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Original Articles

Evaluating the performance of taxonomic and trait-based biomonitoring approaches for fine sediment in the UK

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ABSTRACT

Fine sediment is a leading cause for the decline of aquatic biodiversity globally. There is an urgent need for targeted monitoring to identify where management methods are required in order to reduce the delivery of fine sediment to aquatic environments. Existing sediment-specific biomonitoring indices and indices for general ecological health (taxonomic and trait-based) developed for use in the UK were tested in a representative set of lowland rivers in England that consisted of a gradient of fine sediment pressures (deposited and suspended, organic and inorganic). Index performance was modelled against environmental variables collected during sampling and hydrological and antecedent flow variables calculated from daily flow data. Sediment-specific indices were indicative of surface sediment deposits, whereas indices for general ecological health were more closely associated with the organic content of fine sediment. The performance of biotic indices along fine sediment gradients was predominantly dependent on hydrological variability. Functional diversity indices were poorly related to different measures of fine sediment, and further development of traits-based indices and trait databases are recommended. In summary, the results suggest that sediment-specific biomonitoring tools are suitable for evaluating fine sediment stress in UK rivers when index scores are viewed within the context of local hydrology.

1. Introduction

Excess delivery of fine sediment (particles < 2 mm) is considered a significant pressure to aquatic systems globally. The environmental impacts of fine sediment are widespread and represent a significant threat to ambitions for meeting targets of ecological quality (Owens et al., 2005; Wilkes et al., 2019). Physical methods of measuring fine sediment, while useful, can be time consuming, prone to errors and fail to integrate the conditions of the catchment, often only representing conditions at a single point in time (i.e. instantaneous rather than integrated over time) (Extence et al., 2013). Biomonitoring offers advantages for tracking pressures (including excessive sedimentation) that would otherwise be challenging and / or costly to monitor directly. A community wide approach of biomonitoring involves the use of biotic indices (Bonada et al., 2006; Rosenberg and Resh, 1993). An index system works by assigning each taxon a score based on their ecological preference. The scores can either be derived from expert knowledge, through an empirical approach, or a combination of both (Birk et al., 2012). Aquatic macroinvertebrates are uniquely suited for biomonitoring. They are abundant and near-ubiquitous in freshwaters, exhibit a large response diversity and are relatively easy to identify (Johnson et al., 1993; Relyea et al., 2012). The most well-developed index in the UK, the Walley Hawkes Paisley Trigg index (WHPT) (Paisley et al., 2014; Walley and Hawkes, 1997, 1996), which is a development of the Biological Monitoring Working Party (BMWP) score (Biological Monitoring Working Party, 1978), is used as a general indicator of aquatic health. This index is currently used by UK regulatory authorities to assess the biological status of water bodies.

Pressure-specific indices are those that are optimised to detect community responses to a single stressor. Given the continued degradation of natural environments, these indices can be useful to help disentangle ecological responses in environments which are exposed to

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multiple-stressors (Berger et al., 2018). Over the last two decades, numerous fine sediment-specific indices have been developed globally to quantify the response of the ecological community to fine sediment stress (e.g. Doretto et al., 2018; Gieswein et al., 2019; Hubler et al., 2016; Relyea et al., 2012; Zweig and Rabeni, 2001). In the UK, several indices have been proposed for adoption by management authorities using contrasting approaches in their development making direct comparisons difficult (Table 1). The Proportion of Sediment-sensitive Invertebrates (PSI; Extence et al. 2013) index was initially developed using expert opinion, and later optimised using empirical weightings (EPSI; Turley et al. 2015, 2016). In contrast, an entirely data driven approach was used in the development of the Combined Fine Sediment Index (CoFSI; Murphy et al. 2015). The CoFSI index is the combination of two indices; oFSI represents the organic fine sediment index, and ToFSI is the total fine sediment index. A key part of the development of any biomonitoring index, and even more so for pressure-specific indices, is testing against known gradients of the particular stressor to understand its predictive power, (e.g., by correlation, Birk et al., 2012). Despite the different ways in which CoFSI and EPSI were developed, they have remarkably similar correlations with measures of fine sediment when tested at the community level (Table A.1). Their performance is considered to be within the range for other indices used in the implementation of the Water Framework Directive (Birk et al., 2012). However, when considering the scores or weightings of individual taxa under both indices, there are clear discrepancies (Fig. A.1, Wilkes et al., 2017), indicating differences in the mechanistic basis of the indices - ultimately a relic of their respective development methods.

The utility of the PSI- and CoFSI- related indices has been clearly demonstrated during their development. Further research on their performance alongside other environmental drivers such as antecedent flow will help improve understanding of how these indices perform. Prevailing abiotic conditions will have both a biological and geomorphological interaction on sediment-specific index performance either directly by affecting the invertebrate community and/or indirectly by controlling fine sediment dynamics in stream. Flow is intrinsically linked with fine sediment dynamics in rivers. Slower flowing environments typically have a lower dissolved oxygen concentration and will be more susceptible to sediment deposition through transport limitation. Both EPSI and CoFSI have been shown to have strong correlations with LIFE (Lotic Index for Flow Evaluation; Extence, Balbi, and Chadd 1999) and WHPT (Walley Hawkes Paisley Trigg; Walley and Hawkes 1996) scores when analysed over large scales at many sites (Murphy et al., 2015; Turley et al., 2016, 2015). This is likely because taxa that are sensitive to excess fine sediment are also sensitive to the gradients measured by WHPT and LIFE. The optimal index will be able to detect a particular pressure across its entire gradient regardless of comparable responses to other pressures.

Table 1
A summary of the four main indices (in chronological order) developed for use in sediment specific biomonitoring in England.

