GROWING SEASON PRODUCTIVITY AND TROPHIC CLASSIFICATION OF OAK LAKE, BROOKINGS COUNTY, SOUTH DAKOTA

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ABSTRACT

Changes in lake trophic state present concerns to water resource managers interested in maintaining water quality to support assigned beneficial uses. Contemporary methods of classifying lakes involve the use of surrogate indicators of production. However, some of these measurements are sensitive to wind induced resuspension of sediments, leading to inflated indications of basin production. This source of error is common to many shallow glacial lakes in eastern South Dakota and southwestern Minnesota. The objectives of this effort were to (1) estimate and define the trend in seasonal water column net and gross primary production and community respiration within a shallow pothole basin, (2) compare the mean net primary productivity values among three sub-basin sites and (3) evaluate trophic state classification using surrogate measures against actual production measurements. Water production as measured at three basin sites in Oak Lake, South Dakota, was evaluated using the light/dark bottle method once every two weeks throughout the 2010 growing season. Mean net primary productivity was 741 mg C•m^{-2}•d^{-1}and ranged from 35 to 1,462 mg C•m^{-2}•d^{-1}. Estimated to the light compensation depth, Oak Lake mean net primary production would lead to a eutrophic classification for this basin but would range between mesotrophic and hypereutrophic throughout the growing season. Trophic State Index values, derived from Secchi depth, ranged between 65 and 83, with a mean of 75, leading to an index classification of eutrophic or hypereutrophic. Secchi transparency explained 82% of the variation in net primary production while chlorophyll a explained only 17%. We concluded that Secchi transparency is an adequate surrogate for planktonic production despite consistently overestimating actual production levels within this basin.

Keywords

Primary production, Secchi depth, trophic classification, shallow lake

INTRODUCTION

Changes in lake trophic state present concerns to water resource managers interested in maintaining water quality to support assigned beneficial uses (Carlson and Simpson 1996). Consequences of eutrophication include phytoplankton blooms, oxygen depletion in deep waters, degradation of water supplies, and recreational use limitations (Carlson 1977; Chin 2006, Codd 2000; USEPA 1998; USEPA 2009b). Hypereutrophic waters often suffer from taste, odor, oxygen depletion and even potential neurotoxin production as planktonic production accelerates and die-offs occur. Assessment of lake trophic state and factors influencing production is necessary before corrective measures can be applied to protect the intended uses of a lake (Wetzel 2001). Thus, measurement and control of eutrophication is an important issue for water resource managers (Chin 2006).

The trophic state of a lake describes its potential for primary production and ranges between oligotrophic and hypereutrophic (Carlson and Simpson 1996). An oligotrophic lake has low productivity (50 - 300 mg $C \bullet m^{-2} \bullet d^{-1}$) with clear water and low nutrient concentrations (Wetzel 2001) (Table 1). Mesotrophic lakes are moderately productive (250 – 1,000 mg $C \bullet m^{-2} \bullet d^{-1}$) and moderately clear. A eutrophic lake is highly productive (> 1,000 mg $C \bullet m^{-2} \bullet d^{-1}$) with low transparency and high densities of planktonic algal and/or macrophyte growth. Finally, hypereutrophic lakes are highly productive, with dense macrophytes and algae and very low transparency (Carlson and Simpson 1996).

Table 1. Trophic state classification ranges based on mean daily net primary production and TSI values derived from Secchi depth or chlorophyll a.

Parameter	Oligotrophy	Mesotrophy	Eutrophy	Hypereutrophy
Net Primary Production (mg $C/m^{-2}/d^{-1}$)	50 - 300	250 – 1000	> 1000	
TSI (Secchi depth or Chlorophyll a)[2]	< 30	40 – 50	50 - 60	70 - 80

[1] Modified from Wetzel (2001)

[2] Modified from Carlson and Simpson (1996)

Of 139 monitored lakes in South Dakota 45 (32%) were classified as hypereutrophic, 70 (50%) were eutrophic, 16 (12%) were mesotrophic, 1 (0.7%) was oligotrophic, and 7 (5%) were unclassified (SDDENR 2010). The National Lakes Assessment characterized trophic state based primarily on chlorophyll a values (USEPA 2009b). Of 49,546 U.S. lakes 6,353 (13%) were oligotrophic, 18,128 (37%) were mesotrophic, 14,918 (30%) were eutrophic, and 9,924 (20%) were hypereutrophic.

