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Development and Validation of an Aquatic Fine Sediment Biotic Index

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Abstract The Fine Sediment Biotic Index (FSBI) is a regional, stressor-specific biomonitoring index to assess fine sediment (<2 mm) impacts on macroinvertebrate communities in northwestern US streams. We examined previously collected data of benthic macroinvertebrate assemblages and substrate particle sizes for 1,139 streams spanning 16 western US Level III Ecoregions to determine macroinvertebrate sensitivity (mostly at species level) to fine sediment. We developed FSBI for four ecoregion groupings that include nine of the ecoregions. The grouping were: the Coast (Coast Range ecoregion) (136 streams), Northern Mountains (Cascades, N. Rockies, ID Batholith ecoregions) (428 streams), Rockies (Middle Rockies, Southern Rockies ecoregions) (199 streams), and Basin and Plains (Columbia Plateau, Snake River Basin, Northern Basin and Range ecoregions) (262 streams). We excluded rare taxa and taxa identified at coarse taxonomic levels, including Chironomidae. This reduced the 685 taxa from all data sets to 206. Of these 93 exhibited some sensitivity to fine sediment which we classified into four categories: extremely, very, moderately, and slightly sensitive; containing 11, 22, 30, and 30 taxa, respectively. Categories were weighted and a FSBI score calculated by summing the sensitive taxa found in a stream. There were no orders or families that were solely sensitive or resistant to fine sediment. Although, among the three orders commonly regarded as indicators of high water quality, the Plecoptera (5), Trichoptera (3), and Ephemeroptera (2) contained all but one of the species or species groups classified as extremely sensitive. Index validation with an independent data set of 255 streams found FSBI scores to accurately predict both high and low levels of measured fine sediment.

Keywords Fine sediment · Macroinvertebrates · Aquatic bioassessment · Sediment tolerance · PNW ecoregions

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Introduction

Excessive sedimentation is the most important cause of lotic ecosystem degradation in the United States in terms of stream distance impacted (USEPA 2000). This is a concern to environmental managers because increased inorganic sediment loads alter the natural biotic community (algae, macrophytes, invertebrates, and fishes) in streams (Tebo 1955; Cordone and Kelley 1961; Waters 1995; Wood and Armitage 1997; Kaller and Hartman 2004; Suttle and others 2004; Fudge and others 2008). Increased inorganic sediment loads, over quantities or frequencies that occur naturally, can influence the stream biota in a number of ways. Turbidity increased by sediments can reduce stream primary production by reducing photosynthesis, physically abrading algae and other plants, and preventing attachment of autotrophs to substrate surfaces (Van Nieuwenhuyse and LaPerriere 1986; Brookes 1986). Decreasing primary production can affect many other organisms in the stream food web (Izagirre and others 2009). Sedimentation has been shown to be a major factor in the loss of habitat for mussels worldwide (Poole and Downing 2004; Geist and Aueuswald 2007). Minshall (1984) examined the importance of substratum size to aquatic insects and found that substratum is a primary factor influencing the abundance and distribution of aquatic insects. Aquatic macroinvertebrates are adversely affected by habitat reduction and/or habitat change resulting in increased drift, lowered respiration capacity (by physically blocking gill surfaces or lowering dissolved oxygen concentrations), and reducing the efficiency of certain feeding activities especially filter feeding and visual predation (Lemly 1982; Waters 1995; Runde and Hellenthal 2000 a, b; Suren and Jowett 2001). Macroinvertebrate grazers are particularly affected as their food supply either is buried under sediments or diluted by increased inorganic sediment load thus increasing search time for food (Suren 2005; Kent and Stelzer 2008). Deposited sediments affect fish directly by smothering eggs in redds (Fudge and others 2008), altering spawning habitat, and reducing overwintering habitat for fry (Cordone and Kelley 1961), and, indirectly by altering invertebrate species composition, thereby decreasing abundance of preferred prey (Suttle and others 2004). Declines in salamander abundance also were seen with increases in fine sediment inputs (Lowe and Bolger 2002).

Impacts of natural and anthropogenic disturbances to aquatic ecosystems have been assessed with biomonitoring tools. Most U.S. states currently use biomonitoring in their water quality monitoring programs (Barbour and others 1999), with similar efforts in other countries (Furse and others 2006; Marchant and Norris 2006). Freshwater biomonitoring programs examine aquatic macroinvertebrates (primarily insects), algae (diatoms in particular), and fish. In addition other biotic groups like the post- parasitic stage of mussels have been found to be sensitive to fine sediment deposition (Österling and others 2010), thus offering potential as a tool to both evaluate condition and document changes. The use of various freshwater biota to monitor stream conditions is widespread, with a steady development of tools including those developed for specific stressors.

Macroinvertebrates were chosen for this study because they integrate conditions of the entire watershed. They represent an intermediate trophic level between aquatic primary producers (algae) and higher order consumers (fish) allowing one to infer conditions of upper and lower trophic levels. Algae are typically shorter-lived and respond to small disturbances; for example, a spate may reduce chlorophyll *a* levels dramatically while the invertebrates remain unchanged. Fish, on the other hand, are long-lived but may take longer to respond to non-point sources like increased fine sediment. Problems in biomonitoring also occur with fish because of their greater mobility and the possible need for permits if endangered fish reside in the stream. Consequently, some western U.S. states are banning widespread fish sampling to protect endangered salmonids. Currently in the United States, with the exception of endangered Mollusca, there are no sampling permits required for macroinvertebrates, so their use is widespread in biomonitoring protocols.

