Gross primary production, community respiration, and net primary production as measurements of metabolism at Devereux Slough: When do physical processes dominate?

Introduction

In any given aquatic ecosystem, a balance between photosynthetic activity and anaerobic respiration encompasses the general assumption of metabolism – where gross primary production (GPP) is defined as the assimilation of inorganic carbon into organic material, and community respiration (CR) is defined as the release of CO_2 and uptake of oxygen due to degradation of organic material. Net ecosystem production
(NEP = GPP – R), therefore, is a measurement of trophic status of the ecosystem (Staehr and Sand-Jensen 2007, Odum 1956). A system is considered net autotrophic when primary production exceeds respiration, and heterotrophic when respiration exceeds production (Caffrey 2004). Such parameters of metabolism can provide crucial information about the ecosystem’s health and vitality (Kemp and Boynton 1980). Nevertheless, metabolism cannot be explained by simple models of photosynthesis and respiration, but rather be attributed to a variety of physical factors ranging from wind speed to temperature.

For instance, studies have found that temperature, wind speed, and even rainfall can greatly influence metabolic rates in an aquatic system. One study reported that floodwaters induced by rainfall may replace lake waters with terrestrial runoff that may reduce the apparent transparency within the system, decreasing photosynthetic rates and increasing heterotrophy (Sadro and Melack 2012). Others have supported the notion that gas exchange is linearly dependent on wind speed above 3 m/s (Wanninkhof 1992). However, it would be careless to assume that such physical factors can dominate metabolic rates in an aquatic system, since the relationship between gas transfer and temperature or wind speed is filled with uncertainties. Perhaps it is the coupling of biological and physical processes that can truly define ecosystem metabolism.

This study intends to examine and estimate the rates of GPP, CR, and NEP at Devereux Slough. Using values of wind speed and k600, theoretical gas concentrations corrected and uncorrected for flux are calculated to determine the significance of physical processes on the slough’s metabolism. We hypothesize that temperature and wind speed exerts at least some influence on DO levels. We also hypothesize that rainfall may induce terrestrial runoff which can impact metabolic rates through factors such as increasing turbidity and subsequently intensifying heterotrophy. We ultimately conclude that abiotic forces will dominate over biotic factors in affecting metabolic activity in the slough.

Methods

Dissolved oxygen, conductivity, and temperature are measured in Devereux Slough during a 48 hour period. The variables are measured in 0.25 m intervals of the water column. YSI probes were used for measurements every two hours from 7 A.M. to 9 P.M on February 17, 6 A.M. to 9 P.M on February 18, and 6 A.M. to 9 A.M. February 19. The concentrations are integrated throughout the entire column to give an estimate of oxygen concentrations in one square meter of the water surface. A pair of D-Opto dissolved oxygen loggers (.35 m and .87 m) were set adjacent to 3 conductivity, temperature, and depth (RBR-CTD) loggers in the same sampling area and time period. The concentrations are integrated throughout the entire column to give an estimate of oxygen concentrations in one square meter of the water surface.

Calculations for NEP

Net ecosystem productivity (NEP) values are summed over the time period to give a rate of production in days. The formula for NEP is used as follows:

\[ \text{NEP} = \text{GPP} - \text{CR} \]

Where:

GPP is gross primary productivity.

CR is community respiration, which corresponds to NEP in periods of darkness, as the net production would not be attributed to photosynthesis in the absence of light.

Calculations for Flux
Given that the change in oxygen concentration over time represents net change in DO concentrations, flux was calculated as the difference between oxygen concentration in water and the saturated oxygen concentration in equilibrium with the atmosphere times the coefficient (k) of gas exchange for O\textsubscript{2} at any temperature (Cole and Caraco 1998). The equation is given as:

\[ D = \alpha k (O_2 - O_2\text{sat}) \]

Where \( \alpha \) is the chemical enhancement factor and \( O_2\text{sat} \) is a function of temperature and salinity. The Schmidt number is used to incorporate \( k600 \) and calculate \( k \) for \( O_2 \) at any temperature (Jähne et al. 1987). The equation is given as follows:

\[ \frac{k_{\text{gas1}}}{k_{\text{gas2}}} = \left(\frac{Sc_{\text{gas1}}}{Sc_{\text{gas2}}}\right)^n \]

Where:

\( Sc \) is the Schmidt number of a gas at any temperature (Wanninkohf 1992).

