Ecological Indicators 70 (2016) 209–221

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Mapping the combined risk of agricultural fine sediment input and accumulation for riverine ecosystems across England and Wales

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ARTICLE INFO

Article history:
Received 31 January 2016
Accepted 21 March 2016
Available online 23 June 2016

Keywords:
Fine sediment
Agricultural source
Diffuse pollution
Risk assessment
Geostatistics
Fish habitat
River Habitat Survey

ABSTRACT

Fine sediment inputs from agricultural sources are a potential threat to freshwater ecosystems and may impact on the ability of EU members' states to achieve environmental targets under the Water Framework Directive (WFD).

An index (the Agricultural Sediment Risk index or ASR) representing the risk of agricultural fine sediment accumulation in rivers was produced using estimates of sediment inputs from the process-based PSYCHIC model and predictions of fine sediment accumulation using River Habitat Survey data. The ASR was mapped across the entire river network of England and Wales.

The ASR map and index were combined with a national dataset of fisheries surveys using logistic regression to test its relevance to freshwater biota. The ASR was strongly associated with a group of species sensitive to fine sediment inputs including salmon and trout. Another group of species including roach and perch showed a positive association with low levels of agricultural sediment inputs potentially due to their impacts on predators and competitors.

The proposed approach demonstrates how existing national monitoring data and sediment pressure models can be combined to produce an assessment of risk to aquatic ecosystems from agricultural fine sediment sources at a national scale that can be used alongside WFD classification tools to identify potential causative pressures and design remedial actions.

1. Introduction

With increasing environmental pressures on rivers and their ecosystems, there is a need for simple, robust tools to support environmental management decision-making (Bainbridge, 2014). In Europe, the Water Framework Directive (WFD) requires member states to bring rivers to Good Ecological Status (GES) between 2015 and 2027 by reviewing existing activities and undertaking targeted remedial action (European Union, 2000).

Agriculture is considered a significant pressure on aquatic ecosystem health through the elevated inputs of nutrients, pesticides, herbicides and sediment and their impact on natural populations of fish, invertebrates, macrophytes and diatoms (Collins et al., 2011; Duerdoth et al., 2015; Gayraud et al., 2002; Jones et al., 2012a, 2014; Kemp et al., 2011). Fine sediment from an agricultural origin currently represents the majority of total fine-grained sediment delivered to watercourses across England and Wales, with an estimated 72–76% of all fine sediment considered to originate from this source (Collins et al., 2009a,b; Zhang et al., 2014).

Fine sediment (defined here as inorganic and organic particles of less than 2 mm in diameter) are known to have both positive and negative impacts on instream ecosystems whether directly (e.g. smothering and clogging) or indirectly (e.g. as vectors for contaminants). They can have direct impacts on fish species by clogging gills, reducing oxygen availability to incubating embryo, increasing stress levels, reducing visibility, carrying pollutants and modifying the morphological structure of habitats (Collins et al., 2011; Kemp et al., 2011; Kjelland et al., 2015). They can also have indirect impact on fish behaviour, feeding, swimming ability and reproduction thereby imposing longer term effects on population structure and resilience (Kjelland et al., 2015). Fine sediment also affects

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http://dx.doi.org/10.1016/j.ecolind.2016.03.055

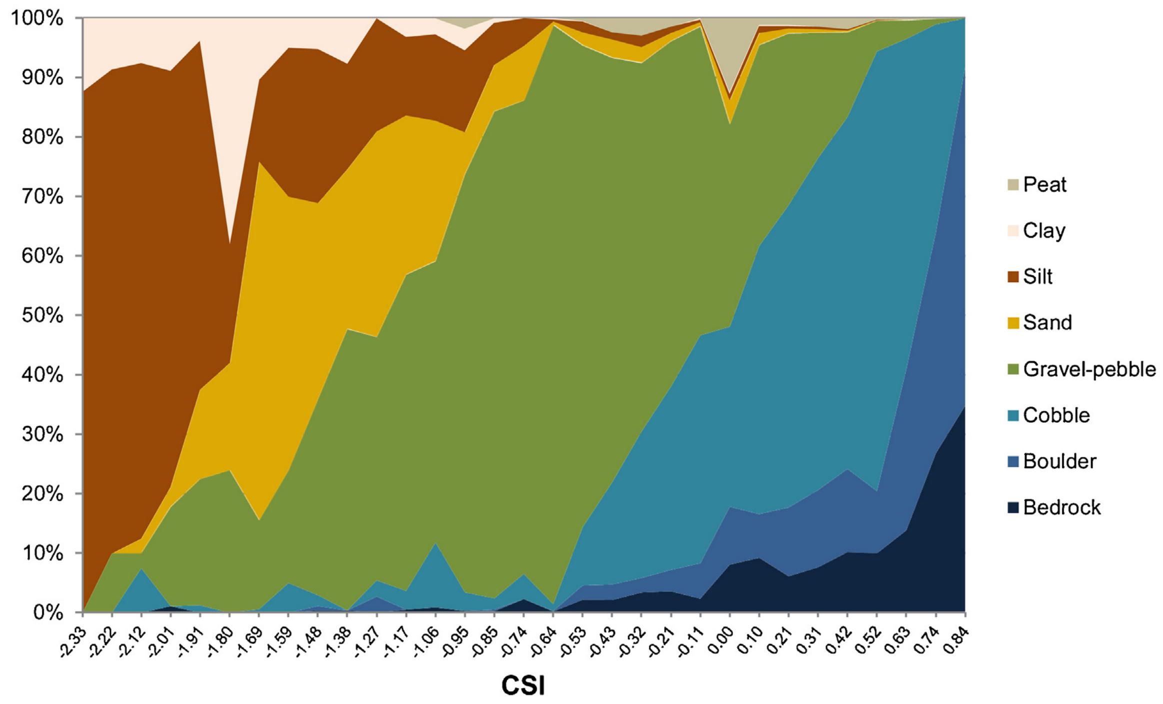


Fig. 1. Channel Substrate Index. RHS sites were grouped into 31 bins based on their CSI index value. The graph displays, for each bin, the average occurrence of 8 channel substrate types. Fine sediment (sand, silt, and clay) are dominant at the lower end of the scale and are gradually replaced by coarser sediments as CSI increases.

macro invertebrates via accumulation on and within the river substrate (Jones et al., 2011; Wood and Armitage, 1997), and through increased concentrations within the water column (Gayraud et al., 2002). Channel sediment size is a key element explaining aquatic macrophyte distribution (Gurnell et al., 2010). Fine sediment and macrophytes interact in complex ways. Fine sediment deposition on river margin favours the settlement and growth of emergent vegetation whose leaves, roots and shoots locally reduce flow velocities leading to further sediment entrapment and accumulation (Clarke and Wharton, 2001; Jones et al., 2012a; Sand-jensen, 1998 Sand-jensen, 1998). Fine sediment and macrophyte interaction encourages channel recovery in widened streams through the development of marginal benches and banks and subsequent reductions in channel width (Gurnell, 2014).

The diffuse nature of sediment inputs makes fine sediment management problematic, especially at catchment scale (Collins et al., 2011). The presence and accumulation of fine sediment in streams is dependent on a series of factors, including: precipitation (intensity and total), land management practice (e.g. tillage), the presence of pathways to rivers, channel morphology, channel modifications, impounding structures, flow regime, sediment transported from upstream, and instream vegetation communities (Bilotta et al., 2008; Collins et al., 2009b, 2011). The complex interaction of all these factors makes it difficult to predict accurately where and how much fine sediment will accumulate in a water body and more importantly its origin. As a result, there are no detailed (<10 km^2) spatial data characterising fine sediment accumulation across rivers, either globally or nationally.