Bioassessments used by the United States Environmental Protection Agency (USEPA) and state governing bodies have continually evolved since the initiation of the USEPA national guidance Rapid Bioassessment Protocols (RBP) were instituted to monitor and address Clean Water Act legislation (Plafkin and others 1989). Traditional macroinvertebrate metrics (taxa richness, density, diversity, EPT (Ephemeroptera, Plecoptera, and Trichoptera) taxa, EPT/D (Diptera) ratio, etc.) initially were augmented by multimetric indices (such as the Hilsenhoff biotic index (HBI)) and various Indices of biotic integrity (IBI's) that incorporated several macroinvertebrate measures into a single score for a stream. Macroinvertebrate and stream modeling such as the River Invertebrate Prediction and Classification Scheme (RIVPACS) model and a variety of multivariate analyses (Karr 1981; Hilsenhoff 1987; Simpson and others 1996) followed. Each method of data analysis builds upon previous measures and several methods can be used concurrently. Most of these bioassessment methods do not consider specific pollutants, but treat all anthropogenic disturbance the same by identifying and enumerating all taxa within the community sampled to assess the overall health of a stream. However, individual species within the same community exhibit broadly differing ranges of tolerance to environmental disturbance (Resh and Unzicker 1975; Mangum and Winget 1991; Winget and Mangum 1991; Angradi 1999). Some species at a given site may remain unaffected by a particular disturbance, while others are negatively impacted. We used this fact to develop an index specific to fine sediment conditions to be used separately or in combination with traditional measures in assessing stream health.

Our objectives were to develop a stressor-specific index for fine inorganic sediment (clay, silt, and sand particles <2 mm in diameter) and to test the utility of the index. We chose 2 mm because most stream monitoring protocols use some form of a Wolman pebble count and we consider 2 mm the smallest size one can measure reliably using pebble count methods. The Fine Sediment Biotic Index (FSBI) we present was developed by first identifying macroinvertebrate taxa that are sensitive to fine sediment from data sets across the Pacific Northwest (PNW) that included both macroinvertebrates and fine sediment data. Second, we tested the efficacy and reliability of the FSBI on a randomly selected group of streams.

Material and Methods

Data Sets

Macroinvertebrate and substrate data were combined from several existing projects for 1394 streams or stream segments in the PNW (Table 1). The sites were located in sixteen Level

III Ecoregions (Omernik 1987; USEPA 2003) (Table 1). The majority of these sites represent a single stream, however in some cases, a stream was sampled upstream and downstream of a sediment-producing disturbance, and both sites were included. There were 97 sites from the Washington Coast Range and Yakima River Basin (Regional Environmental Monitoring and Assessment Program (R-EMAP),Merritt and others 1999), 66 sites representing major Ecoregions of Washington (WA Ambient Biological Assessment, Plotnikoff and Ehinger 1997), 74 sites from Oregon (R-EMAP sites), 69 sites from northern Idaho (Potlatch Corp.), 813 sites from all ecoregions in Idaho (Beneficial Use and Reconnaissance Project (BURP), Clark 1998), 43 sites representing major ecoregions in Idaho (ISU Stream Ecology Center), and 232 sites representing all ecoregions of Wyoming. These sites are mainly Strahler first through fifth order streams. Two hundred and fifty-five Idaho BURP streams were removed from the data set and used to validate the FSBIs. In addition, we used only ecoregions with 25 or more streams, leaving 1,025 streams from nine ecoregions to develop the FSBIs.

Table 1 Number of sites from level III ecoregions considered for development of the fine sediment biotic indices

Ecoregion	Group	States Covered	Number of sites
Coast Range	C	OR, WA	136
Puget Lowlands	*	WA	7
Cascades	NM	OR, WA	38
Blue Mountains	*	ID, OR, WA	21
Northern Rockies	NM	ID, WA	170
Idaho Batholith	NM	ID	220
Wasatch and Uinta	*	ID	8
Middle Rockies	R	ID, WY	171
Southern Rockies	R	WY	28
Columbia Plateau	BP	OR, WA	43
Eastern Cascade Slopes and Foothills	*	OR, WA	13
Snake River Plain	BP	ID, OR	138
Northern Basin and Range	BP	ID, OR	81
Wyoming Basin	*	ID, WY	23
Northwestern Great Plains	**	WY	32
Middle Rockies-East	*	WY	10

Nine northwest US ecoregions were classified into four large ecoregion groupings: Coast (C) (Coast Range ecoregion), Northern Mountain (NM) (Cascades, Northern Rockies, Idaho Batholith ecoregions), Rockies (R) (Middle and Southern Rockies ecoregions), and Basin and Plains (BP) (Columbia Plateau, Northern Basin and Range, and Snake River Plain ecoregions) to create four indices

* Ecoregions with less than 25 streams

** For low taxa numbers, these were excluded from FSBI development

Physical Characteristics of Streams

We used physical characteristics (gradient and elevation) and descriptions (Strahler stream order) to examine relationships between physical variables and percent fine sediment (Strahler 1957; see also Davis and others 2001). Strahler stream order classifies streams based on size and linkages of tributaries. One stream was a Strahler sixth order but it was included with the fifth order streams for analysis. Elevation (*m*) was interpreted from quadrangle maps (1:24 K).

