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Evaluation of a fine sediment biomonitoring tool across a wide range of temperate rivers and streams

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SUMMARY

1. Elevated levels of fine sediment (suspended and deposited) are a common cause of ecological degradation in freshwater ecosystems. However, it is time-consuming and expensive to monitor these parameters to support national and international water resource legislation.
2. The Proportion of Sediment-sensitive Invertebrates (PSI) index is a biomonitoring tool that is designed to identify the degree of sedimentation in rivers and streams. Despite having a sound biological basis, until now, the PSI index has only been tested against observed fine sediment data in two catchments; other published applications of the PSI index have relied on inferred fine sediment values.
3. In this study, we report the results of a comprehensive analysis of the performance of the PSI index across a wide range of reference condition temperate stream and river ecosystems, including 835 sites with data on deposited sediment and 451 sites with data on suspended solids (>12 500 data points measured between 1978 and 2002).
4. The effect of taxonomic level and taxonomic resolution on the performance of the PSI index was also examined, as was the performance of the PSI index against other non-sediment-specific indices, including Average Score Per Taxon (ASPT), Lotic-invertebrate Index for Flow Evaluation (LIFE), Ephemeroptera, Plecoptera and Trichoptera (EPT) abundance, % EPT abundance, EPT richness and % EPT richness.
5. The results of this study show that the PSI index was more correlated with fine sediment metrics than the other biological indices tested: $r_s = -0.64$, ($P < 0.01$, $n = 2502$) for deposited sediment and $r_s = -0.50$ ($P < 0.01$, $n = 1353$) for suspended solids.
6. We highlight the optimal conditions for applying the PSI index, in its current form. Given the variability in the relationship between PSI and fine sediment metrics, we propose that the use of data from more objective, quantitative methods of measuring deposited fine sediment may help to enhance the performance of the model for future applications and advance understanding of fine sediment dynamics and the pressure–response relationship.

Keywords: biomonitoring, deposited fine sediments, macroinvertebrates, sedimentation, suspended sediments

Introduction

The transport of sediments and particulate matter, from nanoscale colloids to sand-sized sediments, by rivers to the oceans, represents (i) an important part of the global denudation system (Walling & Fang, 2003; Bilotta *et al.*, 2012), (ii) an important component of global biogeochemical cycles (Schlesinger & Melack, 1981; Mainstone & Parr, 2002) and (iii) an essential constituent of freshwater ecosystems, critical to habitat heterogeneity and ecological functioning (Wood & Armitage, 1997; Owens *et al.*, 2005). However, when anthropogenic activities

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cause a significant deviation in the dynamics of fine sediment from 'natural' or 'reference' conditions, this can cause ecological degradation (Cordone & Kelley, 1961; Bilotta & Brazier, 2008). It is therefore essential that fine sediment, which is one of the most commonly attributed causes of water quality impairment globally (Richter *et al.*, 1997), is managed in order to minimise these impacts.

Increasingly, freshwater managers and policy-makers require conservation measures that will protect and improve biodiversity, whilst minimising the costs and societal impacts on users and inhabitants of catchments (Turak & Linke, 2011). This includes minimising the costs associated with conventional monitoring of water quality parameters such as suspended and deposited sediment. Conventional monitoring of physicochemical water quality parameters can be relatively expensive and time-consuming; there are tens of parameters that could be analysed, and sampling must be frequent enough to ensure that the values obtained are representative of long-term exposure. Recently, there has been a shift away from these conventional monitoring methods, towards approaches that focus on low-frequency (lower-cost) biomonitoring techniques, defined broadly as 'the use of biota to gauge and track changes in the environment' (Wright, Furse & Armitage, 1993; Gerhardt, 2000; Friberg *et al.*, 2011). This type of approach relies on being able to predict the expected fauna and/or flora for a site if it were in, or close to reference condition (with minimal anthropogenic disturbance). Where the observed community composition does not deviate significantly from the expected community, no major monitoring or mitigation programmes are required. Where the biological community composition does deviate significantly from that expected, then the presence or abundance of certain species or assemblages of species can provide information on the likely causes of the deviation from the reference condition, allowing for monitoring and management resources to be targeted.