The Clean Water Act mandates that state and federal governments restore and maintain the integrity of the nation's waters (USEPA 1998). This requires routine assessment of lakes in an effort to monitor condition and implement restoration. However, limited financial resources prevent direct measurement of production by most monitoring agencies (USEPA 2002). Instead, surrogate measurements, particularly water transparency, phosphorus, and chlorophyll a, are collected to evaluate lake productivity and assign trophic state (USEPA 2009a).

Measurements of water transparency (Secchi depth), total phosphorus, and/or chlorophyll a are applied to the Carlson Trophic State Index to assign lake trophic classes using the equations below (Carlson 1977; Carlson and Simpson 1996). The Trophic State Index (TSI) is a scale ranging from 0 to 100. TSI values falling within different index ranges are assigned to a trophic class as follows: TSI less than 40 indicates oligotrophy, TSI between 40 and 50 corresponds to mesotrophy, TSI between 50 and 60 indicates eutrophy, and TSI values greater than or equal to 70 correspond to hypereutrophy (Carlson and Simpson 1996; USEPA 2009a) (Table 1).

$$\text{TSI Total Phosphorus} = 14.42 * \log_e(\text{TP ug/L}) + 4.15$$
$$\text{TSI Chlorophyll } \underline{a} = 9.81 * \log_e(\text{chlorophyll } \underline{a} \text{ ug/L}) + 30.6$$
$$\text{TSI Secchi Depth} = 60 - 14.41 * \log_e(\text{Secchi depth m})$$

Water transparency generated using a Secchi disc is the most frequently measured surrogate variable for basin production (USEPA 1998, Likens and Wetzel 1991, Vollenweider 1969). The Secchi disc is 20 cm in diameter and is painted black and white in alternating quadrants (Fuller et al. 2004). The mean of the depth at which the disc disappears from view while being lowered into the water and at which it reappears when being raised is the transparency or Secchi depth (Likens and Wetzel 1991). This method of determining transparency is cheap and simple, making it an ideal and common method for state agencies to evaluate trophic state (Vollenweider 1969; Wetzel 2001). In fact, many state agencies conscript the help of lake associations and volunteers for the collection of Secchi transparency data from otherwise unmonitored lake basins (USEPA 2002, USEPA 2009b).

However, a potential problem exists with the Secchi disc as an accurate assessment of trophic conditions. Abiotic factors can influence water transparency and give a false indication of high productivity. For instance, in areas with moderate amounts of non-algal turbidity, the Secchi disc is an inappropriate method of determining algal biomass for the classification of trophic state (Chin 2006; Wetzel 2001).

Eastern South Dakota and southwestern Minnesota are rich with glacial lakes. Due to low transparency values, many of these lakes are classified as hypereutrophic. However, many of these basins are also very shallow and easily mixed from frequent high winds. For example, Oak Lake, Brookings County, South Dakota, has an average depth of 1.2 m and a maximum depth of 2.0 m (Troelstrup 2009). Oak Lake also experiences high and often sustained winds. These winds create waves capable of reaching the bottom and resuspending sediments from the lake bed. Suspended particulates may decrease transparency and inflate phosphorus values without a corresponding productivity increase. Thus, water transparency and total phosphorus levels may falsely suggest high production.

The issue then arises as to the true trophic state for shallow prairie lake basins. The objectives of this project were to (1) estimate and define the trend in seasonal water column net and gross primary production and community respiration within a shallow pothole basin, (2) compare the mean net primary productivity values among three sub-basin sites and (3) evaluate trophic state classification using surrogate measures against actual production measurements.

