (PS) within 38 clear and glacial lakes was found to be inversely related to turbidity

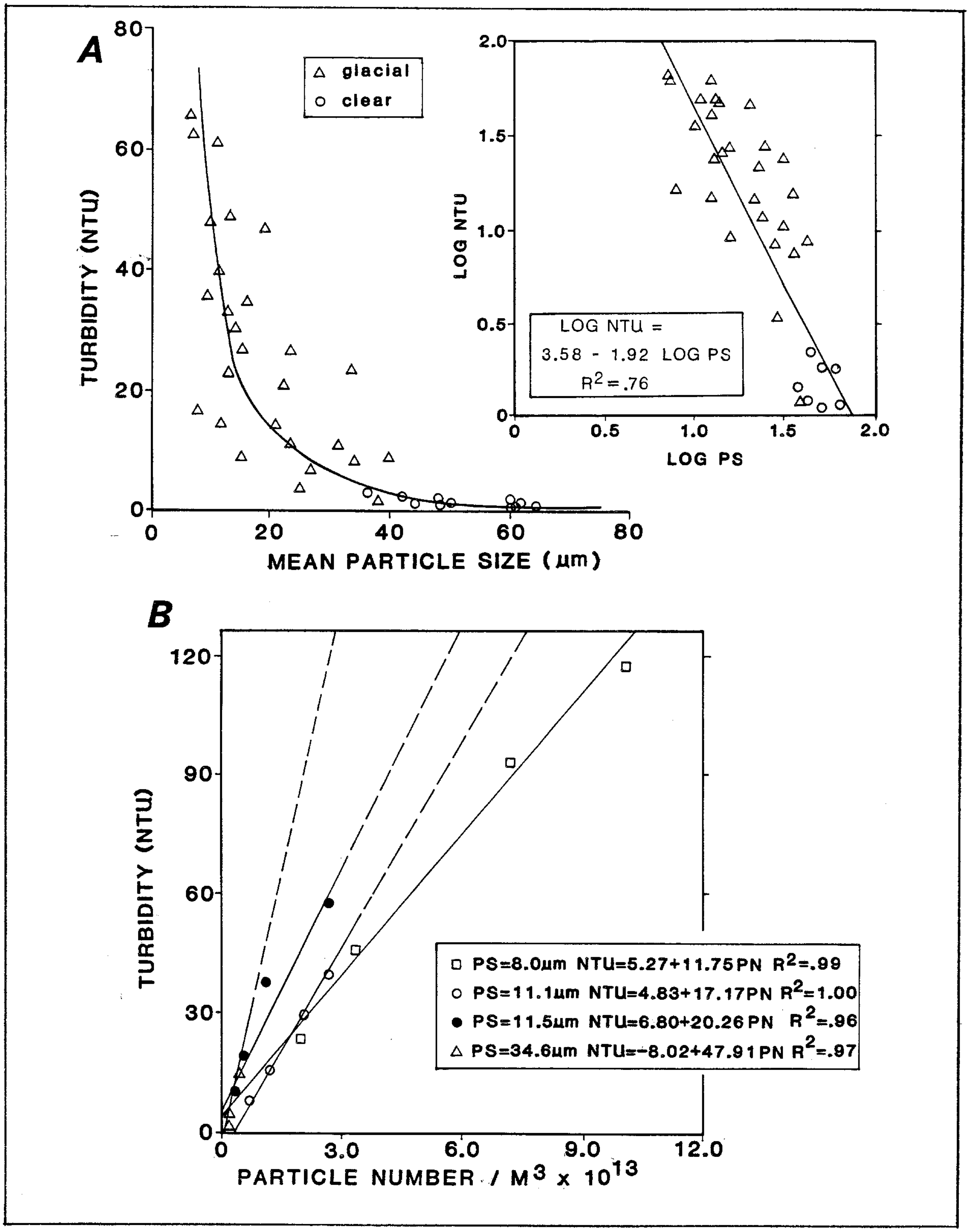

Figure 1. The relationship of (A) turbidity (NTU) to mean particle size (PS) in microns and (B) the relationship of turbidity to particle number per cubic meter (PN) $*10^{13}$ at varying PS.

