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The Biological Sediment Tolerance Index: Assessing fine sediments conditions in Oregon streams using macroinvertebrates

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ABSTRACT

Fine sediments in excess of natural background conditions are one of most globally common causes of stream degradation, with well documented impacts on aquatic communities. The lack of agreement on methods for monitoring fine sediments makes it difficult to share data, limiting assessments of stream conditions across jurisdictions. We present a model that circumvents these limitations by inferring fine sediments in Oregon streams through sampling of macroinvertebrates. Tolerances to fine sediments (<0.06 mm diameter) were calculated for 240 macroinvertebrate taxa, from a calibration dataset of 446 sites across Oregon, as well as an independent validation dataset of 50 samples. Weighted averaging methods were used to infer fine sediment levels in streams by weighting the tolerances of modeled taxa observed in a sample by their abundances. The final model, the Biological Sediment Tolerance Index (BSTI), showed a strong relationship to measured fine sediments (calibration $r^2 = 0.49$, validation $r^2 = 0.58$). Root-mean-squared-error was small in the calibration dataset (2% fines), but larger in the validation dataset (14% fines). Repeatability was assessed by examining variability in BSTI at 14 sites across Oregon. Because field methods for sampling macroinvertebrates are standardized across resource agencies in Oregon and the responses of macroinvertebrates represent the actual effects of fine sediments on stream ecosystems, the BSTI may offer water resource managers' a cost-effective method for assessing fine sediment conditions in their ongoing efforts to improve water quality across the state.

1. Introduction

Excess fine sediments are a leading cause of stream impairments across the world, frequently associated with biological impairments of stream ecosystems (Chutter, 1969; Ryan, 1991; Fossati et al., 2001; Paulsen et al., 2008). Effects from excess sedimentation are known to result in impairments to all levels of stream communities (Wood and Armitage, 1997; Suttle et al., 2004; Jensen et al., 2009; Jones et al., 2012). In the Pacific Northwest (PNW) region of the United States, these impairments have been directly related to declines in culturally and economically important salmon populations. For example, altered sediment regimes were identified as a high stress factor in 31 out of 40 Southern Oregon/Northern California coho salmon populations (NMFS, 2014), with impacts most frequently greater on the earliest life stages (Suttle et al., 2004; Jensen et al., 2009). While it is generally accepted that excess fine sediments may alter ecosystem function, based on both field (Von Bertrab et al., 2013) and experimental studies (Mathers et al., 2014; Jones et al., 2015), agreement on how to measure fine sediments and what levels are protective of aquatic life remains elusive.

Many resource management agencies in Oregon have broad-scale monitoring programs in place to measure and quantify stream substrate composition, however, the ability to easily utilize that information across programs is limited due to differences in field protocols (Roper et al., 2010). Additionally, Oregon's water quality standards for sedimentation provide no guidance on monitoring sediment conditions, nor at what levels may produce impairments: "*The formation of appreciable bottom or sludge deposits or the formation of any organic or inorganic deposits deleterious to fish or other aquatic life or injurious to public health, recreation, or industry may not be allowed (Oregon Administrative Rule 340-041-0007-11).*" This lack of clarity from resource management agencies, in addition to

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complicated field methods, causes confusion in the public—making it difficult to engage citizen-based groups in monitoring sediment conditions. In periods of reduced monitoring budgets, the ability to combine data across resource management agencies or to boost sampling efforts through volunteer monitoring organizations would greatly improve our understanding of the impacts of fine sediments on Oregon's streams.

Biomonitoring of benthic macroinvertebrates offers a potential solution to these problems through stressor-response modeling of macroinvertebrates to fine sediments. Macroinvertebrates are the most widely used indicators of stream biological conditions (Rosenburg and Resh, 1993; Hering et al., 2004) and are commonly used to assess stream conditions at regional (Hawkins et al., 2000; Hargett et al., 2007), state (Ode et al., 2008) and national scales (Wright et al., 1993; Smith et al., 1999; Paulsen et al., 2008). Due to their high taxonomic diversity, central position in stream ecosystem food-webs, and varied feeding strategies and habitat requirements, macroinvertebrates are effective indicators of biological conditions. Furthermore, the relatively longer life-cycles (from several months to several years) of macroinvertebrates integrate stream conditions through time (Hawkes, 1979; Cairns and Pratt, 1993; Hodkinson and Jackson, 2005).