The Proportion of Sediment-sensitive Invertebrates (PSI) index

The PSI index is a biomonitoring tool that is designed to identify the degree of sedimentation in streams, using the benthic invertebrate community (Extence *et al.*, 2011). It was developed using a similar approach to the Lotic-invertebrate Index for Flow Evaluation (LIFE) (Extence, Balbi & Chadd, 1999), through assessment of invertebrate faunal traits and previous literature. PSI assigns benthic macroinvertebrate taxa to one of four Fine Sediment Sensitivity Ratings (FSSR). The weighted relative abundance of FSSR groups is used to calculate a PSI score; 0 being completely sedimented and 100 being unsedimented. Being based on invertebrate faunal traits, such as morphological adaptations that result in either a sensitivity or tolerance to fine sediment, the PSI index is linked to ecological niche theory, which states that organisms are adapted to a specific range of environmental conditions (Hirzel & Le Lay, 2008). This sound biological basis is important for biomonitoring tools (Bonada *et al.*, 2006), but until now, the PSI index has only been tested against observed fine sediment data in two catchments in the United Kingdom (Glendell *et al.*, 2013). Other published applications of the PSI index have relied on inferred sediment values when evaluating the index in the United Kingdom and also in Guinea (Africa), based on assumed relationships between flow regime or land-use/habitat modification and fine sediment levels (Extence *et al.*, 2011; Poole *et al.*, 2013).

The aim of this study is to report the results of a comprehensive analysis of the performance of the PSI index, through examining the relationships between PSI scores and observed fine sediment metrics (suspended and deposited sediment) collected from a wide range of reference condition, temperate stream and river ecosystems. We hypothesise that the PSI score will be negatively related to (i) the percentage of the substratum consisting of fine sediments and (ii) mean suspended solids (SS) concentration. Further aims of this study are the following: (i) to determine whether the taxonomic resolution (family compared to species) and taxonomic level (number of taxa) used to calculate the PSI score, influences the strength of the relationship with fine sediment metrics and (ii) to evaluate the PSI index alongside other, non-sediment specific, commonly used biological indices: Average Score Per Taxon (ASPT) (Murray-Bligh, 1999), LIFE (Extence *et al.*, 1999), Ephemeroptera, Plecoptera and Trichoptera (EPT) abundance, % EPT abundance, EPT richness and % EPT richness.

Methods

Data

The main data set used in this study was the RIVPACS IV (May 2011 version) data set (River Invertebrate Prediction and Classification System – NERC [CEH] 2006. Database rights NERC [CEH] 2006 all rights reserved). The RIVPACS IV data set is described in detail by Wright, Sutcliffe & Furse (2000) and Clarke, Wright & Furse (2003), but is summarised here. The database contains invertebrate, water quality and catchment characteristics data, recorded at each site over at least 1 year, between 1978 and 2004. The 835 reference condition sites, on streams and rivers across the United Kingdom (Fig. 1), encompass a wide range of environments, varying in their (i) climate – mean annual precipitation totals between 1961 and 1990 of 430–2930 mm and mean annual temperatures between 1961 and 1990 ranging from 7.93 to 11.45 °C, (ii) geology – varying from catchments dominated by hard igneous rocks to catchments dominated by soft sedimentary rocks and (iii) topography – altitudes at river source varying from 5 to 1216 m above sea level. The stream and river sites also vary in their morphometry with widths ranging from 0.4 to 117 m and average depths ranging from 0.02 to 3.00 m (widths and depths are a mean of three seasonal measurements). All of the sites are considered to be as close to reference condition as it is possible in the United Kingdom, and they have no, or only very minor, anthropogenic alterations to the values of the hydrochemistry and hydromorphology, supporting biota usually associated with such undisturbed or minimally disturbed conditions.