(NTU). A log-log transformation provided the most linear relationship: defined as LOG NTU = 3.6 - 1.92 LOG PS with a coefficient of determination (r^2) = 0.76. However, there was little overlapping observed in PS between the clear and glacial lakes, as mean particle size ranged from 6.9 to 40.3 μm for the glacial lakes and 36.5 to 64.3 μm for the clear-water systems. Hence, we observed that lakes having less turbidity held larger particles and a gap between 3 NTU and 6 NTU separated clear from glacial waters. Figure 1(B) shows the relationship of particle number (PN) per cubic meter and NTU in four lakes having different mean particle sizes. A decrease in NTU resulted from a decrease in PN by sample dilution. The response remained linear and was significant in each case, although the slope values were found to increase with greater PS. Two lakes that had similar values for mean particle size (PS = 11.1 and 11.5) also had similar slopes. Thus these data suggest that turbidity is a function of both PS and PN.

Increased levels of turbidity were found to be inversely related to euphotic-zone depth (Figure 2). A log-log transformation resulted in a linear relationship; i.e., LOG EZD = 1.23-0.66 LOG NTU : r^2 = 0.94. Although the relationship shows that a small amount of turbidity substantially decreases EZD, this effect was most severely felt at turbidity levels of 5-10 NTU. That is, turbidity levels >10 NTU still resulted in a continued negative response in EZD; however, the rate of decrease was considerably less. Thus the inflection point of the curve occurs at turbidity levels of 5-10 NTU, which corresponds to an EZD range of between 4-6 m.

Composition of Glacial Silt

We observed total phosphorus and iron concentrations to be strongly correlated (r^2 = 0.92 and 0.95, respectively); turbidity is shown in Figures 3(A) and 3(B). This supports the results of our fractionation experiments: in glacial lakes these elements

