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Determining tipping points in aquatic ecosystems: The case of biodiversity and chlorophyll α relations in fish pond systems

Marie Vanacker*, Alexander Wezel, Vincent Payet, Joël Robin

Department of Agroecology and Environment, ISARA Lyon (Member of the University of Lyon), 23 rue Jean Baldassini, 69364 Lyon, France

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A B S T R A C T

The management of biodiversity in aquatic ecosystems requires knowing the state of water quality linked to regime shifts in various taxonomic groups. We examine this question by studying the fish ponds in the Dombes region, France. These waterbodies are characterized by a high diversity of species. High levels of nutrients due to certain fish farming practices may cause significant eutrophication leading to loss in biodiversity and a shift from high coverage of aquatic vegetation to phytoplankton dominance may also be observed. The aim of this study is to assess tipping points, thresholds for effect, along a gradient of chlorophyll α in different taxonomic groups: aquatic vascular plants, phytoplankton, dragonflies and aquatic macro-invertebrates. Tipping points are analyzed with three different statistical methods: a method which evaluates tipping points with a difference in the mean (TMEAN), a second method which evaluates tipping point by comparing the mean and linear regressions before and after the tipping point (FSTAT) and third a method which evaluates linear regressions with a pivotal tipping point (SEGMENTED). We also compare tipping points for the different taxonomic groups using five different diversity indices: Observed richness, Jackknife first order, Fisher's alpha, Simpson index and Evenness.

Our results show that there is an important variation in tipping points following the three statistical methods, but the SEGMENTED is the best method for evaluating tipping points. We observe a high difference of tipping point values for the different taxonomic groups depending on the diversity indices used. Jackknife first order has a better performance to evaluate a eutrophic change according to the diversity than the other indices.

In all taxonomic groups, aquatic vascular plants are the most impacted by the chlorophyll α and almost all their tipping points are observed around 60 μg/L chlorophyll α concentrations. No significant relationship is found between chlorophyll α and phytoplankton diversity, while the two other groups, dragonflies and macro-invertebrates, are both impacted by the chlorophyll α but their relevant tipping points are situated in higher values than aquatic vascular plants.

1. Introduction

Lakes and ponds cover about 4.2 million km^2, more than 3% of the earth's surface (Downing et al., 2006). However, the majority of lakes and ponds with a surface of less than 50 ha are often neglected and are not sufficiently studied (Céréghino et al., 2008; Scheffer et al., 2006). In most cases fish ponds are artificial water bodies and described with a maximal depth of 8 m, offering the opportunity for aquatic vascular plants to colonize the entire area (Oertli et al., 2000). In comparison, lakes are natural waterbodies. The depth of lake can exceed 20 m and presents an aphotic area which prevents the development of aquatic vascular plants in the deep water (Oertli et al., 2013). Most of the fish ponds in Europe were created during the Middle Ages for fish farming and are still used today in different intensities for fish production. The highest densities of fish ponds in the landscape can be found in France, Poland, the Czech Republic, Germany and Austria (Wezel et al., 2013a, 2013b).

The European Water Framework Directive (WFD) was adopted to protect and improve the water quality of all type of waterbodies to achieve a 'good ecological status' by 2015. The WFD recommends to assess a wide array of biotic variables, including phytoplankton, aquatic vascular plants and macro-invertebrates and the concentrations of nutrient loads for the evaluation of water quality (European Union, 2000; Moss et al., 2003; Søndergaard et al., 2005b). The estimation of phytoplankton biomass through the

Abbreviations: CHL, chlorophyll α; FSTAT, F test statistic method; TMEAN, threshold by mean method; SEGMENTED, segmented method; WFD, the European Water Framework Directive.

* Corresponding author. Tel.: +33 427858609.
E-mail addresses: mvanacker@isara.fr, mvanacker39@gmail.com (M. Vanacker).

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parameter chlorophyll α (CHL), is recognized as a better parameter than nutrient levels in the study of the impacts of eutrophication (Honkanen and Helminen, 2000; Robin et al., 2013; Solimini et al., 2008). CHL corresponds strongly to the fluctuations of the food web (Carpenter et al., 2011; Robin et al., 2013) and can be easily measured. Furthermore, CHL is an ecological driver which is strongly correlated with different taxonomic groups (Robin et al., 2013).

Practices like liming and fertilization are commonly used by fish farmers to optimize the trophic capacity and, consequently, increase fish biomass (Broyer and Curtet, 2012). The increase of nutrient concentrations influences the pond system and can cause a regime shift from high coverage of aquatic vascular plants (clear water state) to phytoplankton dominance (turbid water state), often followed by a degradation in the composition of animal species (Jeppesen et al., 1997; Pálffy et al., 2013; Scheffer et al., 2009, 2001, 1993). This regime shift can be defined by a critical threshold, also called tipping point (Scheffer et al., 2009, 2001). A tipping point is characterized by a point at which a perturbation can cause a significant change, in this case a new organization of species, in the state of the system (Lenton et al., 2008; May, 1977; Wall, 2007). Over the last two decades, ecologists have increased their interest in the study of regime shifts in different ecosystems (Andersen et al., 2009; Carstensen and Weydmann, 2012; Jordan et al., 2006; Lenton et al., 2008; Scheffer et al., 2001; Wall, 2007). The existence of ecological tipping points has mostly been investigated by means of theoretical modeling studies and experiments. Methods and software developed recently are efficient for analyzing step change responses. However, data reporting of statistical evidence for such nonlinear responses are remarkably poor (Andersen et al., 2009).

