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Using diatoms to assess river restoration: A pilot study in Whychus Creek, Oregon, USA

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Abstract
A primary goal of river restoration is to reestablish lost ecological functions. Yet the impact of restoration on diatom assemblages and algal biomass in a stream is rarely addressed in the scientific literature reporting the outcomes of restoration projects aimed at improving riverine habitat. To investigate the potential for using benthic diatoms as indicators of the benefits to habitat associated with river restoration, we conducted a pilot diatom study in Whychus Creek, a headwater tributary of the Deschutes River in Oregon, USA. As part of a work study project for college students, we collected periphyton samples in a restored reach, a restored transition reach and an unrestored reach (control) and compared diatom assemblages and algae biomass of these reaches. Diatom assemblages and traits differed substantially between the control and restored reaches and the median percentage of chlorophyll a in the periphyton biomass increased from 9% in the control reach to 12% in the restored reach. The results of this pilot study suggest that benthic diatom assemblage may be useful indicators of river restoration success, particularly for approaches that aim to reconfigure channels and increase floodplain connectivity and habitat complexity.

KEYWORDS
chlorophyll a, diatom traits, diatoms, river restoration, stream function

1 | INTRODUCTION

River restoration seeks to reinstate impaired stream functions, forms and habitats (Geist & Hawkins, 2016; Johnson et al., 2019) often with the aim of aiding the recovery of a particular riverine species that has been driven close to extinction by alteration of the river environment. However, due to the cost, the biological outcomes of most restoration projects are not monitored and there is a well-documented need for basic information about the effect of restoration on target species (Bernhardt et al., 2007; Katz, Barnas, Hicks, Cowen, & Jenkinson, 2007; Palmer, Menninger, & Bernhardt, 2010). Despite their potential as an indicator in stream bioassessment, few studies have investigated the use of diatoms to monitor the benefits of river restoration efforts aimed at increasing habitat diversity.

The autotrophic base of a food web in a stream with an open canopy is comprised of benthic algae living in a matrix called the periphyton. The periphyton consists of algae, bacteria and microbes that live on the surface of rocks and other substrates in the stream bed. Diatoms, single-celled algae with silica cell walls, are frequently used as indicators in stream biomonitoring (Stevenson, Pan & van Dam, 2010). Benthic diatoms are particularly well suited for evaluating river restoration because they rapidly colonize surfaces that are exposed following a disturbance to the stream bed; they represent the main source of primary production and are known to reflect important stream processes such as groundwater flow, sediment transport and nutrient cycling (Stevenson, Pan & van Dam, 2010). Given their potential as indicators of habitat change, it is our hypothesis that diatoms may be useful for monitoring change in ecological function of a river due to restoration.
To establish how this hypothesis might be used in a full-scale investigation, we conducted a pilot study in which academic researchers and students participating in a work study placement with the Upper Deschutes Watershed Council collected benthic diatom samples in unrestored (control), transition (recently restored) and fully restored reaches of Whychus Creek. In this technical note, we present and interpret the results of this pilot study, comment on their significance for evaluating river restoration and outline plans for further investigations.

2 | METHODOLOGY

2.1 | Study site description and restoration approach

Whychus Creek is a fourth-order tributary of the Deschutes River in central Oregon, USA (Figure 1). Approximately one-third the length of the stream is located in conservation easement or designated wilderness, with the remaining two-thirds flowing through National Forest or private lands. The stream water chemistry of Whychus Creek reflects its natural setting and has relatively little solutes, low conductivity (51 μS/cm), low dissolved inorganic nitrogen concentration (<0.01 mg/L) and relatively high orthophosphate due to its volcanic geology (0.095 mg/L; AWQMS 2019). Historically, Whychus Creek supported populations of native salmonids but the creek has been adversely affected by water abstraction for irrigation and loss of habitat due to extensive channelization and straightening (Bartlett, 2013). Current restoration efforts on Whychus Creek involve restoring streamflow, increasing habitat diversity and reconnecting historic wetland, riparian and floodplain habitats. The aim of the restoration is to return the creek to its pre-disturbance state, which is known as “Stage Zero” in the stream evolution model (Cluer & Thorne, 2014). This involves removing artificial levees and other anthropogenically raised sediment structures in the floodplain and using sediment to fill in the incised channel. Rewetting the floodplain and its wetlands then reactivates relict networks of anabranching and anastomosed channels, thereby reconnecting the full stream, wetlands and floodplain habitats (Meyer, 2018).

2.2 | Field sampling and laboratory analyses

Diatom data were collected from three reaches of Whychus Creek (Figure 1). The upstream restored reach was restored in 2012. The control reach was unrestored and located about seven kilometres downstream. The transition reach was restored in 2016 and was located furthest downstream. Our selection of restored and control reaches was constrained by the restoration design and our assumption was that the restored reach was far enough away to have no impact on the...
control and transition reaches downstream. We surveyed stream habitats in the study reaches using standard survey protocols (Moore, Jones, Dambacher, & Stein, 2017). Five hundred metres of sub-reaches were surveyed in the control and restored reaches, while in the transition reach, four 125 m sub-reaches were surveyed to capture the wider range of stream morphologies present in the transition reach (Figure 2). We categorized and mapped stream habitat types using the classifications provided by Moore et al. (2017). To characterize the habitat structure in each reach, we categorized habitat units within each study reach as riffles, in-channel pools or off-channel ponds (isolated pools and puddles). Other stream habitats in Whychus Creek included step/cobble, rapid/boulder, cascade/boulder and dry units.