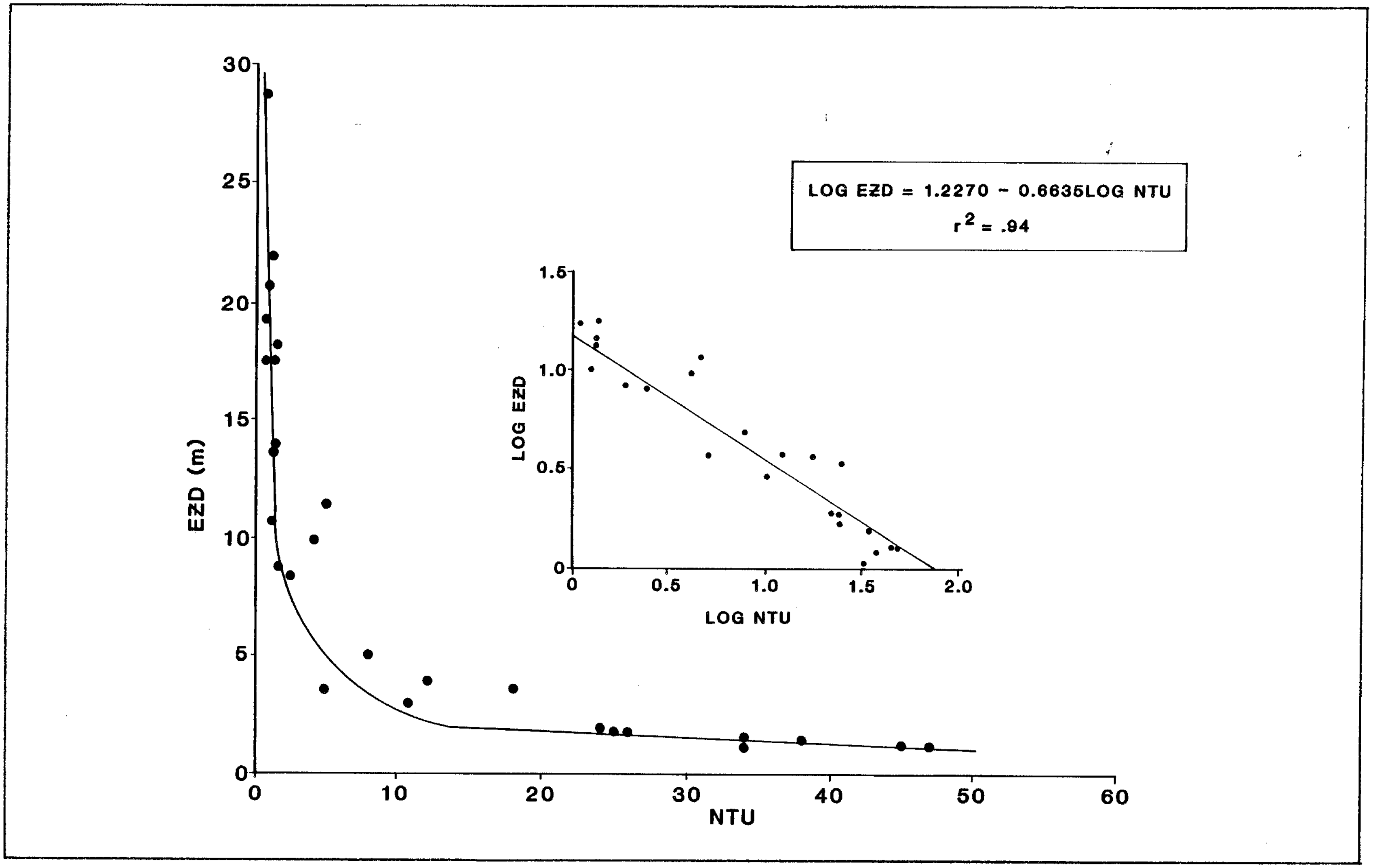

Figure 2. The relationship of euphotic zone depth (EZD) to turbidity (NTU).

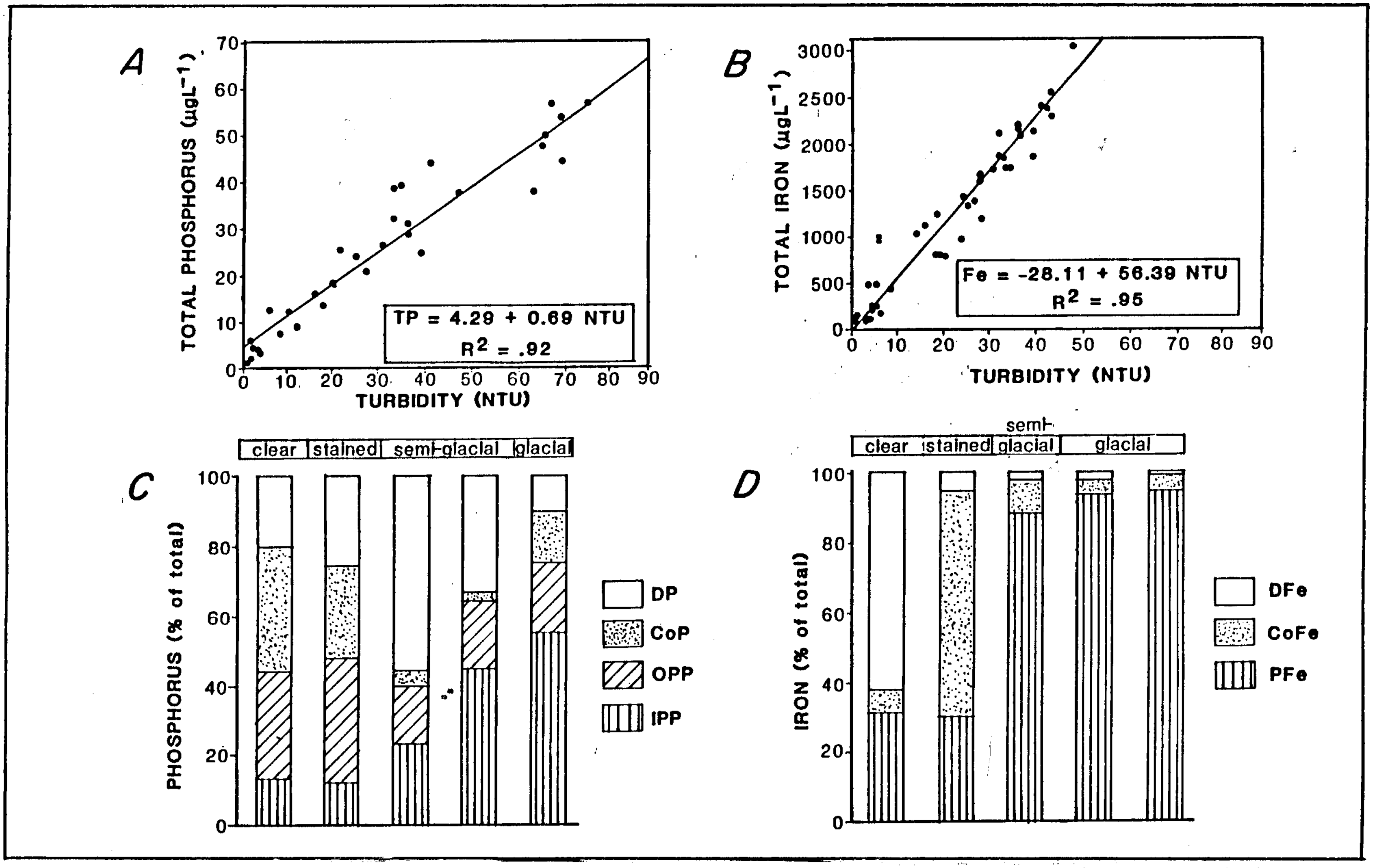

Figure 3. The relationship of total phosphorus (A) and total iron (B) to turbidity and the various fractions used to characterize total phosphorus (C) and total iron (D) in clear, stained, semiglacial, and glacial lakes.

