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High-frequency data within a modeling framework: On the benefit of assessing uncertainties of lake metabolism

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ABSTRACT

We used a Bayesian metabolic model for assessing the gross primary production (GPP), ecosystem respiration (ER) and their uncertainties in lake Võrtsjärv, a large eutrophic lake in Estonia (North-eastern Europe). Diel cycle modeling was based on high-frequency (10-min) measurements of irradiance, water temperature and dissolved oxygen during most of the growing season (from May to August 2011). Posterior distribution of production and respiration was successfully simulated with the model and displayed with highly credible intervals (2.5 and 97.5 percentiles). Considering the mean GPP and ER values, the lake was autotrophic from May to June, at equilibrium in July, and heterotrophic in August. However, adding the uncertainty to metabolism estimates revealed that an ambiguous metabolic state (no clear monthly predominance of auto- or hetero-trophy) represented between 12 and 32% of the period. It is thus incautious to conclude about lake metabolic state in these conditions. A comparison with the existing classical model based on dissolved oxygen measurements showed that metabolic dynamics differed between the two approaches. Though the classical model recorded highest ecosystem productivity in midsummer, the Bayesian model predicted that productivity peaked earlier in the season and gradually declined as the irradiance dropped and the water temperature rose. Coupling between GPP and ER during the whole study period was very variable, resulting that, depending on the month, 50–100% of primary production was consumed in the lake. This coupling variability was caused by extensive diel fluctuation of irradiance-dependent production compared to relatively stable water temperature and respiration. The background respiration was high in spring and declined progressively in summer, reflecting lower inputs of allochthonous organic matter to the lake. With a wider use of high-frequency techniques for measuring lake ecological parameters, this kind of performant models that are able to assess lake productivity within small time steps and take into account the uncertainty, will be increasingly needed in the future.

1. Introduction

The metabolic state of inland aquatic ecosystems is an important research topic considering the disproportionate contribution of inland waters in global carbon cycling relative to their surface area (Cole et al., 1994) whereas lakes in particular have received a substantial attention over the last decades (del Giorgio et al., 1997; Prairie et al., 2002). Because of their well-defined boundaries, lakes constitute ideal sites for modeling. The metabolic state of a lake is determined by its net ecosystemic production (NEP, Lovett et al., 2006) which is the difference between gross primary production (GPP) and ecosystem respiration (ER, Howarth et al., 1996). Lacustrine systems are termed autotrophic or heterotrophic depending whether NEP is positive or negative. As daily NEP cannot be measured directly, estimates of GPP and ER must be obtained first. This requires firstly an empirical method for obtaining the necessary data and, secondly, a computational procedure for constructing the estimates (McNair et al., 2013). Although a standard method for measuring lake metabolic parameters is yet to emerge, measurements of changes in dissolved oxygen (DO) concentration in the surface layer corrected for O_2 exchange at the air–water interface have been the most popular approach to date (Staehr et al., 2012). The DO changes in the upper mixed layer are expected to reflect NEP (plus a diffusion variable) variation (Odum, 1956; Cole et al., 2000). The development of high-frequency (HF) measurements has facilitated the tracing of O_2 fluxes and ecological parameters fluctuations within very short periods of time and has also enabled

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analysis of the drivers of metabolism (Staehr et al., 2010). Furthermore, automated HF measurements of metabolism have been used successfully to detect resilience changes in lakes (Batt et al., 2013).

However, computational procedures for estimating metabolism have been lagging behind compared to the progress that has been made in data collection. For calculating lake metabolism, two types of approaches have been developed so far. The older approach, which tries to back-calculate GPP and ER from an observed time-series of DO measurements (Odum, 1956), is unable to assess the daytime component of ER and thus cannot accurately trace dark–light cycles (McNair et al., 2013). A more recent approach stems from the advent of process-based models of DO dynamics. These models predict time-series of DO concentrations from a variety of environmental variables so that the tracing of diel lake metabolic rates is now possible (McNair et al., 2013). One of these models, PoRGy (Venkiteswaran et al., 2007), can assess GPP, ER and O_2 gas exchange using data collected with HF measurements. However, most of the older and even current approaches omit taking into account uncertainties originating from DO measurements themselves and from the model used for calculating the metabolism (Staehr et al., 2012). Though uncertainties occur at the same frequency in lakes regardless of their size, their magnitude can be particularly critical for larger lakes as large-scale water movements cause important deviations from the expected diel DO curves (Solomon et al., 2013). These uncertainties, which are mostly caused by process errors and low signal-to-noise ratios, are potentially large enough to impair the accuracy of metabolism estimates (Solomon et al., 2013), so that a lake may be identified erroneously as auto- or hetero-trophic. Although observation and process uncertainties are mitigated by HF measurements, model uncertainties, on the other hand, remain difficult to assess. One recent model, BaMM, which is adapted from the aforementioned PoRGy model, is a Bayesian statistical model that can estimate simultaneously GPP, ER and their uncertainties based on changes in DO concentration, water temperature, and irradiance

