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The costs and efficacy of sediment mitigation measures for representative farm types across England and Wales

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Abstract A major collaborative research project in the UK is delivering new science to support improved targeting of on-farm pollution mitigation measures for the benefit of freshwater ecology. One important aspect of the project concerns a national scale evaluation of the costs and efficacy of packages of sediment mitigation measures which can be delivered over and above the existing implementation of abatement through various policy instruments including advice and new targeted agri-environment schemes. The assessment includes typical farm types present across England and Wales. Outputs from this assessment of costs and efficacy will eventually be used to help model the potential for closing the sediment pollution gap in those water bodies currently failing water quality targets due to sediment loss from agriculture. Some preliminary uncertainty ranges in costs (–£146,402 to £175,631) and effectiveness (0–80%) associated with a potential policy scenario implementing a large number (up to 93) of abatement measures at 95% uptake are presented in this paper.

Key words sediment; mitigation; costs; efficacy; farm scale; policy support

INTRODUCTION

Agricultural diffuse sediment pollution in England and Wales has been recognised as one of the key problems requiring improved abatement to help meet environmental targets for freshwater habitats (Collins *et al.*, 2011). In particular, enhanced loadings of fine-grained sediment (<63 μm) are associated with a number of important environmental issues receiving increasing attention from policy teams and catchment managers. Fine-grained sediment mobilisation and delivery through catchment systems exerts an important control on the transport and fate of nutrients and contaminants including, amongst others, phosphorus, heavy or trace metals, dioxins, polychlorinated biphenyls, radionuclides and pathogens (Horowitz *et al.*, 1995; Warren *et al.*, 2003; Kay *et al.*, 2005; Ballantine *et al.*, 2009). Sediment transport (coarse and fine) exerts a fundamental control on the hydro-geomorphological function and health of river systems and excessive fine sediment inputs can result in a range of detrimental impacts on aquatic ecology. High suspended sediment concentrations can, for example, impact on the behaviour and health of fish by reducing capacity to predate and damaging fish gills (Kemp *et al.*, 2011). Increased sediment deposition and retention on the river substrate can degrade habitat quality by reducing permeability and porosity and attenuating hyporheic exchanges critical for supporting fish and macroinvertebrate populations (Milner *et al.*, 2003). Equally, fine sediment can impact negatively on macrophytes or diatoms by smothering, abrasion and scour (Clarke, 2002; Jones *et al.*, 2014).

A range of mitigation measures to ameliorate agricultural diffuse pollution, including that resulting from excessive sediment loss from farms, have been identified by recent policy support projects funded by the Department for Environment, Food and Rural Affairs (Defra) (e.g. Newell-Price *et al.*, 2011). These mitigation measures can be implemented through a number of means (McGonigle *et al.*, 2012) including the basic regulatory expectations (Cross Compliance) of farmers to maintain land in good agricultural and environment condition (e.g. GAEC rule 1 embodied in the Soil Protection Review) as a mandatory requirement for receiving subsidy via the Single Payment Scheme, targeted programmes of advice such as the Catchment Sensitive Farming initiative (CSF) and agri-environment schemes (e.g. the existing Entry-Level scheme in England). However, demonstrating the effectiveness of these policy instruments has proved challenging, especially in the short term, given the complexities of sediment redistribution through the landscape with intermediate storage and remobilisation, highly changeable weather conditions from year to year and on account of the confounding influence of sediment contributions from alternative sources which may not be targeted by abatement strategies. In addition, disentangling the impact of specific policy instruments or mitigation measures present in the agricultural landscape on sediment loss from farms remains a major challenge using empirical methods.

Despite the evidence base for the detrimental environmental impacts of excessive sediment loss from agriculture, in the broader context of food security and the challenges of feeding a growing population, there is an expectation on farmers to increase food production. Consequently, there is renewed focus on sustainable intensification which embodies the balance between maximising agricultural productivity and minimising environmental burden including that on freshwaters (Foresight, 2011). Critical to this balance, is an improved understanding of the national scale cost-effectiveness of potential sediment mitigation strategies which might be delivered by a range of policy instruments. Accordingly, a collaborative scientific policy support project in the UK has been modelling the cost-effectiveness of on-farm sediment mitigation measures to provide insight into the costs to society of minimising the environmental pressures of modern agricultural production.