are contained mostly within the particulate fraction (Figures 3[C] and 3[D]). That is, in the glacial lakes, inorganic particulate phosphorus comprised from 24% to 56% of the total phosphorus, compared to only 13%-14% in the clear and stained lakes. Organic particulate phosphorus comprised 17%-20% of the total phosphorus in the glacial lakes examined, compared to 31%-35% found in the clear-water and stained lakes. In addition, phosphorus contained within the colloidal fraction (CoP) ranged from 2% to 15% in the glacial systems, compared to 36%-27% in the clear-water and stained lakes. Finally, dissolved phosphorus (DP) ranged from a low 9% of the total phosphorus in a highly turbid system (40 NTU) to 56% in one of the semiglacial lakes (NTU <10) examined; whereas, DP fractions of up to 22% and 25% were found in the clear and stained lakes.

Particulate iron (PFe) comprised from 88% to 94% of the total iron present in the glacially influenced systems, compared to 31% and 30% found in the clear and stained lakes (Figure 3[D]). In contrast, dissolved iron dominated the iron cycle within the clear-water lake with 63% of the total iron, compared to less than the respective 2% and 5% total iron in the glacial and stained lakes. Colloidal iron (CoFe) comprised 65% of the total iron present in the stained lake, while only 5%-10% comprised the colloidal fraction in the clear and glacial lakes.

The Effect of Altered Light Regimes on Productivity

The results of the carbon-14 transfer experiments (Figure 4) illustrate the effects of altered light levels on carbon uptake by algae. In each clear-to-glacial-lake transfer experiment (clear inc. glacial), a decrease in the amount of light resulted in a 52%-100% decrease in day-rate productivity. In contrast, the effect of increased light caused by the incubation of glacial-lake samples in a clear lake (glacial inc. clear) showed both light stimulation and inhibition on day-rate productivity.

