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Assessment of the lake biomanipulation mediated by piscivorous rainbow trout and herbivorous daphnids using a self-organizing map: A case study in Lake Shirakaba, Japan

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ABSTRACT

This paper focuses on assessing a lake biomanipulation and introduces self-organizing maps (SOMs) as an analytical tool. In 2000, the biomanipulation using herbivorous plankters (*Daphnia galeata*) and piscivorous fish (*Oncorhynchus mykiss*) was implemented to improve water quality in Lake Shirakaba, Japan. We aimed to identify the relationships among dominant zooplankton and environmental conditions during the study period (pre-: 1997–1999, intermediate-: 2000–2002, and post-biomanipulation: 2003–2006, sampled between May and October on the biweekly basis, $N = 122$). From the SOM, the limnological characteristics of the lake were categorized into five features. The results accommodated that the newly introduced non-native grazers, *D. galeata*, were well stabilized by introducing *O. mykiss* which helped *D. galeata* survive away from predation pressure of *Hypomesus transpacificus nipponensis*. The interplay and relationship between variables projected by the SOM were also supported by the previous research and evidences in compliance with competitions and predations. Hence the results manifest that a regime shift of zooplankton communities in this lake has occurred since the biomanipulation. Furthermore, the present study highlights the applicability of contemporaneous introduction of both top-down cascade regulators (i.e. *D. galeata* and *O. mykiss*) as an alternative choice for the successful biomanipulation.

1. Introduction

Biomanipulation provides an important chance in ecological restoration and evaluation in changes of freshwater ecosystem, such as food web structures and functions (Shapiro et al., 1975). Hitherto the biomanipulation has been widely employed to reduce phytoplankton biomass and subsequently improve water quality in numerous locations. Several studies have depicted 'bottom-up' (i.e., resource-dependent) effects that mediated reduction of external nutrient loading, and claimed difficulties in rehabilitating water quality due to internal nutrient recycling and biological resistance (Kasprzak et al., 2003; Lauridsen et al., 2003; Perrow et al., 1994). Thus, unless the control of the external nutrient sources attained reduction of algal biomass, another approach such as 'top-down' (i.e., consumer-related) control would be an alternative (Shapiro et al., 1975).

The contemporary literature has accommodated controlled changes in a wide variety of freshwater ecosystems. Removal of planktivorous fish has been primarily favored for the top-down control (Bergman et al., 1999; Olin et al., 2006; Wysujack et al., 2001), and subsequently would induce a high proportion of large cladocerans, such as *Daphnia* spp., which are macrozooplankton and effective filter feeders of phytoplankton (Drenner et al., 2002; Meijer et al., 1989; Shapiro and Wright, 1984). Shapiro and Wright (1984) depicted changes of phytoplankton composition from cryptophyte to chlorophyte and vice versa over the biomanipulation period. Drenner et al. (2002) reported a decrease of cyanobacteria density contingent upon employment of piscivorous largemouth in the reservoir, even though the biomanipulation was not successful in improving water quality. Despite plenty of previous research on biomanipulation, most research has selectively used either direct addition of herbivores (Theiss et al., 1990) or piscivore-mediated herbivore control (Lathrop et al., 2002). Given complex interaction among food web components, an idea of the simultaneous control of the ecological entities (i.e., biological species) has been recently raised in Japan (Ha et al., 2013; Hanazato, 2005).

The Lake Shirakaba was a good example of the eutrophic ecosystem, and non-native herbivorous daphnids as well as piscivorous rainbow trout were introduced into the lake for improving water quality, which was a unique attempt in the light of simultaneous top-down food web control modulated by the two heterogeneous predators

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(Hanazato, 2005). Ha et al. (2013) demonstrated the general patterns and temporal trends of physicochemical and biological components such as temperature, DO, nutrients, phyto- and zooplankton and fish, and characterized the lake ecosystem into four disparate features of ecological sections based on macrophyte colonization and daphnid abundance. However, such a subjective determination of the categorization may incur suspicion whether the superficial characterization intimately corresponds to intrinsic aspects of the desired ecosystem or not, even if followed by statistical analyses with mean and standard deviation. Moreover, in the management point of view, it may be very difficult to quantitatively evaluate and explicitly reveal plausible mechanisms for the restoration, since the successful biomanipulation can be founded upon top-down effects of reduced planktivores as well as bottom-up effects of improved nutrient condition.