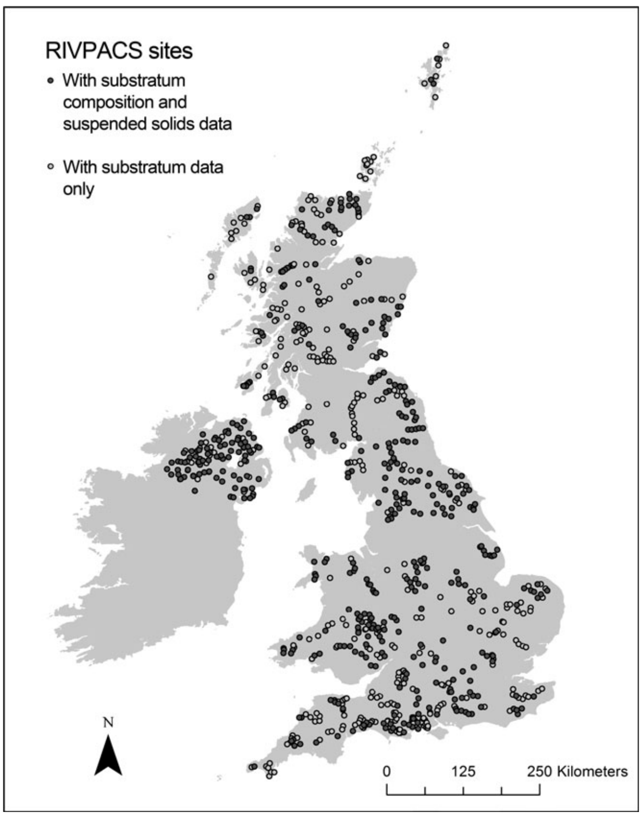

Fig. 1 Distribution of RIVPACS 'reference condition' sites. Dark dots are those sites with both substratum composition data and ≥12 suspended solids measurements; light dots are those sites with only substratum composition data.

The macroinvertebrate data within the RIVPACS IV database were collected from 835 sites, using a standardised 3-min active kick sample technique with a 900-μm mesh pond net, where all in-stream habitats within the site were sampled in proportion to their occurrence. The abundance of different macroinvertebrates identified to species level or to the lowest possible taxonomic unit was recorded numerically (Wright *et al.*, 2000). There are season-specific records of community composition: spring being the community composition from March to May, summer being the community composition from June to August and autumn being the community composition from September to November. There are no records for winter (December to February). The three taxonomic levels of the biological indices recorded within the database and used were all families, 652 species and 415 species.

The fine sediment data available within the RIVPACS IV database include measurements of SS and observations describing the percentage of the substratum consisting of (i) silt and clay (< 0.06 mm), (ii) sand (<2, ≥0.06 mm), and (iii) sand, silt and clay combined. All of the 835 RIVPACS IV sites have data describing the substratum composition. These data were collected using the visual assessment method described in the River Habitat Survey Field Survey Guidance Manual (Environment Agency, 2003). Briefly, this involves the operator, estimating the substratum composition over a given reach, based on a visual inspection. The values used represent a mean of three seasonal measurements. Whilst this technique does not quantify the volume of deposited fine sediment, which PSI is designed to relate to, it does provide a measure of the percentage cover, which theoretically should be related to the PSI index (Glendell *et al.*, 2013).

Four hundred and fifty-one of these sites have 12 or more SS measurements taken over at least 1 year of sampling (between 1978 and 2004), and these were selected for use in this study. Concentrations of SS were determined using the standard gravimetric method which involves filtration of a known volume of sample through a dried and pre-weighed 0.7-mm pore-size glass fibre filter paper, followed by drying at 105 °C and reweighing (Anon, 1980; Gray *et al.*, 2000). The sites exhibit a range of SS concentrations (Bilotta *et al.*, 2012), and the database includes 12 560 analyses of SS concentrations, measured between 1978 and 2002 at the 451 sites used in this study. Although this number of data points may not capture the full range of SS values that occur at each site, they do provide a good indication of mean annual background SS concentrations.