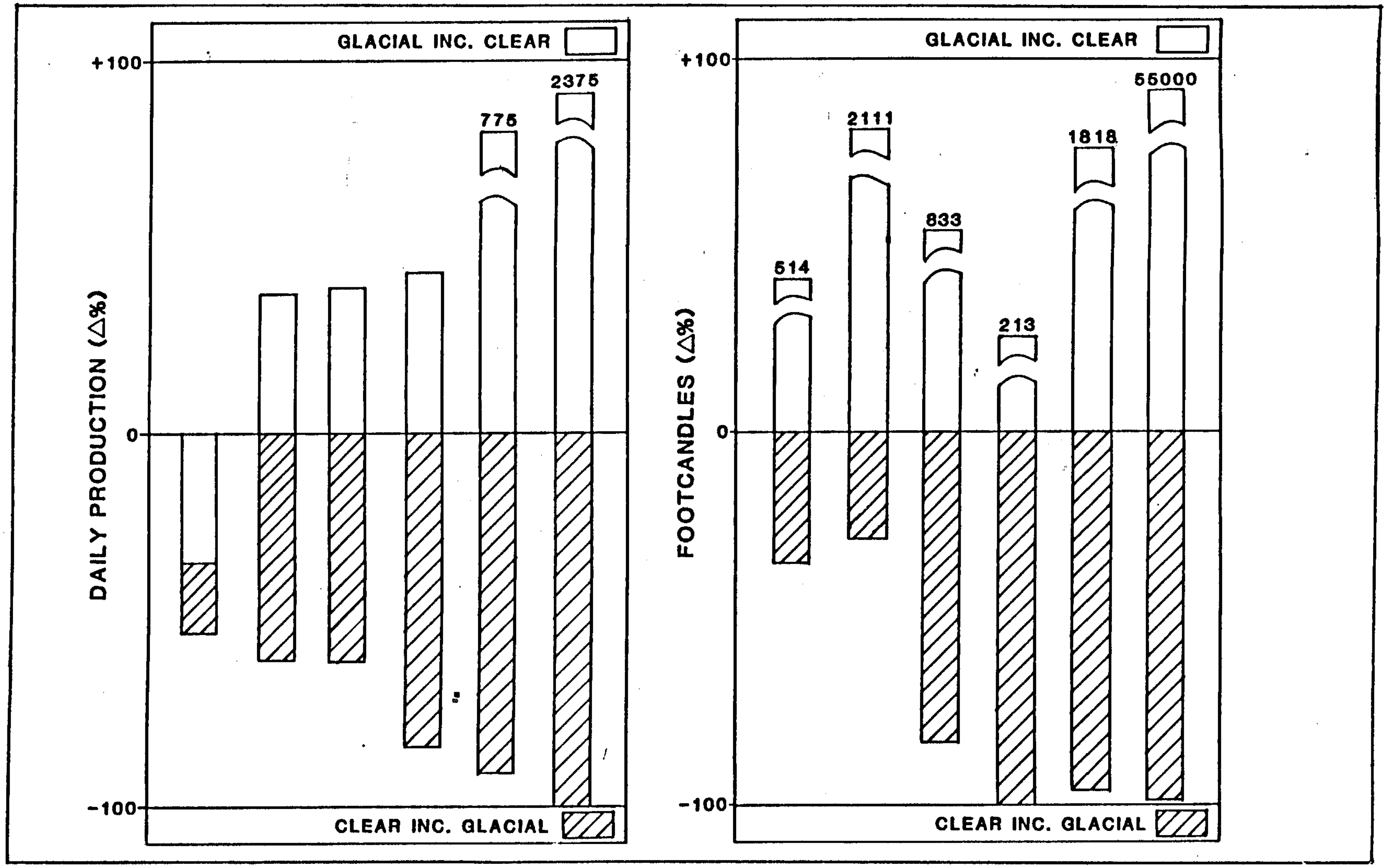

Figure 4. The results of altering light levels on daily production through algal carbon-14 transfer experiments: incubating glacial water in clear lakes (glacial inc. clear) and incubating clear water in glacial lakes (clear inc. glacial).

In five of the six experiments, the daily productivity increased from 37% to 2375%; however, light inhibition was suspected in one instance when a five-fold increase in light intensity resulted in a 44% decrease in productivity.

In both laboratory and in situ experiments involving the addition of glacial silt (final NTU of 40) to clear-lake algal samples prior to incubation, decreases in carbon-uptake rates ranged between 44% and 50% for the turbid samples. However, the addition of silt to equivalent clear-water samples (after photosynthesis had occurred) showed no effect on carbon uptake. We observed a linear response of carbon uptake (CU) over four levels of increased turbidity ($CU[mg\ C/m^3/d] = 23.7 - 0.185\ NTU : r^2 = 0.99$) over the range of turbidity between 0 and 78 NTU. Using the natural-lake samples as a control, the carbon-uptake rate of equivalent water with glacial silt added decreased at 0.8% per increase in NTU unit. Thus the decrease in uptake rates by algae were attributed to light reductions caused solely by turbidity within the incubation bottles.

The Effect of Glacial Silt on Phosphorus-Chlorophyll (P-C) Response Models

We found that the P-C model $LOG\ chl\ \underline{a} = 0.75 + 1.03\ LOG\ TP : r^2 = 0.79$ derived for Alaskan clear-water lakes (Figure 5) compares with those of Dillon and Rigler (1974), Jones and Bachman (1976), Vollenweider (1976), and Prepas and Trew (1983). However, using the clear-water model (Figure 5[A]), observed chl a levels per equivalent TP for glacial lakes were much less than predicted. When chl a levels for all glacial lakes were regressed against total phosphorus, we found no relationship ($LOG\ chl\ \underline{a} = -0.46 + 0.11\ LOG\ TP : r^2 = .02$). We observed, however, that five of the data points, or scatter, from glacial lakes overlapped the range of data points within lakes used for the clear-lake P-C model. These data corresponded to the semiglacial lake systems. When these were omitted from the glacial P-C data set, a linear

