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Determination of tipping points for aquatic plants and water quality parameters in fish pond systems: A multi-year approach

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ABSTRACT

High levels of nutrients in fish ponds by fish farming may cause significant eutrophication leading to a loss in species richness and a decrease of cover of aquatic plants to phytoplankton dominance. This shift can be represented by a tipping point where a significant change in the state of the ecosystem is observed such as a change from high to low aquatic plants species richness and cover. A total of 100 fish ponds were studied during five years in the Dombes region, France, to determine tipping points in aquatic plant richness and cover using chlorophyll α (CHL), water transparency, Total N (TN) and Total P (TP) gradients with two statistical methods. The relationships between tipping points, nutrient loads and yearly variations in weather conditions were also evaluated. Looking at the five years data, tipping points were observed in aquatic plant richness at 6 and 60 µg/L for CHL, and at 3.90 mg/L for TN concentration; as well as at 70 cm for water transparency, but no tipping point was found with TP. For aquatic plant cover, tipping points were observed at 11 µg/L for CHL, 2.42 mg/L for TN, 0.05 mg/L for TP, and at 62 cm for water transparency. These tipping points showed a significant decrease of aquatic plant species richness and cover, linked to the nutrient concentrations which drive the competition between the primary producers phytoplankton and aquatic plants. However, tipping points could vary significantly between years. The inter-annual variability may be due to an early occurrence of phytoplankton blooms in some ponds in a year preventing the establishment of aquatic plants, and thus influencing the value of tipping points. Weather conditions influence the competition between primary producers by impacting chlorophyll α and nutrients concentrations. When weather conditions supported increased nutrient concentrations, the development of phytoplankton and aquatic plants was facilitated and tipping points in aquatic plant richness and cover occurred with relatively high values. Thus, a significant decrease of plant cover and richness occurred at higher level of nutrients compared to the other years. In these cases, aquatic plants dominated over phytoplankton for the spring period, and also often during summer. In conclusion, tipping points observed are mainly linked to the competition between aquatic plants and phytoplankton. In shallow and eutrophic systems like fish ponds where nutrients are not a limiting resource, weather conditions act temporarily during spring as the main regulator of this competition.

1. Introduction

Freshwater waterbodies such as lakes and ponds are very numerous covering more than 3% of the earth's surface (Downing et al., 2006). Most of ponds have small catchment areas, have their own physical-chemical characteristics and are physically heterogeneous habitats (Williams et al., 2003), making them highly different from one to another. Thus, ponds may vary considerably in species richness of the different communities, allowing a high diversity at the regional scale (Davies et al., 2008; Oertli et al., 2002; Rosset et al., 2014; Wezel et al., 2014; Williams et al., 2003).

In fish ponds, all aquatic organisms in the food web are influenced by nutrient levels (Declerck et al., 2005; Moss et al., 2003; Søndergaard et al., 2005a) and by fish farming practices (Broyer and Curtet, 2011; Horvath et al., 2002; Lemmens et al., 2013; Oertli et al., 2013). Weather conditions can also influence the state of fish ponds (Scheffer and van Nes, 2007) by particularly promoting phytoplankton biomass with high temperatures (Jacobsen and Simonsen, 1993; Li et al., 2015; Yang et al., 2013). Primary producers such as phytoplankton and aquatic plants, are crucial for the structuration

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Abbreviations: CHL, chlorophyll α; TP, total phosphorus; TN, total nitrogen; TMEAN, threshold by mean method; SEGMENTED, segmented method.

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of the food web in fish ponds (Korinek et al., 1987; Pálffy et al., 2013; Scheffer, 2004; van Donk and van de Bund, 2002). Phytoplankton is the main source of primary production and works as a precursor for community-level processes (Korinek et al., 1987; Pálffy et al., 2013). Aquatic plants can promote species diversity at the ecosystem level, especially invertebrates diversity (Declerck et al., 2005; Oertli et al., 2002), decrease nutrient levels and reduce the turbidity of the water column (Scheffer et al., 1993; van Donk and van de Bund, 2002). These two groups respond greatly to changes in the environment and are useful to predict ecosystem change (Beck et al., 2014; Korinek et al., 1987; Pálffy et al., 2013).

Fish farmers commonly use several practices like supplementary feeding and water fertilization to optimize the global productivity of the aquatic ecosystem and specifically to increase fish biomass (Broyer and Curtet, 2012; Horvath et al., 2002; Korinek et al., 1987; Wezel et al., 2013b). However, the excessive input of nutrients can cause a regime shift from high coverage of aquatic plants (clear water state) to phytoplankton dominance (turbid water state or algae blooms) (Jeppesen et al., 1997; Pálffy et al., 2013; Rinke et al., 2009; Scheffer et al., 2009, 2001, 1993). This regime shift may be based on three processes: (1) the turbidity increases with increased nutrient levels causing phytoplankton growth, (2) aquatic plants decrease turbidity by storing nutrients and competing for light with phytoplankton, and (3) aquatic plants disappear when the turbidity exceed a critical tipping point (Scheffer and van Nes, 2007).

