TEMPORAL PATTERNS AND VARIABILITY OF TROPHIC STATE PARAMETERS IN MISSOURI RESERVOIRS

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

TEMPORAL PATTERNS AND VARIABILITY
OF TROPHIC STATE PARAMETERS
IN MISSOURI RESERVOIRS

presented by Daniel V. Obrecht

a candidate for the degree of master of science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Temporal Patterns and Variability of Trophic State Parameters in Missouri Reservoirs

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Abstract

Eutrophic reservoirs in Missouri, as a group, do not display the bimodal spring and fall pattern of peak algal biomass that is accepted phenology in eutrophic temperate lakes. Instead, Missouri's eutrophic reservoirs display a range of temporal patterns, influenced by both nutrient and non-volatile suspended solid concentrations. Oligo- and mesotrophic reservoirs mimicked the pattern of algal biomass identified in a previous study of temperate oligotrophic lakes, with a single algal peak during spring. Seasonal trends in the water quality parameters influenced trophic state assessments, with sampling during spring resulting in an over-estimation of trophic state. Seasonal patterns in algal abundance and variability also influenced the number of samples needed to estimate mean trophic conditions. Four samples collected throughout summer would lead to a coefficient of variation of ~25% for algal chlorophyll. Seven samples would be required to achieve the same level of precision in chlorophyll estimation if the sampling period were expanded to spring-fall. Nitrogen and phosphorus display lower temporal variability than chlorophyll, so greater precision in estimating mean conditions is achieved with a given sampling effort. Nutrient stimulation experiments indicate that the nutrient limiting algal growth in Missouri reservoirs does not remain constant temporally, and that limitation of algal growth by a single nutrient is generally not acute.

INTRODUCTION

Algal biomass in temperate lakes and reservoirs is thought to display a seasonal pattern in which a distinct spring bloom is followed by a summertime depression, a secondary fall bloom and a wintertime minimum (Hutchinson 1967, Marshall and Peters 1989). Long-term research on individual waterbodies has demonstrated annual reoccurrences of this bimodal pattern, though the timing and amplitude of peaks and depressions vary (Davis 1964, Sommer et al. 1986, Bailey-Watts et al. 1990, Reynolds and Bellinger 1992, Talling 1993). The reoccurrence of this seasonal pattern in a few well-studied waterbodies however may not describe the general phenology of algae in all lakes and reservoirs.

Marshall and Peters (1989) investigated the adequacy of the bimodal paradigm of algal biomass by pooling data from 56 temperate lakes and reservoirs. Waterbodies were placed into trophic state categories based on mean chlorophyll (CHL) concentrations and patterns were assessed by normalizing individual CHL values to the overall mean CHL for each lake. Oligotrophic systems displayed a general pattern of stable CHL near or slightly above the annual mean from late spring to late fall, with values below mean conditions during the remainder of the year (Figure 1). In comparison, the CHL pattern in eutrophic systems was bimodal with peaks above the annual mean in spring and fall, a summer depression and a more substantial winter depression (Figure 1). Patterns in mesotrophic systems could not be evaluated due to limited data.

Walker (1980) used data from 306 stations located on 76 mid-latitude reservoirs to evaluate seasonal patterns of trophic state parameters during the period March through November. CHL, total phosphorus (TP), and Secchi transparency data were converted into Trophic State Index (TSI) values (Carlson 1977) to allow for comparisons. The overall trend for CHL-TSI mimicked the CHL pattern identified for eutrophic lakes by Marshall and Peters (1989), with a CHL peak in April followed by a decrease through June, a second peak in August, and a continued decrease through November (Figure 2). In a detailed examination of the data, Walker (1980) found that approximately half of the stations did not display a June depression and therefore did not display a bimodal pattern. TP and Secchi transparency patterns differed from CHL in that minimum TSI values occurred in August when CHL-TSI was at its maximum (Figure 2). Also, TSI values for the three parameters varied considerably early and late in the study period (Figure 2).

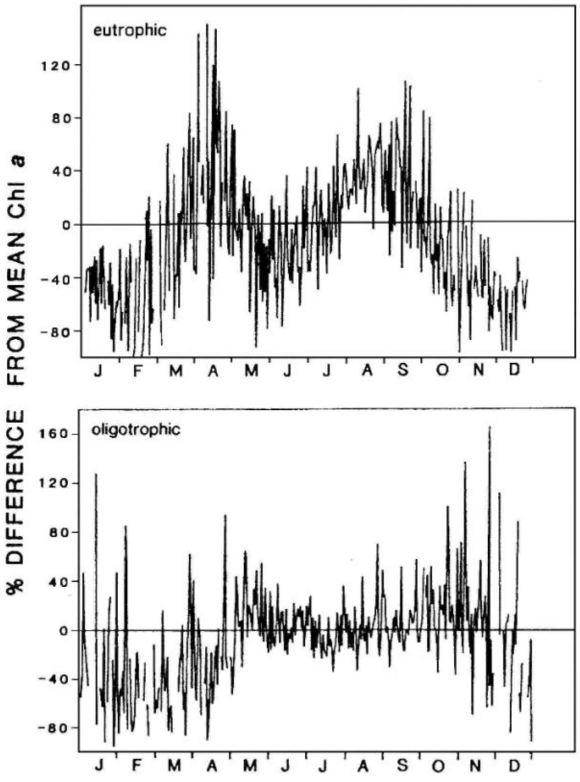


Figure 1. Seasonal chlorophyll patterns for eutrophic and oligotrophic lakes (Figure 1 from Marshall and Peters 1989).

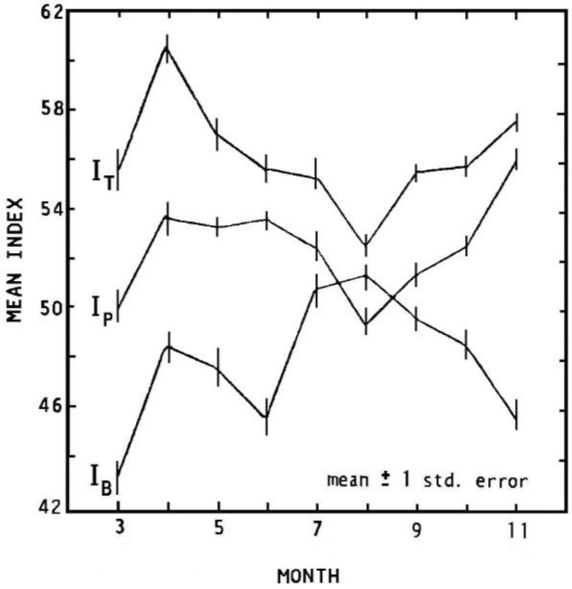


Figure 2. Monthly variations in trophic state indices for a suite of reservoirs (Figure 2 from Walker 1980). I_T = Secchi transparency, I_P = total phosphorus, and I_B = algal chlorophyll.

Brown *et al*. (1998) investigated seasonal patterns for CHL, TP, total nitrogen (TN) and Secchi transparency in 209 Florida lakes with slight modification of the methodology used by Marshall and Peters (1989). Florida lakes were sorted by trophic state based on mean annual CHL values and criteria from Forsberg and Ryding (1980). Oligotrophic, mesotrophic and eutrophic lakes displayed a CHL pattern of concentrations above annual mean during July through October, and below mean during the rest of the year (Figure 3). CHL in hypereutrophic lakes fluctuated at or above mean conditions much of the year, with the exception of winter when values were below mean (Figure 3). Combined data from all trophic state categories showed a pattern similar to oligo-eutrophic systems (Figure 4). Secchi transparency was above the mean during November-February, with below mean values during the rest of the year in the combined data set (Figure 4). Patterns for TP and TN displayed below mean conditions during winter, with values fluctuating near or above the mean during the remainder of the year (Figure 4).

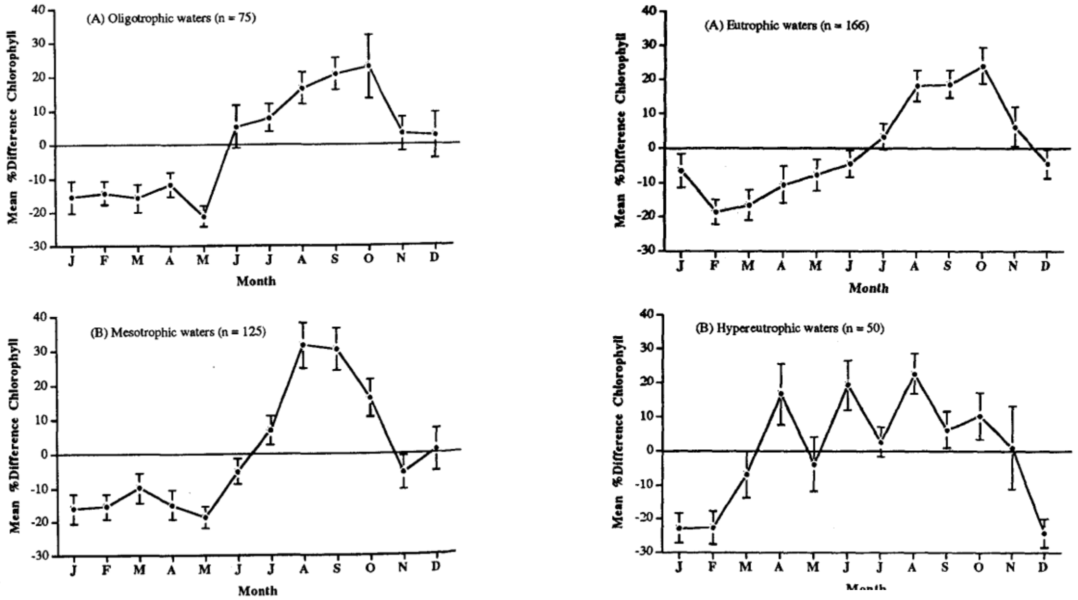


Figure 3. Seasonal patterns of chlorophyll abundance in Florida lakes of different trophic status (Figures 2 and 3 from Brown *et al*. 1998).

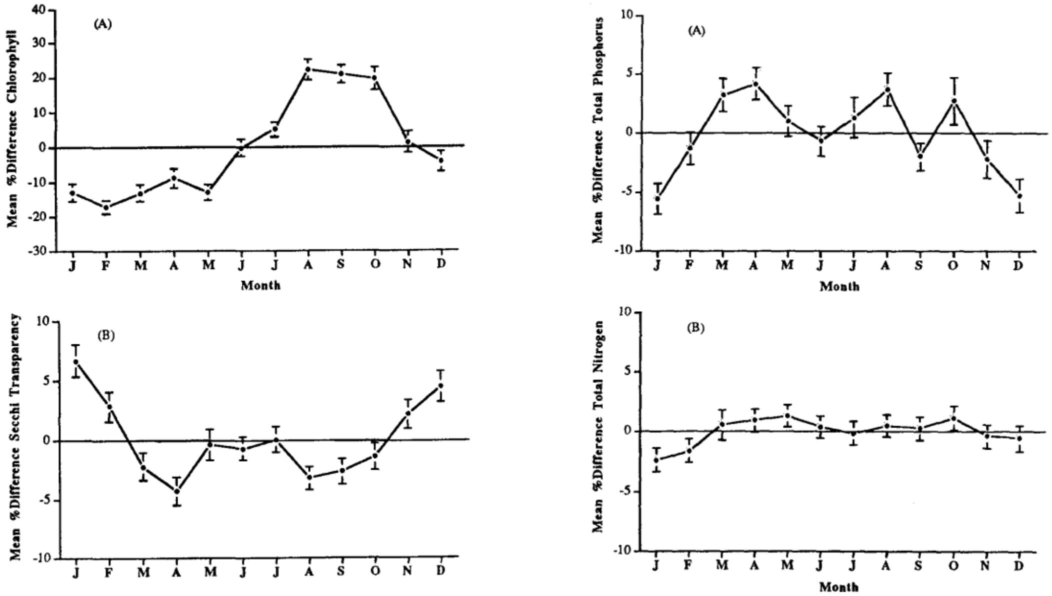


Figure 4. Seasonal patterns of chlorophyll, Secchi transparency, total phosphorus and total nitrogen from combined Florida lake data set (Figures 1 and 4 from Brown *et al*. 1998).

Seasonal patterns of CHL and Secchi transparency during the growing season (May-September) were examined for 145 East-Central Minnesota lakes by Stadelmann *et al*. (2001). Data were normalized following Marshall and Peters (1989) and trophic classifications were based on mean growing season CHL (Stadelmann *et al*. 2001). Findings indicated that all trophic groups (meso-, eutro-, and hypereutrophic) displayed a pattern similar to that found for the period May to September in eutrophic lakes by Marshall and Peters (1989). CHL levels were below mean conditions during May and June, increased through July, and peaked in August-September (Figure 5). The limited sample season disallowed for the evaluation of a springtime peak or a fall decrease in CHL. Comparison of results from the three trophic classifications show that mesotrophic lakes deviated from mean conditions less than eutro- and hypereutrophic lakes (Figure 5). Secchi transparency measurements from the Minnesota lakes were higher than the mean early in the growing season and below mean conditions during July-September. Again, deviations from mean conditions increased with trophic status.

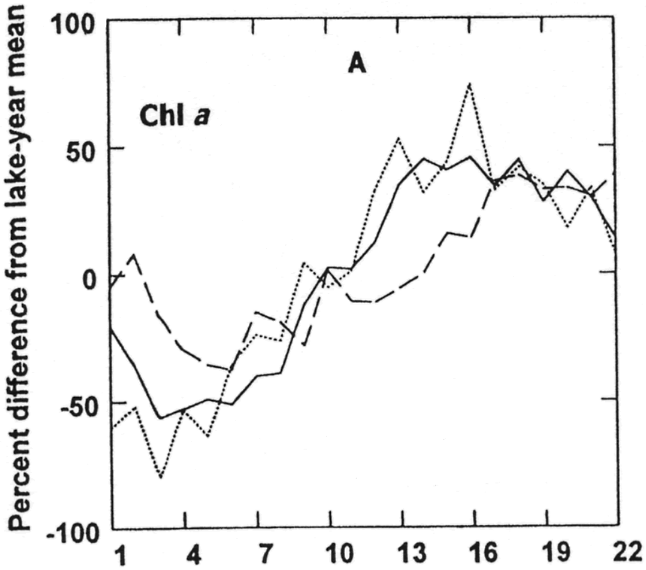


Figure 5. Seasonal pattern of chlorophyll abundance in mesotrophic (dashed line), eutrophic (solid line) and hypereutrophic (dotted line) East-Central Minnesota lakes (Figure 2a from Stadelmann *et al*. 2001). The x-axis represents the week of monitoring starting at May 1 and ending at September 30.

Seasonal patterns of algal biomass described in these four studies display enough variation to challenge the accepted paradigm. While the overall results of Walker's (1980) study mimicked the pattern in eutrophic systems identified by Marshall and Peters (1989), the finding that half the stations did not display a mid-season depression suggests substantial differences in how individual reservoir stations behaved. Florida lakes studied by Brown *et al*. (1998) did not display differences among trophic state categories, with the exception of the hypereutrophic lakes which exhibited a pattern similar to the oligotrophic lakes in Marshall and Peters (1989). The pattern identified for the three other trophic state groups in Florida did not match either pattern described by Marshal and Peters (1989). Thus, none of the trophic state categories in Florida displayed the bimodal pattern of CHL abundance that constitutes the paradigm of traditional limnology. Results of Stadelmann *et al*. (2001) match the eutrophic pattern promoted by Marshall and Peters (1989), but temporally limited data did not allow for investigation of springtime peaks.

Worth noting, these four studies included both lakes and reservoirs located in different geographical regions. Marshall and Peters (1989) included some reservoir data, but the majority of data sets (89%) used in the analysis were from northern, natural lakes. Walker (1980) worked solely with reservoirs, located mostly between 32° and 40° latitude, Brown *et al*. (1998) focused on Florida lakes (25°-30° latitude), while Stadelmann *et al*. (2001) evaluated natural lakes in a seven county area of Minnesota (44° latitude). Differences in regional location, basin type and hydrology can play a significant role in water quality (Jones and Bachman 1977, Canfield and Bachman 1981, Duarte and Kalff 1989) and may explain some of the discrepancies in the phenology of algal biomass among these studies. In their study of temporal patterns, Marshall and Peters (1989) reported a lack of consistency in the CHL patterns of individual oligotrophic lakes, and suggested that evaluation on a more localized geographical scale might explain distinct temporal patterns.

Also, the four studies used different criteria for identifying trophic state. Mesotrophic lakes in Florida were identified as having 3-7 μg/L of CHL (Brown *et al*. 1998) and would have been considered oligotrophic by Marshall and Peters (1989). The mean CHL concentration for mesotrophic lakes in the Minnesota study was 6.3 μg/L (Stadelmann *et al*. 2001) which suggests that many of the 31 lakes in this group would have been regarded as oligotrophic by Marshall and Peters (1989). The monthly mean CHL TSI values in Walker's (1980) combined reservoir data set ranged from 43 to 52, which equates to CHL values of 3.5 to 8.8 μg/L. Seven of nine monthly mean CHL values reported by Walker (1980) would have been considered oligotrophic in the Marshall and Peters (1989) study. Inconsistent results among the four studies suggest large scale descriptions of limnological patterns may have limited merit and therefore, smaller, regional studies may be needed to characterize the phenology of trophic parameters.

A common goal of limnological studies is to make trophic state assessments on individual waterbodies (Nürnberg 1996). Often trophic status is determined using limited data obtained during summer (Walker 1980, Peters 1990, Jones and Knowlton 1993, Ground and Groeger 1994). If parameters display strong seasonal patterns, summer samples may not adequately characterize lake water quality and monitoring may need to include the entire spring-fall period to provide a more useful description of lake trophic status. Along with considerations about when to sample, researchers should be concerned with the number of samples required to estimate lake trophic state. Knowledge of how trophic state parameters vary during the spring-fall period would provide a quantitative basis for planning monitoring protocol.

Managing our lake and reservoir resources requires knowledge of how systems vary temporally and which factors influence variability. Nutrient limitation of algal biomass can change seasonally (Storch and Dietrich 1979; Morris and Lewis 1988; Pollingher et al 1988; Vanni and Tempte 1990), with fluctuations in nutrient limitation being caused by changes in nutrient availability and shifts in nutrient ratios (Smith 1982, Suttle and Harrison 1988) or changes in phytoplankton community (Pollingher *et al*, 1988). Knowledge of how influencing factors change temporally may help explain seasonal patterns in algal abundance.

The relation between nutrients and algal biomass is often described by empirical nutrient-CHL models (Jones and Bachman 1976, Hoyer and Jones 1983, Knowlton *et al*. 1984, Jones and Knowlton 1993, 2005). These models are based on summer mean conditions without considering temporal variability in the parameters (Marshall and Peters 1989). Variability in algal biomass during spring and autumn may be large enough, and factors influencing algal biomass diverse enough, to render empirical nutrient-CHL models ineffective during these seasons (Marshall and Peters, 1989).

A considerable amount of limnological data has been gathered on Missouri's reservoirs. Past research has described the regional water quality and trophic status of Missouri reservoirs (Jones 1977, Wylie and Jones 1987, Jones and Knowlton 1993), modeled factors regulating algal biomass and transparency (Hoyer and Jones 1983, Knowlton and Jones 1989a, Jones and Knowlton 1993, Jones *et al*. 2004, Jones and Knowlton 2005), described the abundance of heterotrophic bacteria (Thorpe and Jones 2005), characterized the distribution of algal toxins (Graham *et al*. 2004), showed the cross-system response of nutrients to land cover and morphology (Jones *et al*. 2004), and determined the magnitude of major sources of variability (Knowlton *et al*. 1984). Other studies have described water quality in individual reservoirs (Jones and Novak 1981, Jones and Kaiser 1988, Knowlton and Jones 1989b, Knowlton and Jones 1990, Perkins *et al* 1999, Obrecht *et al*. 2005). These studies have been conducted largely during summer and constitute the majority of what is known about Missouri reservoirs. The potential influence of seasonal variation on trophic assessment has been recognized (Knowlton *et al*. 1984), but seasonal studies have been outside the scope of past work.

The first objective of this study was to determine the general spring-fall pattern of CHL abundance in a suite of Missouri reservoirs. This objective was a test of findings by Marshall and Peters (1989), and the working hypothesis was that oligotrophic and eutrophic reservoirs would display different patterns of CHL abundance during the spring-fall period. Seasonality of CHL was further examined with a statistical comparison of mean values and variability within spring, summer and fall periods, along with a review of the temporal occurrence of extreme CHL values. Seasonal patterns for TP and TN were also evaluated.

A second objective was to determine how trophic state assessment of Missouri reservoirs was affected by the period of sample collection. Assessments made based on summer data will differ from those made using data from other periods if trophic state parameters fluctuate seasonally in Missouri reservoirs. Quantifying these differences will aid in determining the comparability of data sets collected from different seasons and facilitate in the design of future monitoring programs.

The third objective was to evaluate the number of samples required to estimate mean trophic conditions at a given level of precision. Marshall *et al*. (1988) determined that five or more samples were needed to minimize bias associated with too few samples. The required sample size needed to limit bias should correspond to the variability of the parameter of interest. Marshall *et al*. (1988) determined that estimations of CHL required more samples than estimates of TP because of differences in variability between the two parameters. If seasonal patterns in CHL abundance and variability exist, sampling effort required to estimate mean conditions will differ between summer and spring-fall periods.

The fourth objective was to determine if nutrient regulation of phytoplankton biomass in Missouri reservoirs varied seasonally. The working hypothesis for this objective was that the limiting nutrient did not remain constant during the year in the study reservoirs. Nutrient stimulation experiments (NSE) were conducted after Jones *et al*. (1990) to determine whether algae respond to additions of phosphorus, nitrogen or both nutrients in combination. Nutrient regulation of algal biomass across seasons was also examined with CHL-nutrient regression models (Jones and Knowlton 1993), CHL:nutrient ratios and TN:TP ratios. Comparisons of NSE results, regression models and nutrient ratios provide insight into how fluctuations in nutrient concentrations regulate phytoplankton biomass during the spring-fall period.

METHODS

Study Sites

Figure 6 shows the location of the thirteen Missouri reservoirs sampled in this study. One sample site was established on each reservoir in an area of deep water near the dam, except in Table Rock Lake where the sample site was located 6.4 km from the dam. Reservoirs were chosen to encompass the range of trophic state and physical conditions common to Missouri waterbodies (Table 1).

Table 1. Reservoir names, locations and physical data.

Reservoir	County	Surface Area (acres)	Volume (acre-feet)	Watershed Area (acres)
Blue Spring	Jackson	727	10,800	21,384
Capri	St. Francois	103	2,828	554
Carmel	St. Francois	54	900	642
Catalina	St. Francois	6	71	74
Chesterfield	St. Louis	27	360	495
Kraut Run	St. Charles	145	1,030	4,060
Lafitte	St. Francois	42	555	537
Little Dixie	Callaway	194	3,075	2,315
Longview	Jackson	798	22,100	31,950
Marseilles	St. Francois	47	1,900	376
Shayne	St. Francois	73	2,476	512
Table Rock	Stone	39,913	2,702,000	1,161,870
Weatherby	Platte	161	4,910	2,750

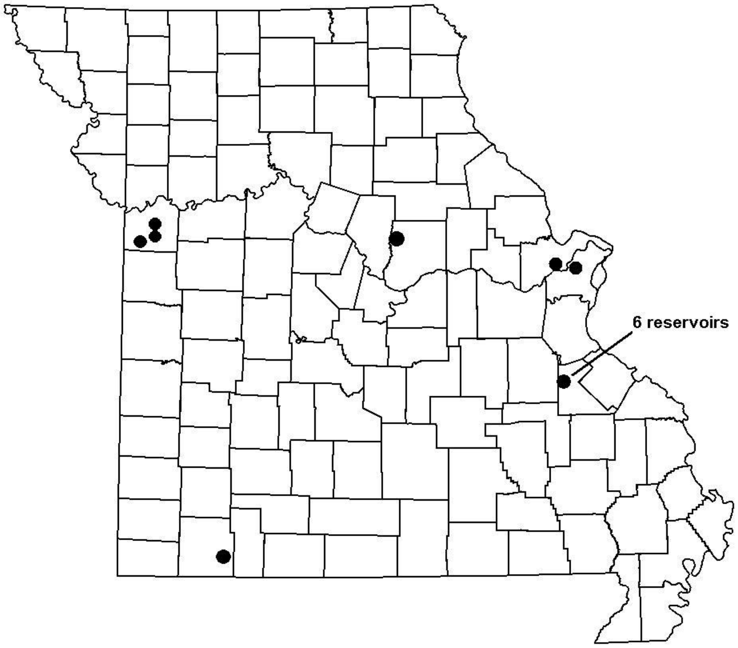


Figure 6. Location of reservoirs monitored for this study.

Sampling, Processing and Analytical Methods

The University of Missouri created a volunteer lake sampling program (Lakes of Missouri Volunteer Program) in 1992. Initial results suggested that the use of volunteers in collecting lake samples was a practical way to generate research quality data (Obrecht et al. 1998). Because this seasonal assessment required frequent sampling from reservoirs across the state, volunteers were enlisted to assist in field collection. Equipment was furnished to the volunteers and University personnel provided training. Volunteers were also supplied reference material to provide supplemental assistance. Materials included a step-by-step manual on water sampling and processing, condensed procedures and a video on sample processing.