METHOD

The approach was founded on the use of the Excel-based decision support tool FARMSCOPER (FARM SCale Optimisation of Pollutant Emission Reductions) recently developed to help inform the management of diffuse agricultural pollution across England and Wales (Zhang *et al.*, 2012; Gooday *et al.*, 2014). FARMSCOPER is founded on a suite of well-established models which have all been used in national-scale predictions for policy support. These models simulate sediment, phosphorus, nitrate, ammonia, methane and nitrous oxide emissions to aquatic environments and the atmosphere. In the case of sediment, FARMSCOPER predictions use the Phosphorus and Sediment Yield CHaracterisation In Catchments (PSYCHIC) process-based model (Collins *et al.*, 2007; Davison *et al.*, 2008; Stromqvist *et al.*, 2008; Collins *et al.*, 2009a). For the construction of FARMSCOPER baseline predictions without prior implementation of abatement measures, the PSYCHIC model was applied using multiple iterations to the whole of England and Wales at 1-km^2 resolution. The results were area-weighted to produce output for six primary rainfall zones and three soil types (see rainfall and soil categories in Table 1). The soil types were chosen to reflect the likelihood of agricultural under-drainage: permeable free draining soils; impermeable soils where artificial drainage is required to make them suitable for arable cultivation; and, impermeable soils where artificial drainage is required to make them suitable for either arable or grassland agriculture. Soils for each 1-km^2 grid cell at national scale were identified using NATMAP1000 (National Soil Resources Institute, Cranfield University) and the corresponding HOST (Hydrology of Soil Types; Boorman *et al.*, 1995) classes used to assign a FARMSCOPER soil category (Table 2). Agricultural management practice is simulated in FARMSCOPER using representative farm types derived from the Defra Robust Farm Type (RFT) classification scheme (Defra, 2010), which is widely adopted in existing farm surveys undertaken across England and Wales. Based on crop specific land areas and categorised livestock data collected in the 2010 June Agricultural Census, default values were identified to describe an 'average' model farm for each farm type for each soil and rainfall combination. Where enterprise specific data are available, FARMSCOPER allows for customisation of these farm types to support more tailored application of the tool. FARMSCOPER comprises a library of 105 mitigation methods, each of which is characterised in terms of its impacts on pollutant emissions and the costs or savings that implementation of the method would incur for farmers. Impacts of multiple mitigation methods are multiplicative, such that the effectiveness of multiple methods targeting the same aspects of pollutant loss will be less than the sum of their individual impacts. The costs of method implementation account for changes to the variable costs and gross margin of a crop or stock enterprise, changes to the fixed costs or overheads associated with labour and machinery and capital investment using a number of sources (e.g. Nix, 2009). Capital costs are typically amortised over 5 to 20 years, depending upon the expected lifetime of the corresponding investment and any associated loans. The simulations reported here are based on the latest mitigation measure costs for 2013. Costs exclude those to government for policy instrument administration and delivery or enforcement on the ground by agencies or officers.

Table 1 The relative frequency distribution of all possible FARMSCOPER rainfall and soil combinations across England and Wales; AAR is Annual average rainfall.

AAR (1961–1990)	Soil categories: Free draining	Drained for arable	Drained for arable and grass
mm	%	%	%
<600	2.5	4.5	2.4
600–700	8.3	8.3	9.1
700–900	13.1	6.8	10.1
900–1200	10.5	2	3.9
1200–1500	7.7	0.4	1.6
>1500	7.8	0.3	0.9

Table 2 The correspondence between HOST classes and FARMSCOPER soil categories.

HOST class	Soil group	HOST class	Soil group
1	Free draining	15	Free draining
2	Free draining	16	Free draining
3	Free draining	17	Free draining
4	Free draining	18	Drained for arable
5	Free draining	19	Drained for arable
6	Free draining	20	Drained for arable
7	Free draining	21	Drained for arable
8	Free draining	22	Drained for arable
9	Drained for arable	23	Drained for both arable and grass
10	Drained for arable	24	Drained for both arable and grass
11	Free draining	25	Drained for both arable and grass
12	Free draining	26	Free draining
13	Free draining	27	Free draining
14	Drained for arable	28	Free draining