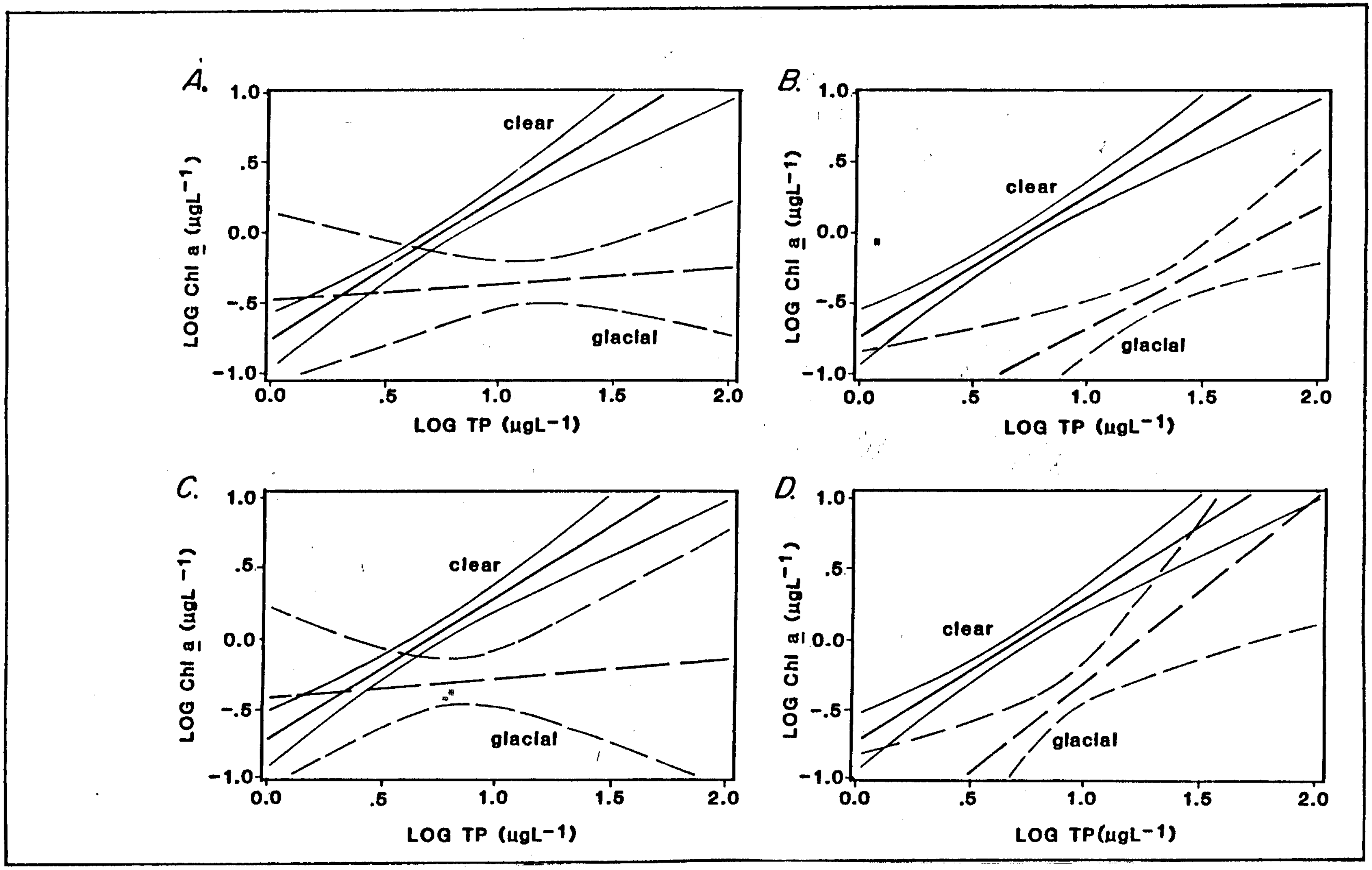

Figure 5. Phosphorus-chlorophyll (P-C) response models derived for our clear (——) and glacial (---) lakes shown with 95% confidence limits (A), glacial lakes excluding semiglacial lakes (B), glacial lakes corrected for IPP (C), corrected for IPP without semiglacial lakes (D).

relationship (LOG chl *a* = -1.55 + 0.88 LOG TP : $r^2 = 0.65$) was derived (Figure 5[B]). The slope was less than that found for the clear-lake P-C model, indicating that phosphorus had a lesser effect on chlorophyll production. In addition, the regression line was shifted downward by a considerable amount (Figure 5[B]). Although the data base is small (n=10), the regression may provide a useful tool in predicting chl *a* levels in highly turbid lakes and justifying the categorizing of glacial systems as a separate lake class.

Total phosphorus measurements were corrected for the presence of IPP by regressing TP against corrected total phosphorus (CTP). The resulting equation (for IPP correction) was CTP = 3.02 + 0.28 TP : $r^2 = 0.73$. The slope (0.28) agreed well with the factor (0.30) that Verduin et al. (1978) empirically derived to essentially correct for nonbiological phosphorus. Our correction for IPP levels resulted in a 47% reduction in predicted chl *a* variation among the semiglacial lakes with turbidity levels <10 NTU, compared to a 70% reduction in glacial lakes with turbidity levels >10 NTU (Table 1). Since IPP only partially explained the variation found in the glacial lake chl *a* response, we considered the euphotic zone as a factor in this discrepancy. We used the P-C expression of Verduin et al. (1978), which used the ratio of euphotic-zone depth to mean-lake depth to reduce the expression of TP as chl *a*. This correction caused no further decrease in variation among the semiglacial lakes; however, it resulted in an additional 22% decrease in chl *a* variation within the glacial systems (Table 1).