Volunteers were asked to collect samples twice weekly, on either a Monday/Thursday or Tuesday/Friday schedule April through November. Along with collecting a grab water sample from the surface ($\leq$ 0.2 m), volunteers measured Secchi transparency and surface temperature on each sample occasion. Samples were refrigerated or kept on ice until processing within 12 hours of collection. Processing involved rinsing and filling an acid washed 60 mL high density polyethylene bottle with lake water for subsequent analysis of TP and TN. Volunteers used a Nalgene filter funnel and a vacuum hand pump to filter lake water through pre-washed and weighed Whatman 934-AH filters (in duplicate) for total suspended solids (TSS) analysis. TSS filters were stored in individual paper envelopes labeled with unique identifying numbers prior to, and after filtration. Volunteers prepared duplicate Gelman A/E filters for CHL analysis using the same filtration equipment and placed these filters in individual paper envelopes. All filters were stored frozen with desiccant in a light-tight container. Filtrate from the chlorophyll preparation was used to rinse and fill a second acid washed 60 mL high density polyethylene bottle for dissolved phosphorus (DP) and dissolved nitrogen (DN) analysis. Nutrient bottles were stored frozen until analysis at the University, which eliminated the need to provide volunteers with acid for sample preservation. Studies have indicated that freezing samples is a suitable form of storage (Lambert et al. 1992, Kotlash and Chessman 1998).

Reservoirs were also sampled by University of Missouri staff every 30-60 days during the period between April 1994 and March 1995. Temperature and dissolved oxygen profiles were measured using a YSI model 50B-115V meter. Light profiles were measured using a Li Cor L1-1000 Datalogger and transparency was measured using a Secchi disk. Water samples were collected from the surface ($\leq$ 0.2m) and Secchi depth on each sampling occasion. Additional samples were collected periodically from the metalimnion and hypolimnion. Deep water samples were collected with a 2 liter Wildco vertical sample bottle. All samples were stored on ice and transferred back to the University for processing within 24 hours of collection. These samples were analyzed for the same parameters as those collected by volunteers as well as the following parameters; soluble reactive phosphorus (SRP), nitrite-nitrate nitrogen (NO_3-N), ammonia nitrogen (NH_4-N), whole water conductivity and turbidity. Analytical method for DP and TP was E.P.A. number 365.3 (1979). DN and TN were analyzed according to Crumpton et al (1992). Chlorophyll (CHL) was evaluated by fluorometry after heated ethanol extraction (Sartory and Grobbelarr 1986). Other parameters were analyzed according to APHA (1989).

Nutrient Stimulation Experiments

Nutrient limitation of algal biomass was evaluated periodically during the study in all but three reservoirs (Catalina, Lafitte and Marseilles) through use of NSEs. The experiments followed procedures described in Jones et al. (1990) with slight modifications. NSEs were conducted in four liter, transparent, polyethylene cubitainers filled with surface water and suspended at one half of the Secchi depth. Four treatments were used in the experiments; control, nitrogen addition, phosphorus addition and combination of nitrogen and phosphorus addition. Nutrient additions were based on historic nutrient concentrations from each reservoir. Phosphorus additions were set at 30% - 80% of ambient levels, with nitrogen being added at a 16N:1P mass ratio to mimic the N:P ratio of the eutrophic reservoirs in the study. Phosphorus and nitrogen spikes were made with Na_2HPO_4 and NH_4NO_3, respectively. Three experimental units, each containing all four treatments, were incubated *in situ* for 4 to 7 days depending on the season, with longer incubations during the winter. At the termination of the experiment, cubitainers were stored on ice and transferred back to the University for processing. Two filters were processed from each cubitainer for CHL. Surface samples were taken at the beginning of each experiment to determine initial concentrations of nutrients and CHL used in the experiment.

Data Analysis

Seasonal Analysis - Scaled Proportion

Data were divided into subsets representing spring, summer and fall collections, with the summer subset consisting of data collected between 16 May and 15 September 1994. These dates were selected because they approximate the beginning and end of summer stratification in Missouri reservoirs based on unpublished data (University of Missouri). Spring and fall subsets consisted of data collected before and after this period, respectively.

Analysis of seasonal patterns was conducted with normalized data following a modified version of methods described by Marshall and Peters (1989). A mean CHL value was calculated for each reservoir using all data collected during the spring-fall period. A scaled proportion, Pt, was then calculated for each individual value from a given reservoir using the equation:

$$Pt = 100 \times [\,(xt - \bar{x})\,/\,\bar{x}\,] \qquad \text{(equation 1)}$$

were xt is the CHL concentration on day t and $\bar{x}$ is the mean CHL concentration for that reservoir. This method normalized data to individual reservoir means, thus allowing for cross system comparison over the range of trophic state conditions.

Reservoirs were divided into trophic state classes and P*t* values were plotted over time using robust locally weighted regression analysis (LOWESS) to evaluate seasonal patterns of CHL. This method differed from that of Marshall and Peters (1989) in that P*t* values were not averaged when multiple reservoirs were sampled on the same day and values were not interpolated to represent conditions for dates when reservoirs were not sampled. This normalization approach was also used to determine seasonal patterns of TN and TP.

Seasonal Analysis - Seasonal Means, Extreme Values and Variability

Seasonal average CHL, TN and TP were calculated for spring, summer, fall and spring-fall periods for each study reservoir. Averages were then statistically analyzed to test for among season differences within each reservoir using the Bonferroni t-test ($\propto = 0.05$) with SAS software.

Extreme low and high values were identified by first calculating means and standard deviations for trophic state parameters for each reservoir using all data from the spring-fall period. Individual values were then examined, and any value more than one standard deviation away from the mean was considered extreme. This method differed from the approach of Marshall and Peters (1989), who used logarithm transformed data and 80% confidence intervals to identify extreme values. When applied to the current study, the Marshall and Peters (1989) approach registered a large number of extreme values in reservoirs with >30 samples. The excessive number of extreme values generated by the Marshall and Peters (1989) approach limited the methods utility in identifying seasonal patterns and necessitating use of a different approach to identifying extreme values.

Coefficient of variance (CV) values were calculated for trophic state parameters during the various sampling periods for individual reservoirs. Use of CV values allowed for comparison of reservoirs of different trophic status, and comparison of the relative variability of the measured parameters.

Trophic State Assessment

Influence of seasonal patterns on trophic state assessment was determined by calculating average CHL for each of the 13 reservoirs during spring, summer, fall and spring-fall periods. Reservoirs were then classified into trophic state categories for these time periods, and comparisons were made across periods to determine seasonal variation in trophic state classification. Classifications based on TN and TP were evaluated following the same procedure. Trophic state criteria used in this analysis were developed by Jones and Knowlton (1993) for Missouri reservoirs based on summertime data.

Sample Size

The number of samples required to estimate mean CHL, TN and TP for various levels of precision were calculated following the approach of Marshall *et al*. (1988). Regression models were developed for both summer and spring-fall periods using individual reservoir mean and variance values (both log transformed). Regression equations were transformed into power formulas, and then integrated into the following equation: $n = s^2 p^{-2} \bar{x}^{-2}$ (equation 2)

where p is the desired precision expressed as coefficient of variation (Marshal *et al*. 1988). The number of observations required to estimate mean conditions were calculated for various p values over the range of CHL concentrations expected in Missouri reservoirs. The required sample effort for estimating mean TN and TP were calculated following the above procedure.

Evaluation of the potential bias in estimating mean CHL and nutrient concentrations associated with various sample sizes were made following a modification of the method described by Marshall *et al*. (1988). Potential bias was evaluated on the six reservoirs with sufficient data for both summer (n >15 samples) and spring-fall (n >30 samples) periods, with separate analysis occurring for each reservoir/time period.

Mock seasonal sub-means for a sample size of two were generated by ordering data chronologically, and then dividing the data set into two equal intervals representing the first and second half of the period being investigated. Mock seasonal sub-mean$_1$ was generated by calculating an average using the first value from the two intervals. An average of the second value in each interval was then generated to create mock seasonal sub-mean$_2$. This process of generating mock seasonal sub-means continued until sub-mean$_X$ was generated, with x = the smallest number of samples within either interval. The ordered data set was then divided into three equal sized intervals and sub-means generated following the above procedure. The process continued until sub-means were generated for a sample size of eight for summer data sets and ten for spring-fall data sets.

The number of values within each interval decreased as sample size increased, and some data manipulation was required to generate a sufficient number of mock seasonal sub-means for analysis. Additional mock sub-means were generated by alternating odd and even values within the even numbered intervals, then following the above procedure to calculate mock sub-means. This slight modification allowed for twice the number of sub-means to be calculated while still maintaining the relative spacing between samples. Once sub-means were calculated, potential bias was calculated using the following formula:

$$100 \text{ x } [(\bar{x}' - \mu) / \mu] \qquad \text{(equation 3)}$$

where $\bar{x}'$ represents an individual sub-mean and μ is the true mean for that reservoir (Marshall *et al*. 1988).

Nutrient Regulation - Nutrient Stimulation Experiments

Nutrient stimulation experiment (NSE) results are reported as a percent change relative to the control treatment and were calculated using the following equation:

$$(T-C)/C*100 \qquad \text{(equation 4)}$$

where T equals the average CHL concentration for a nutrient treatment (nitrogen, phosphorus, or nitrogen and phosphorus) and C equals the average CHL concentration for the control. All NSE results were averages of at least two replicate experimental sets, with the majority being averages from three sets. The lone exception was the nitrogen result from the September 1994 experiment on Little Dixie, which represents only one experimental unit. Statistical analysis was conducted using a T-test procedure (LSD) in SAS software.

Nutrient Regulation - Models and Ratios

Nutrient-CHL models were developed using log transformed mean values from all 13 reservoirs. Models were generated for each individual season as well as for the spring-fall period.

Ratios of TN:TP and DN:DP were calculated for each individual sample date for all reservoirs. The seasonal pattern of ratios was analyzed by plotting ratios over time and using robust locally weighted regression analysis (LOWESS). The same approach was taken for CHL:TP and CHL:TN.

RESULTS

Samples were collected April through November 1994, with the period of collection ranging from 151 to 238 days (median = 201). Six reservoirs were sampled twice each week and are represented in the data set by 46 to 65 samples. The remaining seven reservoirs were represented by 22 to 28 samples.

Based on mean summer CHL (Table 2) and criteria outlined in Jones and Knowlton (1993) four reservoirs were oligotrophic (Capri, Lafitte, Shayne and Weatherby), four mesotrophic (Carmel, Marseilles, Catalina and Table Rock), three eutrophic (Longview, Blue Springs and Little Dixie) and two hypereutrophic (Kraut Run and Chesterfield). Trophic state classifications based on summertime TN (Table 2) differed from CHL in that none of the reservoirs were classified as oligotrophic, seven were mesotrophic, five eutrophic and one hypereutrophic. Classifications based on TP were similar to those based on CHL (Table 2), with two reservoirs differing in their classification; Weatherby was mesotrophic and Kraut Run was eutrophic based on TP. Hypereutrophic reservoirs were combined with eutrophic reservoirs in the ensuing analyses unless otherwise noted.

Table 2. Reservoirs divided into trophic state groups based on mean summer chlorophyll (CHL). Letters following mean total nitrogen (TN) and mean total phosphorus (TP) values indicate trophic state assessment based on nutrient data. O = oligotrophic, M = mesotrophic, E = eutrophic and H = hypereutrophic. All values in μg/L.

Trophic State	Reservoir	CHL	TN	TP
Oligotrophic	Capri	1.4	405 M	8 O
	Lafitte	2.0	364 M	10 O
	Shayne	2.8	436 M	9 O
	Weatherby	2.8	372 M	16 M
Mesotrophic	Carmel	3.5	538 E	14 M
	Marseilles	3.6	456 M	14 M
	Catalina	4.0	593 E	23 M
	Table Rock	5.3	366 M	14 M
Eutrophic	Longview	8.0	737 E	26 E
	Blue Springs	15.3	491 M	31 E
	Little Dixie	18.4	804 E	71 E
Hypereutrophic	Kraut Run	40.0	905 E	84 E
	Chesterfield	41.1	1264 H	110 H

Seasonal Patterns in Oligotrophic Reservoirs

Collectively, the four oligotrophic reservoirs displayed a seasonal CHL pattern of higher than mean levels in spring, with values below the mean during summer and fall (Figure 7). This pattern was similar to the oligotrophic pattern identified by Marshall and Peters (1989), with the springtime peak in CHL occurring about a month earlier in Missouri reservoirs. Also, CHL values were slightly below the mean in Missouri reservoirs during September and October, while Marshall and Peters (1989) found values greater than the mean during these months.

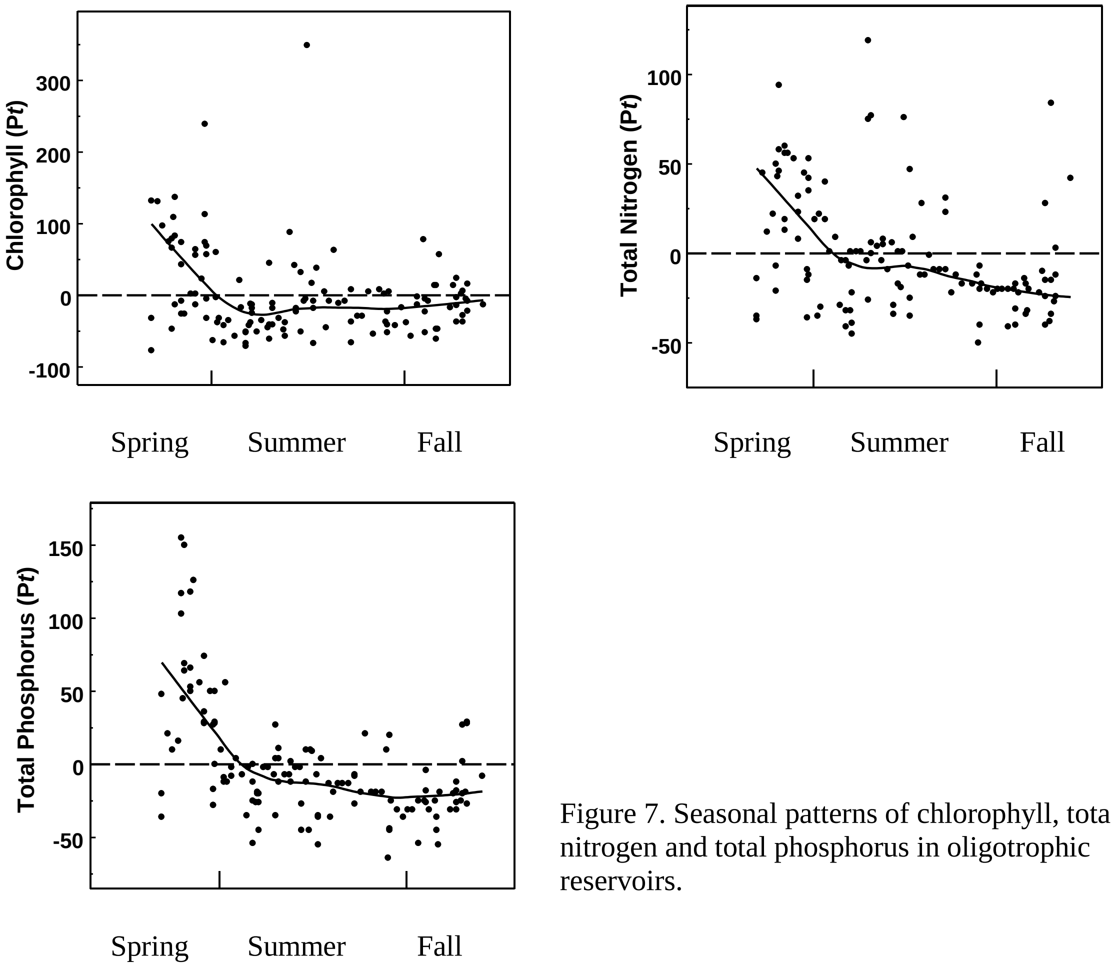


Figure 7. Seasonal patterns of chlorophyll, total nitrogen and total phosphorus in oligotrophic reservoirs.

Individually, oligotrophic reservoirs displayed two different patterns in CHL abundance (Appendix A). The spring period was dominated by the highest CHL values in Capri and Lafitte, with values below mean levels for most of the remaining season; Shayne followed this pattern except for one extreme summer CHL value. The spring season in

Weatherby was also dominated by above mean CHL, but this reservoir differed from others in that periods of both above and below mean CHL occurred in summer and fall. Maximum and minimum values in the four oligotrophic reservoirs ranged from 131% to 349% above and 61% to 77% below individual reservoir means, respectively.

TN values in oligotrophic reservoirs were greater than the mean during spring, near mean during summer, and below the mean during fall (Figure 7). There were two general patterns among these reservoirs. Capri, Lafitte and Shayne had values above and below mean conditions in every season, while TN values decreased over time in Weatherby (Appendix A). Maximum TN values ranged from 56% to 119% above individual reservoir means, and minimum values ranged from 37% to 50% below means.

The oligotrophic reservoirs displayed above mean TP values during spring and values below the mean during summer and fall (Figure 7, Appendix A), with none of the reservoirs deviating from this seasonal pattern. Maximum and minimum TP values for oligotrophic reservoirs ranged from 117% to 155% above and 36% to 64% below individual reservoir means, respectively.

Seasonal Patterns in Mesotrophic Reservoirs

CHL concentrations in mesotrophic reservoirs were above mean levels during spring, decreased through summer and were below mean in fall (Figure 8). Individually, the four reservoirs generally followed the same CHL pattern, although Table Rock had a higher proportion of above mean values than the other three reservoirs during summer and fall (Appendix A). Maximum values among all four reservoirs ranged from 171% to 482%

of individual means and three reservoirs had maximum values greater than 200% of the individual means. Minimum values ranged from 73% to 94% below individual reservoir means.

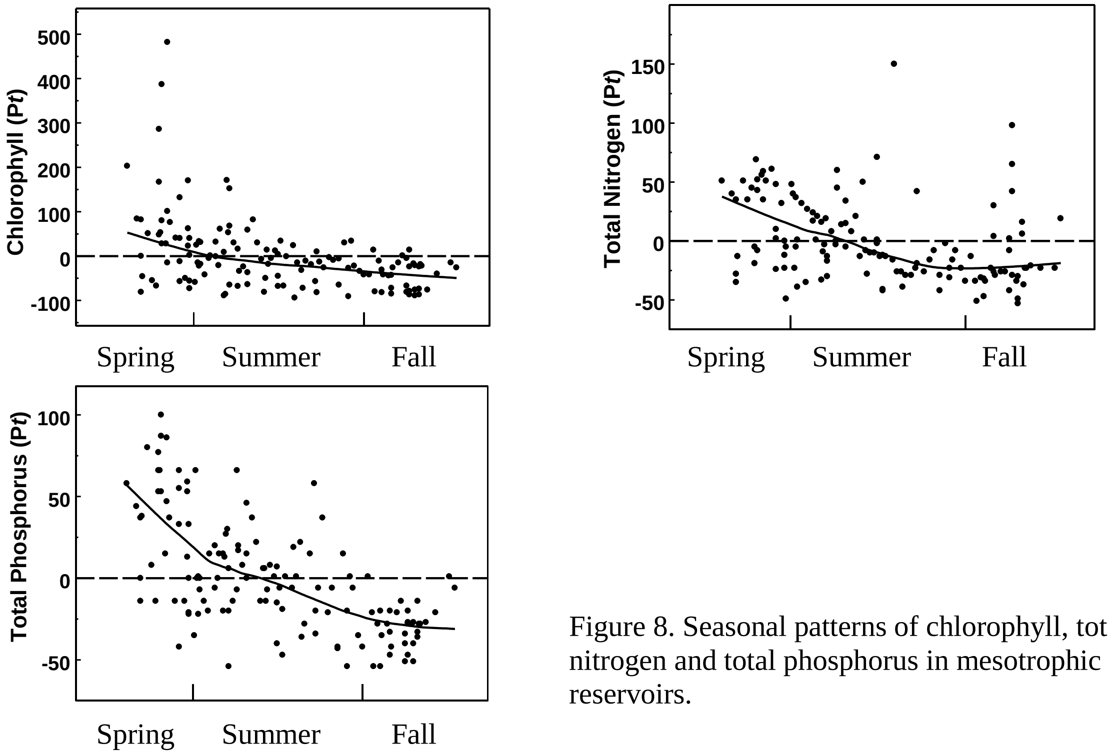


Figure 8. Seasonal patterns of chlorophyll, total nitrogen and total phosphorus in mesotrophic reservoirs.

The TN pattern was similar to CHL, with above mean conditions in spring and below mean values in fall (Figure 8). Two discernable patterns were evident when reservoirs were examined individually (Appendix 1). Table Rock displayed a pattern of high TN in spring with decreasing values through summer and fall, while TN values in the other three mesotrophic reservoirs fluctuated around the mean throughout spring-fall. Maximum TN values range from 61% to 150% higher than the individual means.

Minimum values ranged from 35% to 53% below the individual means.

TP values in mesotrophic reservoirs (Figure 8) were generally greater than the mean during spring, near mean in summer and below the mean during fall. Individually, the four mesotrophic reservoirs displayed the same general pattern, with Table Rock having values above the mean for a longer period compared to the other reservoirs (Appendix A). Maximum TP values ranged from 74% to 101% greater than the individual reservoir means, while minimum values ranged from 37% to 54% below the individual means.

Seasonal patterns in Eutrophic Reservoirs

Collectively, eutrophic reservoirs did not exhibit the bimodal CHL pattern described by Marshall and Peters (1989). Instead, the pattern consisted of values slightly lower than mean in spring and above mean during summer and fall (Figure 9). There was substantial scatter in the data, with values 100% higher and 50% lower than the normalized mean occurring throughout the sampling period. The overall pattern for eutrophic reservoirs did not change when hypereutrophic reservoirs were removed from the analysis (Figure 10).

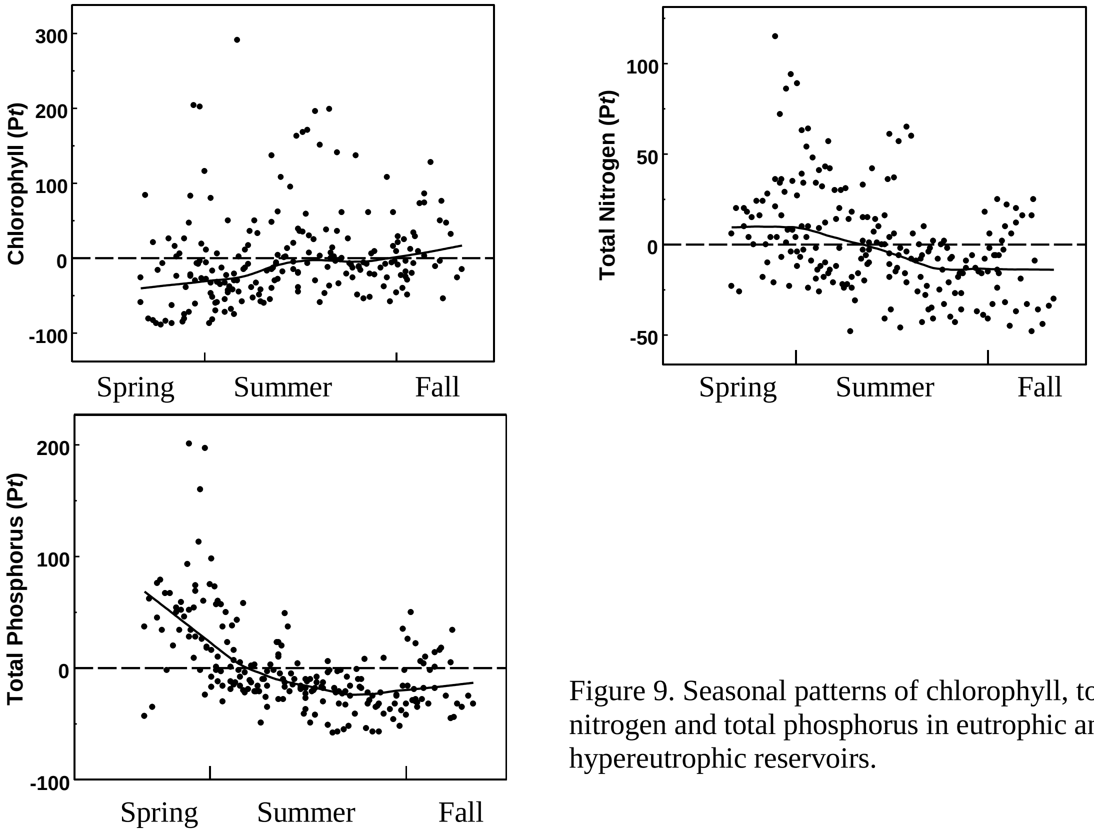


Figure 9. Seasonal patterns of chlorophyll, total nitrogen and total phosphorus in eutrophic and hypereutrophic reservoirs.

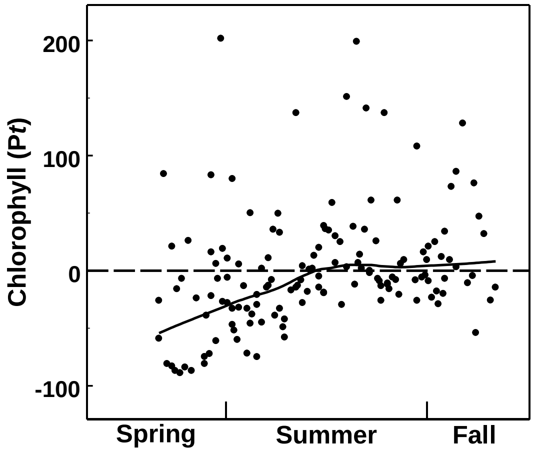


Figure 10. Seasonal patterns of chlorophyll in eutrophic reservoirs.

High levels of NVSS can reduce algal biomass in Missouri reservoirs through light limitation (Hoyer and Jones 1983, Jones and Knowlton 1993). Jones and Knowlton (1993) suggested that an NVSS value >10 mg/L could serve as a cut-point to identify waterbodies in which NVSS reduced algal CHL relative to available nutrients. To evaluate the role of NVSS on seasonal CHL patterns, samples with NVSS >10 mg/L were removed from the Little Dixie, Blue Springs, Longview and Kraut Run data sets. Chesterfield was not included in this analysis because the majority (64%) of NVSS values were >10 mg/L. Mean CHL values were recalculated for each reservoir and used to compute new P*t* values (Figure 11). This approach was repeated for CHL values associated with NVSS >7 mg/L, but the removal of high NVSS samples did not change the overall seasonal pattern of CHL in either of the re-calculated data sets (Figure 11).

