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1 **Contributing Understanding of Mitigation Options for Phosphorus and Sediment to a Review of the**
2 **Efficacy of Contemporary Agricultural Stewardship Measures**

3
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5
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11
12 **Abstract**

13 Experiences from the Mitigation Options for Phosphorus and Sediment (MOPS) projects, which aim to
14 determine the effectiveness of measures to reduce pollutant loading from agricultural land to surface
15 waters, have been used to contribute to the findings of a recent paper (Kay et al. 2009, Agricultural
16 Systems, 99, 67-75), which reviewed the efficacy of contemporary agricultural stewardship measures for
17 ameliorating the water pollution problems of key concern to the UK water industry. MOPS1 is a recently
18 completed three-year research project on three different soil types in the UK, which focused on mitigation
19 options for winter cereals. MOPS1 demonstrated that tramlines can be the major pathway for sediment
20 and nutrient transfer from arable hillslopes, and that although minimum tillage, crop residue incorporation,
21 contour cultivation, and beetle banks also have potential to be cost-effective mitigation options, tramline
22 management is the one of the most promising treatments for mitigating diffuse pollution losses, as it was
23 able to reduce sediment and nutrient losses by 72-99% in four out of five site years trialled. Using
24 information from the MOPS projects, this paper builds on the findings of Kay et al. to provide an updated
25 picture of the evidence available and the immediate needs for research in this area.

26
27 Key words: Agriculture, stewardship, water quality, mitigation, sediment, nutrients

29 **Introduction**

30 A recent paper published in *Agricultural Systems* reviewed the efficacy of contemporary agricultural
31 stewardship measures for ameliorating the water pollution problems of key concern to the UK water
32 industry (Kay et al., 2009). Kay et al. observed that although schemes are available to encourage farmers to
33 adopt environmentally friendly farming practices, there is uncertainty over the specific impacts these
34 measures have on water quality. The purpose of the review of Kay et al. was therefore to establish which
35 agricultural stewardship measures have been proven to impact water quality for three pollutant groups,
36 dissolved organic carbon, nutrients and pesticides. The review concluded that a range of practices are
37 available which have been proven to improve water quality, but that there is little or no evidence available
38 to determine the effectiveness of many agricultural stewardship measures. Kay et al. called for further
39 research to ascertain more fully how contemporary agricultural stewardship measures impact on water
40 quality. However, the review of Kay et al. was unable to draw on the experiences of the most recent
41 research, and in this short commentary, the findings of a recently completed three year research project on
42 three different soil types in the UK, investigating mitigation options for phosphorus and sediment losses
43 from agricultural land, are used to update the relevant sections of the review. Current research which is
44 underway is also described. Using this information, this paper builds on the findings of Kay et al. to provide
45 an updated picture of the evidence available and the immediate needs for research in this area.

46

47 **Methodology**

48 The Mitigation Options for Phosphorus and Sediment (MOPS) projects are two research studies, funded by
49 the UK Department for Environment, Food and Rural Affairs (Defra), which aim to investigate measures to
50 reduce pollutant loading from agricultural land to surface waters. MOPS1, which explored 'in field'
51 mitigation measures for managing winter cereals, has recently been completed, and the majority of the
52 findings are presented in detail elsewhere (Deasy et al. 2008, Deasy et al., 2009a; Silgram et al., 2009,
53 Stevens et al. 2009). MOPS2, which is currently underway, is considering 'in field' measures for spring
54 cereals, and 'edge of field' approaches. These research projects have been designed to produce evidence
55 for the effectiveness of mitigation measures which have potential to improve water quality, and the

56 findings of this research can be fed directly into the design of agri-environment schemes. Of the mitigation
57 options tested in MOPS1, not all are incorporated into current agricultural stewardship schemes. However,
58 the treatments trialled were selected because of their potential to reduce sediment and phosphorus losses,
59 either by reducing the detachment of sediment and nutrients from the soil by splash erosion, by increasing
60 infiltration and reducing surface runoff generation, or by reducing the erosive energy and transport
61 capacity of surface runoff.

