Aquatic Sciences 56/2, 1994

1015-1621/94/020106-09 $1.50+0.20/0

Adjusting chlorophyll-a estimates through temporal weighting based on the seasonal development of phytobiomass

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Key words: Chlorophyll seasonality, temporal correction, lake specificity.

ABSTRACT

North-temperate lakes have been shown to progress through a general cycle of chlorophyll-a phenology. Because estimates of seasonal means are often based on only a few samples collected against this variable background, these estimates can be biased or uncertain. Our goal was to reduce the seasonal uncertainty and thereby produce more accurate estimates of chlorophyll concentration by defining a correction for phenological development. Time-series data from 149 lake-years were used to develop equations from which chlorophyll values could be "corrected" to the seasonal mean in relation to their particular date of measurement. However, we found the seasonal correction to be ineffectual in reducing uncertainty about nutrient-response regressions. After reviewing a number of hypotheses, we conclude that the correction derived from the average response for many lakes will be inadequate to adjust for the seasonal pattern occurring within any particular lake. This occurs because the temporal weighting correction, generated through repeated averaging, underestimates the seasonal variability which exists among individual lakes. An effective correction, if it is developed will have to be based on patterns within single lakes or possibly different lakes within a single region.

Introduction

The residual scatter around phosphorus-chlorophyll relationships and other phosphorus response models is of the order of ten fold (e.g. Nicholls and Dillon, 1981) and remains a visible and annoying weakness for empirical limnology. Although additional factors have been proposed to explain this residual error (e.g. Carpenter and Kitchell, 1987; Prairie et al., 1989), a good deal still remains unaccounted for. A possible explanation for this scatter is provided by analyses of the uncertainty associated with the estimation of mean chlorophyll-a (CHLa) and total phosphorus (TP) concentrations in single lakes (Marshall et al., 1988; France and Peters, 1992). As the errors associated with sampling and analysis are generally small (Hanna and Peters, 1991; Griesbach and Peters, 1991), a likely source for this uncertainty is the seasonal variability in CHLa and TP (e.g. Heyman et al., 1984; Knowlton et al., 1984; France 1992). If this is so, a correction for seasonal differences in CHLa would allow more accurate predictions of CHLa and perhaps exemplify a method of reducing the uncertainty in other phenomena subject to temporal variation.

Marshall and Peters (1989) produced a semi-quantitative, empirical description of the typical development of CHLa in north-temperate lakes (cf. Sommer et al., 1986). We proposed to use this model to generate a quantitative description of seasonality and to use this description to "correct" individual point-in-time estimates of CHLa to the seasonal mean. It was our belief, and that of others with whom we discussed it, that the development of such a phenological correction would be a useful adjunct in predicting mean concentrations through reducing the scatter of individual values. Our intention was that, through the generation of more accurate estimates of mean CHLa by removing temporal effects, the subsequent development of relationships of CHLa to TP would be more precise and therefore enable better decisions regarding lake management. However, the approach was found to be unfruitful. Examination of the reasons underlying this failure provide insight into the individuality of CHLa phenology within lakes with respect to the general pattern in seasonal development of phytobiomass.

Methods

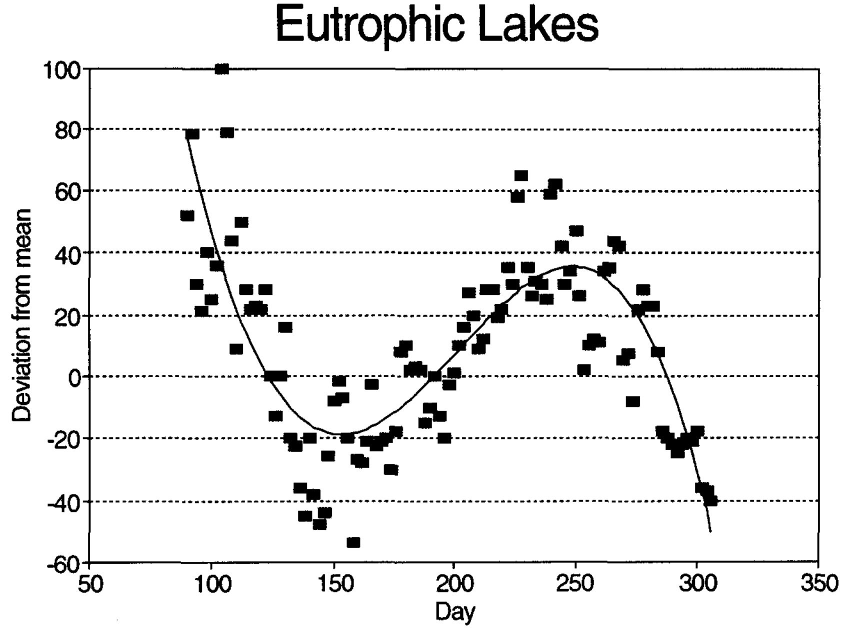
Derivation of the seasonality correction factor

