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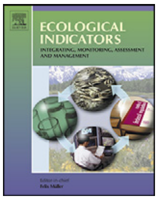

Reference diatom assemblage response to restoration of an acid mine drainage stream

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ABSTRACT

A prevalent legacy of coal mining within Appalachia and elsewhere is acid mine drainage (AMD), which drastically alters both the chemical and biological components of the receiving waters. Hewett Fork is one such affected stream. Although AMD treatment has reduced acidity considerably downstream, the ability of this stream to sustain a biological community compared to those found in reference conditions remains unclear. To assess this, tiles colonized with diatom assemblages from a reference stream were transplanted into Hewett Fork in 5 locations along a 6.9 km stream length and sampled after one, three, and six weeks. Diatom assemblage structure metrics, including species evenness (J'), species richness (S), relative abundance of dominant taxon, and Shannon diversity (H'), as well as chlorophyll *a* concentrations, Bray–Curtis dissimilarities, and Acid Mine Drainage Diatom Index of Biotic Integrity (AMD-DIBI) scores were calculated for each site and sampling time. One-way ANOVAs of structural metrics showed significant differences ($P \leq 0.001$) between the reference site and the 2nd and 3rd most upstream sites within the study reach for the duration of the study, with the exception of the relative abundance of dominant taxa at an intermediate site during the third week. Conversely, the most downstream Hewett Fork assemblage, located 11.6 km from the primary AMD input, did not differ significantly ($P > 0.05$) from that of the reference assemblage for any structural metrics after the initial sampling period. Throughout the study, only three sites obtained "good" AMD-DIBI narrative class:the reference site (weeks 1, 3, and 6), the most downstream site (weeks 1, 3, and 6; 11.6 km downstream of primary AMD input) and the uppermost site (weeks 1 and 6; 4.7 km downstream of primary AMD input). Results suggested that after an initial one-week acclimation period, assemblages at the uppermost and most downstream sites along the reach were relatively similar to those found in reference conditions, while sites within the middle region continued to show signs of impairment, although the factor(s) causing this impairment remain unknown. These findings suggest that while treatment has been effective on a site-specific basis, the expected linear-response to treatment was not achieved due to underlying factors that are inhibiting reference-like biological communities from reestablishing within the affected stream reach.

1. Introduction

Acid mine drainage (AMD) is a prevalent legacy of coal and mineral extraction operations across North America, as well as throughout much of the world (Johnson, 2003). Within the Western Allegheny Plateau (WAP) ecoregion of the United States, AMD affects an estimated 2092 stream km in Ohio alone (Omernik, 1987; Ohio Environmental Protection Agency [OEPA], 2000; Farley and Ziemkiewicz, 2005). Occurrences of AMD are the result of a series of oxidation reactions in which remnant sulfur-rich minerals, commonly associated with coal seams, are exposed to oxygen, sulfidogenic bacteria, and water, all flowing through (often abandoned) mine complexes or over mine tailings, culminating in a highly acidic, metal-rich effluent (Warner, 1971).

AMD seeps have a detrimental impact on aquatic ecosystems, drastically altering the chemical and biological characteristics of the receiving waters (Parsons, 1977; McKnight and Feder, 1984; Johnson, 2003). Elevated H_2SO_4 concentrations are responsible for diminishing stream pH, thereby increasing soluble metal cation concentrations and conductivity (Filipek et al., 1987; Sabater et al., 2003; Bray et al., 2008). As the acidity associated with AMD is neutralized through the dilution of H_2SO_4, the previously dissolved metals form metal oxide precipitates (most commonly $Fe(OH)_3$) which coat the substratum, greatly reducing habitat availability for fish, macroinvertebrates, and periphyton (McKnight and Feder, 1984; Niyogi et al., 2002; Lear et al., 2009).

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Ultimately, AMD-related alterations to stream chemistry and physical habitat contribute to the decline of biotic integrity within the impacted stream. Acidity (Gerhardt et al., 2004; Lear et al., 2009), metal solubility/re-deposition (Niyogi et al., 2001; Sabater et al., 2003; Butler, 2009), and the resulting multi-level trophic disruption have adverse effects on the biological assemblages (i.e. bacteria, algae, macroinvertebrates, and fish) and their functionality within the affected stream (Niyogi et al., 2002; Bray et al., 2008; Simon et al., 2009; Smucker and Vis, 2011a, b). Bacterial and algal components of biofilms may experience phosphorus (P) limitation due to P sorption to iron, thereby limiting P retention in affected streams (Smucker and Vis, 2011a, b). Furthermore, deposition of metal oxides upon dilution of associated acidity may decrease bacterial respiration rates as well as the effectiveness of these communities to decompose leaf litter, further reducing the available nutrient pool in the impacted stream (Niyogi et al., 2001; Simon et al., 2009). Increased osmotic pressure due to higher conductivity can affect diatom growth rates and nutrient uptake (Potapova and Charles, 2003). Periphyton community structure becomes altered due to the replacement of acid/metal sensitive species with more tolerant taxa, resulting in decreased biological diversity in primary producers (Lampkin and Sommerfeld, 1982; Verb and Vis, 2000; Niyogi et al., 2002).