Index	Fine sediment gradient used in calibration	Method of development	Number of scoring taxa
PSI (Extence et al., 2013)	Percentage fine grained sediment (visual estimates)	Expert knowledge	1030 (abundance weighted)
EPSI (Turley et al., 2015)	Percentage fine grained sediment (visual estimates)	Expert knowledge and empirical weightings	433 (abundance weighted)
CoFSI (Murphy et al., 2015)	Total fine-grained sediment mass (disturbance method)	Entirely empirical	105 (presence/ absence)
EPSImixed (Turley et al., 2016)	Percentage fine grained sediment (visual estimates)	Expert knowledge and empirical weightings	424 (abundance weighted)

Historically, most biotic indices have been developed using taxonomic approaches, which relate species assemblages to environmental conditions by combining individual taxon responses at the community level. More recently, interest has developed in functional trait-based approaches to biomonitoring. Functional traits are assigned based on the physiological, morphological, ecological and life-history features of an organism (Verberk et al., 2013). Integrating functional traits in biomonitoring applications is based on the theory that traits are filtered according to the prevailing abiotic and biotic conditions (Statzner et al., 2004). An advantage of trait-based approaches is that they are less sensitive to taxonomic variation across biogeographic regions (Wilkes et al., 2020). Quantifying functional trait diversity within a river system may help to explain interactions that have been missed using taxonomic diversity alone. Detecting a functional response can provide an indication of why a change in abundance may be occurring (rather than purely observing that a change has occurred) (Culp et al., 2011). However, the utility of trait-based biomonitoring for fine sediment pressure remains ambiguous.

Therefore, there is a need to independently test a range of indices to understand how sediment-specific biomonitoring tools can be used to enhance monitoring and management of fine sediment in the UK. This study will expand on existing reviews of macroinvertebrate responses to fine sediment (e.g. Buendia et al., 2013a; Conroy et al., 2016; Doretto et al., 2018) by evaluating performance against a range of environmental and flow pressures. Our objectives were to: (1) test the performance of sediment-specific biomonitoring indices and compare this to the performance of other, non-sediment-specific (non-specific) indices, and (2) determine which environmental variables and flow conditions affect index performance. Based on the methods used in their development, it was hypothesized that the PSI derived group of indices and the CoFSI index would be most indicative of visual estimation of fine sediment deposition and total surface sediment respectively (see Table 1).

2. Methods

2.1. Field methods

In the UK, most lowland rivers are transport-limited in relation to fine sediment and are therefore susceptible to sediment accumulation (Naden et al., 2016). In order to collect data that were robust and representative of (semi-) natural conditions across lowland rivers in England, sites sampled were required to meet a pre-determined set of criteria: provide a good spatial distribution; be representative of river types characteristic of lowland UK; consist of a range of fine sediment pressures (e.g. high or low fine sediment pressure, high or low organic content in fines); and be minimally affected by disturbance from other factors which may confound the effects of fine sediment (e.g. water quality and habitat). Sites were selected by filtering from an existing national monitoring network acquired from the Environment Agency (the regulatory authority of England) (Lathouri et al., 2021). The network was filtered by: water quality (removing sites failing for dissolved oxygen and ammonia for one or more seasons within the previous three years); river type (retaining only sites classified as 'lowland' by the River InVertebrate Prediction And Classification System, (RIVPACS, Wright et al., 1998)); habitat quality (removing sites with extensive channel works considered to affect the natural erosion, transport and deposition of sediment); and hydrology (retaining sites within 2 km of an active flow gauging station). After the filtering process and considering site accessibility, 21 sites were identified as suitable (Fig. 1).

To take account of natural seasonal variation in life-history patterns of diverse macroinvertebrate species, the standard national monitoring practice of sampling macroinvertebrate communities during spring (March-May) and autumn (September-November) was followed. Upon identification of the sampling reach, macroinvertebrate sampling was

Fig. 1. Twenty-one sites in England sampled in spring and autumn (N.B. the proximity of two sites in south-west England plot as a single marker).

carried out using a three-minute semi-quantitative, multi-habitat survey, followed by a one-minute manual hand search, according to standard kick net sampling protocol (Environment Agency, 2014a; Friberg et al., 2006). Macroinvertebrate samples were identified to mixed taxon level (predominately species) following the standard operating procedure of the Environment Agency (2014b).

The fine sediment field data collection follows that of McKenzie et al. (2021). In summary, at each site a 50 ml background water sample was collected to quantify the suspended sediment concentration (SSC mg l^{-1}) at the time of sampling. Two methods of measuring deposited fine sediment were carried out at each site: the disturbance method and visual estimates. These approaches were chosen since they were used in the development of the sediment-specific biomonitoring indices under evaluation in this study. Fine sediment collection via the disturbance method was carried out following Duerdoth et al. (2015). This fully quantitative assessment, also known as the resuspension method, was originally developed by Lambert and Walling (1988) and later Collins and Walling (2007a, 2007b). An open-ended cylinder of 560 mm diameter was pushed into the gravel bed to form a seal and the overlying water depth measured. The water overlying the gravel bed within the cylinder was then vigorously agitated for 60 s using an electric drill with a plaster mixing attachment (to standardise the mixing and reduce any vertical gradient) (Collins et al., 2013) and sampled immediately following agitation. This first water sample represents the surface sediment as only the overlying drape is drawn into suspension by the agitation. This was followed by 30 s of agitation of the gravel bed to a depth of 100 mm using a metal auger and a further 30 s of agitation of the water column using the drill. This second sample represents the total fine sediment of the gravel bed as it contains both the overlying surface drape and the sediment embedded within the top layers of the gravel. The process was undertaken four times in each sampling reach, twice in areas of erosional flow and twice in areas with depositional flow. Each water sample was filtered through a GF/C Whatman glass microfibre filter paper, dried, and weighed. The total organic content for each sample was obtained by mass loss on ignition at 500 °C for 30 min. The concentration of sediment from the water samples was converted to a mass of sediment per unit area of riverbed. The total sediment within the sampling reach was calculated as the geometric mean of the two erosional and two depositional samples (Duerdoth et al. 2015).