Sommer et al. (1986) believed that lakes go through characteristic cycles of CHLa seasonality, and that these cycles depend on trophy. This hypothesis suggests that a date-specific correction for seasonal variation in CHLa may be possible so that better estimates of the means may be derived from smaller numbers of samples. Marshall and Peters (1989) provided the background for such a correction by collating data from 20 eutrophic ($TP > 12\ mg \cdot m^{-3}$) and 31 oligotrophic ($TP < 7\ mg \cdot m^{-3}$) lakes to generate, respectively, 37 and 68 time-series of CHLa seasonality (5 lakes comprised 59% of all observations for eutrophic lakes, and 5 lakes comprised 44% of all derivations for oligotrophic lakes). Data were expressed as percentage deviations from the annual or seasonal means with the technique of Kavvas and Delleur (1975), and these scaled differences averaged whenever multiple values occurred on the same day. The resulting CHLa phenologies displayed synchronous spring and autumn blooms and mid-summer depressions in eutrophic lakes, while less clear patterns emerged for oligotrophic lakes (Marshall and Peters, 1989).

We calculated running averages of two consecutive days from Marshall and Peters (1989) phenologies over the period from April through October, and these new scaled differences were then fitted by polynomial equations (Fig. 1). These polynomial equations were used to generate date-specific "corrections" of CHLa in relation to the expected seasonal mean obtained through more extensive sampling.

Test data and analysis

To avoid mathematical circularity, testing of the utility of the temporally weighted correction for seasonality was conducted with data other than that used to generate the correction factor. We therefore used published data from 26 "eutrophic"



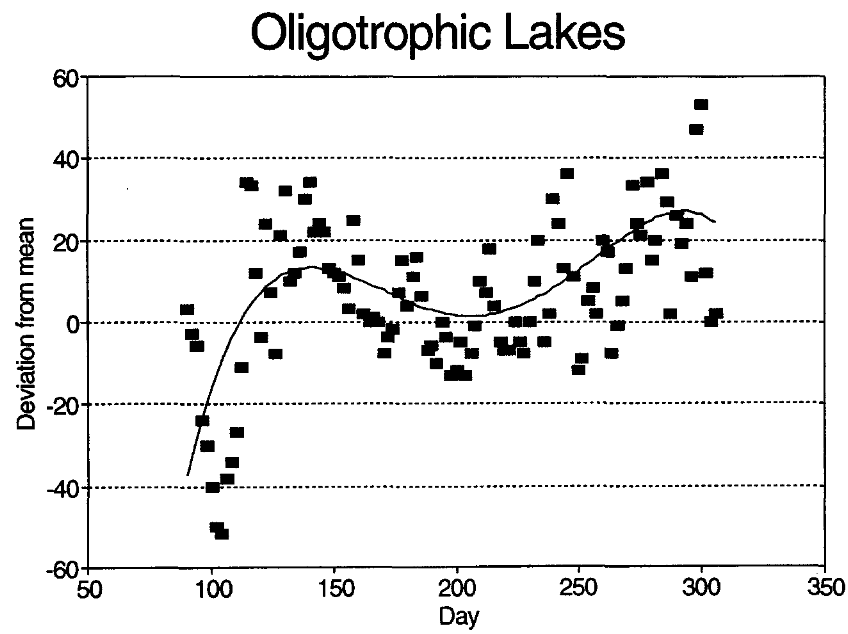


Figure 1. The phenology of CHLa in eutrophic and oligotrophic lakes. Data are running averages between two consecutive days from Marshall and Peters (1989: Fig. 1) with the horizontal line at O representing the seasonal mean. The equation for the eutrophic lake curve is $Y = 827.22 - 13.99\,D + 0.074\,D^2 - 0.000124\,D^3$, $R^2 = 0.65$, $n = 109$; and for the oligotrophic lake curve is $Y = -833.05 + 18.041\,D - 0.1387\,D^2 + 0.000453\,D^3 - 0.000000531\,D^4$, $R^2 = 0.35$, $n = 109$; with Y = percentage deviation from the mean and D = Julian day