While previous reclamation efforts have primarily concentrated on alleviating the impacts of AMD on water chemistry, the ever-growing body of literature acknowledging the link between species diversity and overall ecosystem functionality has shifted the focus of restoration towards a more holistic, ecological approach (Karr, 1991; Battaglia et al., 2005; Dodds et al., 2008; Sabater and Stevenson, 2010). Recent studies have observed significant losses in ecosystem functionality with a decrease in species diversity, indicating that measures of species diversity in and of itself may therefore be an effective means of assessing ecosystem health (Benayas et al., 2009; Cardinale et al., 2011). Moreover, given the chemical variability of natural and impaired waters, assessing the biological components of an ecosystem can provide greater insight into the longer-term impacts that stressors may have on an ecosystem (Karr, 1981).

Diatoms, a species-rich group of microscopic algae that are ubiquitous in aquatic habitats, have become widely recognized as a highly effective means of assessing aquatic health (Lowe and Pan, 1996; Stevenson and Pan, 1999; Hill et al., 2000). Diatoms are exceptional bioindicators due to their strong relationship to stream chemistry, their rapid rate of reproduction, and their role in trophic dynamics (Mayer and Likens, 1987; Stevenson and Pan, 1999; Shieh et al., 2002; Hirst et al., 2004). Successional assemblage development (from adnate, to erect, and finally, to stalked growth forms) allows for biofilm maturity to be assessed, such that structural components of assemblages, based on growth form abundances, can aid in evaluating assemblage maturity (Hoagland et al., 1982). In conjunction with known species-specific tolerances for an array of environmental variables, diatom assemblages can provide significant insight into stream health, allowing for quantification of site quality based on the taxa present (Lowe, 1974; van Dam, 1982; Dixit et al., 1992; Potapova and Charles, 2002). Finally, the development of diatom indices of stream health has further added to the relevance of diatoms as a biomonitoring tool (Hill et al., 2000; Wang et al., 2005). Zalack et al. (2010) proposed the AMD-DIBI, an index specifically designed for assessment of stream health along an AMD gradient. This index was also used effectively in streams receiving treatment for AMD (Pool, 2010).

Since diatom communities are readily used as indicators of water quality and ecological health, and specific indices have been developed, they seem to be well suited to assess stream restoration. The purpose of this research was to examine the effects of AMD remediation on diatom assemblages along a treatment gradient as a means of assessing the ability of treated sites to provide habitats for assemblages indicative of the targeted habitat quality of the restoration project. In order to examine treatment effectiveness, this project was divided into two objectives: (1) to determine the efficacy of an AMD restoration project on a stream's ability to sustain transplanted reference diatom assemblages, and (2) to compare the diatom assemblage structure of a reference assemblage to assemblages from a stream reach receiving treatment for AMD.

2. Materials and methods

2.1. Site description

Hewett Fork is fourth-order stream in the Hocking River watershed and drains approximately 105 km^2 of predominantly forested landscape (70–75%) within the Western Allegheny Plateau (WAP) Level III Ecoregion in southeastern Ohio (Rice et al., 2002). Within Hewett Fork, a number of AMD inputs have been identified. The primary input of AMD occurs at two seeps near river km 17.7, the site of the abandoned Rice Hocking underground mine (HF131) (Farley et al., 2004) (Fig. 1). Two additional AMD inputs are located further downstream, one at the confluence of Hewett Fork with Carbondale Creek (HF190), and the other at the confluence of Hewett Fork and Trace Run (HF120), both occurring near river km 16.1 (Fig. 1). The cumulative effects of these seeps have dramatically diminished the stream quality for the length of the Hewett Fork, resulting in the stream receiving a limited resource water – acid mine drainage (LRW-AMD) designation from the Ohio Environmental Protection Agency (OEPA) (OEPA, 1997b). The LRW-AMD designation is assigned to streams in which biological communities are comprised of species tolerant of AMD conditions, specifically lowered pH and increased metal concentrations (OEPA, 1997b).

In 2004, the Ohio Department of Natural Resources Division of Mines and Reclamation placed an Aqua-Fix® calcium oxide (CaO) doser and a concrete mixing channel at HF131 to actively treat the principle source of AMD pollution. The doser and subsequent mixing channel continuously introduce alkaline materials into the mine waste stream prior to its confluence with Hewett Fork, allowing for an immediate buffering of the AMD. While this alkaline addition has substantially increased the pH downstream of the doser, including an increase in the buffering capacity at both HF120 and HF190 (Farley et al., 2004), the concomitant metal precipitation associated with this pH shift has resulted in a "sacrifice" zone; i.e. a length of stream extending approximately 1.6 km downstream from the treatment site, in which the precipitation of metal oxides inhibits localized biotic recovery in order to facilitate recovery further downstream (McKnight and Feder, 1984; Farley et al., 2004; Bray et al., 2008; Borch, 2010).

The specific study area within Hewett Fork consisted of five sites (Fig. 1) within a putative transition zone from poor to good habitat quality for fish, macroinvertebrates, and diatoms along an AMD treatment gradient (Farley et al., 2004; Bowman, 2010; Pool, 2010). Three of these sites, river km 13.4 (HF090; 4.7 km from the doser), km 10.3 (HF060; 7.7 km from the doser), and km 6.4 (HF039; 11.6 km from the doser), have been given designations of "impaired," "intermediate," and "good," respectively based on their biological (fish and macroinvertebrates) and chemical characteristics (Bowman, 2010). To better study the biological and chemical aspects of this reach, two additional sites were established summer 2010, one between river km 11.9 and km 11.6 (HF075; 5.9 km from the doser), and the other at river km 8.1 (HF045; 9.6 km from the doser), to allow for finer scale monitoring of the AMD treatment gradient (Fig. 1).