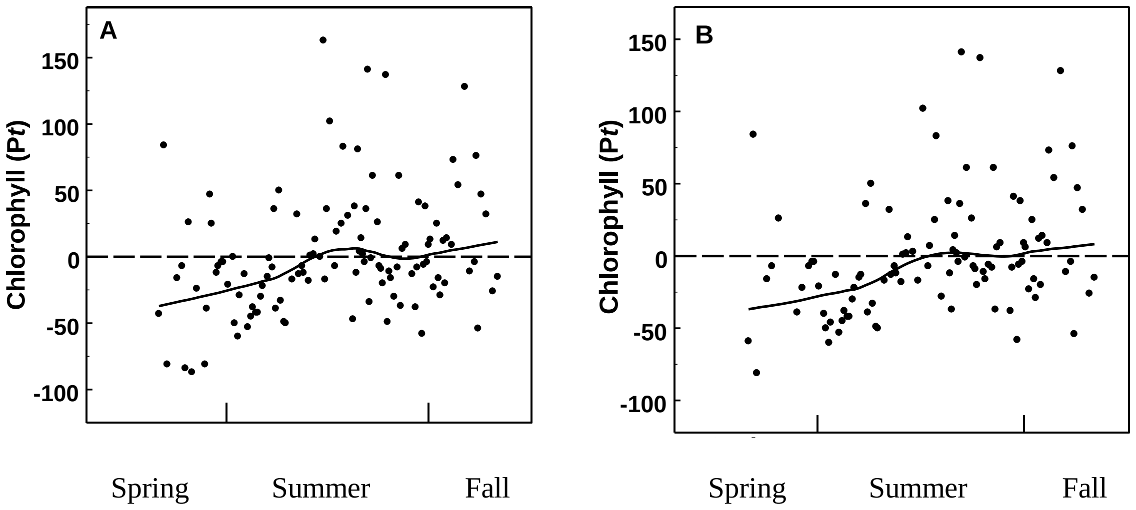


Figure 11. Seasonal patterns of chlorophyll in eutrophic/hypereutrophic reservoirs after data had been reduced by removing chlorophyll values that correspond to non-volatile suspended solids concentrations of >10 mg/L (A) and >7 mg/L (B).

Individual CHL patterns differed among eutrophic reservoirs, displaying no uniform trends (Appendix A). Blue Springs and Kraut Run did display bimodal seasonal CHL patterns that mimicked the pattern for eutrophic lakes identified by Marshall and Peters (1989). The remaining eutrophic reservoirs had CHL patterns that ranged from a single springtime peak (Longview) to an extended mid-summer CHL peak (Little Dixie). Maximum values occurred throughout the sampling period and ranged from 74% to 291% of reservoir means, with three reservoirs having maximum values $\geq$200% the mean. Minimum values ranged from 58% to 89% below reservoir means.

The TN pattern in the eutrophic reservoirs consisted of higher than mean conditions in spring, decreasing values through summer, and below mean levels in fall (Figure 9). Individual reservoirs displayed variable seasonal TN trends. Spring and fall peaks with a summer depression were seen in Kraut Run but not Blue Springs. The pattern of high spring values followed by decreasing values during summer and fall was evident in Longview and Little Dixie, while Chesterfield had values above mean levels into the summer followed by low levels in fall. Maximum TN values ranged from 25% to 115% above individual reservoir means, while minimum values ranged 22% to 48% below TN means.

As a group, eutrophic reservoirs displayed high TP levels relative to the mean during spring, with the most values being below mean during summer and fall (Figure 9). Individually, TP in eutrophic reservoirs showed two general patterns (Appendix A). Blue Springs and Kraut Run had TP values above mean during spring and fall, with summertime depressions. Little Dixie, Longview and Chesterfield had high TP values in spring and values below mean in summer and fall. Maximum and minimum TP values ranged from 54% to 201% above and 30% to 58% below individual reservoir means.

Seasonality of Chlorophyll, Total Nitrogen and Total Phosphorus - Statistical Analysis

Individual seasonal means for CHL, TN and TP from the study reservoirs are presented in Tables 3-5. Mean springtime CHL was significantly larger than summertime means in three of the four oligotrophic reservoirs (Table 3). This pattern differed from the meso- and eutrophic reservoirs where significant differences between spring and summer mean CHL were found in only two of the nine reservoirs; Catalina (mesotrophic) had significantly higher spring CHL, while Little Dixie (eutrophic) had higher summer CHL values (Tables 4 and 5).

There were no consistent seasonal differences in mean TN values within any of the three trophic state categories (Table 3-5). In contrast, reservoirs in all three trophic state categories showed strong seasonal differences in TP. In all four oligotrophic reservoirs mean springtime TP values were significantly larger than summertime means. Three of four mesotrophic reservoirs had mean springtime TP concentrations that were significantly larger than mean values during the other time periods. The same seasonal differences were observed in eutrophic reservoirs, where four of five had mean springtime TP values significantly larger than the other periods.

Table 3. Seasonal averages and statistical differences of three trophic parameters for oligotrophic reservoirs. All average values in μg/L.

Reservoir	Parameter	Spring	Summer	Fall	Spring-Fall
Capri	CHL	3.6^{A}	1.4^{B}	1.8^{B}	2.0^{B}
	TN	457^{A}	405^{A}	360^{A}	407^{A}
	TP	17^{A}	8^{B}	9^{B}	11^{B}
	n	7	13	7	27
Lafitte	CHL	4.8^{A}	2.0^{B}	3.0^{AB}	3.1^{AB}
	TN	490^{A}	364^{A}	356^{A}	399^{A}
	TP	17^{A}	10^{B}	12^{AB}	12^{AB}
	n	7	12	6	25
Shayne	CHL	2.3^{A}	2.8^{A}	1.2^{A}	2.1^{A}
	TN	433^{A}	436^{A}	326^{A}	397^{A}
	TP	17^{A}	9^{B}	8^{AB}	11^{AB}
	n	7	8	8	23
Weatherby	CHL	4.7^{A}	2.8^{B}	3.3^{AB}	3.2^{B}
	TN	532^{A}	372^{B}	294^{C}	385^{B}
	TP	26^{A}	16^{BC}	13^{C}	17^{B}
	n	10	35	11	56

Table 4. Seasonal averages and statistical differences of three trophic parameters for mesotrophic reservoirs. All average values in μg/L.

Reservoir	Parameter	Spring	Summer	Fall	Spring-Fall
Carmel	CHL	27.2^{A}	3.5^{B}	1.5^{B}	9.1^{B}
	TN	508^{A}	538^{A}	458^{A}	508^{A}
	TP	22^{A}	15^{B}	10^{B}	15^{B}
	n	7	12	8	27
Marseilles	CHL	3.1^{A}	3.6^{A}	2.4^{A}	3.2^{A}
	TN	436^{A}	456^{A}	428^{A}	444^{A}
	TP	20^{A}	14^{B}	11^{B}	15^{B}
	n	7	12	6	25
Catalina	CHL	11.3^{A}	4.3^{AB}	1.6^{B}	5.8^{AB}
	TN	611^{A}	569^{A}	712^{A}	621^{A}
	TP	44^{A}	24^{B}	17^{B}	28^{B}
	n	7	10	5	22
Table Rock	CHL	6.4^{A}	5.3^{A}	4.2^{A}	5.2^{A}
	TN	559^{A}	366^{B}	286^{C}	384^{B}
	TP	16^{A}	14^{A}	11^{B}	14^{A}
	n	14	36	15	65

Comparisons between summer and spring-fall means showed no significant differences in any of the 13 reservoirs for CHL or TN (Table 3-5). Summer and spring-fall TP differed significantly in only one reservoir, Blue Springs, where there was a modest difference between means (36 vs. 31 μg/L).

Table 5. Seasonal averages and statistical differences of three trophic parameters for eutrophic reservoirs. All average values in μg/L.

Reservoir	Parameter	Spring	Summer	Fall	Spring-Fall
Longview	CHL	7.8^{A}	8.0^{A}	8.0^{A}	8.0^{A}
	TN	1403^{A}	737^{B}	471	732^{B}
	TP	71^{A}	26^{B}	24^{B}	29^{B}
	n	4	33	10	47
Blue Springs	CHL	20.2^{B}	15.3^{B}	28.0^{A}	18.6^{B}
	TN	550^{A}	491^{B}	550^{A}	515^{AB}
	TP	49^{A}	31^{C}	37^{BC}	36^{B}
	n	12	29	8	49
Little Dixie	CHL	4.9^{B}	18.4^{A}	10.6^{AB}	14.4^{A}
	TN	954^{A}	804^{A}	708^{A}	833^{A}
	TP	105^{A}	71^{B}	51^{B}	78^{B}
	n	11	30	5	46
Kraut Run	CHL	52.7^{A}	40.0^{A}	65.2^{A}	48.1^{A}
	TN	1147^{AB}	905^{B}	1198^{A}	1016^{AB}
	TP	107^{A}	84^{A}	108^{A}	94^{A}
	n	4	13	5	22
Chesterfield	CHL	49.9^{A}	41.1^{A}	25.6^{A}	41.5^{A}
	TN	1159^{A}	1264^{A}	1130^{A}	1239^{A}
	TP	216^{A}	110^{B}	88^{B}	125^{B}
	n	7	37	3	47

Extreme Values

Extreme low CHL values (-1 standard deviation from individual reservoir means) were measured in oligotrophic reservoirs April through October (Figure 12). While extreme high CHL values (+1 standard deviation) also occurred during this period, the majority (78%) were measured in April and May. TN also exhibited extreme low and high values throughout the period, with the majority (68%) of high values occurring in April and May. TP differed in that no extreme low values were measured in April and May in the oligotrophic reservoirs, while all extreme high values were measured in these two months (Figure 12).

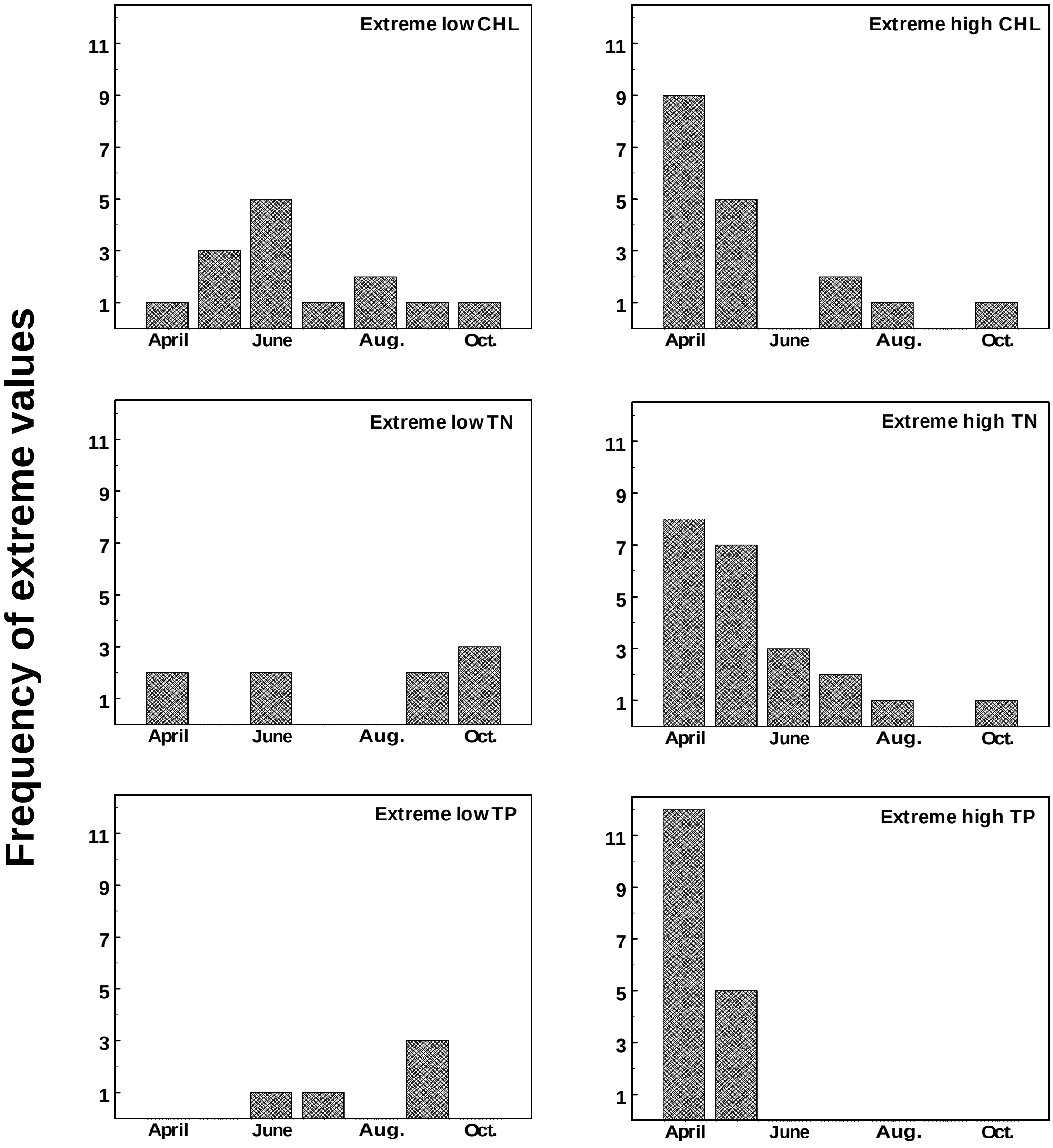


Figure 12. Frequency of extreme chlorophyll (CHL), total nitrogen (TN) and total phosphorus (TP) values in oligotrophic reservoirs.

Among mesotrophic reservoirs, seven of eight extreme low CHL measurements occurred in the first two months (Figure 13). The pattern for high CHL values was similar; all were measured in April and June. Extreme low TN and TP values occurred throughout the period but the majority (TN=80%, TP= 67%) were measured in September and October, while most extreme high values (TN=64%, TP=77%) were measured in April and May.

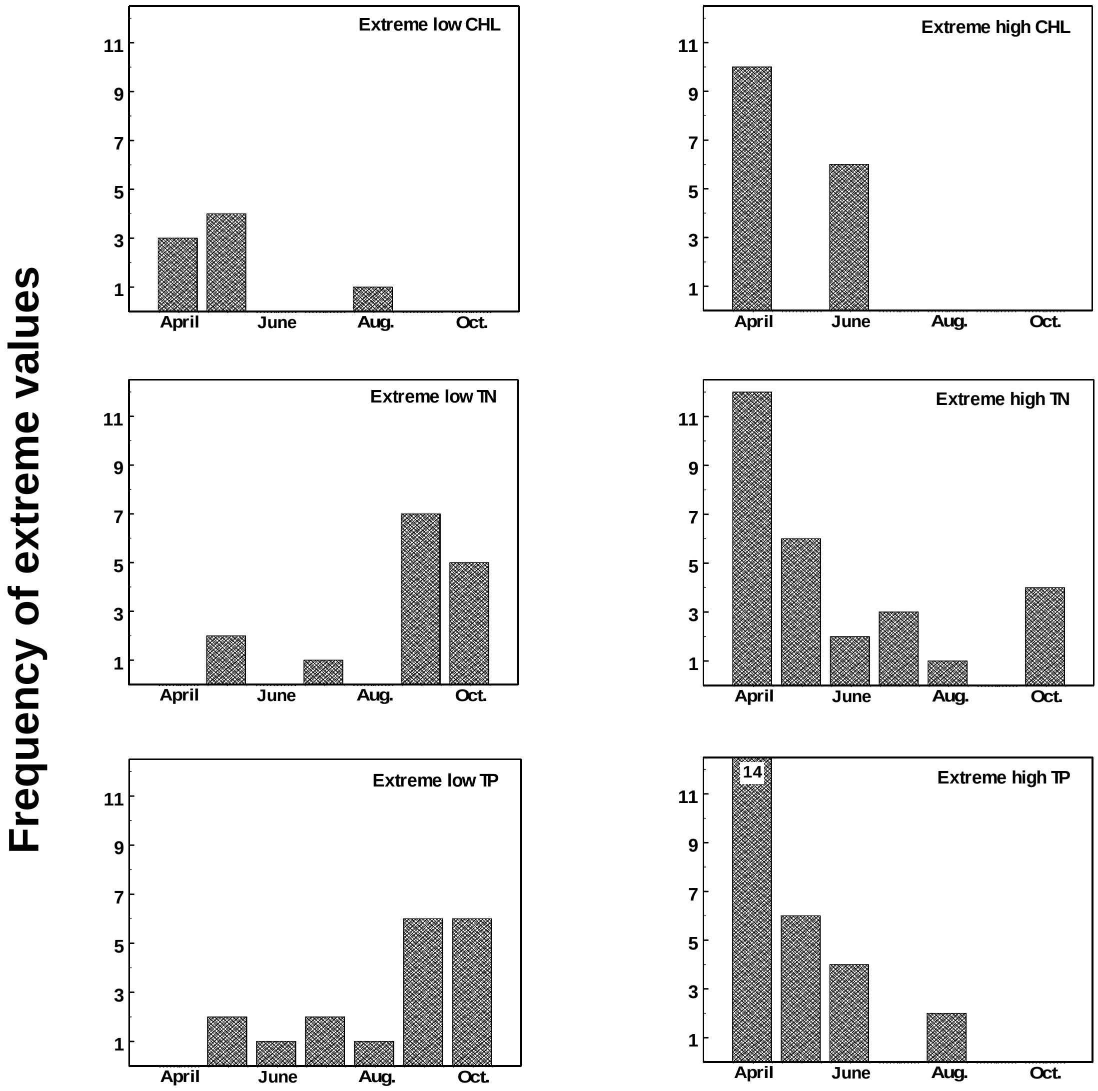


Figure 13. Frequency of extreme chlorophyll (CHL), total nitrogen (TN) and total phosphorus (TP) values in mesotrophic reservoirs.

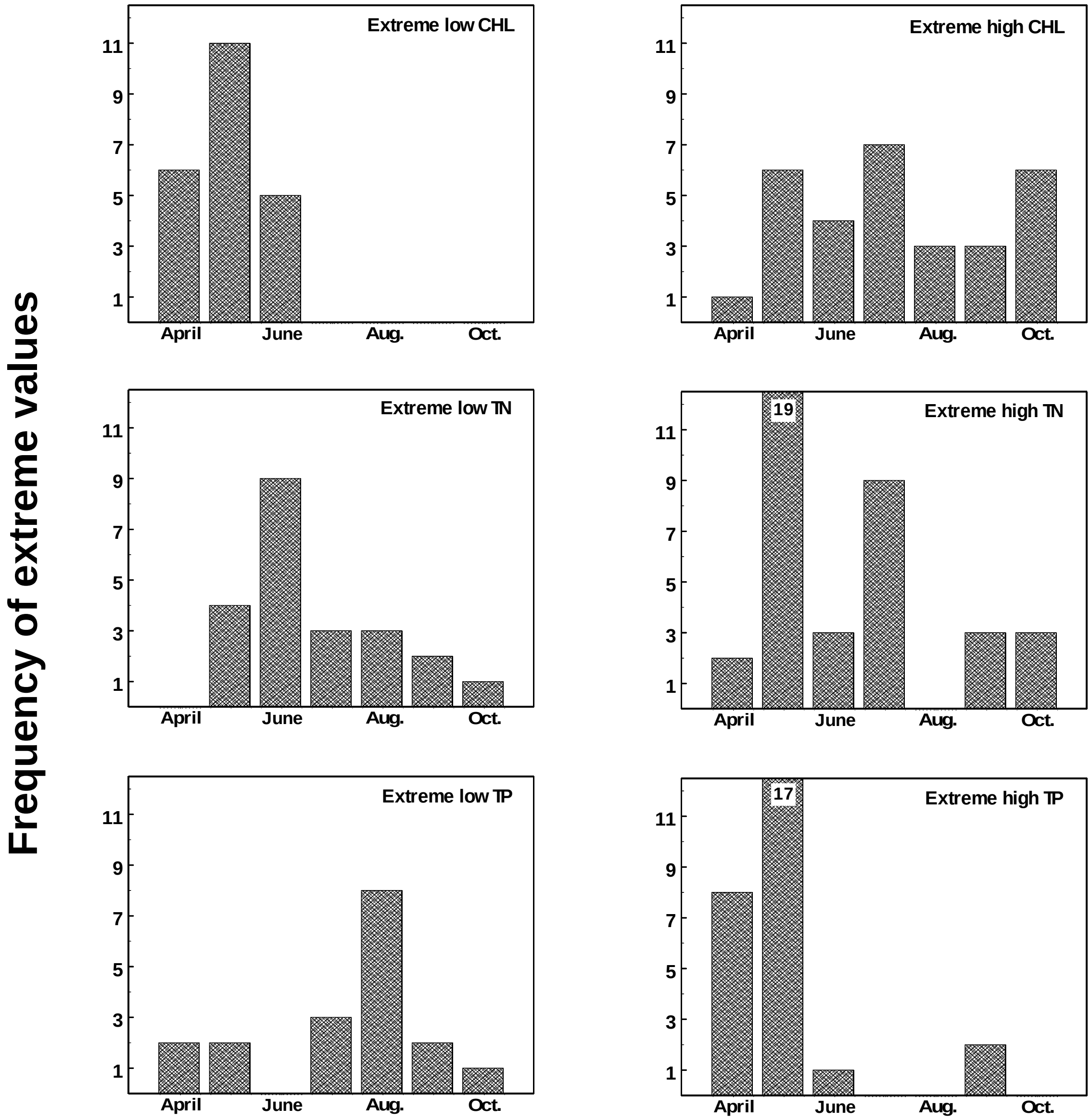


Figure 14. Frequency of extreme chlorophyll (CHL), total nitrogen (TN) and total phosphorus (TP) values in eutrophic reservoirs.

Extreme low CHL in eutrophic reservoirs occurred April-June, while extreme high values were measured throughout the period, with no discernable seasonal pattern (Figure 14). Extreme low TN values were measured each month except April and extreme high TN values were measured throughout the period, with ~50% occurring in May. Extreme low TP values in eutrophic reservoirs were measured each month except June, with 44%

occurring in August. The majority (89%) of extreme high TP values occurred during April and May.

Variance and Coefficient of Variation

The regression relationship between CHL mean and variance (log transformed data) for the 13 reservoirs was similar across all time periods (Table 6), with the y-intercept displaying minor differences. Marshall *et al*. (1988) described this relationship using growing season CHL data with the following equation:

$$\log (s^2) = -1.03 + 2.50 (\log \bar{x})$$

Results from this study differ from those found by Marshall *et al*. (1988) in that the y-intercept was closer to zero (0.33) and the slope shallower (1.93) among Missouri reservoirs. When the two regression lines are plotted together they intersect at a CHL value of 16.8 µg/L. Below this value Missouri reservoirs showed more variability than data of Marshall *et al*. (1988) and less variability for CHL values above 16.8 µg/L (Figure 15).

Table 6. Chlorophyll variance – chlorophyll mean regression equations for different seasonal periods.

Period	Line Equation	r^2
Spring	$\log (s2) = -0.40 + 1.91 (\log \bar{x})$	0.91
Summer	$\log (s2) = -0.51 + 1.93 (\log \bar{x})$	0.91
Fall	$\log (s2) = -1.21 + 1.93 (\log \bar{x})$	0.99
Spring-Fall	$\log (s2) = -0.33 + 1.93 (\log \bar{x})$	0.93

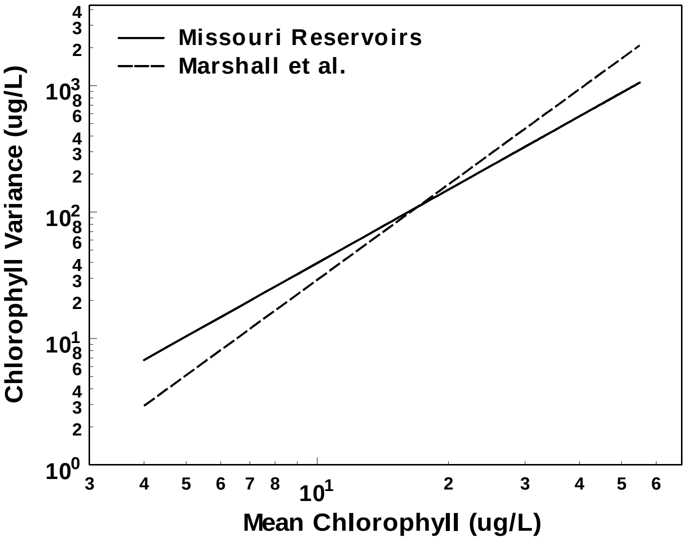
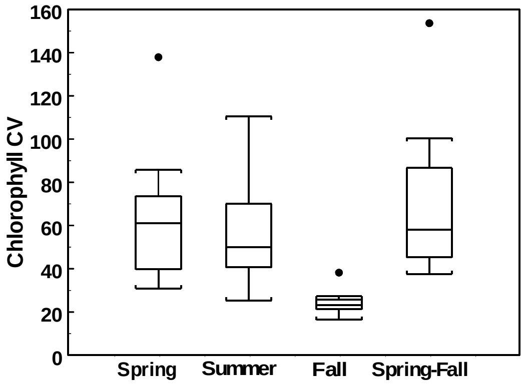


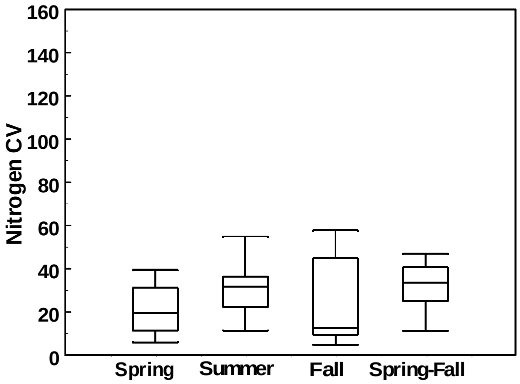
Figure 15. Relation between mean chlorophyll and variance for Missouri reservoirs and lakes studied by Marshall *et al.* (1988).

