The dynamics of dissolved oxygen and metabolic rates in a shallow subtropical urban lake, Louisiana, USA

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Abstract Ecosystem metabolism is an important indicator of biological activities in the context of enhanced nutrient fluxes to freshwater. In this study, we assessed both the gross and net primary production, and respiration of a shallow subtropical lake that is influenced by a highly developed urban environment. A real-time water quality monitoring platform with multi-parameter probes was deployed in the centre of the lake to record changes in dissolved oxygen (DO) concentration and other water quality parameters at 15-minute intervals from July 2008 to July 2009. The measurements were used to quantify lake productivity with a single station diel oxygen change method. The data suggested a mean annual gross primary productivity of 4.41 g O_2 m^{-2} d^{-1}, a mean annual net primary production of 2.13 g O_2 m^{-2} d^{-1}, and a mean annual respiration of 5.90 g O_2 m^{-2} d^{-1}. Annually, a total of 1610 g O_2 m^{-2} were produced compared with a respiratory consumption of 2150 g O_2 m^{-2}. Monthly respiration rates were equal to, or greater than, monthly productivity rates during the monitored year, suggesting that this shallow subtropical urban lake was heterotrophic in net terms throughout most of the year.

Keywords lake eutrophication; dissolved oxygen; metabolic rates; net productivity; community respiration; subtropical urban lake

INTRODUCTION

Population growth and intensified human activities have altered physical, chemical and biological processes in many natural water bodies. Today, surface water pollution has become a serious environmental issue for many urban areas around the world. In the United States, about 44% of all lakes and 59% of man-made lakes are classified to be in fair or poor biological condition (US EPA, 2009). Many urban lakes are impaired due to excess nutrient inputs and organic enrichment, which can cause algal blooms, fish kills, and pungent smells (e.g. Persson, 1982; Venugopalan *et al.*, 1998; Smith, 2003). The large percentage of impervious surface in urban environments alters site hydrology, such as infiltration, surface and subsurface flow, and ground-water recharge, while municipal and industrial discharges increase nutrient loads (cf. Whitehead *et al.*, 2009).

The impaired aquatic environment in urban areas is often reflected by the availability of dissolved oxygen (DO). The concentration of DO in a lake system is affected by chemical, physical, and biological interactions, including metabolic activity rates, atmospheric diffusion and temperature. These interactions typically result in irregular patterns over time (Ginot & Herve, 1994; Gelda & Effler; 2002; D'Autilia *et al.*, 2004; Lopez-Archilla *et al.*, 2004). While DO is considered one of the most important water quality parameters, metabolism is often used as a measure of freshwater ecosystem health (Fellows *et al.*, 2006; Bernot *et al.*, 2010) because of its responsiveness to natural and anthropogenic changes. In the past several decades many studies on primary productivity rates of lakes have been conducted. However, only a few of them have dealt with the evaluation of shallow lake productivity (Lopez-Archilla *et al.*, 2004). Furthermore, most of the shallow lake studies (Anderson, 1974; Mitchell, 1989; Robarts *et al.*, 1995; Bachmann *et al.*, 2000) were conducted in cold temperate regions.

Against the above context, this study monitored continuous DO concentrations over an entire year in a shallow urban lake in south Louisiana, USA. The study aimed to: (1) determine diurnal and seasonal fluctuations in DO in this subtropical study lake; (2) quantify daily ecosystem metabolic rates within the study lake including community respiration, as well as both gross and net primary production; and (3) assess autotrophic/heterotrophic trends of the study lake in relation to climatic factors.

