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Apportioning sediment sources in a grassland dominated agricultural catchment in the UK using a new tracing framework

ADRIAN L. COLLINS[1], **YUSHENG ZHANG**[1], **DESMOND E. WALLING**[2] & **KEVIN BLACK**[3]

1 *Environment Group, ADAS, Woodthorne, Wergs Road, Wolverhampton WV6 8TQ, UK*
adrian.collins@adas.co.uk

2 *School of Geography, Archaeology and Earth Resources, University of Exeter, Amory Building, Rennes Drive, Exeter EX4 4RJ, UK*

3 *Partrac Ltd., 141 St James Road, Glasgow G4 0LT, UK*

Abstract A novel tracing framework combining conventional sediment source fingerprinting and a dual signature tracking method has recently been tested in a grassland catchment in Cumbria, northwest England, UK. The former component of the framework provided information on the relative importance of generic sediment sources characterised as pasture (75±1%) or arable (9±1%) surface soils, damaged road verges (6±1%), channel banks/subsurface sources (9±1%) and the local sewage treatment works (1±1%), whereas the latter component was used to apportion sediment loss from grass fields between poached gateways (1±1%) or cattle tracks (28±1%) and wider areas of general pugging and poaching damage (46±1%). Uncertainty and prior information are explicitly recognised by the novel source tracing framework.

Key words grassland; source fingerprinting; tracking; uncertainty; prior information

INTRODUCTION

Whereas well-managed low intensity grassland agriculture can be beneficial to the environment (Rook & Tallowin, 2003), it has been recognised for some time that intensive grazing systems can be associated with appreciable rates of soil loss and concomitant water quality problems. Grassland accounts for ~40% of the agricultural area across Western Europe (Peeters, 2004) and ~27% of that area in the UK is under intensive grazing management (Deeks *et al*., 2008). Excessive defoliation by grazing animals reduces vegetation cover in grass fields, exposing bare soils to erosive agents. Continued over-grazing prevents vegetation recovery and sustains exposure of topsoil, with extended grazing seasons compounding the problem. Repeated treading and trampling by livestock results in compaction, pugging and poaching, which reduce the porosity, hydraulic conductivity and infiltration capacity of soil, promoting surface runoff and sediment mobilisation (Drewry, 2006). Machinery trafficking can also be responsible for soil compaction in grass fields and in contrast to areas of arable farming where such movements are frequently restricted to wheelings, can impact the entire area of both top and subsoil (Jorajuria & Draghi, 1997). Against the above background, a number of studies have underscored the important contributions of improved grassland to catchment scale sediment loadings and pressures (Collins *et al*., 2009a) and modelled national scale sediment delivery to rivers (Collins *et al*., 2009b).

Due to widespread concerns across England about diffuse pollution, including sediment, the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) was launched in April 2006, identifying priority catchments where stakeholders require assistance to reduce the degradation of agricultural land and aquatic habitats. In 50 (originally 40) priority areas, Catchment Sensitive Farming Officers (CSFOs) are responsible for appraising pollutant pressures and for delivering programmes of advice based on workshops, seminars and on-farm demonstrations. It is widely acknowledged that sediment mitigation requires reliable information on the principal sources of the problem at catchment scale. Such information has been provided using a range of techniques, including sediment tracing. However, although conventional sediment fingerprinting has considerably improved the evidence base on generic sediment source types (e.g. relative contributions from different land uses and eroding channel banks), there remains a challenge to assemble higher resolution data, especially since CSFOs require this understanding to assist the targeting of capital grant options. In view of these requirements, a project was commissioned to apply and test a novel sediment sourcing framework combining conventional source fingerprinting and a dual signature tracking technique.

STUDY AREA

The novel high resolution sediment sourcing procedure was tested during an investigation of the primary sources of the sediment problem reported in the Biglands Bog ECSFDI priority catchment, Cumbria, northwest England, UK (Fig. 1). This study catchment is part of the ECSFDI priority catchment number 19 (River Waver and Biglands Bog) and is drained by the Aikton and Bampton Becks. Local land use is dominated by intensive livestock grazing, but the cultivation of high risk crops including maize has recently started to expand to provide improved fodder supplies. Cattle graze the grass fields during the summer and sheep during the winter, thereby resulting in sustained grazing and trampling pressures and widespread evidence of pugging and poaching. Soils are frequently waterlogged, thereby rendering them susceptible to compaction. Excessive sediment delivery is considered responsible for the siltation of the Biglands Bog SSSI (Site of Special Scientific Interest) at the outfall of the catchment, comprising acidic mire, bog and rich fen.