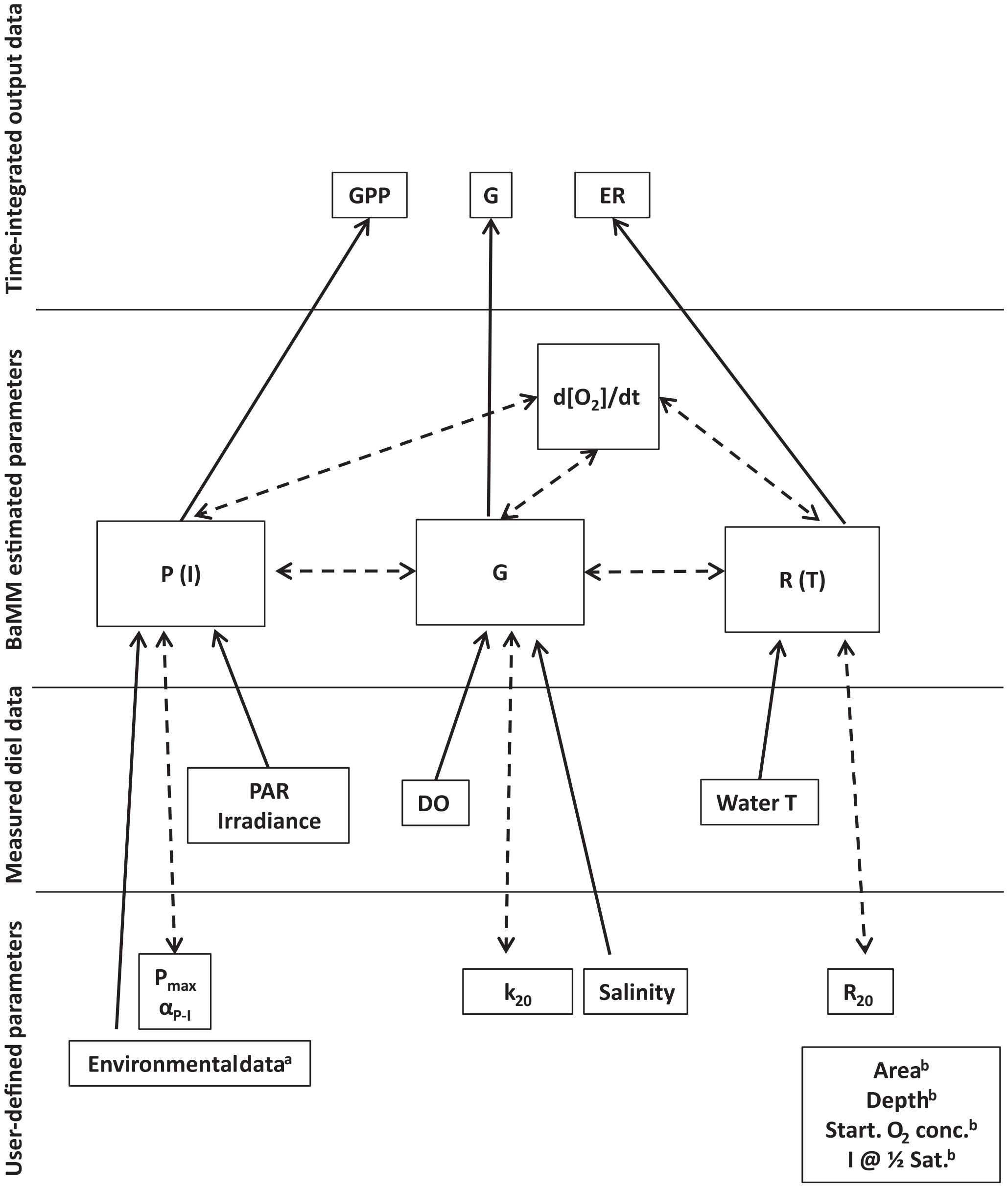

Fig. 1. Conceptual diagram of BaMM based on equations and model parameters. Simple solid arrows represent one-way interactions of parameter-dependent data, double dashed arrows signify interrelated parameters that are model-adjusted with Bayesian methods. Parameter units are listed in Table 1 and in Holtgrieve et al. (2010).
a: Environmental data used only in the irradiance sub-model in case of missing data; b: general user-defined parameters.