Visual estimates of fine sediment within the sampling reach were carried out following the River Habitat Survey Guidance manual (Environment Agency, 2003). For each reach the operator estimated the percentage of substratum using size categories clay (cohesive material), silt (<0.0625 mm), sand (0.0625 – 2 mm), gravel (2 – 4 mm), cobbles (64 – 256 mm) and bedrock/boulders (>256 mm). The percentage fine sediment within each reach was calculated as the total sum of the sand, silt, and clay fractions.

Several other abiotic variables were recorded at each study site: mean wetted channel width (m), mean channel depth (m), channel shading (%), in-channel macrophytes (%), filamentous/non-filamentous algae (%), detritus (%), bed stability (i.e., stable, unstable, soft), and presence of local flow types (i.e., riffle, pool etc). Additional environmental variables were obtained from baseline data (provided by the Environment Agency): altitude (m), distance from source (km), slope (m km^{-1}), discharge category (m^3 s^{-1}). As an estimate of the quantity of fine sediment from agricultural origin delivered to river reaches through run off, the Agricultural Sediment Loading (ASL) index was also obtained for each site (Naura et al., 2016). The ASL index is derived from GIS mapping processes through the Phosphorous and Sediment Yield CHaracterisation In Catchments (PSYCHIC) model (Collins et al., 2007; Davison et al., 2008; Strömqvist et al., 2008).

2.2. Data preparation

The fuzzy coded (Chevene et al., 1994) European trait database of Tachet et al. (2010) was used to assign trait scores to each taxon (see Table A.2 for a full list of trait categories). This trait database was chosen as it is one of the most comprehensive databases and is widely used in ecological studies (Dangles et al., 2004; Gulis et al., 2006; Statzner and Bêche, 2010). Only true traits, and not preferences, were assigned to each taxon (Violle et al., 2007). True traits classify taxon based on biological profiles (i.e. maximum body size, feeding group, mode of respiration) as opposed to an ecological preference (e.g. saprobity or salinity preferences) (Statzner and Bêche, 2010; Verberk et al., 2013). Functional trait diversity was calculated using the dbFD function in the *FD* package in R (Laliberté et al., 2014). Prior to calculating functional diversity (FD), the traits were converted to proportions within trait categories, then each trait modality was centred (following Chevene et al., 1994). The dbFD function implements a distance-based framework to compute multidimensional functional indices (Laliberté et al., 2014). The FD indices calculated were functional richness (FRic; Villéger, Mason and Mouillot 2008), functional dispersion (FDis; Laliberté and Legendre 2010) and the community-level weighted means (CWMs) of trait values for shredders (Lavorel et al. 2007). The CWMshredders and shredder percentage (CWMshredders relative to the CWMs of all feeding groups) was chosen as existing literature has pointed to shredders showing a particular sensitivity to fine sediment (Rabení, Doisy and Zweig 2005; Scott and Zhang 2012; Mathers, Rice, and Wood 2017). As well as the sediment-specific biomonitoring indices and FD indices, indices used in national biomonitoring practices were calculated (Table 2). For indices scored at family level, the *biotic* package in R was used (Briers, 2016).

Mean daily flow (m^3 s^{-1}) was obtained from the National River Flow Archive for each site for the period 01/01/2000 – 31/05/2017. Missing data were imputed using the *missForest* package (Stekhoven and Buhlmann, 2012) and standardized (e.g. Mathers et al., 2019b). A number of metrics of flow regime and antecedent flow were calculated (Tables A.3

Table 2
A full list of macroinvertebrate indices calculated for analysis.

Index	Short name
Proportion of Sediment-sensitive Invertebrates	PSI
Empirical Proportion of Sediment-sensitive Invertebrates	EPSI
Empirical Proportion of Sediment-sensitive Invertebrates mixed - contains more mixed taxa level scoring (i.e., species, genus and family) than EPSI.	EPSImixed
Combined Fine Sediment Index	CoFSI
Organic Fine Sediment Index (constituent of CoFSI)	oFSI
Total Fine Sediment Index (constituent of CoFSI)	ToFSI
Wally Hawks Paisley Trigg Index - average score per taxon	WHPT_ASPT
Wally Hawks Paisley Trigg Index - number of scoring taxa	WHPT_NTAXA
British Biomonitoring Working Party score	BMWP
British Biomonitoring Working Party - average score per taxon	BMWP_ASPT
British biomonitoring working party - number of scoring taxa	BMWP_NTAXA
Lotic Index Flow Evaluation	LIFE
Percentage of Ephemeroptera, Plecoptera and Trichoptera	%EPT
Abundance	Abundance
Shannon's Diversity	Shannons
Functional richness	FRic
Functional dispersion	FDis
Percentage of shredder taxa	Shredderpercentage
Community weighted means (extracted from dbfd) of shredders	CWMshredder

and A.4) and the high degree of redundancy reduced using dimensionality reduction (Monk et al., 2007; Olden and Poff, 2003; White et al., 2017). See McKenzie et al. (2021) for more details of this process.