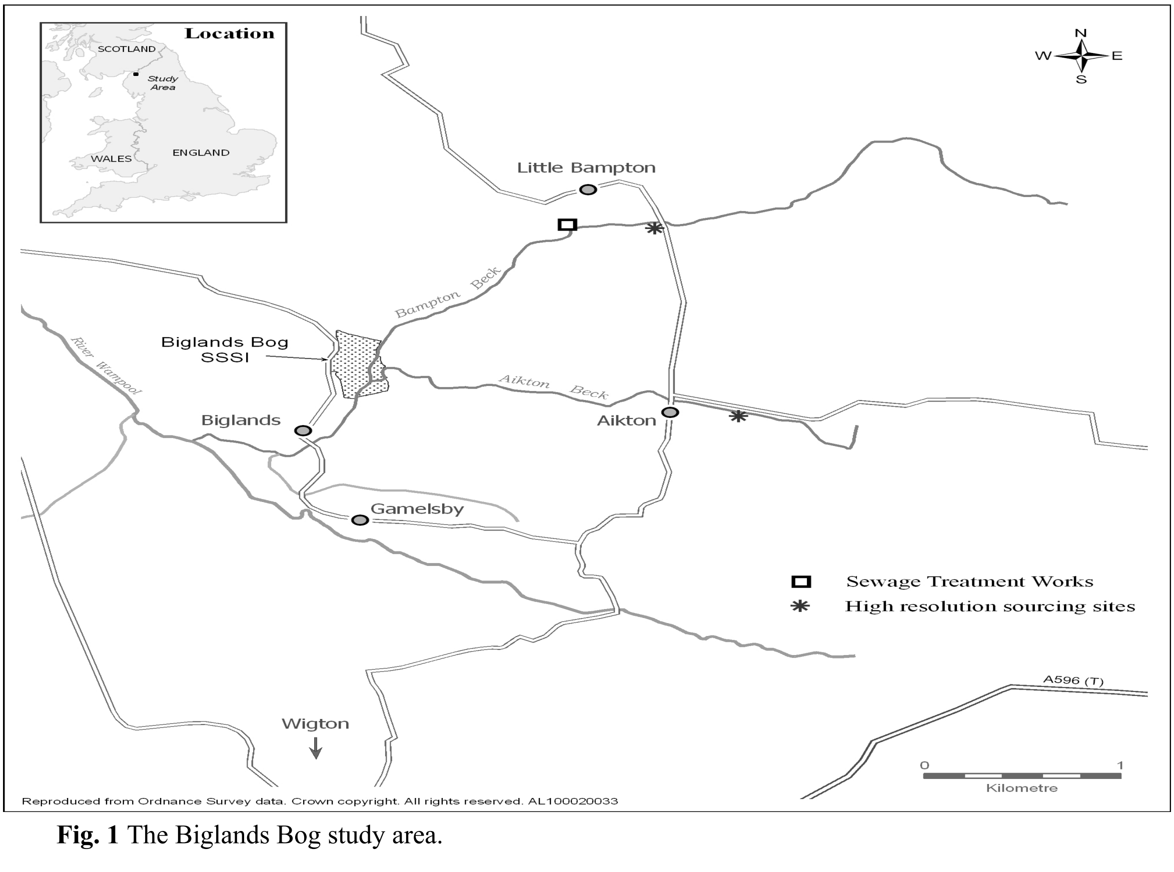

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Fig. 1 The Biglands Bog study area.