The effective management of fine sediment is also limited by the structure and nature of existing decision-making. Organisations responsible for policy development, environmental management and the implementation of European directives are subject to continued resource cuts in the face of ongoing economic challenges, meaning that national scale monitoring is constantly being rationalised, thereby increasing the need for robust modelling approaches to support strategic decision-making (Collins and McGonigle, 2008; Naura, 2014). On this basis, there is a need to develop simple modelling tools for predicting agricultural sediment levels in rivers that can be easily applied to fine sediment management by regulatory bodies, and that permit strategic extrapolation in the context of the limited availability of data and knowledge on fine sediment origin and delivery (Bainbridge, 2014; Collins and McGonigle, 2008; Collins et al., 2009c).

One approach that has been widely used in environmental organisations is risk assessment. Risk assessment is one means of identifying potential levels of threats posed by contaminants based on data, models or expert opinion (Fairman et al., 1999). Risk levels can easily be represented in the form of maps and communicated to all stakeholders (Zerger, 2002). In the absence of specific or accurate data sources and knowledge, risk assessment may provide a meaningful way of supporting decision-making using existing resources (Jones, 2001). To the users, the relative simplicity and openness of outputs and derivation process may bring clarity and transparency and foster trust.

In this paper, we develop a risk-based approach towards assessing the likelihood that accumulated fine sediments on the river bed are of agricultural origins and we test the resulting fine sediment index on existing biological monitoring data. We choose fine sediment accumulation rather than concentration within the stream, for the following reasons: (a) data on fine sediment accumulation on the stream bed are more widely available and relatively simple to measure; (b) accumulation represents both the concentration of fine sediment in the water column and the deposition rate of entrained sediment, and; (c) it has been shown to be a major cause of change in biological communities (Jones et al., 2012a, 2014, 2012b).

The risk of fine sediment accumulation was assessed by combining a map of fine sediment distribution produced with spatially explicit predictive models based on existing River Habitat Survey (RHS) data (Naura et al., 2016), with a map of agricultural fine sediment inputs derived from the sediment module of the process-based ADAS Pollutant Transport (APT) framework (Collins et al., 2012b; Davison et al., 2008; Zhang et al., 2014). The correlation between the final risk map and aquatic biota was tested statisti-

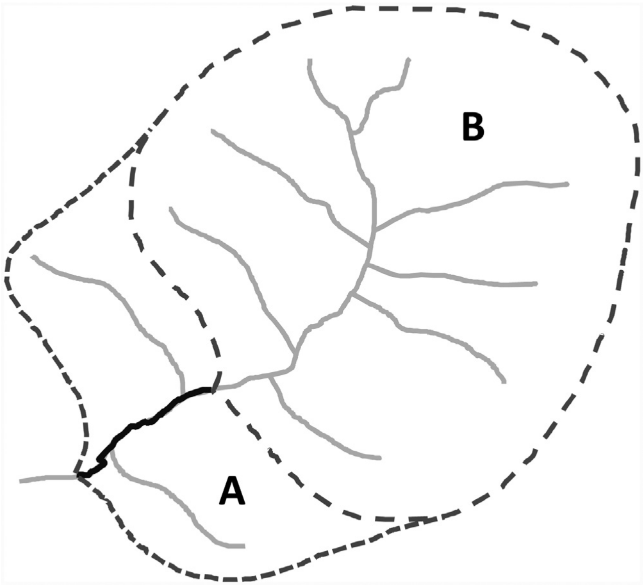


Fig. 2. Derivation of agricultural fine sediment inputs and river length for the calculation of Agricultural Sediment Load as part of the ASL equation for a 500 m section (in bold). A- sub-catchment area directly feeding into the example 500 m reach; B sub-catchment area upstream generating fine sediment also entering the example 500 m reach in sub-catchment A. The network length in sub-catchments A and B correspond to LRN and CRN, respectively in the ASL equation. The agricultural fine sediment inputs terms, LS and CS, are derived using the respective sub-catchment boundaries for A and B.

cally using the Environment Agency (EA) National Fish Population Database (NFPD) and predictions of natural fish populations using the Fisheries Classification Scheme (FCS) (Wyatt, 2003). Further validation could be undertaken in the future using national scale invertebrate or macrophyte datasets. These additional datasets were not available to this project.

2. Material and methods

To produce the agricultural fine sediment risk map, two indices were derived: the Fine Sediment Accumulation index (FSA) which represents the extent of fine sediment (i.e. sand, silt, and clay) on the river bed, and the Agricultural Sediment Load index (ASL) which provides an estimate of the amount of fine sediment from agricultural origin delivered to individual reaches through run-off from agricultural land and channel network transport.

2.1. Fine sediment accumulation index

Fine sediment accumulation was mapped using an index of sediment size called the Channel Substrate Index (CSI) derived as part of prior research using RHS data (Naura et al., 2016). RHS is a standard methodology for hydromorphology assessment under the WFD that has been implemented at more than 25,000 sites across the UK since 1994. During a River Habitat Survey, a visual estimate of the dominant channel substrate is recorded at a series of 10 equally spaced transects along a 500 m reach (Raven et al., 1997). Each site can be described according to the relative occurrence of nine substrate types across 10 transects. The CSI was derived using Correspondence Analysis on 2680 semi-natural RHS sites (i.e. sites with few or no in-channel bank structures/modifications) and represents average channel substrate size along a continuous scale from fine to coarse sediment (Fig. 1). The CSI index was modelled against a series of GIS attributes representing gradients of geomorphological change (e.g. slope, geology) using a geostatistical technique called regression kriging (Webster and Oliver, 2007). The resulting model was applied to every 500 m section on the 1:50,000 river network across England and Wales to produce a national map of river substrate sediment size distribution (Naura et al., 2016). The Fine Sediment Accumulation (FSA) index was created by partitioning CSI values into 5 categories to reflect the likelihood of fine sediment occurrence and their extent. Partitioning was undertaken by manually splitting the CSI scale based on the relative occurrence of sand, silt and clay in each category.

2.2. Agricultural sediment load index

The ASL index was derived using estimates of fine sediment delivered to rivers across England and Wales using the APT model (Collins et al., 2012a; Zhang et al., 2014).

APT builds upon the widely used and validated PSYCHIC (Phosphorus and Sediment Yield CHaracterisation In Catchments) model (Collins and Anthony, 2008; Collins et al., 2009a,b; Collins et al., 2014a,b; Collins et al., 2007; Comber et al., 2013; Davison et al., 2008; Strömqvist et al., 2008) for agricultural emissions to rivers. APT simulates fine sediment loss from agricultural land and woodland and estimates the load delivered to watercourses. It operates at a daily time step and can output at a 1 km^2 spatial resolution. APT simulates sediment losses at field scale, with a WFD water body represented as a large number of fields which are then subject to landscape scale retention factors to estimate delivery of mobilised fine sediment from agricultural land to the river network. Critically, field drainage as a sediment delivery pathway is represented, as well as surface runoff. The APT model uses as input three types of data; daily weather, physical attributes of the land, and crop and livestock management data. The daily weather data was interpolated for each WFD water body from existing UK Meteorological Office records using an inverse distance weighting function in the IRRIGUIDE tool (Bailey and Spackman, 1996). During the simulations, a WFD water body is represented by a small number of major soil types taken from the NSRI Natmap Soils Database. Other physical data required as input include slope and altitude, plus field boundary features (based on the Countryside Survey; Hornung, 1998) which are a key control on agricultural land-to-river connectivity. Crop areas were based on the 2010 June Agricultural Survey completed by farmers in England and Wales, which has been mapped to a 1 km grid using the approach described in Comber et al. (2013). APT models crops as either part of a three year rotation, or (primarily for permanent grassland) as continuous cropping. The primary benefit of this approach is that it allows the simulations to include the effects of crop management in previous years. APT runs encompassed a 20-year period (1991–2010) and annual average agricultural fine sediment losses over this period per WFD water body were calculated for inclusion in the approach detailed by this paper.