METHODS

Study site

The study focused on the University Lake (latitude 30°24′50″N; longitude 91°10′00″W) located in Baton Rouge, Louisiana, USA, on the Louisiana State University campus. It is a 74.6 ha shallow lake with a perimeter of about 6.7 km (Fig. 1). There are five small lakes surrounding University Lake and the entire lake watershed has a drainage area of ~187.4 ha (Reich Assoc., 1991). The climate of this area is classified as humid-subtropical, with long hot summers and short mild winters. Long-term climatic data were collected from Baton Rouge Ryan Airport by the National Weather Service (station ID# 160549). The long-term (1931–2009) annual temperature was 19.9°C, with monthly averages ranging from 10.9°C in January to 27.9°C in July. The annual average air temperature at Ben Hur weather station during the 12 month study period (July 2008 to June 2009) was 19.7°C. Mean monthly temperature ranged from 9.9°C in December 2009 to 27.1°C in July 2008. During most of the 12-month study period, monthly averages were colder than average long-term temperatures. Exceptions to this pattern were during the winter of 2008–2009, where above average temperatures were observed. Long-term precipitation data (1930–2000) revealed an average annual rainfall of 147.7 cm, ranging from 15.9 cm in July to 8.1 cm in October. The highest precipitation totals occurred during the summer, while the autumn typically received the least. Total precipitation during the study period was 125.3 cm, ranging from a low monthly total of 1.1 cm in October 2008 to a high of 23.2 cm in September 2008.

The watershed of University Lake consists almost entirely of some form of urban use, which is mostly residential, recreational, and institutional. The lake was created when the area was initially dredged in the 1930s. This transformed a cypress swamp to an open water environment.

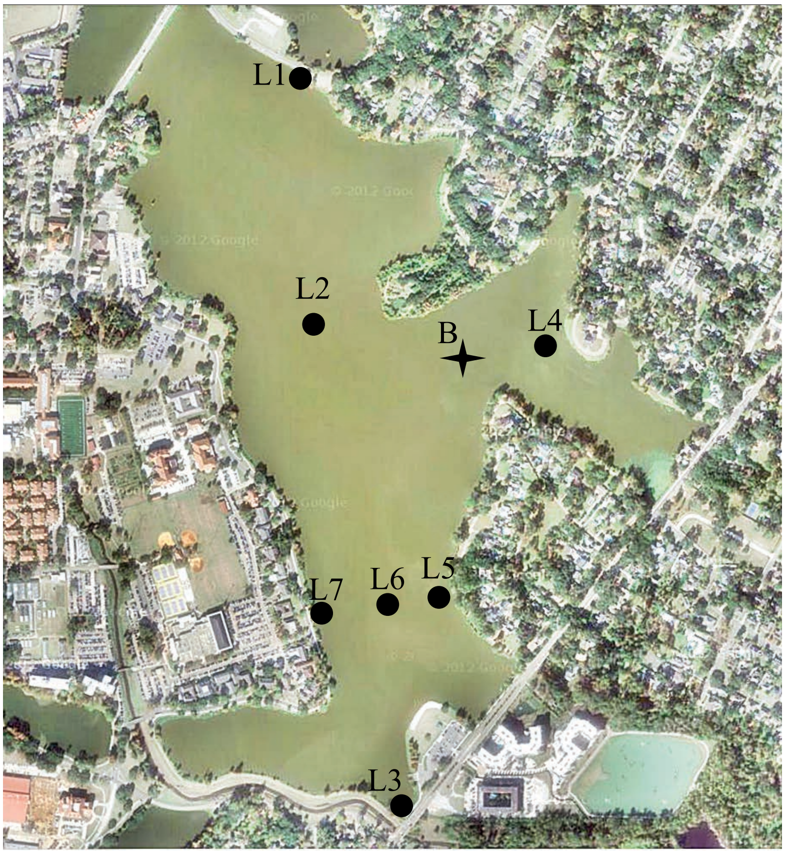

Fig. 1 The University Lake, buoy monitoring site (B) and sampling locations (L1–L7) in Baton Rouge, Louisiana, USA.

The lake was most recently dredged in 1983 to remove sediment and excess nutrients, resulting from surface runoff (Reich Assoc., 1991). During the study period, the lake depth averaged 90.0 cm, fluctuating from 73.9 cm in November 2008 to 98.9 cm in September 2008.

Field measurements

An Environment Monitoring Buoy (EMB) (YSI Inc., Yellow Springs, OH, USA) was deployed in an approximately central location within the lake (Fig. 1). The EMB system consisted of a heavy-duty floating platform with a YSI 6600 multi-parameter probe, solar panel, and data transmission antenna. The system automatically collected a series of water quality parameters at 15-minute intervals, including water temperature, pH, conductivity, chlorophyll-a, turbidity, dissolved oxygen, and cyanobacteria concentration data at about 1 m below the lake water surface.