METHODOLOGY

Source material and sediment sampling

Collection of representative source material samples in the two sub-catchments (Aikton Beck and Bampton Beck) comprising the Biglands Bog study area was completed in December 2008 and was stratified to encompass five primary potential sediment sources. These source types comprised pasture topsoils, cultivated topsoils, damaged road verges, channel bank/subsurface sources (including gullies and ditches cutting into subsoil) and the STW located in the study area. Samples retrieved from agricultural topsoils and damaged road verges comprised surface scrapes (up to 2 cm depth) susceptible to mobilisation during surface runoff events. Channel bank/subsurface source sampling targeted actively eroding bank sections and gully systems or ditches. Each source material sample (approx. 500 g) comprised a composite of smaller scrapes (n ~5) collected within approx. 300 m^2 of an individual site, in order to increase the representativeness of the individual samples and of the overall sampling strategy. Channel bank samples comprised material from the full vertical extent of the eroding bank profile. The sampling of material originating from the STW was undertaken in the channel system immediately adjacent to the outfall in order to provide general characterisation of sediment released from this point source during both routine and by-pass discharge. A summary of the source material sampling exercise is provided in Table 1. Surface sediment sampling (up to 2 cm depth) in the Biglands Bog SSSI targeted recent deposits at the outfall of each tributary. Comparison of catchment source material and Biglands Bog sediment samples permitted examination of sediment provenance during flood events representative of recent time (approx. 2–5 years). Table 2 summarises the surface sediment sampling exercise.

Table 1 Source material sampling summary.

Sub-catchment	Source type				
	Pasture topsoils	Cultivated topsoils	Damaged road verges	Channel banks/ subsurface sources	STWs
Aikton Beck	8	8	8	8	–
Bampton Beck	15	15	15	15	5

Table 2 Sediment sampling summary.

Sub-catchment	No. surface sediment samples
Aikton Beck	8
Bampton Beck	8

Labelling high resolution sources in grass fields and capturing mobilised tracer grains

The implementation of the dual signature tracking technique necessitated the selection of appropriate monitoring sites. Two representative sites, one in Aikton Beck at 54°52′11N, 003°07′31W and one in Bampton Beck at 54°52′57N, 003°07′59W were selected on the basis of field walking and discussions with the CSFO. These sites were judged to be representative of the high sediment mobilisation risk configurations in local grass fields comprising clusters of poached gateways or cattle tracks and wider pugging or poaching damage, with obvious connectivity to neighbouring watercourses. The site in the Aikton Beck sub-catchment was selected to be characteristic of those grass fields exhibiting less severe compaction and poaching problems, whereas the site in the Bampton Beck sub-catchment was used to represent fields with more severe poaching damage. The dual signature tracking method is based on labelling target areas with synthetic magnetic tracer grains. These grains comprise a mixture of reduced density biodegradeable polymeric and quartz density particles, combined with commercially-available fluorescent and ferrous inclusions bound in a naturally occurring calcite-rich compound. Target areas are labelled with unique fluorescent signatures in order to assist the apportionment of inputs to neighbouring river channels. The synthetic tracers were carefully manufactured to resemble the modal particle size and density of the target areas identified in the grass fields. In each case, the density of the dual signature tracer was within ±2% of that measured for the host soil particles. Dual signature tracers were applied using a road salt spreader to ensure an even distribution of tracer grains over deployment areas. Tracer seeding was undertaken on days with calm weather conditions to avoid significant aeolian redistribution. A yellow tracer was used to label areas of wider pugging or poaching damage, whereas pink and blue tracers were deployed to seed poached cattle tracks and gateways, respectively.

In order to capture the tracer grains mobilised from the target areas in the grass fields by water erosion, 11 000 gauss bar magnets (neodymium, iron, boron) were placed in adjacent river channels. The magnets were protected by thin plastic sheaths and end caps to prevent magnetic material becoming permanently fixed to the actual magnet surfaces. During the recovery of the magnet samples *in situ*, the sheaths were carefully removed from the magnetic bars and placed into sample bags. A large plastic tray was used to capture any tracer grains dislodged during this recovery process. New sheaths were placed over all magnets prior to their redeployment at the sampling sites.