METHODS

Site Description—We evaluated planktonic gross primary production, net primary production and community respiration from Oak Lake, Brookings County, South Dakota, utilizing the facilities of the Oak Lake Field Station (Lat 40° 30' 30.36", Long 96° 31' 52.98") (Figure 1). Oak Lake has been classified as a hypereutrophic basin with an average depth of 1.2 m and a maximum depth of 2.0 m (SDDENR 2010; Troelstrup 2009). The watershed for this basin drains portions of the Northern Glaciated Plains Level III Ecoregion and falls within the headwaters of the Minnesota-Mississippi river system. Basin area is 163 ha and basin length is 3,081 m (Troelstrup 2009). Three basin sites (north, middle, and south) are routinely monitored (1970 - present) and were thus chosen as sites for production measurement (Figure 1). This allowed assessment of correlations between production measurements and biophysical monitoring data.

Measurement of Production—Plankton production was measured from each basin site every two weeks throughout the growing season months of May through August and once in September using the light/dark bottle method (Vollenweider

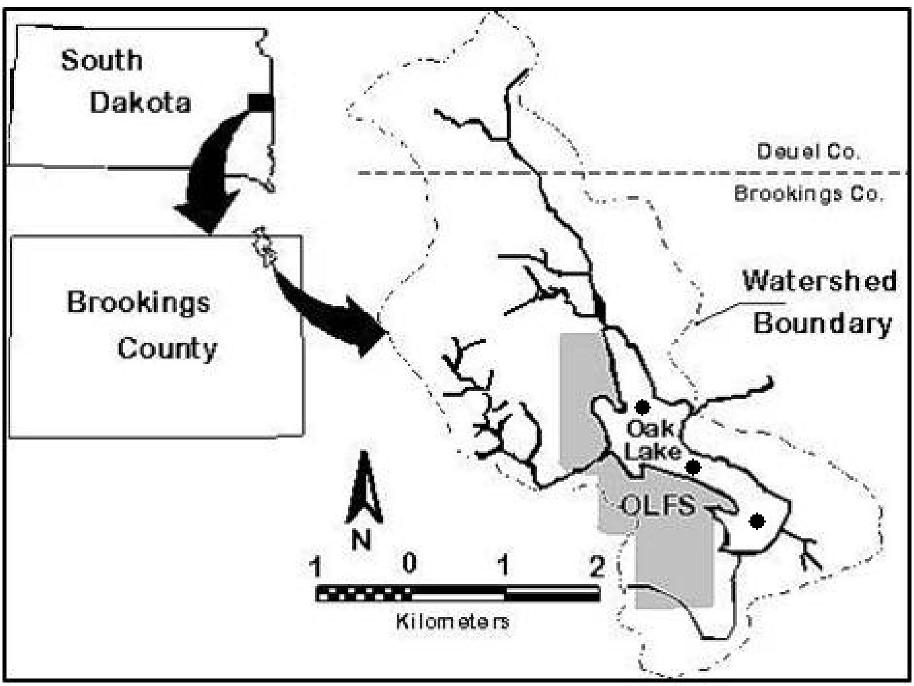

Figure 1. Basin monitoring sites within the Oak Lake basin (Brookings County) where light/dark productivity and monitoring measurements were taken.

1969). Paired light and dark bottles were filled and suspended to a depth of 16 cm at each site. A duplicate set was suspended at one randomly chosen site as a quality control measure. One set of water samples was collected and fixed with manganese sulfate, alkali iodide azide and sulfamic acid per site at the time of suspension to establish initial dissolved oxygen concentration. Suspended bottles were collected and fixed after an incubation period of between 2.2 and 4.9 hr. Samples were then transported back to the Oak Lake Field Station laboratory where 200 ml of each sample was titrated with sodium thiosulfate to determine oxygen concentration. Due to technical difficulties, erroneous data collected in mid-June were excluded from analysis.

Initial and final oxygen concentrations from each bottle were used to estimate gross and net primary production and community respiration (Lind 1985). Net primary production was estimated by first dividing the change in dissolved oxygen by the incubation time and then multiplying that value by the number of hours in the photoperiod of each testing day (USNO 2010). The photoperiod was determined using sunrise and sunset times for Oak Lake as listed by the U.S. Naval Observatory after subtracting two hours for low sun angle at sunrise and sunset. Daily community respiration was estimated by extrapolating hourly oxygen change observed in dark bottles through a 24-hr period. Daily gross primary production was determined by adding the estimated daily values for net primary production and community respiration from a given site.

