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Can agri-environment initiatives control sediment loss in the context of extreme winter rainfall?

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ABSTRACT

Soil erosion and sediment losses are likely to increase with projected climate change and increasing storm intensity, causing detrimental impacts to agriculture and the degradation of aquatic ecosystems. Agri-environment initiatives aim to mitigate these losses through farmer engagement and incentivisation for best practice. There is, however, limited evidence regarding the impacts of their delivery and their capacity to deliver resilience to extreme wet weather. As such, the aim of this study was to determine how fine-grained sediment provenance changes with flow condition in eight high priority English catchments targeted through a strategic agri-environment initiative and to compare the estimated sediment source proportions to the targeted advice being delivered to farmers. The provenance of fine-grained sediment was determined using sediment source fingerprinting over low flow conditions and the winter of 2019–2020 which was characterised by severe flooding. Details on the advice delivered to farmers through the Catchment Sensitive Farming initiative were obtained from a delivery agency database and interviews with catchment officers. Dominant sediment sources varied considerably between catchments and were not easily predicted based upon their characteristics meaning that targeting on-farm advice effectively is challenging. Critically, however, changes in sediment sources rarely occurred with the extreme wet winter of 2019–2020. It is recommended that the greater availability of empirical catchment-specific evidence could significantly improve the delivery of such agri-environment initiatives. In the current absence of this evidence an assumption that riparian woodland is effective at preventing sediment losses and the targeting of advice to sediment sources proportionally based upon the area of the catchment they cover may improve the benefits of such initiatives.

1. Introduction

High intensity storms and higher daily rainfall totals are occurring with increasing frequency with changing climate (Kendon et al., 2014; Burt et al., 2016). Over Europe, there was an average 45% increase in days with heavy precipitation between 1981 and 2013 compared to 1951–1980 (Fischer and Knutti, 2016). As a result, an urgent need to study the impacts of meteorological conditions on water quality impairments has been identified (Michalak, 2016).

The introduction of modern agriculture has increased soil erosion and sediment loss globally with associated elevated emissions of nutrients and carbon to freshwater (Quinton et al., 2010; Borrelli et al., 2017; Alewell et al., 2020). Concomitantly, these emissions have generated off-site impacts such as reductions in water quality or aquatic biodiversity, disruption of biogeochemical cycling, and costs to society (Bilotta and Brazier, 2008; Elser and Bennett, 2011; McDonald et al., 2016). Soil erosion and sediment loss are likely to become more severe with an increasing frequency of high intensity storms and extreme wet weather periods forecast with changing climate, representing a significant challenge to agricultural sustainability (Burt et al., 2016; Ockenden et al., 2017). Extreme wet weather can change landscape sediment sources (Bracken and Croke, 2007; Fryirs, 2013) challenging the resilience of management interventions.

Current agri-policy typically encourages improved sustainability through a combination of regulation, incentivisation and on-farm advice. Business-as-usual has, however, been recognised as not delivering sufficient reduction in water pollution for meeting policy targets (Poole et al., 2013; Collins and Zhang, 2016). Agri-environment initiatives encourage the increased uptake of best practice to deliver enhanced outcomes (McDowell et al., 2016) but there remains a paucity of evidence on their efficacy (Kay et al., 2009; Deasy et al., 2010; Lloyd, 2019; McGonigle et al., 2014; Randall et al., 2015). In the absence of

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empirical data on sediment provenance, farm advisors must rely on expert judgement and visual appraisals to target advice and capital grants through agri-environment initiatives. Little evidence exists on how these judgements correspond to the actual sources of sediment delivered to watercourses. Meeting the need to optimise mitigation to deliver cost-effectiveness from the public purse is therefore challenging (Gooday et al., 2014). The limited evidence available suggests that many agri-environment initiatives have had limited success for environmental sustainability (Oenema et al., 2009; Sutton et al. 1995; McGonigle et al., 2012; OECD, 2012; Jones et al., 2017). In particular, the resilience of on-farm measures for delivering sustainability in the context of changing climate warrants investigation, which stimulates an important question – are agri-environment initiatives delivering targeted best practice uptake that is resilient to extreme wet weather under changing climate?

The Catchment Sensitive Farming (CSF) initiative and Countryside Stewardship (CS) scheme provide targeted advice and grants to farmers in England with the aim of reducing pollutant losses to water and the atmosphere. The initiative is similar in structure to many implemented globally (OECD, 2012; McDowell et al., 2016; Smith et al., 2017). As of 2019, 19,776 farms had been engaged by targeted advice from CSF, representing 34% of the farmed area of the country (Environment Agency, 2019). Davey et al. (2020) estimated using modelling that the initiative has reduced the mean river suspended sediment concentration of targeted catchments by 4.4%. However, as with other similar initiatives, it remains unclear how well targeted its delivery is and how resilient it is likely to be to increasing climate extremes. As such, the aim of this study is to determine how fine-grained sediment provenance changes with flow conditions in eight high priority English catchments targeted by CSF and to compare the new empirical evidence on sediment source proportions to the advice delivered through the initiative as well as catchment officer opinions on the relative importance of potential sediment sources. The study period included 2018 which was