Laboratory work

All soil source material and surface sediment samples were returned to the laboratory, oven-dried at 40°C, homogenised using a pestle and mortar, and dry sieved using a 63-µm mesh. Screening facilitated comparison of the fingerprint properties measured for source material and sediment samples. The STW outfall samples were de-watered using settling, freeze-dried and sieved through a 63-µm mesh. A total of 47 potential fingerprint properties were selected for analysis. Concentrations of Al, As, Ba, Bi, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Hf, Ho, In, K, La, Li, Mg, Mn, Mo, Na, Nd, Ni, Pb, Pd, Pr, Rb, Sb, Sc, Sm, Sn, Sr, Tb, Ti, Tl, U, V, Y, Yb, Zn and Zr were determined using ICP-MS, post-direct digestion with aqua regia. The absolute grain size composition of all samples was measured using a Micromeritics laser diffraction granulometer following pre-treatment with hydrogen peroxide to remove organics, chemical dispersion with sodium hexametaphosphate (Calgon), and exposure to ultrasound. Particle size analysis assumed spherical particles in the estimation of specific surface area. An automatic C/N analyser was used to measure C and N content.

Upon return to the laboratory, all magnet samples were washed through a 500-µm sieve to remove any large native magnetic or vegetation debris. The <500 µm fraction was repeatedly exposed to an 11 000 gauss magnet until no further material was retrieved. The efficiency of the tracer grain separation procedure was verified using three replicate samples spiked with a known mass (1 g, 0.1 g and 0.01 g) of synthetic tracer. This test suggested an overall tracer grain recovery efficiency of 97.3±1.9%. High resolution microscope analysis was used to distinguish the tracers with unique fluorescence attached to the individual magnets. During the microscope analysis, a sub-sample of the magnetic grains recovered from the magnets was placed on a microscope slide with a small volume of distilled water. A minimum of 300 discrete particles were selected from each sample, dried and weighed, in order to assess the relative proportions of the individual fluorescent tracers applied to the target areas in the grass fields. All microscope analysis was undertaken using a Zeiss fluorescent microscope fitted with an excitation filter set.

Discrimination of generic sediment sources

The two-stage statistical verification procedure proposed by Collins *et al.* (1997) was employed to test the ability of the fingerprint properties to discriminate between the five individual generic sediment source types. Stage one was based on the use of the Kruskal-Wallis H-test to examine the ability of individual constituents to distinguish the generic sediment sources in an unequivocal manner. Stage one of the procedure provides a basis for eliminating redundant fingerprint properties. All fingerprint properties passing the Kruskal-Wallis H-test survived the elimination process and entered stage two of the statistical verification.

Stage two of the tracer verification procedure involves the use of multivariate Discriminant Function Analysis (DFA) to test the ability of the properties passing the Kruskal-Wallis H-test to discriminate the source material samples into the correct categories. The minimisation of Wilks' lambda is used as a stepwise selection algorithm to identify the optimum (i.e. smallest) combination of properties, or composite fingerprint, for discriminating the source samples collected from a given sub-catchment (see example in Table 3).

Table 3 The optimum composite fingerprint for discriminating individual generic sediment source types in the Aikton Beck sub-catchment.

Step	Fingerprint property selected	Cumulative % source type samples classified correctly	Wilks' lambda	% source type samples classified correctly	Tracer discriminatory weighting
1	Ce	56.3	0.418	56.3	1.6
2	Ba	81.3	0.184	43.8	1.3
3	Zr	87.5	0.105	50.0	1.5
4	Cr	84.4	0.058	34.4	1.0
5	Tl	93.8	0.033	37.5	1.1
6	Sn	96.9	0.017	62.5	1.8

Generic sediment source ascription

The recently revised multivariate mixing model described by Collins *et al.* (2009a) was used to apportion generic sediment sources in the Biglands Bog study catchment. Two linear boundary conditions are imposed on the mixing model iterations to ensure that the relative contributions from the individual generic sediment source types are non-negative and that these contributions sum to unity. The mixing model algorithm optimises estimates of the relative contributions from the potential generic sediment sources by minimising the sum of squares of the weighted relative errors, but includes revised property weightings, viz.:

$$\sum_{i=1}^{n}\left\{\left(C_i-\left(\sum_{s=1}^{m}P_sS_{si}Z_sO_sSV_{si}\right)\right)/C_i\right\}^2 W_i \tag{1}$$

where: C_i is concentration of fingerprint property (i) in Biglands Bog surface sediment sample; P_s is the optimised percentage contribution from generic source category (s); S_{si} is mean concentration of fingerprint property (i) in generic source category (s); Z is particle size correction factor for generic source category (s); O is organic matter content correction factor for generic source category (s); SV_{si} is weighting representing the within-source variability of fingerprint property (i) in source category (s); W_i is tracer discriminatory weighting; n is number of fingerprint properties comprising the optimum composite fingerprint; m is number of generic sediment source categories.