Wolman pebble-count methods were used in each study (with one exception) and streambed substrate data were presented as percent fine inorganic sediment. Most federal and state agencies used a modified Wolman pebble count measuring particles (B-axis) across the stream channel at pre-determined distances from bank to bank including non-wetted and wetted channel width (Davis and others 2001; Platts and others 1983; Clark 1998). A subset of Washington streams used a gridded hoop and determined the quantity of fine sediment at the grid intersections (Plotnikoff and Ehinger 1997). Percentage of deposited fine sediment (particles <2 mm in diameter: sand, silt, and clay) from the field data was classified for each stream at 10% increments from 0 to 100% fine sediment. Two millimeters was chosen because it is a size that can be consistently measured with the Wolman type methods (randomly selected particles with one's finger). Physical habitat data were analyzed for significant differences among means (SPSS) with a one-way ANOVA followed by a Bonferroni multiple comparison test. Homogeneity of variance was determined with the Levene test (SPSS for Windows 1999).

Development of the FSBI

Seven hundred and seven invertebrate taxa were reported which included all aquatic insect orders, as well as Turbellaria, Nematoda, Mollusca, Annelida, Hydracarina, and Crustacea (see Relyea 2007—Appendix A for entire taxa list). The macroinvertebrate data were collected by several different methods (Kick-net, Surber, and Hess samplers and in a variety of habitats). Therefore, initial emphasis was placed in the analysis on the presence or absence of individual macroinvertebrate taxa. Several criteria: widespread geographic utility, ease of use, and cost-effectiveness, were important in the development of a robust bioassessment index. Keeping these criteria in mind, we made two taxonomic exclusions in order to develop an index that is both sensitive and robust given existing levels of biomonitoring effort. These exclusions were coarse levels of taxonomic resolution (which includes the Dipteran family Chironomidae) and rare taxa. The first exclusion removed taxa at family, order, phylum, or unknown ($n = 124$). In addition, if all species in a particular genus had the same occurrence value, we assigned one value for the genus. Macroinvertebrate pupae also were excluded because they were not always considered in the different studies. The second exclusion removed rare taxa ($n = 377$). We defined rare taxa as occurring in less than 2% of the streams. Those exclusions reduced the 685 taxa to 206 for use in the index development.

To develop the fine sediment index we modeled relative abundance (as a percent of total sampled taxa abundance in each stream) for each of the 206 taxa and compared relative abundance to percent fine sediment. Scatter plots of each of the 206 taxa plotted taxon relative abundance against percent fine sediment to examine patterns between a taxon and varying quantities of fine sediment (See Relyea 2007—Appendix B for all scatter plots).

Relative abundance of taxa is used to develop the taxon tolerance category, whereas only presence of a taxon is used to calculate FSBI. We assigned each of the 206 taxa into six fine sediment-tolerance categories. Each taxon was assigned a fine sediment tolerance category based on a taxon's 75th percentile of occurrence (i.e., the cumulative 75th % of site occurrences). The six categories began with 10% extending to 50% fine sediment in 10% increments for the four sensitive categories, along with two categories for greater than 50% fine sediment. None of the taxa's 75th percentile of occurrence was in streams of less than 10% fine sediment. Macroinvertebrate taxa in streams with 0 to 20% fine sediment were classified *extremely sensitive* and assigned a FSBI taxa value of 20. Those in streams with 21 to 30% fine sediment are classified v*ery sensitive* (FSBI taxa value = 15), those in streams with 31 to 40% fine sediment are classified m*oderately sensitive* (FSBI taxa value = 10), and those in streams with 41 to 50% fine sediment are classified *slightly sensitive* (FSBI taxa value = 5) (Table 2). Taxa in streams with >50% fine sediment are considered *moderately resistant* (51–70 %) to *extremely resistant* (71 to 100 %) had a FSBI taxa value of zero and do not influence the FSBI score. The FSBI score is the sum of the FSBI value of all taxa from the four most sediment sensitive categories.

For each ecoregion, stream occurrences of a taxon were expressed as the proportion of the number of streams in which a taxon occurred in each 10% increment of fine sediment category. The 75th percentile was then determined by summing the proportions for each sediment category in 10% increments from 0 to 100% fine sediment. We chose the 75th percentile over maximal occurrence (100th percentile) because organisms at their maximal limits typically experience physiological and reproductive stress.

Table 2 Western U.S. macroinvertebrate taxa, number of sites, and FSBI Scores for 93 sediment sensitive macroinvertebrates

Taxon*	ORDER	Number of sites	FSBI
Extremely fine sediment sensitive (0–20%)			
Ampumixis dispar	C	28	20
Claassenia sabulosa	P	44	20
Despaxia augusta	P	102	20
Ecclisomyia	T	64	20
Megarcys	P	220	20
Neaviperla	P	38	20
Oligophlebodes	T	107	20
Perlinodes aurea	P	30	20
Rhithrogena hageni	E	34	20
Rhithrogena robusta	E	58	20
Rhyacophila hyalinata grp.	T	123	20
Very fine sediment sensitive (20–30%)			
Antocha monticola	D	37	15
Arctopsyche	T	199	15
Arctopsyche grandis	T	190	15
Atrichopogon	D	53	15
Attenella margarita	E	50	15
Brachycentrus americanus	T	191	15
Caudatella	E	194	15
Caudatella hystrix	E	55	15
Cultus	P	70	15
Doroneuria	P	179	15
Drunella coloradensis/flavilinea	E	155	15
Drunella doddsii	E	499	15
Epeorus grandis	E	174	15
Epeorus longimanus	E	306	15
Hesperoconopa	D	50	15
Hesperoperla pacifica	P	248	15
Kogotus	P	39	15
Rhithrogena spp.	E	561	15
Rhyacophila angelita grp.	T	114	15
Rhyacophila sibirica grp.-pellisa	T	85	15
Rhyacophila vofixa grp.	T	91	15
Setvena	P	55	15
Moderately fine sediment sensitive (30–40%)			
Apatania	T	112	10
Arctopsychinae	T	48	10
Attenella	E	95	10
Calineuria californica	P	160	10
Dicosmoecus	T	95	10
Dicosmoecus gilvipes	T	54	10