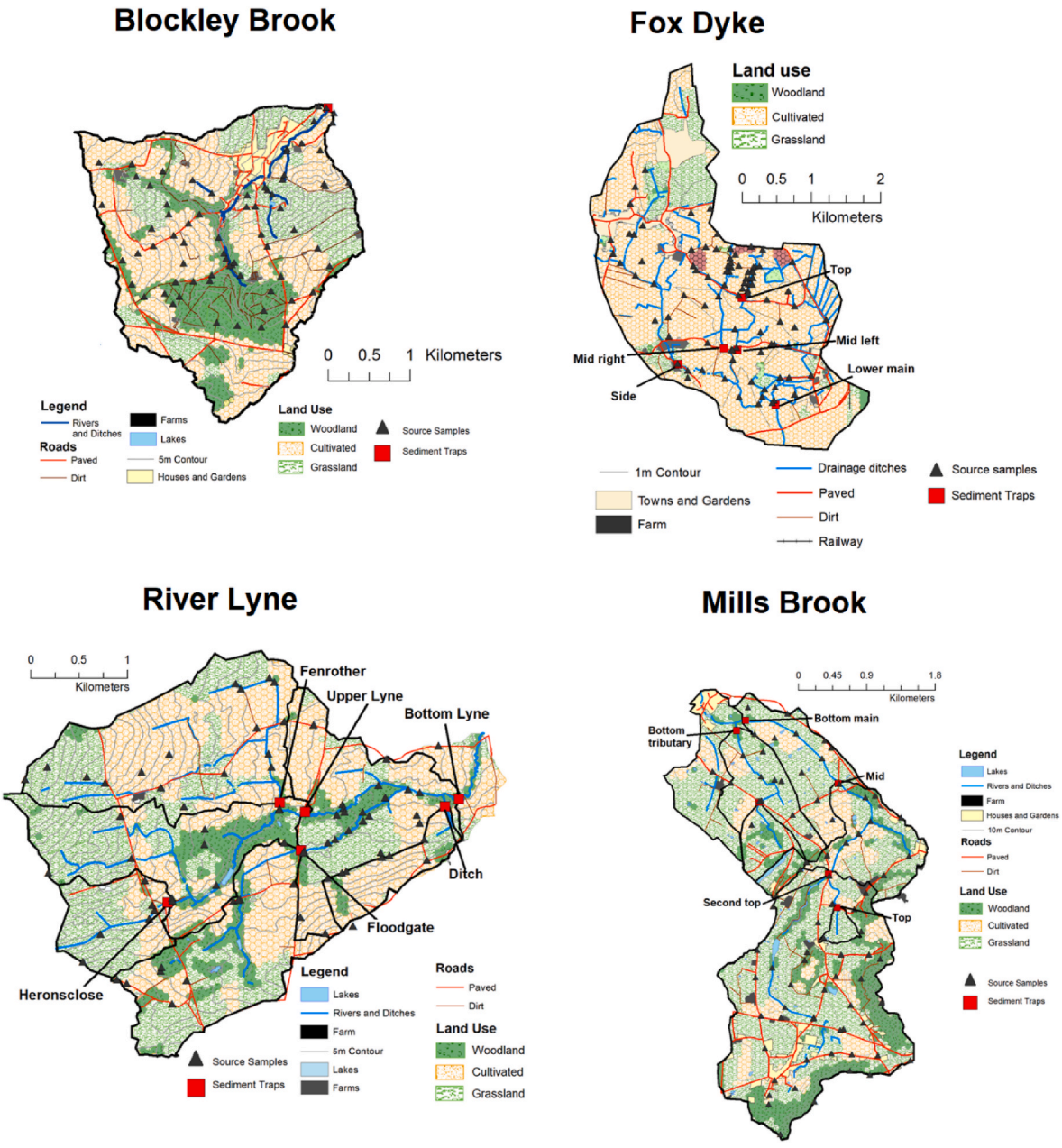


Fig. 1. The study catchments and sampling locations, Land use mapped from the Crop Map of England (CROME) (Rural Payments Agency, 2018) and manually ground-truthed.

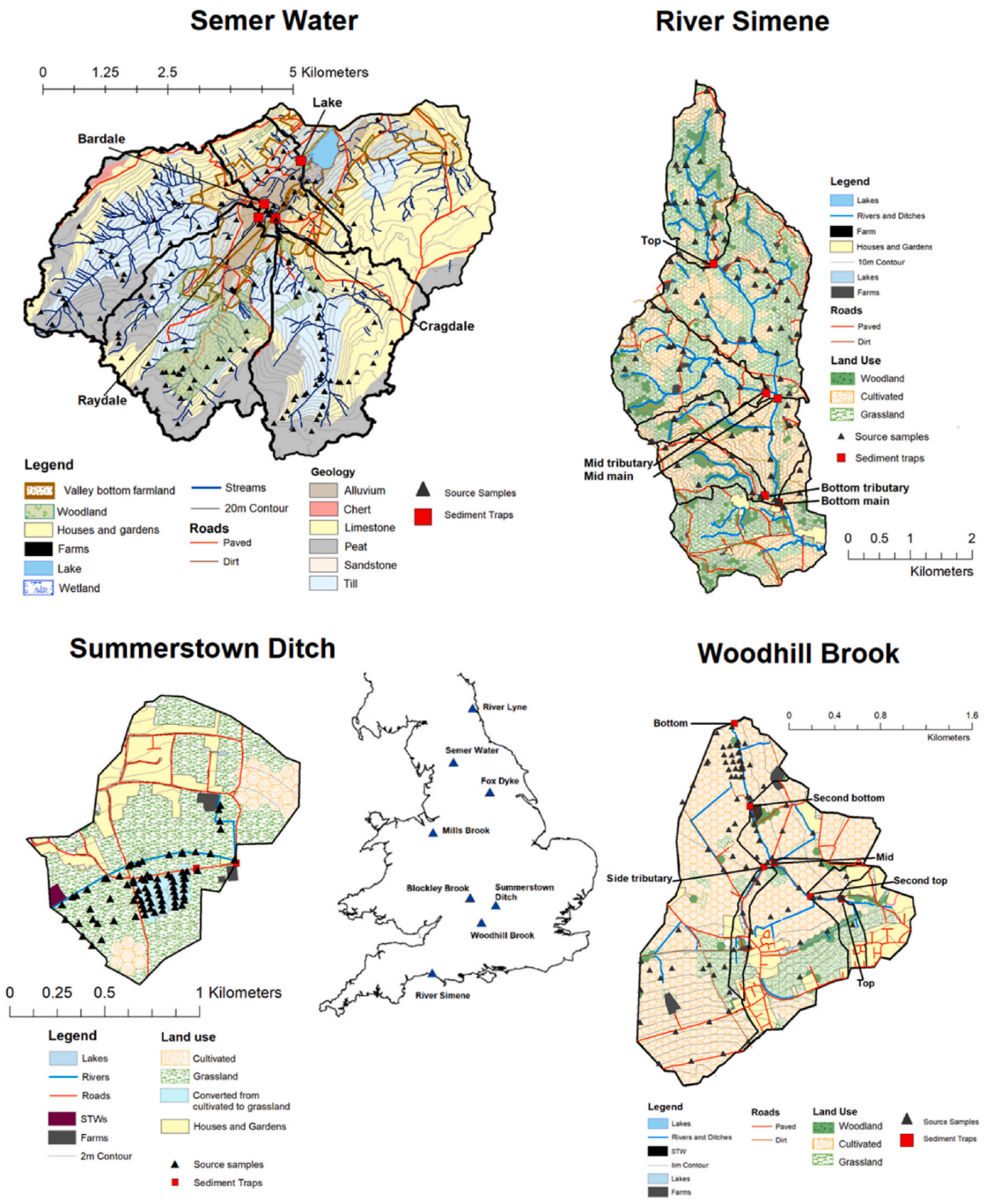


Fig. 1. (*continued*).

characterised by low rainfall and the extreme wet winter of 2019–2020 which was characterised by widespread flooding (Muchan et al., 2019; Parry et al., 2020).

2. Material and methods

2.1. Study site descriptions

Eight study sites were selected to be representative of the areas of England classified as high or medium priority in the CS scheme and therefore most heavily targeted for CSF advice and CS grants (Fig. 1). Water quality in each catchment was identified by the UK Environment Agency as being impacted by sediment pressures through routine monitoring, anecdotal evidence, and local knowledge. Water quality information for the catchments can be viewed using the Catchment Data Explorer (Environment Agency, 2020). The catchments were also inside a larger Water Framework Directive (WFD) waterbody which was classified as having bad or moderate ecological status. The Catchment Matcher tool developed by Lovett et al. (2018) was used to compare the characteristics of WFD operational catchments (Mean % Slope, % Sand, % Clay, % Productive Aquifer, Mean Precipitation, Mean Av Temperature, % Agricultural Land Cover, % Arable & Crops, % ALC Grades 1 & 2, % Designated Areas, % NVZs, % CSF & Partnerships, and % WFD Good Status) that the study catchments reported herein are within to other

English WFD catchments. This was done so that, albeit in due recognition of caveats, the representativeness of the catchment types investigated could be assessed (Supplementary Figure 1).

