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Multi-model approach to predict phytoplankton biomass and composition dynamics in a eutrophic shallow lake governed by extreme meteorological events

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ABSTRACT

A multi-model approach to predict phytoplankton biomass and composition was performed in a eutrophic Uruguayan shallow lake which is the second drinking water source of the country. We combined statistical (spectral analysis and Machine learning techniques) and physically based models to generate, for the first time in this system, a predictive tool of phytoplankton biomass (chlorophyll-*a*) and composition (morphology-based functional groups). The results, based on a 11-year time series, revealed two alternating phases in the temporal dynamics of phytoplankton biomass. One phase is characterized by high inorganic turbidity and low phytoplankton biomass, and the other by low inorganic turbidity and variable (low and high) phytoplankton biomass. A threshold of turbidity (29 TNU), above which phytoplankton remains with low biomass (<15–20 ug/l) was established. The periods of high turbidity, which in total cover 30% of the time series, start abruptly and are related to external forcing. Meteorological conditions associated with the beginning of these periods were modeled through a regression tree analysis. These conditions consist of moderate to high wind intensities from the SW direction, in some cases combined with high antecedent precipitation or low water level. The results from the physically-based modeling indicated that the long decaying time-scale of turbidity and intermediate resuspension events could explain the prolonged length of the high turbidity periods (~1.5 years). Random Forests models for the prediction of phytoplankton biomass and composition in periods of low turbidity resulted in a proportion of explained variance and a classification error over a test sample of 0.46 and 0.34 respectively. Turbidity, conductivity, temperature and water level were within the most important model predictors. The development and improvement of this type of modeling is needed to provide management tools to water managers in the current water supply situation.

1. Introduction

Predicting phytoplankton biomass and composition is a central issue for freshwater ecosystems used as drinking water reservoirs, mainly due to harmful cyanobacterial blooms and the potential presence of cyanotoxins that can cause serious and occasionally fatal human diseases (Carmichael, 2001; Paerl et al., 2001; Falconer and Humpage, 2006). In addition, the occurrence of cyanobacterial blooms leads to ecosystems simplification and loss of multiple ecosystem services, affecting trophic dynamics and biodiversity,

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and consequently hindering the reversion of this non desirable configuration (Scheffer et al., 1993). The relation between anthropogenically induced nutrient over-enrichment (eutrophication) and the occurrence of cyanobacterial blooms in lakes is well documented (Heisler et al., 2008; Paerl and Huisman, 2009; Carpenter et al., 2011; O'Neil et al., 2012; Martinuzzi et al., 2014). However, despite the importance of nutrient availability, several additional drivers control the spatial and temporal variability of phytoplankton dynamics, such as light availability, temperature, residence time, grazing pressure and climatic variability (Cymbola et al., 2008; Moss et al., 2011, Kosten et al., 2012).

In lakes with frequent and intense sediment resuspension events, light attenuation due to high concentrations of suspended solids in the water column can significantly affect the planktonic primary productivity (Beaver et al., 2013). However, light attenuation is not the only effect of sediment resuspension. During periods of high winds, sediment resuspension can also generate inoculation of phytoplankton from cysts or akinetes and nutrient release into the water column, leading to enhanced phytoplankton biomass in the water column (Søndergaard et al., 1992). The importance of wind induced sediment resuspension in shallow lakes points out to the fact that lake morphometry and the wind regime, including extreme events, can strongly modulate the lake dynamics by affecting turbidity, nutrients and primary productivity (Evans, 1994; Scheffer and van Nes, 2007). Phytoplankton species differ broadly in their responses to environmental change, including resources acquisition (light and nutrients), and mortality avoidance (sinking, washout and grazing) (Margalef, 1978; Reynolds, 1984a; Naselli-Flores et al., 2007). These features can be combined to describe the species habitat template (*sensu* Southwood, 1977). This concept considers the habitat as a template on which evolution forges characteristic traits of the species (Southwood, 1988), and can be used to predict community organization (Keddy, 1992). Morphological traits are relatively easy to measure and have clear relationships with the functional properties of phytoplankton (Lewis, 1976; Reynolds 1984b; Naselli-Flores et al., 2007; Kruk et al., 2010; Pacheco et al., 2010). The morphology-based functional groups (hereafter MBFGs) approach, classifies organisms in seven groups in terms of morphological traits (e.g. volume, presence of flagella) independently from the organism's taxonomy (Kruk et al., 2010, Kruk and Segura, 2012).