To be able to produce estimates of agricultural fine sediment entering the river network at any given point, it was necessary to derive catchment boundaries for every 500 m point on the river network. Catchment areas were derived by burning the Centre of Ecology & Hydrology (CEH) 1:50,000 digitised river network into the 50 m SAR Digital Elevation Model (DEM) and building a reconditioned DEM using the AGREE (Hellweger, 1997) reconditioning tool in *ArcHydro* (Maidment, 2002). Because of inconsistencies between the DEM and river network, a substantial number of points failed to generate valid catchment areas. The number of failures was reduced by running them through the same delineation process but using a flow direction grid built from a non-stream burnt DEM.

An estimate of the amount of agricultural fine sediment delivered to individual 500 m reaches was derived using a combination of the local agricultural sediment input value for that 500 m reach plus an assessment of sediment transported into the reach but orig-

Fig. 3. Distribution of 9406 fisheries electro-fishing survey sites from the 2000–2005 EA monitoring programme.

inating from the upstream catchment. The Agricultural Sediment Load (ASL) metric was calculated using the following equation:

$$\mathrm{ASL} = (\mathrm{LS}/\mathrm{LRN} \times 500) + (\mathrm{CS}/\mathrm{CRN} \times 500)$$

where LS represents the agricultural fine sediment load entering a given 500 m reach; LRN is the length of river network in metres within the catchment area feeding into the 500 m reach; CS represents the amount of fine sediment delivered to the catchment upstream of the 500 m reach, and CRN is the length of river network in the catchment upstream in metres (Fig. 2).

The ASL thus represents the sum of two predicted estimates of fine sediment load delivered to rivers, standardised to a 500 m section. The first value considers local sources of fine sediment feeding into the reach of interest and will account both for run-off and for transported sediment from any tributary that may enter the river section in question. The second value deals with sediment transported from upstream. It represents the quantity of sediment delivered to an average 500 m reach in the upstream catchment. Both quantities act as an estimate of the amount of agricultural fine sediment delivered each year to individual 500 m reaches.

2.3. *Agricultural sediment risk*

Agricultural Sediment Risk categories (ASR) were defined using a matrix combining the FSA and ASL indices to represent increasing risk of agricultural fine sediment accumulation in-channel and their potential impacts on biota. The ASL index was split into 5 categories based on the distribution quintiles derived from the range of sediment inputs generated using APT. The matrix was drawn using the combined expertise of all authors. On this basis, a map of ASR was produced for the entire river network.

2.4. *Link to biota*

The relevance of the ASR map to aquatic biota was assessed against Environment Agency (EA) single-run fish density estimates

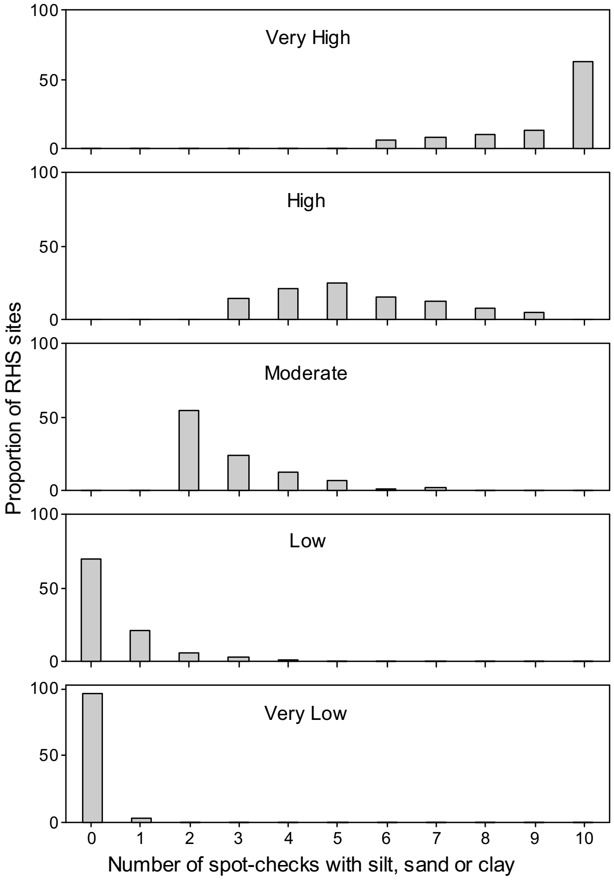


Fig. 4. Proportion of RHS sites within five FSA risk categories with sand, silt or clay as dominant channel substrates across 10 transects.

from 9406 electro-fishing surveys between 2000 and 2005 alongside prediction of occurrence at reference condition from the FCS (Fig. 3). FCS predictions were used to select sites with high habitat suitability (i.e. sites with a predicted likelihood at reference condition greater than 60%). Fish presence/absence was modelled against ASR using logistic regression. ASR was treated as a factor and each level was tested against the lowest available control level, generally ASR level I or 2. Overall factor significance was tested using chi-square statistics and individual factor levels were tested against the control using Z-statistics for associated odds-ratios. Odds-ratios provided the direction of change with an odds-ratio greater than one signifying a positive impact on fish occurrence and an odds-ratio less than one a negative impact. Odds-ratios not significantly different from one indicated no observable impact of ASR on fish.

3. Results

3.1. Fine sediment accumulation index

Partitioning of the CSI yielded 5 categories with increasing occurrence of fine sediment (Fig. 4). More than 60% of sites in the 'very high' FSA class ($CSI < -1.56$) had fine sediment dominant at 10 transects; 80% of sites with 'high' FSA ($-1.56 < CSI < -1.02$) were dominated by fines at 5 or more transects. The 'moderate' FSA class ($-1.02 < CSI < -0.8$) contained a majority of sites (80%) with 3 or 4 transects with fine sediment dominant whereas 'low' FSA ($-0.8 < CSI < 0.29$) sites had between 0 and 2 transects with fines dominant. The 'very low' category ($CSI > 0.29$) represented sites with no or little fine sediment.

3.2. Agricultural sediment load

ASL estimates were produced for most 500 m sections following DEM processing. The final number of invalid catchment delineations for individual sections was 55,224 out of a total of 342,586 (16.1%). Most invalid catchments were located in hydrometric areas with missing data, and in low gradient areas where low relief associated with complex grid like river channels made catchment delineation unreliable.

The FSA map (Fig. 5) showed a split between upland and lowland areas with high levels of fine sediment observed in East Anglia, Lincolnshire, Kent, Sussex and also large cities such as Manchester, Liverpool, Birmingham and London whereas the uplands in Wales, Cornwall and the Lake District showed low levels of agricultural fine sediment accumulation.