([TP] > 12 mg · m^{-3}) and 25 "oligotrophic" ([TP] < 12 mg · m^{-3}) lakes comprising 74 and 75 lake-years, respectively to independently test the effectiveness of temporal correction (Schindler and Comita, 1972; Glooschenko et al., 1974; Kalff and Welch, 1974; Dodson et al., 1974; Vollenweider et al., 1974; Schindler, 1974; Fee, 1976; Kwiatkowski, 1978; Stockner, 1981; Depinto et al., 1986; Reynolds, 1980; Bailey-Watts et al., 1990; and data sources listed in France and Peters [1992]).

Marshall and Peters' (1989) examination of CHLa seasonalities were influenced by 5 well represented lakes which had been sampled very intensively. Sampling programs of such comprehensive effort are, however, rare (Peters, 1990). Marshall et al. (1988) determined that bias in estimation of mean CHLa occurs when fewer than 5 samples are collected during the year. To ensure that a standardized sampling program of equal replication and similar date was applied to all lakes (since differences in both these variables can dramatically alter subsequent CHLa analyses – e.g. Horn, 1984; Kwaitkowski, 1985), 4 to 7 CHLa values were extracted from each lake's time-series at approximately mid-monthly intervals from April through October (see France and Peters, 1992). Due to the importance of spring values which often have deviations from the seasonal mean opposite to that present for much of the rest of the summer (this is especially the case for oligotrophic lakes, see Marshall and Peters, 1989 and Fig. 1), only those test data sets which contained one or both of April and/or May samples were selected to avoid possibilites of bias. Data presented in figures were read with a HIPADc digitizing pad (Houston Instru., Austin, Texas). All individual CHLa values were then "corrected" by the equations developed for temporal weighting with respect to their seasonal means and respective dates of measurement (Fig. 1).

We assessed the success of the seasonality correction by calculating the average CHLa concentration before and after correction, and the average scatter (Sy:x, R^2) associated with TP-CHLa regressions using both corrected and uncorrected means. Our expectation was that, given the TP dependency of CHLa in north-temperate lakes (e.g. Smith and Shapiro, 1981), through producing more accurate estimates of mean CHLa by removing the influence of seasonality, we would therefore obtain more precise nutrient-response relationships. To this end, we further examined the effects of phenological corrections with respect to other models of interest to lake managers: (A) patterns in the seasonal development of CHLa; i.e. seasonal mean vs. late summer (either Aug. or Sept.) maxima as proposed by Jones et al. (1979) and Walmsley (1984), and initial (April) spring vs. seasonal mean concentrations as used by Dillon et al. (1987); and (B) the possibility of generating individual date or "time-specific" phosphorus response models based on combining data from single samplings using both our own test data and also that of Megard (1972) which has in turn been re-analyzed by both Smith and Shapiro (1981) and Knowlton et al. (1984).

Results and discussion

To our chagrin, the seasonality correction proved ineffectual. Corrected regression equations between water quality variables were no more certain than were uncorrected ones (Table 1). We therefore examined three possibilities which might

Table 1. Regression statistics for relationships (X:Y) developed using corrected (C) and uncorrected (U) log TP and log CHLa concentrations. R^2 = coefficient of determination; Sy:x = standard error of estimate; N = number of lake-years; "test data" = independent data from sources listed in text; "original data" = data from Marshall and Peters (1989) used to derive the temporally weighted correction factor; "mean" = seasonal average derived from 4 to 7 mid-monthly samples from April through October; "maximum" = the higher of either the August or September values; "spring" = April value; "time-specific" = single date values combined from through out the open-water season; "Megard time-specific" = single date values combined from throughout the open-water season from Megard (1972) as also re-analyzed by Smith and Shapiro (1981) and Knowlton et al. (1984)

