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Sources of sediment-bound organic matter infiltrating spawning gravels during the incubation and emergence life stages of salmonids

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ABSTRACT

The biodegradation of organic matter ingressing spawning gravels in rivers exerts an oxygen demand which is believed to contribute to detrimental impacts on aquatic ecology including salmonids. Catchment management strategies therefore require reliable information on the key sources of sediment-bound organic matter. Accordingly, a novel source fingerprinting procedure based on analyses of bulk stable ^{13}C and ^{15}N isotope values and organic molecular structures detected using near infrared reflectance (NIR) spectroscopy was tested for assessing the primary sources of sediment-bound organic matter infiltrating artificial Atlantic salmon spawning redds in five rivers across England and Wales. Statistically-verified source fingerprints were identified using a combination of the Kruskal–Wallis *H*-test, principal component analysis and GA-driven discriminant function analysis. Interstitial sediment samples were obtained from artificial redds using retrievable basket traps inserted at the start of the salmonid spawning season and extracted subsequently in conjunction with critical juvenile phases (eyeing, hatch, emergence, late spawning) of fish development associated with incubation and emergence. Over the duration of these four basket extractions, the overall relative frequency-weighted average median source contributions to the interstitial sediment-bound organic matter sampled in the study rivers ranged between 26% (full uncertainty range 0–100%) and 44% (full uncertainty range 0–100%) for farm yard manures/slurries, 11% (full uncertainty range 0–75%) and 48% (full uncertainty range 0–99%) for damaged road verges, 16% (full uncertainty range (0–78%) and 52% (full uncertainty range (0–100%) for decaying instream vegetation and 4% (full uncertainty range 0–31%) and 10% (full uncertainty range (0–44%) for human septic waste. The results of mass conservation tests suggest that the procedure combining bulk ^{13}C and ^{15}N isotope values and NIR spectroscopy data on organic molecular structures is sensitive to the risks of significant non-conservative tracer behaviour in the fluvial environment and will therefore not necessarily work at all in-channel sites in all catchments.

1. Introduction

The quality of hyporheic river water exerts an important control on aquatic ecology by influencing many in-channel ecological processes including biogeochemical processing (Boulton et al., 1998; Duff and Triska, 2000; Storey et al., 2004). A particularly important linkage between hyporheic water quality and aquatic ecology is represented by the issue of low dissolved oxygen supply in the benthic zone (Malard and Hervant, 1999; Finn, 2007). In this regard, a specific area that has been studied intensively is the effect of low dissolved oxygen supply on the survival of salmonid embryos incubating in river spawning beds (Chevalier et al., 1984; Peterson and Quinn, 1996; Rubin and Glimsater, 1996; Malcolm et al., 2003; Armstrong et al., 2003; Youngson et al., 2004; Greig et al., 2006; Sear et al., 2013). Incubating salmonids spend a period of months (typically 4–6) in the hyporheic zone between oviposition and emergence or 'swim up', and transient episodes of de-oxygenation have been identified as the cause of sub-lethal or lethal outcomes which ultimately impact on recruitment to populations (Youngson et al., 2004; Malcolm et al., 2008).

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Episodes of low dissolved oxygen supply in the benthos have been attributed to various causes including groundwater upwelling (Malcolm et al., 2003), reduced gravel permeability due to fine sediment ingress (Lisle, 1989; Zimmerman and Lapointe, 2005) which can hamper the removal of toxic metabolic products (Shumway et al., 1964) and enhanced oxygen consumption arising from the infiltration of fine particulate organic matter (Greig et al., 2006; Malcolm et al., 2008; Soulsby et al., 2009; Sear et al., 2013). More specifically, sediment-bound organic matter influences dissolved oxygen supply to incubating progeny in the spawning substrate via two principal mechanisms: direct competition from microorganisms during organic matter decomposition, and; the growth of biofilms which hamper intragravel flow and oxygen availability and may also scavenge potentially toxic substances (House, 2003; Greig et al., 2007; Sader et al., 2011).