We implemented a multi-model approach, combining statistical and physically-based models, to predict and better understand the dynamics of phytoplankton biomass (through chlorophyll-*a* concentration, hereafter chl-a) and composition (through MBFGs) in Laguna del Sauce, a shallow eutrophic lake (the second drinking water source of Uruguay) strongly influenced by wind regime (Inda and Steffen, 2010). Given the eutrophication process observed in the last decades, the intensification of cyanobacterial blooms (higher frequency of occurrence, higher biomasses, wider distribution, increased persistence and toxicity) and associated drinking water supply crisis, the prediction of phytoplankton dynamics becomes crucial for water management authorities. In this sense, we confer great importance to the setting up of predictive models of phytoplankton biomass and composition using records provided by the drinking water supply company and the meteorological station at El Sauce lake airport.

2. Materials and methods

2.1. Study site

Laguna del Sauce (34°43′S, 55°13′W, Maldonado, Uruguay, Fig. 1a) conforms a system of three connected shallow lakes: El Sauce (4045 ha), De los Cisnes (205 ha) and El Potrero (411 ha) (Fig. 1b). The mean depth is 2.5 m while the maximum depth reaches 5 m. Laguna del Sauce has two main freshwater inputs (Arroyo Pan de Azúcar and Arroyo del Sauce) and one main output (Arroyo del Potrero), which is a natural connection to the Río de la Plata (Inda and Steffen, 2010) (Fig. 1b).

Laguna del Sauce is a eutrophic system. Total phosphorus has reached values above 80 ug/L in several periods (and even higher than 100 ug/L during low water periods) and total nitrogen shows considerable temporal oscillations, with values between 200 and 1000 ug/L (Inda and Steffen, 2010). Cyanobacterial blooms, which have been observed since the 1960s, have become more intense in recent years (Rodríguez et al., 2010a). The phytoplankton biomasses are shown in the Results section. The increase of cyanobacterial blooms has been related to enhanced nutrient inputs from the basin during the last decades as a consequence of agricultural and cattle production intensification, and the significant growth of urbanization and tourism (Mazzeo et al., 2010; Rodríguez et al., 2010b).

While Laguna de los Cisnes and Laguna del Potrero exhibit a large fraction covered by submerged vegetation, Laguna del Sauce does not present submerged macrophytes (except in the littoral zone), mainly because of wave action and higher inorganic turbidity (Inda and Steffen, 2010).

2.2. Data availability

Next, we present all the data sets considered, which are available to OSE-UGD managers.

2.2.1. Water quality data

Water quality data for the period 2002–2012 was provided by OSE-UGD. Daily data is available for the following water attributes: conductivity (Orion DuraProbe™, 4-Electrode Conductivity Cells, model 013010), chl-a, temperature (LDO101 HACH) and turbidity (HACH CatN° 47000-88, model 2100N). Daily (except weekends) measurements and analyses are performed at the OSE-UGD lab on samples taken at 6 am from the water intake point, located 100 m offshore from OSE-UGD water treatment unit (Fig. 1b). Temperature is measured *in situ*. Chl-a is considered as proxy of total phytoplankton biomass and is estimated by extraction from GF/F Whatman filter using hot ethanol (90%), according to Nusch (1980) and spectrophotometry (Macherey-Nagel UV/VIS). Starting in 2004, samples are taken from the lake every one or two weeks to estimate phytoplankton species abundance (org/ml); the sampling becomes daily during periods when cyanobacteria blooms occur. Phytoplankton samples are counted from fixed Lugol samples, by using the settling technique and random fields (Utermöhl, 1958) considering at least 100 individuals of the most frequent species (Lund et al., 1959). We did not include the picoplankton fraction (less than 2 μm in greatest dimension) or tychoplanktonic groups (associated with periphyton).

The abundance data was transformed into biovolume considering the volume of organisms of each species. Biovolume estimations were performed based on Hillebrand et al. (1999).

The sum of the biovolumes of all species included in the same morphologically-based functional group (MBFG, see below) was performed to obtain the biovolume of functional groups.

The response of the phytoplankton composition to environmental variables was analyzed following the morphologically-based functional approach (MBFGs) proposed by Kruk et al. (2010). This classification scheme is based on morphological traits, which reflect functional abilities for resources uptake, growth, sedimentation, grazing and flushing avoidance. It includes seven groups: Group I: small organisms with high surface/volume (S/V) ratio (e.g. Chroococcales, Chlorococcales), Group II: small flagellated organisms with siliceous exoskeletal structures (i.e.,