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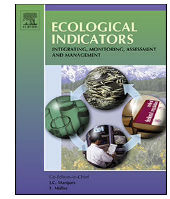

Original Articles

Use of diatoms for developing nutrient criteria for rivers and streams: A Biological Condition Gradient approach

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ABSTRACT

Nutrient enrichment is one of the most important causes of ecological impairment in surface waters. More effective management of this problem is constrained by a lack of nutrient criteria that link phosphorus and nitrogen concentrations to levels of biological impairment as defined in management agency regulations. We used a new approach for identifying potential nutrient criteria using diatom assemblages and the Biological Condition Gradient (BCG). We first used diatom count data to assign study sites to BCG impairment categories (levels), then determined P and N concentrations corresponding with the boundaries between those levels. We studied diatom counts and environmental data from 95 river and stream sites throughout the state of New Jersey (NJ), USA. The sites represent five ecoregions, primarily forested uplands and coastal plains, and a wide range of nutrient concentrations (total P range of 15 to $> 200\ \mu g\ L^{-1}$ and total N 0.5 to $> 4\ mg\ L^{-1}$). Advantages of NJ as a study region are the ready availability of streams with a large gradient in nutrient concentrations and similarity to nutrient-stressed systems in many other geographic regions. BCG levels represent a range of ecological conditions from natural to highly impaired. A panel of experts on use of diatoms as ecological indicators assigned 57 study sites to BCG levels based on diatom assemblage composition. Potential nutrient criteria were subsequently derived by determining the measured TP and TN concentrations associated with the boundary between impaired sites and non-impaired sites (BCG levels greater than 4). Based on this approach, statewide criteria of no greater than $50\ \mu g\ L^{-1}$ TP and $1.0\ mg\ L^{-1}$ TN are indicated for maintaining or restoring sites to unimpaired condition. In some least-disturbed ecoregions, lower concentrations (e.g., $25\ \mu g\ L^{-1}$ of TP) would be more appropriate to maintain current ecological conditions. Existing diatom TP and TN metric values for the study sites correlate well with BCG level assignments and can be used to determine if nutrient criteria are met. Overall, results demonstrate the usefulness of data derived from diatom assemblages in management of nutrient issues, and the potential widespread applicability of the BCG approach to develop nutrient criteria and to monitor compliance.

1. Introduction

Nutrient enrichment is a major water quality problem (Dubrovsky et al. 2010), and regulatory agencies have a significant need for science-based nutrient criteria to better protect and manage these resources. One of the most relevant and effective approaches for developing nutrient concentration guidelines is to base them on relationships with biological indicators of ecological condition and designated uses (US EPA, 1998, 2014). United States Environmental Protection Agency (US EPA) guidance for interpreting standards and criteria, which is passed down to state agencies for enforcement, includes the concept of "independent assessment," which requires an equal evaluation of both chemical (e.g. phosphorus) and biological standards (e.g., algae bioindicator levels). This approach has been criticized as being too conservative, as some streams may have low levels of phosphorus but high algal biomass, and not be listed as impaired, whereas other streams with high levels of nutrients but low biomass, and no deleterious biological effects due to localized physical factors, will be listed as impaired. Proposals have been made by states and other agencies to use both chemical and biological metrics in a weight-of-evidence approach (e.g., Smith and Tran, 2010) where multiple indicators and levels of ambient condition can be used for regulatory management.

Diatoms have one of the strongest relationships with nutrient concentrations of all aquatic biota and have been used widely as trophic and impairment indicators (Porter et al., 2008, Potapova and Charles, 2007, Smucker et al., 2013, Stevenson, 2014). But most of the

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relationships developed to date are continuous, and it is difficult to identify response thresholds that could be used to set nutrient regulatory boundaries. The Biological Condition Gradient approach (Davies and Jackson, 2006) provides a process for creating categories (BCG levels) defined in terms of extent of impairment, which can then be used to develop regulatory guidelines for nutrients. We applied this approach to diatom assemblages in rivers and streams and associated the resulting BCG level boundaries with N and P concentrations and corresponding diatom nutrient indices. We then identified potential criteria based on these relationships.

1.1. Background

Biological indicators that relate assemblage composition and nutrient concentrations are useful tools, but they do not, in and of themselves, indicate the level of impairment of a site, especially within a regulatory context. Specific criteria values separating impaired from unimpaired sites are also needed. Sites with values above the criteria would be considered impaired, and those below would be considered unimpaired. These values need to reflect protection of designated uses, primarily aquatic life and biotic integrity. The process of determining criteria values is problematic, however, because a selection of these 'bright line' scores requires both a technical and a policy perspective, with consensus of respected scientists being a key step in translating obtuse technical jargon into clear water-quality goals. To that end, the U.S. EPA has required and supported state efforts to develop uniform assessments of aquatic resource condition and to set more consistent aquatic life protection and restoration goals. These efforts have led to a conceptual model that describes ecological changes, from pristine to completely degraded, that take place with increased anthropogenic degradation. This model, called the Biological Condition Gradient (BCG) (Davies and Jackson, 2006), promotes more uniform application of the Clean Water Act by identifying levels or condition categories that can be operationally defined in a consistent manner. These levels can then be used to represent degree of impairment and be incorporated in a process of developing nutrient criteria.