Given increased recognition of the potential for sediment-bound organic matter to contribute to the degradation of salmonid spawning habitats, management strategies require a reliable evidence base on the key sources of this specific problem to ensure effective targeting of interventions (Collins et al., 2009). Previous work has, however, predominantly focussed on understanding the key sources of minerogenic fine sediment infiltrating spawning substrates (Walling et al., 2003; Collins et al., 2010a, 2012a). More recently, Collins et al. (2013) reported the application of a source fingerprinting procedure specifically for the sediment-bound organic matter ingressing salmonid spawning gravels in the River Blackwater catchment, in southern England. Given the initial success of that study, it was considered useful to apply and test the sourcing procedure elsewhere and to continue refining it. On that basis, the specific objectives of this second study were:

- To extend the application of a composite fingerprinting procedure combining the use of bulk stable ^{13}C and ^{15}N isotope values and NIR spectra to five new study rivers across England and Wales to test its wider applicability for distinguishing and apportioning the primary sources (farm manures/slurries, damaged road verges, instream decaying vegetation and human septic waste) of sediment-bound organic matter infiltrating salmonid spawning gravels.
- To use the outputs where the expanded application of the tracing procedure was successful to deliver hitherto unavailable evidence on the relative contributions of the different sources to the sediment-bound organic matter infiltrating salmonid spawning gravels.

2. Study catchments

The location of the study catchments is presented in Fig. 1. Table 1 provides summary information on a number of catchment attributes including area, land cover, stocking densities, applications of organic carbon to farm land in association with manure/slurry spreading and the estimated number of domestic properties unconnected to mains sewage and therefore assumed to have septic tanks. All study sites were known spawning grounds of Atlantic salmon (*Salmo salar*).

3. Methods

3.1. Catchment sampling to characterise potential sources of the sediment-bound organic matter infiltrating salmonid spawning gravels

Spatially representative source material samples for the sediment-bound organic matter infiltrating salmonid spawning gravels were collected during the autumn and winter of 2010. This

Fig. 1. The location of the five study catchments across England and Wales.

sampling encompassed farm yard manure/slurries, damaged road verges, instream decaying vegetation and point sources in the form of septic tanks and sewage treatment works. 10 composite samples (each comprising 10 sub-samples) were collected for each source

Table 1
Background information for the study catchments and sampling sites.

Attribute	River Aran	River Ithon	River Lugg	River Rede	River Test
Area (km^2)	12	32	230	214	104
% Urban[a]	0	1	4	1	8
% Water[a]	1	1	1	1	0
% Woodland[a]	0	4	16	29	15
% Rough pasture[a]	47	13	9	48	10
% Improved pasture[a]	51	80	58	21	16
% Arable[a]	1	1	12	0	51
Average annual rainfall (1961–1990; mm)[a]	1086	1086	748	941	576
Unconnected properties (count/km^2)	1.4	2.0	3.8	0.2	11.9
Cattle (heads/ha)[a]	25	40	44	10	12
Sheep and lambs (heads/ha)[a]	876	852	670	175	44
Pigs (heads/ha)[a]	0	1	1	2	14
Poultry (heads per ha)[a]	318	807	1789	1	1103
Organic carbon loading to land from farm manures ($t\,km^{-2}\,yr^{-1}$)[b]	591	565	637	140	167
Surface bed material D_{50} (mm)[c]	24.0	45.5	43.2	46.0	28.4
Surface bed material D_{95} (mm)[c]	34.7	62.4	58.5	59.1	55.6
Subsurface bed material D_{50} (mm)[c]	10.4	11.9	31.4	26.9	6.3
Subsurface bed material D_{95} (mm)[c]	34.3	42.3	63.2	54.3	37.0
% Sand[c]	15.9	22.5	9.6	12.4	25.0
% Silt/clay[c]	4.7	6.3	5.0	10.5	7.3

[a] ADAS land use database 2010 (see Comber et al., 2008 for background information).
[b] Based on ADAS manures GIS tool.
[c] Based on field survey data.