Relationship	Intercept		Slope		R^2		Sy:x		N
	C	U	C	U	C	U	C	U	
Test data									
Mean TP:mean CHLa	−0.11	−0.07	0.78	0.77	0.68	0.69	0.26	0.26	108
Mean CHLa:maximum CHLa	0.06	0.07	0.96	1.03	0.85	0.87	0.20	0.19	149
Spring CHLa:mean CHLa	0.56	0.55	0.59	0.60	0.44	0.55	0.35	0.31	120
Time-specific TP: time-specific CHLa	−0.23	−0.17	0.77	0.74	0.38	0.36	0.49	0.49	263
Megard time-specific TP: Megard time-specific CHLa	−0.64	0.49	0.37	0.46	0.05	0.07	0.26	0.29	72
Original data									
Mean TP:mean CHLa	−0.59	−0.54	1.01	1.01	0.81	0.83	0.17	0.17	32
Time-specific TP: time-specific CHLa	−0.34	−0.35	0.84	0.87	0.50	0.56	0.34	0.32	79

account for this discrepancy between our optimistic expectations and disappointing results: (1) the method of data extraction based on 4 to 7 mid-monthly values unrealistically represented CHLa phenology; (2) our test data differed markedly from the original data used by Marshall and Peters (1989) upon which the seasonality correction was derived; and (3) the average response from many lakes will not correct for seasonal patterns observed within any individual lake.

To test the possibility that our data extraction procedure obscured the seasonal pattern, we applied the same procedure to 203 data points from 30 eutrophic lake-years from Marshall and Peters (1989) upon which the phenology in Fig. 1 was based. The distribution of these individual percentage deviations from their respective means closely followed the same general seasonal pattern displayed in Fig. 1 for more intensive sampling, and matched those values determined by the polynomial equation used for temporal weighting. As well, the extracted means based on 4 to 7 samples were strongly correlated ($R^2 = 0.98$) with, and differed little ($< 8\%$) from the means determined through intensive sampling. It seems, therefore, that our procedure of obtaining literature data at a standardized sampling frequency and interval did not induce the dismal performance of the seasonality correction factor.

To test the hypothesis that the test data were somehow atypical, we compared both the overall pattern of, and seasonal variability in, CHLa with that from other data sets. The regression to describe temporal variance of mean CHLa from the uncorrected test data is:

$$\log \text{variance} = -0.86 + 2.15 (\log \text{mean});\ R^2 = 0.88,\ Sy{:}x = 0.41,\ n = 163$$

This variance function is very similar to those derived by Walmsley (1984), Walker (1985) and Marshall et al. (1988) for independent data sets. The overall degree of CHLa variability in our test data is therefore not atypical. The proportional distribution of highest and lowest monthly values derived through the data extraction procedure for both test and original data for eutrophic lakes were also similar (Fig. 2). The expected bimodality of the April–May and August–September peaks and the June and October throughs in CHLa phenology appears in both data sets (though more so for the original data). Our test data were therefore not atypical.

We tested the performance of the seasonality correction upon the sub-set of original data and found, as with the test data, no improvement in predictability for either mean or time-specific (i.e. single sampling visits per lake-year) data (Table 1). Given that the data extraction procedure was unbiased, failure of the seasonality correction to reduce uncertainty in some of the very data from which it was derived (even with the increased potential for mathematical dependency in such circumstances), indicates that it is the correction procedure itself which is at fault.

We found the degree of CHLa variation within individual lakes to be so great that any correction obtained from the average pattern displayed by a group of lakes is just as likely to increase the error as to decrease it. For instance, the average intra-annual CVs of CHLa from corrected and uncorrected original eutrophic lakes were identical at 62%, as were the number of cases in which the error was either reduced or increased following correction. In other words, the average response among lakes is no useful guide to the particular quantitative response of individual lakes. Further, our hope that through reducing CHLa uncertainty by temporal correction, we could therefore reduce the number of samples required to estimate the mean (cf. Marshall et al., 1988), was unfortunately unfulfilled.

The temporal dynamics of CHLa within particular lakes, although following the general averaged trend, are different enough that a single universal seasonality correction cannot be based on the average response. The average trends in Fig. 1 only explain from 35 to 65% of the seasonal amplitude of CHLa variation among lakes. In particular, the time-series data (Fig. 1) indicate that the percentage differences from means can range from + 100% to + 8% within a single week. Recall that these values are smoothed means between two consecutive days from Marshall and Peters' (1989) Fig. 1, which in turn shows that the deviations from the mean to range from + 135% to − 75% over the same week interval. Further, each point in Marshall and Peters Fig. 1 is a date-specific mean for several lakes. Because of the notable inter-lake specificity in CHLa variation, our temporal weighting correction, obtained through repeated averaging, does not represent the actual magnitude of the differences present among lakes.