Blockley Brook is a tributary of the River Sour in the Cotsworlds district of Gloucestershire. It has an area of 8.52 sq km and a mean slope of 4.85°. Its land cover is 5% houses and gardens, 48% cultivated land, 24% woodland and 23% grassland. Cereals and legumes are grown on cultivated land and grassland is grazed by sheep and cattle. Catchment geology is limestone of the Salperton, Chipping Norton and Aston Formations in the upper catchment, with Whitby and Charmouth formation mudstones and Dyrham Formation sand and mudstones in the lower catchment. Shallow lime rich soils are present over the limestone, freely draining loamy soils over sand and mudstone and loamy and clayey soils with impeded drainage over mudstones. Its notable features are that in the upper and middle catchment, a discontinuous stream channel is present due to a series of small ponds. The channel here is bordered by woodland presenting a wide (100 m–600 m) buffer from agricultural land. In the lower catchment, a well-defined channel is present with high (>1 m) channel banks and no significant woodland buffer.

The Fox Dyke catchment is in North Yorkshire and contains the village of Church Fenton. It has an area of 10.8 sq km with a very low mean slope of 0.01°. Land use is almost entirely cultivation for cereal and potato production with an area of grassland (13% of catchment area) used as an airfield in the upper catchment. Its geology is Hemingbrough Glaciolacustrine Formation clays, silts and sands in the lower catchment, with the Breighton Sand Formation and Sherwood Sandstone Group in the upper catchment. Soils in the lower catchment are slowly permeable seasonally wet slightly loamy and clayey. Soils over the sandstones are loamy and naturally high in groundwater. Large pools of standing water can be observed during wet months. The stream network consists of artificial drainage channels up to ~2.5 m deep and 5 m wide which flow into the Rive Ouse. The ditch banks are well-vegetated indicating little probability of their erosion. Buffer strips between cultivated land and ditches are often narrower (<50 cm). Subsurface drains are present extensively within the catchment and sediment can be observed to enter the ditches through them.

The River Lyne catchment is located in Northumberland in the North East of England and has an area of 11.7 sq km and a mean slope of 2.21°. It is used for a mixture of cereal cultivation (46% of the catchment area) and cattle and sheep grazing (39%), with woodland present in the centre of the catchment (14%). Its geology is Devensian glacial diamicton with slowly permeable seasonally wet loamy and clayey soils. Throughout most of the middle catchment, woodland separates agricultural land from the river channels and the upper catchment is primarily used as grassland. In the lower catchment, several sediment risks could be observed such as cattle entering the river channels and narrow riparian buffers.

Mills Brook is a tributary of the River Dee located in the North West of England. It has an area of 11 sq km and a mean slope of 4.88°. Grassland covers 58% of the catchment area and is used for cattle and sheep grazing, 19% is used for maize cultivation and 19% is woodland. Woodland is primarily located on the sandstone hills present along the southern and eastern watersheds. Catchment geology is Wilmslow and Helsby formation sandstone in the upper catchment and Devensian diamicton in the lower catchment. Soils in the flatter lower catchment are slowly permeable slightly loamy and clayey and in the upper and middle catchment are freely draining and sandy. Rilling can be observed on maize fields present within the middle catchment. A small pond with an area of 0.016 sq km separates the upper catchment from the middle and lower catchment.

The catchment of Lake Semer Water is located in the Yorkshire Dales National Park. It has an area of 43 sq km with a large difference in altitude between the lake (246 m. a.s.l) and watershed (700 m. a.s.l) resulting in a high mean slope of 9.27°. Blanket peat deposits are present along the watershed at high altitude covering 18% of the catchment area. Commercial forestry is taking place in the catchment of Raydale Beck, one of the three tributaries of the lake, and covers 5% of the catchment area. Hillslopes covering 59% of the catchment area are used for light sheep grazing whilst the flatter valley bottom area which covers 18% of the catchment is more intensively grazed by both cattle and sheep. Geology consists of Simonstone, Yoredale, Three Yard and Main Limestone formations on hillslopes, Devensian diamicton in tributary valleys and alluvium in the flatter lower catchment. Soils vary from free draining over the limestone geology to clayey and poorly permeable over the diamicton and in the valley bottoms. Tributary channel banks are shallow (<20 cm) and primarily composed of large stones. In the lower catchment, banks become high (~2 m) over the alluvium deposits close to the lake. Landslips are present extensively adjacent to tributary channels where the underlying diamicton valley fill is exposed; these are most abundant in Bardale Beck. Restoration efforts are currently being undertaken to mitigate the erosion of the blanket peat deposits.

The River Simene is close to the town of Bridport in the South West of England. It has a catchment area of 16.4 sq km and a mean slope of 6.75°. Cereal and beet cultivation covers 54% of the catchment area, 26% is used for cattle and sheep grazing, and 8% is small patches of woodland which are often adjacent to river channels. Geology in the lower catchment and along the watershed in the upper catchment is Down Cliff and Thorncombe sand members overlain by freely draining loamy soils. In the centre, Eype Clay Member siltstone and limestone overlain by clayey soils with impeded drainage are present. In the upper catchment, Green Ammonite Member Mudstone overlain by slowly permeable loamy and clayey soils dominates. There is a trend of cultivated land being most abundant in the lower catchment and grassland being most abundant in the middle catchment with a mixture of land uses in the upper catchment. Metalled roads and woodland corridors provide a buffer between streams and agricultural land in the lower catchment.

Summerstown Ditch is south of Marsh Gibbon in Buckinghamshire and has a small catchment of 1.1 sq km and a low mean slope of 0.77°. Its land use is primarily grassland used for cattle grazing covering 69% of the catchment area with two cultivated fields used for wheat also present covering 13% of its area. One of these was, however, converted to grassland in early 2019. Its geology is Peterborough Member Mudstone and Kellaways Clay Member with slowly permeable, seasonally wet, loamy and clayey soils. The ditch is seasonally dry close to its source and flow is impeded by woody debris and a culvert at the catchment outlet. A sewage treatment works is present at the top of the ditch.

Woodhill Brook is a tributary of the River Ock with an area of 4.4 sq km and a mean slope of 1.76°. Its catchment contains the village of East Challow in Oxfordshire. Cereal and field bean cultivation covers 67% of the catchment area, 15% is used for light sheep grazing, and a narrow woodland corridor (<20 m) along the stream covers 4%. Its geology is Gault Formation mudstones in the lower catchment with Upper Greensand Formation sands and West Melbury formation Marl chalk in the upper catchment. Soils over the mudstone are clayey and slowly permeable whilst those over the sands are freely draining, and shallow soils are present over the chalk. Channel banks are mostly shallow (<30 cm) increasing in height in a downstream direction. Bank profiles are partially vegetated. Stream beds consist of a deep layer (~30 cm) of thick anoxic mud which itself represents a major sediment source. Woodland and a paved path along the stream presents a buffer of variable width, which is narrowest in the lower catchment (<1 m in places). An abandoned canal channel is present across the entire width of the catchment and presents a barrier between the upper and lower catchments; however, streams flow underneath it at multiple points.

2.2. Data collection

The recommendations made by CSFOs were retrieved from the Environment Agency central database for farms in each study catchment. The frequency each recommendation was made was tabulated and each was classified by its primary target (cultivated land, grassland, soil

structure, connectivity, nutrients, pesticides and gaseous). Each CSFO was also interviewed to identify their opinions on the water quality issues in each catchment and the surrounding region and their corresponding priorities for on-farm advice delivery.