Table 1. Variations in chl a from observed values (A) using the clear-water phosphorus-chlorophyll (P-C) response model (B), our corrections for IPP (C), and the EZD corrected P-C expression (D) of Verduin et al. (1978). Values for both chl a and total phosphorus are seasonal means (May-October) from surface (1 m) strata.

Lake-year	Euphotic zone depth (EZD)	Turbidity (NTU)	Observed chl a ($\mu g\ l^{-1}$) A	Predicted chl a using clear water P-C model ($\mu g\ l^{-1}$) B	Chl a variation ($\mu g\ l^{-1}$) B-A	Predicted chl a using IPP corrected P-C model ($\mu g\ l^{-1}$) C	Chl a variation ($\mu g\ l^{-1}$) C-A	Predicted chl a using EDZ corrected P-C expression ($\mu g\ l^{-1}$) D	Chl a variation ($\mu g\ l^{-1}$) D-A
1	6.9	3.9	0.2	1.6	+1.4	1.1	+0.9	1.1	+0.9
2	8.6	2.8	0.3	2.6	+2.3	1.6	+1.3	2.0	+1.7
3	8.3	2.9	0.6	1.7	+1.1	1.0	+0.4	1.3	+0.7
4	6.3	4.4	0.6	1.9	+1.3	1.1	+0.5	1.9	+1.3
5	8.1	3.0	1.1	1.2	+0.1	0.9	-0.2	1.2	+0.1
6	7.7	3.3	0.7	1.4	+0.7	0.7	0.0	1.3	+0.6
7	5.2	5.9	0.2	2.8	+2.6	1.5	+1.3	2.0	+1.8
8	9.0	2.6	0.6	0.8	+0.2	0.1	-0.5	0.7	+0.1
9	0.9	46	1.3	8.5	+7.2	2.9	+1.6	0.3	-1.3
10	0.1	46	0.3	6.9	+6.6	1.6	+1.3	0.3	0.0
11	1.1	46	0.9	8.0	+7.1	3.3	+2.4	0.3	+0.6
12	1.3	47	0.6	5.1	+4.5	2.0	+1.4	0.5	+0.1
13	1.6	34	0.3	4.4	+4.1	1.8	+1.5	0.4	-0.1
14	3.8	12	0.2	1.7	+1.5	1.0	+0.8	0.6	+0.4
15	4.0	11	0.4	2.3	+1.9	1.2	+0.8	0.5	+0.1

DISCUSSION

Glacial Silt: Form and Function

A comparison of glacial particles found in differentially turbid lakes reveals features useful to water-quality managers. We have shown that turbidity levels in different lakes are a function of both PS and PN. The results indicate that a higher turbidity level is associated with both smaller PS and larger PN. The different values for the slopes (NTU versus PN) derived through sample dilutions (*see* Figure 1[B]) indicate that a given decrease in NTU at a small PS would require the removal of a larger number of particles than would be necessary for a larger PS. Thus lakes having higher turbidity levels are more likely to remain at a given turbidity because of the larger number of smaller particles that would tend to stay in suspension. This is opposed to less turbid systems because they have relatively larger particles that tend to settle out and thereby decrease turbidity.

As inorganic particles are responsible for much of the turbidity in glacial lakes, we questioned the effect of such a large number of particles on nutrient cycles; e.g., iron levels in clear lakes at chemical equilibrium exist in concentrations of less than 20 $\mu g\ L^{-1}$ (Stumm and Lee 1960), but the large concentrations of total iron (2000 $\mu g\ L^{-1}$) always found in glacial systems indicate an allochthonous source for this element. The fact that total iron correlates with turbidity (*see* Figure [3B]) suggests the source as glacial-silt intrusion. We were interested in similar large-scale effects on phosphorus levels because there were correlations between phosphorus, iron, and turbidity (*see* Figures 3[A] and 3[B]). As our fractionation analysis showed that the particulate phase comprised the major fraction of both elements, we determined by chemical analysis that inorganic particulate phosphorus comprised a significant amount (24% to 56%) of the total phosphorus in glacial systems (Figure 3[C]). Thus our fractionation studies confirmed our belief that high levels of inorganic particulate phosphorus (and iron) were derived from glacial-silt input; i.e., a significant fraction of TP in glacial lakes is comprised of rock phosphorus.