In order to capture the spatial variation in the natural environment and farm types across England and Wales, the work to date has been running FARMSCOPER at the Environment Agency Water Management Catchment (WMC) scale (Fig. 1). The WMCs provide 100 reporting units although one was discounted due to its small area (<1 km^2). Ongoing work is down scaling the WMC outputs to individual non-coastal water bodies (~4500) used for reporting environmental status under the European Union Water Framework Directive (WFD; European Parliament, 2000). To create the typical model farms for each WMC, the livestock numbers and categories, land cover and cropping data derived for each RFT from the 2010 June Agricultural Census survey were paired up with corresponding rainfall and soil combinations. Default typical farm and field management practices for each farm type were used in conjunction with the structural information provided by the agricultural census returns. Among the 99 WMCs included in the simulations, 44% have nine RFTs and 48% have eight RFTs. Seven WMCs have fewer than eight RFTs. While the majority of WMCs are in England, eight WMCs are entirely inside Wales and five have water bodies in both countries. In total, >5000 typical model farms were created for England, >700 for Wales and nearly 400 for the border areas between England and Wales.

Existing or so-called prior implementation of mitigation measures is incorporated into FARMSCOPER to ensure that the technical potential for environmental change is not over-estimated. Prior uptake represents a number of factors including the physiographic environment, farm type (i.e. applicability of a mitigation method) and the history of incentives via support or regulation. Estimates of prior implementation (for 2010) are expressed as a percentage of the applicable area or number of livestock or farm holdings. An additional distinction is made between measured uptake within and outside of Nitrate Vulnerable Zones (NVZs) since these have a regulatory Action Programme and although this is designed to target nitrate pollution, recent Defra

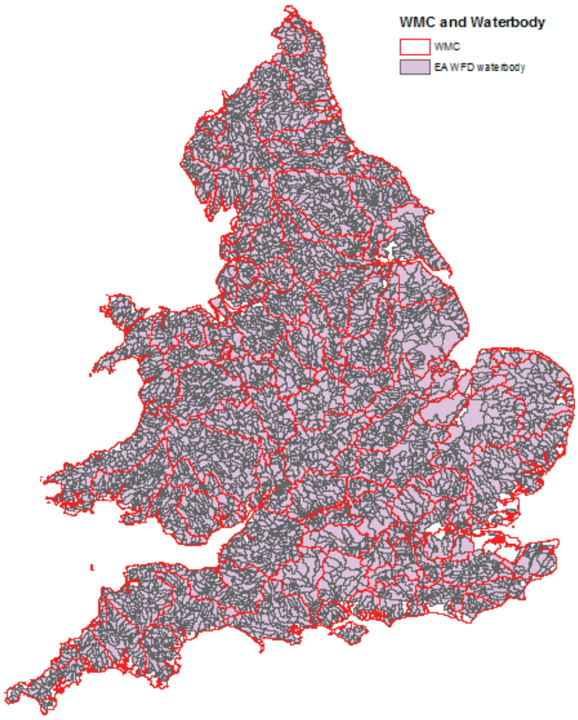

Fig. 1 Water Management Catchments (WMCs) and WFD water bodies across England and Wales.

Farm Practice Survey returns have collected some data which distinguish the uptake of some measures (e.g. management of grassland compaction) which can impact on sediment loss. The efficacy of individual mitigation methods in the FARMSCOPER library is based on a number of literature reviews (e.g. Newell-Price *et al.*, 2011) and elicitation of expert judgement. To help account for gaps in the empirical evidence base for some mitigation options and the range in efficacy values reported for the same abatement measures by different studies (e.g. see review by Collins *et al.*, 2009b), method efficacy is summarised in FARMSCOPER on an indicator scale to provide an uncertainty range for the potential pollutant reduction impacts (Table 3). The estimates of average efficacy are lower than the central values of the ranges to provide a conservative assessment of impact. Table 4 summarises the mitigation measures simulated in FARMSCOPER that have the potential to impact on sediment loss. When multiple methods are simulated, FARMSCOPER applies a multiplicative, rather than additive approach for efficacy, again, to avoid over-estimation of environmental impact. On the basis of this approach, the impact or efficacy of simulating the uptake of additional abatement measures decreases rapidly. FARMSCOPER takes explicit account of abatement method competition and thereby ensures that opposing management options (e.g. un-intensive *versus* intensive ditch management on arable or grassland; Table 4) cannot be simulated at the same time. Abatement method dependency is also included in the computational routines, meaning that an option dependent upon another can only be simulated in excess of its prior implementation if the measure upon which it depends is also implemented at a higher uptake rate.

Table 3 Average efficacy classes and corresponding uncertainty ranges.