A weighting to reflect the within-source variability of individual tracers is included to ensure that the fingerprint property values for a particular source characterised by the smallest standard deviation exert the greatest influence upon the optimised solutions. It is logical that as the standard deviation of the fingerprint property values increases, the uncertainty associated with the source ascription also increases. The weighting is calculated using the inverse of the root of the variance associated with each fingerprint property measured for each generic source type. The within-source variation weighting provided a means of representing the compound effects of a number of sources of uncertainty, including the variance of the tracer data sets for specific sources and the differing levels of precision associated with laboratory measurements of those tracers. Recent work has underscored the utility of the within-source variability weighting for narrowing the uncertainty ranges in predicted source contributions (Collins *et al.*, 2009a). The weighting to reflect tracer discriminatory power (equation (1)) is based on information on the discriminatory efficiency of each individual tracer included in any given composite fingerprint provided by the results of the DFA (Table 3). Sensitivity analysis during previous work has supported the inclusion of a tracer specific weighting (Collins *et al.*, 2009a). It can be advantageous to incorporate informative priors into numerical mass balance modelling. A review of sediment sources in the UK by Walling and Collins (2005) suggested that typical channel bank contributions rarely exceed 50%. On this basis, the upper boundary constraint for the bank erosion/subsurface source contribution in the numerical mass balance sediment mixing model is set at 0.5.

Table 4 Estimates of the overall mean goodness-of-fit (GOF).

Sub-catchment	GOF[1]	GOF[2]	GOF[3]	GOF[4]
Aikton Beck	0.873	0.876	0.875	0.879
Bampton Beck	0.944	0.949	0.938	0.950

[1]random sampling with simulated deviates based on mean/standard deviation; [2] random sampling with simulated deviates based on median/S_n; [3]stratified (Latin Hypercube) sampling with simulated deviates based on mean/standard deviation; [4]stratified (Latin Hypercube) sampling with simulated deviates based on median/S_n.

The uncertainty of the optimised results obtained using the revised sediment mixing model was investigated using a Monte Carlo framework comprising four permutations. Simulated deviates (Normal distributions) for mixing model input were generated using either the conventional approach based on the measured mean and standard deviation of each fingerprint property for each source type and set of sub-catchment sediment samples, or corresponding robust statistics represented by the median and the scale estimator S_n proposed by Rousseeuw & Croux (1993) as an alternative to the median absolute deviation (MAD). The sampling of the simulated deviates during 5000 repeat iterations was based on either a conventional random or stratified (Latin Hypercube) approach. Using either the former or the latter sampling approaches with the simulated Normal distributions based on the measured mean/standard deviation or median/S_n yielded four sets of uncertainty analyses. The four permutations incorporated the uncertainty associated with both source material and sediment sampling (cf. Collins *et al*., 2009a). Solving the set of linear equations pertaining to the optimum composite fingerprint for each sub-catchment 5000 times for each permutation of uncertainty analysis, provided a basis for calculating 95% confidence limits about the mean or median contributions from individual sources. The robustness of the optimised mixing model solutions was assessed using the overall mean goodness-of-fit (GOF) between the simulated and measured sediment sample fingerprint property mixtures (Table 4).