Daily net primary production (NPP) and community respiration (CR) estimates were expressed in carbon units per square meter following the unit conversion of Lind (2.67 mg O_2 = 1 mg C, 1985) and multiplication by the depth of bottle placement for net primary production (NPP_B) and total depth for community respiration. These figures were used in analyzing seasonal production trends, comparing basin sites, and analyzing the relationship between production and lake monitoring data. A one-way ANOVA test was used to evaluate differences among basin sites. Relationships between production and water transparency, production and planktonic chlorophyll a and transparency and chlorophyll a were evaluated using linear regression following log transformation of raw data.

Net primary production data were then extrapolated to the light compensation point (1% surface intensity of photosynthetically active radiation) (NPP_C) to calculate an estimate of total water column gross primary production. Because production is known to decrease rapidly with depth, we applied half the measured production (16-cm depth) to the compensation point. These production values provided a rough estimate of total water column planktonic production calculated only for direct comparison with trophic classification standards and productivity values reported for other water bodies. The determined trophic classification (TSI) of Oak Lake using both Secchi and chlorophyll a data was compared to actual production measurements to evaluate the accuracy of classification.

Oak Lake Monitoring Data—Oak Lake water quality and physical habitat features were monitored every other week during the growing season at three basin sites (Figure 1). Measurements included dissolved oxygen, specific conductance, pH and water temperature using a YSI Model 556. Sonar depth soundings were made at each basin site on each monitoring date. Secchi transparency was measured at each basin site (Lind 1985) and vertical profiles of photosynthetically active radiation were measured at 25-cm intervals from the surface to the bottom at each site using a LICOR LI-1000 radiation sensor. Grab samples were collected below the surface, filtered, and chlorophyll a was extracted using 90% acetone. Planktonic chlorophyll a concentrations corrected for phaeophytin were measured spectrophotometrically (Clesceri et al. 1998).

RESULTS

Production within the Oak Lake basin displayed significant seasonal variation but very little variation among different basin sites. NPPB ranged from 35 to 1,462 mg C•m^{-2}•d^{-1} (mean = 741 mg C•m^{-2}•d^{-1}). Community respiration to the lake bottom ranged from 760 to 18,229 mg C•m^{-2}•d^{-1} (mean = 3,375 mg C•m^{-2}•d^{-1}) and gross primary production ranged from 1,054 to 18,636 mg C•m^{-2}•d^{-1} (mean = 4,115 mg C•m^{-2}•d^{-1}). Net and gross primary production increased between May and early August before decreasing sharply in September (Figure 2). Mean NPP_B was 85 mg C•m^{-2}•d^{-1} in May and 400 mg C•m^{-2}•d^{-1} in September. Peak net primary production occurred in mid-August (1,352 mg C•m^{-2}•d^{-1}). Mean ratios of NPP_C to community respiration were 0.26 and 0.53 in May and September, respectively. However, ratios were greater than 1.0 throughout the period June - August. Net primary production, gross primary production and community respiration did not vary significantly among basin sites on any measurement date (ANOVA , $P > 0.05$).

Mean NPP_C within the Oak Lake basin was 3,575 mg C•m^{-2}•d^{-1} and ranged from 174 to 6,259 mg C•m^{-2}•d^{-1}. Oak Lake mean TSI values generated from Secchi transparency data generally indicated hypereutrophy, ranging between 65 and 83 (mean = 75) while those calculated from chlorophyll a measurements generally indicated eutrophy, ranging between 44 and 71 (mean = 58) (Table 2).