\( n \) depends on what process dominates diffusion.

\( n = -\frac{2}{3} \) when \( U10 < 2 \text{ m/s} \).

\( n = -\frac{1}{2} \) when \( U10 > 2 \text{ m/s} \) (Engle and Melack 2000).

**Wedderburn Number**

The Wedderburn number was calculated using the equation:

\[ W = \frac{g}{p} \left( \frac{(dp \times h^2)}{(U_w \times L)} \right) \]

Where:

\( g \) is gravity (9.8 m/s\(^2\)).

\( p \) is density (1000 kg/m\(^3\)).

\( dp \) is the change in density across the thermocline.

\( h \) is the upper mixed layer depth.

\( U_w \) is 0.001 times the wind speed.

\( L \) is the length of the water body (90 m).

W on 2/18 at 13:00 was calculated as follows:

\[ W = \frac{9.8}{1000} \times \frac{(1015.225 - 1011.475) \times 0.75^2}{(0.001 \times 9.4)^2 \times 90} = 2.6 \]

W on 2/17 at 13:00 was calculated as follows:

\[ W = \frac{9.8}{1000} \times \frac{(1015.557 - 1011.426) \times 0.5^2}{(0.001 \times 1.79)^2 \times 90} = 35.097 \]

**Results**

Wind speeds recorded during the 48 hour period peaked at noon and afternoon hours on 2/17 and 2/18, and
were at their minimum on 2/18 at night. The calculated k600 values as well as flux (D mg/m³/h) are proportionally changes in wind speed, indicating that flux as estimated from the Schmidt number ratio is in the least a function of wind speed.

The D-Opto data for dissolved oxygen showed two subtle peaks, which are associated with the day time. However, a noticeable dip in conductivity (0.87 m) starting at 12:00 P.M. on 2/18/16 was compared to the wind speed at the same time. The calculated Wedderburn number was 2.6, whereas the Wedderburn number for one day prior to the wind peak was at 35.1. There also seemed to be an anomaly at 11:00 P.M. on 2/18/16, where an apparent spike in oxygen levels was observed. When the time period of this physical process was taken out of the picture, the value corrected for flux in the D-Opto data increased from 1492 mg/m³/d to 1561 mg/m³/d (Table 2).

Figure 1. Conductivity (mS) measurements at 0.87 m depth at Devereux Slough over time (h). Readings were recorded using CTD loggers (RBR).

Figure 2. Dissolved oxygen concentrations (mg/L) at 0.87 m depth at Devereux Slough over time (h). Readings were recorded using D-Opto loggers.

Looking at the YSI data, dissolved oxygen concentrations fluctuated amongst the different depth and time intervals, but were consistent respective to the distance from surface. As expected, waters were anoxic below one meter, so there were no significant trends in oxygen levels at low depths; the data for at these depths were mostly left out. However, there was a noticeable shift in DO concentrations of the depth at one meter, where the levels dropped significantly at 6 A.M. 2/18/2016, but rose rapidly at 3 P.M. the same day. This corresponds to the decrease in temperature and conductivity at the same depth and time period. Similarly, the DO concentrations of the surface water (0.0 m) were inversely proportional to conductivity and temperature.

Figure 3. Temperature (°C) across a gradient of depths over time (h). Readings were recorded using YSI probes at Devereux Slough.

Figure 4. Conductivity (mS) across a gradient of depths over time (h). Readings were recorded using YSI probes at Devereux Slough.

