Journal of Environmental Management 199 (2017) 172–180

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

A macrophyte bioassessment approach linking taxon-specific tolerance and abundance in north temperate lakes

Alison Mikulyuk [a, b, *], Martha Barton [b, c], Jennifer Hauxwell [d], Catherine Hein [e], Ellen Kujawa [b], Kristi Minahan [e], Michelle E. Nault [f], Daniel L. Oele [b], Kelly I. Wagner [b, 1]

[a] University of Wisconsin-Madison, Center for Limnology, 680 N Park Street, Madison, WI 53706, United States
[b] Wisconsin Department of Natural Resources, Bureau of Science Services, 2801 Progress Road, Madison, WI 53716, United States
[c] Mississippi State University, P.O. Box GY, MS 39762, United States
[d] University of Wisconsin-Madison, Aquatic Sciences Center, 1975 Willow Drive, Madison, WI 53706, United States
[e] Wisconsin Department of Natural Resources, 101 South Webster Street, Madison, WI 53703, United States
[f] Wisconsin Department of Natural Resources, 2984 Shawano Avenue, Green Bay, WI 54313, United States

ARTICLE INFO

Article history:
Received 20 November 2016
Received in revised form
4 May 2017
Accepted 6 May 2017
Available online 19 May 2017

Keywords:
Ecological quality
Ecological integrity
Biological assessment
Lake management
Aquatic plants
Anthropogenic disturbance

ABSTRACT

Bioassessment methods are critically needed to evaluate and monitor lake ecological condition. Aquatic macrophytes are good candidate indicators, but few lake bioassessment methods developed in North America use them. The few macrophyte bioassessment methods that do exist suffer from problems related to subjectivity and discernibility along disturbance gradients. We developed and tested a bioassessment approach for 462 north temperate lakes. The approach links macrophyte abundance to lake ecological condition via estimates of taxon-specific abundance-weighted tolerance to anthropogenic disturbance. Using variables related to eutrophication, urban development and agriculture, we calculated abundance-weighted tolerance ranges for 59 macrophyte taxa and clustered them according to their tolerance to anthropogenic disturbance. We also created a composite index of anthropogenic disturbance using 20 variables related to population density, land cover and water chemistry. We used a statistical approach to set ecological condition thresholds based on the observed abundance of sensitive, moderately tolerant and tolerant taxa in each lake. The resulting lake condition categories were usually stable across multiple survey events and largely agreed with condition rankings assigned using expert judgment. We suggest using this macrophyte bioassessment method for federal water quality reports, restoration and management on north temperate lakes.

1. Introduction

Healthy freshwater ecosystems are essential for life on Earth. They provide water for consumption, regulate water quality, support biodiversity, control floods and provide cultural value (Aylward et al., 2005). Furthermore, freshwaters are sentinels of environmental change that integrate terrestrial, atmospheric and in-water processes (Williamson et al., 2008). Expanding human development threatens both the health of freshwaters and their ability to render valuable ecosystem services (Baron et al., 2002; Dodds et al., 2013; García-Llorente et al., 2011; Vörösmarty et al., 2010). It is imperative that we develop the capacity to track the ecological condition of lakes. There are nearly 100 bioassessment methods currently used in Europe to report on a range of biotic groups, but few lake assessment methods have been developed in the United States, and most of them focus on fish (Beck and Hatch, 2009; Brucet et al., 2013).

The central goal of any biological assessment method is to describe the ecological integrity of a system using aspects of its biota. The input variables employed in assessment can take various forms, but may be conceptually divided by those describing taxonomy (in terms of richness, abundance, diversity or composition), and those that describe ecological traits (e.g. disturbance tolerance, trait or condition values, or invasive status; Birk et al., 2012). Depending on the input data, there are two general biological assessment methods (and Collier, 2009 combines the two). The first uses an integrated biotic index (IBI), to combine information on

* Corresponding author. University of Wisconsin-Madison, Center for Limnology, 680 N Park Street, Madison, WI 53706, United States.
E-mail addresses: mikulyuk@wisc.edu, mikulyuk@gmail.com (A. Mikulyuk).
[1] Present address: 236 Zephyr Road, Williston, VT 05495, United States.

http://dx.doi.org/10.1016/j.jenvman.2017.05.012
0301-4797/

multiple biological attributes that respond to anthropogenic disturbance. IBIs thus produce a single score that represents a system's ecological condition (Karr and Chu, 1997). The second approach uses multivariate analysis of taxonomic data. For example, a researcher may quantify a community's deviation from that which would be expected under least-disturbed conditions (e.g. Green and Chapman, 2011; Raapysjarvi et al., 2016), or categorize communities based on the environmental preferences of their constituent species (Penning et al., 2008a). Unlike IBIs, which often require selecting a subset of responsive species, multivariate techniques allow the use of all data collected from a community. They are often more precise and accurate than IBIs, but they are computationally intensive and can be more complicated to implement (Kanninen et al., 2013; Reynoldson et al., 1997).