Statistical analyses

The relevant data were extracted from the RIVPACS IV database and compiled in Microsoft Excel prior to analysis. In addition to PSI, the biological indices, ASPT, LIFE, EPT abundance, % EPT abundance, EPT richness and % EPT richness were also assessed for any relationships to fine sediment metrics. Given the semiqualitative methods used for invertebrate sampling, log abundances were used to calculate PSI, LIFE, EPT abundance and % EPT abundance. Using SPSS statistical software (IBM® SPSS® Statistics 20 Armonk, NY, USA.), the data were found to be non-normally distributed and show heteroscedasticity and could not be successfully transformed. The nonparametric Spearman's rank correlation was used to analyse the relationship for spring, summer and autumn, between the biological indices of different taxonomic resolution and levels, with fine sediment metrics. The seasonal data were then combined to provide a single Spearman's rank correlation for each biological index and sediment metric. The PSI and fine sediment metric which exhibited the strongest correlation were analysed using the Kruskal–Wallis test, as it was expected that this relationship would have the greatest predictive capabilities. This was performed for both deposited and suspended fine sediment metrics by grouping the PSI scores into independent groups (0–20, 21–40, 41–60, 61–80, 81–100); the Kruskal–Wallis test returns a P-value which is used to determine whether any of the groups are significantly different. Pairwise comparisons were then performed using Dunn's's (1964) procedure with a Bonferroni correction for multiple comparisons, to determine which groups were significantly different.

Results

PSI and fine sediment metrics

The PSI index was negatively correlated to the percentage of the substratum consisting of fine sediment (Table 1). The strongest relationship, for all seasons and all taxonomic levels, was between PSI and the percentage of the substratum consisting of sand, silt and clay; the highest of which was $r_s = -0.65$, $P < 0.01$ (observed in summer). The strongest relationship for the percentage of substratum consisting of silt and clay was $r_s = -0.63$, $P < 0.01$ (observed in spring). For the percentage of the substratum consisting of sand, the strongest relationship with PSI under all conditions was $r_s = -0.42$, $P < 0.01$ (observed in summer). The PSI score was also negatively correlated with the mean SS concentration, the strongest relationship, for all seasons and all taxonomic levels, being $r_s = -0.55$, $P < 0.01$.

Due to the similar correlations between PSI score and fine sediment metrics (both deposited and suspended) across all sampling seasons, for example PSI (652 species) versus % sand, silt and clay varied by 0.01 (spring $r_s = -0.64$, summer $r_s = -0.65$, autumn $r_s = -0.64$, $P < 0.01$), the three seasons were combined and hereafter considered as one set of data (Table 1).

PSI, taxonomic resolution and taxonomic level

The PSI scores based on family data had consistently weaker correlations with all fine sediment metrics, compared to PSI scores calculated using species data. The correlations between mean SS and species or family PSI had

Table 1 Spearman's correlation coefficients for relationship between combined seasons of biological indices and fine sediment metrics at 'reference' condition RIVPACS sites

Biological index	Silt and clay	Sand silt and clay	Sand	Suspended solids mean (mg L^{-1})
ASPT (family)	−0.44	−0.50	−0.29	−0.34
LIFE (family)	−0.53	−0.57	−0.33	−0.28
LIFE (652 species)	−0.54	−0.58	−0.36	−0.31
LIFE (415 species)	−0.51	−0.55	−0.34	−0.28
PSI (family)	−0.58	−0.61	−0.37	−0.41
PSI (652 species)	−0.62	−0.64	−0.40	−0.50
PSI (415 species)	−0.60	−0.63	−0.40	−0.47
EPT abundance	−0.20	−0.21	n/s	−0.11
% EPT abundance	−0.55	−0.59	−0.35	−0.46
EPT richness (family)	−0.24	−0.26	−0.06	−0.22
% EPT richness (family)	−0.52	−0.55	−0.31	−0.47

ASPT, Average Score Per Taxon; EPT, Ephemeroptera, Plecoptera and Trichoptera; LIFE, Lotic-invertebrate Index for Flow Evaluation; PSI, Proportion of Sediment-sensitive Invertebrates.
Unless otherwise stated, all correlations are significant at the 0.01 level (2-tailed).
Indices calculated using either family data or species data (652 or 415 species).

the largest differences ($r_s = -0.50$, $P < 0.01$, compared to $r_s = -0.41$, $P < 0.01$, respectively). Spearman's rank correlations (Table 1) show that the PSI with the highest number of species (652 species) had similar moderate correlations to PSI (415 species) scores, which were calculated with fewer taxa (sand, silt and clay: $r_s = -0.64$, $P < 0.01$, compared to $r_s = -0.63$, $P < 0.01$, respectively).