62

63 The options tested in MOPS1 were crop residue incorporation, contour cultivation, minimum tillage, beetle
64 banks (2 m wide raised vegetative barriers) on the contour, and tramline modification, where compacted
65 tramline wheelings (unvegetated wheel marks) were disturbed with a simple tine. These treatments can be
66 broadly considered as soil surface protection, cultivation direction, cultivation type, slope length reduction
67 and tramline management options. Currently, the first three are broadly incorporated into agricultural
68 stewardship schemes, such as in the stewardship measures table of Kay et al. under the labels 'ensure soil
69 is bare for a minimum of time', 'traffic fields across slope', and 'use direct drilling'. The beetle bank can be
70 considered as a specialised form of buffer zone, which also reduces slope length, while tramline
71 modification is an entirely new option which was pursued because of recent research indicating the
72 importance of these management features on losses of sediment and phosphorus from arable fields
73 (including unpublished work by the authors, Heathwaite et al., 2005; Ulen and Jakobsson, 2005; and
74 Withers et al., 2006).

75

76 The trials of each of these mitigation options were undertaken at the hillslope scale, using 52 unbounded,
77 3 m wide hillslope lengths of 70-270 m, on silt, sand and clay soils over three years. Treatments were
78 replicated at each site (Table 1). Between 24 and 36 events were monitored for each soil type. Runoff from
79 each hillslope length was collected after rainfall events and sampled for analysis of suspended sediment
80 (SS), total phosphorus (TP) and total nitrogen (TN). These data were then combined with runoff volumes to
81 calculate erosion and diffuse pollution losses in runoff for each hillslope segment, and determine the most
82 effective 'in field' treatments for reducing erosion and nutrient loss from arable hillslopes. The project also

83 considered the economics of mitigation, and the cost of the different options trialled was determined for
84 each of the three farm sites using simple spreadsheet models. Further descriptions and explanations of the
85 experimental design are given in Deasy et al. (2008; 2009a), Silgram et al. (2009) and Stevens et al. (2009).

86

87 **Results and discussion**

88 The results from MOPS1 demonstrated that each of the treatments trialled has the potential to be
89 effective, but that effectiveness varied with climatic conditions, soil type and management (Table 1).

90

91 ***Soil management measures***

92 Kay et al. (2009) note that some specific soil management measures have been proven to be effective at
93 reducing nutrient pollution, with studies by Goss et al. (1988), Shepherd et al. (1993) and Lord et al. (1999)
94 demonstrating that cover crops can lead to a 50% reduction in nitrate leaching. However, cover crops have
95 a number of drawbacks, which include the need for good early establishment to ensure effectiveness,
96 additional time and cost associated with sowing and destruction, the risk of additional weed burden, and
97 the difficulty in estimating the timing of release of cover crop nitrogen via mineralisation. In addition, cover
98 crops are only feasible at a particular point in a crop rotation prior to a spring crop (e.g. in one year in four).
99 An alternative soil management measure, the incorporation of cereal straw residues in addition to stubble,
100 has an immediate cover effect, avoids some of the costs and risks associated with cover crops, and would
101 be an option in most years of an arable rotation. The results from the MOPS1 project suggest that
102 protecting poorly-structured sandy soils by incorporating crop residues, as opposed to baling and removing
103 the straw, may have a similar effect to using a cover crop (Deasy et al. 2008; 2009a). However, as
104 decomposing straw may release soluble phosphorus over the longer term (e.g. Schreiber, 1999; Silgram and
105 Chambers, 2002), the wider advantages and disadvantages of this option need to be considered, and
106 further work is still needed to explore the potential of such soil management measures. The incorporation
107 of crop residues may result in increased farm-scale costs, where straw chopping is not part of the harvest
108 operation, and/or where a local market for baled straw produces loss of revenue from straw sales.
109 Alternatively, where baling and removal presents an additional cost to the farmer, straw incorporation may

110 reduce farm-scale costs. The cost-effectiveness of crop residue incorporation therefore depends
111 considerably on the farming system within which it is implemented.

112

113 ***Ensuring a rough soil surface through conservation tillage***

114 Surface roughness is desirable as it reduces runoff velocity, erosion and transport capacity, and promotes
115 deposition of material during transport. Kay et al. (2009) consider that ploughing or discing soil to create a
116 rough soil surface can have a useful impact on nutrient transport. However, ploughing up the surface leaves
117 soils bare, which may have a negative effect on sediment yields as soil is easily eroded from unprotected
118 surfaces (Evans, 2005). The results of the MOPS1 project suggest that there may be more effective ways to
119 increase surface roughness, such as the incorporation of crop residues discussed above, or minimum
120 tillage, where stubble and residues are left on the soil surface. Kay et al. (2009) found that conservation
121 tillage techniques (including no tillage or direct drilling, and minimum tillage or reduced tillage where
122 shallow cultivation is usual but soil is not inverted) could have significant impacts on nutrient losses to
123 water. Quantification of conservation tillage techniques in MOPS1 also showed that minimum tillage is
124 generally an effective means of controlling sediment and nutrient loss compared to ploughing, but that the
125 effect may differ between sites and between years (Deasy et al. 2008; 2009a).