Table 2 continued

Taxon*	ORDER	Number of sites	FSBI
Dolophilodes	T	118	10
Drunella coloradensis	E	187	10
Drunella grandis	E	107	10
Drunella grandis/spinifera	E	132	10
Epeorus spp.	E	949	10
Epeorus albertae	E	155	10
Epeorus deceptivus	E	131	10
Glossosoma	T	432	10
Neophylax	T	184	10
Neothremma	T	188	10
Neothremma alicia	T	57	10
Ordobrevia nubifera	C	42	10
Oreogeton	D	46	10
Paraleptophlebia bicornuta	E	67	10
Paraperla	P	115	10
Petrophila	L	47	10
Polycelis coronata	TU	157	10
Pteronarcys	P	101	10
Pteronarcys californica	P	52	10
Rhyacophila betteni grp.	T	271	10
Rhyacophila sibirica grp.-narvae	T	166	10
Rhyacophila sibirica grp.-valuma	T	34	10
Rhyacophila sibirica grp.-valuma/ pellisa	T	29	10
Suwallia	P	96	10
Slightly fine sediment sensitive (40–50%)			
Acentrella	E	176	5
Acentrella insignificans	E	74	5
Acentrella turbida	E	72	5
Agapetus	T	68	5
Amiocentrus aspilus	T	40	5
Anagapetus	T	58	5
Antocha	D	347	5
Atherix	D	113	5
Baetis bicaudatus	E	324	5
Cinygmula	E	612	5
Drunella spp.	E	1199	5
Drunella spinifera	E	100	5
Ecdyonurus criddlei	E	56	5
Ephemerella tibialis	E	370	5
Heterlimnius	C	584	5
Ironodes	E	39	5
Matriella teresa	E	31	5
Narpus concolor	C	52	5
Nixe	E	101	5
Octogomphus	O	27	5
Parapsyche	T	522	5
Prosimulium	D	172	5
Protoptila	T	28	5
Rhabdomastix	D	107	5
Rhyacophila verrula grp.	T	66	5
Serratella	E	436	5
Visoka cataractae	P	172	5
Yoraperla	P	396	5
Zapada frigida	P	25	5
Zapada oregonensis grp.	P	153	5

Order key: *C* Coleoptera, *D* Diptera, *E* Ephemeroptera, *L* Lepidoptera, *P* Plecoptera, *O* Odonata, *T* Trichoptera, *TU* Turbellaria

* Note: Taxonomic conventions change as taxonomists refine species identifications. We have upgraded naming in these data sets from the 1990's where possible. However, genera that have undergone major revisions, such as Ephemeroptera genera *Serratella* and *Nixe*, we revised the species names, but also kept the genera names from the older data sets

Each ecoregion's data established the FSBI range for that ecoregion. To reduce and consolidate the FSBIs, we combined ecoregions that had similar FSBI ranges to create four ecoregion groupings: the Coast (Coast Range ecoregion (136 streams), Northern Mountains (Cascades, N. Rockies, ID Batholith ecoregions) (428 streams), Rockies (Middle Rockies, Southern Rockies ecoregions) (199 streams), and Basin and Plains (Columbia Plateau, Snake River Basin, Northern Basin and Range (NBR) ecoregions) (262 streams).

FSBI score and physical data (percent fine sediment) were analyzed for differences among FSBI means for each ecoregional group in the statistical software package (SPSS for Windows 1999) with a one-way ANOVA followed by a Bonferroni multiple comparison test. Homogeneity of variance was determined with the Levene test (SPSS for Windows 1999).

Validation of the FSBI

We validated FSBI using a randomly selected group of streams ($n = 255$ streams) from the 1997 ID DEQ BURP data. We did not use these streams in development of the FSBI. Three of the four major ecoregion groupings were represented: Northern Mountains (118), Basin and Plains (119), and Rockies (18) streams. We compared by overlaying scatter plots of % fine sediment and FSBI scores to original FSBI distributions for each ecoregion.

Results

Physical Characteristics of Streams

Sediment transport and deposition are affected by several physical controls. Streams with gradients over 11% typically did not have over 30% fine sediment (Fig. 1). Low gradient streams (0 to 5%) had a wide range of percent fine sediment from 0 to 100% (Fig. 1). Streams with greater than 50% fine sediment usually had a gradient of 3% or less and none had a gradient over 6.5% (Fig. 1).

There were differences among the different Strahler orders and the percent of fine sediment (Fig. 2). First order streams had more fine sediment ($P = <0.001$) than all the other Strahler orders. Second order streams had less fine sediment than first order streams, similar amounts as third streams but more than fourth and fifth orders ($P = <0.001$). It is noteworthy that in the first through fourth orders some streams had up to 100% fine sediment (Fig. 2).