In ecological research, an important part of data analysis involves choosing the most relevant analytical tools to reveal complex relationships between ecological entities and driving forces. This is especially important in field-measured data, which may contain a variety of unpredictable factors, convoluting the underlying patterns; moreover, coarse and missing values may further complicate matters. Nature is a multifaceted and intricate system; complicated interplay and contemporaneous associations among environmental components can make a formal “*strong inference*” methodology lead to fallacious conclusions in elucidating potential causes of patterns in nature (Quinn and Dunham, 1983). In this regard, Ludwig and Reynolds (1988) stated that conventional statistical methods might be limited to linear data and inflexible in handling missing data. Chon et al. (1996) also contended that the conventional statistics could be difficult to extract a clear pattern of ecological aspects that entail highly nonlinear complexity. Recently, with the new drift of ecological research, some computational approaches that train and learn data associated with artificial intelligence have been introduced and attempted to search for the solutions when dealing with nonlinearity of complex data in a non-supervised manner in contrast with principal component analysis (Giraudel and Lek, 2001; Recknagel, 2006).

A self-organizing map (SOM), a type of artificial neural networks, is introduced as a new type of ecological data-learning method. The SOM has discriminative properties such as competition, adaptation and self-organization in the process of information extraction (Kohonen, 1997). It is capable of searching for an optimal solution by reflecting nonlinearity of parameter interaction in data learning. Striving for reducing the dimension of the complex and nonlinear field-measured data, we hypothesize that the SOM will be able to provide more refined resolution in the categorization of ecological aspects of Lake Shirakaba. Prior to data analysis, we postulate that zooplankton communities and ambient conditions would reflect ramifications of the lake biomanipulation as proxies of ecosystem changes, which reflects the motivation and novelty of the study towards gaining insight into the functioning role of zooplankton communities. To this end the aim of the present study is to evaluate the successful application of introducing two different top-down controllers connected via food web cascade (e.g., piscivorous fish, *Oncorhynchus mykiss* and herbivorous zooplankton, *Daphnia galeata*) into the Lake Shirakaba. Finally, we examine if the data classification assigned by morphological features of the lake landscape is capable of identifying well the ecological regime of the target ecosystem, and further discuss the interaction and relationships among zooplankton community groups corresponding to environmental driving forces based on the SOM visualization.

2. Materials and methods

2.1. Study site overview

Lake Shirakaba is a small and shallow lake (surface area, 36 ha; maximum depth, 9.1 m) located at a high elevation (1416 m above sea level) in a quasi-national park in central Japan (Fig. 1). The lake was artificially established in 1946 for the supply of warm water for agriculture. This lake is moderately meso-eutrophic (ca. 0.4–34.6 μg L^{-1} of chlorophyll *a* between 1997 and 2006), and many recreational facilities are distributed adjacent to the lake boundary. Water transparency recorded in a range of 220 ± 50 cm over the study period (Table 1), and a thermocline usually developed at a depth of about 4 m in the middle of June and persisted until September with an anoxic hypolimnion (≈1.6 mg L^{-1} of DO, refer to the Fig. 2 in Ha et al. (2013) study).

2.2. Background history of biomanipulation in the Lake Shirakaba

Lake Shirakaba area is known as a tourist spot in Japan. During the 1960s and 1970s, many artificial constructions (hotels and amusement facilities) were built along the lake, and the water quality subsequently deteriorated, resulting in recurrent cyanobacterial blooms. After construction of a sewage treatment plant in 1981, the blooms mostly diminished, but recurred in 1994 and have remained thereafter. In 2000, the restoration project associated with biomanipulation was initiated for the purpose of water quality restoration (Hanazato, 2005).

In 1997, prior to the biomanipulation, a preliminary survey was preceded to opt for the most effective approach to improve water quality. There were no *Daphnia* species but small zooplankton species such as

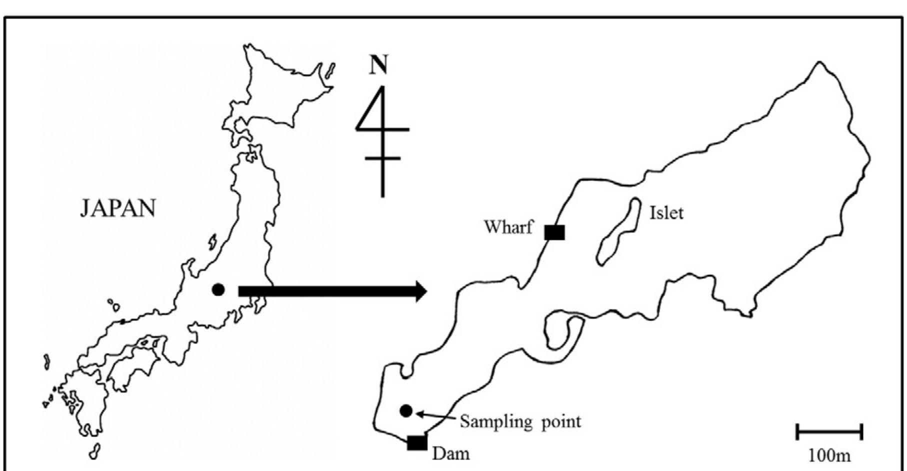

Fig. 1. Map of the study site in Lake Shirakaba.