All aquatic organisms in the food web are influenced by external (e.g. weather) and internal (e.g. nutrient levels) conditions in fish ponds (Declerck et al., 2005; Moss et al., 2003; Søndergaard et al., 2005a) and are strongly influenced by fish farming practices (Lemmens et al., 2013). Phytoplankton, aquatic vascular plant and aquatic invertebrates are essential for the dynamic of fish ponds (Korinek et al., 1987; Pálffy et al., 2013; Scheffer, 2004). Phytoplankton is the main source of primary production, functioning as a precursor for community-level processes and responses to changes in the environment (Korinek et al., 1987; Pálffy et al., 2013). As regards to aquatic vascular plants, they affect nutrient levels and reduce the turbidity of the water column (Scheffer, 2004). They are the main contributor to the species diversity at the ecosystem level, especially for the diversity of invertebrates (Declerck et al., 2005). Macro-invertebrates and dragonflies are also good indicators of environmental conditions in freshwater ecosystems (Patrick and Palavage, 1994; Silva et al., 2010) and especially in the case of eutrophication of pond systems (Menetrey et al., 2011, 2005). Therefore, the richness of habitat and species is crucial to the fish pond dynamic and conservation of biodiversity. At local scale, small waterbodies, such as small ponds, may vary considerably in Observed richness. This variability of the species richness in these waterbodies allows high diversity at the regional scale (Davies et al., 2008; Oertli et al., 2002; Williams et al., 2003). This high diversity is explained by the fact that ponds have small catchment areas, individual physical–chemical characteristics and are physically heterogeneous habitats, making them highly different one from another (Williams et al., 2003).

Diversity indices are useful tools for managing natural resource, monitoring the environment and planning land use (Magurran, 2004). However, often the only indicator of observed species used (species richness) is down-biased for the estimation of the complete species richness in a local assemblage (Lande, 1996; Magurran and McGill, 2011). There are also many similarity indices based on presence/absence data, species abundance and individual abundance for comparing assemblages or studying spatial patterns of species diversity (Krebs, 2014; Magurran, 2004). However, no reliable method has yet been developed to predict the complete species richness in a terrestrial or an aquatic area (Chiarucci, 2012; Krebs, 2014). Fisher et al. (1943) were the first to propose a diversity measure based on a log series distribution. However, due to the complexity of logarithmic series and the lack of a theoretical justification for the use of a parametric method, ecologists have turned to a variety of non-parametric measures that do not take into account species abundance curves. Today, the number of diversity indices is quite large and the choice of one indicator rather than another is sometimes difficult (Krebs, 2014). However, the ideal indicator would be unbiased (near to an asymptotic species richness), precise (similar estimates with replicate samples) and efficient (needing only a small number of samples) (Magurran and McGill, 2011; Walther and Moore, 2005).

The aim of this study is the determination and evaluation of tipping points along a CHL gradient in fish pond systems in the Dombes region in southeastern France. The tipping points may help to anticipate regime shifts, e.g. from clear to turbid water states due to strong proliferation of algae and can provide helpful indications for the management to these systems. We therefore first compare different statistical methods to determine tipping points along a CHL gradient. For this we use aquatic vascular plants, phytoplankton, dragonflies and macro-invertebrates data of 35 nutrient-rich fish ponds of the Dombes region, France. Second, we test different diversity indices in relation to CHL and third we evaluate their usefulness for defining tipping points for indicating regime shifts in fish pond systems.

Table 1
Characteristics of the fish ponds sampled in the Dombes study area, France ($n = 35$).
* The median of CHL is evaluated during all the sampling period meaning between April and October.

	Mean	Standard deviation	Minimum value	Maximum value
Fish pond surface (ha)	15.0	14.6	2.2	79.0
Fish pond depth (m)	0.7	0.2	0.5	1.1
Fish production (kg/ha)	211.0	119.2	8.0	443.6
CHL median in spring (μg/L)	59.3	65.8	2.4	211.6
CHL median (μg/L)*	104.5	101.2	2.8	474.5

2. Material and methods

2.1. Study sites

The study was carried out in the Dombes region in southeastern France which is characterized by about 1100 man-made fish ponds and 11,500 ha of water surface organized in connected networks. Fish are stocked in spring and are harvested during autumn or winter when ponds are emptied. After a dry period, the ponds are refilled with water from either upstream fish ponds or from rainfall in the pond catchment. Fish species introduced in fish ponds in the Dombes area are similar. The dominating fish species raised in fish ponds is the common carp with more than 60% on the total fish yield, followed by roach and rudd, and a lower quantity of tench, pike or pikeperch (Wezel et al., 2013b). For this study we use data of 35 fish ponds sampled in 2008. Phytoplankton, aquatic vascular plants, dragonflies and macro-invertebrates were analyzed as well as CHL and fish production. Characteristics of the fish ponds are shown in Table 1. The surface area of fish ponds can vary significantly as well as chlorophyll α (CHL). Net fish production is relatively low, with an average of 211 kg ha^{-1}. The pond surface area varies considerably from 2 ha to more than 79 ha for the largest pond and the average depth is 0.73 m.