Upon examination of our phosphorus-chlorophyll response models, the effects of IPP and light limitation on chl a production were evident. As Lambou et al. (1982) and Robinson (1957) suggested that the presence of inorganic suspended solids was associated with high levels of nonbiologically available phosphorus, we corrected glacial-lake total phosphorus estimates for IPP and found that the variation in P-C response was considerably reduced (*see* Figures 5[C] and 5[D]). There remained, however, a significant variation in chl a response that was not explained by the presence of IPP. Hoyer and Jones (1983) attempted to correct variation in P-C response by considering concentrations of suspended solids (in reality, an index of transparency), and Verduin et al. (1978) derived a P-C expression that considered the EZD to mean depth (Z) ratio as a means to reduce the amount of chl a expressed as phosphorus. We felt that because the EZD in glacial lakes was defined by turbidity levels (*see* Figure 2), an EZD correction would prove useful. Applying the Verduin et al. (1978) model to our glacial systems resulted in no improvement over our correction for IPP in lake-years 1-8, but it accounted for most of the variation in lake-years 9-15 (*see* Table 1). Lake-years 1-8 were characterized by turbidity levels <10 NTU and an EZD of from 5-10 m; whereas, lake-years 9-15 had turbidity levels >10 NTU and an EZD <5 m.

Glacial Silt and Lake Typology

Turbidity has been associated with decreased zooplankton and phytoplankton production (Rawson 1953; Goldman 1960; Oglesby 1977). However, more recent investigations have stressed the specific role of turbidity (caused by suspended nonalgal material) in generating much of the variability within P-C relationships (Lambou et al. 1982; Hoyer and Jones 1983; Hunter and Wilhm

1984). While these studies address the negative aspects of turbidity, Verduin (1954) and Tizler et al. (1976) found increased algal production in turbid plumes. Tizler et al. (1976) concluded that turbidity (caused by sediment loading) would not only lessen the effect of light inhibition but also provide needed nutrients to counteract any potential negative effects of light limitation. In turn, we observed a decrease in carbon-uptake rates with increased turbidity in both our transfer and silt-addition experiments and increased carbon-uptake rates with a decrease in turbidity (*see* Figure 4). Our results also provide evidence that the productive potential of glacial lake water is large, but it can only be realized when sufficient light is made available through the elimination of turbidity. Thus we suggest that productivity in glacial systems may be a balanced positive and negative response to silt-induced nutrient (phosphorus) input and light limitation (turbidity), respectively.

We found that even low levels (5-10 NTU) of turbidity significantly affect light regimes (*see* Figure 2), which can be used to distinguish clear-water lakes from glacial lakes. The level of turbidity separating clear from glacial lakes (by PS analysis) also ranged from 3 to 6 NTU (*see* Figure 1). Thus a combination of three criteria distinguishes glacial from clear-water lakes; i.e., EZD <4-6 m, turbidity >5-10 NTU, and PS <20-40 μm. Moreover, according to their responses to IPP and EZD corrections, glacial lakes can be separated into two classes by turbidity and/or EZD levels (*see* Table 1). That is, the P-C response in >10 NTU systems can be corrected by a further consideration of EZD. It may actually be more appropriate to utilize a separate regression; i.e., LOG chl a = -1.62 + 1.31 LOG TP : $r^2 = 0.62$ (Figure 5[D]). This model describes a P-C trend similar to that found for the clear-water lakes, but because of the EZD (light) factor, it showed a consistently lowered chl a response to a given TP level. It is important to note that, although >10 NTU glacial lakes may constitute a unique lake type, the chl a response to changing TP levels is much the same as in clear-water lakes. Overall, primary production is lowered to a new plateau by the presence of suspended glacial-silt particles, forcing these lakes towards increased oligotrophy. In contrast, lakes within the 5-10 NTU range may be better modeled by a consideration of IPP and a utilization of our clear-water P-C response model. This is appropriate, because within this 5-10 NTU range (corresponding to an EZD of 4-6 m), the impact of glacial-silt particles on EZD, while considerable, is not equal to that occurring in lakes with NTU levels >10 (where the EZD is severely compressed). It appears that 5-10 NTU glacial lakes show reductions in chl a (*see* Table 1) that are caused by the presence of glacial silt; however, at times of moderate meltwater intrusion, these lakes tend to mimic nonturbid lakes. Consequently, such systems would have characteristics resembling both clear-water and glacial lakes and, thus, constitute an intermediate lake type (semiglacial). Further P-C model corrections in these types of lakes may need to emphasize the importance of morphometric and climatic factors, including flushing rate, temperature, and elevation.

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