Aquatic macrophytes are suitable indicators of ecological condition because they are sensitive to multiple forms of anthropogenic disturbance (Alahuhta and Aroviita, 2016; Clayton and Edwards, 2006; Schneider and Melzer, 2003; Seo et al., 2014). Macrophyte species abundance and community composition respond to nutrient enrichment, which is most often implicated as the cause of lake impairment worldwide (Egertson et al., 2004; Herschy, 2012; Scheffer and van Nes, 2007). Nearshore urbanization results in decreased macrophyte cover, likely due to shoreline modification, boating activity, and physical removal of vegetation (Patrick et al., 2016; Radomski and Goeman, 2001). Macrophyte cover also responds to invasive species while water level regulation and extraction can result in decreased species richness (Chappuis et al., 2011; Gallardo et al., 2016). Furthermore, aquatic macrophytes are widespread, abundant, and quite easy to sample.

Most of the macrophyte bioassessment methods developed for use in North American lakes are IBIs that rely in part on biologists' subjective ranking of macrophyte tolerance to anthropogenic disturbance (e.g. Beck et al., 2010; Nichols, 1999). In addition, IBIs can confound relationships among component indicators in a way that makes a single score difficult to interpret (Beck et al., 2013). Some show poor sensitivity to increasing anthropogenic disturbance, especially when disturbance is low (Nichols et al., 2000). While a greater diversity of methods have been developed in Europe, several of the reported 13 macrophyte-based approaches currently in use are IBIs that rely on expert judgment (Benoit, 2011). Several other European methods produce single trophic index from scores that reflect species' position along a eutrophication gradient. A third group of assessment methods employs abundance estimates of groups of species that vary with respect to their tolerance of eutrophication or their association with reference conditions (Poikane, 2009; Water Information System for Europe (WISE), 2012).

We developed a macrophyte-based ecological assessment method for use in north temperate lakes of North America. We use data-driven estimates of taxon-specific tolerance limits to describe groups of species that vary in their tolerance to multiple anthropogenic variables, but we explicitly include variables that describe nearshore- and watershed-scale land cover in addition to those describing water quality and eutrophication. We then use a statistical approach to define ecological condition across an index of anthropogenic disturbance to ultimately categorize lakes that range in their ecological condition.

2. Methods

2.1. Overview of the approach

We used taxon-specific tolerance to anthropogenic disturbance coupled with abundance estimates (here, frequency of occurrence) to explain patterns in anthropogenic disturbance affecting lakes and watersheds. The constituent steps of the method depicted in Fig. 1 were: (a) collect aquatic macrophyte abundance data, (b) relate macrophyte taxon abundance to anthropogenic disturbance, (c) cluster taxa by their tolerance to disturbance and (d) calculate abundance by tolerance clusters in each lake. Concurrently, we used (e) 20 anthropogenic disturbance variables to create an index of lake anthropogenic disturbance. Finally, we combined the results from (a)-(d) with (e) in order to (f) create decision trees that determine ecological condition thresholds (Fig. 1).

2.2. Aquatic macrophyte surveys

We collected data on aquatic macrophyte species occurrence between May 25 and September 04, 2005–2012 using 983 point-intercept surveys conducted on 542 unique Wisconsin waterbodies (Fig. 1a). Waterbodies were distributed across Wisconsin's three lake-rich ecoregions with surface area ranging 1.36–3958 ha and sampled as part of a monitoring and research program conducted by the Wisconsin Department of Natural Resources (WDNR; Omernik et al., 2000). Watersheds ranged from being almost entirely forested to those that were largely agricultural or urbanized. We observed species presence from a boat at every point on a grid scaled by lake littoral zone size and shoreline complexity (Mikulyuk et al., 2010). Total number of points ranged from 45 to 4149 points per lake. On average, 207 sample points fell within littoral zones, defined per lake by areas equal to or more shallow than the 99th percentile of ordered depths at which aquatic macrophytes were observed. At each sampling point, observers used a double-sided bow rake attached to a 4.5 m pole to collect macrophytes from a 0.3 m^2 area. A similar rake head attached to a rope was used to collect macrophytes from sites deeper than 4.5 m (Hauxwell et al., 2010). All live macrophytes detached by the rake were identified to species, and some cryptic species were lumped by genus (Crow and Hellquist, 2000a; b; Table S1). The inclusion of cryptic taxa at the genus level enhances the applicability of the approach, but may limit our ability to discern species-specific patterns in the greater macrophyte community. We expressed taxon abundance as relative frequency of occurrence in the littoral zone. We also identified species growth forms following methods used in the National Lakes Assessment, which divides species by growth form and leaf width (USEPA, 2011, 2012). Growth form categories included floating leaf, free-floating, emergent, submersed-compact (<20 cm tall), submersed-wide (≥20 cm tall with leaves >1 mm) and submersed-narrow (≥20 cm tall with leaves <1 mm) groups.

2.3. Taxon tolerance clusters

Next, we explored patterns in taxon-specific tolerance to anthropogenic disturbance gradients across all lakes (Fig. 1b). Macrophyte abundance was often distributed unimodally along anthropogenic disturbance gradients; we used an abundance-weighted average to estimate species-specific optimal values of 20 disturbance variables describing population, land use and water quality (See section 2.4 for details; Akasaka et al., 2010; Mikulyuk et al., 2011). We excluded taxa that were not present in at least 15 surveys, resulting in 59 taxa for which we were able to estimate abundance-weighted optimal values (u_k) using the formula:

$$u_k = \sum_{i=1}^{n} \frac{y_{ki} x_i}{\sum_{i=1}^{n} y_{ki}} \quad (1)$$

where y is the abundance of taxa k in lake i, and x is the value of the anthropogenic disturbance variable in lake i (Ter Braak and Prentice, 2004). Next, we calculated each taxon's tolerance range: