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Using algal metrics and biomass to evaluate multiple ways of defining concentration-based nutrient criteria in streams and their ecological relevance

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ABSTRACT

We examined the utility of nutrient criteria derived solely from total phosphorus (TP) concentrations in streams (regression models and percentile distributions) and evaluated their ecological relevance to diatom and algal biomass responses. We used a variety of statistics to characterize ecological responses and to develop concentration-based nutrient criteria (derived from ecological effects) for streams in Connecticut, USA, where urbanization is the primary cause of watershed alteration. Mean background TP concentration in the absence of anthropogenic land cover was predicted to be 0.017 mg/l, which was similar to the 25th percentile of all study sites. Increased TP concentrations were significantly correlated with altered diatom community structure, decreased percent low P diatoms and diatoms sensitive to impervious cover, and increased percent high P diatoms, diatoms that increase with greater impervious cover, and chlorophyll *a* ($P < 0.01$). Variance partitioning models showed that shared effects of anthropogenic land cover and chemistry (i.e., chemistry affected by land cover) represented the majority of explained variation in diatom metrics and chlorophyll *a*. Bootstrapped regression trees, threshold indicator taxa analysis, and boosted regression trees identified TP concentrations at which strong responses of diatom metrics and communities occurred, but these values varied among analyses. When considering ecological responses, scientifically defensible and ecologically relevant TP criteria were identified at (1) 0.020 mg/l for designating highest quality streams and restoration targets, above which sensitive taxa steeply declined, tolerant taxa increased, and community structure changed, (2) 0.040 mg/l, at which community level change points began to occur and sensitive diatoms were greatly reduced, (3) 0.065 mg/l, above which most sensitive diatoms were lost and tolerant diatoms steeply increased to their maxima, and (4) 0.082 mg/l, which appeared to be a saturated threshold, beyond which substantially altered community structure was sustained. These criteria can inform anti-degradation policies for high quality streams, discharge permit decisions, and future strategies for watershed development and managment. Our results indicated that management practices and decisions at the watershed scale will likely be important for improving degraded streams and conserving high quality streams. Results also emphasized the importance of incorporating ecological responses and considering the body of evidence from multiple conceptual approaches and statistical analyses for developing nutrient criteria, because solely relying on one approach could lead to misdirected decisions and resources.

1. Introduction

Cultural eutrophication of streams, largely a result of nonpoint sources of phosphorus and nitrogen, continues to be a leading cause of stream impairment throughout the United States and around the world (Carpenter et al., 1998; Dodds et al., 2002; USEPA, 2002; MEA, 2005). Urbanization and agricultural activities are common sources of elevated nitrogen and phosphorus, which are expected to continue increasing in the coming decades due to growing populations, further development, and greater demand for food production (Carpenter et al., 1998; MEA, 2005; Duan et al., 2012). Elevated loads of nutrients to streams can negatively affect ecosystem structure and function by altering biological communities and food webs, increasing algal biomass, changing dissolved oxygen regimes, and altering rates of nutrient and carbon cycling (Meyer et al., 2005; Clapcott et al., 2010; Miltner, 2010). Ecological

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responses to excessive nutrient loads can contribute to economic losses and negatively affect human wellbeing as a result of lost biodiversity, reduced recreational opportunities, decreased property values, and increased health risks (Dodds et al., 2009). As a result, effective stream assessments and watershed management strategies based on defensible science are needed.

Several states and agencies are developing nutrient criteria to protect high quality waters, to prevent further degradation of aquatic resources, and to inform restoration efforts (Wang et al., 2007; Stevenson et al., 2008; Zheng et al., 2008; Smith and Tran, 2010). Initial guidance in the United States focused on using nutrient concentrations at the 75th percentile of reference sites or the 25th percentile of all sites within a region as criteria (USEPA, 1998, 2000a). Other ways to define criteria include modeling expected nutrient concentrations in the absence of human-modified land cover in watersheds (Dodds and Oakes, 2004) and establishing natural background nutrient concentrations (i.e., reference conditions; Smith et al., 2003). Percentiles help account for natural variability, establish baselines, and describe general trends, but nutrient concentrations representing percentiles of all sites could be affected by non-random or skewed percentages of land cover and be ineffective when applied at smaller spatial extents due to environmental heterogeneity (Dodds et al., 2002; Rohm et al., 2002; Smith et al., 2003). As a result, relying solely on percentile-based criteria could over- or under-protect streams, disregards ecological responses, and could potentially mislead management strategies.

Criteria based on ecological effects of nutrients are becoming increasingly common (Dodds, 2007; Wang et al., 2007; Smith and Tran, 2010). Characterizing relationships between nutrients and ecological effects is important to restoring and protecting aquatic life uses and ecosystem structure and functions. Algal communities are particularly useful for developing criteria for streams because they are the largest source of primary production, are important to ecosystem processes, and are strongly affected by nutrient concentrations (Biggs, 2000; Dodds et al., 2002). Altered community structure could contribute to changes in food webs, dissolved oxygen regimes (Miltner, 2010), rates of nutrient and carbon cycling (Cardinale, 2011; Cardinale et al., 2011), and esthetics (Suplee et al., 2009). Diatoms are highly effective indicators used in stream biomonitoring because they are ubiquitous, have high diversity, and respond strongly to nutrients (Potapova and Charles, 2007; Porter et al., 2008; Black et al., 2011). Stressor-response relationships between diatom metrics and nutrients can be used to communicate complex results to stakeholders and policymakers and to inform management decisions by determining concentrations that support or degrade valued ecological attributes.

Statistical analyses relating ecological responses to stressors support effects-based criteria. A variety of statistics have been used to define stressor-response relationships for deriving nutrient criteria, but comparisons of their results have been largely neglected. Differing results could lead to misdirected or ineffective management actions. Statistical methods that identify ecological change points have received increasing attention for creating nutrient criteria (King and Richardson, 2003; Stevenson et al., 2008; King and Baker, 2010). Depending on the analysis, well supported change points provide evidence of (1) ecological thresholds at which a large change, or a discontinuity, in a response variable (e.g., diatom metric) occurs across a small change in a predictor variable (e.g., phosphorus) or (2) a point along an environmental gradient at which a response rate or pattern changes. Considering the weight-of-evidence and appropriateness of multiple analyses (change point and non-change point statistics) can provide robust results that benefit stream monitoring and management efforts.

Our goals were to relate anthropogenic increases in total phosphorus (TP) concentrations to changes in benthic algal communities and to inform future efforts to develop effects-based nutrient criteria. To address these goals, we (1) first developed concentration-based nutrient criteria for streams using land cover regression models and percentiles of TP concentrations at all sites, (2) related the effects of nutrients on diatoms to urban land cover, (3) characterized the ecological relevance of these TP-based criteria to algal biomass and diatom communities by documenting stressor-response relationships using multiple statistical analyses, and lastly, (4) we used these stressor–response relationships to establish more refined, ecologically relevant TP criteria (similar to a biological condition gradient; Davies and Jackson, 2006). We focused on TP because it was most strongly related to metrics and likely regulated algal communities. Our results can help inform strategies for developing nutrient criteria in other regions or countries and provide support for implementing protective and restorative actions for streams and watersheds.

2. Methods

2.1. Study sites and sampling

Sampling was conducted throughout the State of Connecticut, which has a total land area of approximately 13,000 km^2 and encompasses approximately 9334 km of rivers and streams at the 1:100,000 map scale (State of Connecticut, 2006). Connecticut is located in the northeastern United States and has four primary physiographic regions (Bell, 1985). The central valley is a flat low lying area in the middle of the state that extends south from the northern bordering state Massachusetts to Long Island Sound estuary. The coastal region extends along the southern boundary of Connecticut. The eastern uplands and western uplands are characterized by rolling hills with higher elevations than the central valley and coastal region. Urban development patterns are most dense through the central valley and along the southwestern coastal region, while large parts of the eastern and western uplands are primarily forested (Fig. 1). The climate in Connecticut has four seasons with a mean annual precipitation of 114 cm that is distributed fairly evenly throughout the year (Miller et al., 2002).

During July to September 2002–2004, 87 stream sites distributed throughout Connecticut were sampled for benthic algae and water chemistry by the Connecticut Department of Energy and Environmental Protection (Fig. 1). Sites were selected using an integrated approach that combined probabilistic and targeted monitoring. An integrated approach can provide a more complete assessment of conditions to support water quality management (Stein and Bernstein, 2008). Of the 87 sites, 61 were selected using a probabilistic sampling design and 26 selected using a more targeted approach. At each site, 15 rocks were selected every 10 m throughout a 150 m stream reach in riffle and run areas. Algae were removed from within a 5.1 cm^2 area on each rock and composited into one sample. 5 ml of the algal sample was filtered onto a 47 mm glass fiber filter for chlorophyll *a* analysis. The remaining sample was preserved and sent to a laboratory for diatom taxonomic identification. Diatom samples were processed using acid to remove organic material before mounting on slides using NAPHRAX^{TM}. Diatoms were identified to the lowest practical taxonomic level, typically species, and at least 600 valves were enumerated. The chlorophyll *a* samples were frozen and sent to a separate lab for quantification using EPA fluorometric method 445.0/AERP 12 and a Turner Design Fluorometer TD-700.

At each site, a surface water chemistry sample was collected. Nitrogen was determined as $NO_2 + NO_3$ (subsequently referred to as NO_x) using a cadmium reduction technique and an autoanalyzer for colorimetric measurements (EPA method 353.2). Total phosphorus was determined using the colorimetric EPA methods 365.1 and 365.4, which used persulfate and acid digestion. EPA method 300.1