Figure 5. Dissolved oxygen concentrations (mg/L) across a gradient of depths over time (h). Readings were recorded using YSI probes at Devereux Slough.

Figure 6. Temperature (°C), dissolved oxygen (mg/L), and conductivity (mS) profiles across 3 m of water column depth. The measurements were taken at 7:00 on 2/17/16.

Figure 7. Temperature (°C), dissolved oxygen (mg/L), and conductivity (mS) profiles across 3 m of water column depth. The measurements were taken at 21:00 on 2/17/16.

From the YSI probes, the system seemed to be net heterotrophic when flux was not accounted for. Gross primary production (GPP) uncorrected for flux (1562 mg/m²/d) was lower than the value corrected for flux (2671 mg/m²/d), and community respiration (R) showed similar patterns (-1668 mg/m²/d for no flux, -1998 mg/m²/d flux corrected). The calculated net primary productivity (NPP) uncorrected for flux (-106 mg/m²/d) was thus significantly lower than the value corrected for flux (673 mg/m²/d). When periods where physical processes dominated were excluded, the values uncorrected and corrected for flux also differed (GPP: -200 mg/m²/d, 19 mg/m²/d for no flux and flux corrected, respectively; NPP: -2959 mg/m²/d, -2333 mg/m²/d, respectively; R: -2760 mg/m²/d, -2351 mg/m²/d, respectively). There seemed to be a general trend that values corrected for flux yielded at least slightly higher productivity than values uncorrected for flux, corresponding to the same relationship that corrected flux values were also higher than uncorrected flux values (Figure 8.)
Data for the D-Opto loggers displayed similar patterns. GPP for the slough’s upper layer was measured at 124 mg/m²/d with no flux integration, but estimated to be 2906 mg/m²/d when flux was corrected for. Respiration (R) was determined to be -143 mg/m²/d without flux, but 1345 mg/m²/d with flux. Likewise, the NPP (NEP) was calculated to be at -19 mg/m²/d without flux, and 1561 mg/m²/d with flux. In the upper 0.5 m layer, GPP (226 mg/m²/d with no flux, 3225 mg/m²/d with flux), along with R (155 mg/m²/d with no flux, 1643 mg/m²/d with flux), was used to calculate NPP (72 mg/m²/d with no flux, 1583 mg/m²/d with flux).

YSI

Including periods when physical processes dominate Excluding period when physical processes dominate

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<td>-114.99 -98</td>
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<tr>
<td>GPP (mg/m²/day)</td>
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<td>200 19</td>
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Table 1. Flux corrected and uncorrected NPP (mg/m²/day), R (mg/m²/day and mg/m²/hour), and GPP (mg/m²/day) values calculated for the entire sampling period. Values for when physical processes dominate were excluded to show the effect of these processes on metabolism. Readings were recorded using YSI probes.

D-Opto

Upper Meter Upper .5 m Upper .5 m (Physical processes excluded)

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Table 2. Flux corrected and uncorrected NPP (mg/m²/day), R (mg/m²/day and mg/m²/hour), and GPP (mg/m²/day) values calculated for the entire sampling period and between two different depth profiles (1m and 0.5m). Values for when physical processes dominate were excluded to show the effect of these processes on metabolism. Readings were recorded using D-Opto instruments.

Figure 8. Corrected (orange) and uncorrected (blue) flux values (mg/m²/day) over time (h).

Looking at the rainfall data, low DO concentrations corresponded to the rain event. A dip in DO levels on both Feb 17 and Feb 18 could be correlated with the peak in rainfall.