Sediment source fingerprinting compares the properties (tracers) of sediment retrieved from a waterbody to those of its potential sources present in its catchment (Klages and Hsieh, 1975). Using a mathematical unmixing model, a percentage contribution of sediment from each source can be calculated (Collins et al., 1997). The methodology consists of source and sediment sampling, tracer analysis, source group classification, tracer conservatism testing, source group discrimination using a composite fingerprint, unmixing modelling and model validation steps (Collins et al., 2017).

Samples of potential sediment sources were retrieved from each catchment with the aim of sampling its entire area which is likely to contribute sediment to watercourses (Supplementary Table 1; Fig. 1). Cultivated, grassland and woodland topsoils were retrieved from the top 2 cm of the soil profile using an enamelled stainless-steel trowel. This depth was selected as it is the depth to which wash erosion processes are expected to operate (Evans et al., 2016). Woodland was not sampled in the Woodhill Brook and Summerstown Ditch study catchments as it did not cover a significant percentage of their areas. Channel banks were sampled from the bottom two-thirds of the profiles of visibly eroding reaches to avoid sampling near-surface material. Because of the well-vegetated ditch banks of Fox Dyke, subsurface sediment was most likely to originate from field drains. As such, subsurface material was retrieved using a gouge corer from the bottom two-thirds of the bank profiles to a depth of 20–30 cm, discarding the top 5 cm which was likely to be characteristic of topsoils. Landslips in the Semer Water catchment were sampled to a depth of approximately 10 cm using a trowel once the top 1 cm of material was removed to avoid potential contamination from displaced topsoils. The anoxic mud deposits on the bed of Woodhill Brook were grab sampled to a depth of approximately 20 cm. All samples of topsoils, landslips and channel banks were retrieved as a composite of 3–5 subsamples from within a 3 m radius of the sampling point to increase the representativeness of the sampling.

Suspended sediment samples were retrieved using time-integrated traps designed by Phillips et al. (2000). The traps were positioned in the stream networks with the aim to separate the catchments into their major tributaries, or at roughly even intervals along the stream length if only one major channel was present. In small catchments only one trap was placed at the catchment outlet. The traps were emptied at intervals of three to ten months to obtain representative samples of sediment over a range of different flow conditions (Supplementary Table 2; Fig. 1).

2.3. Tracer analysis

Sediment samples were initially passed through a 2 mm stainless steel mesh to remove any aquatic life and coarse plant matter. Both source and sediment samples were then oven dried at 105 °C and disaggregated using a mechanised pestle and mortar. The dried samples were wet sieved to <25 μm using a stainless-steel mesh. A mesh diameter of 25 μm was selected for analysis to reduce the potential for changes to sediment particle size during its erosion, transport and deposition to introduce uncertainties into the fingerprinting procedure (Laceby et al., 2017). This decision was also based upon the particle size distribution data of the sediment samples collected, as the majority of silt and clay sized material transported in each river fell within this size range (Supplementary Figure 2). The sediment in several sites was composed of significant amounts of sand; however, due to its small potential for pollutant transport, it was judged to be of little risk to water quality.

Colourimetric, geochemical, C and N isotope and radionuclide tracers were analysed as potential sediment tracers (Collins et al., 2020). The prepared source and sediment samples were packed into fresh clear polythene bags before being scanned using a Ricoh MP colour scanner. Colour images were captured in pdf format and imported into Gimp 2 photo editing software where the mean values of reflected red, green and blue light were quantified on a scale of 0–255 in the RGB colour space (Pulley and Rowntree, 2016).

The concentrations of Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mo, Mn, Na, Ni, P, Pb, S, Ti and Zn were determined using a PerkinElmer Optima 7300 DV Inductively Coupled Plasma - Optical Emission Spectrometer. Approximately 0.25 g of the prepared samples was digested using 4 ml of 36% HCl and 1 ml of 70% HNO_3 in straight sided Pyrex glass tubes. Samples were left at room temperature overnight before being heated at 105 °C in a digestion block for 1 h, and then at 140 °C until the samples were dry. The samples were then re-dissolved using 20% HCl, filtered through a Whatman No.40 paper and made up to 50 ml using ultrapure water (McGrath and Cunliffe, 1985). Every tenth sample was repeat analysed to assess analytical precision.

The activities of ^{137}Cs, ^{228}Ac, ^{4} K, ^{234}Th, ^{235}U and ^{212}Pb were quantified using Ortec hyper-pure germanium detectors. Approximately 2.5 g of each sample was packed tightly into PTFE sample pots to a depth of 4 cm. Count times were a minimum of 80,731 s, with a mean of 126,386 s. The number of decay counts for each radionuclide were quantified and converted into activity (mBq g^{-1}) using Ortec Gamma Vision software. Activities were corrected for detector efficiency (Foster et al., 2007).

Total Carbon and Nitrogen concentrations, δ^{13}C and δ^{15}N, were measured using a Carlo Erba NA2000 analyser and a SerCon 20–22 isotope ratio mass spectrometer. Between 4 mg and 93 mg of the prepared samples were packed into pure tin capsules and sealed for analysis. Wheat flour (IA-R001 from Iso-Analytical, Crewe, UK; 1.88% N, 40.2% C, 2.55 δ^{15}N and −26.43 δ^{13}C) calibrated against IAEA-N-1 for nitrogen and IAEA-CH6 for carbon by Iso-Analytical, Crewe, UK, was used as a reference standard (Collins et al., 2013).

2.4. Sediment source fingerprinting procedure

The SIFT (SedIment Fingerprinting Tool) version 1.2.3 was used to apportion the contribution of the sediment sources to the sampled sediments (Pulley and Collins, 2018a; Pulley and Collins, 2018b). The methodology used consisted of the following steps:

An initial linear discriminant analysis to determine which of the a-priori land use source groups should be combined or reclassified into a single source group to ensure adequate discrimination (Pulley and Collins, 2018a). Bi-plots of sources and sediments were used to visually identify any potentially non-conservative tracers (Oldfield and Wu, 2000). A mass conservation test was used to remove any tracers whose concentrations in the sediment samples fell outside of the minimum-maximum ranges in the source groups in more than 10% of sediment samples (Foster and Lees, 2000). Tracers failing these tests are presented in Supplementary Table 4.

A linear discriminant analysis was then used to identify the composite fingerprint of tracers best able to discriminate between the source groups (Collins et al., 1997; Supplementary Table 5).

Virtual sample mixtures of a 100% contribution from each source group (expressed as source group median tracer values) and equal contributions from all sources (expressed as the median of source group medians) were then used to validate a sediment unmixing model and ensure that each source was recognised by the model (Palazón et al., 2015). Source apportionment errors were calculated as the mean absolute differences between the modelled and virtual mixture compositions. Tracer weightings were trialled with the virtual mixtures to determine if they improved source apportionment. These were based upon an increased weighting of those tracers correlated with the second discriminant function extracted from the linear discriminant analysis output (Supplementary Table 5).

