Final Report: Defra PE0206 Field Testing of Mitigation Options

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1. Executive summary

The Mitigation Options for Phosphorus and Sediment (MOPS) project aimed to investigate the efficacy and cost-effectiveness of different in-field mitigation options which could be used to control diffuse pollution losses in surface runoff from arable fields under combinable crops. In order to achieve this, a literature review, field experimentation, and economic analysis were undertaken.

A review of the literature highlighted the large toolbox of mitigation measures available to land managers, but also demonstrated that there are few studies determining the effectiveness of these measures for controlling diffuse pollution across a range of soils in the UK. In particular, little reference could be found in the literature addressing the control of diffuse pollution from tractor wheelings.

Field studies of mitigation options were carried out over three years at three sites in the UK with contrasting soil types: clay soils at Loddington (Leicestershire), silty-clay-loam soils at Rosemaund (Herefordshire) and sandy soils at Old Hattons (Staffordshire). All sites had similar long-term annual rainfalls (range 650-700 mm) and similar slope gradients (4-5°). Over the nine site-years, a total of 19 treatment options were trialled. These included conventional cultivation measures (as controls) and a range of mitigation measures (tramline disruption, residue incorporation, minimum tillage, contour cultivation, and vegetative barriers), which were considered both separately and in combinations. Losses of runoff, suspended sediment (SS) and phosphorus (P) were monitored from 52 hillslope lengths (68-270 m) giving a total of 156 plot-years of data collected. Table E1 summarises the effectiveness of each of the treatments at controlling losses of runoff, SS and P from arable fields under winter-sown combinable crops, and shows the results of the economic analysis of mitigation options, which was undertaken at the farm scale using standard farm rotations for the three years of the project. The results of this work demonstrate that:

- **Compacted, unvegetated tractor wheelings (tramlines)** were important sources and pathways for pollutant transport at all sites. At Rosemaund, on silty soils, runoff from tramlines was around 20 to 40 times greater, and losses of SS and total P (TP) were up to 300 times greater from tramlines than losses from vegetated areas without tramlines. At Old Hattons on coarser sandy soils, losses of runoff, SS and TP were between five and 30 times greater from tramline areas, and at Loddington, on heavy clay soils in year 3, losses from tramline areas were between two and six times greater than from areas without tramlines. The results reported in this project indicate that practical management options for tramlines could substantially reduce the risk of surface loss of runoff and associated SS and P.
- **Disrupting tramlines** using a simple tine reduced runoff by 69-97%, losses of SS by 75-99%, and losses of TP by 72-99%, compared to losses from conventionally-wheeled tramline areas. Tramline disruption was effective in four out of five site-years at Rosemaund and Old Hattons. Costs at the farm scale are low at £2-5 ha^{-1}, assuming a typical field rotation, 24 m tramline spacing and a work rate of 5-10 ha hr^{-1} depending on soil type. The importance of tramlines in influencing diffuse pollution means that focusing on tramline losses of SS and P using a form of the tramline disruption treatment trialled in this project, or another tramline management option, could be a very effective way to reduce sediment and P losses from arable land on moderate slopes. Further research is needed to ensure that practical recommendations are made for different soil types, but once this is completed tramline disruption has the potential to be one of the most cost-effective methods of reducing diffuse pollution losses from combinable crops.
- **Crop residue incorporation** rather than baling and removal of straw reduced runoff, SS and TP losses by 24-50% at Old Hattons in year 1, although these results were not found to be statistically

significant. Incorporation of crop residues may incur costs through lost revenues from straw sales, and additional costs of £25 ha^{-1}, where straw chopping is not part of the harvest operation.