A tipping point may be defined by the threshold where a significant change in the state of an ecosystem is observed (Lenton et al., 2008; May, 1977; Wall, 2007). In this study, a tipping point is defined as a significant change from high to low species diversity and cover in aquatic plants. In fact, a decrease of aquatic plant richness can lead to a decrease of the global productivity of the fish pond system (Scheffer, 2004) due to the fact that aquatic plants promote the diversity of other species such as macro-invertebrates (Declerck et al., 2005).

The aim of this study is first to determine tipping points where significant changes occur in aquatic plant richness and cover using chlorophyll α (CHL), water transparency, Total N (TN) and Total P (TP) gradients, and to evaluate variations over different years with the fish ponds analyzed. Secondly, we evaluate the relationship between tipping points, nutrient loads and yearly variations in weather conditions.

2. Materials and methods

2.1. Study area and site selection

The study was carried out in the Dombes region in south eastern 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 few days or weeks, the ponds are refilled with water from either upstream fish ponds or from rainfall in the pond catchment. 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).

The pond surface area varies considerably from 1.8 ha to more than 79 ha and the surface of fish ponds in our data averaged 14.8 ± 13.3 ha. The average of depth of ponds is 0.7 ± 0.2 m with a minimum of 0.3 and maximum of 1.2 m. The average net fish production in the studied fish ponds is 209 ± 142 kg ha^{-1}, ranging from a negative production of −1.4 (less fish harvested at the end than fish placed in the pond at the beginning of the breeding) to a maximum of 720 kg ha^{-1}.

In this study, a total of 100 fish ponds were studied during five years in the Dombes region, France, including 26 ponds which were monitored several years (two or three years). A multiannual study scale was chosen in order to analyze the variability of tipping points over years and to study the seasonal effect due to variations of weather conditions. As fish ponds are emptied every year for fish harvest, the inter-annual variability of the 26 multiannual ponds is significantly different in term of CHL and plant cover (p-value of Levene test <0.001). Thus, a multiannual sampled pond is considered as different form one year to another and the statistical analyses will consider these different years as independent data. The number of ponds sampled per year was: $n = 24$ (2008), $n = 25$ (2009), $n = 17$ (2012), $n = 21$ (2013) and $n = 13$ (2014).

2.2. Aquatic plants

Aquatic plants were determined at the beginning of summer, following the protocol described in Arthaud et al. (2013) and Vanacker et al. (2015). The number of sampled quadrats increased with the surface area of the fish pond and varied from 18 to 140. For each quadrat, submerged and floating aquatic plants were identified to species level and their abundance was recorded using cover-abundance estimates of Braun-Blanquet (1932). The richness of aquatic plants was determined by the Jackknife first order which is the best diversity index to determine tipping points in this taxonomic group (Vanacker et al., 2015). Jackknife first order was developed by Burnham and Overton (1979) and reduces the underestimation of the number of species in an assemblage based on the number represented in the sample. Plant cover of each fish pond was determined by averaging the cover values of each species in each quadrat. A total of 87 aquatic plant species were recorded in the Dombes area during the five years of sampling.

2.3. Water samples

In order to decrease the effect of strong temporal variability that occurs in eutrophic waterbodies (Jeppesen et al., 1997), we collected between 8 and 6 samples in spring depending of the year. For each sample, CHL and nutrient concentrations were determined and the water transparency measured. The water quality was evaluated in spring during all the aquatic plant development until the maturity of plants. Water samples were collected with a Van Dorn sampler (Uwitech, Austria) in one point near the outlet of each pond, the deepest part of the pond.

2.4. Chlorophyll α

CHL was extracted for 24 h in a 90% acetone solution and was then measured with a Shimadzu UV/VIS spectrophotometer UV-2101 (Schimadzu Corporation, Kyoto, Japan) in 2008 and for the following years with a spectrophotometer JASCO UV/VIS spectrophotometer V-530 (JASCO, Japan) at 630, 645, 663 and 750 nm. The CHL concentration per unit volume was then calculated using the Parsons and Strickland formula (Parsons and Strickland, 1963). The median

2.5. Water transparency

The transparency of the water was evaluated since 2009 with a Secchi disc in each sampling date. No transparency data was recorded in 2008. However, these missing values were determinate by modelling the transparency from CHL values. In each sampling date in spring 2008, we determinate the transparency by the relationship of the other years $y = 142.43\,x^{-0.329}$ ($R^2 = 0.609$, $n = 610$) where y is the transparency (cm) and x is the CHL.