2.3. Data analysis

Spearman's rank correlation was used to assess the performance of the indices against fine sediment metrics, with p values for pairwise comparisons undergoing Holm-Bonferronni corrections (Holm, 1979). Linear models were used to relate site-level biotic index scores to individual gradients of fine sediment (e.g., Fig. 2). Sediment variables were transformed ($\log_{10}(x + 1)$ for visual estimates and arcsin sqrt for all other metrics) prior to analysis to reduce skewness. The residuals from these models were then assessed against a combination of environmental variables. The hydrological metrics retained from the dimensionality reduction procedure were combined with the other environmental data recorded at site or from baseline data (e.g., width, depth, shading, altitude etc.) to derive a full list of predictors. Ordinal variables (e.g., bed stability) were converted to numerical values for analysis. Local flow type categories were converted to a proportion of erosional (e.g., riffle or run) or depositional (e.g., pool, glide) flow types per reach. The variance inflation factor (using *corvif* function in R) was used to reduce the number of predictors based on their collinearity (Zuur et al., 2009). This process was conducted manually and the higher value of 5 (VIF < 5) was chosen to reduce the risk of excluding ecologically relevant variables. A full list of the original predictors and the refined list after the VIF analysis is in Table A.5. Model selection was used to determine whether season (spring or autumn) should be included as a fixed or random effect. The optimal models were determined as the most parsimonious model with the lowest Akaike's Information Criterion (AIC) value, or the next lowest if the difference was < 2 AIC points (Burnham and Anderson 2004). In each case, season was included only as a fixed effect (Table A.6). Predictor variables were scaled prior to the model selection process (using the *scale* function in R). Stepwise selection was used to refine the optimal models for each index (using the *StepAIC* function in R, direction = 'both').

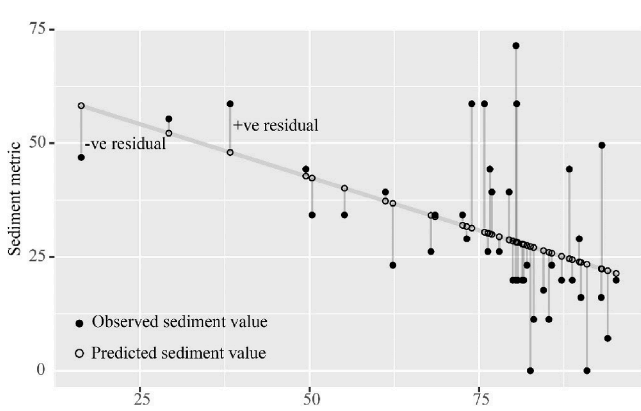

Fig. 2. Example model of biotic index-sediment metric relationships (assuming a higher biotic index score equates to a low sediment pressure). Residual sign and magnitude show the extent to which the sediment quantity is under or over predicted by the biotic index. The example here shows the visual fines metric as a function of EPSI index.

3. Results

The observed PSI and EPSI index scores covered almost the full range of possible values (PSI 7.14% – 86.67% and EPSI 16.33 – 95.21%). However, most sites scored towards the upper end of the scale, indicating that they were not particularly impacted by excess fine sediment. The CoFSI index score usually ranges from 3.0 to 6.5. The scores for the sites fell within this range (3.89 – 5.01). All PSI derived indices were significantly correlated with visual fines, with correlation coefficient size following the pattern PSI < EPSI < EPSImixed reflecting the improvement of each subsequent iteration of the index (Table 3). CoFSI correlated significantly with both visual fines (ρ = -0.54, p = 0.022) and total surface sediment (ρ = -0.55, p = 0.019). However, total surface sediment correlated most strongly with EPSImixed (ρ = -0.59, p = 0.006). The oFSI (organic fine sediment index) component correlated significantly only with total organic sediment (ρ = -0.55, p = 0.016) whilst ToFSI (total fine sediment index) was not significantly correlated with any fine sediment metrics. Total organic sediment was significantly correlated with PSI (ρ = -0.54, p = 0.018), EPSImixed (ρ = -0.58, p = 0.008), oFSI (ρ = -0.55, p = 0.016) and CoFSI (ρ = -0.52, p = 0.046). Neither total sediment nor background suspended sediment concentrations, were significantly correlated with any of the sediment-specific indices. No non-specific sediment indices had higher correlation coefficients than sediment-specific indices with visual fines or total surface sediment. The %EPT index had the strongest pairwise correlation with organic surface and total organic sediment. There were no significant pairwise correlations between the functional indices (FRic, FDis, CWMshredders or shredder percentage) and any fine sediment metrics.

Linear models were used to relate site-level biotic index scores to individual gradients of fine sediment as an alternative way of assessing index performance (Table A.7). Multiple regressions examining the influence of flow and environmental variables on sediment-specific (Fig. 3) and non-specific index performance (Fig. 4) highlighted the importance of antecedent hydrological metrics. In particular, the flow that was exceeded 50% of the time in the previous summer (Q50preSum) was strongly associated with high positive residuals for visual estimates and surface sediment metrics across both EPSI and CoFSI indices (Fig. 3a-d). In contrast, the same antecedent flow variable was strongly associated with negative residuals for the organic surface metric under the EPSI model (Fig. 3e). A similar pattern was found for non-specific indices, with Q50preSum having a positive effect on residuals for visual estimates in the LIFE model (Fig. 4a) but a negative effect on organic sediment metrics for a range of other indices (Fig. 4b, d, e, f). Other variables which were retained in several models, albeit with lower estimate sizes, included bed stability, filamentous algae, macrophytes, detritus and the ASL index.

Table 3
Spearman's rank correlation matrix of observed biomonitoring index scores against fine sediment metrics. Asterisks show significant correlation pairs ($p < 0.05$) and values in bold represented the strongest individual pairwise correlation for each sediment metric.