Macroinvertebrate monitoring offers several advantages to monitoring fine sediments alone. First, macroinvertebrate field sampling methods have been standardized among the major PNW monitoring programs since the early 2000s (Hayslip, 2007), allowing for ease of transfer of comparable data among programs. Second, macroinvertebrate taxonomists in the PNW routinely work collaboratively to increase similarity in taxonomic information across laboratories (PNAMP, 2015). Another advantage provided by macroinvertebrate monitoring is public engagement. Macroinvertebrate field collection methods are relatively simple and easy to train to novices, and as long as taxonomic identification is standardized can show a high degree of similarity between professional and non-professional samples (Fore et al., 2001; Engel and Voshell, 2002). Finally, macroinvertebrate sampling offers a more cost-effective way of assessing stream ecological conditions than by monitoring for a single stressor. While monitoring for instream fine sediments alone may indicate a potentially impaired system, it is particularly useful to understand whether or not excess fine sediments are resulting in actual impairments to the community of organisms that we are trying to protect. Macroinvertebrate diagnostic indices have been developed for temperature (Yuan, 2007), stream acidity (Hamalainen and Huttunen, 1996; Larsen et al., 1996), and fine sediments (Extence et al., 2013; Relyea et al., 2012). Thus, the true cost-effective nature of biomonitoring can be realized when we integrate a suite of diagnostic indexes capable of identifying multiple potential causes of biological impairments, while requiring a single sample (e.g., Chessman and McEvoy, 1998). This last step requires thorough knowledge of individual taxonomic responses to a given stressor, such as we present here with fine sediments.

Macroinvertebrates may be strongly influenced by excess fine sediments (McClelland and Brusven, 1980; Lemly, 1982; Wood and Armitage, 1997). Responses to fine sediments are often taxon-specific, with effects observed on survival (Strand and Merritt, 1997), burial (Wood et al., 2005), egg hatching success (Kefford et al., 2010), growth (Kent and Stelzer, 2008), feeding (Hornig and Brusven, 1986), and relative abundance and richness (Angradi, 1999; Kaller and Hartman, 2004). Analyzing taxon-specific responses, or tolerances, to fine sediments allows for the creation of a diagnostic index to identify for a specific cause of impairment.

In the field of bioassessment, the term tolerance is often used to reflect taxon-specific responses to environmental gradients potentially altered by human activities (Yuan, 2004). There has been a recent movement to develop more rigorous and quantitative tolerance designations for individual taxa at various spatial scales. Carlisle et al. (2007) examined macroinvertebrate genera and families throughout the United States (US), developing tolerances to ions, nutrients, temperature, and both suspended and bedded fine sediments. Yuan (2004) determined tolerances to pH, nutrients, sulfate, and stream habitat within the Mid-Atlantic region of the US. Tolerances for land-cover (e.g., % forested) were developed for macroinvertebrates in the PNW (Black et al., 2004). Relyea et al. (2012) quantified macroinvertebrate taxa responses to fine sediments, then developed an index based on classification of those tolerances into discrete classes. Taken further, tolerances (i.e., optima) across taxa can be adapted into an assemblage-level index to infer stressor levels.

There are various approaches used in modeling tolerances to environmental gradients from biological samples. The need for transparent and quantifiable methods in setting management goals has moved the science away from the long-time standard of expert opinion. A frequently used approach is to rank tolerances into discrete classes. For example Extence et al. (2013) used a traits-based approach to model linkages between fine sediments and morphological or physiological adaptations in macroinvertebrates. Relyea et al. ranked macroinvertebrate tolerances based on abundance percentiles across a fine sediment gradient. Multivariate ordination, followed by ranked tolerances was used by Murphy et al. (2015) for fine sediments and Carlisle et al. (2007) for multiple stressors. But for developing continuous tolerances, which arguably is a more objective approach, weighted averaging (WA) (ter Braak and Barendregt, 1986) is perhaps the most commonly used technique.

WA has been frequently used to make inferences of historical environmental gradients for diatoms in lentic systems (Ter Braak and van Dam, 1989; Birks et al., 1990; Hall and Smol, 1992). More recently, WA has been used to infer environmental gradients in streams for diatoms (Pan et al., 1996; Ponader et al., 2007) and macroinvertebrates (Hamalainen and Huttunen, 1996; Larsen et al., 1996; Yuan, 2007). Performance and bias in WA models are susceptible to the range and evenness of sampling along the environmental gradient (ter Braak and Looman, 1986; Yuan, 2005) and to covarying factors (Yuan, 2007). WA may be considered less rigorous than other methods of inferring environmental gradients, such as maximum likelihood (ML) (Ter Braak and van Dam, 1989; Yuan, 2007), WA partial-least-squares regression (WA-PLS) (Ter Braak and van Dam, 1989; Larsen et al., 1996; Birks, 1998), or Boosted Regression Trees (Juggins et al., 2015). However, WA frequently performs as well as other methods and offers a suitable alternative to more complex methods (Ter Braak and van Dam, 1989; Birks et al., 1990; Birks, 1998; Juggins et al., 2015).

Our primary objective was to develop a biological index for inferring fine sediment conditions in streams across Oregon. We expanded on prior studies by modeling macroinvertebrate tolerances to smaller substrate particle sizes (<0.06 mm) than were previously examined (<2 mm; Yuan, 2007; Relyea et al., 2012). First, we quantitatively defined taxon-specific responses of macroinvertebrates to fine sediments. Second, we used these taxa responses to infer fine sediment levels, based exclusively on a macroinvertebrate sample. Our goal is to generate an index, the Biological Sediment Tolerance Index (BSTI) which may be used as a cost-effective method for assessing fine sediment conditions in Oregon streams. We intend for the index to be used by a broad range of resource managers, such as government agencies with well-developed biological monitoring programs to citizen-based monitoring organizations with relatively minimal resources and experience.