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Deriving nutrient criteria to support 'good' ecological status in European lakes: An empirically based approach to linking ecology and management

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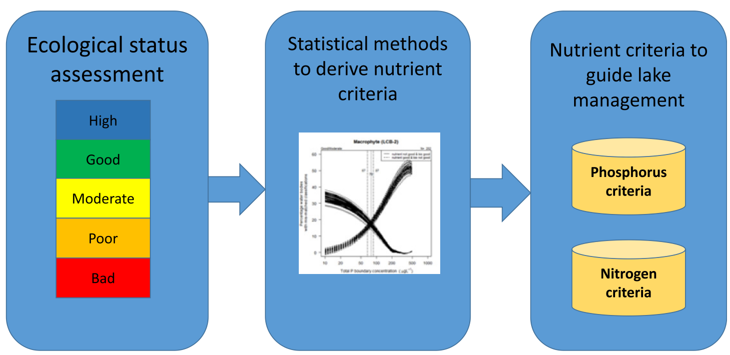
HIGHLIGHTS

- We link ecological status of lake macrophyte communities to nutrient levels.
- We establish nutrient criteria for 'good' ecological status in shallow lakes of Europe.
- Different regression and categorical methods yield similar nutrient criteria.
- Empirically derived nutrient criteria can guide lake restoration efforts.
- This methodology can be applied to other ecosystems and indicators.

GRAPHICAL ABSTRACT



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ABSTRACT

European water policy has identified eutrophication as a priority issue for water management. Substantial progress has been made in combating eutrophication but open issues remain, including setting reliable and meaningful nutrient criteria supporting 'good' ecological status of the Water Framework Directive.
The paper introduces a novel methodological approach - a set of four different methods - that can be applied to different ecosystems and stressors to derive empirically-based management targets. The methods include Ranged Major Axis (RMA) regression, multivariate Ordinary Least Squares (OLS) regression, logistic regression, and minimising the mismatch of classifications. We apply these approaches to establish nutrient (nitrogen and phosphorus) criteria for the major productive shallow lake types of Europe: high alkalinity shallow (LCB1; mean depth 3–15 m) and very shallow (LCB2; mean depth < 3 m) lakes.
Univariate relationships between nutrients and macrophyte assessments explained 29–46% of the variation. Multivariate models with both total phosphorus (TP) and total nitrogen (TN) as predictors had higher R^2 values (0.50 for LCB1 and 0.49 for LCB2) relative to the use of TN or TP singly. We estimated nutrient concentrations at the boundary where lake vegetation changes from 'good' to 'moderate' ecological status. LCB1 lakes achieved 'good' macrophyte status at concentrations below 48–53 μg/l TP and 1.1–1.2 mg/l TN, compared to LCB2 lakes below 58–78 μg/l TP and 1.0–1.4 mg/l TN. Where strong regression relationships exist, regression approaches offer a reliable basis for deriving nutrient criteria and their uncertainty, while categorical approaches offer

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advantages for risk assessment and communication, or where analysis is constrained by discontinuous measures of status or short stressor gradients.
We link ecological status of macrophyte communities to nutrient criteria in a user-friendly and transparent way. Such analyses underpin the practical actions and policy needed to achieve 'good' ecological status in the lakes of Europe.

1. Introduction

Human activities – intensive agricultural land use, wastewater disposal and combustion of fossil fuels – have dramatically increased nutrient loading to the aquatic environment (Carpenter et al., 1998; Smith and Schindler, 2009). The rate of nitrogen input into the terrestrial nitrogen cycle has doubled since pre-industrial times (Vitousek et al., 1997), while there has been an approximately threefold increase in phosphorus inputs to the biosphere, mainly through use of fertilizers (Bennett et al., 2001). Undesirable disturbances in lakes, such as toxic cyanobacterial blooms (Carvalho et al., 2013a), loss of submerged vegetation (Sand-Jensen et al., 2000; Zhang et al., 2017), severe oxygen deficiency (Diaz and Rosenberg, 2008) and decline in sensitive fish species (Müller and Stadelmann, 2004) are commonly associated with nutrient enrichment. Therefore, eutrophication impairs ecosystem services and incurs high economic costs (Dodds et al., 2008; Le et al., 2010).

Evidence suggests that lowering anthropogenic nutrient loading to aquatic ecosystems is key to controlling eutrophication (Schindler et al., 2016; Vollenweider, 1992), but how low is 'low' and which nutrients to target? Nutrient management is costly and complex (Schindler, 2012) so an appropriate nutrient management strategy is critical if it is to deliver the sought-after ecological gains (Conley et al., 2009).