In addition, from July 2008 to December 2009, monthly water samples were collected at seven sites across the lake: four sites located along the shoreline and three sites located in open water (Fig. 1). These grab samples were collected at 0.3 m below the water surface. Samples were analysed for five day biochemical oxygen demand (BOD_5) using a modified version of the *Standard Methods for the Examination of Water and Wastewater*, Section 5210B (APHA, 2005). The reported BOD_5 values are the mean values of the seven sampling sites. In addition to water sample collection, dissolved oxygen was measured *in situ* using a YSI 556 multi-probe (YSI Inc., Yellow Springs, OH, USA). At the four sites that were located along the shore (L1, L3, L5 and L7; Fig. 1) measurements were taken at about 6 m from the shoreline on the lake bottom sediment. For the three sites that were located in open water (L2, L4 and L6) measurements were taken at four depths: 30 cm and 60 cm below the surface, 30 cm above the bottom, and on the lake bottom sediment.

Two pressure sensors were installed in the lake to record hydrostatic pressure at 15-minute intervals. The measurements, along with atmospheric pressure data were used to calculate average lake depth at 15-minute intervals. Climatic data were obtained from the Louisiana Agriclimatic Information System (LAIS). These data included hourly precipitation, air temperature, maximum wind speed, average wind speed, relative humidity, solar radiation, and atmospheric pressure measured at Ben Hur, which is located about 5 km southeast from University Lake.

Metabolism estimation

A single station diel oxygen change method for an open system was used to estimate the individual components of metabolism, including community respiration (*R*) and net primary productivity (*NPP*) (Odum, 1956). Two critical assumptions were made: (1) the water column throughout the shallow lake is well-mixed; and (2) biomass and nutrients are evenly distributed across the lake and throughout the study period. From these estimates, gross primary production (*GPP*) was estimated. *NPP* (g O_2 m^{-2} d^{-1}), R_{hr} (g O_2 m^{-2} h^{-1}), and *GPP* (g O_2 m^{-2} d^{-1}) were calculated as follows:

$$NPP = \sum_{sunrise}^{sunset} (\Delta[O_2]) \times Z_i$$

$$R_{hr} = -\Big(\sum_{i=(sunset+1)}^{sunrise-1} (\Delta[O_2] / \Delta t) \times Z / (24 - (sunset - sunrise))$$

$$GPP = NPP + (R_{hr} \times (24 - (sunset - sunrise)))$$

where ΔO_2 is the hourly change in DO concentration in mg L^{-1}, Z is the average hourly water depth in metres, *sunrise* is the time the sunrise occurred and, *sunset* is the time the sunset occurred.

Community respiration was assumed to be consistent throughout both day light and night time hours. Average hourly respiration was determined between one hour after sunset and one hour before sunrise, to ensure that no photosynthesis was occurring. Total daily respiration (*R* in g O_2 m^{-2} d^{-1}) was calculated by multiplying hourly respiration (R_{hr}) by 24 (hours). Average monthly values of *GPP* and *R* were calculated to determine the productivity to respiration ratio (*P/R* = *GPP/R*). This ratio provides insight to the heterotrophic and autotrophic processes within a waterbody system.

Estimation error may arise in the calculation of respiration and productivity rates due mainly to mechanical and/or physical processes controlling DO concentrations (Cornell & Klarer, 2008). In a natural system, if DO concentration is solely the result of metabolism, the respiration rate and the *GPP* should be greater than zero, and *NPP* should be less than *GPP*. During the study period, 299 days were recorded where continuous sampling occurred throughout the day in order to calculate respiration and productivity rates. During much of September 2008, technical problems prevented accurate measurement of DO and, consequently, data for the period were omitted from analysis. After screening ($R > 0$, $GPP > NPP$) 246 observations (82.3%) remained for analysis and interpretation.

RESULTS AND DISCUSSION

The daily and seasonal trend of DO

DO concentrations measured by the EMB showed a monthly average of 7.3 mg L^{-1}, ranging from 4.4 to 10.2 mg L^{-1} in October 2008 and February 2009, respectively (Table 1). Overall, winter (November–March) mean daily DO concentrations (6.2 mg L^{-1}) were significantly higher than the corresponding values (8.7 mg L^{-1}) for summer (April–October; (*t*-test, df = 316, $t = -9.64$, $p = <0.0001$). Daily variance in DO was significantly greater (*t*-test, df = 333, $t = 8.26$, $p = <0.0001$) during the summer season than winter. Summer DO concentrations also appeared to have greater variation at finer time scales.

DO concentrations during the winter were about double summer concentrations as the monthly average temperature of the lake water fluctuated from 14 to 31°C (Table 1). The larger variation of daily DO concentration during the summer time (Fig. 2) was also observed by Xu *et al.* (2010) and DaSilva *et al.* (2013) in their studies on diurnal DO dynamics conducted in a forested stream in central Louisiana. The results from this study suggest a strong biological influence in this subtropical urban lake system. Other lake characteristics such as water depth may also affect DO concentrations. Shallow lakes often display unique characteristics distinct from commonly studied deeper lakes (Petaloti *et al.*, 2004) because their entire water column can be within the photic zone, depending on the depth of the lake and the turbidity of the water. D'Autilia *et al.* (2004) found that the rate of oxygen accumulation is faster than its utilization, particularly in the early morning. This was observed in this study at the daily time step throughout the monitored year, possibly the result of active photosynthesis, as shallow lakes have been shown to support highly diverse biota due to more extensive littoral zones (Arora & Mehra, 2009).

Table 1 Monthly average (with minimum, maximum and standard deviations, SD) weather and water quality parameters for University Lake, Baton Rouge, Louisiana, USA.

Parameters	Mean *(min-max)*	SD
Air temp. (°C)	19.7 *(9.9–27.1)*	5.9
Total precipitation (mm)	105 *(11–232)*	72.2
Avg. wind speed (kph)	10.1 *(6.2–13.5)*	1.5
Solar radiation (kw m^{-2})	0.186 *(0.092–0.291)*	0.065
Water temp. (°C)	22.6 *(14.4–31.0)*	6.3
Water depth (cm)	90.0 *(73.9–101.6)*	8.7
pH	7.86 *(7.48–8.06)*	0.18
BOD_5 (mg L^{-1})	7.2 *(5.4–9.5)*	1.2
Chlorophyll-a (µg L^{-1})	26.5 *(20.3–33.5)*	4.3
Turbidity (ntu)	106.4 *(32.9–303.1)*	87.3
EMB DO (% sat)	81.8 *(50.2–111.7)*	19.2
EMB DO (mg L^{-1})	7.3 *(4.4–10.2)*	2.2
Cyanobacteria (cells mL^{-1})	32300 *(12600–65400)*	17800

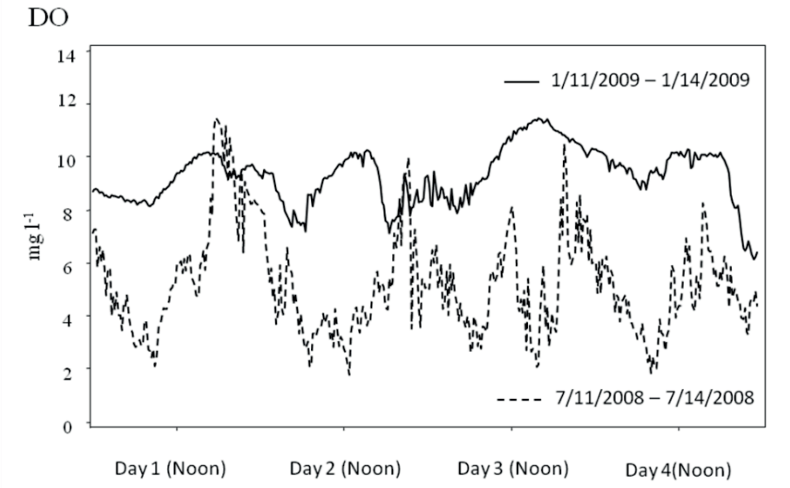

Fig. 2 Difference in diurnal fluctuation of DO for part of a winter and summer season at University Lake, Baton Rouge, Louisiana, USA.