Because CHL variance correlates to mean CHL, use of variance for comparing reservoirs of different trophic status had limited value. To overcome this limitation, coefficient of variation (CV) values were calculated to compare reservoirs across the range of trophic status (Table 7). The CHL CV values for the 13 reservoirs were lowest in fall (median = 23.2), with the other three seasonal periods having similar ranges of CV and medians that were 2-3 times higher than the fall median (Figure 16, Table 7). The range of TN CV values overlapped for all seasonal periods, with fall having the lowest median CV value as well as the largest range of values (Table 7, Figure 16). CV values for TP were lowest in fall, highest during spring-fall period, with spring and summer being intermediate (Table 7, Figure 16). The CV data indicate that CHL was more variable than TN and TP, with median CHL CV values that were often double those of the nutrients (Table 7).

Table 7. Coefficient of Variation data for the 13 reservoirs as a group.

		Minimum	Maximum	Mean	Median
Chlorophyll	Spring	30.9	137.9	62.5	61.5
	Summer	25.3	110.4	57.7	50.0
	Fall	16.5	38.2	23.8	23.2
	Spring-Fall	37.6	153.6	69.1	58.1
Total Nitrogen	Spring	5.9	39.5	21.7	19.5
	Summer	11.2	54.9	30.3	31.8
	Fall	4.6	57.9	25.0	12.5
	Spring-Fall	11.1	47.0	32.0	33.5
Total Phosphorus	Spring	13.3	43.7	28.5	29.9
	Summer	9.1	48.7	25.8	24.4
	Fall	2.3	40.1	18.4	16.6
	Spring-Fall	22.5	55.5	39.3	37.1





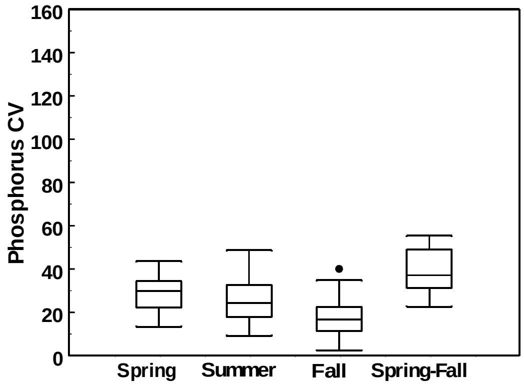


Figure 16. Distribution of coefficient of variation data for chlorophyll, total nitrogen and total phosphorus from different seasonal periods.

Non-Volatile Suspended Solids

Mean non-volatile suspended solids (NVSS) values during spring were larger than summer values for all thirteen reservoirs (Table 8). Differences between spring and summer mean NVSS ranged from < 0.5 mg/L (Carmel and Table Rock) to > 14 mg/L (Chesterfield and Longview). Inadequate sample size during fall for half of the reservoirs limited statistical comparison, but in those reservoirs with ≥4 fall samples mean NVSS values were similar to summer values. The exception was Kraut Run, which displayed the largest mean NVSS in fall.

Table 8. Mean Non-Volatile Suspended Solids values (mg/L)

Reservoir	Spring	Summer	Fall	Spring-Fall
Capri	6.2	0.7	0.8	3.0
Lafitte	1.4	0.5	1.1	0.9
Shayne	3.4	1.6	0.8	2.3
Weatherby	4.8	2.0	1.4	2.4
Carmel	3.7	3.6	No data	3.7
Marseilles	2.4	1.2	0.2	1.6
Catalina	5.6	3.5	1.6	4.4
Table Rock	1.7	1.5	0.8	1.4
Longview	19.2	4.0	3.0	5.0
Blue Springs	6.9	2.8	3.7	3.9
Little Dixie	10.7	6.9	4.6	7.7
Kraut Run	8.4	4.2	10.5	6.3
Chesterfield	28.9	14.0	12.9	16.3

Trophic State Assessment

Trophic state classifications based on average CHL values from the individual seasons indicate a shift toward lower algal biomass from spring to summer and then fall (Table 9). The number of reservoirs classified as oligotrophic increased from one during spring, to four and five based on summer and fall data, respectively. This increase in oligotrophic reservoirs corresponds with a concurrent decrease in mesotrophic reservoirs, while the number of reservoirs classified as eutrophic or hypereutrophic remained constant (Table 9).

Table 9. Rankings and trophic state assessments based on average chlorophyll concentrations during different seasonal periods.

	Spring	Summer	Fall	Spring-Fall
Oligotrophic ≤ 3µg/L	Shayne	Capri Lafitte Shayne Weatherby	Shayne Carmel Catalina Capri Marseilles	Capri Shayne
Mesotrophic >3 - 7µg/L	Marseilles Capri Weatherby Lafitte Little Dixie Table Rock	Carmel Marseilles Catalina Table Rock	Lafitte Weatherby Table Rock	Lafitte Marseilles Weatherby Table Rock Catalina
Eutrophic >7 - 40µg/L	Longview Catalina Blue Springs Carmel	Longview Blue Springs Little Dixie	Longview Little Dixie Chesterfield Blue Springs	Longview Carmel Little Dixie Blue Springs
Hypereutrophic >40µg/L	Chesterfield Kraut Run	Kraut Run Chesterfield	Kraut Run	Chesterfield Kraut Run

None of the 13 reservoirs were classified as oligotrophic based on spring TN or TP values (Tables 10 and 11). There was a shift based on nutrients toward oligotrophic classifications during summer and fall, though the shift was less dramatic than observed with CHL. Also, shifts in trophic state classifications based on nutrients occurred across the range of trophic states; as oligotrophic classifications increased, eutrophic classifications decreased.

Table 10. Rankings and trophic state assessments based on averaged total nitrogen concentrations during different seasonal periods.

	Spring	Summer	Fall	Spring-Fall
Oligotrophic ≤ 300µg/L			Table Rock Weatherby	
Mesotrophic >300 - 500µg/L	Shayne Marseilles Capri Lafitte	Lafitte Table Rock Weatherby Capri Shayne Marseilles Blue Springs	Shayne Laffite Capri Marseilles Carmel Longview	Table Rock Weatherby Shayne Lafitte Capri Marseilles
Eutrophic >500 - 1200µg/L	Carmel Weatherby Blue Springs Table Rock Catalina Little Dixie Kraut Run Chesterfield	Carmel Catalina Longview Little Dixie Kraut Run	Blue Springs Catalina Little Dixie Chesterfield Kraut Run	Carmel Blue Springs Catalina Longview Little Dixie Kraut Run
Hypereutrophic >1200µg/L	Longview	Chesterfield		Chesterfield

When compared to classifications from individual seasons, the spring-fall trophic state classifications for CHL and TP were most similar to those from spring, while spring-fall classifications for TN were intermediate between spring and summer classifications (Tables 9-11).

Table 11. Rankings and trophic state assessments based on average total phosphorus concentrations during different seasonal patterns.

	Spring	Summer	Fall	Spring-Fall
Oligotrophic ≤ 10µg/L		Capri Shayne	Shayne Capri Carmel	
Mesotrophic >10 - 25µg/L	Table Rock Shayne Lafitte Capri Marseilles Carmel	Lafitte Marseilles Table Rock Carmel Weatherby Catalina	Table Rock Marseilles Lafitte Weatherby Catalina Longview	Capri Shayne Lafitte Table Rock Marseilles Carmel Weatherby
Eutrophic >25 - 100µg/L	Weatherby Catalina Blue Springs Longview Little Dixie	Longview Blue Springs Little Dixie Kraut Run	Blue Springs Little Dixie Chesterfield	Catalina Longview Blue Springs Little Dixie Kraut Run
Hypereutrophic >100µg/L	Kraut Run Chesterfield	Chesterfield	Kraut Run	Chesterfield

Required Sample Effort

Analyses indicate that fewer summer samples are required to estimate mean CHL, TP and TN at a desired level of precision than during spring-fall (Figure 17). And for a given level of precision more CHL samples are required than for nutrients.

Four CHL samples collected throughout summer equated to a CV of 25% and increasing sample effort to six improved precision by lowering CV to 20% (Figure 17). Further gains in precision would require substantial increases in sampling effort, with CHL CV values of 15% and 10% equating to ~11 and ~25 samples, respectively. A CV of 15% was achieved for both nutrients with three summer samples. In order to increase precision to 10% CV for nutrients the sample size would need to be doubled.

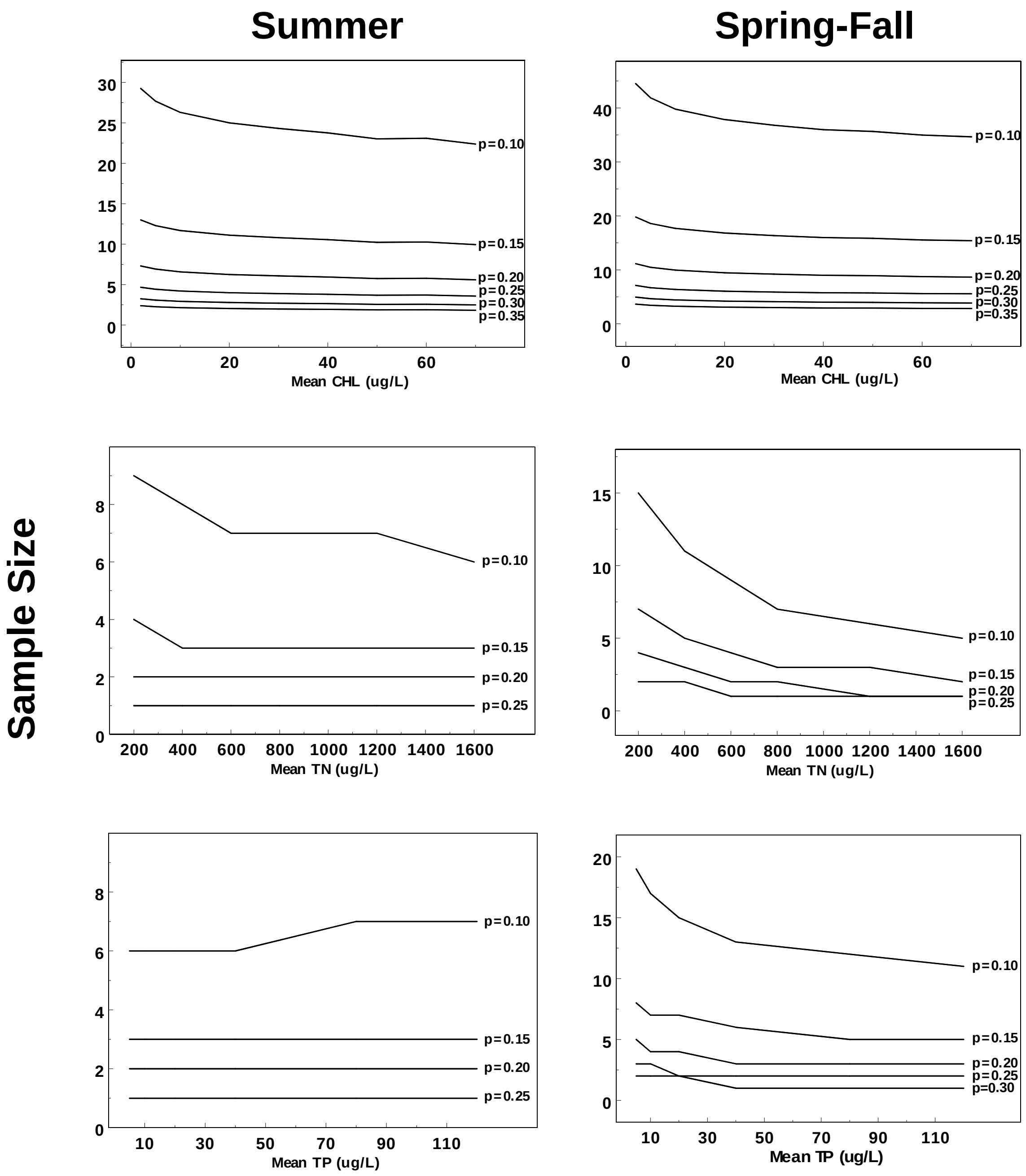


Figure 17. Required sample size to estimate mean chlorophyll, total nitrogen and total phosphorus at different levels of precision during summer and spring-fall periods.

During the spring-fall period, seven CHL samples equated to a CV of 25% (Figure 17). Increasing sample effort to nine reduced CV to 20%, while a reduction of CHL CV to

15% would require 17 samples. Five nutrient samples during spring-fall would provide a CV of 20%, while an increase to seven samples would decrease CV to 15%.

Analysis of the Potential Bias in Estimating Means

The potential bias associated with estimating mean concentrations of nutrients and CHL differed among reservoirs and was a function of variability (Appendix B). Four samples collected during summer from Blue Springs had a potential bias that ranged from -18% to 13% of the mean for CHL estimation. Potential bias for the same sampling effort in Chesterfield ranged from -49% to 83% of mean CHL. Potential bias associated with estimating mean CHL was two to four times that of TN and TP. Differences in bias as a function of sampling season were minor, with the spring-fall period resulting in slightly higher potential bias values for a given number of samples relative to summer.

Results from the analysis indicate that collection of four samples throughout summer is optimal for reducing potential bias associated with estimating mean trophic state conditions for this suite of reservoirs, relative to effort. Potential bias for CHL estimation ranges from -34% to 50% for three samples, with the 25th and 75th quartiles at -21% and 15%, respectively (Table 12). Four samples during the summer reduce the overall potential bias to a range of -27% to 39%, with quartiles at -13% and 11%. Additional sampling effort results in only minor reductions in the potential bias associated with estimating mean CHL.

The potential bias for TN associated with three samples ranged from -16% to 22%, with 25th and 75th quartiles at -8% and 6%, respectively (Table 12). A fourth sample resulted in a reduction of the potential bias to a range of -14% to 16%, with quartiles at -6%

and 7%. Three samples during summer resulted in potential bias that ranged from -19% to 28% for TP, with 25th and 75th quartiles of -10% and 9%, respectively (Table 12). An additional sample reduced overall potential bias to a range of -15% to 19%, with quartiles at -4% and 9%. Additional samples lowered potential bias values for both nutrients, but reductions were minimal.

A sampling effort of five or six during spring-fall is needed to limit potential bias associated with estimating mean CHL. Four samples results in a potential bias range of -36% to 57%, with quartiles at -21% and 14%. An increase to five samples reduced overall potential bias to a range of -32% to 37%, with the 25th and 75th quartiles at -13% and 12%, respectively. Potential bias is reduced moderately until seven samples are collected; at this point additional sampling provides minimal reduction in overall potential bias in CHL.

The potential bias of TN estimation associated with four spring-fall samples ranges from -13% to 12%, with quartiles of -5% and 6% (Table 12). Additional TN samples had minimal impact of the potential bias. Four spring-fall samples equates to a range of potential bias of -18% to 26% for TP, with quartiles at -8% and 8%. Additional samples reduced overall potential bias but not the 25th and 75th quartiles.

Table 12. Summary of potential bias (% of mean) in estimating chlorophyll (CHL), total nitrogen (TN) and total phosphorus (TP) for various sample sizes during summer and spring-fall.

Summer		Sample Size						
		2	3	4	5	6	7	8
CHL	Max	59%	50%	39%	31%	24%	21%	26%
	75%	19%	15%	11%	10%	8%	7%	12%
	25%	-21%	-21%	-13%	-12%	-12%	-10%	-11%
	Min	-43%	-34%	-27%	-23%	-26%	-18%	-19
TN	Max	31%	22%	16%	14%	14%	11%	9%%
	75%	9%	6%	7%	4%	4%	5%	6%
	25%	-10%	-8%	-6%	-4%	-3%	-4%	-4%
	Min	-25%	-16%	-14%	-10%	-10%	-8%	-6%
TP	Max	36%	28%	19%	13%	12%	12%	12%
	75%	11%	9%	9%	6%	7%	4%	6%
	25%	-9%	-10%	-4%	-4%	-3%	-5%	-4%
	Min	-24%	-19%	-15%	-11%	-7%	-10%	-9%

Spring-Fall		Sample Size								
		2	3	4	5	6	7	8	9	10
CHL	Max	109%	58%	57%	37%	33%	28%	29%	24%	26%
	75%	22%	20%	14%	12%	14%	13%	13%	11%	14%
	25%	-27%	-25%	-21%	-13%	-6%	-14%	-13%	-14%	-12%
	Min	-55%	-41%	-36%	-32%	-28%	-23%	-16%	-22%	-20%
TN	Max	31%	22%	12%	10%	11%	9%	9%	6%	8%
	75%	11%	9%	6%	6%	4%	5%	4%	4%	5%
	25%	-11%	-9%	-5%	-5%	-4%	-3%	-2%	-2%	-1%
	Min	-25%	-18%	-13%	-11%	-8%	-7%	-8%	-6%	-5%
TP	Max	58%	37%	26%	18%	15%	14%	9%	16%	12%
	75%	15%	14%	8%	8%	10%	7%	6%	5%	6%
	25%	-14%	-13%	-8%	-7%	-6%	-5%	-5%	-3%	-1%
	Min	-34%	-26%	-18%	-16%	-12%	-10%	-9%	-9%	-8%

Nutrient Stimulation Results

Results from nutrient stimulation experiments indicate that a shift in nutrient limitation occurred in this suite of reservoirs (Table 13 and Figure 18). During June-September, nitrogen (N) was limiting in 67% (14 of 21) of experiments, while six experiments were co-limited and one experiment showed phosphorus (P) limitation. In contrast, only 10% (1 of 10) of experiments conducted November-January resulted in N-limitation. Four experiments during this period showed P-limitation, three experiments resulted in co-limitation, and no significant difference among treatments was found in two experiments.

Only Blue Springs displayed a consistent response to stimulation experiments, with N-limitation throughout the study (Table 13 and Figure 18). Kraut Run, Longview, Shayne, and Table Rock were both N– and P-limited at different times during the study, while the other five reservoirs demonstrated limitation by an individual nutrient, as well as co-limitation by both nutrients during the study.

In 30 of the 38 experiments (79%), the combination of both N and P led to a greater stimulation of algal growth than either of the individual nutrient treatments. This response suggests these reservoirs were not acutely limited by either nutrient, and that a moderate addition of the limiting nutrient would change the factors regulating algal growth.

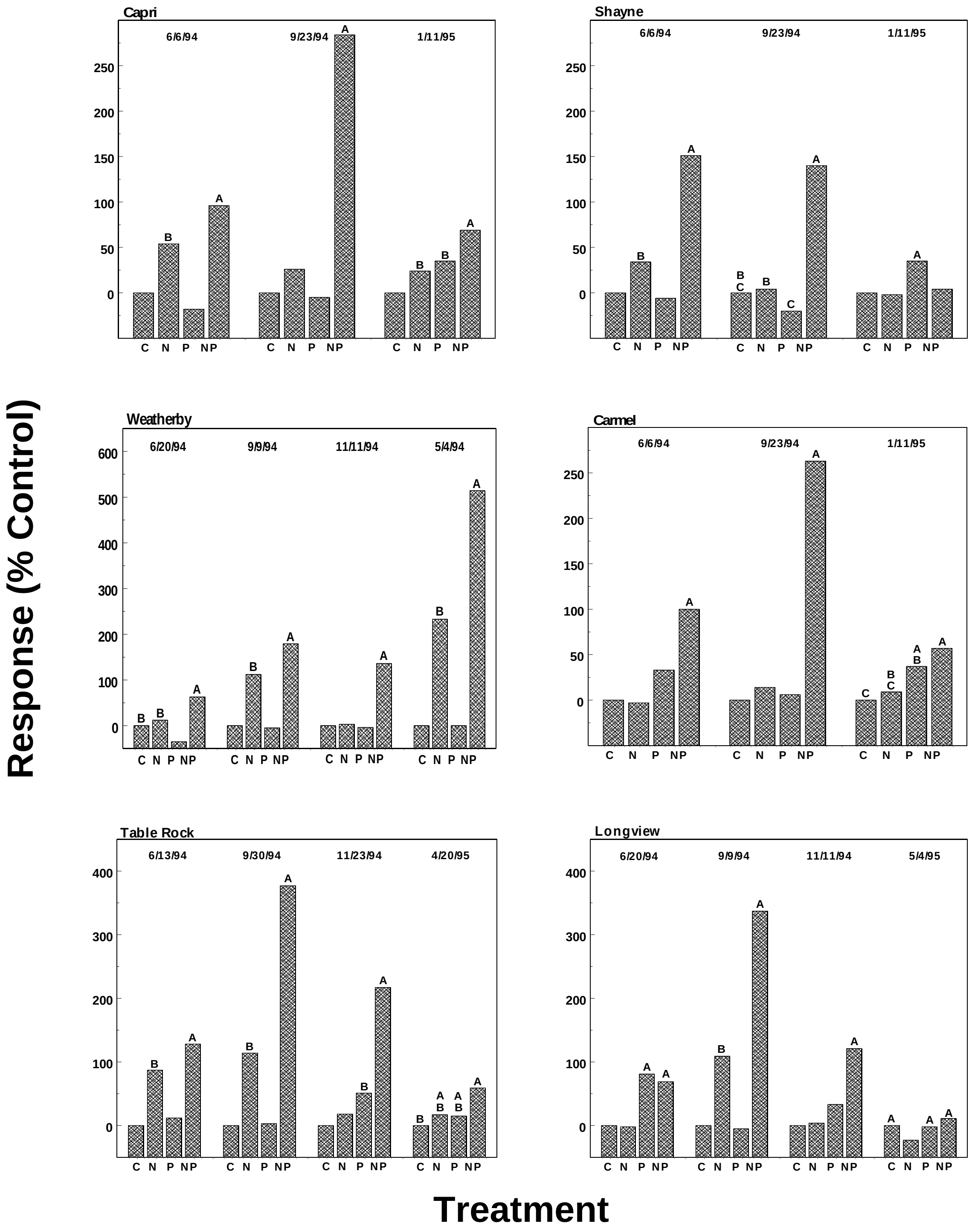


Figure 18. Results from nutrient stimulation experiments. Treatments include control (C), nitrogen addition (N), phosphorus addition (P) and combination nitrogen and phosphorus addition (NP). The letters above the bars indicate statistical difference amoung treatments in individual experiments.

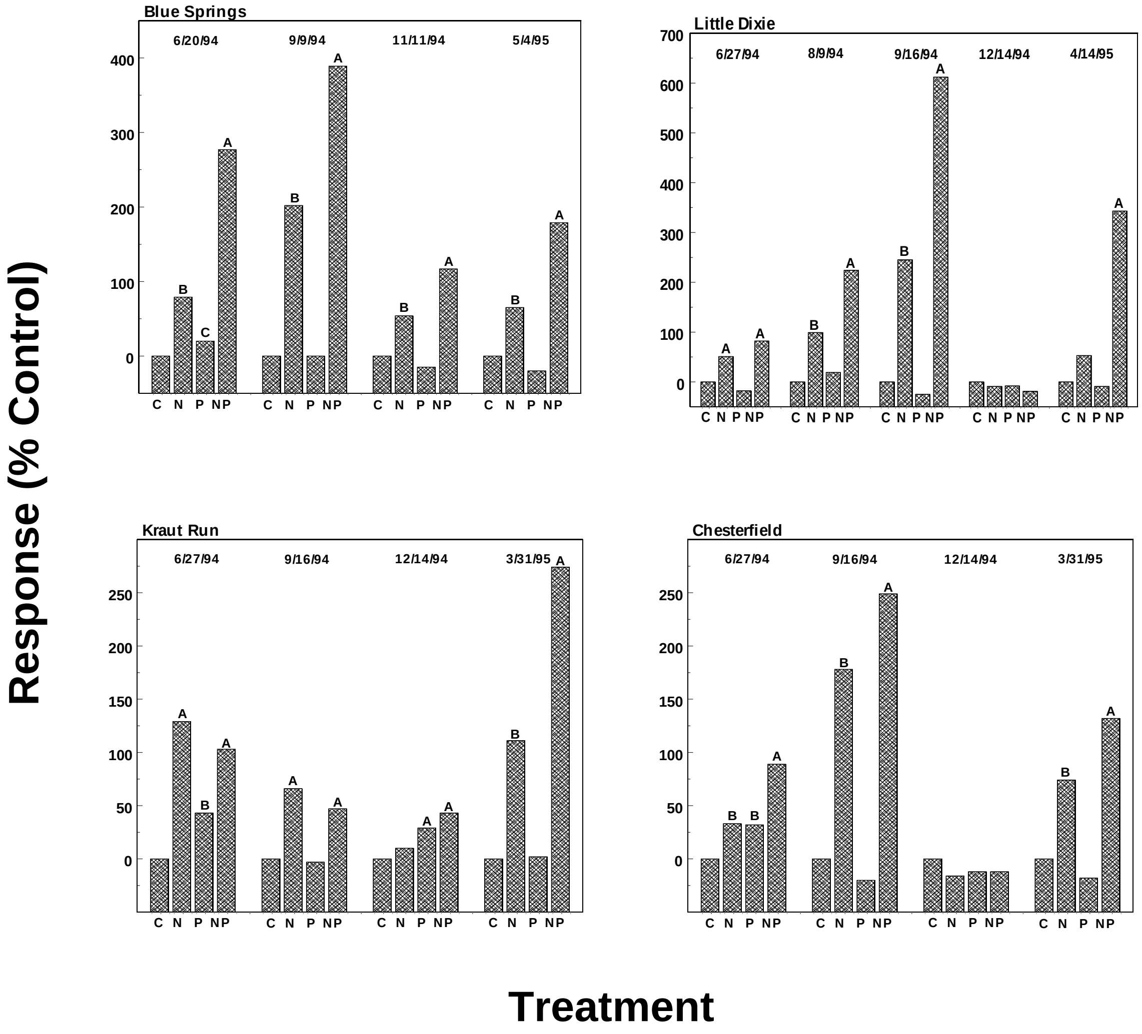


Figure 18 continued. Treatments include control (C), nitrogen addition (N), phosphorus addition (P) and combination nitrogen and phosphorus addition (NP). The letters above the bars indicate statistical difference amoung treatments in individual experiments.

Table 13. Results from nutrient stimulation experiments. Treatments were C = control, N = nitrogen addition, P = phosphorus addition and NP = nitrogen and phosphorus addition.

Reservoir	Date	Average Chlorophyll (µg/L)				% difference from C		
		C	N	P	NP	N	P	NP
Capri	6/6/94	0.9	1.4	0.8	1.8	54	-18	96
	9/23/94	1.9	2.4	1.8	7.3	26	-5	284
	1/11/95	2.1	2.6	2.8	3.5	24	35	69
Shayne	6/6/94	1.2	1.6	1.1	2.9	34	-6	151
	9/23/94	1.3	1.3	1.0	3.0	4	-20	140
	1/11/95	6.8	6.7	9.2	7.1	-2	35	4
Weatherby	6/20/94	3.9	4.4	2.5	6.4	12	-35	63
	9/9/94	1.9	4.0	1.8	5.2	112	-5	179
	11/11/94	9.9	10.2	9.5	23.3	3	-4	136
	5/4/95	2.8	9.4	2.8	17.4	233	0	514
Carmel	6/6/94	3.3	3.2	4.3	6.5	-3	33	100
	9/23/94	2.4	2.7	2.5	8.7	14	6	263
	1/11/95	2.9	3.1	3.9	4.5	9	37	57
Table Rock	6/13/94	5.5	10.3	6.2	12.6	87	12	128
	9/30/94	3.8	8.2	3.9	18.3	114	3	377
	11/23/94	8.4	9.8	12.6	26.5	18	51	217
	4/20/95	11.6	13.6	13.4	18.5	17	15	59
Longview	6/20/94	3.8	3.8	7.0	6.5	-2	81	69
	9/9/94	4.6	9.7	4.4	20.3	109	-5	337
	11/11/94	15.9	16.6	21.1	35.2	4	33	121
	5/4/95	11.7	9.0	11.4	12.9	-23	-2	11

Table 13 continued. Treatments were C = control, N = nitrogen addition, P = phosphorus addition and NP = nitrogen and phosphorus addition.

Reservoir	Date	Average Chlorophyll (µg/L)				% difference from C		
		C	N	P	NP	N	P	NP
Blue Springs	6/20/94	7.6	13.7	9.2	28.8	79	20	277
	9/9/94	10.4	31.4	10.4	50.9	202	0	389
	11/11/94	27.0	41.7	22.8	58.5	54	-15	117
	5/4/95	9.7	16.1	7.8	27.2	65	-20	179
Little Dixie	6/27/94	25.2	38.0	20.6	45.9	51	-18	82
	8/9/94	14.1	28.1	16.8	45.7	99	19	224
	9/16/94	7.0	24.2	5.2	49.9	245	-25	612
	12/14/94	5.9	5.4	5.4	4.8	-9	-8	-19
	4/14/95	10.0	15.4	9.1	44.5	53	-9	343
Kraut Run	6/27/94	22.5	51.6	32.1	45.6	129	43	103
	9/16/94	54.7	90.7	53.3	80.6	66	-3	47
	12/14/94	31.0	34.2	40.1	44.3	10	29	43
	3/31/95	16.3	34.5	16.7	61.1	111	2	274
Chesterfield	6/27/94	29.5	39.2	38.8	55.8	33	32	89
	9/16/94	23.2	67.2	18.6	81.0	189	-20	249
	12/14/94	14.7	12.3	12.9	12.9	-16	-12	-12
	3/31/95	14.3	24.9	11.7	33.1	74	-18	132

Nutrient Ratios

Oligotrophic and mesotrophic reservoirs had similar TN:TP through the year, with ratios for these two groups of reservoirs ranging between 20 and 40 (Figure 19). Eutrophic reservoirs had lower TN:TP ratios, with values remaining under 20 during the sampling period. All three trophic state categories exhibited the lowest ratios in spring, with values increasing into summer and fall.

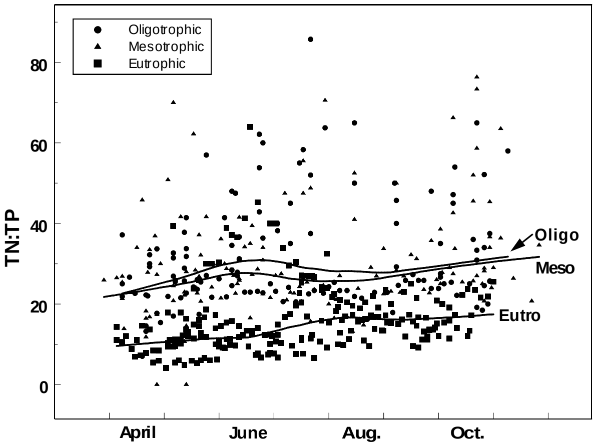


Figure 19. Seasonal trends of Total Nitrogen:Total Phosphorus ratios in oligotrophic, mesotrophic and eutrophic reservoirs.

Oligotrophic reservoirs displayed a CHL:TP that remained near 0.2 throughout the spring-fall period (Figure 20). Ratios were near 0.5 for mesotrophic reservoirs during early spring, decreased as summer approached and remained near 0.3 during summer and fall. Eutrophic reservoirs had CHL:TP near 0.2 in spring and values increased through late spring into summer and remained above 0.4 through fall. A comparison among the trophic groups shows mesotrophic reservoirs having the highest CHL:TP ratio in spring, with eutrophic reservoirs having highest values from mid-summer through fall (~2 fold higher than oligo- and mesotrophic reservoirs). Seasonal patterns for CHL:TN were similar to those for CHL:TP; with oligo- and mesotrophic reservoirs exhibiting decreasing CHL:TN from spring to summer/fall, while eutrophic reservoirs had increasing CHL:TN during the same period (Figure 21). CHL:TN ratios in eutrophic reservoirs were higher than oligo- and mesotrophic reservoirs during most of the spring-fall period, with summer and fall values that were ~3 fold higher than measured in oligo- and mesotrophic reservoirs.

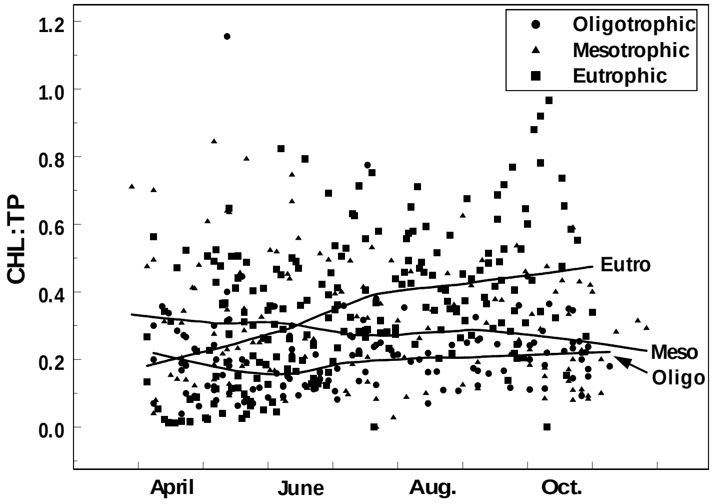


Figure 20. Seasonal trends of Chlorophyll:Total Phosphorus ratios in oligotrophic, mesotrophic and eutrophic reservoirs.

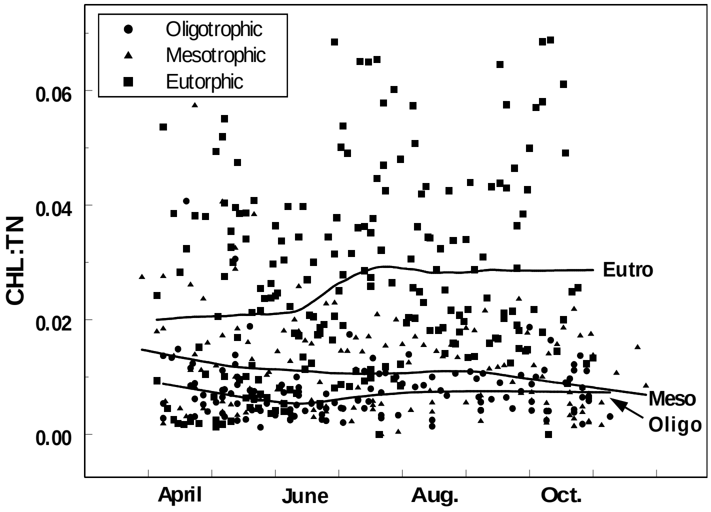


Figure 21. Seasonal trends of Chlorophyll:Total Nitrogen ratios in oligotrophic, mesotrophic and eutrophic reservoirs.

Models

Results from cross system regression CHL-TN models indicate the strongest relation occurred during summer, with the weakest relation in spring (Figure 22). The CHL-TP relation was also weak in spring, with fall showing the strongest CHL-TP relation (Figure 23). TP explained more of the cross-system variation in CHL than TN in each season.

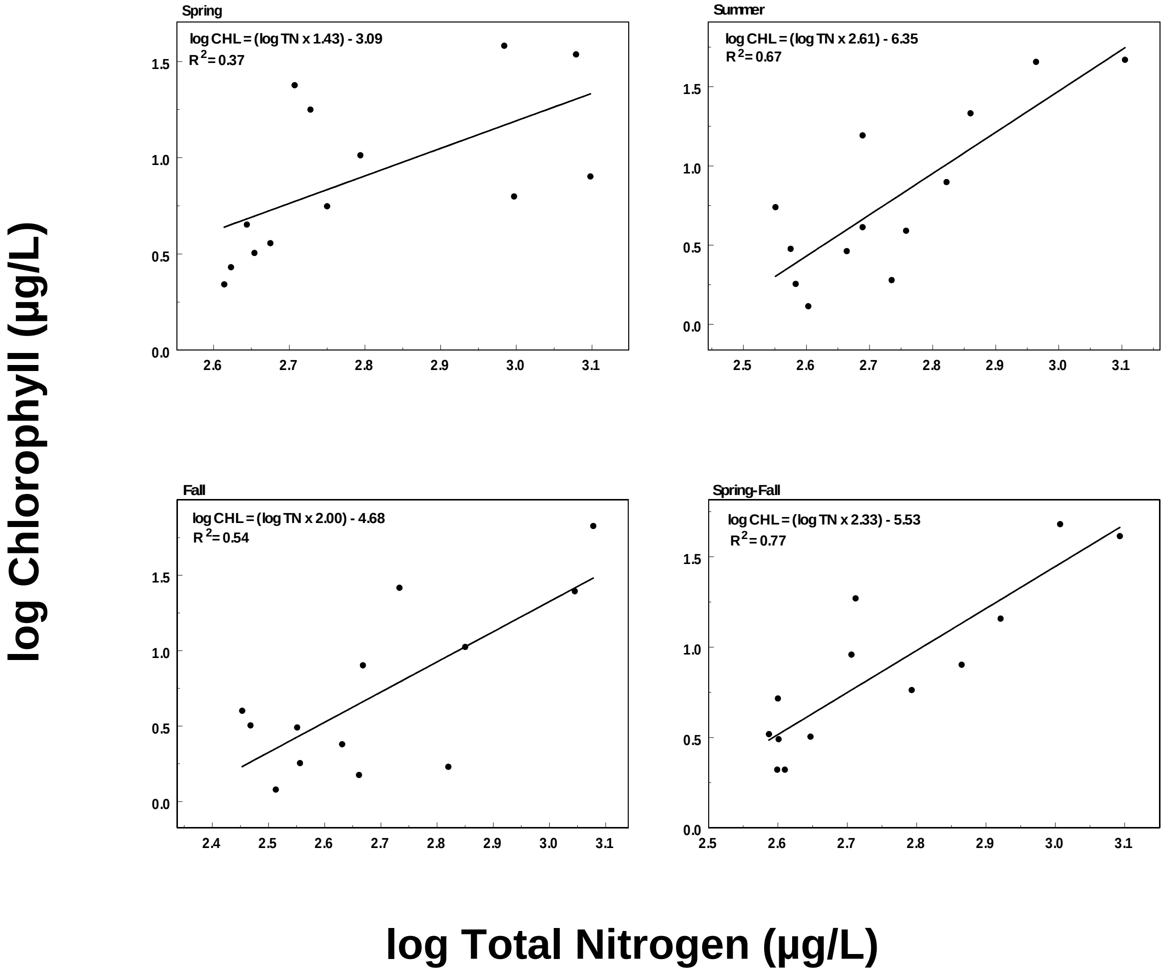


Figure 22. Chlorophyll – Total Nitrogen regression models for different seasonal periods.

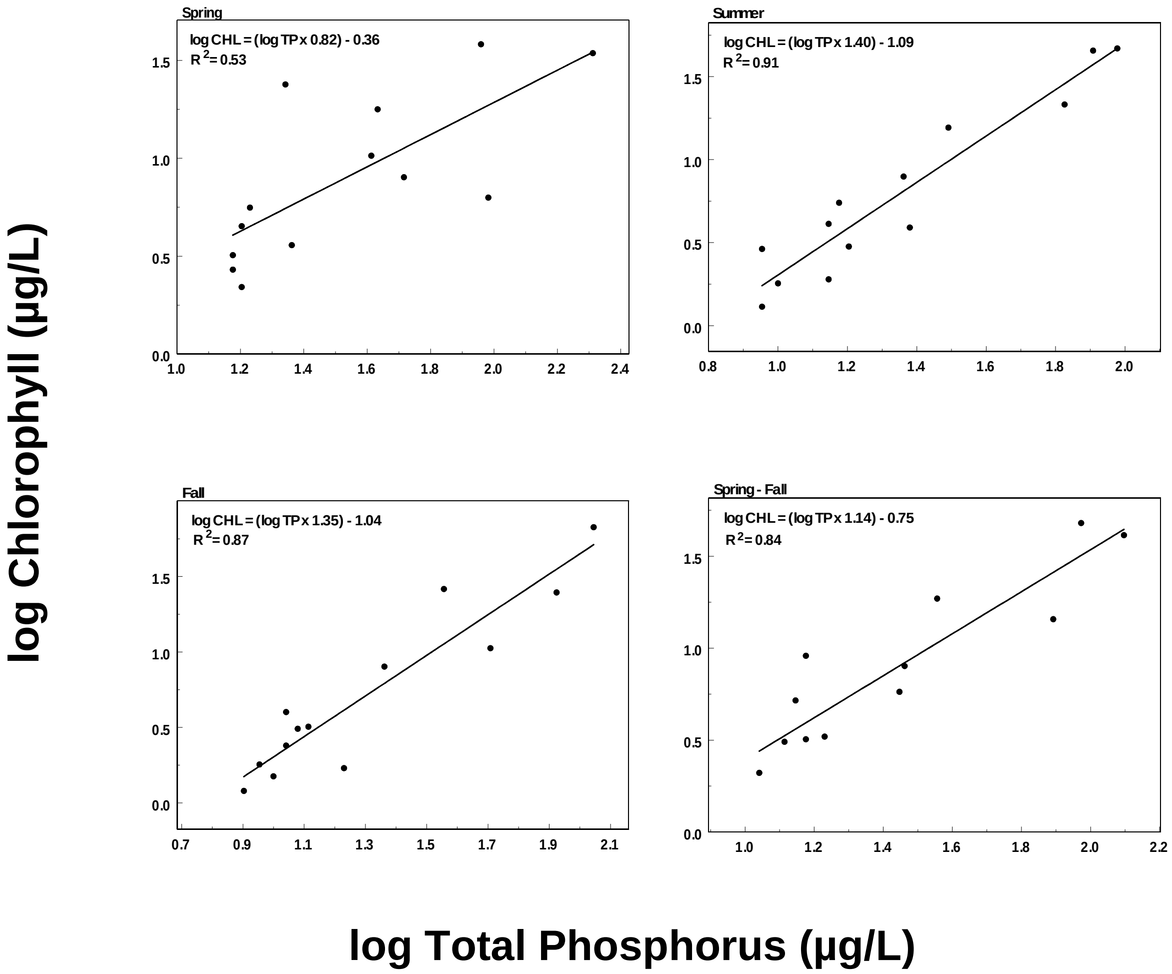


Figure 23. Chlorophyll – Total Phosphorus regression models for different seasonal periods.

DISCUSSION

As a group, eutrophic waterbodies in this study did not support the accepted bimodal paradigm of algal biomass proposed by Marshall and Peters (1989). The data set used to describe the bimodal pattern was dominated by natural lakes (Marshall and Peters 1989), while the current study focused solely on reservoirs. These two water body types generally differ in morphology and hydrology, which in turn influences water quality. Reservoirs tend to have greater flushing rates due to having larger watershed to volume ratios compared to natural lakes (Kalff 2003). The larger watershed equates to more inputs while the greater flushing rate means less time for in-lake processes such as sedimentation to take place. Differences in hydrology between these two waterbody types may explain why Missouri's eutrophic reservoirs did not follow the bimodal pattern of CHL.

Another common feature of reservoirs is the presence of NVSS associated with the erosional nature of the valleys in which they are located (Jones and Knowlton 2005). In-reservoir NVSS concentrations are often a function of watershed disturbances such as row cropping, a land use that shows a strong positive relation to reservoirs trophic state in Missouri (Jones *et al*. 2004). Because relatively few Missouri reservoirs have point source inputs, watershed disturbances are the principal factor in determining eutrophic conditions in these waterbodies. Thus eutrophic reservoirs in Missouri generally have moderate to high levels of NVSS. The median NVSS value from a suite of eutrophic Missouri reservoirs was 5.8 mg/L (n = 45) compared to 1.7 mg/L (n = 10) for oligotrophic reservoirs (Jones and Knowlton 1993). NVSS levels may be especially high in spring when inflows have the greatest impact on surface waters. The presence of NVSS in moderate to high concentrations can reduce available light and bind nutrients, having a negative impact of phytoplankton growth (Walker 1980, Jones and Knowlton 1983, Knowlton and Jones 2000, Jones and Knowlton 2005).

In this study, the eutrophic reservoirs with the largest concentrations of NVSS during spring diverged most from the bimodal pattern. For example, Little Dixie had low levels of CHL in spring, during the period of high nutrient levels (mean TP 105μg/L, TN

950μg/L, CHL 4.9μg/L). CHL did not peak until summer in Little Dixie (mean CHL 18.5μg/L), after NVSS levels had decreased from a springtime mean of 10.7 mg/L to a summer mean of 6.9 mg/L due to sedimentation. In contrast, Blue Springs had low NVSS (spring and summer means of 6.9 mg/L and 2.8 mg/L, respectively) and followed the bimodal CHL pattern predicted by Marshall and Peters (1989). The limited impact of NVSS on the light environment of Blue Springs during spring allowed algal biomass to use available nutrients. Subsequent decreases in CHL were a product of nutrient loss due to sedimentation and possibly shifts in zooplankton grazing that are often associated with the early summer clear water phase (Sommer *et al*. 1986).

Reservoirs studied by Walker (1980) also displayed the influence of NVSS on algal biomass. During March-June TSI values for CHL in the Walker study were half the expected levels suggested by TP TSI and a third of expected values based on Secchi TSI. This finding suggests the light environment was less than optimal, and helps explain the limited algal growth relative to TP. During summer, TSI values based on TP, CHL and Secchi converged, and in August they differed by <4 TSI units. Similarity among the three TSI metrics suggest that during August influences of NVSS in these reservoirs was minimal, thus allowing for more efficient use of the available TP by the algae. In essence, loss of NVSS due to sedimentation allowed for nutrients and algae to behave more like the empirical models in which the TSI was based on (Carlson 1977).

Walker (1980) found that about half of the reservoir stations in his study did not display a June depression and thus did not fit the bimodal paradigm. Data represented 306 stations on 76 reservoirs, and mixed results may reflect longitudinal gradients in NVSS concentration within the reservoirs. Up-reservoir, riverine stations would have higher

NVSS values and fail to follow the bimodal CHL pattern, while down-reservoir stations with lower NVSS levels would be more likely to display the bimodal pattern observed in natural lakes.

Oligotrophic and mesotrophic reservoirs in the current study mimicked the CHL pattern identified by Marshall and Peters (1989). Moderate nonpoint source disturbances in the watersheds of these reservoirs resulted in limited nutrient inputs and modest in-reservoir nutrient levels (Jones et al. 2004). NVSS inputs would also be moderate from the predominately non-agricultural watersheds (Jones and Knowlton 2005), and would have minimal impact on algal growth. Low NVSS concentrations allow oligotrophic and mesotrophic reservoirs to behave much like the natural lakes reviewed by Marshall and Peters (1989). The comparability of mesotrophic reservoirs in this study to the oligotrophic pattern identified by Marshall and Peters (1989) was predictable given that the Marshall and Peters oligotrophic classification included lakes with up to 7 µg/L CHL (1989), a level that matches mesotrophic classification in Missouri. Slight differences in the timing of the spring increase in CHL can be attributed to differences in climate associated with differing latitudes, as suggested by Marshall and Peters (1989).

Unlike eutrophic lakes, oligotrophic lakes reviewed by Marshall and Peters (1989) did not show consistent CHL patterns. Marshall and Peters postulated that the relative lack of consistent temporal patterns in oligotrophic lakes was a reflection of watershed influences on a localized geographical scale (Marshall and Peters 1989). Water quality parameters in Missouri oligo- and mesotrophic reservoirs also exhibited non-uniform temporal patterns, most notably was TN (Appendix A). Weatherby and Table Rock both displayed steady decreases in TN through the sample period, compared to modest fluctuations around the mean in the other oligo- and mesotrophic reservoirs. All of the oligo- and mesotrophic reservoirs with the exception of Weatherby and Table Rock are located in the St. Francois subsection of the Ozark Highlands (Jones and Knowlton 1993). This region is distinctive in the state due to the Precambrian age bedrock and acidic soils (Nigh and Schroder 2002). The influence of catchment geology and geochemical variables on lake water quality has been previously documented (Duarte and Kalff 1989, Nürnberg 1996) and may explain the difference in seasonal TN patterns observed in the oligo- and mesotrophic reservoirs. The varying TN patterns in these reservoirs support Marshall and Peters' (1989) contention that temporal patterns in waterbodies with low amounts of human impact reflect localized watershed conditions. It is reasonable to expect water quality in lakes and reservoirs with relatively undisturbed watersheds to strongly reflect the distinctive nature of the individual watersheds. Temporal patterns in water quality parameters would be expected to vary according to differences in factors such as hydrology and natural nutrient sources within the individual watershed. In contrast, eutrophic waterbodies have disturbed watersheds, and the influences that disturbances such as agriculture and urban development have on water quality and seasonal patterns may override any inherent differences among watersheds.

Nutrient-Chlorophyll Relation

Downing and McCauley (1992) proposed that in-lake N:P may reflect the nutrient ratio of inputs, and that relatively undisturbed watersheds such as forest and unfertilized grasslands, would have runoff with a high N:P ratio. In contrast, disturbed watersheds would have runoff with lower N:P which reflect the ratio of the nutrient sources such as sewage, fertilizers and urban runoff (Downing and McCauley 1992). Results from the current study support the concept of in-lake nutrient ratios reflecting inputs, and thus the level of watershed disturbance. Eutrophic reservoirs in Missouri have disturbed watersheds (Jones *et al*. 2004) and TN:TP in these waterbodies remained < 20 throughout the study (Figure 19). In comparison, TN:TP ranged between 20 and 40 during the study for the oligo- and mesotrophic reservoirs (Figure 19), which have more forested watersheds (Jones *et al*. 2004).

Increases in TN:TP were observed for all trophic state categories during late spring-early summer period in the current study (Figure 19). This shift in nutrient ratio is probably a function of the timing of nutrient inputs and in-reservoir processes. Surface water quality is impacted by inputs occurring in spring prior to stratification (Jones and Knowlton 2005), and reservoir surface water should reflect the low TN:TP of impacted inflows (Downing and McCauley 1992). After the establishment of stratification in the late spring/early summer, watershed inputs often plunge below the surface layer as a thermal density flow and have reduced influence on surface waters (Jones and Knowlton 2005). Also, nutrient losses associated with sedimentation occur in the surface layer after stratification. The reduction in low TN:TP inputs that influence surface waters coupled with the loss of nutrient through sedimentation explains the observed shift in TN:TP during late spring/early summer.

The measured TN:TP ratios during June-September were a poor predictor of NSE results. Because algal species have differing optimal N:P ratios (Rhee and Gotham 1980), there is no single point when nutrient limitation shifts from TN to TP. It is generally accepted that TN limitation occurs when TN:TP ratios drop <10-14:1 (Smith 1982, Downing and McCauley 1992) and TP limitation occurs when the ratio is > 20:1 (Smith 1982). The eutrophic reservoirs in this study had TN:TP ratios ~18 during June-September and it would seem reasonable to expect a mix of N and P limitation, yet a full 82% of NSEs resulted in N limitation (Figure 18).

Disparity between nutrient ratios and NSE results were even greater during June-September in the oligo- and mesotrophic reservoirs. TN:TP ratios were ~30 in these reservoirs, a ratio that would suggest strong P limitation. However, 60% of NSEs conducted in the oligo- and mesotrophic reservoirs resulted in N limitation, with the remaining 40% indicating co-limitation (Figure 18).

Previous studies have called into issue the predictive strength of nutrient ratios at low nutrient levels. McCauley and Downing (1991) found that algal biomass was uncorrelated to TN:TP at low levels of TP, which would describe the oligotrophic and mesotrophic reservoirs in this study.

The large number (79%) of NSEs that showed higher algal biomass in combination treatments (both N and P) than single nutrient additions supports the contention that both nutrients are important in determining algal growth in natural systems (Smith 1982, Elser *et al*. 1990). The eutrophic reservoirs in this study did not display extreme nutrient ratios, and TN:TP ratios were generally within the range between N limitation (10:1) and P limitation (20:1). Small additions of the limiting nutrient in these reservoirs would cause a shift in the growth limiting nutrient. Also, heterogeneous phytoplankton populations would have varying nutrient requirements, thus both N– and P-limitation could be expected for a mixed phytoplankton population at the TN:TP ratios found in eutrophic reservoirs in this study. The response in oligo- and mesotrophic reservoirs to the combination treatments in the NSEs can be attributed to low ambient nutrient levels in the reservoirs.

Sample Design

Results from the current study support the findings of Marshall *et al*. (1988) that a CHL CV = 20% can be achieved with the collection of 10 samples when the sampling period extends beyond summer. The two studies differed in that Marshall *et al*. (1988) worked with annual data while this study used data collected April - November. When the monitoring period was reduced to May-September, Marshall *et al*. (1988) found that required sampling effort did not change for meso- and eutrophic lakes, while required effort was reduced to 3-7 samples in oligotrophic lakes. The Missouri data set was not partitioned by trophic state, and the combined data indicated that a summer monitoring effort of 6-7 samples would lead to a CHL CV = 20% (Figure 17). Review of the CHL patterns for the different trophic states (Figure 7-9) show greater variation during summer in eutrophic reservoirs than in oligo- or mesotrophic reservoirs. More scatter in the data suggest that a larger number of samples should be required to achieve a selected level of CHL CV in eutrophic reservoirs compared to the oligo- and mesotrophic reservoirs. It is quite possible that results from Missouri reservoirs, had they been separated by trophic state and then analyzed, would have supported the finding of Marshall *et al*. (1988) that eutrophic systems require more sampling effort in summer than do oligotrophic waterbodies.

Nutrients tend to be less variable than CHL on a temporal scale (Knowlton *et al*. 1984), and therefore fewer samples are required to estimate mean conditions at a selected level of precision (France and Peters 1992). The current study found that mean TN and TP could be estimated in Missouri's reservoirs at a CV level $\leq$20% with four and two samples for the spring-fall and summer periods, respectively. This effort represents substantially less than needed to estimate mean CHL at the same level of precision. France and Peters (1992) contented that the most variable parameter of interest (which would require the largest number of samples) should dictate sampling scheme. Given this viewpoint, studies interested in determining TP-CHL relations should collect the five to seven samples needed to estimate CHL as described in Marshall *et al*. (1988).

Using the most variable of the parameters (CHL) to determine required sampling effort is sensible if the goal of a study is to describe the nutrient-CHL relation. When long-term monitoring for changes in water quality is the goal, setting sample requirements based on the less variable causal parameters should be considered. By reducing the number of samples per waterbody to 3 or 4 during summer, resources are freed to increase the number of lakes/reservoir being monitored. In Missouri, this monitoring effort would provide a level of precision for the nutrients of CV < 15%, while limiting potential bias associated with extreme values.

Potential bias in the estimation of CHL was limited if five or more samples were collected during summer based on analysis done by Marshall *et al*. (1988). Results from the analysis of Missouri's reservoirs generally concur with the findings of Marshall *et al*. (1988); with four samples limiting potential bias during summer sampling, and five samples limited potential bias in spring-fall sampling. In both studies an increase in sampling effort resulted in marginal reductions of potential bias. The four waterbodies analyzed by Marshall *et al*. (1988) ranged in trophic state condition (mean CHL 3.3 - 63.3

μg/L), but did not exhibit any distinguishable differences in the potential bias associated with a selected number of samples. Five of the six Missouri reservoirs did not display notable differences in potential bias, with Chesterfield being the exception (Appendix B). This reservoir maintains bias values up to 25% even when summer sampling effort was increased to eight. Chesterfield, which was originally impounded for retention of flow from an urban area, was considerably smaller in size than the other reservoirs evaluated in this analysis (Table1), and differences in hydrology and morphology may explain the extreme fluctuations observed in CHL during summer (Appendix A). Four summer samples in Missouri's reservoirs are probably enough to limit potential bias in most waterbodies, but increased sample effort may be required when monitoring smaller, more dynamic reservoirs.

Along with the number of samples required to accurately estimate parameter means, it is also important to consider timing of sample collection. France *et al*. (1995) identified August and September as the months in which a single sample would best estimate the overall annual mean CHL and TP, with April being identified as the worst month to collect a single sample to be used for estimating annual means. While this study did not mimic the analysis preformed by France *et al*. (1995), some results support their findings. Extreme high values for both TN and TP were more frequent in April and May in all trophic state categories (Figure 12-14). Extreme high CHL values were also prevalent during these two months for oligo- and mesotrophic reservoirs (Figures 12 and 13). Biases in estimating mean conditions are associated with the influence of extreme values (Marshal . 1988), and collection of samples spaced evenly through the summer should reduce the influence of extreme low and high measurements.

Monitoring over the spring-fall period can provide a view of how Missouri's dynamic reservoirs change during the growing season, but results from this study indicate that the seasonality of trophic parameters, especially TP, can overestimate trophic status (Table 8-10). This finding is supported by those of Nürnberg (1996), who felt that summer epilimentic TP concentrations were a better predictor of trophic state than TP averages from different seasons. Increased variability associated with monitoring during the spring-fall period also increases the number of samples required to meet a selected level of precision (Figure 17), increases the potential bias in estimating means (Table 12, Appendix B), and reduces the strength of predictive models (Figures 22 and 23). Unless a research project specifically needed to monitor water quality when nutrients and CHL (in oligo- and mesotrophic reservoirs) were at the maximum levels, summer sample collection offers the best return for effort.

BIBLIOGRAPHY

American Public Health Association. 1989. Standard methods for the examination of water and waste water, 17th ed. American Public Health Association, New York, NY.

Bailey-Watts, A.E., A. Kirika, L. May and D.H. Jones. 1990. Changes in phytoplankton over various time scales in a shallow, eutrophic: the Loch Leven experience with special reference to the influence of flushing rate. Freshwater Biol. 23:85-111.

Brown, C.D., D.E. Canfield Jr., R.W. Bachmann and M.V. Hoyer. 1998. Seasonal patterns of chlorophyll, nutrient concentrations and Secchi disk transparency in Florida lakes. Lake and Reserv. Manage. 14:60-76.

Canfield, Jr., D.E. and R.W. Bachmann. 1981. Predictions of total phosphorus concentrations, chlorophyll-a and Secchi depths in natural and artificial lakes. Can. J. Fish Aquat. Sci. 38:414-423.

Carlson, R.E. 1977. A trophic state index for lakes. Limnol. Oceanog. 22:361-369.

Crumpton, W.G., T.M. Isenhart and P.D. Mitchell. 1992. Nitrate and organic N analysis with second derivative spectroscopy. Limnol. Oceanogr. 37:907-913.

Davis, C.C. 1964. Evidence of eutrophication of Lake Erie from phytoplankton records. Limnol. Oceanogr. 19:767-773.

Downing, J.A. and E. McCauley. 1992. The nitrogen:phosphorus relationship in lakes. Limnol. Oceanogr. 37:936-945.

Duarte, J.A. and J. Kalff. 1989. The influence of catchment geology and lake depth on phytoplankton biomass. Arch. Hydrobiol. 115:27-40.

Elser, J.J., E.R. Marzolf, and C.R. Goldman. 1990. Phosphorus and nitrogen limitation of phytoplankton growth in the freshwaters of North America: a review and critique of experimental enrichments. Can. J. Fish. Aquat. Sci. 47:1468-1477.

Forsberg, C. and S.O. Ryding. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Arch. Hydrobiol. 88:189-207.

France, R.L. and R.H. Peters. 1992. Temporal variance function for total phosphorus concentrations. Can. J. Fish. Aquatic. Sci. 49:975-977.

France, R.L., R.H. Peters and R.H. Rishikof. 1995. Optimal sampling periods for predicting phosphorus and chlorophyll concentrations in north-temperate lakes. Can. J. Fish. Aquatic. Sci. 52:1812-1815.

Graham, J.L., J.R. Jones, S.B. Jones, J.A. Downing and T.E. Clevenger. 2004. Environmental factors influencing microcystin distribution in the Midwest United States. Water Research. 38:4395-4404.

Ground, T.A. and A.W. Groeger. 1994. Chemical classification and trophic characteristics of Texas reservoirs. Lake and Reserv. Manage. 10:189-201.

Hoyer, M.V. and J.R. Jones. 1983. Factors affecting the relation between phosphorus and chlorophyll a in midwestern reservoirs. Can. J. Fish Aquat. Sci. 40:192-199.

Hutchinson, G.E. 1967. A treatise on limnology v. 2. Introduction to lake biology and the limnoplankton. Wiley. 1048p.

Jones, J.R. 1977. Chemical characteristics of some Missouri reservoirs. Trans. Mo. Acad. Sci. 10/11:58-71.

Jones, J.R. and R.W. Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. J. Water Pollut. Cont. Fed. 48:2176-2182.

Jones, J.R. and M.S. Kaiser. 1988. Limnological characteristics of Lake of the Ozarks, Missouri II: measurements following formation of a large reservoir upstream. Verh. Int. Ver. Limnol. 23:976-984.

Jones, J.R. and M.F. Knowlton. 1993. Limnology of Missouri reservoirs: An analysis of regional patterns. Lake and Reserv. Manage. 8:17-30.

Jones, J.R. and M.F. Knowlton. 2005. Suspended solids in Missouri reservoirs in relation to catchment features and internal processes. Water Research. 39:3629-3635.

Jones, J.R. and M.F. Knowlton. 2005. Chlorophyll response to nutrients and non-algal seston in Missouri reservoirs and oxbow lakes. Lake and Reserv. Manage. 21:361-371.

Jones, J.R., M.F. Knowlton, D.V. Obrecht and E.A. Cook. 2004. Importance of landscape variables and morphology on nutrients in Missouri reservoirs. Can. J. Fish. Aquat. Sci. 61:1503-1512.

Jones, J.R., J.D. LaPerriere and B.D. Perkins. 1990. Limnology of Walker Lake and comparison with other lakes in the Brooks Range, Alaska, (USA). Verh. Int. Ver. Limnol. 24:302-308.

Jones, J.R. and J.R. Novack. 1981. Limnological characteristics of Lake of the Ozarks, Missouri. Verh. Int. Ver. Limnol. 21:919-925.

Kalff, J. 2003. Limnology: inland water ecosystems. Prentice-Hall, Upper Saddle River, NJ.

Knowlton, M.F., M.V. Hoyer and J.R. Jones. 1984. Incorporating temporal variability in the sampling design for trophic state assessment. Water Res. Bull. 20:397-407.

Knowlton, M.F. and J.R. Jones. 1989a. Comparison of surface and depth integrated composite samples for estimating algal biomass and phosphorus values, and notes on the vertical distribution of autotrophs in midwestern lakes. Archiv. Hydrobiol./Suppl. 83:175-196.

Knowlton M.F. and J.R. Jones. 1989b. Summer distribution of nutrients, phytoplankton and dissolved oxygen in relation to hydrology in Table Rock Lake, a large midwestern reservoir. Archiv. Hydrobiol./Suppl. 83:197-225.

Knowlton, M.F. and J.R. Jones. 1990. Occurrence and prediction of algal blooms in Lake Taneycomo. Lake and Reserv. Manage. 6:143-152.

Knowlton, M.F. and J.R. Jones. 2000. Non-algal seston, light, nutrients and chlorophyll in Missouri reservoirs. Lake and Reserv. Manage. 16:322-332.

Kotlash, A.R. and B.C. Chessman. 1998. Effects of water sample preservation and storage on nitrogen and phosphorus determiniations: implications for the use of automated sampling equipment. Water Res. 32:3731-3737.

Lambert, D., W. Maher and I. Hogg. 1992. Changes in phosphorus fractions during storage of lake water. Wat. Res. 26:645-648.

Marshall, C.T., A. Morin and R.H. Peters. 1988. Estimates of mean chlorophyll-a concentration: precision, accuracy, and sampling design. Water Resour. Bull. 24:1027-1034.

Marshall, C.T. and R.H. Peters. 1989. General patterns in the seasonal development of chlorophyll-*a* for temperate lakes. Limnol. Oceanogr. 34:856-867.

McCauley, E. and J.A. Downing. 1991. Different effects of phosphorus and nitrogen on chlorophyll concentrations in oligotrophic and eutrophic lakes. Reply to Seip. Can. J. Fish. Aquat. Sci. 48:2552-2553.

Morris, D.P. and W.M. Lewis, Jr. 1988. Phytoplankton nutrient limitation in Colorado mountain lakes. Freshwater Biology. 20:315-327.

Nigh, T.A. and W.A. Schroeder. 2002. Atlas of Missouri ecoregions. Missouri Department of Conservation. Jefferson City, MO.

Nürnberg, G.K. 1996. Trophic state of clear and colored, soft- and hardwater lakes with special consideration of nutrients, anoxia, phytoplankton and fish. Lake and Reserv. Manage. 12:432-447.

Obrecht, D.V., M. Milanick, B.D. Perkins, D. Ready and J.R. Jones. 1998. Evaluation of data generated from lake samples collected by volunteers. Lake and Reserv. Manage. 14:21-27.

Obrecht, D.V., A.P. Thorpe and J.R. Jones. 2005.Response in the James River Arm of Table Rock Lake, Missouri (USA) to point source reductions. Verh. Int. Ver. Limnol. 29:1043-1048.

Perkins, B.D., K. Lohman, E. Van Niewenhuyse and J.R. Jones. 1999. An examination of land cover and stream water quality among physiographic provinces of Missouri, USA. Verh. Int. Ver. Limnol. 26:940-947.

Peters, R.H. 1989. Some pathologies in limnology. Mem. Ist. Ital. Idrobiol. 47:175-212.

Pollingher, U., T. Berman, B. Kaplan and D. Scharf. 1988. Lake Kinneret phytoplankton: response to N and P enrichments in experiments and in nature. Hydrobiologia. 166:65-75.

Reynolds, C.S. and E.G. Bellinger. 1992. Patterns of abundance and dominance of the phytoplankton of Rostherne Mere, England: evidence from an 18-year data set. Aquatic Sciences. 54:10-36.

Rhee, G. and I.J. Gotham. 1980. Optimum N:P ratios and coexistence of planktonic algae. J. Phycol. 16:486-489.

Sartory, D.P. and J.U. Grobbelaar. 1986. Extraction of chlorophyll-*a* from freshwater phytoplankton for spectrophotometric analysis. Hydrobiologia 114:117-187.

Smith, V.H. 1982. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr. 27:1101-1112.

Sommer, U., Z.M. Gliwicz, W. Lampert and A. Duncan. 1986. The PEG-model of seasonal succession of planktonic events in fresh waters. Arch. Hydrobiol. 106:433-471.

Stadelmann, T.H., P.L. Brezonik and S. Kloiber. 2001. Seasonal patterns of chlorophyll-*a* and Secchi disk transparency in lakes of east-central Minnesota: Implications for design of ground and satellite based monitoring programs. Lake and Reserv. Manage. 17:299-314.

Storch, T.A. and G.A. Dietrich. 1979. Seasonal cycling of algal nutrient limitations in Chautauqua Lake, New York. J. Phycol. 15:399-405.

Suttle, C.A. and P.J. Harrison. 1988. Ammonium and phosphate uptake rates, N:P supply ratios, and evidence for N and P limitation in some oligotrophic lakes. Limnol. Oceanogr. 33:186-202.

Talling, J.F. 1993. Comparative seasonal changes, and inter-annual variability and stability, in a 26-year record of total phytoplankton biomass in four English lake basins. Hydrobiologia. 268:65-98.

Thorpe, A.P. and J.R. Jones. 2005. Bacterial abundance in Missouri (USA) reservoirs in relation to trophic state and global patterns. Verh. Int. Ver. Limnol. 29:239-245.

U. S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. EPA Washington, DC.

Vanni, M.J. and J. Temte. 1990. Seasonal patterns of grazing and nutrient limitation of phytoplankton in a eutrophic lake. Limnol. Oceanogr. 35:697-709.

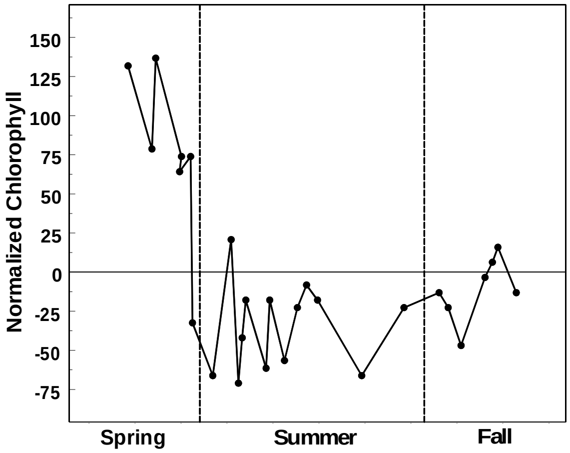
Walker, W.W. 1980. Variability of trophic state indicators in reservoirs, p. 344-348. In Restoration of lakes and inland waters. U.S. EPA 440/5-81-01

Wylie, G.D. and J.R. Jones. 1987. Diel and seasonal changes of dissolved oxygen and pH in relation to community metabolism of a shallow reservoir in southeast Missouri. J. Freshwater Ecol. 4:115-126.

APPENDIX A.

Seasonal patterns of chlorophyll, total nitrogen and total phosphorus in individual reservoirs.

Capri



Normalized Chlorophyll
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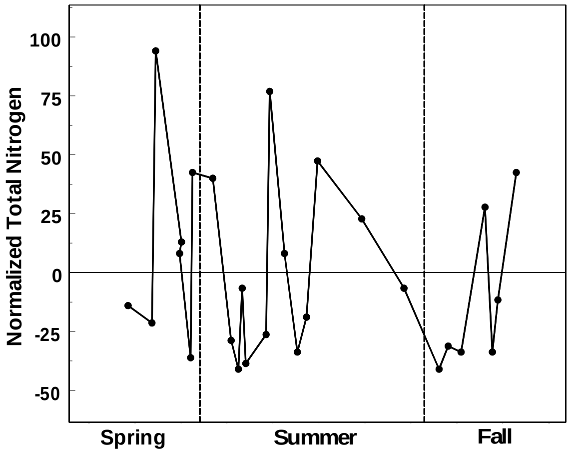
75
50
25
0
-25
-50
-75
Spring
Summer
Fall



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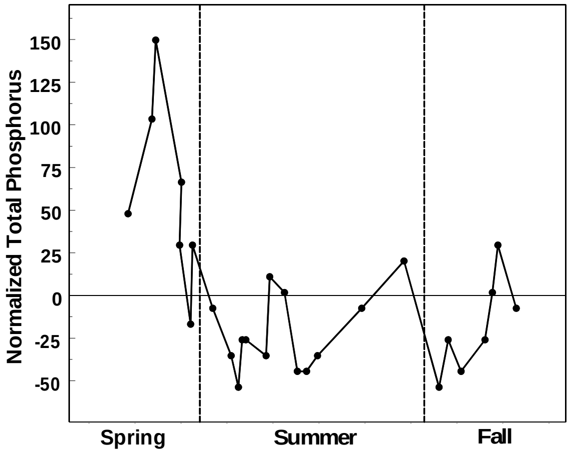
0
-25
-50
Spring
Summer
Fall



Normalized Total Phosphorus
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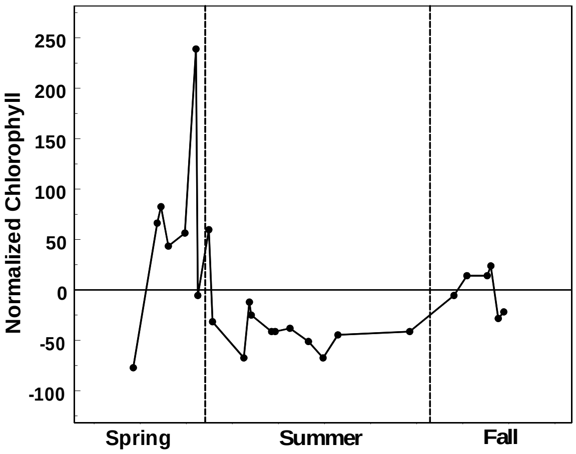
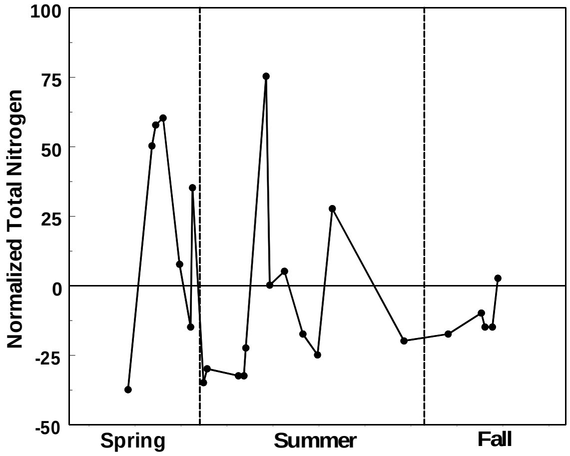
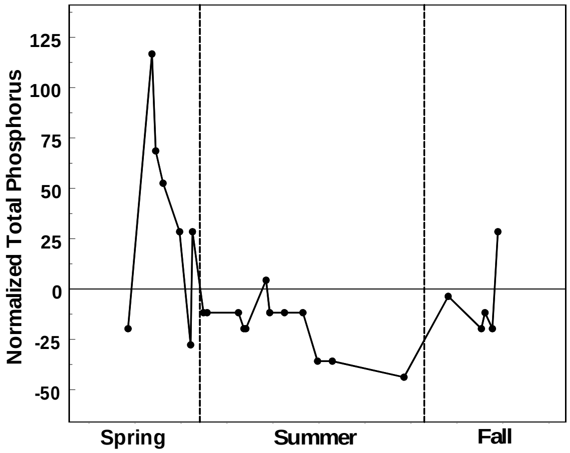
100
75
50
25
0
-25
-50
Spring
Summer
Fall

Lafitte


Normalized Chlorophyll
250
200
150
100
50
0
-50
-100
Spring
Summer
Fall


Normalized Total Nitrogen
100
75
50
25
0
-25
-50
Spring
Summer
Fall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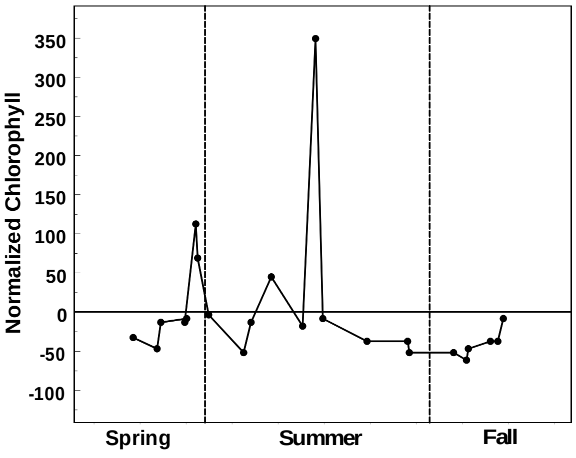
100
75
50
25
0
-25
-50
Spring
Summer
Fall

Shayne


Normalized Chlorophyll
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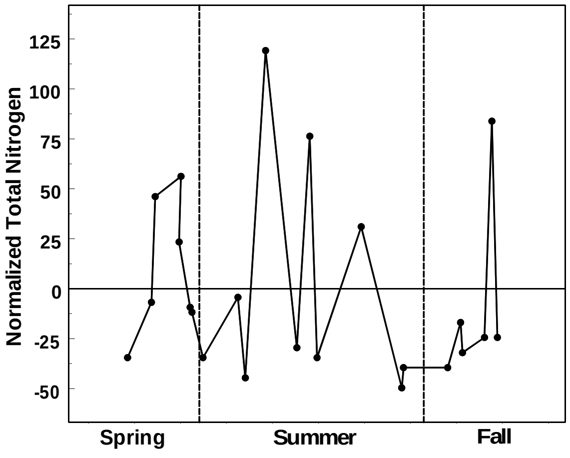
250
200
150
100
50
0
-50
-100
Spring
Summer
Fall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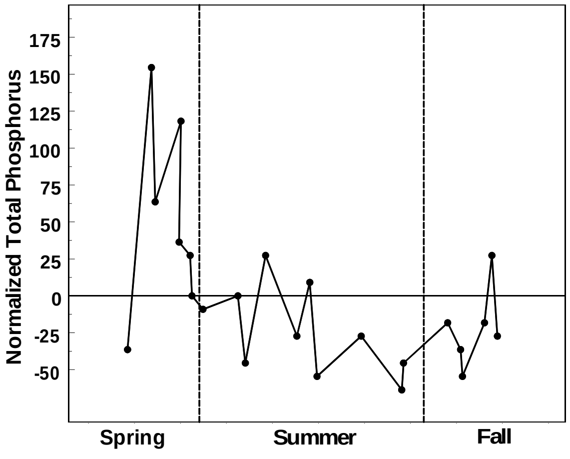
100
75
50
25
0
-25
-50
Spring
Summer
Fall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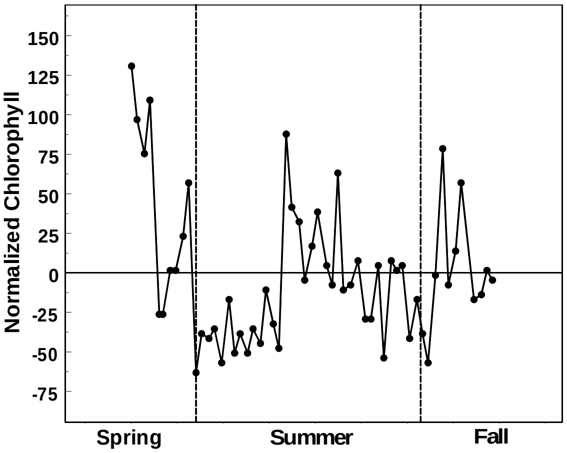
100
75
50
25
0
-25
-50
Spring
Summer
Fall