RESULTS

As an example, Fig. 2 presents the results of the Monte Carlo analysis for the Bampton Beck sub-catchment. On the basis of the GOF results in Table 4, the mixing model output generated using stratified sampling of simulated fingerprint property Normal distributions based on the median/Sn as location and scale estimators was used to quantify the typical contributions from the individual generic sediment sources in each sub-catchment (Fig. 3). For the Bampton Beck sub-catchment, these inputs were estimated at 73±1% (pasture topsoils), 17±1% (cultivated topsoils), 1±1% (damaged road verges), 8±1% (channel banks and subsurface sources) and 1±1% (the STW). The corresponding respective estimates for the Aikton Beck sub-catchment were 77±1%, 1±1%, 12±1% and 10±1%. No STW was present in this sub-catchment. Synthesis of the typical sediment source apportionment data for the Bampton and Aikton Beck sub-catchments, suggested that the overall generic sediment source median inputs to the Biglands Bog SSSI from the entire upstream catchment were 75±1% (pasture topsoils), 9±1% (cultivated topsoils), 6±1% (damaged road verges), 9±1% (channel banks and subsurface sources) and 1±1% (the STW).

High resolution tracking suggested that the median relative losses of tracer grains from the three high risk components of grassland fields were of the order of 79% (wider areas of pugging and poaching damage), 20% (poached cattle tracks) and 1% (poached gateways) in the Bampton Beck sub-catchment. Tracking results for the Aikton Beck sub-catchment suggested that the respective relative losses were 44%, 54% and 2%. These results were judged to be consistent with field observations in that wider areas of grassland in the Aikton Beck sub-catchment were less damaged than those corresponding areas in Bampton Beck. The results of synthesizing these tracking estimates with the overall median generic source fingerprinting estimates are presented in Fig. 4. Over the duration of the study period, wider areas of pugging and poaching damage across pasture fields contributed 46±1% of the total sediment delivered to Biglands Bog, compared to