	Visual fines	Surface sediment	Organic surface	Inorganic surface	Total sediment	Total organic	Total inorganic	SSC
PSI	−0.57*	−0.53	−0.50	−0.51	−0.45	−0.54*	−0.44	−0.28
EPSI	−0.60*	−0.51	−0.41	−0.49	−0.45	−0.50	−0.44	−0.23
EPSI mixed	**−0.65***	**−0.59***	−0.50	**−0.56***	−0.50	−0.58*	−0.49	−0.29
oFSI	−0.37	−0.39	−0.48	−0.36	−0.35	−0.55*	−0.33	−0.25
ToFSI	−0.45	−0.41	−0.18	−0.41	−0.29	−0.17	−0.31	−0.25
CoFSI	−0.54*	−0.55*	−0.51	−0.54*	−0.43	−0.52*	−0.44	−0.13
WHPT ASPT	−0.42	−0.48	−0.47	−0.47	−0.49	−0.59*	−0.48	−0.35
WHPT Ntaxa	−0.21	−0.45	−0.36	−0.50	−0.42	−0.40	−0.42	−0.06
BMWP	−0.26	−0.49	−0.42	−0.48	−0.46	−0.49	−0.46	−0.11
LIFE	−0.52	−0.43	−0.52	−0.41	−0.34	−0.52	−0.32	−0.08
%EPT	−0.49	−0.48	**−0.56***	−0.48	−0.49	**−0.66***	−0.48	−0.21
Abundance	−0.45	−0.51	−0.39	−0.52	−0.35	−0.31	−0.37	−0.09
Shannon index	−0.03	−0.20	−0.22	−0.17	−0.21	−0.26	−0.20	−0.05
FRic	−0.06	−0.33	−0.13	−0.33	−0.27	−0.14	−0.28	−0.07
FDis	0.30	0.13	0.16	0.15	0.03	0.10	0.04	−0.01
Shredder percentage	−0.02	−0.11	−0.06	−0.09	0.02	0.00	0.03	−0.10
CWM shredder	−0.02	−0.07	−0.10	−0.06	−0.03	−0.04	0.03	−0.07

4. Discussion

Excessive fine sediment remains a significant threat to freshwater environments. Understanding the effects of fine sediment on macroinvertebrate communities is crucial in the development of appropriate monitoring practices and multiple efforts over the last decade have sought to develop sediment-specific biotic indices (Extence et al., 2013; Murphy et al., 2015; Turley et al., 2015). This paper reviews the performance of these sediment-specific indices and a suite of other biotic indices used for assessment of riverine health in the UK. We also consider their interaction with other abiotic and flow variables in influencing their performance in detecting fine sediment stress.

Using traditional methods for biotic index assessment (Spearman's rank correlation coefficient), the empirically enhanced EPSI mixed taxon level index demonstrated the strongest correlation with visual estimates for fine sediment. This supports our first hypothesis, i.e. that the PSI derived group of indices would be strongly correlated with visual estimates of surface deposition. On the other hand, we found no support for our hypothesis that the CoFSI index would be strongly correlated with total surface sediment. No indices showed significant associations with total sediment with indices clearly responding to the surface sediment and organic content. Most macroinvertebrate taxa live on the surface of the riverbed or at least within the uppermost layers of sediment, with only meiofauna and some macrofauna penetrating the subsurface layers. Macroinvertebrates have been shown to use the hyporheic zone during disturbances such as floods (Lancaster and Hildrew, 1993a, 1993b) or dewatering (Patel et al., 2021; Vadher et al., 2018). Availability of hyporheic refugia can be impacted via surface deposition and filling of interstices through colmation (Loskotová et al., 2019; Mathers et al., 2019a; Patel et al., 2021). However, we found no clear associations between index scores and total sediment during baseflow conditions.

Both sediment-specific indices and non-specific indices showed a significant association with the organic component of fine sediment. While organic matter is vital as a food source for benthic organisms, anthropogenic disturbances can alter the trophic state of riverine systems. An increase in organic matter can increase metabolic rates at the ecosystem level, particularly by bacteria decomposing the organic material, which increases the requirement for oxygen (biological oxygen demand) (Bjornn and Reiser, 1991). The oFSI index is specifically related to organic fine sediment and the results of this study support the idea that the oFSI index is detecting a response to organic stress. When modelling individual taxon scores for the oFSI index with their corresponding trait scores, Wilkes et al. (2017) showed oFSI to be strongly related to traits describing respiration. High organic content in fine sediments can cause chemical changes in the benthic zone and reduce oxygen availability for aquatic organisms (Von Bertrab et al. 2013). Flocculation of organic matter facilitates the settling and storage of particles on the stream bed (Burban et al., 1990). These deposited particles can cause 'capping or blocking' of intra-gravel flow which exacerbates the effect of smothering from inorganic particles and reduced oxygen from organic particles (Owens et al., 2005). Organisms with a tolerance for low oxygen environments, such as the families Asellidae, Viviparidae and Sialidae (Jones et al., 2009; Surber and Bessy, 1974), tend to dominate in areas affected by sediment deposition (Hinchey et al., 2006). However, other non-specific indices also indicated a potentially stronger relationship with organic metrics. The WHPT (ASPT), and %EPT indices had stronger associations with organic content of fine sediment than the sediment-specific indices. Despite undergoing several rounds of optimisation, and often used as an index for general ecological health, WHPT was originally based on organic pollution sensitivity (i.e. BMWP; Armitage et al., 1983; Paisley et al., 2014). This most likely explains why the WHPT index is closely associated with the organic component of fine sediment.

The %EPT index appears to have no significant association with total surface sediment or visual fines but displayed the strongest statistical relationship with total organic sediment relative to any other biotic index tested here. Ephemeroptera, Plecoptera and Trichoptera are true aquatic insects (Class: Insecta) and are generally considered to be sensitive to habitat and water quality. Several variations of EPT as a biotic index exist in the literature (e.g., EPT richness, EPT abundance, %EPT richness, EPT relative abundance). The sensitivity of the EPT index to fine sediment is supported by existing evidence from the literature (Bona et al., 2016; Descloux et al., 2013; Larsen et al., 2011; Piggott et al., 2015). Conroy et al. (2016) documented %EPT abundance as the best identifier of fine sediment stress from a combination of field and laboratory experiments. The results of the present study support the use of %EPT as an indicator of the organic content of fine sediment. Using the %EPT index in conjunction with a sediment-specific index (e.g., CoFSI or EPSImixed) as a monitoring tool could help distinguish between fine sediment pressures in aquatic environments driven by the surface sediment or the proportion of organic matter. All sediment-sensitive indices evaluated in this study require analysis of macroinvertebrate samples to species level (with EPSImixed including scores at family level). The time and effort involved in identification to this taxonomic level is costly and can often be prohibitive to its wider adoption due to the specialist training required. Both WHPT and EPT indices can be used at the family level. Despite the large differences in sensitivity between species within the same family, species level identification sometimes provides limited additional information for the effort required to identify to this resolution (e.g. Chironomidae, Zweig & Rabeni, 2001). The EPT index has additional benefits over sediment-specific indices that are typically