**FIGURE 2** Aerial images of the (a) control, (b) transition and (c) restored reaches in Whychus Creek. Aerials provided by the Upper Deschutes Watershed Council [Color figure can be viewed at wileyonlinelibrary.com]
In August 2018, we sampled periphyton from five riffles in each reach and one off-channel habitat (restored reach) using standard methods (Baird, Eaton & Rice, 2017; Kelly et al., 1998). At each sample location, we used a toothbrush to scrub the periphyton off five randomly selected cobbles, rinsed the cobbles with distilled water and composited them into a single sample, which we then split into three subsamples. One subsample was preserved in 37% formalin for diatom composition analysis, while two unpreserved subsamples were composited into a single sample, which we then split into three randomly selected cobbles, rinsed the cobbles with distilled water and composited them to the genus level. We estimated the Chl \( a \) per unit organic biomass of the periphyton by calculating the percentage of Chl \( a \) in the periphyton AFDM (\% Chl \( a \)), which allowed us to characterize the proportion of the algae biomass in the periphyton.

2.3 | Data analysis

We analysed diatom data using non-metric multidimensional scaling (NMDS) to reveal differences in the diatom assemblages and by comparing diatom traits and \% Chl \( a \) across the three study reaches. NMDS displays the diatom assemblage of each sample in two-dimensional space, which can be viewed as a “map” wherein points (i.e., diatom assemblages) that are closer together have more similar assemblages than points that are further apart. To better understand the stream processes operating at each reach, we examined diatom traits. Based on the expected effects of the restoration on Whychus Creek, we classified diatoms as \% cold-water diatoms, \% nitrogen fixers and \% sediment tolerant taxa (Stevenson & Bahls 1999; van Dam, Mertens & Sinkeldam, 1994). Due to small sample sizes, we did not test the statistical significance of differences between samples. The data used in this study are available in the supplementary materials.

3 | RESULTS

3.1 | Stream habitat characteristics

The proportion of riffles, in-channel pools and off-channel ponds varied amongst the three study reaches (Table 1). Riffles were the dominant feature in the control reach representing more than 90% of the surveyed stream habitat. Riffles were also the dominant habitat in the restored and transition reaches; however, pools were more abundant in the restored and transition reaches. Off-channel ponds were only present in the transition and restored reaches and represented less than 5% of the stream habitat surveyed.

3.2 | Diatom assemblages

The ordinations revealed that each reach contained a different diatom assemblage. NMDS axis 1 represents variability in diatom assemblage between reaches, while NMDS axis 2 represents the within-reach variability of diatom assemblage (Figure 3a). In general, diatom assemblages of each reach were more similar than the assemblage between habitat types, with the exception of the pond sample, which had a distinctive diatom assemblage (Figure 3b).

In the control reach, the most common diatoms were *Epithemia*, *Cocconeis* and *Navicula*. In the transition reach, the most common diatoms were *Gomphonema*, *Navicula* and *Cymbella*. The off-channel pond sample in the restored reach contained a distinctly different diatom assemblage, primarily due to the increased presence of *Achnanthidium* and *Diatoma* and reduced abundance of *Cymbella* and *Synedra*.

3.3 | Chlorophyll \( a \) and diatom traits

The median \% Chl \( a \) in the periphyton ranged from 7 to 38%, with the highest value observed in the off-channel pond. The median \% Chl \( a \) in the periphyton increased from 9% in the control reach to 12% in the restored reaches (Figure 4a), primarily driven by the off-channel pond sample and a shallow, braided riffle sample in the transition reach.

Diatom traits and \% Chl \( a \) varied between reaches, with more sediment-tolerant diatoms in the restored reach and more nitrogen fixing diatoms in the control reach. Cold-water diatoms were uncommon in all reaches (<5%) but were slightly more abundant in the restored reach. The off-channel pond contained the highest percentage of cold-water diatoms (Figure 4b). Nitrogen fixers decreased from a median of 27% in the control reach to less than 1% in the restored reach (Figure 4c). Sediment tolerant diatoms increased from a median of 48% in the control reach to 74% in the restored reach (Figure 4d).