During the last few decades, substantial achievements in nutrient control have been made (e.g., Kronvang et al., 2005). However, improvements in the ecological status of lakes have been relatively slow, with some lakes failing to recover their original clear water state despite substantially reduced nutrient loading (Søndergaard et al., 2007). Delayed recovery has been recorded, in particular for lake macrophyte communities (Bakker et al., 2013; Eigemann et al., 2016; Jeppesen et al., 2005; Lauridsen et al., 2003). Explanations include high internal loading of phosphorus from sediments (which may last longer than 20 years; Søndergaard et al., 2003) and complex biotic interactions, especially for shallow lakes, which can switch between alternative stable states (Hilt et al., 2018; Scheffer and van Nes, 2007). As nutrient concentrations increase such lakes are more prone to switch from a vegetated to turbid state (Phillips et al., 2016), but to restore the desired vegetated clear water state, nutrient levels may need reducing to well below those at which vegetation collapsed (Ibelings et al., 2007). Setting appropriate nutrient criteria is therefore key to effective lake management.

A wide variety of approaches have been used to derive nutrient criteria (Charles et al., 2019; Dodds and Welch, 2000; Huo et al., 2017). The stressor-response approach involves modelling statistical relationships between nutrient concentrations and biological metrics (Dolman et al., 2016; US EPA, 2010). This method has the advantage of linking nutrient criteria directly to predefined ecological outcomes. For instance, in rivers, nutrient criteria are set to prevent benthic chlorophyll exceeding specific levels (Dodds and Welch, 2000), whilst for lakes, critical thresholds for cyanobacterial blooms have been used to define nutrient criteria (Carvalho et al., 2013a; Downing et al., 2001; Yuan et al., 2014; Yuan and Pollard, 2015).

However, this approach necessitates quantifying robust stressor-response relationships which in some cases has proved to be a task of daunting complexity (Borics et al., 2013; Dodds et al., 2002). Many studies have established strong empirical links between phytoplankton and nutrients (Carvalho et al., 2013b; Phillips et al., 2013), yet macrophyte-nutrient relationships are much less studied. Relationships have been established between nutrients and macrophyte metrics such as colonization depth (Søndergaard et al., 2013), total cover (Han and Cui, 2016) or trophic indices (Lyche-Solheim et al., 2013; Penning et al., 2008). However, on their own these are of little use for lake management, as different metrics can respond differently to eutrophication and re-oligotrophication processes (Pall and Moser, 2009) or responses can vary between lake types (Kolada et al., 2014). There is a need to establish stressor-response models linking nutrients and holistic assessments of macrophyte communities that integrate several measures of plant composition and abundance, and on a type-specific basis. However, the issue is complex as various lake properties, such as lake size and depth, as well as climate, will influence these criteria (Scheffer and van Nes, 2007).

In theory, waterbody-specific criteria could be developed, considering all relevant factors. However, in real-life situations, where managers must cope with restricted resources, limited data, transboundary water issues and a huge number of water bodies (Finland - 4275, Poland - 1038 and Sweden - 7232 lake water bodies; ETC/ICM, 2012) establishing broad-scale type-specific nutrient criteria is justified. These type-specific criteria also offer a high-level screening tool for prioritizing lakes ahead of more focused nutrient-management activities (Bennion et al., 2005).

The Water Framework Directive (WFD; EC, 2000) was adopted to protect and enhance Europe's water resources. It requires the ecological status of water bodies to be classified according to (1) biological elements (phytoplankton, benthic invertebrates, fish fauna, macrophytes and phytobenthos), (2) chemical and physico-chemical elements (e.g. nutrients, oxygen, transparency, salinity, temperature, and specific pollutants), and (3) hydromorphological elements (e.g. lateral connectivity). Water bodies are classified into five status categories: high (no or minor anthropogenic impact), good (slight anthropogenic impact) - which represents the required minimum goal for water management, and moderate, poor or bad. Two decades have been devoted to developing and harmonizing the biological assessment systems of EU member states (Birk et al., 2012, 2013; Poikane et al., 2014, 2015). However, gaps remain regarding nutrient criteria, i.e. the values required to support biology of a given status. Recent analysis (Phillips and Pitt, 2016) found that the methods used to set nutrient criteria varied widely between member states, with large ranges in the nutrient values stated to support 'good' ecological status (GES). While variation is expected due to specific environmental conditions, large differences remain within common water body types. Moreover, the relationship between nutrients and biology that underpins these criteria is often unclear.

This study (1) establishes stressor-response models linking macrophyte status and nutrient concentrations; (2) estimates nutrient (total phosphorus and total nitrogen) criteria that support GES for macrophytes in the commonest lake types of lowland Europe and (3) compares these criteria and discusses their applicability.

Macrophyte status reveals the onset of undesirable ecological changes in productive shallow lakes, while empirically derived nutrient criteria guide the urgency, scale and design of remedial action, and serve as a benchmark for assessing progress.

We focus here on high alkalinity shallow lakes as these are commonly degraded by nutrient enrichment and are therefore among the most challenging to manage, while macrophytes play a pivotal role in their functioning and the restoration of macrophytes is therefore a