Even with the high variability in percent fine sediment for each ecoregion (Fig. 3), there were significant differences among some ecoregions. The Coast Range ecoregion had the highest median percentage fine sediment at 27% and was higher than all other ecoregions except the Northern Basin and Range ecoregion ($P = 0.1$). The mountainous ecoregions had the lowest median range of fine sediment (4 to 10%) and were different from the Coast Range, Snake, and NBR ecoregions, ($P = 0.037$ to <0.0001). The Columbia Plateau had a median value of 6% fine sediment while the other Basin and Plains ecoregions (Snake, and NBR) had medians of 18 and 21% fine sediment respectively (Fig. 3).

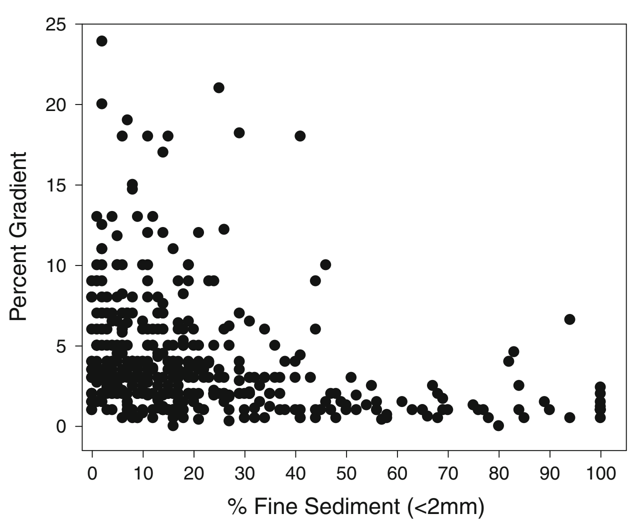

Fig. 1 Percent fine sediment (<2 mm) and stream gradients

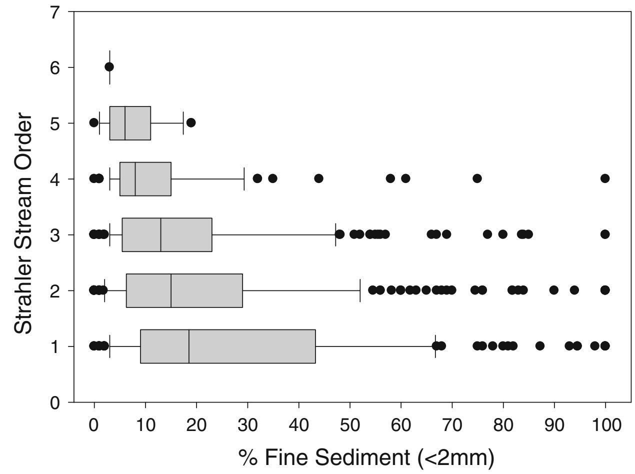

Fig. 2 Percent fine sediment (<2 mm) at different Strahler stream orders (n = first—172, second—292, third—207, fourth—88, fifth—27, sixth—1) *Box plot* median is *vertical line, box* ends the 25th and 75th percentiles, *error bars* the 10th and 90th percentiles, and *filled circles* represent full range of data

Fine Sediment Biotic Index (FSBI)

Some sensitivity to fine sediment was detected in 93 of the 206 taxa. All taxa could tolerate fine sediment up to 10%. Eleven taxa were *extremely sensitive*, 22 taxa *very sensitive*, 30 taxa *moderately sensitive* and 30 taxa *slightly sensitive* to fine sediment. Each of their 75% percentile values were in progressively higher levels of fine sediment up to 50% fine sediment (Table 2). Taxa in *moderately*

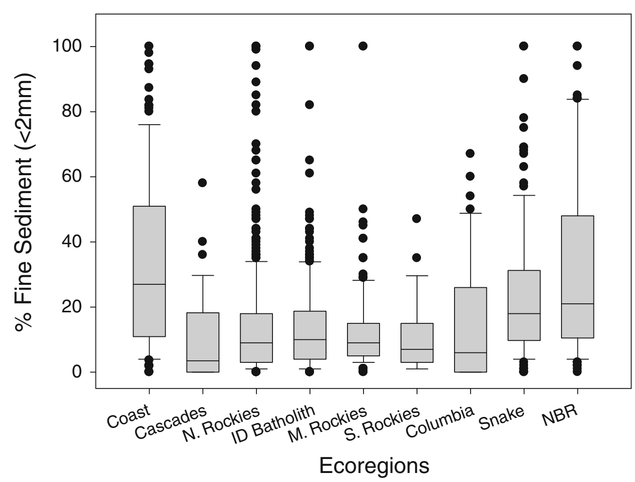

Fig. 3 Percent fine sediment (<2 mm) in nine Level III Ecoregions. Ecoregions are organized by ecoregion groupings: Coast (Coast Range ecoregion), Northern Mountains (Cascades Northern Rockies and Idaho Batholith ecoregions), Rockies (Middle Rockies and Southern Rockies ecoregions) and Basin and Plains (Columbia, Snake and NBR ecoregions). The *horizontal line of the box* plot represents the median, the *ends of the box* represent the 25th and 75th percentile, *error bars* represent the 10th and 90th percentile, and *filled circles* represent the full range of data

resistant (50–70 % fine sediment) and *very resistant* (70 %) categories had 86 and 27 taxa, respectively.