### Table 1

<table>
<thead>
<tr>
<th>Reach</th>
<th>Number of habitat units surveyed</th>
<th>Total area surveyed (m²)</th>
<th>Number of habitat subunit types</th>
<th>Riffle area (m²) (%)</th>
<th>Pool area (m²) (%)</th>
<th>Off-Channel pond area (m²) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>11</td>
<td>4,062</td>
<td>4</td>
<td>3,719 (92%)</td>
<td>317 (8%)</td>
<td>0</td>
</tr>
<tr>
<td>Transition</td>
<td>60</td>
<td>12,878</td>
<td>10</td>
<td>7,750 (60%)</td>
<td>3,933 (31%)</td>
<td>350 (3%)</td>
</tr>
<tr>
<td>Restored</td>
<td>169</td>
<td>27,032</td>
<td>14</td>
<td>8,082 (30%)</td>
<td>14,216 (53%)</td>
<td>476 (2%)</td>
</tr>
</tbody>
</table>
DISCUSSION

One of the main goals of restoration is to increase stream productivity, but few studies have addressed the effect of restoration on the algal base of a stream food web. In this pilot study, diatom assemblages and traits varied substantially between the control and restored reaches of Whychus Creek, suggesting that physical habitat characteristics of these reaches are different. This was confirmed by the habitat

FIGURE 3  Ordinations of diatom assemblages plotted by (a) reach and (b) habitat type in Whychus Creek. Habitat abbreviations: riffle (rfle), glide (glde), glide with filamentous algae (glde.fil.algae), braided riffle (braid.rfle), off-channel pond (side. pond)

FIGURE 4  Percentage chlorophyll a in the periphyton biomass (a) and relative abundance of select diatom traits for the study reaches at Whychus Creek (b–d)
survey data which showed that the restored reach appears to have a more complex physical habitat than the control reach. Increased habitat complexity is known to alter stream functions by reducing stream velocity, increasing coarse wood retention and boosting nutrient uptake (Roberts, Mulholland, & Houser, 2007). In the restored reach, we observed more cold-water diatoms and sediment-tolerant motile diatoms than in the control reach, possibly due to increased groundwater connectivity and increased fine-sediment deposition associated with slower velocities in the restored reach. In a study of urban streams in China, the association of motile sediment-tolerant diatoms and restoration condition was also observed (Chen et al. 2019). We also documented a unique diatom assemblage in the off-channel pond. This finding illustrates the importance of small-scale habitat features present in anabranchled and anastomosed stream channels that are fully connected to their floodplains.

The % Chl α in the periphyton appeared to be slightly higher in the restored and transition reaches, mostly due to samples from a shallow, braided riffle and the off-channel pond. There are several possible explanations for the higher % Chl α observed in the restored reach. First, restoration may have increased the input and retention of organic material from the riparian zone or disturbance during restoration construction may have temporarily released organic matter. However, construction in the restored reach was completed 6 years prior to this study and it is unlikely that construction disturbance is the sole explanation for the observed increased % Chl α in the restored reach. Regardless of the cause, increased decomposition of organic matter retained in the restored reach would increase the availability of inorganic nitrogen. A second possible explanation for the observed increase in algal biomass may be related to a stream process known as nutrient spiralling (Webster, Newbold & Lin, 2016). In Whychus Creek, restoration may have affected both the retention and availability of nutrients; thereby reducing the uptake length of the nutrient spiral and increasing primary productivity. Finally, the geomorphic characteristics of the restored reach of Whychus Creek may have increased nutrient inputs through hyporheic exchange (Kasahara & Wondzell, 2003). These findings highlight the importance of stream habitat features that are associated with hyporheic upwelling, such as off-channel ponds and shallow, braided riffles.

We acknowledge that it would have been ideal to identify diatoms to species; however, we wanted to pilot a study using low-cost methods. In many restoration projects, most of the funds are used for the restoration construction and few funds are dedicated for post-restoration monitoring and bioassessment (Rumps et al. 2007). Collection and identification of biotic data can be cost prohibitive for many restoration projects and one way to reduce monitoring costs is to use volunteers to collect field samples (Edwards, Shaloum & Bedell, 2018) and/or use taxonomically coarse biotic data. In the case of diatom-based stream bioassessments, there are several studies that show genus and species-level diatoms provide similar information about stream condition (e.g., Rimet & Bouchez 2012). Until more funding is available, we may need to rely on low-cost interdisciplinary approaches such as community-based science or educational programmes for generating biologic data for use in restoration monitoring and bioassessment.

Despite the fact that the scope of our pilot study was limited to genus-level identifications, a small sample size that did not include all stream habitats and a lack of true replications for the treatment effect (i.e., restoration), our findings provide valuable insights that can inform how more comprehensive studies could be conducted in the future. First, a multi-habitat sampling design would allow for better characterization of the range of habitats created by restoration. These habitats would not be represented in a riffle-only sampling design, which is typically used in diatom-based bioassessments. Second, the restoration of Whychus Creek may have prompted reestablishment of the creek’s natural functions resulting in a larger areal footprint of the stream, increased in-channel complexity and reconnection of the stream to its floodplain. Slowing the flow and increasing stream area in itself represent a mechanism for increasing stream productivity through restoration, even without the associated increase in primary production per unit area. Finally, the off-channel pond had a distinct diatom assemblage and much higher biomass than we observed in the riffle habitats. These findings suggest that floodplain ponds and other types of off-channel habitat may become local-scale “hot spots” of primary productivity while also providing habitat refugia for cold water and sediment-tolerant diatoms.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

DATA AVAILABILITY STATEMENT
The authors confirm that the data supporting the findings of this study are available within the Supporting Information.

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