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

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Abstract

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

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

Introduction

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

Methodology

The Mitigation Options for Phosphorus and Sediment (MOPS) projects are two research studies, funded by the UK Department for Environment, Food and Rural Affairs (Defra), which aim to investigate measures to reduce pollutant loading from agricultural land to surface waters. MOPS1, which explored ‘in field’ mitigation measures for managing winter cereals, has recently been completed, and the majority of the findings are presented in detail elsewhere (Deasy et al. 2008, Deasy et al., 2009a; Silgram et al., 2009, Stevens et al. 2009). MOPS2, which is currently underway, is considering ‘in field’ measures for spring cereals, and ‘edge of field’ approaches. These research projects have been designed to produce evidence for the effectiveness of mitigation measures which have potential to improve water quality, and the findings of this research can be fed directly into the design of agri-environment schemes. Of the mitigation options tested in MOPS1, not all are incorporated into current agricultural stewardship schemes. However, the treatments trialled were selected because of their potential to reduce sediment and phosphorus losses, either by reducing the detachment of sediment and nutrients from the soil by splash erosion, by increasing infiltration and reducing surface runoff generation, or by reducing the erosive energy and transport capacity of surface runoff.

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

The trials of each of these mitigation options were undertaken at the hillslope scale, using 52 unbounded, 3 m wide hillslope lengths of 70-270 m, on silt, sand and clay soils over three years. Treatments were replicated at each site (Table 1). Between 24 and 36 events were monitored for each soil type. Runoff from each hillslope length was collected after rainfall events and sampled for analysis of suspended sediment (SS), total phosphorus (TP) and total nitrogen (TN). These data were then combined with runoff volumes to calculate erosion and diffuse pollution losses in runoff for each hillslope segment, and determine the most effective 'in field' treatments for reducing erosion and nutrient loss from arable hillslopes. The project also considered the economics of mitigation, and the cost of the different options trialled was determined for each of the three farm sites using simple spreadsheet models. Further descriptions and explanations of the experimental design are given in Deasy et al. (2008; 2009a), Silgram et al. (2009) and Stevens et al. (2009).

Results and discussion

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

Soil management measures

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

Ensuring a rough soil surface through conservation tillage

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

Minimum tillage can also have negative effects, and Kay et al. (2009) cite the study of Rasmussen (1999), which reported that a build up of organic matter in the top soil layers can lead to an increase in soluble nutrient losses. However, the effects of minimum tillage on soluble nutrient losses are far from clear, and Kay et al. also reference the study of Benham et al. (2007), where losses of soluble nutrients were reduced as a result of direct drilling, with reductions in losses of 49% for nitrate, and 17% for orthophosphate (soluble reactive P). The impact of minimum tillage on soluble nutrient losses is discussed further in a recent review of pollution swapping (Stevens and Quinton, 2009). Long-term use of minimum tillage can also result in soil compaction, and this may result in reduced macroporosity. Kay et al. refer to the study of Schjønning and Rasmussen (2000), which demonstrated a smaller macropore volume in the topsoil for soils under reduced tillage compared to ploughed soils. However, conservation tillage may also increase transport through macropores (Edwards and Lofty, 1982), and ploughing may reduce macropore activity (Shipitalo et al., 2000; Petersen et al., 2001). In the MOPS1 study, the general decrease in runoff observed under minimum tillage compared to ploughing is likely to have resulted from increased infiltration, which may be due to increased macroporosity, or to increased surface roughness, improved organic matter content, or reduced soil surface crusting. Notwithstanding high initial investment costs, minimum tillage can give rise to considerable cost savings within an arable rotation as a result of reduced trafficking (Table 1). Minimum tillage may therefore be a cost-effective option on suitable soils, although problems with increased weed burdens, pest and disease problems and compaction can have a negative impact (Environment Agency, 2003).