The FSBI score summed all sensitive taxa in a sample. Range of values differed among the nine ecoregions (Fig. 4). We combined ecoregions with similar range of values into groups to create four FSBIs. The Coast ecoregion had the highest median fine sediment percentage (Fig. 3) and a FSBI median value of 70 and was left as a group. We formed two ecoregion groupings from the mountainous ecoregions; Northern Mountains (Cascades, N. Rockies, ID Batholith) and Rockies (Middle Rockies, Southern Rockies). These groups had the lowest median fine sediment percentage and the highest FSBI scores (Figs. 3, 4). The mountainous ecoregions can be distinguished, with a median FSBI above 150 in the Northern Mountain grouping, and the Rockies grouping with a median FSBI below 150 but above 100. The Basin and Plains ecoregion group (Columbia Plateau, Snake River Basin, Northern Basin and Range ecoregions) had intermediate levels of fine sediment (Fig. 3) but the lowest FSBI scores with medians all below 50 (Fig. 4).

Streams were diverse including pristine streams in wilderness, streams with single pollutants, and streams with multiple pollutants. Despite this variety, no stream had a high FSBI score (indicating fine sediment intolerant taxa) and moderate to high reported fine sediment. All streams over the FSBI 90th percentile and most over the 75th percentile had less than 30% fine sediment. The response to the stressor in all ecoregion groupings was wedge shaped similar to shown for the Northern Mountain ecoregion group in Fig. 5, with a greater range of responses in streams with low fine sediment and a narrow range at high fine sediment levels.

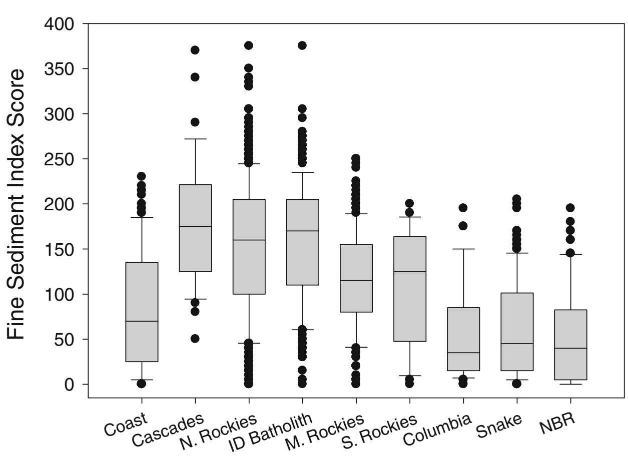

Fig. 4 Range of FSBI scores for nine Level III Ecoregions. Ecoregions are organized by ecoregion grouping: Coast (Coast Range ecoregion), Northern Mountains (Cascades Northern Rockies and Idaho Batholith ecoregions), Rockies (Middle Rockies and Southern Rockies ecoregions), and Basin and Plains (Columbia, Snake and NBR ecoregions). *Box plot median is horizontal line*, *box ends* the 25th and 75th percentiles, *error bars* the 10th and 90th percentiles, and *filled circles* represent the full range of data

Validation of the FSBI

The Idaho data set used for validation incorporated three of the ecoregion groupings (Northern Mountain, Rockies, and Basin and Range). The distribution of FSBI scores from the 255 randomly selected validation streams were very similar to streams used to create the FSBI. Superimposition of actual and validation data sets (Fig. 6) shows well-mixed distributions and wedge shaped distributions. In addition, most streams over the 75th percentile had less than 30% fine sediment and all streams with greater than 50% fine sediment scored below the 25th percentile in both actual and validations data sets (Fig. 6). In the Rockies grouping (not shown) the results were similar, with a smaller set of streams (18).

Discussion

Most biomonitoring metrics examine overall stream health and there generally has not been a way to separate single stressors from the suite of stressors that can occur in a stream. The FSBI is a diagnostic index designed to target only the effect of fine inorganic sediment on stream organisms. Diagnostic indices may well be the next step in the evolution of bioassessment metrics (Chessman and McEvoy 1998; Clews and Omerod 2008; Friberg 2010). Targeting fine sediment and developing an index that uses macroinvertebrates sensitive to increases in fine sediment, FSBI advances traditional macroinvertebrate biomonitoring by identifying a specific pollutant and not just the overall health of the stream macroinvertebrate community.

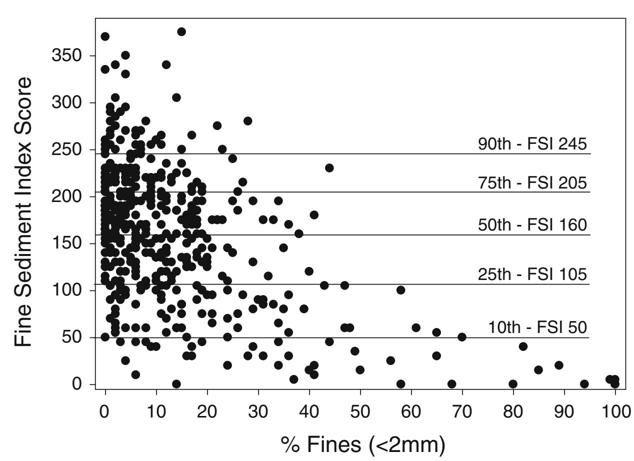

Fig. 5 Fine Sediment Biotic Index Scores with percentiles and % fine sediment for the Northern Mountains ecoregion group (Cascade, Northern Rockies, Idaho Batholith ($n = 428$))