The map of ASL (Fig. 6) shows high sediment supply from agricultural sources in Norfolk, Suffolk and parts of Lincolnshire where agricultural field drains are present. In contrast to the previous map, the uplands of Wales, the south-west and the north-west display high levels of sediment supply reflecting higher levels of soil erosion and run-off from steeper slopes driven by higher rainfall totals, compared to those received in eastern areas of England.

3.3. Risk based matrix

The ASR matrix (Table 1) was designed in a symmetrical way to give equal importance to the ASL and FSA indices in determining integrated risk. The 'very high' and 'high' ASR categories combine high levels of fine sediment accumulation in river channels with high supply from agricultural land use. Sites belonging to those categories are likely to feature large amounts of accumulated fine sediment from agricultural origins. The "low" ASR categories represent sites with little fine sediment accumulation or sites with fine sediment dominant but with low contributions from agricultural land use. High levels of ASR are predicted for East Anglia, Lincolnshire and Kent in the east of England, as well as Merseyside and Manchester in the northwest of England area and around some big cities with the exception of London (Fig. 7).

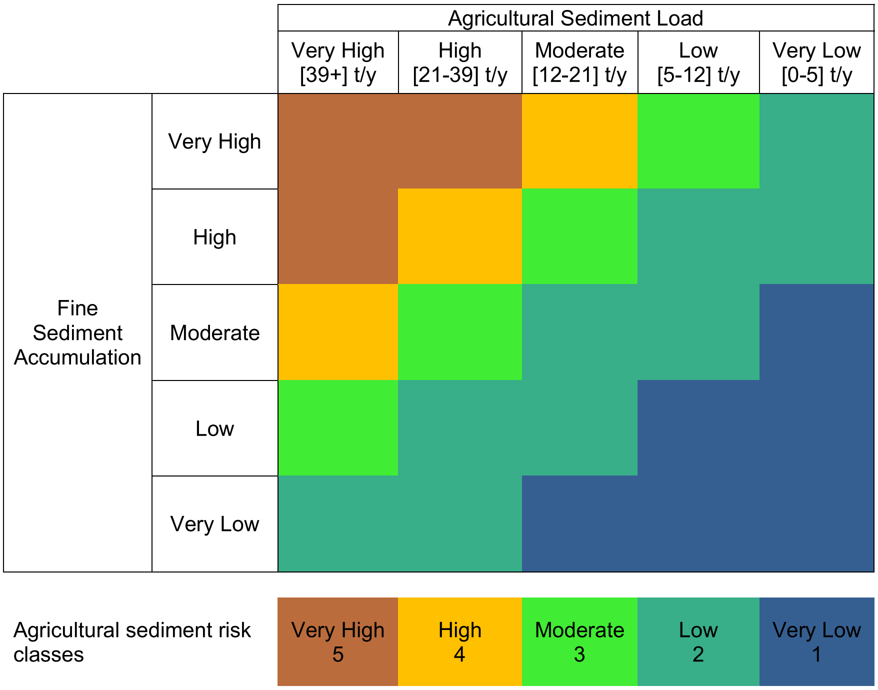
3.4. Correlation between agricultural sediment risk and fisheries data

Out of 23 fish species used in conjunction with the ASR assessments, seven did not have enough data to enable analysis (Table 2). Overall fish species prevalence varied from 1% (carp) to 70% (trout) and the number of sites with high habitat suitability at reference condition ranged from 0 to 6227. The remaining 16 fish species could be split into 3 groups according to the direction and strength of correlative relationships.

The first group of eight species shared a sensitivity to agricultural fine sediment. It included salmonids, eels and some cyprinids (bleak, gudgeon, pike and bullhead). These species were found to have a negative relationship with ASR. Trout and salmon displayed the strongest relationships with very low odds-ratios at nearly all levels of ASR. A gradual increase in impact typified by decreasing odds-ratio values with increasing ASR was discernible for salmon and trout. Trout had the strongest response to ASR with low odds-ratios at ASR 2 and 3. Odds-ratios for salmon were somewhat higher and significantly dropped at ASR categories 4 and 5.

ASR also had significant or near significant overall impact on bleak, gudgeon, bullhead and eel. Pairwise comparisons showed significant impacts for high or very high levels of ASR. Results for Pike were altogether less clear. Although ASR had an overall high level of significance, pairwise comparisons yielded contradictory results, with ASR category 4 being significantly different from ASR category 1, but no difference could be observed between ASR cat-

Table 1
Agricultural Sediment Risk matrix combining FSA and ASL categories. The boundaries for ASL categories are shown in tonnes per year.



		Agricultural Sediment Load				
		Very High [39+] t/y	High [21-39] t/y	Moderate [12-21] t/y	Low [5-12] t/y	Very Low [0-5] t/y
Fine Sediment Accumulation	Very High	🟫	🟫	🟧	🟩	▨
	High	🟫	🟧	🟩	▨	▨
	Moderate	🟧	🟩	▨	▨	🟦
	Low	🟩	▨	▨	🟦	🟦
	Very Low	▨	▨	🟦	🟦	🟦

Agricultural sediment risk classes	🟫 Very High 5	🟧 High 4	🟩 Moderate 3	▨ Low 2	🟦 Very Low 1

Table 2
Test of 23 fish species occurrence against ASR for sites with high habitat suitability at reference condition using logistic regression. P_v = Species prevalence; N_{60} = number of sites with probability of occurrence at reference condition less than 60%; NS = not significant; NED = not enough data; significance levels symbols: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Species	P_v	N_{60}	ASR factor significance	Pairwise comparisons to control. Odds-ratio and significance level			
				ASR2	ASR3	ASR4	ASR5
Trout (Salmo trutta)	70%	6627	χ^2 = 435***	0.66***	0.27***	0.09***	0.10***
Salmon (Salmo salar)	32%	3557	χ^2 = 33.3***	0.81**	0.87	0.19***	0.07***
Bleak (Alburnus alburnus)	6%	119	χ^2 = 18.2***	control	0.53	0.08***	0.10***
Gudgeon (Gobio gobio)	23%	1298	χ^2 = 16.7***	1.35	1.03	1.21	0.62**
Eel (Anguilla Anguilla)	39%	2589	χ^2 = 9.1*	0.85	0.89	1.22	0.67**
Bullhead (Cottus gobio)	54%	5137	χ^2 = 7.9*	1.1	1	0.92	0.77*
Pike (Esox Lucius)	23%	1360	χ^2 = 18.5***	1.24	1.44	0.58**	1.01
Grayling (Thymallus thymallus)	7%	101	χ^2 = 1.1	0.75	0.53	N/A	N/A
Roach (Rutilus rutilus)	31%	2130	χ^2 = 18.8***	1.87***	1.32	1.40***	1.06**
Perch (Perca fluviatilis)	25%	806	χ^2 = 14***	2.25***	1.74**	1.28	1.07
Stone Loach (Barbatula barbatula)	39%	2462	χ^2 = 8.3*	1.33***	1.29**	1.17	1.18
Chub (Leuciscus cephalus)	28%	2109	χ^2 = 11.3**	1.09	1.44**	1.19	1.67***
Minnow (Phoxinus phoxinus)	35%	2408	χ^2 = 9.1*	0.95	1.1	1.65***	0.95
Stickleback (Gasterosteus aculeatus)	13%	404	χ^2 = 6.2	0.89	1.29	2.05	0.99
Spined Loach (Cobitis taenia)	1%	42	χ^2 = 2.7	control	4.5	1	1.6
Dace (Leuciscus leuciscus)	24%	1320	χ^2 = 44.6***	1.61**	0.64**	2.06**	0.79
Bream (Abramis brama)	7%	28	NED				
Barble (Barbus barbus)	4%	3	NED				
Ruffe (Gymnocephalus cernuus)	4%	0	NED				
Lamprey (Lampetra planeri)	12%	0	NED				
Rudd (Scardinius erythrophthalmus)	4%	0	NED				
Carp (Cyprinus carpio)	1%	0	NED				
Tench (Tinca tinca)	5%	0	NED				