126

127 Minimum tillage can also have negative effects, and Kay et al. (2009) cite the study of Rasmussen (1999),
128 which reported that a build up of organic matter in the top soil layers can lead to an increase in soluble
129 nutrient losses. However, the effects of minimum tillage on soluble nutrient losses are far from clear, and
130 Kay et al. also reference the study of Benham et al. (2007), where losses of soluble nutrients were reduced
131 as a result of direct drilling, with reductions in losses of 49% for nitrate, and 17% for orthophosphate
132 (soluble reactive P). The impact of minimum tillage on soluble nutrient losses is discussed further in a
133 recent review of pollution swapping (Stevens and Quinton, 2009). Long-term use of minimum tillage can
134 also result in soil compaction, and this may result in reduced macroporosity. Kay et al. refer to the study of
135 Schjønning and Rasmussen (2000), which demonstrated a smaller macropore volume in the topsoil for soils
136 under reduced tillage compared to ploughed soils. However, conservation tillage may also increase

137 transport through macropores (Edwards and Lofty, 1982), and ploughing may reduce macropore activity
138 (Shipitalo et al., 2000; Petersen et al., 2001). In the MOPS1 study, the general decrease in runoff observed
139 under minimum tillage compared to ploughing is likely to have resulted from increased infiltration, which
140 may be due to increased macroporosity, or to increased surface roughness, improved organic matter
141 content, or reduced soil surface crusting. Notwithstanding high initial investment costs, minimum tillage
142 can give rise to considerable cost savings within an arable rotation as a result of reduced trafficking (Table
143 1). Minimum tillage may therefore be a cost-effective option on suitable soils, although problems with
144 increased weed burdens, pest and disease problems and compaction can have a negative impact
145 (Environment Agency, 2003).

146

147 ***Working fields along the contour***

148 Kay et al. (2009) briefly consider the evidence for tillage direction as an influence on water quality, noting
149 that working across the slope may have a beneficial effect. The results of the MOPS1 project demonstrate
150 that contour cultivation on clay soils was an effective mitigation treatment for ploughed clay soils in both
151 the years it was trialled (Deasy et al. 2008; 2009a). However, contour cultivation may increase sediment
152 and nutrient losses if cultivation does not take place exactly on the contour and rilling and gullyng may
153 occur as water is concentrated in hillslope depressions (Quinton and Catt, 2004). The possible negative
154 effects of this treatment also need to be emphasised, and further research is needed to understand the
155 potential of contour cultivation to improve water quality in streams draining arable land. In the MOPS1
156 study, a beetle bank in combination with contour cultivation was able to reduce runoff, SS, TP and TN
157 losses by a further 9-97%, significantly reducing runoff, SS, TP and TN losses only in one year out of two
158 years trialled ($p < 0.01$), but being effective in both years trialled for ploughed soils. Although contour
159 cultivation was not explicitly costed in the MOPS1 project, costs of £5 ha⁻¹ have been reported elsewhere as
160 a result of potentially reduced work rates (D'Arcy and Frost, 2001). Contour cultivation may be cost-
161 effective on suitable slopes, but has limited applicability and there is a need to overcome farmer resistance
162 to this option. The cost of a beetle bank is heavily dependent on field size, and although there are
163 additional establishment and annual maintenance costs, these are relatively low (Nix, 2005. See Nix

164 (annual) for current cost examples). Beetle banks may therefore provide additional cost-effectiveness on
165 simple slopes, with additional biodiversity benefits.