- **Minimum tillage** was generally an effective means of controlling sediment and nutrient loss, although this effect differed between sites and between years. Minimum tillage was effective on the clay soils at Loddington in year 2 ($p<0.05$), significantly reducing runoff, SS and TP losses; runoff losses were reduced by 36-53%, SS losses were reduced by 37-62% and TP losses by 37-52%. In year 3, minimum tillage was not effective for areas under contour cultivation, or for areas containing tramlines, but reduced losses of runoff, SS and TP from areas cultivated up-and-down the slope by 34-62%. On sandy soils at Old Hattons in year 3, minimum tillage proved highly effective, reducing SS and TP loads by over 92% compared to traditional plough cultivation. At Rosemaund in year 3, SS and TP losses increased under minimum tillage, but these results should be considered in the context of a relatively dry winter monitoring period. Minimum tillage generates cost savings at the farm scale of £44 to £50 ha^{-1}, although savings from as little as £10 ha^{-1} are reported in the literature.
- **Cultivation on the contour** under traditional ploughing was an effective mitigation treatment for traditionally ploughed soils at Loddington in both the years it was trialled, reducing TP losses by 48-79%, which is higher than the figure of 25-25% reported in the DWPA manual (Cuttle *et al.*, 2007). Reductions for contour cultivation for both minimum tillage and ploughed areas were significant in year 2. The cost of converting to contour cultivation was not explicitly costed, although costs of £5 ha^{-1} have been reported elsewhere. Contour cultivation has the potential to be an effective mitigation option on the slopes where it can be implemented, if farmer resistance can be overcome.
- **Including a 2 m wide vegetative barrier** on the contour reduced SS and TP losses for all treatments by 9-97%. The beetle bank significantly reduced runoff, SS and TP losses only in year 1 ($p<0.01$), but was effective in both years 1 and 2 for the traditionally-ploughed soils, reducing losses by 32-97%, which suggests the mitigation effect may be higher than the 40% reduction in soil P loss reported in the DWPA manual. Costs are modest at £2-5 ha^{-1}, although a maintenance cost of £21 ha^{-1} is also applicable to the area of the barrier. In-field vegetative barriers on the contour may promote contour cultivation and may also have further biodiversity benefits. However, this treatment was unpopular with the farmer, and may be difficult to implement on complex slopes.
- **Treatment interactions** occurred at some of the sites. Minimum tillage appears to reduce the effectiveness of contour cultivation under some conditions.

Table E1. Effectiveness of mitigation options trialled on different soil types for between one and three years, and estimated per-crop costs. Figures are calculated by comparing mean values for treatments and control treatments by year and by site, and represent the results for all treatment combinations.

Treatment	Impact on farm margin (£ ha^{-1})	No. of Site-years trialled	Mitigation effectiveness (Reduction in overwinter loss, with% relative change)								
			Runoff (mm)			SS (kg ha^{-1})			TP (kg ha^{-1})		
			Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay
Tramline disruption[1]	- 2-5	5	3.5-11.0 (69-88)	5.3-75.4[a] (95-97)	N/A	49-223 (75-96)	373-4780[a] (98-99)	N/A	0.19-2.14 (72-95)	0.72-2.89[a] (97-99)	N/A
Crop residues[2]	0	1	0.2-2.0 (24-50)	N/A	N/A	9-200 (40-43)	N/A	N/A	0.03-0.52 (34-50)	N/A	N/A
Minimum tillage[3]	+ 44-50	5	2.2-7.8 (66-81)	N/E[a]	0.8-31.6[bc] (4-62)	107-841 (94-98)	N/E[a]	54-1133[bcf] (37-62)	0.33-2.28 (92-97)	N/E[a]	0.04-0.86[bcf] (29-52)
Contour cultivation[4]	0	2	N/A	N/A	16.5-56.0[d] (64-76)	N/A	N/A	90-1223[d] (45-79)	N/A	N/A	0.09-1.00[d] (48-79)
Vegetative barrier[5]	- 2-5	2	N/A	N/A	11.9-17.6[e] (45-91)	N/A	N/A	41-228 16-94	N/A	N/A	0.04-0.45 (9-97)

N/A = Not applicable. N/E = not effective in this project. [1]Trialled for 2 years on sandy and 3 years on silty soils. [2]Trialled for 1 year on sandy soils. [3]Trialled for 1 year on sandy, 1 year on silty and three years on clay soils. [4]Trialled for 2 years on clay soils. [5] Trialled for 2 years on clay soils. [a]Not effective when trialled in year 3. [b]Not effective when trialled in year 1. [c]Not effective when trialled under contour cultivation in year 3. [d]Not effective when trialled under minimum tillage in year 3. [e]Not effective when trialled under minimum tillage in year 2. [f]Not effective for tramline losses when trailled in year 3. N.B. While these results reflect our findings, the three year duration of the project may not have been long enough to accurately reflect the impact of the treatments on diffuse pollution losses.

List of Abbreviations

General:
DWPA = Diffuse water pollution from agriculture
C = Carbon
TC = Total carbon
TDC = Total dissolved carbon
P = Phosphorus
TP = Total phosphorus
TDP = Total dissolved phosphorus
N = Nitrogen
TN = Total nitrogen
TDN = Total dissolved nitrogen
SS = Suspended sediment
ANOVA = Analysis of variance
p = Significance level
SEM = Standard error of the mean

Measurements:
m = metre
mm = millimetre (0.001 m)
µm = micrometre (0.000001 m)
ha = hectare (10000 m^2)
l = litre
ml = millimetre (0.001 l)
µl = microlitre (0.000001 l)
g = gram
kg = kilogram (1000 g)
mg = milligram (0.001 g)
µg = microgram (0.000000 g)
yr = year