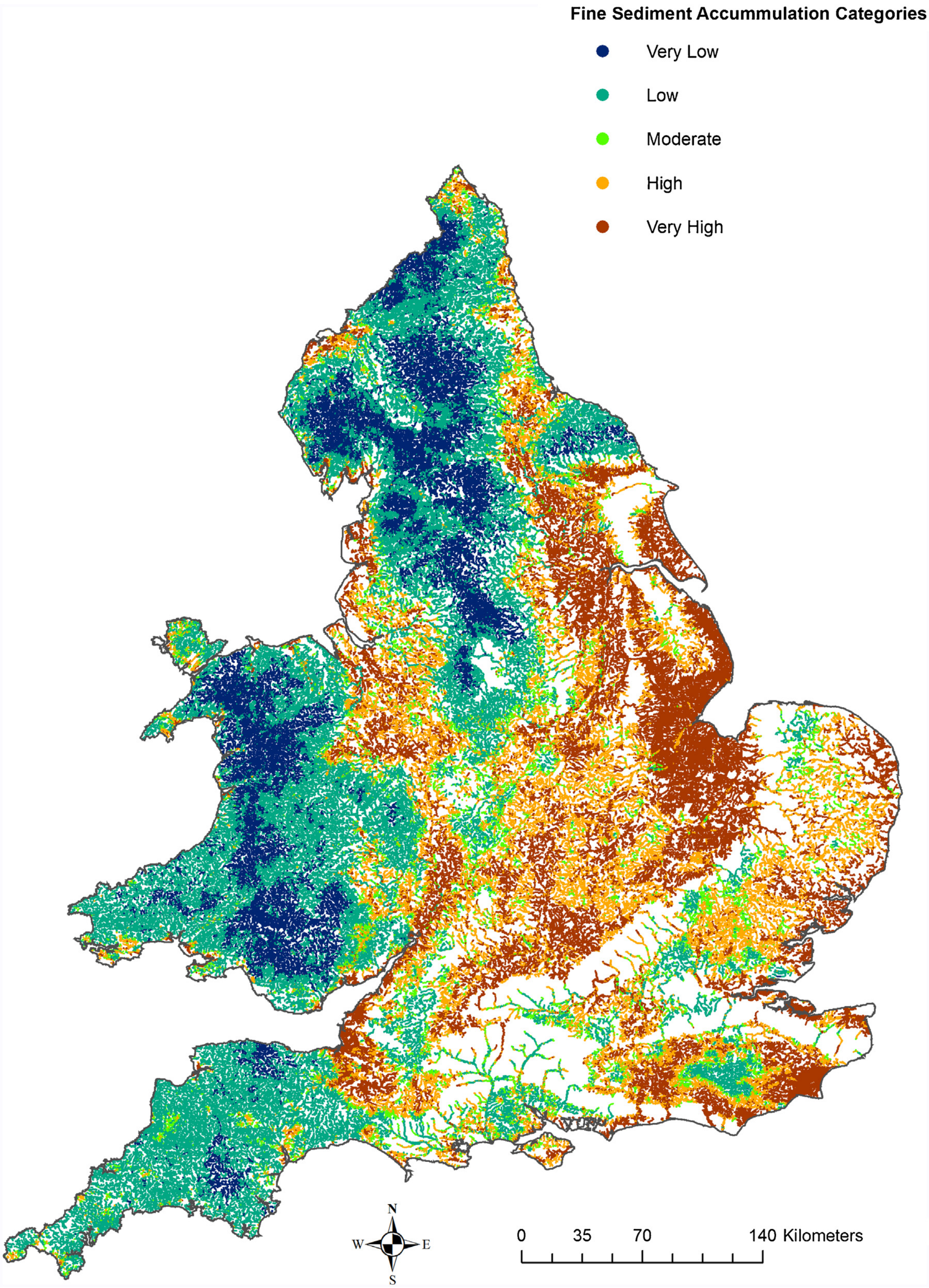


Fig. 5. FSA category distribution across England and Wales.

egory 5 and the control. Grayling had too small a sample size to enable meaningful analysis and comparison although the odds-ratios suggested a potential negative impact of agricultural fine sediment on species occurrence.

The second group of seven fish species displayed significant positive relationships to ASR. Increasing risk was thereby associated with increasing likelihood of finding the species. Roach, perch and stone loach displayed the highest levels of association with FSA. The odds-ratios, however, decreased with increasing ASR, which sug-