166

167 ***Tramlines***

168 The results of the MOPS1 project indicate that management of tramlines has considerable potential as an
169 agricultural stewardship measure, as tramlines can be a major pathway for the loss of surface runoff,
170 sediment, phosphorus and nitrogen from fields cropped with winter cereals. Tramlines were modified using
171 a simple tine as a method to prove the concept of tramline management by reducing the near-surface
172 compaction and increasing the infiltration rate in tramline areas (Deasy et al. 2008; 2009a, Silgram et al.
173 2009). Kay et al. (2009) do not consider tramline management as a stewardship measure. However, the
174 importance of tramlines in influencing diffuse pollution shown in this study and by others (Heathwaite et
175 al., 2005; Ulen and Jakobsson, 2005; Withers et al., 2006) means that focusing on tramline losses of
176 sediment and nutrients using some form of tramline management option could be a very effective way to
177 reduce diffuse pollution from arable land on moderate slopes. Costs of tramline modification are low at the
178 farm scale (Table 1) but dependent on soil type, and although tramline modification has the potential to be
179 a cost-effective mitigation option, further research is needed on the best ways to manage tramlines on
180 different soil types at a whole-field scale. A consortium of scientific and engineering partners is currently
181 investigating a wide range of practical management options for tramline wheelings in cereal crops,
182 including seeding tramlines and the use of low ground pressure tyres (LINK project LK09109).

183

184 ***'Edge of field' measures***

185 Kay et al. (2009) found that the installation of 'edge of field' measures could potentially offer significant
186 water quality gains to water companies. They consider buffer zones, for which a wide variety of information
187 sources are now available, although uncertainty in their effectiveness is still high (Stevens and Quinton,
188 2009), and wetlands. Although wetlands as mitigation options for agriculture are a new concept in the UK
189 and there has been little research undertaken in this area, wetlands can operate as control measures at
190 locations where hillslope pathways have already discharged their pollutant loads into receiving streams,

191 and may have more potential for mitigating diffuse pollution losses than buffer zones. The MOPS1 study
192 has demonstrated that a suite of 'in field' mitigation options have the potential to be effective in the UK for
193 controlling losses of sediment and nutrients in surface runoff, but preferential surface runoff pathways can
194 operate at field scale which cannot be easily controlled 'in field', and pollutants can still be lost from
195 hillslopes unchecked via subsurface runoff pathways, some of which (e.g. field drains) may contribute very
196 high loads of sediment and phosphorus to streams (Foster et al., 2003; Gelbrecht et al., 2005; Deasy et al.,
197 2009b). Kay et al. refer to subsurface losses in relation to increased nitrate leaching losses as a response to
198 the injection of slurry, but otherwise focus purely on pollutant losses in surface runoff. However, the
199 traditional view that the majority of pollutants are lost from agricultural land in surface runoff may be
200 invalid under certain conditions, for example in tile-drained catchments. A combination of spatially
201 targeted mitigation measures is therefore needed, including both 'in field' measures to reduce the
202 mobilisation and transport of pollutants, and 'edge of field' measures to reduce the delivery of pollutants
203 to water courses. An approach coupling both 'in field' and 'edge of field' measures will have the greatest
204 potential for improving surface water quality.

205

206 **Future research needs**

207 The list of measures that Kay et al. (2009) show have been proven to improve water quality include a
208 number of measures which have also been considered directly or indirectly in the MOPS1 three year, three
209 site study ('ensure soil is bare for a minimum of time', 'traffic fields across slope', 'use direct drilling'). In the
210 light of the evidence presented here from the MOPS1 study, minimum tillage, beetle banks (vegetative
211 barriers) and tramline management, could also be added to the list, although these have not been tested
212 for their effectiveness on dissolved organic carbon or pesticide losses, and options for managing tramlines
213 require further research. In addition, attention should be drawn to measures where the uncertainty in
214 effectiveness is high (e.g. 'traffic fields across slope'), or where measures are difficult to implement
215 correctly, for example, for those options for which Kay et al. consider training may be necessary for farmers
216 to ensure that measures can be implemented effectively.

217

218 Kay et al. (2009) note that the success of all measures will be site specific due to factors such as soil type,
219 hydrology and pollutant chemistry and so measures should be implemented on a case by case basis, and
220 this is reinforced by the results of the MOPS1 research undertaken over three years on three UK soil types.
221 Unsurprisingly, in the light of the lack of evidence from the UK, Kay et al. draw on examples from outside
222 the UK and from outside Europe (e.g. the results of Benham et al. (2007), which were from soils under
223 tobacco cultivation in southwest Virginia). However, extrapolating results from different climatic and
224 agricultural areas to the UK may lead to greater uncertainty in the effectiveness of different measures, and
225 this emphasises the need for further evidence on stewardship options from similar agricultural and climatic
226 environments.