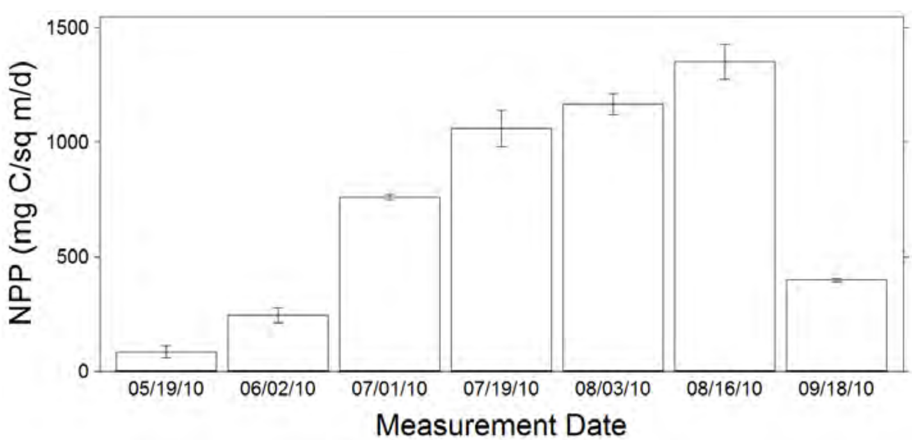

Figure 2. Net primary productivity of Oak Lake (Brookings County) in mg C•m^{-2}•d^{-1} during the summer of 2010 (mean +/- 1 standard error). Production measured to 16-cm depth.

Table 2. Secchi depth, chlorophyll a and associated trophic state index scores from monitoring data collected within the Oak Lake basin during 2010.

Parameter	North Basin	Middle Basin	South Basin	Overall	Range
Secchi Depth (cm)	35.3	37.6	40.0	37.6	20 - 71
TSI (Secchi Depth)	75.9	75.1	74.1	75.0	65 - 83
Chlorophyll a (ug/L)	19.0	27.2	17.3	21.2	4.0 - 61.4
TSI (Chlorophyll a)	57.4	60.8	56.4	58.2	44.2 - 71

We observed a significant negative linear relationship between NPP_B and Secchi transparency (R^2 = 0.82, P < 0.01; Figure 3a). In contrast, the relationship between NPP_B and planktonic chlorophyll a was far weaker (R^2 = 0.17, P = 0.048; Figure 3b). A significant negative relationship was observed between growing season Secchi transparency and corrected planktonic chlorophyll a (R^2 = 0.30, P = 0.01; Figure 4), although this relationship was also not as strong as that observed between net primary production and Secchi transparency. Addition of wind speed measured at the time of data collection did not explain a significant amount of additional variation in water column transparency. We were able to explain 88% of the variation in NPP_B in a multiple regression using log transformed Secchi transparency and surface water temperature taken at the time of incubation (logNPP = 11.2784 – 2.09234logSD + 0.1049*EnWaT, P < 0.01, R^2 = 0.88).

DISCUSSION

The determined NPP_C had a mean of 3,575 mg C•m^{-2}•d^{-1} and a range from 174 to 6,259 mg C•m^{-2}•d^{-1}. These values fall largely within or above the ranges reported for other shallow basins. For example, oligotrophic Lawrence Lake in Michigan yielded a mean daily productivity of 99 mg C•m^{-2}•d^{-1} and ranged between 5 and 497 mg C•m^{-2}•d^{-1} (Wetzel 2001). Alternatively, shallow Sylvan Lake in Indiana is classified as eutrophic with a mean daily productivity of 1,564 mg C•m^{-2}•d^{-1} and a range between 9 mg C•m^{-2}•d^{-1} and 4,959 mg C•m^{-2}•d^{-1}. A study of Northern Great Plains saline lakes in North and South Dakota and Montana yielded a mean production rate of 125 mg C•m^{-3}•h^{-1} in the summer with a range between 15 and 544 mg C•m^{-3}•h^{-1} (Salm et al. 2009). Although slightly higher in productivity than other lakes reported in the literature, the production values for Oak Lake are not unreasonable.

We observed that net and gross primary productivity were low in May, increased and peaked in August, and declined in fall. This seasonal pattern in production followed previously observed seasonal patterns for other lakes (Nõges et al. 2011; Sterner 2010; Wetzel 2001) and corresponded with seasonal changes in light availability and water temperature. Light and temperature are critical abiotic drivers of production (Brylinsky and Mann 1973; Goldman and Carpenter