Productivity, respiration, and the P:R ratio

The estimated monthly mean *NPP* rate was 2.13 g O_2 m^{-2} d^{-1}, resulting in an annual sum of 780 g O_2 m^{-2} *NPP* for this subtropical shallow urban lake. The rates ranged from 0.83 g O_2 m^{-2} d^{-1} in November 2008 to 3.79 g O_2 m^{-2} d^{-1} in June 2009, with a corresponding standard deviation of ±0.97. Although *NPP* exhibited a seasonal trend, the rates were not significantly different between the summer (April–October) and winter (November–March). Monthly mean *R* rates averaged 5.90 g O_2 m^{-2} d^{-1}, varying from 2.38 g O_2 m^{-2} d^{-1} in November 2008 to 11.77 g O_2 m^{-2} d^{-1} in June 2009, with a standard deviation of ±2.87. This resulted in an annual *R* sum of 2150 g O_2 m^{-2}, which is significantly higher than the annual *NPP* rate (780 g O_2 m^{-2}). The *R* rates were significantly greater during the summer than the winter months. Monthly mean *GPP* rates averaged 4.41 g O_2 m^{-2} d^{-1}, ranging from 1.96 g O_2 m^{-2} d^{-1} in November 2008 to 7.68 g O_2 m^{-2} d^{-1} in June 2009, with a corresponding standard deviation of ±1.71. The estimated annual sum of *GPP* was 1610 g O_2 m^{-2} $year^{-1}$. *GPP* showed a clear seasonal trend with significantly higher rates during the summer compared with the winter.

Calculated metabolic rates appear to fluctuate substantially depending on time period, location and method of calculation. When compared with the estimated *GPP* and *NPP* rates, the *R* rates showed the largest variation throughout the monitored year (Fig. 3). The estimated *NPP* rates showed the least variation. Wang (2003) reported highly variable photosynthetic rates in an agricultural environment (9.6–74.8 g O_2 m^{-2} d^{-1}), when compared to those in a metropolitan environment (4.4–12.6 g O_2 m^{-2} d^{-1}). Similarly, respiration rates ranged from 17.24 to 169.88 g O_2 m^{-2} d^{-1} in an agricultural environment and from 23.01 to 57.74 g O_2 m^{-2} d^{-1} in a metropolitan environment (Wang *et al.*, 2003). In their review, however, Lopez-Archilla *et al.* (2004) reported much narrow ranges of *GPP* ($<$20.45 g O_2 m^{-2} d^{-1}) and *R* ($<$25.79 g O_2 m^{-2} d^{-1}) found for various shallow lakes across the world. The results of this present study (*GPP*: 4.41 g O_2 m^{-2} d^{-1}; *R*: 5.90 g O_2 m^{-2} d^{-1}) fell within the ranges and tended to agree with those of multiple previous investigations showing a decreasing trend of *GPP* and *R* from July until November (e.g. Cornell & Klarer, 2008).

The *P*/*R* ratio was less than one throughout most of the monitored year, suggesting that *R* was greater than *GPP* throughout most of the year (Fig. 4). However, during the winter months of January and February 2009, *GPP* was nearly equal to *R*. These results suggested that University Lake was net heterotrophic throughout most of the monitored year. Winter months (lower left side of Fig. 4) were characterized by lower respiration and productivity, while the summer months (upper right side of Fig. 4) were typified by higher levels of respiration and productivity. Winter months were also observed to be more autotrophic than the rest of the monitored year. These patterns suggested a net consumption of internal carbon throughout most of the year.