227

228 The majority of the studies that have taken place have been undertaken at the plot and individual field
229 scale. Kay et al. (2009) call for further research into combinations of different mitigation options at the
230 catchment scale, but although this is a crucial research gap, few studies into mitigation effectiveness have
231 yet been trialled even at the field scale. The MOPS projects differ from previous studies in that the results
232 relate to the hillslope scale, which is much more representative of practical field-scale applications than the
233 small bounded plots used in the majority of studies into the effectiveness of agricultural stewardship
234 options. In the MOPS1 project, 'edge of field' effects were observed which may influence the results, for
235 example the channelling of runoff from contour cultivated hillslope areas down headland areas and the
236 edge of the beetle bank. These field-scale effects may strongly influence the effectiveness of agricultural
237 stewardship options for improving water quality, and field-scale trials of options such as cultivating fields
238 across slope, direct drilling or minimum tillage, and buffer zones, are urgently needed to determine not
239 only their effectiveness at management scales, but also their practicability for farmers.

240

241 Although they refer to the economic aspects of mitigation in relation to agri-environment schemes, Kay et
242 al. fail to recognize the economic implications of the mitigation options, which are not limited to income
243 from stewardship. The results published here, and in Deasy et al. (2008; 2009a) have considered the costs
244 of different treatments, and upscaled these to field and farm scale. However, the cost of different

245 mitigation options is dependent on the farming system and farm characteristics. For some options, such as
246 minimum tillage, there may be substantial economic benefits, while other options involve a cost to the
247 farmer. Kay et al. (2009) also note that research quantifying the impacts of agricultural stewardship on farm
248 incomes is largely lacking and is urgently needed if farmers and land managers are to be convinced that
249 environmental stewardship represents business sense. As Kay et al. (2009) state, overall there is a lack of
250 scientific evidence to underpin the use of agri-environment measures for water quality management, but
251 this research gap is now recognised by Natural England and Defra, and projects such as MOPS which aim to
252 feed research findings directly into stewardship schemes will help bridge this gap by providing the scientific
253 evidence urgently needed to reduce diffuse pollution from agriculture to surface waters.

254

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263

264

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353 **Tables**

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355 Table 1. Effectiveness of successful mitigation treatments trialled in the MOPS1 project.

Treatment (sites trialled)	Number of site years effective/ site years trialled	Number of replicates in each site year	Impact on farm margin (£ ha ⁻¹)	Reduction in overwinter loss (with % relative change) [†]			
				Runoff (mm)*	SS (kg ha ⁻¹)	TP (kg ha ⁻¹)	TN (kg ha ⁻¹)
Crop residues (sand)	1/1	4	0	0.2-2.0 (24-50)	9-200 (40-43)	0.03- 0.52 (34-50)	0.05-0.67 (37-56)
Contour cultivation (clay)	1/2	3	0	16.5-56.0 (64-76)	90-1223 (45-79)	0.09- 1.00 (48-79)	0.98-2.25 (63-71)
Minimum tillage (sand, silt, clay)	2/5	3 to 4‡	+44 to +50	0.8-31.6 (4-81) [#]	54-1133 (37-98)	0.04- 2.28 (29-97)	0.15-1.01 (26-94) [#]
Beetle bank (clay)	2/2	3	-2 to -5	11.9-17.6 (45-91)	41-228 (16-94)	0.04- 0.45 (9-97)	0.40-3.61 (30-97)
Tramline modification (sand, silt)	4/5	4	-2 to -5	3.5-75.4 (69-97)	49-4870 (75-99)	0.19- 2.89 (72-99)	0.13-5.31 (74-98)

356 SS = suspended sediment, TP = total phosphorus, TN = total nitrogen. *Runoff is given in mm for consistency with
357 other publications. 1 mm of runoff is equivalent to 10 m³ ha⁻¹ runoff. † % relative change in overwinter loss is
358 calculated by: (mitigation treatment loss-control treatment loss)/control treatment loss*100 for replicate
359 experimental hillslope lengths over the number of site years trialled. ‡ Minimum tillage was trialled at all three sites, with
360 three replicates used in three site years at Loddington, and four replicates used in the final year at Old Hattons and Rosemaund.
361 #Effectiveness range is greater for runoff and TN than for SS and TP as minimum tillage was effective for a greater
362 number of treatments for runoff and TN.

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