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# An ecological-network-analysis based perspective on the biological control of algal blooms in Ulansuhai Lake, China

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ABSTRACT

Biological control is considered as an environmentally and effective means of reducing or mitigating harmful algal blooms. By biological remediation approach (addition of predators or competitors), it may alter the ecological relationships between the dominant algae and their associated populations in ecosystems. However, it cannot quantify the indirect effects of this approach and the long-term and system-level ecological consequences are hard to assess. Here we focus on the "bloom" areas of the Ulansuhai Lake in Inner Mongolia. Based on historic data, field monitoring and experimental data, we constructed a quantitative phosphorus cycle network model. Using Ecological Network Analysis (ENA), we evaluated how indirect flow influences dominant algal species and alters network control and utility relationships. Results indicate that: (1) Indirect flows have strong influence on the mutual and control relationships between blooming algae and its related functional groups in the Ulansuhai Lake; (2) Some opposite interspecific relationships between the blooming algae and other functional components have been found by ENA; (3) Key populations controlling the blooming algae are observed from the intuitive *Zooplankton and Detritus* to network-based *Microorganisms, Zoobenthos, Zooplankton and Detritus*(*water*). The research results indicate the importance of including indirect relationship into the control of lake algae bloom. The application of ENA was good at revealing indirect effects for ecological restoration of eutrophic lakes.

## 1. Introduction

Algal blooms severely reduce marine and fresh water quality, seriously harm aquatic organisms, threaten human health, and weaken aquatic ecosystem services, with serious ecological consequences (Carpenter et al., 1996; Postel and Carpenter, 1997; Smith et al., 2006; Brooks et al., 2016). Biological control method is considered an environmentally-friendly, economical, and efficient way of reducing or mitigating algal blooms through both bottom-up (competition for nutrients) and top-down (increased predation on algae) (Carpenter et al., 1995). Taking advantage of biological and biochemical functions and food-chain control, biological methods degrade and transform excessive nutrient salts in lakes, inhibit algae growth, and purify the water (Sharipo et al., 1975). At present, biological control methods mainly include planting vascular plants, microbial purification, food chain control technology, etc., from or through predation, competition for nutrients, mutual benefit, and other ecological relationships that directly or indirectly control algae growth (Quiros, 1998; Waajen et al., 2016; Sun et al., 2018).

The relationship between bloom-forming algae and other aquatic components has received great attention because they are reported to closely interact (Olrik et al., 1984; Elser et al., 2000). Different aquatic organisms interact through the transfer of matter and energy, contributing to ecological networks with complex relationships, such as predation, competition, symbiosis and so on (Schindler, 2006). The current biological control technologies tend to inhibit algae growth by targeting directly-related organisms, leading to the function of other related communities and the entire aquatic biological network being overlooked (D'Alelio et al., 2016). In fact, any organism at any trophic level may be affected by other organisms through predation, competition or mutually-beneficial effects (Lima-Mendez et al., 2015). During the biological control of lake bloom, all algae-related biological communities should be taken into account in application (Carpenter et al., 1996). First, system-level ecological network relations should be examined so one can take appropriate measures to inhibit algae growth with respect to the network integrity and sustainability (Šulčius et al.,

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2017). One of the current difficulties is in identifying the ecological relationship between dominant algae and related species. Networks are one tool that we can use to examine these ecological relationships.

Ecological network analysis (ENA) was derived from economic input–output analysis (Leontief, 1966). It is assumed that the system is a network composed of a series of nodes (also called subdivisions or units) and connecting arcs. A specific analytical method, such as control or utility analysis, is used to study the direct and indirect effects of matter and energy flow in ecosystems, and to analyze the ecological relationships among different organisms and depict all of the characteristics of these ecosystems (Ulanowicz, 1997; Fath and Patten, 1999). One of the characteristics of this method is that it can include direct and indirect ecological processes in the system and provide a quantitative analysis and judgment on ecological relations among the system nodes (Fath and Borrett, 2006). ENA has been applied in many fields, such as ecology, society and economy, and has led to abundant research achievements, such as distributed control in ecosystems, global virtual water trade system, urban water metabolism and so on (Schramski et al., 2006; Zhang et al., 2010; Mao and Yang, 2011; Yang et al., 2012a; Zhang et al., 2016; Haak et al., 2017; Borrett et al., 2018). Based on the findings of ENA, we can comprehensively consider the direct and indirect ecological processes among populations, interpret and judge the ecological relations in ecosystems, and provide more complete and accurate information for ecosystem restoration and management.

This study focused on the bloom-prone area in the Ulansuhai Lake, Inner Mongolia. Based on dynamic field monitoring and laboratory experiments in the field, a network model based on phosphorous nutrient cycling was constructed and quantified. The ENA was used to determine which population(s) directly or indirectly affected algal growth and to analyze the quantitative ecological relationships between the algae and related populations. Network-based biological control measures were proposed for the lake based on these results.