An unmixing model based upon that developed by Collins et al. (1997) which included a Monte Carlo uncertainty routine was used with the composite fingerprints to apportion contributions from the sediment

source groups. The Monte Carlo routine sampled random numbers between the 25th and 75th percentile ranges found in the source groups (Pulley et al., 2020) and maintained correlations between the tracers which were found in the source dataset (Laceby and Olley, 2015). Unmixing model results were presented as the median contribution from each source with a 25th-75th percentile uncertainty range. The mean values from all sampling sites in each catchment are presented in the main text and results for individual sites in Supplementary Table 6. Further details of the sediment fingerprinting procedure are provided by Pulley and Collins (2018b). Due to the loss of the sediment traps from the Lake and Bardale Beck sites in Semer Water during the floods of early 2020, its summary graph only uses results from Raydale and Cragdale Becks.

3. Results

3.1. Study catchment characteristics and targeting of mitigation measures through CSF

The characteristics of the eight study catchments are outlined in Table 1. They were selected based upon the impact of sediment pressures on water quality as determined through routine monitoring by the UK Environment Agency, representativeness of different catchment characteristics in England (Supplementary Figure 3) and being classed as high priority targets for CSF. Table 2 summarises the recommendations delivered through CSF extracted from the central CSF database, administered by the Environment Agency and the most important sediment sources expressed by Catchment Sensitive Farming Officers (CSFOs) in discussions.

In all catchments, advice targeting nutrients featured prominently. Measures targeting sediment losses were recommended less frequently, although still featuring prominently, as were measures relating to soil structure and the mitigation of connectivity pathways between farmed land and watercourses. Opinions on the most important sources of sediment according to CSFOs varied, although where present, cultivated land was always identified as being high risk. In all catchments, where it is present, erosion rates on cultivated land are expected to increase with heavy rainfall. However, it is unclear if a similar increase would also occur with other sources, resulting in unpredictable changes in their relative importance and therefore where the targeting of CSF measures will deliver optimum value.

The potential sources of sediment vary significantly between catchments, as do landscape features which could impact their relative importance during different rainfall conditions. For example, the catchments of Blockley Brook, the River Lyne, the River Simene and Woodhill Brook contain large amounts of cultivated land which is judged by the CSFOs to be a major erosion risk. However, riparian woodland is also present which could prevent sediment losses to watercourses but could also be breached during extreme wet periods. Fox Dyke is also dominated by cultivated land with only narrow grassland buffers separating it from watercourses, representing a major erosion risk. However, clayey soils, flat terrain and extensive subsurface field drains may result in the proportion of sediment originating from topsoils being lower than expected and sensitive to rainfall patterns.

The proportion of each catchment covered by high-risk sources also represents a source of uncertainty. For example, significant areas of the River Simene and Semer Water catchments are covered by what the CSFOs identify as high-risk sources, namely sloped cultivated land in the former and intensively grazed valley bottom farmland in the latter. However, their relative importance when compared to other sediment sources such as commercial forestry in the Semer Water catchment and large areas of cattle grazing in the River Simene catchment is unclear, and these sources are also viewed by the officers as potential erosion risks. The lower River Lyne catchment contains multiple high-risk sources whilst its upper catchment is considered as low risk by the CSFO due to more sustainable farming practices and the presence of riparian woodland. However, given the larger area of the upper catchment it is unclear if this assumption is correct and how their relative importance might change during extreme wet weather. Mills Brook represents a more extreme example of this issue as visibly eroding maize fields are a high-risk source which was identified by the CSFO and given priority for mitigation. However, these fields only cover a small proportion of the overall catchment area and therefore their impact on the total sediment load is uncertain.

An additional consideration is that secondary or non-agricultural sources including channel bed mud deposits, sewage treatment, and

Table 1
Study catchment characteristics.

Catchment	Area (sq km)	Land use	Notable characteristics
Blockley Brook	8.5	Cultivated 48%, Woodland 24%, Grassland 23%	Thick woodland buffers. Small ponds disrupt longitudinal connectivity.
Fox Dyke	10.8	Cultivated 78%, Grassland 13%	Mean slope 0.01°. Subsurface drains present. Narrow (<50 cm) riparian buffers often present.
River Lyne	11.7	Cultivated 46%, Grassland 39%, Woodland 14%	Riparian woodland present extensively. Poaching by cattle and narrow riparian buffers in the lower catchments. Two major roads cross the catchment.
Mills Brook	11.1	Grassland 58%, Cultivated 19%, Woodland 19%	Woodland covers sandstone hills along the south east watershed. Visibly eroding maize fields are present in the middle catchment and mitigation measures are being targeted here. A pond separates the upper and lower catchment.
Semer Water	43	Hillslope topsoils 59%, Valley bottom farmland 18%, Blanket peat 18%, Woodland 5%	The catchment is steeply sloped (mean 9.27°). The flatter valley bottom area contains some cattle farming whilst hillslopes are used exclusively for sheep. Landslips are widespread on glacial diamicton adjacent to stream channels. Blanket peat along the watershed has suffered extensive erosion.
River Simene	16.4	Cultivated 54%, Grassland 36%, Woodland 8%	Wooded buffers and metalled roads separate the river from agriculture in the lower catchment.
Summerstown Ditch	1.2	Grassland 69%, Cultivated 13%	A sewage treatment works is present at the top of the ditch. Poor flows occur due to its small catchment area, woody debris and a culvert. Its water has a poor odor and cloudy appearance.
Woodhill Brook	4.4	Cultivated 67%, Grassland 15%, Woodland 4%	Thick channel bed mud deposits are present extensively. A sewage treatment works is located 2/3 of the distance down the brook. A woodland corridor and paved roads separate arable land from the brook. A disused canal channel separates the upper and lower catchment.

Table 2
The categorised frequency of advice delivered through CSF and most important sediment sources according to local CSFOs, specific advice delivered is provided in Supplementary Table 3.

Site	Number of CSFO recommendations for best practice						Key CSFO opinions on the sources of soil erosion and sediment pollution
	Nutrients	Cultivated	Grassland	Connectivity	Soils	Land use change	
Blockely Brook	15	3	6	6	0	0	Cultivated land is likely the dominant source of sediment.
Fox Dyke	0	0	0	0	0	0	The presence of subsurface drainage will bypass buffers and therefore influence what recommendations are delivered.
River Lyne	32	6	8	6	7	0	Road runoff may pipe directly into streams. Livestock is allowed access to streams to drink. Silt can be observed to run down some minor roads. Ploughing methods are sometimes poor. Grassland soils are compacted and poorly drained. The lower catchment is likely the source of most sediment losses.
Mills Brook	28	3	2	7	4	0	Arable is likely to be the most major sediment source. Visibly eroding maize fields in the middle catchment are particularly important. Grassland in the lower catchment suffers from waterlogging and high runoff and its soils are often compacted.
Semer Water	321	0	8	35	21	0	Sediment and phosphorus are the biggest problems. Valley bottom cattle farming may be more of an issue than elsewhere. Small dairies when combined with the wet catchment and waterlogged soils are a problem. Livestock is often left out when soils are saturated and there are compaction issues. Presumably a lot of sediment comes from the forestry, many farmers think so. Advice delivered targets farms across the entire catchment area.
River Simene	187	94	37	110	22	18	High sediment concentrations have been observed in the stream, cultivated land is likely its most important source. Maize growing is a major problem. Farmers are not adequately considering rainfall and quantities when muck spreading. The overwintering of sheep in fields is likely a problem. Advice targets farms across the entire catchment area.
Summerstown Ditch	20	0	0	2	0	0	See below
Woodhill Brook	8	1	0	0	0	0	Sediment, pesticides, phosphorus and nitrate are problems. Cultivated land is likely the most important sediment source. Buffer strips, cover crops, taking land out of production and appropriate timing of ploughing would all have a beneficial impact. The quality of grassland management is mixed.

landslips are present in the Woodhill Brook, Summerstown Ditch and Semer Water catchments. Similarly, in all catchments, channel bank erosion represents a potential source of sediment. These sources may contribute significantly to stream sediment loads limiting the potential benefits CSF actions targeting farmed land and steadings can deliver. They may also vary in relative importance with rainfall patterns meaning that CSF only has the potential to deliver significant benefits during certain weather conditions.