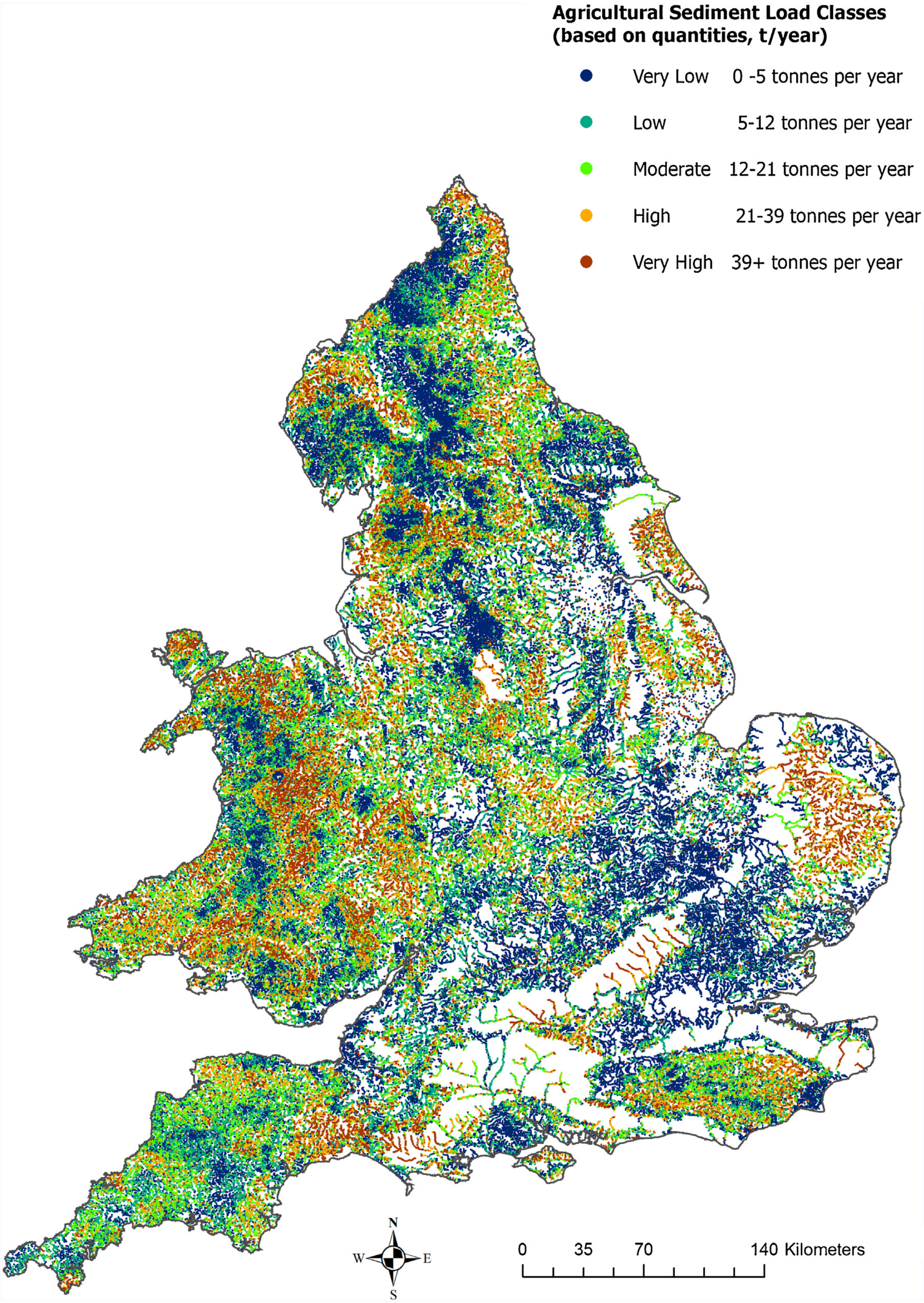


Fig. 6. ASL categories across England and Wales.

gests that agricultural sediment may benefit these particular fish species at low levels but its impacts may change as ASR increases. Chub and minnows displayed inconsistent patterns across the scale despite reaching overall significance. These results suggest that ASR may not directly benefit these species but may have an indirect effect through its impact on competing species. Sticklebacks and Spined Loach both failed to reach significance for all tests despite showing overall positive relationships to ASR.

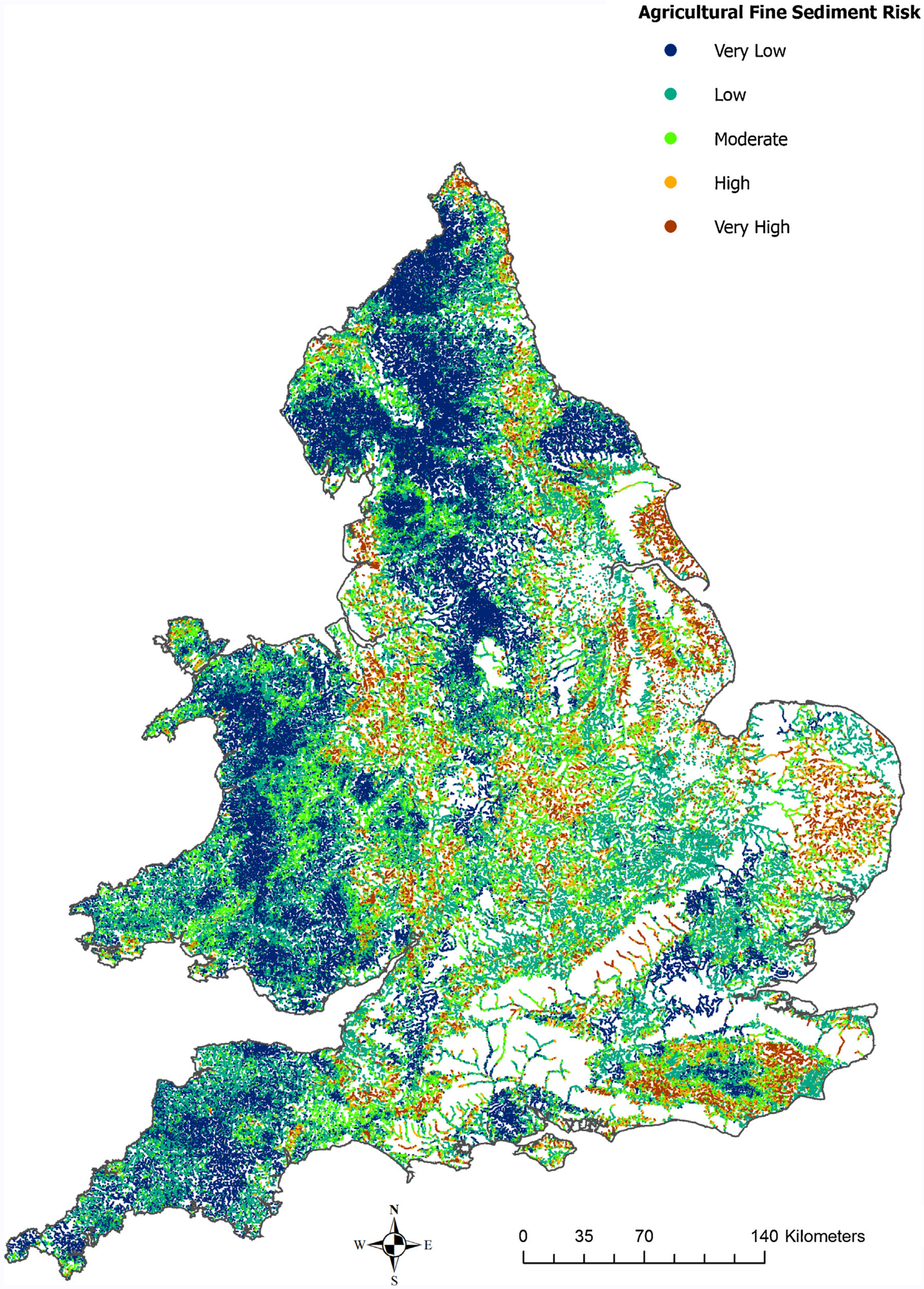


Fig. 7. ASR categories across England and Wales.

The last group contained only one species (Dace) and was characterised by no clear pattern of relationship between ASR and species occurrence or density. Individual pairwise differences yielded conflicting results with ASR having a positive impact on Dace occurrence at both low and high levels of ASR and a negative impact at moderate risk.

4. Discussion

4.1. Fine sediment risk mapping

The CSI provided a useful means of mapping fine sediment accumulation across the entire river network of England and Wales by concentrating on its finer fractions (i.e. sand, silt and clay) and creating an index representing its relative occurrence. The resulting FSA categories were good indicators of fine sediment accumulation potential with, at one end of the scale, sites that tend to retain fine sediment across most of their length, and at the other end, sites that are free of fine sediment accumulation.

The FSA gives an indication of substrate coverage but does not reflect the actual quantity of accumulated fine sediment over the reach. Future quality checks could be made to determine the strength of the relationship between the estimates of FSA and available fine sediment storage data (Collins and Walling, 2007a,b; Walling and Amos, 1999). Such comparisons would be assisted by the fact the modelled sediment pressure layer represents typical conditions over a twenty year period (1991–2010) as opposed to a specific modelled year.

The sediment pressure modelling was generated using the latest policy-support national scale framework for fine sediment loss from agriculture. It is, however important to note that some difficulties were experienced in deriving meaningful catchment areas for 16.1% of 500 m reaches across the river network of England and Wales. These reaches were consistently in lowland areas where sedimentation impacts on biota are likely to be detectable. The pressure modelling generates predictions of agricultural fine sediment loads delivered to the river channel network but does not include any subsequent routing and storage or remobilisation. Ongoing work is developing improved representation of current practice by farmers (e.g. on field drain maintenance, implementation of sediment control measures) and this new understanding will need to be combined with the framework reported here to update national scale understanding of sediment pressure from agriculture. The national pressure layer used herein includes crop areas and livestock numbers but not on-farm implementation of mitigation measures for erosion and sediment delivery control such as those supported by agri-environment schemes.