Field sites:
L = Loddington
OH = Old Hattons
RM = Rosemaund

Crops:
B = Winter barley
O = Winter oats
W = Winter wheat

Treatments:
B = Straw baled and removed
BB = Beetle bank
C = Contour cultivation
DTL = Disrupted tramline
MD = Mixed-direction cultivation
MT = Minimum tillage
OTL = Offset tramline
P = Plough
R = Straw residue incorporation
TL = Tramline
UD = Up-and-down-slope cultivation

1. Introduction

1.1. Context

Diffuse pollution inputs from agriculture play a central role in influencing water quality and biodiversity. As a result, controlling the transfer of diffuse pollutants from land to water is a priority for catchment managers and stakeholders (Kronvang *et al.*, 2005). The Water Framework Directive (WFD) places requirements on European governments to set water quality objectives for achieving good chemical and ecological status (European Commission, 2001, Moss *et al.*, 2003). Corresponding objectives relating to the restoration of key species and habitats and targets for favourable conditions on conservation sites are outlined in legislation represented by the UK Biodiversity Action Plan and the UK Government's Quality of Life indicators and the EU Habitats Directive.

Phosphorus (P) and Nitrogen (N) losses from agricultural soils are of particular concern, because of their role in limiting algal growth in surface waters. Of the two, P is currently of particular concern as the key limiting nutrient in rivers, lakes and reservoirs. The critical concentration of total P entering water bodies in relation to eutrophication is recognized by a range of organizations to be 0.1 mg l^{-1} (Withers and Sharpley, 1995). Studies commissioned by the Environment Agency (2000a, 2000b) indicate that P concentrations need to be one order of magnitude lower in fresh waters to meet the biodiversity levels designated in the EU Water Framework Directive. Phosphorus has low solubility, and is strongly bound by the soil, being associated primarily with the finer soil fractions (Quinton *et al.*, 2001, Sharpley, 1980). However, runoff preferentially transports the finer fractions of the soil (Quinton *et al.*, 2001), and P can therefore be transferred from hillslopes to surface waters in particulate form in association with eroded sediments, where it may later be released and become available for plant uptake (McDowell *et al.*, 2001a). Losses of P in dissolved form may also occur, and are of particular concern from grazed grasslands and from arable land after P additions in the form of fertilisers and manures (Sharpley *et al.*, 2000). The typical loss of P to water from farming land in the UK is currently estimated at 1 kg ha^{-1} yr^{-1} (Defra, 2002, Heathwaite *et al.*, 2005), but agricultural systems in most European countries are currently operating at an annual P surplus, which in the UK has been estimated to be around 16 kg P ha^{-1} yr^{-1} (Edwards and Withers, 1998, Withers and Jarvis, 1998). In total, agricultural activities are thought to be responsible for 30% of P inputs to surface waters (White and Hammond, 2006). In contrast to P, the transfer of N into surface waters occurs primarily in dissolved form, but N may also be transferred in particulate form in association with sediments and organic matter.

In addition to the on-site problems of soil erosion reducing available land area, sediment eroded from hillslopes is a pollutant in its own right. Increased fine sediment loadings are responsible for a range of off-site environmental problems, including channel bed siltation (Collins *et al.*, 2005) and associated detrimental impacts on fish populations, macroinvertebrate biodiversity and macrophyte communities (e.g. Clarke and Wharton, 2001). Sediments are also associated with the transport of other nutrients, pesticides, pathogens and metals (Quinton and Catt, 2007, Quinton *et al.*, 2001, Tyrrel and Quinton, 2003). Land in fallow and winter cereal crops is especially susceptible to soil erosion, where ground is bare or crop cover is low during the autumn and winter months (Chambers and Garwood, 2000), and a number of studies investigating the provenance of suspended sediment loads in UK catchments have reported the significance of cultivated fields as sediment sources (Chambers *et al.*, 1992, Collins and Walling, 2004, Robinson and Naghizadeh, 1992).