The lake specificity CHLa phenologies can be demonstrated by examining the "expected"(Sommer et al., 1986; Marshall and Peters, 1989) April maxima and June minima. The CVs of the scaled differences among eutrophic lakes observed in April were 233% and 338% for the original and test data, respectively, and for June were 280% and 182%. It is also important to note that there are individual lakes that actually displayed a time trend opposite to that expected. For example, between 12 to 16% of the cases (both data sets) in Fig. 2 actually showed maxima in June and minima in April, contrary to the predictions of the general trend discussed by

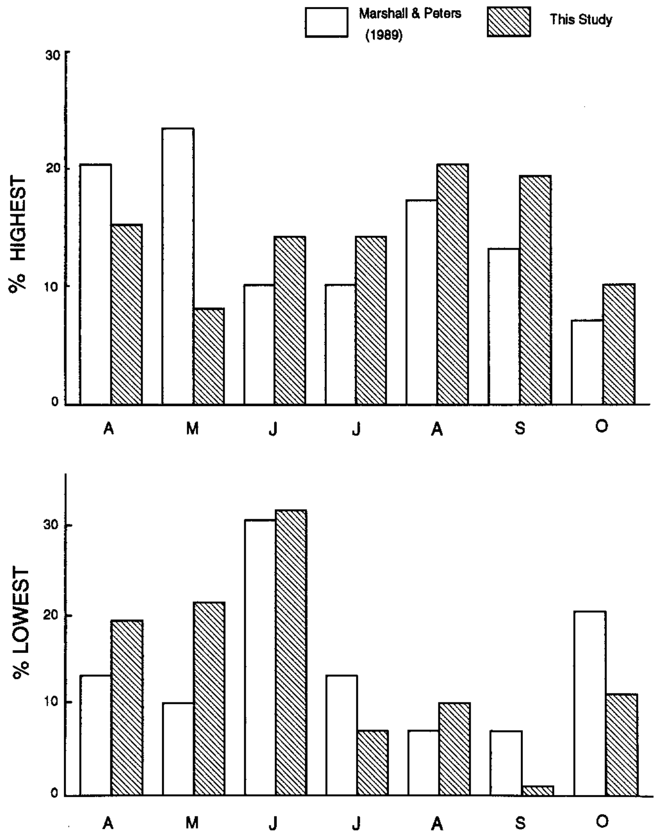


Figure 2. Proportional distribution of months with either the highest or lowest CHLa value for eutrophic lakes obtained through sampling 4 to 7 times from April to October. Open bars represent Marshall and Peters (1989) original data while closed bars denote the independent test data

Sommer et al. (1986). As well, in only 26% of the cases for the April test data were the actual percentage differences from their means positive as the general model predicts.

It is possible that some of the dramatic inter-lake variability in CHLa phenology could be reduced through more refined correction factors which removed the climatic (Marshall and Peters, 1989), morphometric (Sommer, 1986), or some combination of the two's (Stauffer, 1991), influences on the seasonal development of phytobiomass. We attempted one such correction for climate-induced delays by introducing a time shift in the data so that all lakes had a synchronous spring maxima in "April". Temporal corrections were applied as before, but once again failed to reduce the variance compared to the uncorrected data. Although such time-shifting made the data for "April" approximate the general phenological mode, as often as not, data for "June" became asynchronous with the expected pattern. Such a result occurs because not only do the positions of the peaks and throughs change in relation to climatic conditions, but also their shape as well; i.e. the time frame in which lakes progress through the seasonal cycle of CHLa is progressively truncated at higher latitudes. Therefore, until we have the ability to predict other salient features of CHLa phenologies in addition to their spring bloom dates, a general seasonality correction obtained from the average response of all lakes will be ineffective in reducing the scatter about phosphorus-response regressions or in estimating mean CHLa more precisely.

The observation that the various time-specific models were also unimproved following seasonality correction, indicates that combining TP and CHLa values from single visits to numerous lakes at different times will not be a profitable direction worth pursuing. However, it may still be possible that by restricting sampling to only specific periods, an inter-lake TP-CHLa relationship could still be developed based on a few or even single visits to lakes.

ACKNOWLEDGEMENTS

This work was supported by the National Science Engineering Research Council of Canada, Les Fonds pour la Formation de Chercheurs et l'Aide a la Recherche of the Province of Quebec, and the Group for Inter-university Research in Limnology for the universities of Montreal, Quebec and McGill. D. McQueen and T. Marshall are thanked for providing published data, and an anonymous reviewer for providing constructive and valuable criticism of the manuscript.

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Received 5 February 1993;
manuscript accepted 29 September 1993.