Efficacy class	Average efficacy	Uncertainty range	Pollutant reduction
A	-	-	None
B	2	0–10	Very low
C	10	2–25	Low
D	25	10–50	Moderate
E	50	25–80	High
F	80	50–95	Very high
G	100	100	Total

Table 4 Mitigation measures relevant to sediment control simulated in the FARMSCOPER tool.

Mitigation method ID	Description	Policy mechanism
1	Establish cover crops in the autumn	Land management
2	Early harvesting and establishment of crops in the autumn	Best practice / voluntary
3	Cultivate land for crops in spring rather than autumn	Land management
4	Adopt reduced cultivation systems	Best practice / voluntary
5	Cultivate compacted tillage soils	Best practice / voluntary
6	Cultivate and drill across the slope	Best practice / voluntary
7	Leave autumn seed beds rough	Best practice / voluntary
8	Manage over-winter tramlines	Incentive (capital)
9	Establish in-field grass buffer strips	Incentive (land management)
10	Establish riparian buffer strips	Incentive (land management)
11	Loosen compacted soil layers in grassland fields	Best practice / voluntary
12	Allow field drainage systems to deteriorate	Incentive (land management)
13	Intensive ditch management on arable land	Incentive (land management)
14	Intensive ditch management on grassland	Incentive (land management)
32	Reduce the length of the grazing day / season	Incentive (land management)
34	Reduce field stocking rates when soils are wet	Best practice / voluntary
35	Move feeders at regular intervals	Best practice / voluntary
36	Construct troughs with concrete base	Incentive (capital)
65	Fence off rivers and streams from livestock	Incentive (capital)
66	Construct bridges for livestock crossing rivers/streams	Incentive (capital)
67	Re-site gateways away from high risk areas	Incentive (capital)
68	Farm track management	Incentive (capital)
69	Establish new hedges	Incentive (capital)
80	Protection of infield trees	Incentive (land management)
82	Management of infield ponds	Incentive (land management)
83	Un-intensive ditch management on arable land	Incentive (land management)
84	Un-intensive ditch management on grassland	Incentive (land management)
88	Uncropped cultivated margins	Incentive (land use change)
89	Skylark plots	Incentive (land management)
87	Beetle banks	Incentive (land management)
85	Management of field corners	Incentive (land management)
90	Uncropped cultivated areas	Incentive (land management)
92	Unharvested cereal headlands	Incentive (land management)
93	Undersown spring cereals	Incentive (land management)
94	Take field corners out of management	Incentive (land use change)
95	Leave over-winter stubbles	Incentive (land management)
97	Use correctly-inflated low ground pressure tyres on machinery	Best practice / voluntary
98	Locate out-wintered livestock away from watercourses	Best practice / voluntary

EXAMPLE RESULTS

Table 5 presents a national-scale summary of the uncertainty ranges in the annual costs and corresponding efficacy of a policy scenario supporting the implementation of all mitigation measures, on the basis of individual Robust Farm Types present across England and Wales. The total numbers of mitigation measures implemented on each Robust Farm Type (Table 5) exceed the number of measures relevant to sediment control (Table 4) because FARMSCOPER simultaneously examines the potential reduction in additional pollutants of the aquatic environment (phosphorus, nitrate) and the atmosphere (ammonia, methane, nitrous oxide). Accordingly, the ranges in total costs in Table 5 reflect the simulation of all mitigation measures relevant to these multiple pollutants rather than just sediment alone. Summary statistics presented in Table 5 are relative to the existing uptake of abatement measures as driven by various current policy instruments including regulation and advice or support. These predictions are for average farms for each Robust Farm Type within each WMC and assume an uptake of 95% since 100% implementation was considered unrealistic. Table 5 shows that the predicted efficacy ranges for sediment do not differ significantly between those farms within or outside of NVZs since the statutory instrument for NVZs delivers an Action Programme which targets the control of nutrient rather than sediment pollution, although recent survey returns do suggest that the uptake of a limited number of measures relevant to sediment

Table 5 Predicted national scale uncertainty ranges (relative to existing uptake of mitigation measures) in the annual costs and efficacy of a potential policy scenario supporting the implementation of all sediment mitigation methods, summarised by robust farm types present across England and Wales.