3.2. *Rainfall and stream discharge – the extreme UK winter of 2019–2020*

Mean annual rainfall for the UK during the 2017–2020 period was 953 mm in 2017, 912 mm in 2018 and 1095 mm in 2019 (Met Office, 2020). When compared to the long-term (1766–2020) mean of 919 mm, 2019 was the 19th wettest year on record. On a monthly basis, November 2019 was the 37th wettest November in the 255-year dataset with 138 mm of rainfall compared to a long-term mean of 93 mm, and February 2020 was the wettest February on record experiencing 169 mm compared to a mean of 66 mm (Met Office, 2020). This rainfall resulted in series of extreme high flow events which were associated with widespread flooding throughout much of the UK (Muchan et al., 2019; Parry et al., 2020, Fig. 2). The summers of 2018 and 2019 experienced little rainfall and therefore lower streamflow, and moderate flows occurred during the winter of 2017–2018 and spring of 2019. All study sites had a comparable trend in river discharge over the 2017–2020 period. For example, 43% of discharge at the River Simene on the South coast and 45% of the Mills Brook discharge (measured at Tattenhall) in the North of England occurred in the winter of 2019–2020.

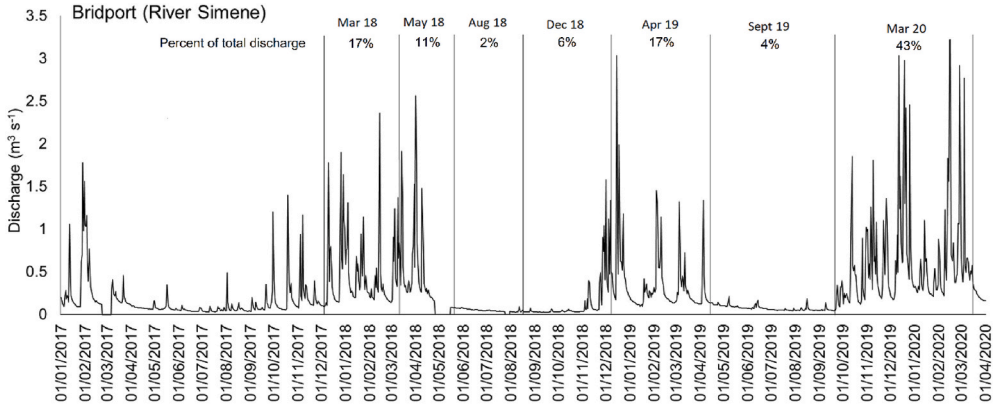


Fig. 2. Discharge at the monitoring station closest to the River Simene study site, illustrating the higher flows during the wet winter of 2019–2020.

3.3. Sediment provenance estimates from the fingerprinting approach

Few changes in sediment provenance can be observed when comparing the winter of 2019–2020 to drier conditions apart from in Fox Dyke and Summerstown Ditch (Fig. 3; Supplementary Table 5). During periods of low rainfall in Summerstown Ditch there was a small contribution of sediment from manures and a high contribution from channel banks. In contrast, during the two periods when flows were highest (Mar–May 2018 and Sept 2019–June 2020) topsoil sources dominated and contributions from other sources were insignificant. In Fox Dyke, during moderate or high rainfall, surface sources dominate, whilst during dry periods, such as the summer of 2018, subsurface sources are most important. As the dyke's banks are well vegetated and unlikely to undergo fluvial erosion, the high low-flow subsurface contribution suggests sediment transport takes place through land drains. As a result, in both catchments, mitigation measures targeting cultivated land which is identified as high priority by CSFOs, may not deliver benefits during lower flows.

Dominant sediment sources vary significantly between sites where no major changes were observed during periods of extreme rainfall challenging the optimum delivery of CSF. In Blockley Brook and Woodill Brook, non-agricultural sediment sources dominate. Woodland is most important in Blockley Brook due to the presence of wide buffers separating agriculture from its channels (Fig. 3; Supplementary Table 5). The tall channel banks present in the lower catchment also contribute approximately 25% of its sediment load. The woodland and road buffers separating cultivated land from Woodhill Brook are effective at preventing sediment losses, with only ~15% originating from this source. Most suspended sediment instead originates from the thick channel bed mud deposits present. These findings contradict the opinion of local CSFOs that cultivated topsoils are likely to be dominant. Similarly, despite the low contribution of sediment originating from sewage treatment in Summerstown Ditch, this source is likely causing severe sediment-associated phosphorus enrichment (mean concentration of