This study is based on a five-year project funded by the New Jersey Department of Environmental Protection (NJ DEP). The primary goal was to bolster NJ's existing quantitative nutrient criteria (and narrative policies) through establishment of scientifically defensible response indicators (diatom total phosphorus (TP) and total nitrogen (TN) indices); and to possibly augment the state's routine water quality monitoring network (Cohen et al., 2009). This study assessed the relationship between benthic diatom and water chemistry samples collected from 77 river and stream sites in all major NJ ecoregions. Multivariate analysis showed that nutrient concentrations explain significant proportions of the variation in diatom species composition. Nutrient inference models and Diatom TP and TN Indices were developed that provided good measures of biological response to nutrient conditions (Ponader et al., 2007, Ponader et al., 2008; Horwitz et al., 2016).

1.2. The biological condition gradient

The BCG, as originally proposed by Davies and Jackson (2006) and being implemented by the US EPA (US EPA, 2016), is a conceptual model relating biological response to a generalized gradient of stress caused by human activities. It is designed to apply to aquatic systems in the U.S. and has been tested and implemented primarily using benthic macroinvertebrates and fish. It is intended to provide a nationally consistent approach that will allow BCG status to be compared among different types of aquatic ecosystems and geographic regions.

The BCG approach defines levels of impairment due to human activities based on presence, absence, abundance, and relative abundance of several groups of taxa, as well as statements on system connectivity and ecosystem attributes (production, material cycling). The statements are consensus best-professional judgments based on years of experience of many biologists in a region and reflect accumulated biological knowledge. In 2004, NJ DEP and the US EPA supported a BCG assessment of NJ's large macroinvertebrate (AMNET) biomonitoring dataset. The report of the study (Gerritsen and Leppo, 2005) described the successful application of the BCG to streams in NJ and the development of operationally defined tiers for setting restoration goals and aquatic life protection criteria. A similar approach was applied in this current project. This, and a related study (Hausmann et al., 2016), are two of the first studies applying the BCG approach to algae, and, as far as we know, the first to use it with diatoms to identify potential nutrient criteria. The most closely-related studies involve use of BCG diatom metrics to quantify impairment categories in Maine rivers and streams (Danielson et al., 2011, Danielson et al., 2012), development of BCG approaches for macroinvertebrates (e.g., Gerritsen et al., 2017), and use of non-BCG algae-based approaches for assigning sites to impairment categories (e.g., Lavoie et al., 2014, Smith and Tran, 2010, Smucker et al., 2013). Algal taxonomists and ecologists at the ANSP performed most of the work to assign taxa to ecological categories. NJ DEP staff provided the primary data and expertise to help characterize levels of impairment of sites and evaluated how well diatom indicators defined categories. They also made recommendations for improvements.

1.3. BCG taxon attributes

We used the attribute categories presented by Davies and Jackson (2006) and as defined in EPA's Practitioner's Guide to the BCG (US EPA, 2016), quoted below:

> "Attribute I: Historically documented, sensitive, long-lived or regionally endemic taxa.
> Attribute II: Highly Sensitive Taxa: … typically occur in low numbers relative to total population density, but they might make up a large relative proportion of richness……. They are often the first taxa lost from a community following moderate disturbance or pollution.
> Attribute III: Intermediate Sensitive Taxa: …ordinarily common and abundant in natural communities. They tend to have a broader range of tolerances than highly sensitive taxa, and they usually occur in reduced abundance and reduced frequencies at disturbed or polluted sites. These taxa often comprise a substantial portion of natural communities.
> Attribute IV: Taxa of Intermediate Tolerance: …commonly comprise a substantial portion of an assemblage in undisturbed habitats, as well as in moderately disturbed or polluted habitats……. These species have little or no detectable response to moderate stress, and they are often equally abundant in both reference and moderately stressed sites. Some intermediate tolerant taxa may show an "intermediate disturbance" response, where densities and frequency of occurrence are relatively high at intermediate levels of stress, but they are intolerant of excessive pollution loads or habitat alteration.
> Attribute V: Tolerant Taxa: …typically comprise a low proportion of natural communities. These taxa are … resistant to a variety of pollution or habitat induced stress. They may increase in number (sometimes greatly) under severely altered or stressed conditions….
> … These are the last survivors in severely disturbed systems.
> Attribute VI: Non-native or Intentionally Introduced Taxa:" Because it was not possible in this study to determine if a diatom taxon was non-native or introduced, attribute VI was redefined to mean Very Tolerant, usually found in abundance only in very highly stressed conditions.

1.4. BCG site levels

We used descriptions of the first six BCG levels presented in Davies and Jackson (2006), and defined in US EPA (2016), quoted below.

Level descriptions are expressed in terms of changes in the structure