Weatherby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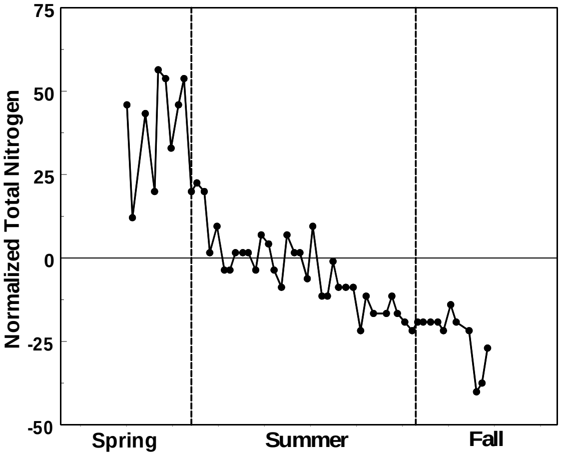
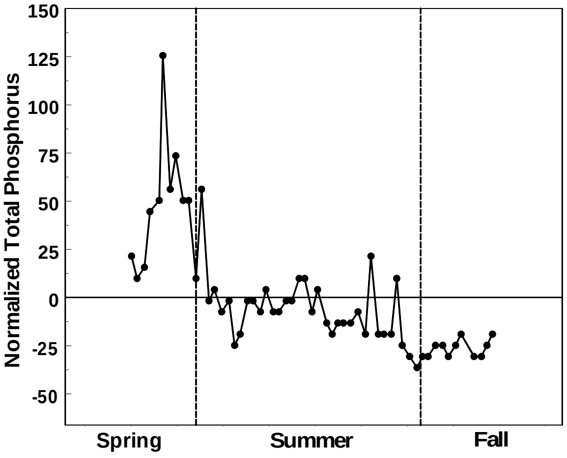
-75
Normalized Chlorophyll
Spring
Summer
Fall


75
50
25
0
-25
-50
Normalized Total Nitrogen
Spring
Summer
Fall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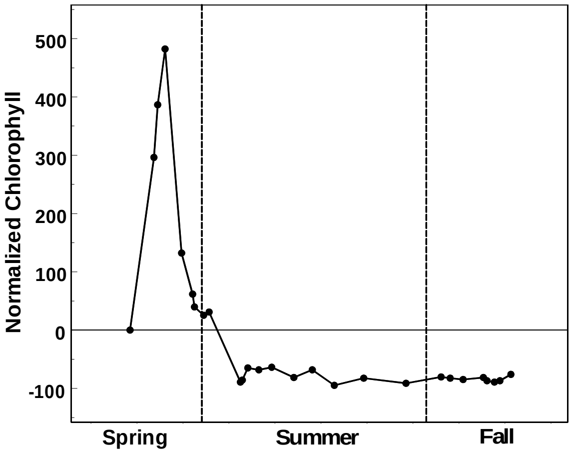
125
100
75
50
25
0
-25
-50
Normalized Total Phosphorus
Spring
Summer
Fall

Carmel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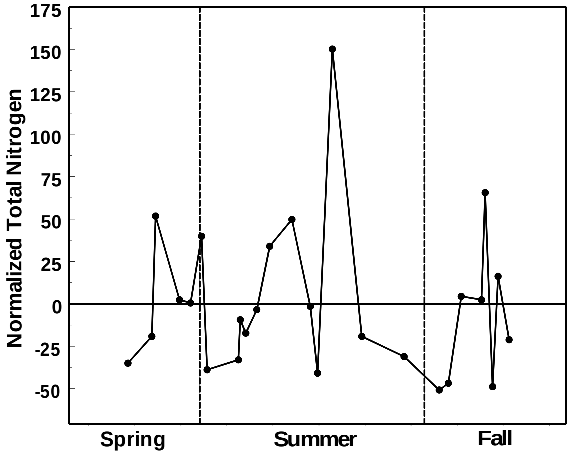
300
200
100
0
-100
Spring
Summer
Fall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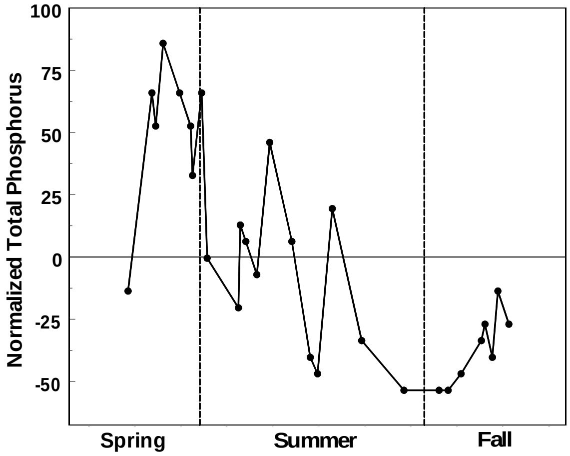
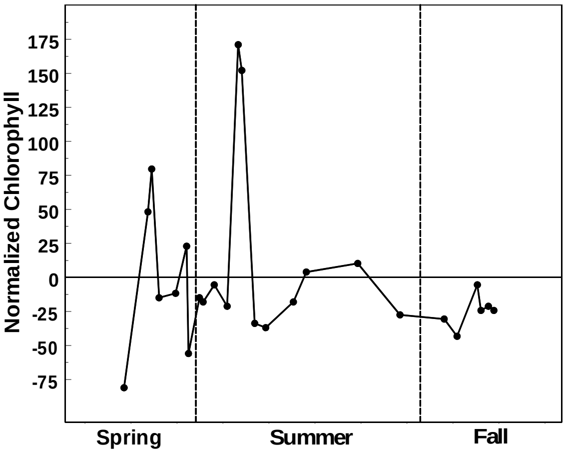
125
100
75
50
25
0
-25
-50
Spring
Summer
Fall


Normalized Total Phosphorus
100
75
50
25
0
-25
-50
Spring
Summer
Fall

Marseilles



Normalized Chlorophyll
175
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-25
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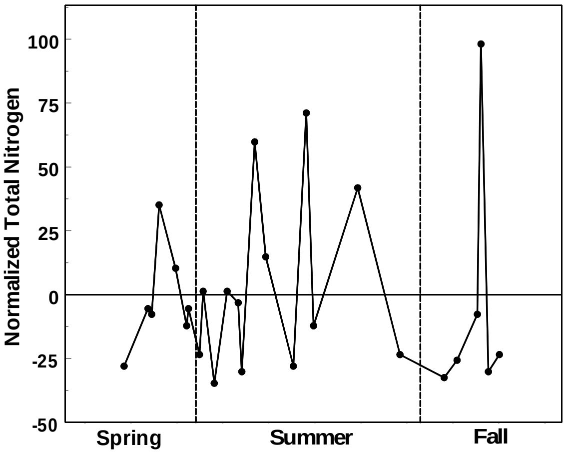
-75
Spring
Summer
Fall



Normalized Total Nitrogen
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75
50
25
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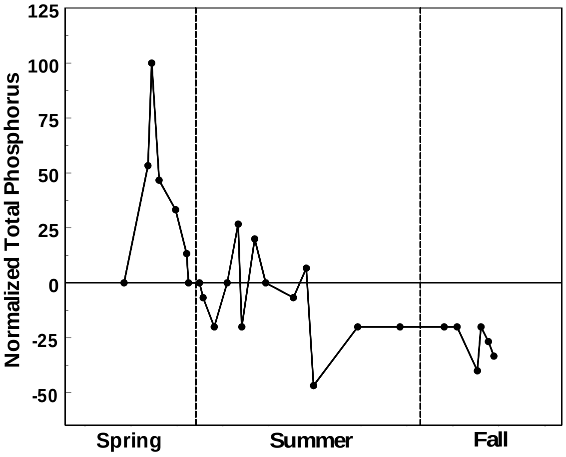
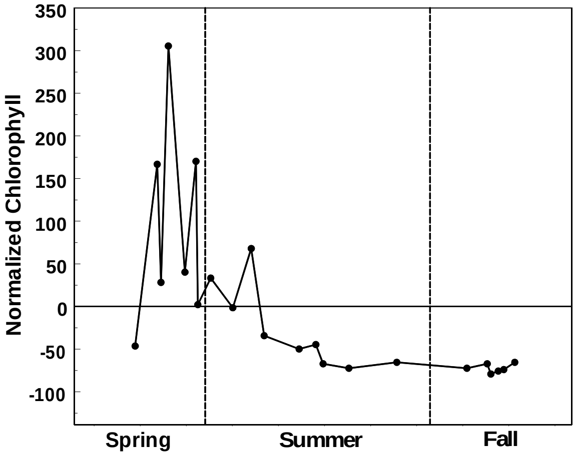
-25
-50
Spring
Summer
Fall



Normalized Total Phosphorus
125
100
75
50
25
0
-25
-50
Spring
Summer
Fall

Catalina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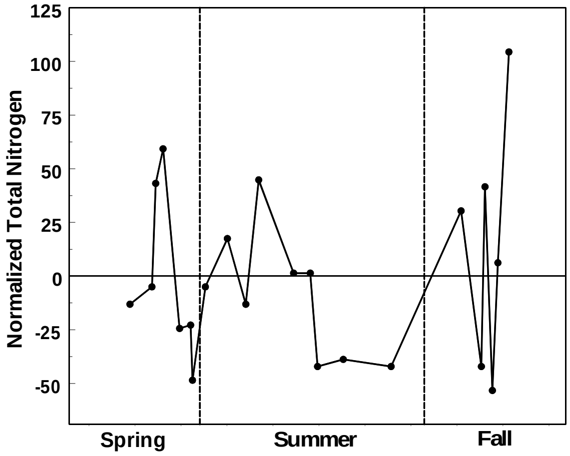
-100
Spring
Summer
Fall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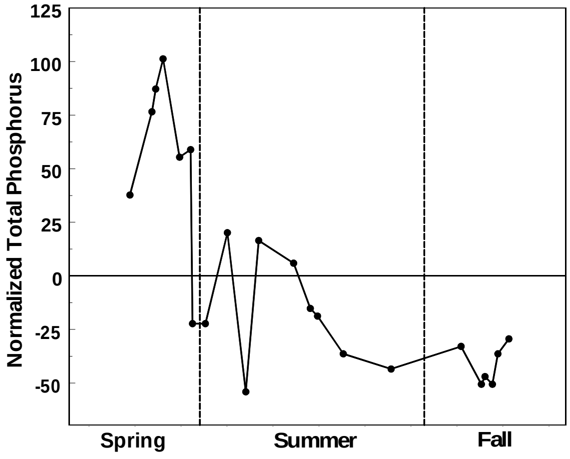
Spring
Summer
Fall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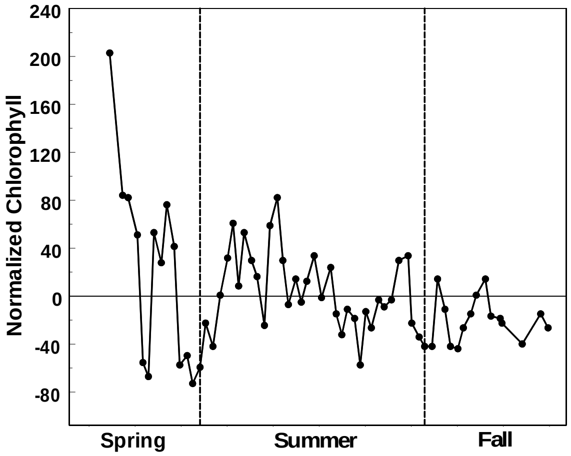
75
50
25
0
-25
-50
Spring
Summer
Fall

Table Rock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40
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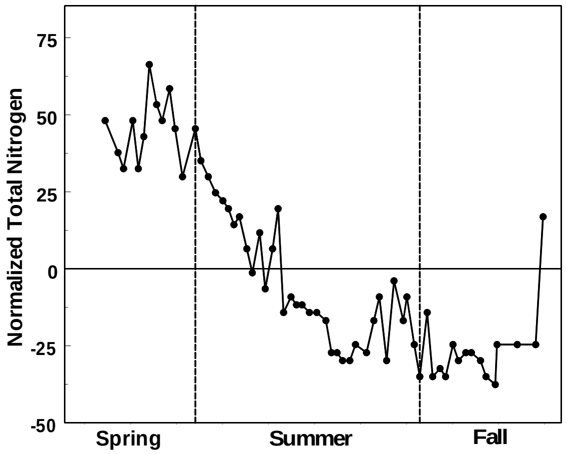
-80
Spring
Summer
Fall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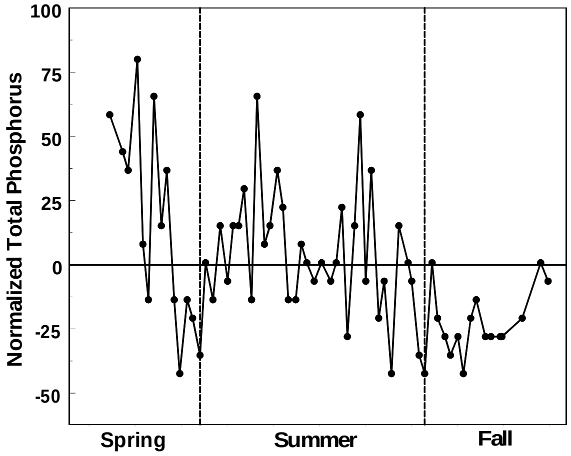
-50
Spring
Summer
Fall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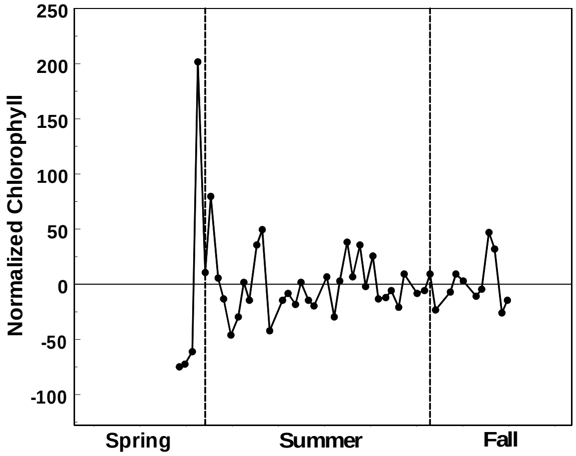
75
50
25
0
-25
-50
Spring
Summer
Fall

Longview



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150
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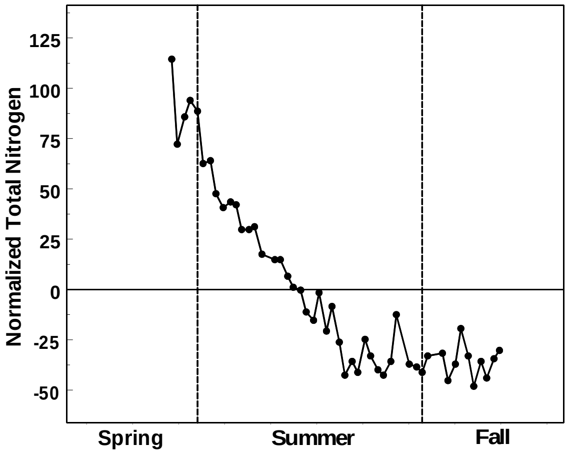
0
-50
-100
Spring
Summer
Fall



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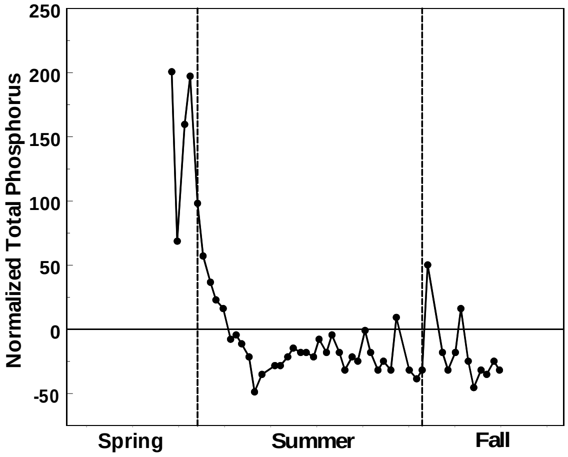
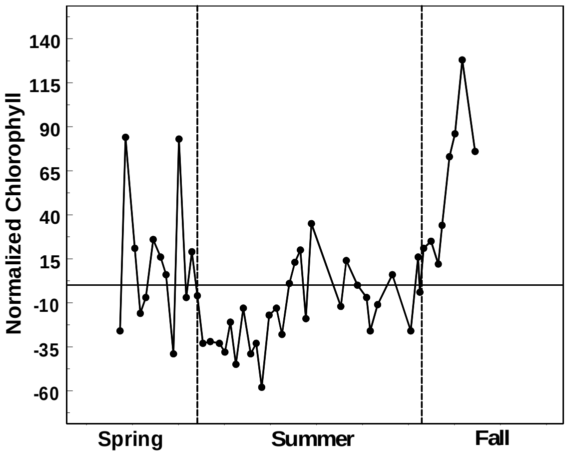
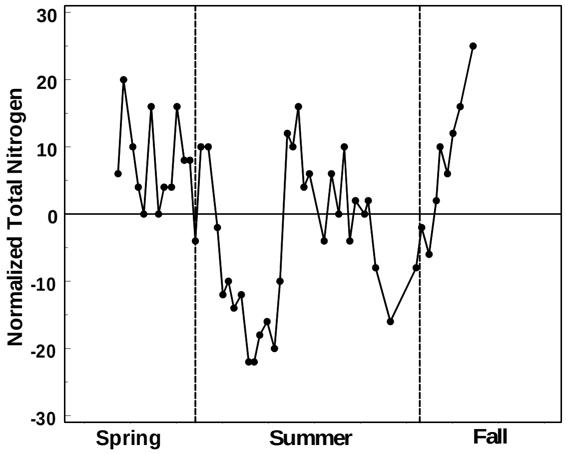
125
100
75
50
25
0
-25
-50
Spring
Summer
Fall

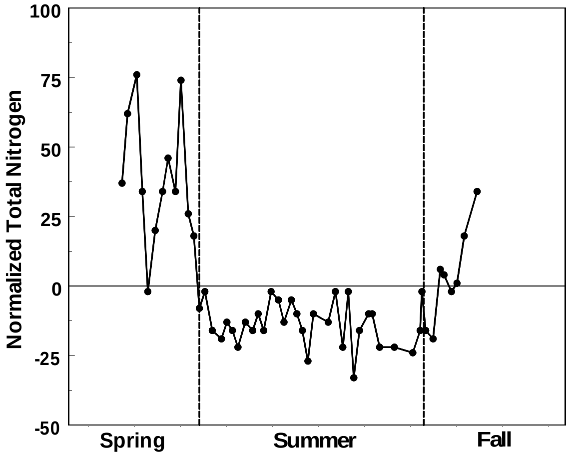


Normalized Total Phosphorus
250
200
150
100
50
0
-50
Spring
Summer
Fall

Blue Springs







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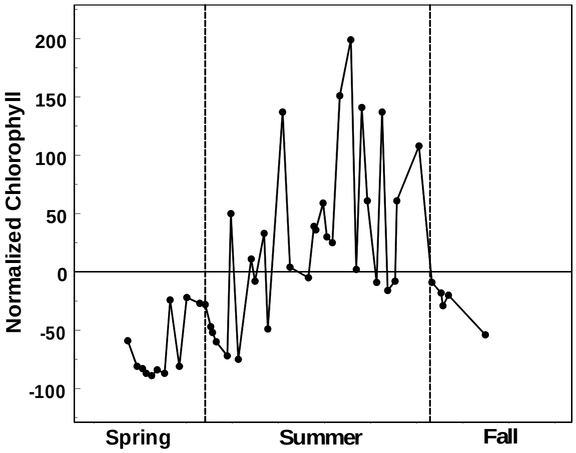
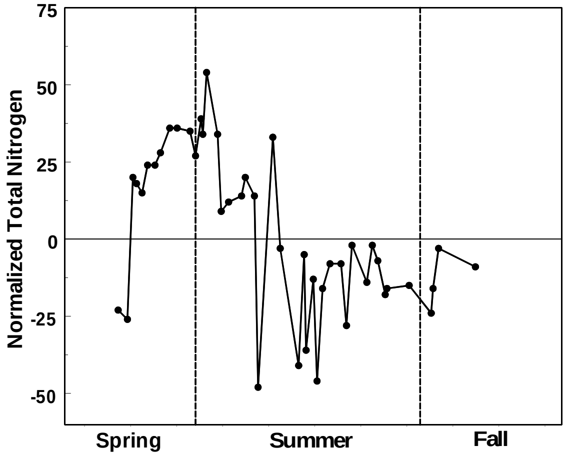
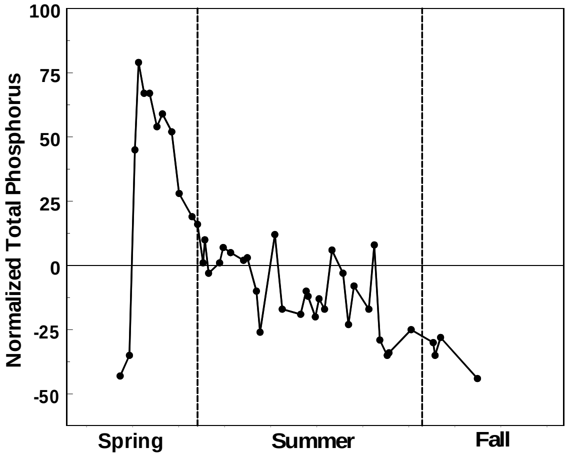
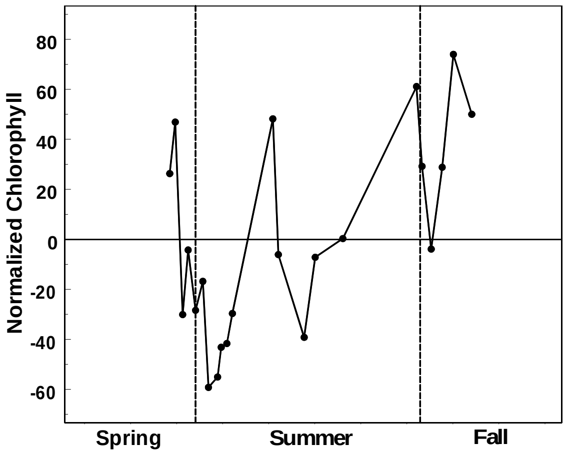






Kraut Run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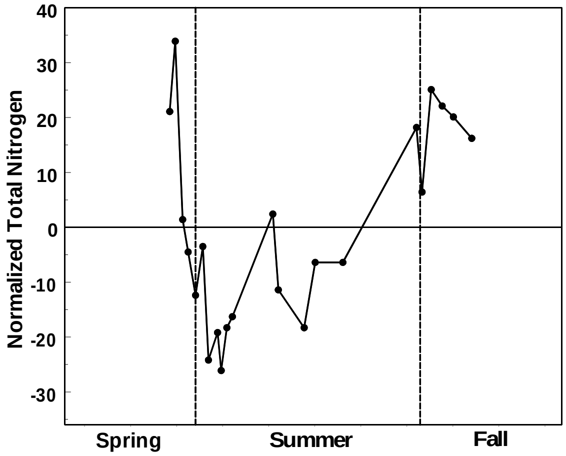
60
40
20
0
-20
-40
-60
Spring
Summer
Fall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20
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0
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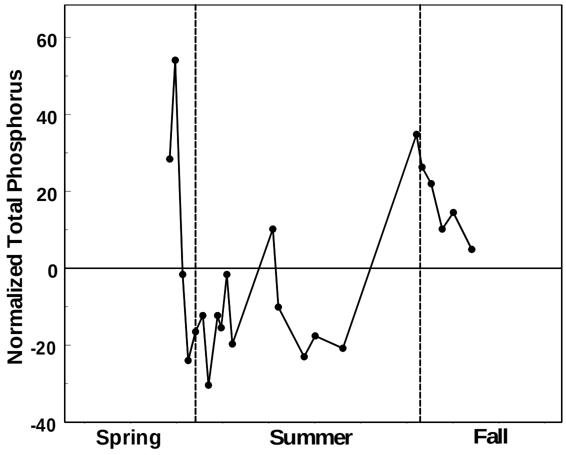
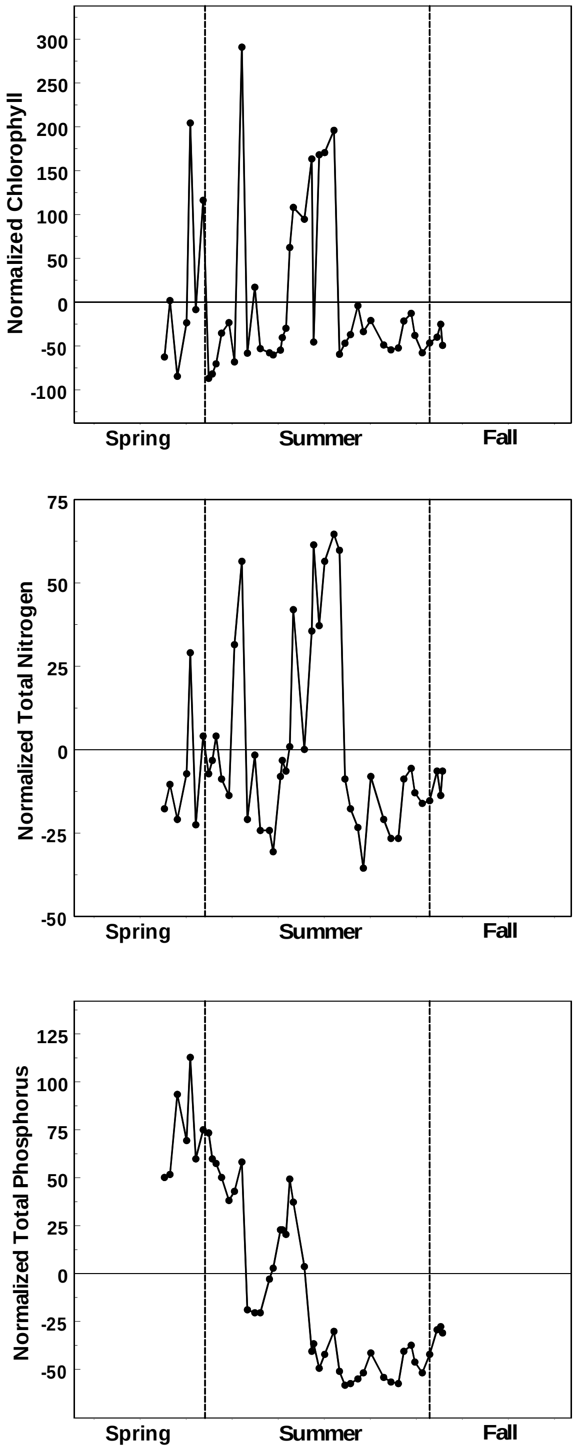
-20
-30
Spring
Summer
Fall