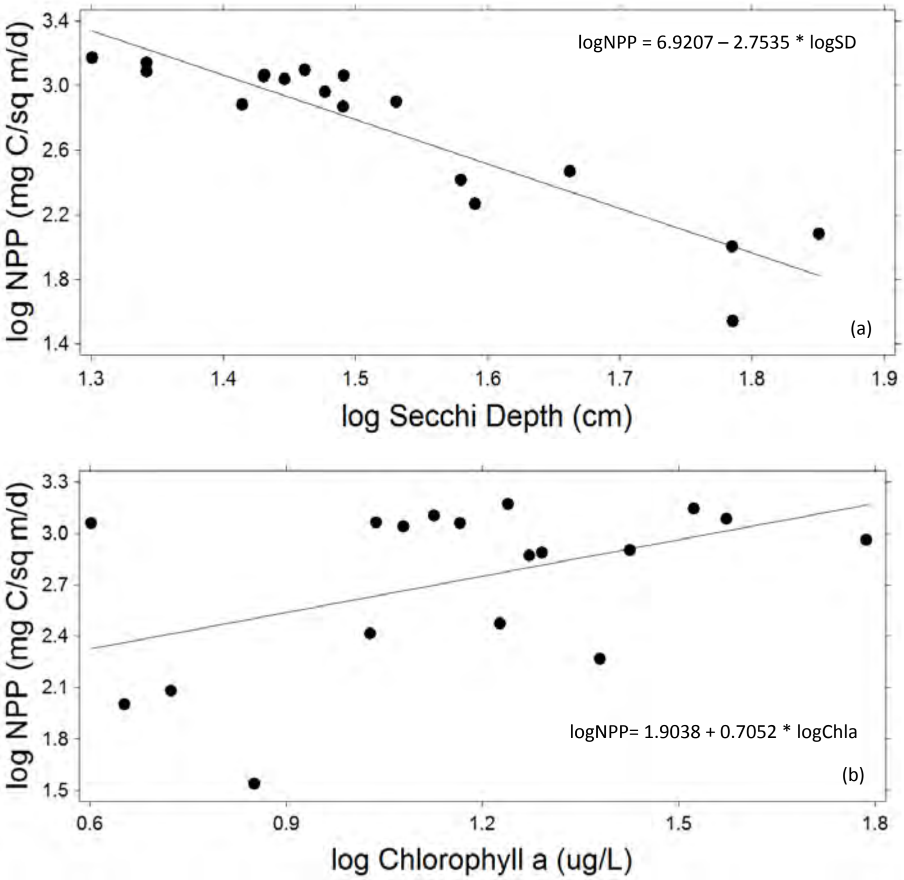

Figure 3. Relationships between net primary production of Oak Lake to 16-cm depth and (a) Secchi depth (cm) (R^2 = 0.82, P < 0.01) and (b) corrected chlorophyll a (R^2 = 0.17, P = 0.048) during the 2010 growing season.

1974; Wetzel 2001), even in shallow lakes experiencing wind driven sediment resuspension (Wielgat-Rychert et al. 2010). Temperature increased between May and early August before starting to decline in late August. Similarly, photoperiod increased until the end of June before decreasing throughout the remainder of the summer (USNO 2010). Significant variation in NPP_B was explained by water temperature observed on the day of production measurements.

Ratios of net primary productivity to community respiration suggested heterotrophic conditions early in the growing season (P/R<1), autotrophic conditions throughout the summer months (P/R>1), and a transition back to heterotrophy late in the season. Studies have shown a positive correlation between water temperature and algal growth (Goldman and Carpenter 1974), and a similar relationship between light and photosynthesis (Wetzel 2001). Therefore, an increase in available light or water temperature results in increased growth or photosynthesis, and subsequently increased production. However, the extent of these relationships varies according to species, and at higher temperatures