Working fields along the contour

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

Tramlines

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

‘Edge of field’ measures

Kay et al. (2009) found that the installation of ‘edge of field’ measures could potentially offer significant water quality gains to water companies. They consider buffer zones, for which a wide variety of information sources are now available, although uncertainty in their effectiveness is still high (Stevens and Quinton, 2009), and wetlands. Although wetlands as mitigation options for agriculture are a new concept in the UK and there has been little research undertaken in this area, wetlands can operate as control measures at locations where hillslope pathways have already discharged their pollutant loads into receiving streams, and may have more potential for mitigating diffuse pollution losses than buffer zones. The MOPS1 study has demonstrated that a suite of 'in field' mitigation options have the potential to be effective in the UK for controlling losses of sediment and nutrients in surface runoff, but preferential surface runoff pathways can operate at field scale which cannot be easily controlled 'in field', and pollutants can still be lost from hillslopes unchecked via subsurface runoff pathways, some of which (e.g. field drains) may contribute very high loads of sediment and phosphorus to streams (Foster et al., 2003; Gelbrecht et al., 2005; Deasy et al., 2009b). Kay et al. refer to subsurface losses in relation to increased nitrate leaching losses as a response to the injection of slurry, but otherwise focus purely on pollutant losses in surface runoff. However, the traditional view that the majority of pollutants are lost from agricultural land in surface runoff may be invalid under certain conditions, for example in tile-drained catchments. A combination of spatially targeted mitigation measures is therefore needed, including both 'in field' measures to reduce the mobilisation and transport of pollutants, and 'edge of field' measures to reduce the delivery of pollutants to water courses. An approach coupling both 'in field' and 'edge of field' measures will have the greatest potential for improving surface water quality.

Future research needs

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

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

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

Although they refer to the economic aspects of mitigation in relation to agri-environment schemes, Kay et al. fail to recognize the economic implications of the mitigation options, which are not limited to income from stewardship. The results published here, and in Deasy et al. (2008; 2009a) have considered the costs of different treatments, and upscaled these to field and farm scale. However, the cost of different mitigation options is dependent on the farming system and farm characteristics. For some options, such as minimum tillage, there may be substantial economic benefits, while other options involve a cost to the farmer. Kay et al. (2009) also note that research quantifying the impacts of agricultural stewardship on farm incomes is largely lacking and is urgently needed if farmers and land managers are to be convinced that environmental stewardship represents business sense. As Kay et al. (2009) state, overall there is a lack of scientific evidence to underpin the use of agri-environment measures for water quality management, but this research gap is now recognised by Natural England and Defra, and projects such as MOPS which aim to feed research findings directly into stewardship schemes will help bridge this gap by providing the scientific evidence urgently needed to reduce diffuse pollution from agriculture to surface waters.

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Tables

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	9-200	0.03-0.52	0.05-0.67
				(24-50)	(40-43)	(34-50)	(37-56)
Contour cultivation (clay)	1/2	3	0	16.5-56.0	90-1223	0.09-1.00	0.98-2.25
				(64-76)	(45-79)	(48-79)	(63-71)
Minimum tillage (sand, silt, clay)	2/5	3 to 4‡	+44 to +50	0.8-31.6	54-1133	0.04-2.28	0.15-1.01
				(4-81)#	(37-98)	(29-97)	(26-94)#
Beetle bank (clay)	2/2	3	-2 to -5	11.9-17.6	41-228	0.04-0.45	0.40-3.61
				(45-91)	(16-94)	(9-97)	(30-97)
Tramline modification (sand, silt)	4/5	4	-2 to -5	3.5-75.4	49-4870	0.19-2.89	0.13-5.31
				(69-97)	(75-99)	(72-99)	(74-98)

SS = suspended sediment, TP = total phosphorus, TN = total nitrogen. *Runoff is given in mm for consistency with other publications. 1 mm of runoff is equivalent to 10 m^{3} ha^{-1} runoff. † % relative change in overwinter loss is calculated by: (mitigation treatment loss-control treatment loss)/control treatment loss*100 for replicate experimental hillslope lengths over the number of site years trialled. ‡ Minimum tillage was trialled at all three sites, with three replicates used in three site years at Loddington, and four replicates used in the final year at Old Hattons and Rosemaund. #Effectiveness range is greater for runoff and TN than for SS and TP as minimum tillage was effective for a greater number of treatments for runoff and TN.