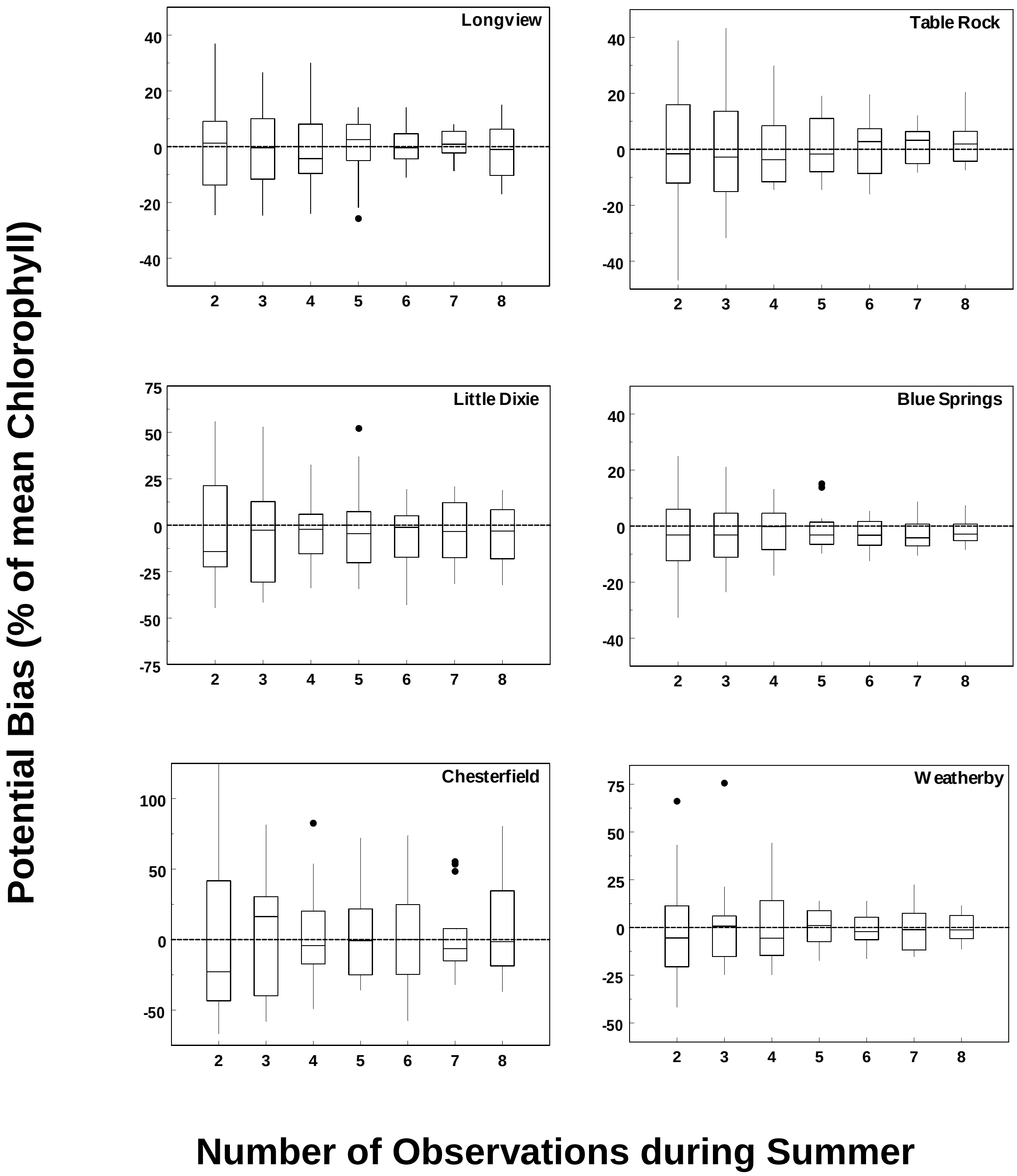

Normalized Total Phosphorus
60
40
20
0
-20
-40
Spring
Summer
Fall

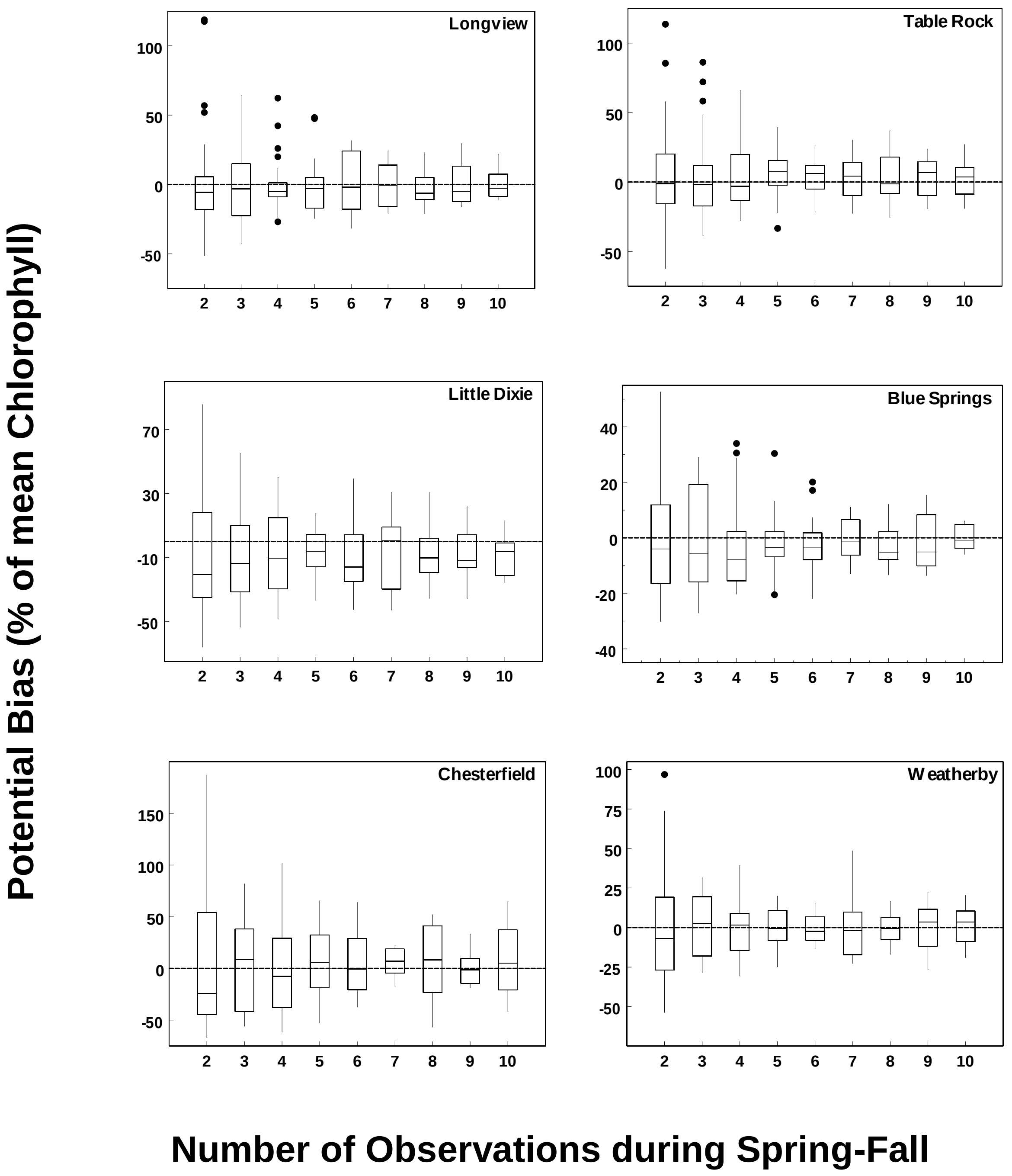
Chesterfield

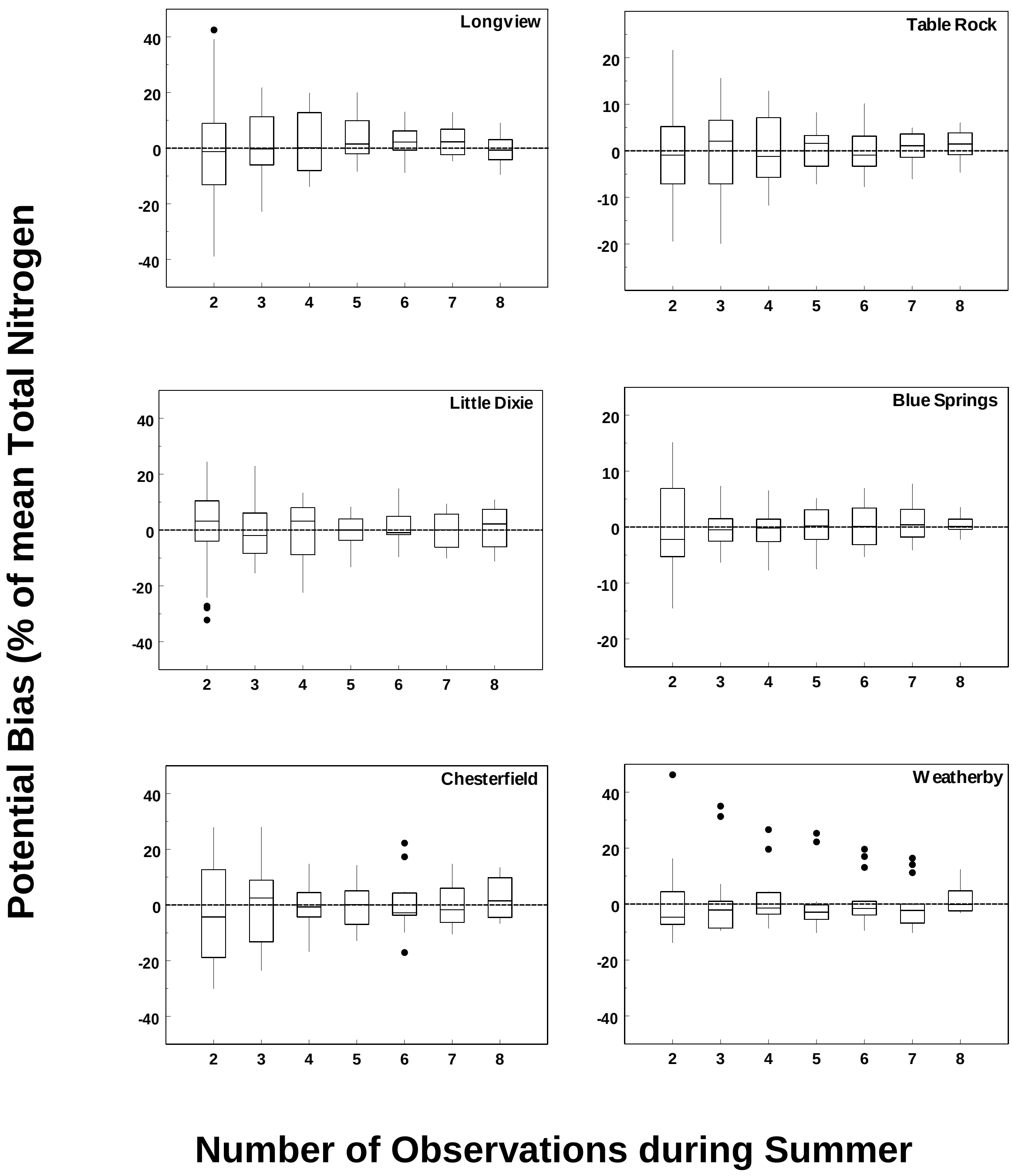


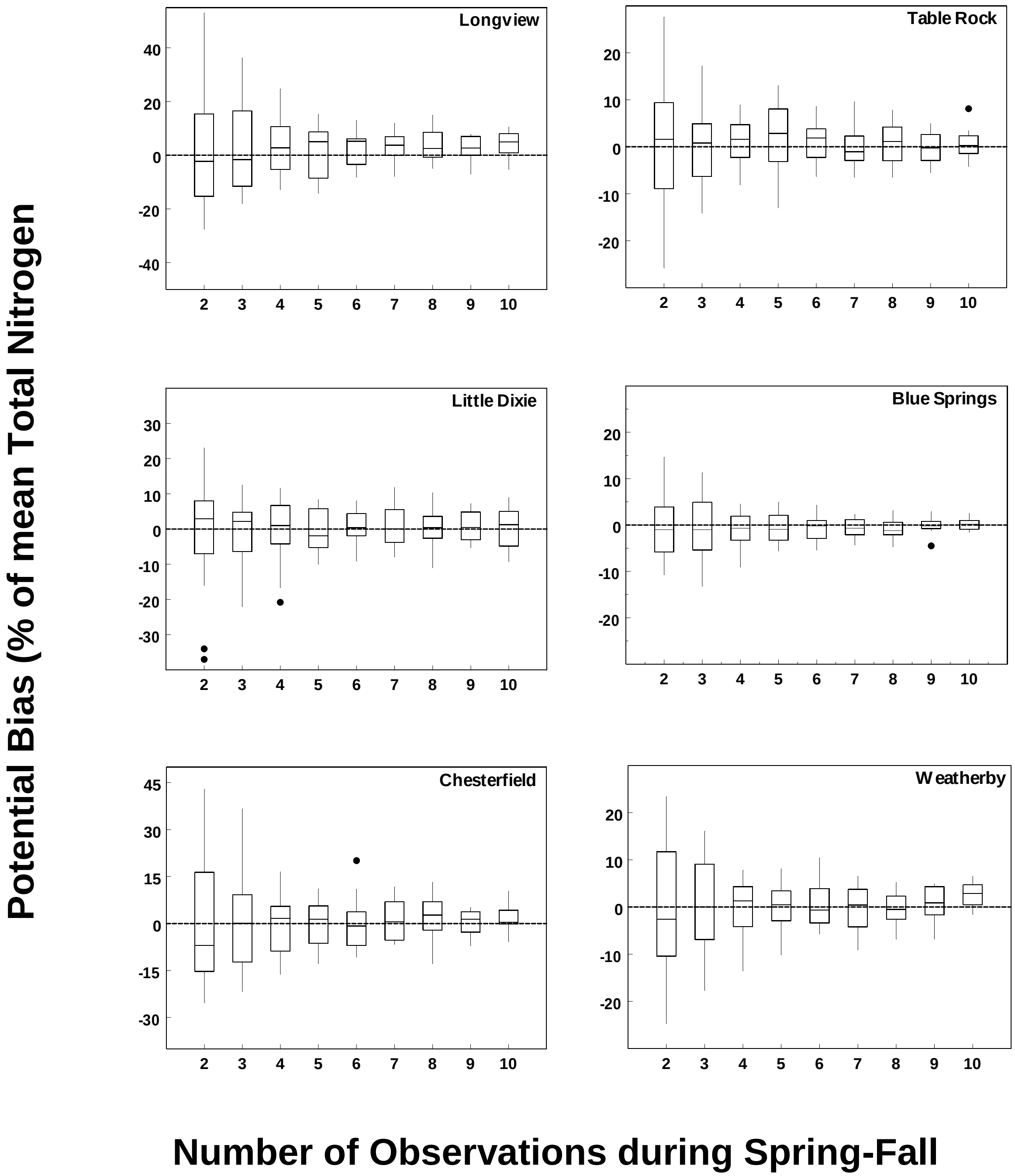
APPENDIX B.

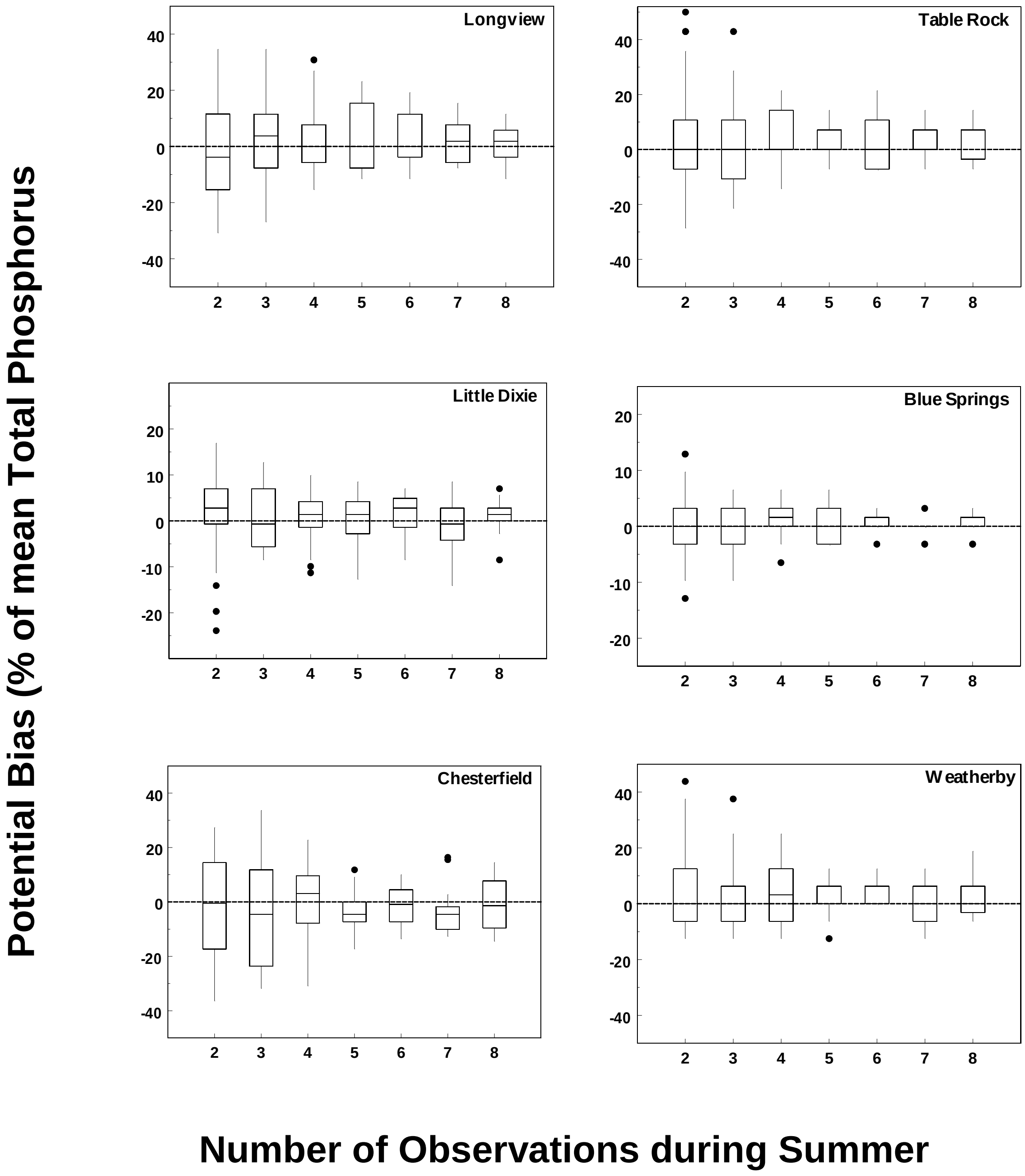
Potential bias in estimating chlorophyll, total nitrogen and total phosphorus associated with varying sample sizes collected during summer and spring-fall periods.

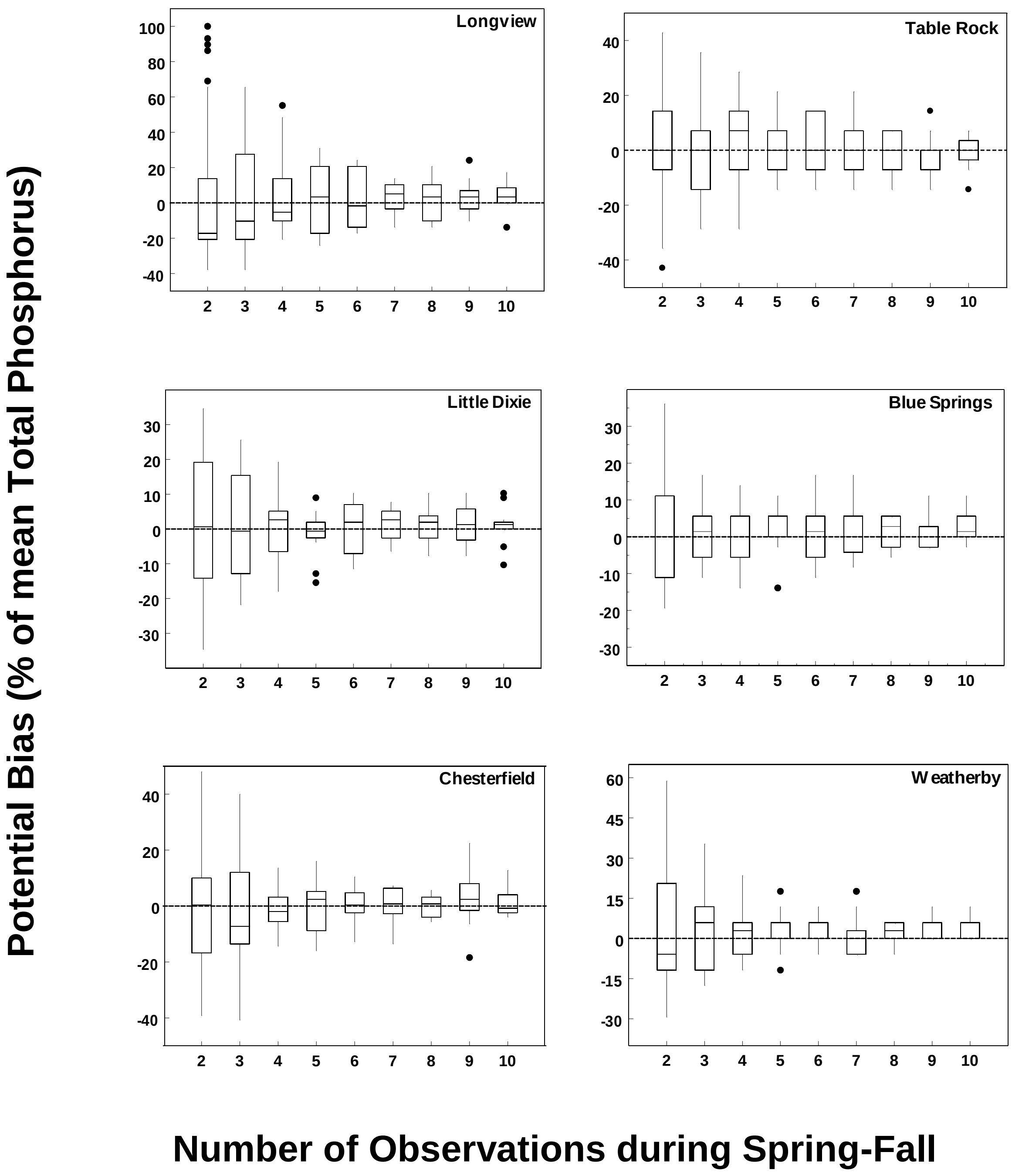

Potential Bias (% of mean Chlorophyll)
Number of Observations during Summer
Longview
Table Rock
Little Dixie
Blue Springs
Chesterfield
Weatherby
40
20
0
-20
-40
75
50
25
-25
-50
-75
100
2
3
4
5
6
7
8


Potential Bias (% of mean Chlorophyll)
Longview
100
50
0
-50
2 3 4 5 6 7 8 9 10
Table Rock
100
50
0
-50
2 3 4 5 6 7 8 9 10
Little Dixie
70
30
-10
-50
2 3 4 5 6 7 8 9 10
Blue Springs
40
20
0
-20
-40
2 3 4 5 6 7 8 9 10
Chesterfield
150
100
50
0
-50
2 3 4 5 6 7 8 9 10
Weatherby
100
75
50
25
0
-25
-50
2 3 4 5 6 7 8 9 10
Number of Observations during Spring-Fall


Potential Bias (% of mean Total Nitrogen
Longview
40
20
0
-20
-40
2
3
4
5
6
7
8
Table Rock
20
10
0
-10
-20
2
3
4
5
6
7
8
Little Dixie
40
20
0
-20
-40
2
3
4
5
6
7
8
Blue Springs
20
10
0
-10
-20
2
3
4
5
6
7
8
Chesterfield
40
20
0
-20
-40
2
3
4
5
6
7
8
Weatherby
40
20
0
-20
-40
2
3
4
5
6
7
8
Number of Observations during Summer


Longview
Table Rock
Little Dixie
Blue Springs
Chesterfield
Weatherby
40
20
0
-20
-40
20
10
0
-10
-20
30
20
10
0
-10
-20
-30
45
30
15
0
-15
-30
2
3
4
5
6
7
8
9
10
Potential Bias (% of mean Total Nitrogen
Number of Observations during Spring-Fall


Potential Bias (% of mean Total Phosphorus
Longview
40
20
0
-20
-40
2 3 4 5 6 7 8
Table Rock
40
20
0
-20
-40
2 3 4 5 6 7 8
Little Dixie
20
10
0
-10
-20
2 3 4 5 6 7 8
Blue Springs
20
10
0
-10
-20
2 3 4 5 6 7 8
Chesterfield
40
20
0
-20
-40
2 3 4 5 6 7 8
Weatherby
40
20
0
-20
-40
2 3 4 5 6 7 8
Number of Observations during Summer


Potential Bias (% of mean Total Phosphorus)
Longview
100
80
60
40
20
0
-20
-40
Table Rock
40
20
0
-20
-40
Little Dixie
30
20
10
0
-10
-20
-30
Blue Springs
30
20
10
0
-10
-20
-30
Chesterfield
40
20
0
-20
-40
Weatherby
60
45
30
15
0
-15
-30
2
3
4
5
6
7
8
9
10
Number of Observations during Spring-Fall