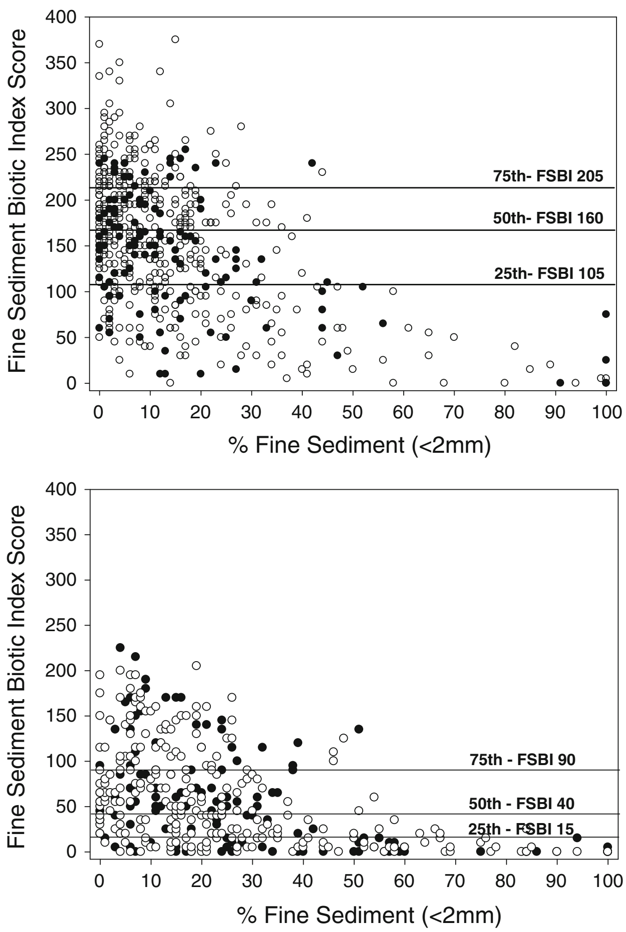

Fig. 6 Comparisons of Fine Sediment Biotic Index Scores with % fine sediment from two ecoregion groups and sites from streams within those groups in validation data set. Upper panel—the Northern Mountain ecoregion group (Cascade, Northern Rockies, Idaho Batholith (*open dots*) (*n* = 428)). *Solid dots* are streams used to verify FSBI (*n* = 118). Lower panel—Basin and Plains ecoregion group (Columbia Plateau, Snake River, Northern Basin and Range (*open dots*) (*n* = 262)). *Closed dot* is a stream used to verify FSBI (*n* = 126)

We present a biomonitoring tool to detect fine sediment in streams that uses presence of common taxa to assess degrees of impairment. In other efforts investigating macroinvertebrate sensitivity to fine sediment, macroinvertebrate responses to ranges of fine sediment levels in streams were documented (Appalachian—Angradi 1999; Western US—Bryce and others 2008; Canada—Kreutzweiser and others 2005; United Kingdom—Larsen and Omerod 2010; New Zealand—Suren and Jowett 2001). This study expands on the work by Relyea and others (2000) and focuses on NW US. The approach can be used by others with a well-distributed network of sampled streams with standard taxonomy to develop other stressor specific local index. This index uses a broad suite of common taxa to the genus or species, but avoids difficult groups (Chironomidae and Oligocheates). Exclusion rules reduce the region-wide taxa list from 685 to 206. In addition, by only requiring presence of a taxa, FSBI streamlines laboratory and computational requirements. We recognize that sampling effort affects the likelihood of presence; however, users of the index can set efforts levels for their particular monitoring effort. In addition, given the taxa are common; typical sampling efforts would collect the majority of those taxa.

All 206 taxa examined were found in streams with up to 26% fine sediment; however, at higher fine sediment levels taxa started disappearing. Even so, taxa impairment began occurring between 10 and 20% deposited fine sediment for certain sensitive species. We classified these taxa as being extremely sensitive to fine sediment. A few of the taxa previously have been reported as sediment sensitive or resistant (McClelland and Brusven 1980; Lemly 1982; Mahoney 1984; Magnum and Winget 1991; McHenry 1991). In this effort, we started with 685 taxa and identified 93 taxa exhibiting some sensitivity to fine sediment.

This biomonitoring metric for fine inorganic sediment had broad applicability in western US, and the development of other regionally targeted indices elsewhere should be possible where robust data sets data sets are available. Central to our efforts here, the single FSBI introduced in Relyea and others (2000), and other efforts (Huff and others 2008; Bryce and others 2008, 2010) was a broad undertaking by the US EPA (Environmental Assessment and Monitoring Program (EMAP)) designed to monitor trends in environmental conditions. The EMAP program used randomly-selected sites across broad landscapes (Stoddard and others 2005). In addition, the EMAP program strongly influenced methods of other efforts by individual states, allowing us some similarity in methods across data sets, although there were minor methodological differences.

Our results are in agreement with a large-scale data set of 900 streams in the western United States that examined the relationships of certain Ephemeroptera (mayflies) to streambed substrate (Magnum and Winget 1991; Winget and Mangum 1991). They found *Drunella doddsii* to be highly correlated to streams with coarse substrates and streams with moderate to high percentages of fine sediments did not support *D. doddsii*. This also was true in this study as *D. doddsii* (*n* = 499), which was common, was classified as *very sensitive* (75th percentile of occurrence at 30% fine sediment). Another mayfly, *Tricorythodes minutus,* which we classified as moderately resistant in this index (75th percentile of occurrence at 70% fine sediment) they found preferred fine sediment over coarser substrates and were abundant when a large amounts of fine sediment was present.