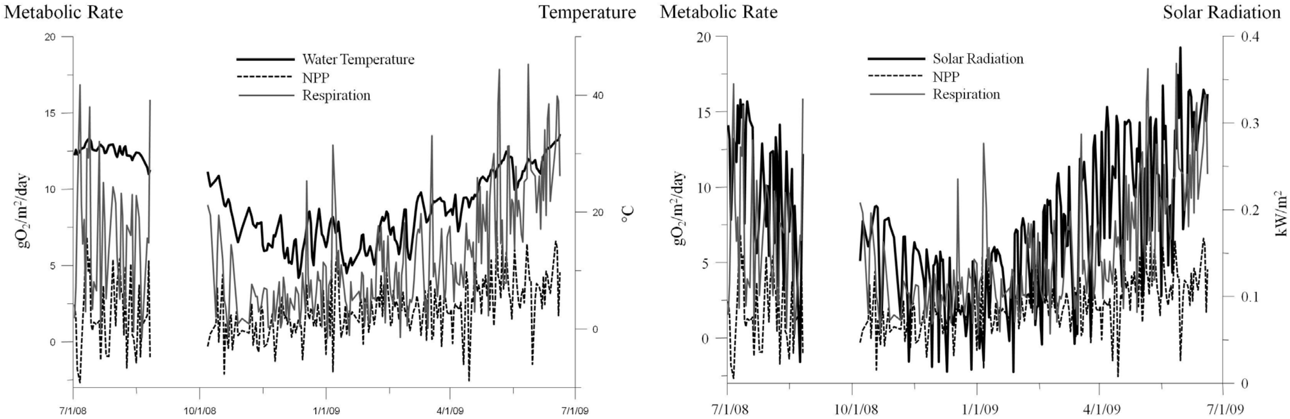

Fig. 3 Relationships of lake respiration (*R*) and net primary productivity (*NPP*) with water temperature (left) and solar radiation (right) at University Lake, Baton Rouge, Louisiana, USA.

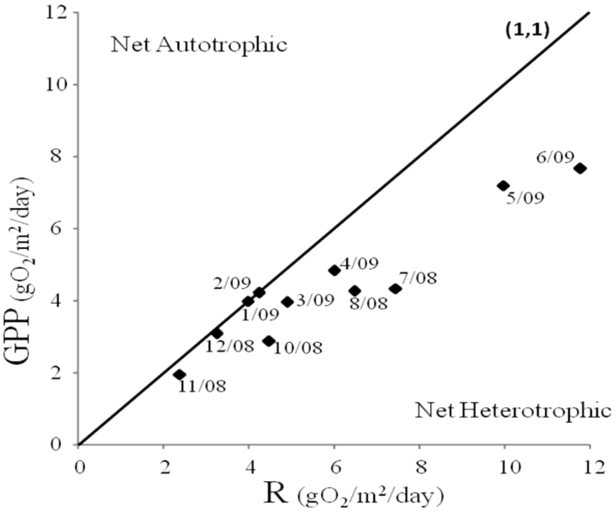

Fig. 4 Ratio of monthly mean gross primary productivity (*GPP*) and respiration (*R)* at University Lake, Baton Rouge, USA.

P/R ratios <1 can be common in unproductive oligotrophic lakes (Urabe *et al.*, 2005). However, the *P/R* ratio may be dependent on the geographic region and method of calculation. An urban stream has been observed by Wang *et al.* (2003) to remain heterotrophic throughout their study period (July–September) in Indiana, USA, while a non-urban site became autotrophic. In urban lake environments, surface runoff makes up a large percentage of the total water budget. Storm water runoff transports nutrients, including nitrogen and phosphorus, as well as organic matters from the surrounding landscape to lakes and these inputs can have an impact on respiration and production (Brezonik & Stadelmann, 2002; McTammany *et al.,* 2003). Influx of excess nutrients and organic material is the most likely explanation for respiration being greater than productivity in the study lake throughout most of the year. The tendency of lower metabolic rates to occur during the winter, with higher rates during the summer, is most likely primarily determined by ambient temperature, since metabolic rates are higher as temperatures increase (cf. Whitehead *et al.*, 2009).