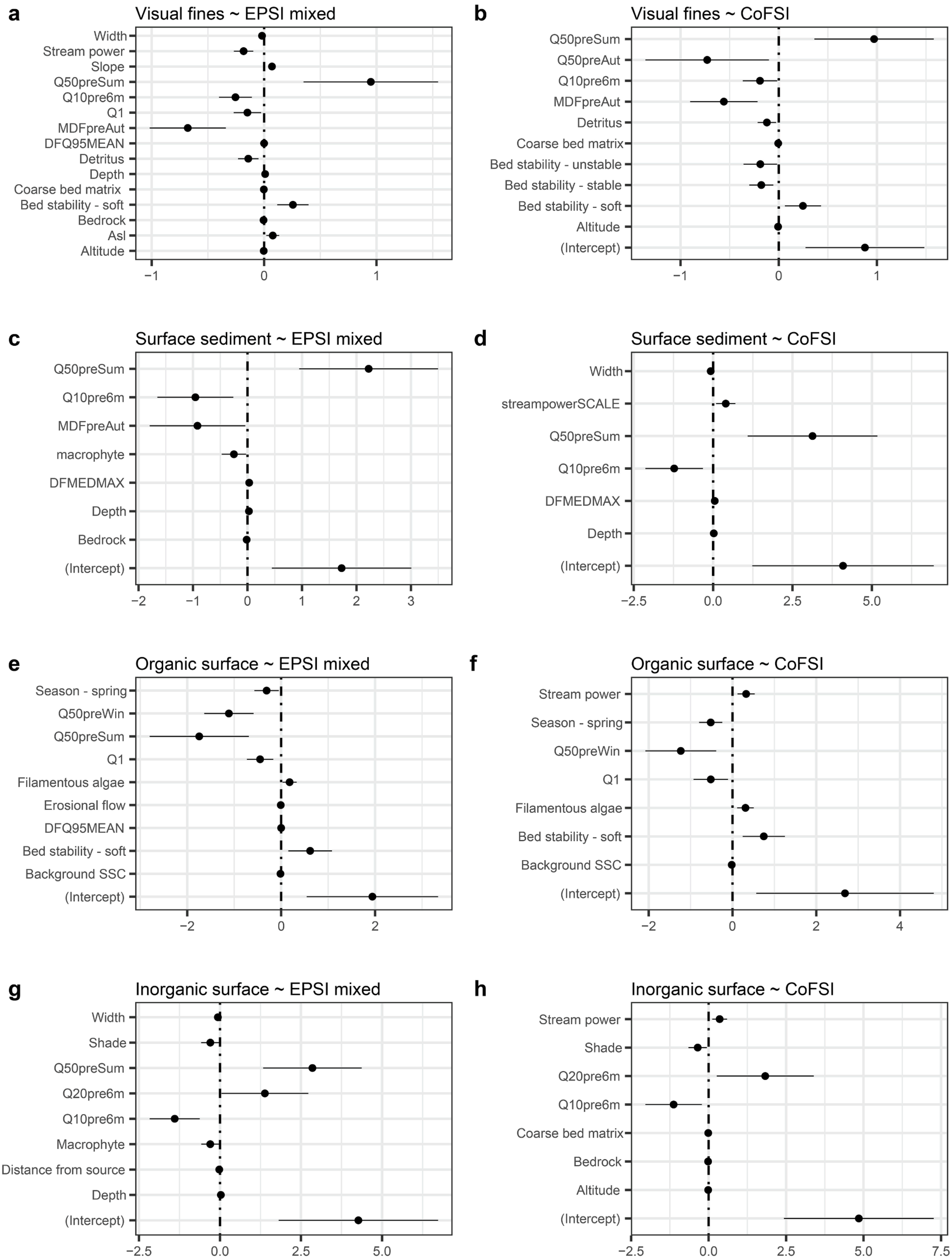

Fig. 3. Estimate sizes for predictors contributing to the residuals of site level sediment-specific biotic index scores and metrics of fine sediment. Only significant predictor variables are presented in each figure ($p < 0.05$).