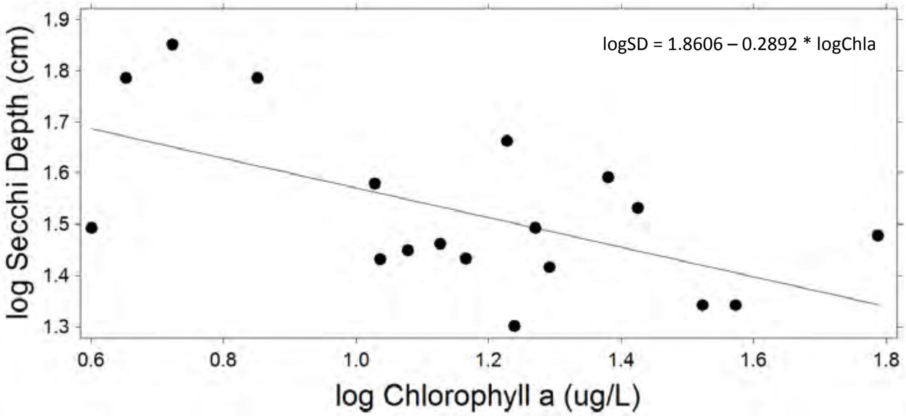

Figure 4. Relationship between Secchi depth (cm) and corrected chlorophyll a (R^2 = 0.30, P = 0.011) of Oak Lake during the 2010 growing season.

respiration rates also increase (Wetzel 2001). The basin may then be said to be net autotrophic during the bulk of the growing season (Del Giorgio and Peters 1994).

We observed no significant spatial pattern in production or community respiration among the Oak Lake basin sites. Uniform basin morphology and wind driven mixing along the fetch of the lake likely created homogeneous production conditions in these open basin sites. Horizontal differences in primary productivity may be minor in lakes with relatively small variations in different parts of the lake (Wetzel 2001). However, the light/dark bottle measurements we employed were not effective in capturing variation in production or respiration between open basin sites and littoral areas near the shoreline. Like many shallow prairie basins, Oak Lake is fringed with *Typha* spp. and *Scirpus* spp. beds which are highly productive (Wetzel 2001). Our results simply reflect plankton production in the open pelagic zone of the basin where lake monitoring data are typically collected (USEPA 1998). Thus, total basin production likely displays very different spatial and temporal patterns than those we observed in the pelagic zone.

Based on our calculated mean NPP_C, Oak Lake could be classified as eutrophic, ranging between mesotrophic and hypereutrophic throughout the growing season (Wetzel 2001). Secchi depth and chlorophyll a TSI values would suggest that this basin be classified as eutrophic or hypereutrophic (Carlson and Simpson 1996). Overall, trophic state class assignment using Secchi depth data would suggest higher production than that observed through direct measurement. This may be the result of increased turbidity caused by sediment resuspension. This is supported by higher TSI values from Secchi depth than those generated from chlorophyll a. This occurs when non-algal particulates cause light attenuation (Carlson and Simpson 1996). However, differences in classification among the three methods were not large and the classifications were approximately the same across much of the growing season. This seems to indicate that Secchi depth may be sufficient for classification of shallow pothole basins.

NPP_B displayed a significant log-log relationship with Secchi depth values, however approximately 18% of the variation in NPP_B was unexplained. This unexplained variation (18%) may have been due to sampling error, factors circumstantial to the site or test date, and/or resuspended bottom sediments that decrease transparency without a corresponding increase in production. The negative relationship we observed between production and transparency is consistent with that expected if transparency changes are driven by primary production. However, the relationship between chlorophyll a and net primary production was far weaker than that with Secchi depth. This is interesting since one might expect a good relationship between net primary production and chlorophyllous pigment concentrations. Perhaps the weaker relationship was due to variations in chlorophyll content among different phytoplankton species (Wetzel 2001), or to light limitations on phytoplankton growth by suspended non-algal particulates (Robarts et al. 1992). Plotting Secchi depth versus chlorophyll a displayed a significant negative linear relationship, yet only 30% of Secchi depth was explained by chlorophyll a. This leaves 70% that is unexplained by chlorophyll. This relationship is weaker than those noted by Carlson ($R^2 = 0.93$, 1977) and LaBounty ($R^2 = 0.71$, 2008). Thus Secchi depth may be used as a means of classifying lake trophic status, but may still overestimate actual production in shallow lakes like those of eastern South Dakota and southwestern Minnesota.

Additional production studies are needed to evaluate temporal variation among multiple growing seasons and vertical variation in production within the water column. Because many of the abiotic factors controlling production are likely to vary by basin, production studies are also needed on multiple shallow glacial prairie lakes to evaluate regional central tendencies and variation. These statistics might then be used within a biogeographic framework to establish production-based standards for future monitoring. Such a study may also assist in building improved uniform water analysis and monitoring on a national scale, identified as necessary by the National Lakes Assessment (USEPA 2009b).

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