Discrimination ability of the PSI index

In order to evaluate the ability of PSI to discriminate between different levels of sedimentation, PSI (652 species) scores were grouped and analysed using the Kruskal–Wallis test. The process of selecting group sizes for PSI scores was a balance between selecting groups which were very small (i.e. PSI scores of 0–5, 5–10, 10–15, etc.) which would need to be based on highly accurate and precise measurements of fine sediment, and selecting groups that were very large, which would limit the potential for discrimination between different levels of sedimentation. Grouped PSI scores of 20% were tested (Fig. 2) and found to have significant differences between groups ($P < 0.05$). Pairwise comparisons identified all groups as being significantly different from each other ($P < 0.05$).

Similarly, this analysis was carried out on the relationship between PSI and mean SS concentration. A statistically significant difference ($P < 0.05$) was observed between mean SS concentrations grouped by PSI, with the two upper groups (PSI 60.1 – 80 and 80.1 – 100), being statistically different from each other and the three lower groups (PSI 0 – 20, 20.1 – 40 and 40.1 – 60.0).

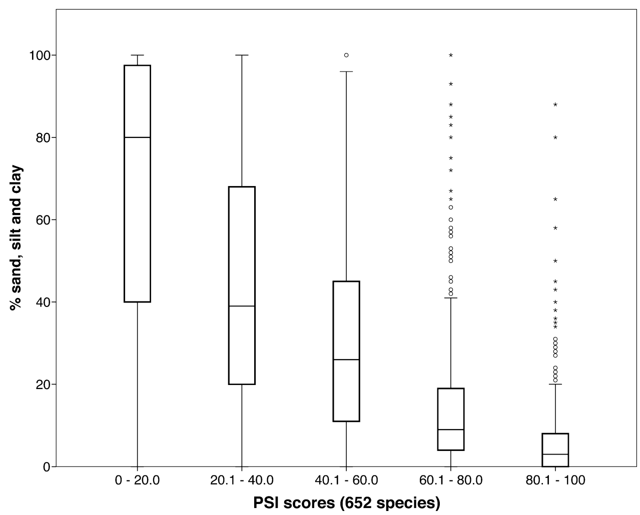

Fig. 2 Boxplots showing the relationship between grouped PSI (652 species) scores and % sand, silt and clay substratum (based on visual assessment) derived from RIVPACS combined seasons, reference site data. SPSS identifies potential outliers as >1.5 times (○) or >3 times (*) the interquartile range above the 75th percentile.

Comparison of the PSI index against other biological indices

The PSI index had slightly, to moderately, stronger correlations with all fine sediment metrics than all other biological indices tested. The % EPT abundance, % EPT richness and LIFE (652 species) had slightly weaker, moderate correlations with % sand, silt and clay ($r_s = -0.59$, $r_s = -0.55$, and $r_s = -0.58$, $P < 0.01$ respectively, compared to $r_s = -0.64$, $P < 0.01$, for PSI) as well as for % silt and clay ($r_s = -0.55$ and $r_s = -0.52$, $r_s = -0.54$, $P < 0.01$, respectively, compared to $r_s = -0.62$, $P < 0.01$, for PSI). Two indices (EPT abundance and EPT richness) had much weaker correlations with all sediment metrics, their strongest correlations being with % sand, silt and clay ($r_s = -0.21$ and $r_s = -0.26$, $P < 0.01$, respectively).