## 2. The research area

Ulansuhai, China's eighth largest lake, is situated in the Urad Qianqi, Bayannao'er City, Inner Mongolia (N40°36′ ~ 41°03′, E108°43′ ~ 108°57′), see Fig. 1.

It is a typical shallow lake, covering an area 293 $km^2$, with an average depth of 0.8–1.5 m. It is in a typical temperate continental monsoon climate zone, with 200 mm of annual rainfall and 2300 mm of annual evaporation. Freshwater lakes in dry grasslands and deserts, such as Ulansuhai Lake, are rare. The lake provides important ecosystem services (e.g., fish supply, water and soil conservation, habitats) to the local region (Zhang et al., 2017). As it is downstream of the Hetao Irrigation District, the lake receives a large amount of nitrogen and phosphorus from farmland irrigation return water discharged from nearly 10 upstream channels each year. The ecosystem structure and function are continuously being degraded by nutrient inputs that exceed the water environmental capacity of the lake, resulting in algal bloom under appropriate conditions. Due to the relatively closed topology and low flow velocity of water bodies, a bloom-prone area is forming in the Xidayang region in Ulansuhai that covers about 10$km^2$. The surface of the region is covered by aquatic plants, the two dominant species being *Phragmites communis* and *Potamogeton pectinatus L*. The average depth of the region is 1.2 m and water flow velocity is 0-0.7 m/s.

## 3. Network model construction and analysis

### 3.1. Network model construction

Long-term monitoring results indicate that phosphorus is a limiting factor for algal bloom in this region (Cui, 2013). A network model containing 11 components was constructed based on the phosphorus cycle, see Fig. 2.

The dominant algal genus in the lake is *Chaetoceros*, and it is accompanied by other filamentous green algae including *Spirogyra*, *Zygnema* and *Mougeotiarotunda*. Filamentous algae attach to submerged macrophytes and the sediment surface during the primary growth stage. With increasing biomass, it aggregates and floats up to the water surface with the aid of bubbles produced by photosynthesis. Based on the whole growth process of algae, we included microbes, zooplankton, zoobenthos, fish, water birds, detritus, sediments, submerged and emergent plants in the ecological network model. The ecological relationships resulting from the physical, chemical and biological processes are depicted in Supplementary material.

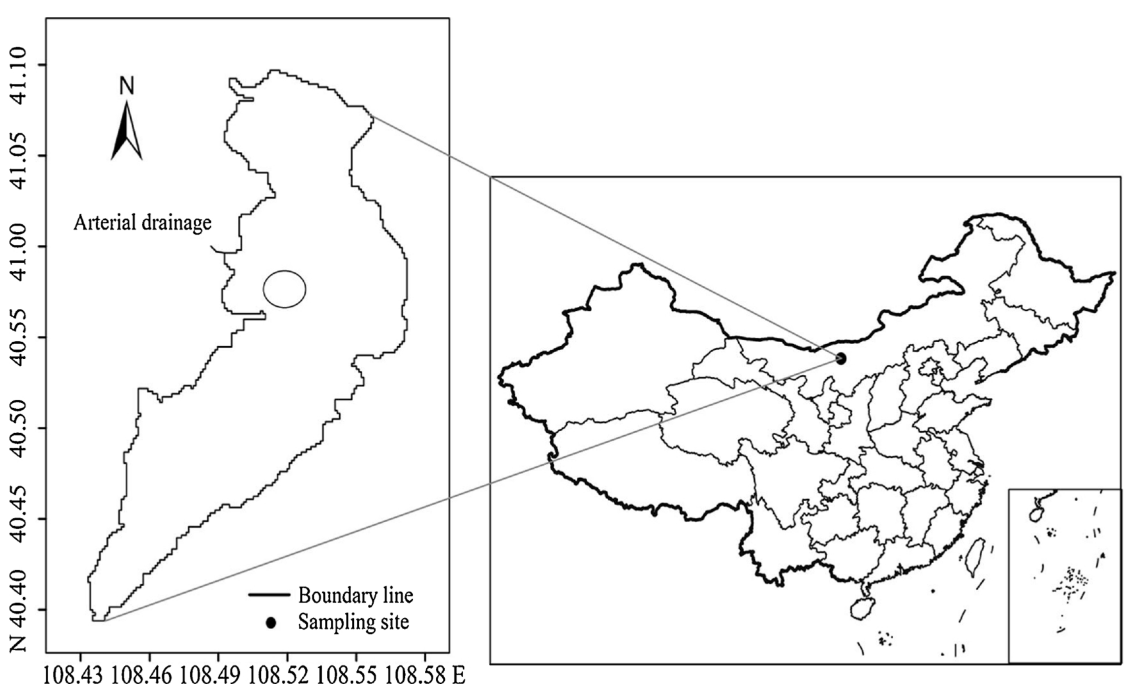


**Fig. 1.** Location of the Ulansuhai Lake.