Figure 9. Rainfall increments over time (h).
It is likely that physical factors played a significant role in shaping the changes in dissolved oxygen concentrations in the slough. Values corrected for flux for both the YSI probes and D-Opto loggers suggest that abiotic processes can greatly increase GPP and NPP, as there were noticeably dramatic shifts between metabolic rates corrected and uncorrected for flux. Studies have indicated that daily GPP values are strongly related to temperature, which may couple with irradiance and algal biomass to give more accurate metabolism readings (Staehr and Sand-Jensen 2007). The evident increase in DO concentrations with respect to the decrease in temperature during certain periods supports the initial hypothesis that the solubility of oxygen increases with decreasing water temperatures, and vice versa. This is in accordance with the Le Chatlier's principle, which states that any system in equilibrium will readjust to a new equilibrium when subject to change; in our case, a decrease in temperature alters the composition of O_2 gas in that it becomes more soluble in cold waters (Fernandez-Prini 1982).

Wind speed may have also played a role in impacting metabolic rates. The corresponding values of flux as a function of wind speed are relative to the fluctuations in DO concentrations, where, peaks in the flux of oxygen are proportional to peaks in the wind speed and the coefficient of gas exchange at a Schmidt Number of 600. In fact, when flux was taken out of the picture, metabolic rates were significantly reduced, coinciding with the general assumption that physical processes such wind speed and temperature influence readings for gross and net primary productivity. In certain cases, a higher temperature and lower wind speed can promote warmer surface waters compared to bottom waters, which can induce stratification in oxygen saturation and manipulate metabolism measurements. The observed variability in GPP would thus likely be due to wind driven changes in water column stability (Tonetta et al. 2016). The D-Opto data for conductivity also correlated with the wind event. The low Wedderburn value at the same time the wind speeds peaked suggest that the shear created by the wind had tilted and depressed the thermocline enough to influence the readings on the instrument. In this case, the wind may have affected the data through a different physical process.

Furthermore, the rainstorm may have affected DO concentrations as well. The drop in DO was associated with the presence of rainfall by increments. This is supportive of the second hypothesis that rainfall may lead to an inflow of terrestrial material, which act to increase turbidity and reduce transparency; the resulting attenuation of light decreases photosynthetic activity, and increases the relative heterotrophy that would otherwise be buffered by primary production (Sadro and Melack 2012). In effect, rainfall, yet another abiotic factor, could have influenced metabolism by reducing autotrophy and increasing respiration.

However, the accuracy of our metabolism data may be open to disputation, and are subject to discussion since a variety of factors can affect not only the readings but also the calculations of flux. There is speculation that wind speed-based models underestimate k600 at low wind speeds, mostly due to penetrative convection when air temperatures are lower than water temperatures (Cole and Caraco 1998). Furthermore, other water movements and turbulence not affected by wind may also impact calculations for flux (Cole et al. 2010). Additionally, thermal stratification can regulate the estimation of metabolism, as processes like microstratification in surface waters can prevent gas exchange from occurring by isolating the sonde and probes from the atmosphere (Coloso et al. 2011). Given that the slough was thermally stratified, microstratification is logically possible in complicating the measurements of volumetric metabolic rates and calculations for gas exchange.

 Needless to say, such assumptions that abiotic factors often overshadow biotic factors are too broad to be applied in the natural setting, where stochasticity and environmental differences amongst different aquatic systems greatly alter the methods by which such ecosystems are measured. It is therefore critical to account for both factors, so that the most precise measurements are made for any given system. In essence, temporal and spatial constraints limit the scope of this study, and are an indication that further empirical data are needed to examine a closer relationship between physical processes and metabolism. The study paves the
way for future studies on the effects of abiotic factors on aquatic systems. Ideally, an understanding of thermal influences on the slough’s metabolic rates along a depth gradient could lead to discoveries about the effects of climate change on estuarine systems, where rises in global temperature can be experimentally tested and associated with possible reductions in metabolic rates. Still, such assumptions must be supported with equivocal empirical evidence, so further research is encouraged.

References


Sadro, Steven, and Melack, John M. The effect of an extreme rain event on the biogeochemistry and ecosystem metabolism of an oligotrophic high-elevation lake.


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