The correlations between the biological indices were also analysed using Spearman's rank correlation. Strong, statistically significant, positive relationships (r_s = >0.74, $P < 0.01$) were observed between PSI and a number of the non-sediment-specific indices: % EPT abundance, % EPT richness, LIFE and ASPT (Table 2).

Discussion

The ability of PSI to identify sedimentation

The results of this study show that the PSI index was moderately, negatively correlated to (i) percentage of the substratum consisting of sand, silt and clay, (ii)

Table 2 Spearman's correlation coefficients for relationships between biological indices from combined seasons, at reference condition streams in RIVPACS database

Biological index	PSI (family)	PSI (652 species)	PSI (415 species)
ASPT (family)	0.79	0.74	0.75
LIFE (family)	0.89	0.85	0.86
LIFE (652 species)	0.85	0.89	0.89
LIFE (415 species)	0.83	0.85	0.87
EPT abundance	0.33	0.27	0.29
% EPT abundance	0.83	0.80	0.80
EPT richness (family)	0.41	0.36	0.37
% EPT richness (family)	0.82	0.78	0.79

ASPT, Average Score Per Taxon; EPT, Ephemeroptera, Plecoptera and Trichoptera; LIFE, Lotic-invertebrate Index for Flow Evaluation; PSI, Proportion of Sediment-sensitive Invertebrates. All correlations are significant at the 0.01 level (2-tailed).

percentage of the substratum consisting of % silt and clay and (iii) mean SS concentration, thus supporting both hypotheses. The strongest correlation observed in the data, when seasons were combined, was between PSI and the percentage of the substratum consisting of sand, silt and clay ($r_s = -0.64$, $P < 0.01$). To put this into context, a study of 297 bioassessment methods (comprising invertebrate, macrophyte, phytoplankton and diatom indices), that are used for the implementation of the Water Framework Directive (WFD) across Europe, found the median correlation coefficient of invertebrate-based indices to be 0.64 in relation to their respective stressor (Birk *et al.*, 2012). Based on that analysis, the correlation observed in this study (between PSI score and the percentage of the substratum consisting of sand, silt and clay) is comparable to other indices used in the implementation of the EU WFD. Nevertheless, given the implications of incorrect assignment of ecological status of streams for both water and land managers, greater effort is needed to evaluate and improve the performance of biological indices to achieve robust models.

Statzner *et al.* (2005) concluded that a robust model should be able to predict group assignments correctly in *c.* 70% of cases. The results from the Kruskal–Wallis and *post hoc* test show that when PSI was grouped (0–20, 21–40, 41–60, 61–80, 81–100), the % of sand, silt and clay in the groups were statistically significantly different between all groups. However, the large overlaps between groups (Fig. 2) prevent the development of an effective predictive model and highlight the need for detailed validation and further development of the index.

The variability and 'wedge shaped' response observed for PSI to fine sediment metrics are at least partly due to the natural variability in biological communities (Resh & Jackson, 1993) and natural habitat variables (Zweig & Rabeni, 2001). It may also be attributed to the invertebrates responding to multiple stressors (Ormerod *et al.*, 2010), although, as these are reference condition sites, it is more likely to be due to the quality of the underlying biological or fine sediment data (Friberg, 2010). For example, there is likely to be significant error introduced by utilising these sediment metrics which are annual averages, and (i) are not necessarily intended to quantify the rate or degree of sedimentation, (ii) do not necessarily provide information on the sediment conditions preceding the biological sampling and (iii) rely on the visual assessment method (deposited sediment) which is subjective and will have been collected by different observers potentially adding to the variance (Wang, Simonson & Lyons, 1996). Despite these limitations, the visual assessment data used in this study benefit from its large spatial coverage and high number of 'reference condition' sites.