The ASL calculation provided an estimate of the amount of fine sediment delivered to a reach from both local inputs and from upstream sources. As there was no absolute definition of what constitutes a ‘high’ or ‘low’ agricultural sediment load, the use of quintiles based on the overall predicted range of agricultural fine sediment delivery to rivers enabled an unbiased classification of ASL and introduced an element of proportionality. Future work could make use of estimates of sediment delivery under lower-intensity pre-World War II agriculture derived from palaeo-records such as those recently proposed (Collins et al., 2012a; Foster et al., 2011) to assess the impact of current agricultural land use and practise on ASR.

The risk matrix attempted to combine indices of agricultural fine sediment load and accumulation so as to reflect the likelihood that mobilised fine sediment delivered to river channels across England and Wales is from agricultural origin and is likely to be stored in the channel network.

The risk maps produced for England and Wales show how agricultural fine sediment delivery to the river network can be high (Fig. 6) in the upland areas of England and Wales, but that the overall risk is reduced by the transfer of this material through the river network (Fig. 7). Areas at high-moderate risk from agriculturally derived fine sediment are shown to be largely in low gradient rivers where the combination of high delivery from the farmed landscape coincides with high accumulation in the river channel. It is important to note that these areas may naturally have channels dominated by fine sediment because of local hydraulics and sediment supply from upstream sources (Church, 2002). As a result, future work will aim to assess how current land use and farming practise have potentially increased the accumulation of fines in river substrates relative to natural background levels. Such additional work could also be expanded further to project the potential impacts of both climate and land use change forecasts. Reducing inputs from agriculture will not significantly affect sediment accumulation and local biota in areas where agriculture is not the dominant source of fines delivered to river channels. Although it is possible to overestimate the importance of sediment from agricultural sources using the ASR map, statistics derived from the ASL map showed that agriculture appears to be the main source of fine sediment for the majority of rivers. In England and Wales, 58% of the river network sediment sources were overwhelmingly agricultural in nature (80–100% agricultural) and an additional 19% had high levels of agricultural inputs (from 60 to 80% agricultural). Previous work by Collins and Anthony (2008), Collins et al. (2009a,b) and Zhang et al. (2014) consistently identified agriculture as the dominant source of fine sediment delivered to the river channel network in the majority of water bodies across England and Wales. When considering the whole river network, however, the proportion of river reaches falling into the high ASR categories are relatively small with only 6.5% and 7.8% of 500 m sections having ‘high’ or ‘very high’ risk from agricultural sediment input (Fig. 8). This compares with a majority of river reaches falling into the ‘very low (31.8%) or “low” (35.1%) categories. In spite of the high proportion of fine sediment that originates from agricultural origins, we found a minority of river reaches with high in-channel accumulation risks associated. Such information provides an additional data layer for supporting the spatial targeting of sediment remediation measures.

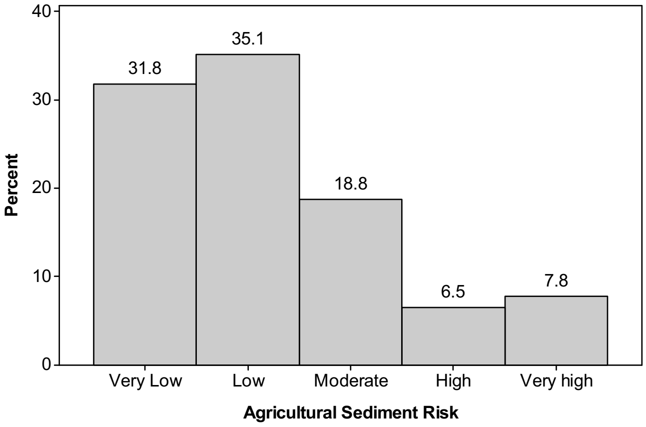


Fig. 8. Proportion of the 1/50,000 river network in England and Wales falling within each ASR category.

4.2. Link to fish species

Salmon and trout were the species most correlated with ASR. Sediment infiltration within gravels used for spawning is known to severely reduce salmon and trout egg survival (Sear, 2010). Salmon and trout are also sensitive to pollution by phosphates, pesticides and herbicides potentially carried on the surface of clay-sized particles (Kemp et al., 2011).

Bleak, gudgeon and eel showed responses to high sediment risk levels although with less of a marked trend than for salmonids. In their literature review, Kemp et al. (2011) could not find any reference to potential threats to egg survival of Bleak and Gudgeon resulting from fine sediment although eggs are deposited on gravel, which makes them potentially susceptible to fine sediment accumulation and smothering. The negative relationship of eels to ASR