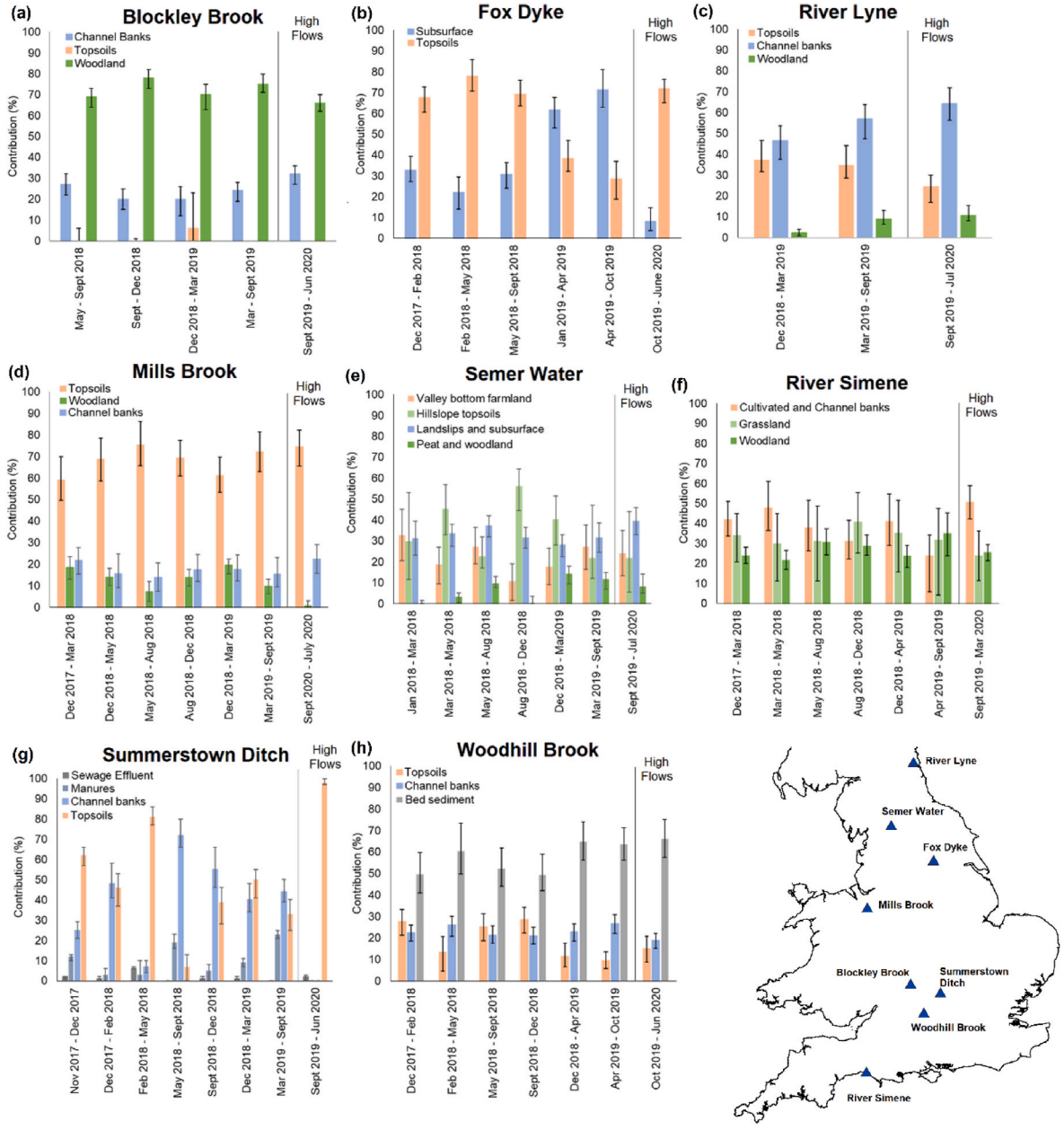


Fig. 3. Mean modelled contributions from sediment sources presented as a composite of all sampling points in each catchment with 25th–75th percentile uncertainty ranges generated from the Monte Carlo routine.

3193 mg kg^{-1} compared to a mean of 1040 mg kg^{-1} in grassland topsoils). This source may therefore also limit the improvement in water quality that can be achieved by targeting agricultural sources alone.

A scaling issue can be identified in the Mills Brook catchment presenting an additional challenge for the optimum delivery of CSF. Whilst sediment fingerprinting is only able to determine that a combination of cultivated and grassland topsoils were the dominant sources of sediment, a bi-plot of source and sediment carbon and nitrogen indicates that most of this sediment originated from grassland (Fig. 3; Fig. 4). Local CSFOs and catchment advisors identify that visibly eroding maize fields are priorities for mitigation; however, our results suggest that due to the small proportion of the catchment they cover, their contributions to overall sediment yield are low. Cultivated land is also determined to be of lesser importance than might be expected in the River Simene catchment despite it covering a much larger proportion of the catchment area. Mixed contributions of sediment from cultivated land + channel banks, grassland and woodland were found despite large areas of sloped cultivated land being present. This is, however, likely related to the presence of riparian roads and woodland disrupting connectivity pathways rather than a scaling issue. Within both catchments, the delivery of CSF targets all sediment sources, although increasing the priority of grassland for mitigation would deliver improved cost-benefit.

In the River Lyne and Semer Water catchments, sediment sources largely correspond well to the opinions of the CSFOs and current delivery of CSF. In the lower River Lyne catchment, agricultural topsoils are the dominant source of sediment where multiple risks such as narrow riparian buffers and poaching by cattle were identified. In contrast, channel banks contribute most of the small amounts of sediment originating from the upper and middle catchment where large areas of riparian woodland are present. Sediment in the Semer Water catchment originates roughly equally from hillslope topsoils, valley bottom farmland and landslips + subsurface sources, with low inputs from blanket peat or woodland. The high contributions of sediment originating from valley bottom grassland despite it only covering 18% of the catchment area suggests that the opinions and advice delivered by the CSFO are well targeted by prioritising this source. However, the opinion that forestry is likely to be an important sediment source is incorrect.

4. Discussion

4.1. Sediment sources and the fit of recommended interventions

The sediment source types present, and relative contributions of sources, varied significantly among the catchments. As a result, delivering optimum cost-benefit through CSF is challenging as there is no size fits all best practice plan for the delivery of interventions. Visual observations of likely pollutant sources proved mostly effective in the River Lyne and Semer Water catchments but in the other six there was a partial or total mismatch between what had been concluded through visual appraisal and the actual sediment sources resolved using sediment fingerprinting. The causes of these mismatches varied and included pre-existing woodland buffers, a small proportion of the catchment area covered by a high-risk source and the importance of non-agricultural sources. As a result, there is a requirement for empirical catchment-specific evidence to ensure optimum cost benefit from CSF and similar agri-environment initiatives. Where a highly engaged CSFO was present, all important sediment sources were, however, targeted by best practice advice, meaning that where non-agricultural sediment sources do not dominate water pollution problems, the initiative is likely to deliver a reduction in sediment losses.

Where present, cultivated land was always viewed by the CSFOs as the most important potential source of sediment, especially where it was present on a slope. This is a reasonable assumption as the Soil Survey of England and Wales (1982–87) identified that, in the UK, topsoil texture, landform and land use were the dominant controls on visible erosion with cultivated land being of particular importance (Evans, 1990). Similarly, in the widely used Revised Universal Soil Loss Equation (RUSLE), the C (cover and management) factor is a key predictor of soil loss (Renard et al., 1997). However, the results of this study show that structural connectivity within the landscape is generally more important than other factors when considering the sources of the sediment entering a stream (Fryirs, 2013), reflecting the fact that sediment sources are

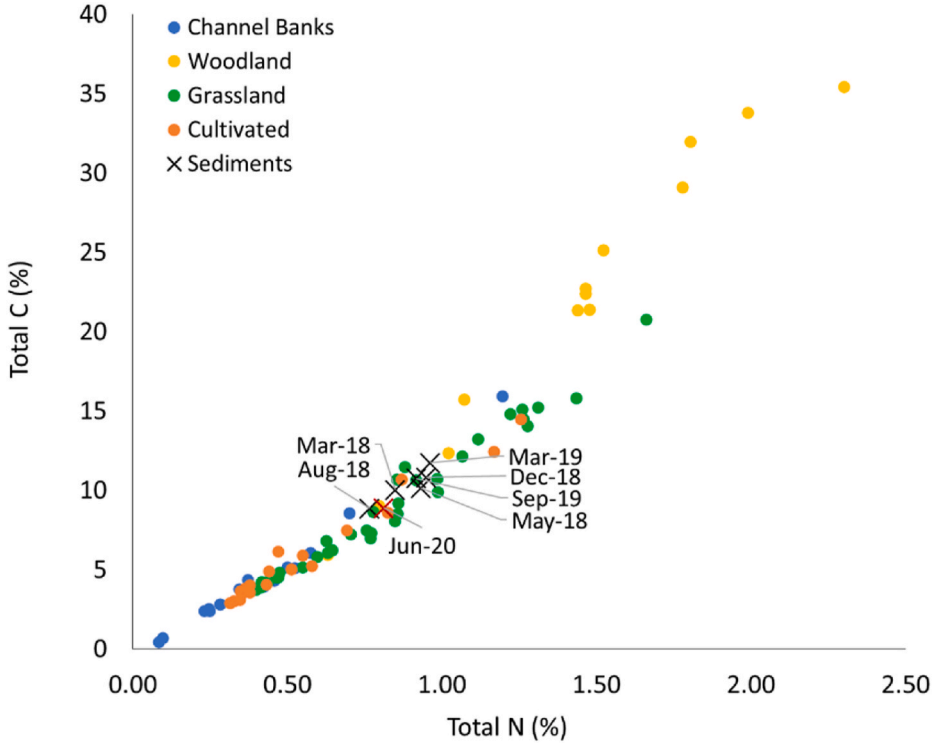


Fig. 4. Bi-plot of Total Carbon and Total Nitrogen in Mills Brook source and sediment samples.

controlled by both erosion for sediment mobilisation and subsequent efficiency of delivery of mobilised particulate material from source to the sampling point in the stream channel (Collins and Walling, 2004). As a result, the prediction of sediment sources through visual observation, modelling and remote sensing approaches is likely to be challenging since the controlling effect of connectivity cannot be measured explicitly (Turnbull et al., 2018). In addition, different connectivity models can potentially show little agreement in European arable landscapes (Baartman et al., 2020). As a result, the potential for finding direct methods to predict dominant sediment sources as alternatives to source fingerprinting is limited and even where methods offer indirect approaches to estimating sediment sources, they are hampered by many logistical and cost issues (Collins and Walling, 2004).

Three general observations made during our work could act to improve the targeting of on-farm interventions by CSF and similar agri-environment initiatives in temperate agricultural landscapes. First, is that the presence of a high-risk sediment source covering only a small proportion of the catchment area is unlikely to have a significant impact on river sediment load at a catchment scale, as was the case with cultivated land in the Mills Brook study area. Biddulph et al. (2017) found that remediation of a polluting farm track in South West England failed to deliver an in-stream impact due to the small proportion of the catchment area it covered. This may not, however, apply when the source is directly connected to the river channel and the catchment is particularly small, such as for the channel bed mud deposits found in the Woodhill Brook study catchment. A second observation relates to this finding as it is important to identify the presence of any non-agricultural sources such as channel bed deposits, landslips and sewage treatment which could dominate stream sediment loads limiting the potential in-stream benefits that can be delivered through improved agricultural practices. However, it may be challenging to determine the importance of such sources through visual observation as forestry was incorrectly viewed as being a major source of sediment in the Semer Water catchment. The third observation is that the effectiveness of riparian woodlands at preventing sediment losses in the Blockley Brook, Woodhill Brook, River Lyne and River Simene study catchments suggests that it is reasonable to assume that such features are highly effective at preventing sediment delivery to streams; thereby potentially improving the general targeting of on-farm mitigation measures for water quality benefits.

4.2. Changes in sediment sources during the extreme 2019–2020 winter

At most study sites, the provenance of fine-grained sediment did not change substantially when comparing the extreme winter of 2019–2020 to other flow conditions. This empirical evidence suggests that approaches such as the interaction between CSF and CS can therefore provide future resilience for soil erosion and sediment loss and associated pollutant emissions during weather extremes provided that on-farm best practice is targeted using robust evidence.

The magnitude of changes in sediment provenance with flow condition reported in previously published studies is variable. Sherriff et al. (2018) reported consistent sources over time (May 2012–May 2014) at most of their sampling sites in three lowland intensive agricultural catchments in Ireland. Similarly, when comparing sediment provenance during four years in Southwestern Alberta, Canada, Liu et al. (2017) reported less than a ~25% difference in contributions from each sediment source. Walling et al. (1999), in contrast, found much larger temporal changes in sediment sources on the River Ouse, UK as did Carter et al. (2003) working on the River Aire, UK. However, these particular studies examined a wider particle size range (<63 μm) than our investigation. As a result, changes in the particle size distributions of sediment samples during the corresponding study periods may have caused the modelled changes in sediment source contributions (Laceby et al., 2017). Pulley et al. (2019), however, found significant changes in sediment sources even when comparing winter and summer periods in the River Torridge in the South West UK when source tracing with the <25 μm fraction. It is also informative to note that the catchments investigated in the previous studies noted above are all significantly larger than the eight in our new study herein. As a result, the greater temporal variability in sediment sources reported by the earlier work may also be a result of landscape complexity and the greater scope for more pronounced variability in sediment mobilisation and delivery patterns. Connectivity driven by rainfall (functional connectivity) is often viewed as more representative of catchment processes than structural connectivity (Baartman et al., 2020). As such, a change in sediment source would be expected as different parts of the landscape become connected to watercourses with increased rainfall during extreme wet periods (Fryirs, 2013). Theoretically, another possible explanation for the lack of such a change found in our study is that sediment deposited on channel beds during the falling limb of storm events is being re-mobilised during low flow periods. Walling et al. (1998) found that in the large River Ouse catchment, in the UK, ~10% of the annual sediment yield was stored on the channel bed. As the catchments studied in our new work are far smaller, the opportunities for sediment storage on the channel bed would be expected to be lower. However, the quantity stored may be significant when considering the small mass of sediment transported during summer months. The small size of our study catchments studied may also provide another explanation for the lack of temporal variation in sediment sources as it limits the potential for the storage of eroded sediment within the landscape, meaning that connectivity is high even during relative dry periods. However, the observed effectiveness of riparian woodland suggests that there are significant areas of many of the catchments which are not coupled to stream channels even during extreme overbank events.

5. Conclusions

The results of this study indicate that the combined CSF and CS approach can likely provide catchment resilience during increasing weather extremes. However, demonstrating tangible improvements delivered through agri-environment initiatives to stakeholders is likely to remain difficult (Kleijn and Sutherland, 2003). But, given that currently applied best practice is unlikely to counter the increases in water pollution losses predicted under the extremes of changing climate (Ockenden et al., 2017), the further refinement of such initiatives is likely to be a necessity for agri-environmental policy. Here, significant improvements in cost-benefit depend upon a greater availability of catchment-specific empirical, rather than currently visually-based, sediment provenance information. As structural connectivity is likely the dominant control on sediment sources in many of the studied catchments, the accurate prediction of dominant sediment source contributions through visual inspection, remote sensing and modelling approaches is likely to be challenging.

Obtaining catchment-specific evidence is challenging when considering the large size of most river catchments; however, because of the observed lack of any major changes in sediment source even during the extreme winter of 2019–2020, it is likely that a small number of time-integrated samples collected over 3–6 months would be sufficient to identify the dominant sediment sources in a catchment for targeting best practice effectively. The availability of this evidence is likely to have the additional benefit of increasing farmer and stakeholder engagement in the need for greater uptake of recommended best practice in support of the sustainability of modern farming (Vrain and Lovett, 2016). When provided with the results of this study, all CSFOs expressed its usefulness for farmer engagement as well as for directing their own recommendations for on-farm interventions.

Author contribution statement

A Collins: Conceptualization, Funding acquisition, Project Administration, Supervision, Writing - Original Draft, Writing: Reviewing and

Editing.

S Pulley: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing- Original draft preparation, Writing- Reviewing and Editing, Visualization.

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.jclepro.2021.127593.

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