Furthermore, Sutherland, Culp & Benoy (2012) found the visual assessment method to provide the strongest correlation of eight sediment metrics, ($r^2 = 0.78$, $P < 0.001$) to their Modified Family Biotic Index, in 15 agricultural streams in Canada. Similarly, Zweig & Rabeni (2001) observed moderate–strong correlations ($r_s = -0.534$ to -0.907, $P < 0.001$) for deposited sediment ranging from 0 to 100% fines (visual assessments) with various biological metrics across four streams in Missouri, U.S.A. The lower correlations seen in this present study may be partly due to the wide range of ecosystems and regions from which the data are collected. Nonetheless, it is important from a policy perspective that indices are applicable and standardised over larger scales (Statzner & Beche, 2010); therefore, the use of large data sets which derive from a wide range of environments are essential if we are to develop improved biomonitoring tools.

There is likely to be further error related to the inability of invertebrate sampling to collect information on the full diversity at sampling sites (Wright *et al.*, 2000). A U.K. study found that one standardised 3-min RIVPACS sample typically contained 50% of the species and 60% of the families found amongst six replicate samples at the same site (Wright *et al.*, 2000). However, the biological sampling method of kick-sampling is the U.K. standard protocol for sampling invertebrates under the EU WFD, and the biological data gained from this technique are the basis for calculating other biological indices.

To refine sediment-specific indices, it may be necessary to collect more objective and quantitative measures of deposited fine sediment, particularly as increased sedimentation is often accompanied by other factors such as flow variation, removal of riparian vegetation and nutrient enrichment, all of which will alter macroinvertebrate communities (Zweig & Rabeni, 2001). The empirical testing of the pressure–response relationship of a biological index is therefore an essential step in the development and validation process (Borja *et al.*, 2011; Friberg *et al.*, 2011); yet for *c.* 30% of biological assessment methods used in Europe for the purpose of assessing WFD ecological status, this has not occurred (Birk *et al.*, 2012).

Effect of taxonomic level and taxonomic resolution on the performance of the PSI index

The results suggest that whilst the taxonomic level (number of species) used to calculate the PSI score had little effect on the performance of the PSI index, increasing the taxonomic resolution (family to species level data) increased the strength of the relationship with fine sediment metrics. The effect of taxonomic resolution on biological indices has been an extensively reviewed topic, with consensus being that species identification is preferred due to the variability of sensitivity within families and genera (Furse *et al.*, 1984; Resh & Mcelravy, 1993; Schmidt-Kloiber & Nijboer, 2004; Monk *et al.*, 2012). The collection and use of species data are often considered to be appropriate as ecological niche theory states that each species is adapted to thrive in a specific range of environmental variables (Grinnell, 1917; Hirzel & Le Lay, 2008). Identification to a coarser taxonomic resolution may be time- and cost-efficient, likely to result in fewer identification errors, and does not require taxonomic specialists (Furse *et al.*, 1984; Bailey, Norris & Reynoldson, 2001). The calculation of PSI scores using species data in this study shows some benefits to that of PSI scores calculated with family data, the greatest of which being for SS; $r_s = -0.51$, $P < 0.01$ (652 species) compared to $r_s = -0.41$, $P < 0.01$ (all families). This may be an important consideration for monitoring agencies with time and budget constraints. However, with more quantitative measures of deposited fine sediment, the importance of species responses may become more apparent.

Effect of substratum particle size on the performance of the PSI index

The different strength correlation coefficients between PSI and the four fine sediment metrics suggest that the correlation between PSI score and substratum varies with substratum particle size. The correlations between PSI and % silt, and clay and % sand, silt and clay were stronger than with mean SS concentration. This may be expected as the PSI index is designed to identify sedimentation, that is deposited fine sediment and not necessarily SS (Extence *et al.*, 2011). The moderate correlation between PSI and SS is likely to be due to the link between SS and deposited sediment as well as the impacts caused by the SS to aquatic invertebrates (reviewed in Bilotta & Brazier, 2008).