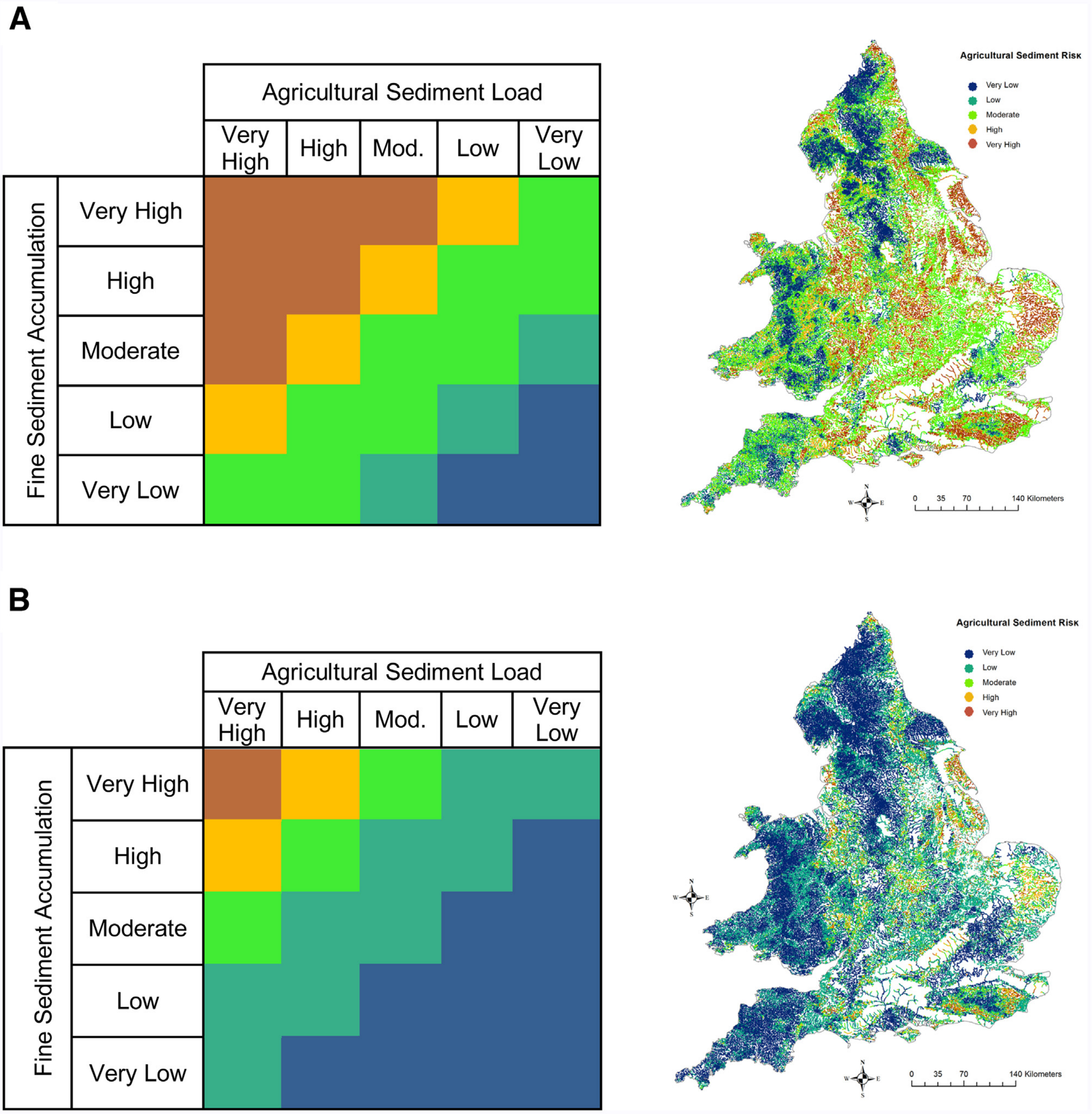


Fig. 9. A- ASR matrix and map illustrating a precautionary approach towards sediment management. B- ASR matrix and map illustrating a more stringent approach towards defining risk associated with elevated agricultural fine sediment.

is more puzzling as eels are known to prefer muddy habitats and do not incubate in freshwater (Maitland and Campbell, 1992). ASR may have an impact on their foraging ability and invertebrate food but this requires further investigation and analysis.

Grayling eggs have been reported as being sensitive to fine sediment. Although odds-ratios suggested a potential negative impact, they failed to reach significance as sample sizes were low.

Bullhead was loosely correlated with increased ASR. Although bullhead requires coarse substrate to reproduce and fairly clean water, eggs are laid on the underside of a stone excavated by the male. Fine sediment impacts may therefore be mitigated by nest building choice and spawning strategy. High density of sediment may impact on fish eggs by reducing spawning site availability and affecting egg survival by adhering to the surface.

Pike rely on vegetation to spawn and eggs are therefore unlikely to be affected by fine sediment accumulation unless sediment in suspension carries pollutants or sticks to the eggs. The level of significance of ASR, despite being high for overall effect was inconsistent between factor levels and may be the consequence of inherent uncertainties in the data used by this study.

ASR was positively correlated to a group of seven species who seemed to benefit from increasing agricultural sediment accumulation. The reasons behind these relationships are not clear although there may be a link to indirect effects on competitors and predators. The case of roach and perch was interesting as it showed a notable decrease in sediment impact with increasing ASR which suggests an indirect effect. Young roach rely on the presence of mud that they ingest to feed (Maitland and Campbell, 1992). They are therefore more likely to be found in places where fine sediment occurs. But roach are also typical prey for pike, trout and perch (as well as riverine birds). A relatively small increase in sediment input may therefore impact on trout and reduce predation through increased turbidity. As sediment load increases, local habitats and vegetation get gradually smothered and roach may suffer from an absence of cover to avoid other predators such as pike and perch, and a shortage of more nutritious food such as molluscs and invertebrates.

Perch do not rely on clean substrate for spawning. Their eggs are laid in shallow water around plants or other submerged objects. Perch feed on a wide range of prey, from invertebrates, molluscs to other fish species. Like pike, they can effectively detect and capture prey in the absence of visibility. They are therefore unlikely to be affected by elevated turbidity. Perch diets and feeding habits are similar to that of trout. The presence of fine sediment impacting trout populations may therefore give perch an opportunity to colonise adjacent habitats and survive in higher numbers.

Chub generally prefer diverse habitat with coarse and fine substrate. They spawn on vegetation, stones and gravel with a preference for weed. No mention of adverse impacts of fine sediment on chub eggs was found by Kemp et al. (2011) but it was suggested that their spawning habits may make them vulnerable. Evidence from the analysis here does not seem to support this. However, the positive relationships observed could also be the result of the adverse impact on competing species or random factors (e.g. variability/uncertainty introduced by survey techniques).

Minnows and Stone Loach displayed slight correlation with ASR. As for chub, the results are slightly counterintuitive as they lay their eggs over gravel and should be more susceptible to elevated fine sediment inputs. Minnows are also sensitive to low oxygen levels and pollution. They share a similar diet to trout and they are thought to potentially compete when both species are present (Maitland and Campbell, 1992). Considering their sensitivity to pollution, it is not clear why the analysis presented herein suggests that high levels of ASR benefit minnows.

Sticklebacks showed no significant preference for fine sediment although the males build their nests with particles of silt and sand. As the male sticklebacks fan their eggs during incubation, they are less likely to be affected by changes in sedimentation.

The case of Dace is confusing as it shows greater probability of occurrence at low and high levels of ASR and lower probabilities at moderate levels. Dace like to live in fast flowing rivers and rely on clean gravel for spawning. Silt has been shown to impact on egg survival (Kemp et al., 2011); therefore it is not clear why dace should benefit from agricultural fine sediment inputs.

4.3. Management implications

Despite its limitations outlined briefly above, the approach presented herein shows its potential usefulness as a management tool. Sediment accumulation can effectively be predicted using RHS data and sites potentially at risk from agricultural sources can be identified. Used in combination with WFD classification tools, it could help practitioners identify sites at risk of failing GES because of agricultural sediment inputs. The ASL and FSA maps could also help identify whether high sediment accumulation is due to high sediment delivery to river channels or to the retentive capacity of streams receiving the fine sediment delivered from agricultural sources. This could, in turn, be used to help inform management and ensure that actions taken on the ground reflect an understanding of the problem at hand.

Fine sediment accumulation results from both natural and human modifications to the land surface and river network. Thus an important element of any risk based approach is to account for natural accumulation in order to reveal excess accumulation resulting from human modifications. Future work will attempt to model natural sediment accumulation and delivery to streams using data from unimpacted RHS sites and national scale estimates of modern background delivery to rivers (Foster et al., 2011).

The ASR risk matrix is somewhat arbitrary and represents the authors' consensus on risks of agricultural fine sediment accumulation. From a management viewpoint, different matrices may be derived depending on the level of caution that environmental managers and regulators wish to exert when dealing with the specific issue of elevated agricultural fine sediment inputs to rivers and streams. As an example, two additional matrices and corresponding risk maps were produced to reflect a more precautionary approach towards managing ASR to biota (Fig. 9A), and one that is more stringent in its definition of risk (Fig. 9B). The resulting maps (Fig. 9A & B) show observable changes in the distribution of ASR with high risk sites being far more prevalent for the precautionary approach (26% of river reaches at 'high' or 'very high risk' compared to 6% for the more conservative approach).

For the purpose of this study, the analyses concentrated on fine sediment from agricultural origin but the approach could equally be applied to other sources of sediment such as sewage treatment works, urban areas and bank erosion using the national scale modelled layers reported in Collins et al. (2009a,b) and Zhang et al. (2014).

Acknowledgements

RHS and NFPD data can be found on the UK government data portal (http://data.gov.uk/) or by contacting the Environment Agency. FCS outputs can be obtained by contacting the Environment Agency. Funding provided by the Department for Environment, Food and Rural Affairs (Defra) under project WQ0128 (Extending the evidence base on the ecological impacts of fine sediment and developing a framework for targeting mitigation of agricultural sediment losses) is gratefully acknowledged.

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