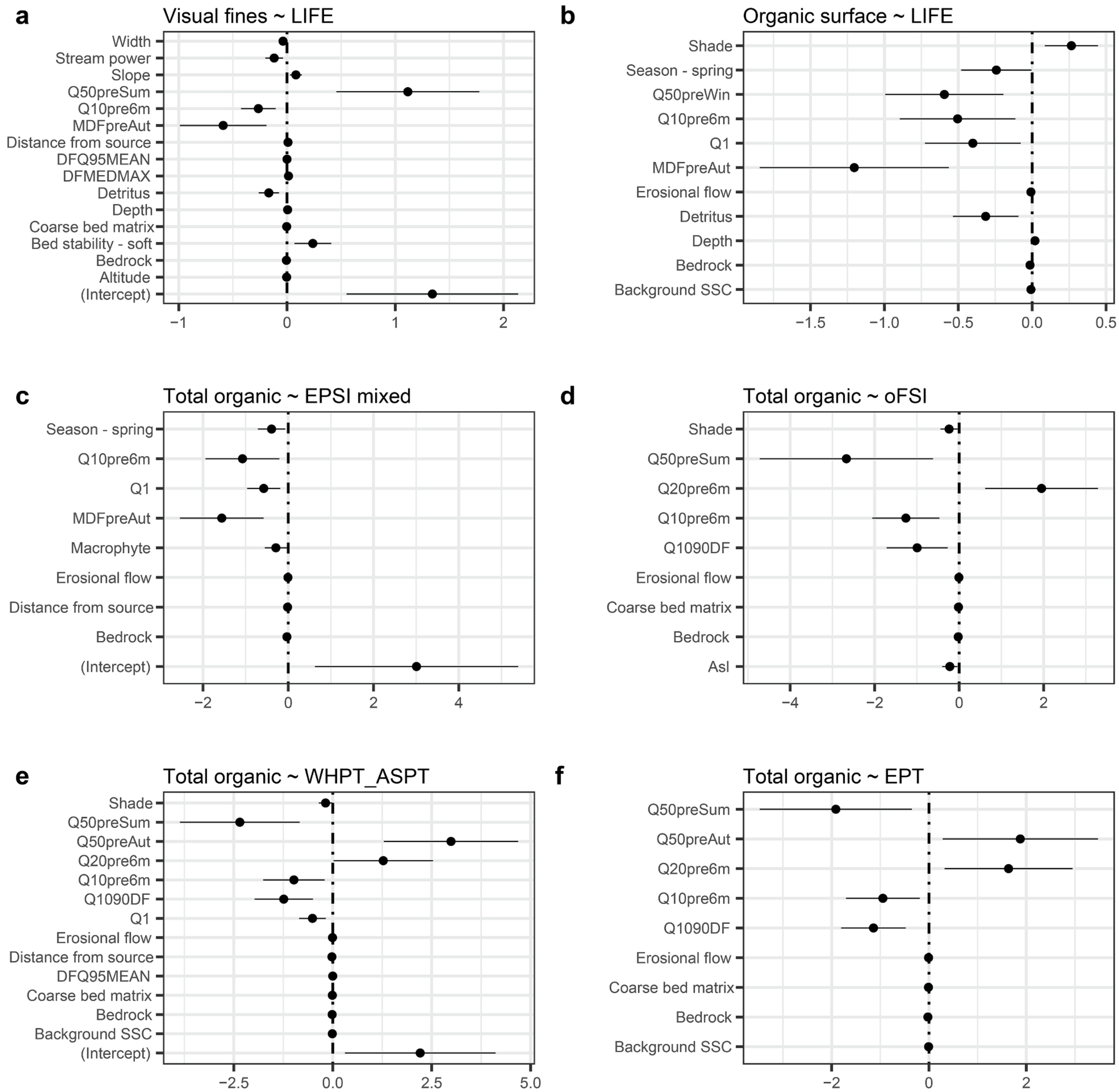

Fig. 4. Estimate sizes for predictors contributing to the residuals of site level non-specific biotic index scores and metrics of fine sediment. A selection of models (those with high goodness-of-fit) shown in Table 3 are presented in the figure. Only significant predictor variables are presented in each figure ($p < 0.05$).

limited to application within the country in which they are developed in that it is universal and without reliance on a regional or national taxa specific scoring system.

Functional trait-based indices, either at the community (functional richness and functional dispersion) or individual trait (shredders) level, were poorly associated with fine sediment in this study. Individual functional feeding trait group responses to fine sediment are commonly reported in the literature. An increase in fine sediment deposition can bury food resources (Couceiro et al., 2010), affect quality and quantity of periphyton (Buendia et al., 2013a), reduce exchange of water and dissolved substances (i.e. hyporheic exchange flow) (Descloux et al., 2014) and dilute available food resources (Broekhuizen et al., 2001). Shredder sensitivity is the most unequivocal trait-fine sediment relationship reported in the literature (e.g. Doretto et al., 2017; Louhi et al., 2017; Mathers et al., 2017; Rabení et al., 2005; Scott and Zhang, 2012). The mechanisms behind shredder sensitivity are thought to be associated with burial of leaf litter and a reduction in its quality through inhibition of fungal growth (Couceiro et al., 2010; Doretto et al., 2016; Louhi et al., 2017). Additionally, Wilkes et al. (2017) found shredders to be consistently associated with sensitivity scores across five fine sediment-specific indices (PSI, EPSI, CoFSI, oFSI and ToFSI). The lack of associations found during this study between community level functional indices and fine sediment suggests that combining all trait categories (e.g., measures of functional diversity) may not be the most appropriate method for detecting responses. Some functional traits may not have a linear response to fine sediment. Evidence suggests filter-feeders have a subsidy-stress response whereby an initial increase in fine sediment could increase food supply and be beneficial for filter feeders. As fine sediment continues to increase further, filter feeding becomes ineffective as feeding apparatus becomes clogged and gut filling by inorganic particles occurs (Fossati et al., 2001; Lemly, 1982; Strand and Merritt, 1997). It is clear that trait-based approaches need further work through either development of the trait-based indices or the trait databases themselves. Wilkes et al. (2017) recommended a refined set of traits specifically for fine sediment biomonitoring, including the ability or potential to excavate in the event of fine sediment burial (Conroy et al., 2018; Wood et al., 2005); splitting the filter-feeding trait modality into those that can and cannot excrete excess fine sediment (Fossati et al., 2001; Lemly, 1982; Strand and Merritt, 1997); and, behavioural or anatomical adaptations allowing gill respiration in highly sedimented environments (McKenzie et al., 2020). However, such refinements to the trait categories are currently not present or do not have enough mechanistic information behind them to enable such reclassification.