Relationships between metabolism and environmental conditions

Lake water temperatures fluctuated from 14.4°C in December 2008 to 31°C in July 2008, with a monthly mean of 22.6°C. Trends in community respiration and water temperature were closely related when analysed at an annual time step (Fig. 3). Both variables had a distinct seasonal variation, with higher levels during the summer months and lower values during the winter. Mean daily water temperature explained about 37% (n = 246, r^2 = 0.37) of the variation in the estimated respiration (*R*), while only explaining about 7% (n = 246, r^2 = 0.07) of net productivity.

Solar radiation also exhibited a highly seasonal variation (Fig. 3) and explained 19% of respiration (*R*) (n = 246, r^2 = 0.19) and only 8% of net productivity (n = 246, r^2 = 0.08). The lowest monthly average of *GPP* (1.96 g O_2 m^{-2} d^{-1}) occurred in November 2008 and rates increased during the winter, when solar radiation and water temperature were at their minimums. A similar seasonal pattern was observed for rates of *R*.

Mean BOD_5 during the study period was estimated to be 7.2 mg L^{-1}, fluctuating from 5.4 in March 2009 to 9.5 mg L^{-1} in June 2009. The nitrogen inhibited BOD_5 had a mean value of 3.9 mg L^{-1} ranging from 2.6 to 5.4 mg L^{-1} in March 2009 and August 2008, respectively. BOD_5 results explained about 18% of the variability in *GPP* (n = 11, r^2 = 0.18), and 39% of respiration (*R*) (n = 11, r^2 = 0.39). The BOD_5 values were much higher than those found by Mallin *et al.* (2006) in several shallow urban lakes in North Carolina, USA (1.9–4.0 mg L^{-1}), and were on average comparable to, but less variable than, the values observed by Lv *et al.* (2009) in 15 shallow urban lakes in central China (6.7 mg L^{-1}, ranging 1.2–16.0 mg L^{-1}) and by Arora & Mehra (2009) in a shallow urban lake in Delhi, India (6.8 mg L^{-1}, ranging 4–12 mg L^{-1}) under a more or less similar climate.

The discrepancies between the correlations of metabolism and water temperature and solar radiation during the winter may in part be due to low water levels resulting from below average precipitation. Low water levels have been shown to affect the alkalinity and nutrient concentrations of shallow eutrophic lakes, which can consequently affect the phytoplankton composition of a lake (Nõges & Nõges, 1999). Robinson *et al.* (1997) found that with increasing water depth, phytoplankton productivity increased in a prairie wetland. This finding may indicate that water depth can play an important role in controlling metabolic rates at low water levels, due to the proximity of the entire water column to the lake bed sediment layer. It is also possible that another variable that has not been measured is affecting metabolic rates during the autumn and winter season.

SUMMARY

The results of this study suggested that urban, shallow, subtropical lakes may display seasonal variations in oxygen dynamics similar to those observed for many deeper stratified systems. More specifically, this study suggested that DO concentrations in the shallow urban study lake were significantly higher and less variable during the winter months compared to the summer months. Monthly mean *NPP* was 2.13 g O_2 m^{-2} d^{-1}, varying from 0.83 g O_2 m^{-2} d^{-1} in November 2008 to 3.79 g O_2 m^{-2} d^{-1} in June 2009. Monthly mean *R* was 5.90 g O_2 m^{-2} d^{-1}, ranging from 2.38 g O_2 m^{-2} d^{-1} in November 2008 to 11.77 g O_2 m^{-2} d^{-1} in June 2009. The mean *GPP* was 4.41 g O_2 m^{-2} d^{-1} ranging from 1.96 to 7.68 g O_2 m^{-2} d^{-1} in November 2008 and June 2009, respectively. Metabolic rates displayed seasonal variation mainly due to changes in water temperature that explained up to 37% of the variability in *GPP* and *R*, respectively. Fluctuations of temperature, solar radiation, and biochemical oxygen demand also appeared to affect metabolic rates in the shallow, urban study lake. During the winter months, *GPP* was equal to *R* rates. Annually, a total of 1610 g O_2 m^{-2} were produced, while a total of 2150 g O_2 m^{-2} were respired, indicating a net heterotrophic lake system throughout most of the monitored year.

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