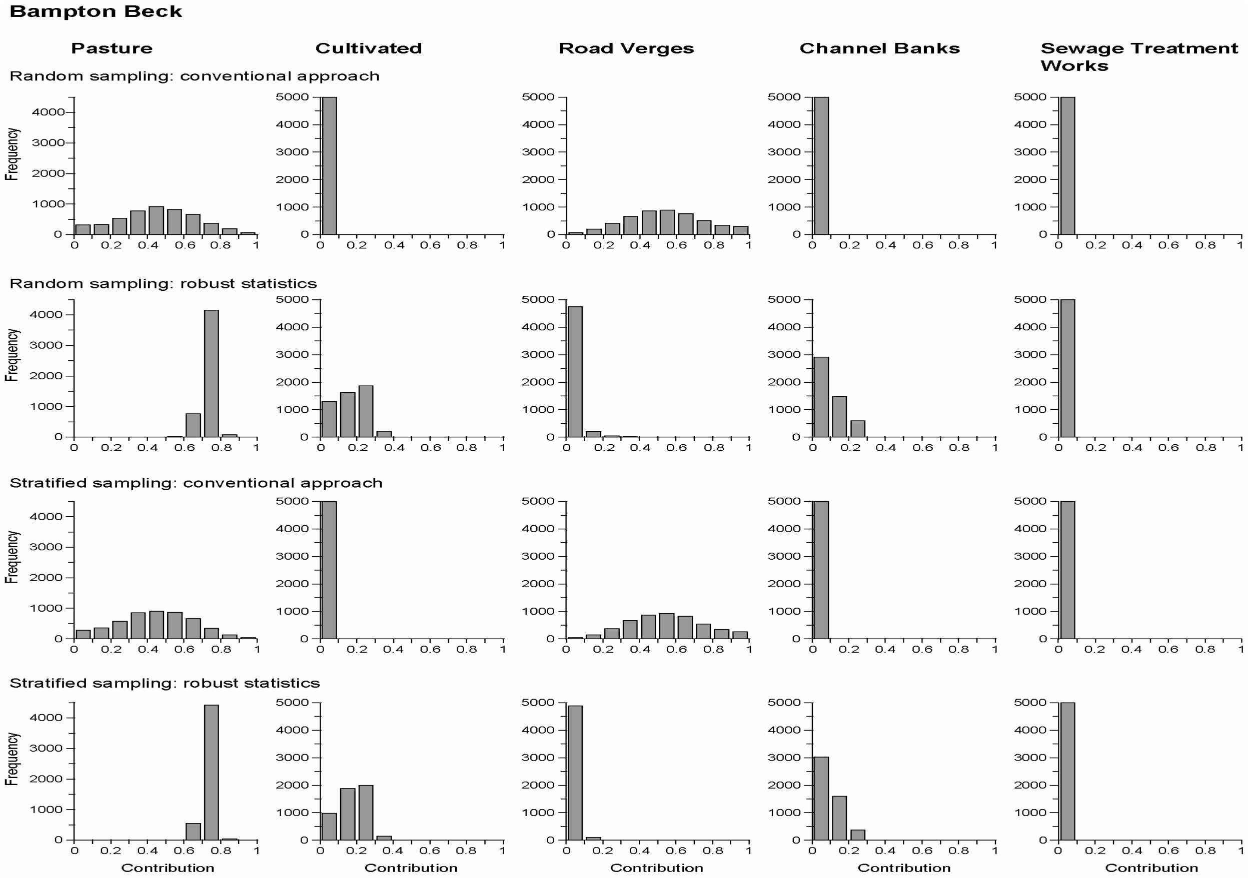

Fig. 2 Uncertainty ranges in the relative contributions from the generic sediment sources in the Bampton Beck sub-catchment.

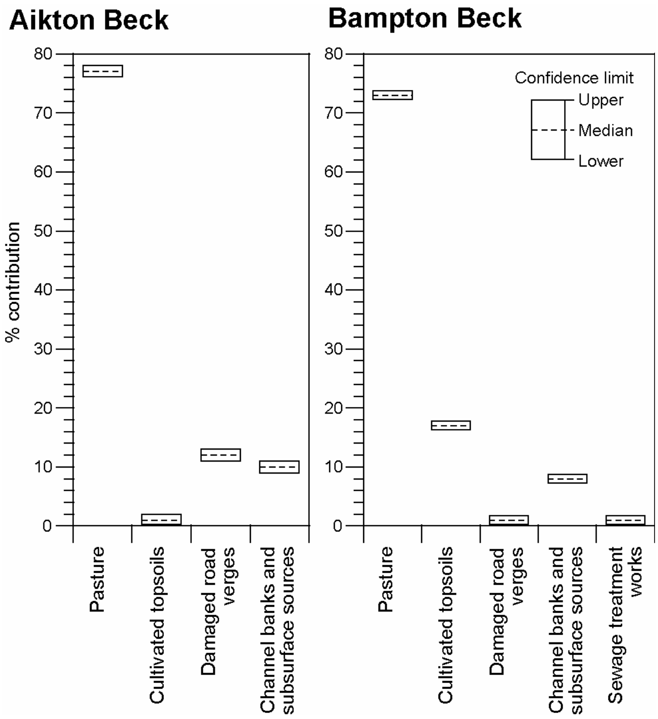

Fig. 3 Median relative contributions (±95% confidence limits) from the individual generic sediment sources.

28±1% from poached cattle tracks and 1±1% from poached gateways. These results should be viewed as tentative given the spatial extrapolation to catchment scale on the basis of the tracking work at two target sites.

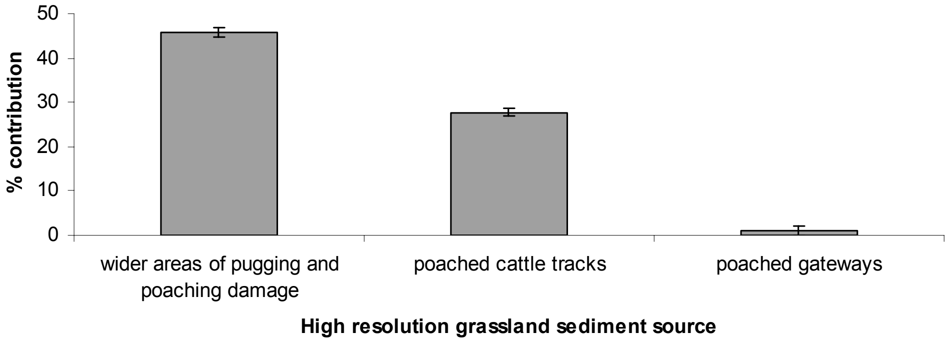

Fig. 4 Tentative catchment scale median relative contributions from high resolution grassland sediment sources.

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