Macroinvertebrate community change as a result of excessive fine sediment delivery to aquatic environments is likely a result of a complex mix of direct and indirect effects. There is little evidence on the mechanisms which drive these effects (Buendia et al., 2013b; Connolly and Pearson, 2007; Cover et al., 2008; Culp et al., 2013). Understanding the mechanisms by which fine sediment affects communities is crucial to the development, improvement, and adoption of biological monitoring practices for fine sediment. We have sought to contribute to this understanding through assessment of the environmental variables affecting the performance of biomonitoring indices. Antecedent flow conditions appeared to be the most important predictors of index performance (by having the greatest effect on model residuals). The flow that was exceeded for 50% of the time in the previous summer (Q50preSum) was significant for all sediment-specific indices and was also the predictor with the largest coefficient-estimate size across the indices. The coefficient-estimates were positive for the visual fines and total surface sediment but negative where the variable was retained for organic sediment metrics. In other words, a higher Q50 in the previous summer meant that visual fines and total surface sediment was higher than expected (i.e., the index is underpredicting the sediment quantity), whereas organic content was lower than expected (i.e., an over-prediction). Flow is likely controlling the supply and breakdown of organic matter in river reaches. High summer flows have also been shown to be instrumental in controlling algal communities which compete with macrophyte growth (*Ranunculus* spp.) in UK chalk rivers (Wilby et al., 1998; Wright et al., 1982). River type could also play a role, with more sustained summer flows in rivers underlain by chalk or limestone compared to those dominated by surface water runoff subjected to flashy systems (Dunbar et al., 2010a). The significance of these flow metrics in the model could be a result of flow effects on macroinvertebrates as opposed to a direct link with fine sediment. Relatively high discharges could have affected macroinvertebrate recruitment at a key time in the macroinvertebrate reproductive cycle. Dunbar et al., (2010b) showed preceding summer flows to be three times as important as winter flows in affecting LIFE scores. No recent antecedent flows or local flow patterns (proportion of erosional or deposition flow) were retained in the model. Recent antecedent flow indices could have counteractive influences on macroinvertebrate communities, affecting the performance of biotic indices in complex ways. Recent high flows could have a flushing effect, removing fine sediment from the bed whilst also stimulating insect dispersal through drift or reduced abundance through scour of individual organisms (as a result of increased velocities or potentially suspension of fine sediment) (Mackay, 1992; Svendsen et al., 2004). Care should be taken when interpreting how these environmental variables effect index performance, particularly flow, due to the tentative nature of these interpretations. We recommend further investigation to determine whether these factors have a direct physical impact (i.e., by impacting sediment erosion and deposition) or an indirect ecological effect (such as recruitment or competition) on index performance (Fig. 5).

This study sought to test the performance of general and sediment-specific indices and understand which environmental variables affect their performance by measuring a broad range of abiotic variables. Whilst numerous flow and sediment variables were measured and included in the analysis, this study did not incorporate the effect of water quality (e.g., dissolved oxygen, temperature, pH) or sediment quality (e.g., sediment size distribution, presence of sediment associated contaminants). Water and sediment quality can have significant impacts

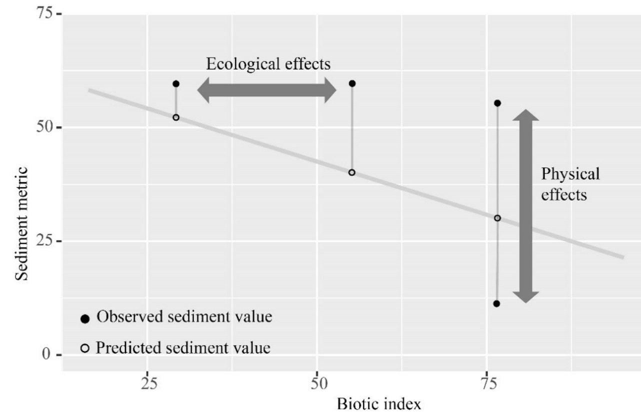

Fig. 5. Conceptual model showing the factors affecting index performance.

on macroinvertebrate community structure and therefore affect biological index performance (Azrina et al., 2006). However, the robust site filtering process conducted prior to field sampling removed any sites with poor water quality status which could confound results. We therefore believe that unaccounted for water and sediment quality effects are minimal in our study. Whilst mitigations to reduce overfitting the residual models were carried out, we recognise this risk given the large number of predictor variables relative to the number of observations in this study. Further investigations using a larger sample size would help strengthen the conclusions made here. It should be noted that many biotic variables are highly correlated with one another (Gallardo et al., 2008) and whilst the methodology applied here was rigorous in removing collinearity from any modelling analyses, such analyses raises questions surrounding the potential difficulties in isolating cause and effect of fine sediment effects on macroinvertebrates (Peres-Neto et al., 2006). Further research is therefore needed to understand the mechanisms driving macroinvertebrate responses to fine sediment.

5. Conclusion

Given the need to target actions to effectively manage fine sediment impacts it is essential that management decisions are informed by evidence using effective and appropriate biomonitoring indices. The results presented in this paper represent the first full independent assessment of sediment-specific indices developed for use in the UK as well as providing new insights into macroinvertebrate responses to fine sediment, showing how physical and ecological processes affect the performance of biomonitoring indices. Both sediment-specific and non-specific indices showed a significant association with the organic content of fine sediment, and despite large variations in sediment quantity between sites, antecedent flow seemed to be the overall driving force of index performance. The functional indices assessed in this study were not significantly related to any metrics of fine sediment. It is clear that trait-based approaches need further work through either development of the trait-based indices or the trait databases themselves.

CRediT authorship contribution statement

Morwenna McKenzie: Conceptualization, Investigation, Methodology, Data curation, Software, Formal analysis, Visualization, Writing – original draft. **Judy England:** Conceptualization, Validation, Writing – review & editing. **Ian Foster:** Conceptualization, Validation, Writing – review & editing. **Martin Wilkes:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108502.

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