Independence of PSI

The results of this study show that the PSI index had a much stronger correlation with the fine sediment metrics, compared to EPT abundance and EPT richness, and was slightly more strongly correlated than LIFE, ASPT, % EPT abundance and % EPT richness, which also showed moderate relationships to fine sediment metrics; the PSI index was able to explain slightly more of the variation (% sand silt and clay: PSI, $r_s = -0.64$, $P < 0.01$ compared to % EPT abundance, $r_s = -0.59$, $P < 0.01$). Whilst this is a relatively small difference, the benefits of the PSI are that it also provides a mechanistic linkage for the invertebrate responses to fine sediment, being based on faunal traits that cause the organism to be sensitive or tolerant of fine sediment (Extence *et al.*, 2011). In contrast, the EPT indices are more generic, but nevertheless are often used as indicators of fine sediment impacts or overall habitat degradation (Wagenhoff, Townsend & Matthaei, 2012). Treating EPT indices as sediment-specific indices may potentially provide misleading results in some situations, given that some EPT are relatively tolerant of fine sediment (e.g. many Caenidae and Limnephilidae species). Despite this, other studies have shown weak to strong correlations between fine sediment metrics and EPT indices. Angradi (1999), for example, observed relatively subtle changes to EPT taxa richness, at sites with a narrow range of sediment characteristics (5–30% fine sediment, < 2 mm), whereas Zweig & Rabeni (2001) found Spearman's rank correlations between visual assessments of fine deposited sediment and EPT density and EPT richness which ranged from $r_s = -0.498$ to $r_s = -0.868$, $P < 0.01$. These strong correlations may be due in part to the experimental design which included sampling only four streams, and, other than fine sediment characteristics, attempted to minimise habitat variables. Another study of 18 streams (32 reaches) found that at the reach-scale, fine sediment could not be related to EPT indices, but at the patch-scale, in eight streams (12 reaches), significant declines in EPT richness (25% less EPT taxa) were found at sediment-rich sites (Larsen, Vaughan & Ormerod, 2009). These studies are in contrast to the present study which includes over 835 sites (three seasons, $n = 2502$), with a wide range of different temperate river and stream ecosystems. EPT relative abundance has also previously been shown to be moderately correlated to visual assessments of fine sediment (Sutherland *et al.*, 2012; Burdon, Mcintosh & Harding, 2013).

All indices showed at least some moderate relationships with fine sediment metrics, but all were strongly correlated with the PSI score, demonstrating the need for further development of the PSI index if it is to be considered a fine sediment-specific index. The positive correlation between PSI and ASPT ($r_s = 0.82$, $P < 0.01$) and PSI and LIFE can be expected as higher scoring taxa are likely to be more prevalent at sites with higher PSI scores (sites with better water quality and faster flows).

Additionally, the strong statistically significant correlation between PSI and LIFE (r_s = 0.92, P < 0.01) may be due to the relationship between flow and fine sediment transport-deposition (Matthaei, Piggott & Townsend, 2010). Similar correlations between PSI, LIFE and ASPT were also observed in two contrasting catchments in the south west of the United Kingdom (see: Glendell *et al*., 2013). In contrast, a study of conservation priority habitats (woodland, agri-environment schemes and organic farming) in the Upper Thames catchment reported a link between PSI and these land uses, with no such link for the LIFE index. This suggests a certain independence between PSI and LIFE, although the lack of fine sediment metrics in the study prevents the PSI index being conclusively linked to sedimentation (Poole *et al*., 2013).

Future evaluation of the PSI index

This study represents the first evaluation of the PSI index, across a wide range of temperate rivers and streams. Given the importance of empirically testing the ability of biological indices to identify particular stressors, further work is needed in order to validate the PSI approach. Whilst this study highlights the relationship between the PSI index and visual assessment of the percentage of substratum consisting of sand, silt and clay, it also shows the large variances observed, even at reference condition sites.

With the documented methods for measuring deposited fine sediment consisting largely of destructive, semi-quantitative and subjective techniques, the understanding of deposited fine sediment dynamics and the pressure–response relationship would benefit from a more objective, quantitative method at the reach-scale. In addition, information on the size and geochemical composition of the sediment may help disentangle the pressure–response relationship. Data from a more objective, quantitative method of measuring deposited fine sediment could benefit the further development of the PSI index, with the aim of enabling accurate predictions of the levels of fine sediments, along with estimates of uncertainty.

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