Robust Farm Type	Total no. of mitigation measures implemented[1]	Minimum total cost (£)[1]	Maximum total cost (£)[1]	Minimum efficacy (%)	Maximum efficacy (%)
WITHIN NVZs	WITHIN NVZs				
Cereals	62–89	–16,346	75,609	1.3	79.7
General cropping	48–90	–27,234	53,181	1.5	78.6
Horticulture	44–90	–146,402	51,222	0.4	
Specialist pigs	52–89	884	82,549	0.5	79.6
Specialist poultry	53–84	320	29,209	0	78.7
Dairy	45–89	467	175,631	2.0	74.1
Less favoured area grazing livestock	65–93	4,456	60,480	2.1	51.8
Lowland grazing livestock	62–91	3,031	73,817	2.0	65.2
Mixed	65–89	221	99,760	0	78.7
OUTSIDE NVZs	OUTSIDE NVZs				
Cereals	63–91	–81,629	76,860	1.3	79.7
General cropping	49–92	–26,476	54,877	1.5	78.6
Horticulture	45–92	–145,035	52,164	0.4	79.7
Specialist pigs	55–91	774	74,816	0.5	79.6
Specialist poultry	56–86	–971	29,090	0	78.7
Dairy	46–91	487	170,177	2.0	74.1
Less favoured area grazing livestock	66–93	4,287	59,503	2.1	51.8
Lowland grazing livestock	63–91	2,992	72,943	2.0	65.2
Mixed	68–91	–226	100,932	0	78.7

[1] The total number of mitigation measures and estimated annual costs reflect the implementation of additional abatement measures (i.e. in excess of those listed in Table 4) relevant to the control of phosphorus, nitrate and gaseous emissions

control does vary on the basis of whether farm businesses are within or outside of designated NVZs. Contrasts in the predicted uncertainty ranges for annual costs and effectiveness within or outside of NVZs are greater for other pollutants such nitrate or phosphorus. The uncertainty ranges in the predicted efficacy of the potential policy scenario by Robust Farm Type are significant, reflecting the spatial heterogeneity of abatement method effectiveness in the context of pollutant losses driven by the rainfall gradient across England and Wales (Table 1) and low to high risk soils supporting the same farm systems. In addition, variations in the predicted uncertainty ranges associated with the total annual efficacy and costs of the policy scenario reflect, in part, the applicability of individual abatement measures to the different Robust Farm Types (see numbers of measures implemented in Table 5). As a result, both the dairy and mixed farm types have particularly high maximum predicted annual costs given that the presence of a greater range of potential sources, such as grass and arable areas (e.g. fodder cropping on dairy farms and cereals on mixed farms) or farm steadings and manure/slurry stores on these farm systems, means that more mitigation measures are applicable. A number of measures applicable to arable land including 'establish cover crops in the autumn', 'early harvesting and establishment of crops in the autumn' and 'cultivated land for crops in spring rather than autumn' are relatively expensive, again increasing the maximum predicted costs for those farm system types where such methods are applicable. It is likely that some of the more expensive mitigation methods for cultivation systems will continue to be unpopular with the farming industry. The substantial cost savings in Table 5 (minimum cost predictions) for some farm system types reflect the positive impacts on mitigation costs associated with improved manure and fertiliser management options, rather than sediment control methods. Table 5 suggests that the maximum technical efficacy of sediment abatement for individual Robust Farm Types could be ~80% and it is likely that reductions in sediment loss of this magnitude will be required in some areas to support healthier aquatic ecology.

CONCLUDING REMARKS

Ongoing work as part of a policy support science project is assessing the national-scale costs and efficacy of different policy scenarios aimed to improve the protection of the freshwater aquatic environment across England and Wales from a number of pollutants including sediment. The results presented above suggest that significant reductions in current sediment loss from different farm system types are technically feasible although the associated uncertainty ranges are substantial. As an example, the modelled policy scenario is complex, with up to 93 measures, and is most likely impractical for delivery on the ground. The next phases of the work will merge the modelled outputs from FARMSCOPER with information on the spatial coverage of each farm type within the WMCs or WFD water bodies provided by the agricultural census returns for 2010 to estimate the weighted efficacy of sediment reduction for different spatial units used for environmental auditing and reporting. These latter outputs will be used within a wider modelling framework to assess the potential for different policy scenarios to close the pollutant gap between present day losses from the agricultural sector and those required to meet environmental targets. The latter work will correct the efficacy of on-farm mitigation measures and potential policy scenarios on the basis of source apportionment for the contributions from additional sectors such as urban areas and point source discharges (cf. Collins *et al.*, 2014).

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