The range in responses with those mayflies, suggests that biomonitoring metrics at the order level may be inadequate. Other Ephemeroptera that were *moderately sensitive* or *slightly sensitive* to fine sediment both in the literature and in this research were *Acentrella*, *Caudatella*, *Epeorus,* and *Rithrogena* (McClelland and Brusven 1980; Lemly 1982; Mahoney 1984; McHenry 1991; Angradi 1999). Ephemeroptera that were *resistant* to *moderately resistant* to fine sediment both in the literature and in this research were *Ameletus*, *Baetis*, *Ephemerella*, *Heptagenia criddlei*, *Paraleptophlebia*, and *Tricorythodes minutus*. Therefore, use of order as an indicator lacks discriminatory power.

Other orders had taxa with a similar range of sensitivity. Trichoptera (T) and Plecoptera (P) have been reported both in the literature and found in this research to exhibit a large range tolerance. Some taxa are *very sensitive* or *moderately sensitive* (*Arctopsyche* (T), *Brachycentrus* (T), *Glossosoma* (T), *Neothremma* (T), *Hesperoperla pacifica* (P), and *Cultus* (P)) while others are *resistant* and *moderately resistant* - *Hydropsyche* (T), *Sweltsa* (P), Leuctridae (P), and *Zapada* (P). Plecoptera had the most taxa (5) in the *extremely sensitive* category. The majority of these were semivoltine, so they are exposed to sediment fluxes over 2–3 years, which may make them more susceptible than univoltine taxa to increases in fine sediment. This agrees with other research that reports a decline in certain Plecoptera taxa densities after anthropogenic disturbance or sediment additions (Murphy and Hall 1981; Culp and Davies 1983). The majority of the Diptera were found to be fine sediment *resistant*. While we did not include Chironomidae, ten Diptera taxa showed some sensitivity to fine sediment, although none was in the extremely sensitive category. With the family Chironomidae, Angradi (1999) observed different responses in proportions between sub families with Orthocladiinae increasing, and Chironominae declining with increasing levels of fine sediment. Thus, there appear to be no orders of invertebrates that were solely sensitive or resistant to fine sediment. This implies that metrics at the ordinal level such as the EPT and D taxa are poor indicators of fine sediment conditions.

At the family level, there are broad differences as well. Within the family of net spinning, caddis flies (Hydropsychidae), *Arctopsyche* (very sensitive), and *Parapsyche* (moderately sensitive) were sensitive whereas *Cheumatopsyche* and *Hydropsyche* were present in streams with 70% fine sediment. This range in responses underscores that even family level indices are insufficient in targeting a specific pollutant. The FSBI uses a straightforward scoring system of common aquatic insect larvae/nymphs, the majority of which are identified to genus. Scores for streams fall on a continuum from high scores, representing streams with a low percent of fine sediment, to low scores representing streams with a high percentage of fine sediment. In addition, enumeration of insects is not needed; this could accelerate macroinvertebrate processing and analysis as well as reduce cost.

In an earlier version, a single FSBI was developed for the entire northwest in an effort to promote simplicity (Relyea and others 2000). The mountainous streams had high FSBI scores and low-lying streams had low FSBI scores. It soon was apparent that the appropriate monitoring scale for the macroinvertebrate substrate relationship was at the ecoregion. Ecoregions have different FSBI signatures reflecting geologic, thermal, and hydrologic regimes, as well as present and past human alterations (Relyea 2007). Typical watersheds within an ecoregion will presumably have similar FSBI scores. Any observed differences could reflect differences in sediment regime, perhaps related to land management history and practices.

The wedge shaped distribution in response to fine sediment suggests limiting response at an upper threshold response to fine sediment in each ecosystem groupings. Lancaster and Belyea (2006) found that a limiting response model better described hydraulic variables and macroinvertebrate relationships. Bryce and others (2008 and 2010), using some of the same data sets as FSBI, also examined fine sediment and aquatic macroinvertebrate relationships with quantile regression. Other aquatic examples of wedge shaped limiting responses to stressors include nutrient level constraints to macroinvertebrate communities (Wang and others 2007) and fish standing stock with habitat variables (Terrell and others 1996).

There are several possible applications of the Fine Sediment Bioassessment Index for streams. The first is to compare the FSBI score for a study stream to the established percentiles developed for ecoregions in this study. This allows the investigator to determine impairment and to compare the study stream to others in the same ecoregion. Secondly, the FSBI could be used to predict the amount of fine sediment in a stream based on the macroinvertebrate assemblage using the FSBI score distribution developed for each ecoregion. Thirdly, the index could be used in combination with other metrics or incorporated into a bioassessment multi-metric or model, such as an IBI or the RIVPACS model (Simpson and others 1996; Barbour and others 1999). Finally, by using only taxa lists, one could go to data from past collections to assess if condition over time changed, and if fine sediment inputs were a factor. This allows managers to determine effects of the land-use practice by having "before and after" fine sediment index score.

Advantages of the FSBI are that a specific widely occurring pollutant is targeted, it is easy to use, taxa lists can be used from previous studies, not all taxa need be identified, and no enumeration of insects is necessary. The impact of fine sediment on aquatic organisms is complex, yet the FSBI and the macroinvertebrate sediment tolerances associated with this metric provide a valuable diagnostic bioassessment tool that is superior to traditional bioassessment metrics in discerning fine sediment impacts on the macroinvertebrate community. The FSBI currently is applicable only to the northwestern United States; it was developed from stream data in Idaho, Oregon, Washington, and Wyoming and tested successfully with data from three ecoregional groupings in Idaho. The approach used to develop the FSBI for the northwest United States is applicable anywhere sufficient data exist to determine macroinvertebrate and substrate relationships.

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