1.2. Rationale

Since the 1920s, research into the control of soil erosion has produced extensive scientific literature describing the functioning and design of erosion control features (Morgan, 2005, Schwab *et al.*, 1996). Transport management options concentrate on topsoil protection and the interception of surface runoff, and commonly include: the early sowing of winter cereals, sowing winter cover crops, using rough seed beds, reduced (i.e. non-inversion) or zero tillage, and establishment of in-field or riparian buffer strips

(Pierzynski *et al.*, 2000). Tramlines are undrilled compacted tractor wheelings, typically spaced 18 m, 20 m or 24 m apart, which serve as bout markers for spraying operations, ensuring accurate positioning and application of fertilisers and pesticides and minimising crop damage. Tramlines are of particular interest in the transport of sediment and nutrients, as research in previous Defra-funded projects (NT1033 and PE0111), and other recent research at the same Herefordshire site (Deasy, 2007) has shown that they represent a significant surface loss pathway for runoff and diffuse pollution. Practical management options to reduce runoff and erosion from tramlines are limited: for example, they can be established late by deferring the autumn spray operation (with increased risks of pests and diseases); vegetation cover can be established by drilling tramlines (with similar risks); or the compaction in tramlines can be broken up (disrupted) using some type of narrow tine or tine/disc combination once following the autumn spray operation.

Vegetative barriers of different types have been used successfully worldwide to control soil erosion (e.g. Dabney *et al.*, 1999), and there is potential for introducing these in-field along the contour to reduce slope length. A form of vegetative barriers (beetle banks) are already funded under Higher-Level Stewardship (HLS) although no guidance is provided concerning their potential effectiveness as mechanisms to trap sediment and P. Vegetative barriers and buffer-strips have frequently been used as edge-of-field mitigation options, but barriers can also be used as in-field mitigation options, where, if placed on the contour, they can act as barriers to surface runoff and retain sediment from up-slope, and reduce slope length. A positive relationship between slope length and surface runoff loss from hillslopes has been demonstrated in a previous Defra project (PE0111). In-field contour grass strips have received some research attention, and have been shown to reduce sediment losses on 5% and 10% slopes in the laboratory (Ligdi and Morgan, 1995). Introducing vegetative barriers along the contour would also promote cultivation on the contour, which is cited as a practice by which losses of runoff, sediment and associated nutrients from arable land can be controlled (Morgan, 2005), as tillage lines and tramlines run along the contour rather than up-and-down the slope, increasing runoff resistance. Contour cultivation has been successfully used to reduce soil erosion in trials at Woburn (Quinton and Catt, 2004). However, there is some farmer resistance to the idea of contour cultivation in the UK, partly due to the practical difficulties it introduces to field management. Although unsuitable for steep or complex slopes, contour cultivation represents a viable management option for shallow or moderate uniform slopes, but is not yet widely practiced.

Conservation tillage (also known as non-inversion or minimum tillage) reduces soil disturbance through non-inversion of the soil and a reduced number of tillage operations. Conservation tillage can reduce erosion risk by increasing aggregate stability, mean aggregate diameter and soil pore connectivity (Bradford and Huang, 1994), hence increasing infiltration, and reducing losses of sediment and sediment-bound pollutants (Quinton and Catt, 2004). This type of tillage is increasingly being adopted on soils across the UK in order to reduce farm costs. Unpublished data from the same authors shows that it can also be effective in controlling losses of total P. Another mitigation approach is to provide physical protection to the soil surface using residues from the previous crop to help maintain an open structure allowing water to infiltrate, reducing runoff and the mobilisation of sediment and P due to rainsplash and runoff. Crop residue management has been widely used in the United States as an erosion control methodology (Dickey *et al.*, 1986). However, its effectiveness for reducing P loss is less well understood, as decomposing straw may have the potential to release soluble P over the longer term (Schreiber, 1999), while studies considering N and carbon dynamics in the UK in response to crop residue incorporation show mixed results (e.g. Silgram and Chambers, 2002).

In the UK, there have been relatively few trials of in-field mitigation options in a replicated, structured manner. The potential for applying mitigation methods suitable for controlling soil erosion and diffuse pollution losses by surface runoff has been explored in previous projects, including the Woburn Erosion Reference Experiment (Catt *et al.*, 1994, Quinton and Catt, 2004, Quinton *et al.*, 2001), the MAFF Buffer Zone Project (Leeds-Harrison *et al.*, 1996), and Erosion Control in Maize Fields (SP0404). While these trials have demonstrated the potential for using different mitigation measures to control sediment and associated nutrient losses from agriculture, there are still many knowledge gaps to fill before some mitigation treatments can be widely recommended. In particular, these knowledge gaps include the effect of treatments on particulate and diffuse nutrient losses, the effect of different site characteristics, such as soil type, and the effect of treatments when trialled at large unbounded hillslope scale, rather than the small bounded plot areas usually used in experimental work, which poorly represent management scales and have edge effect problems. There remains considerable scope for modifying existing mitigation practices and for improving subsidiary benefits associated with biodiversity gains, but the identification of appropriate mitigation strategies for diffuse pollution loss is dependent upon improved knowledge and understanding of the effects of various management methods in controlling pollution losses.

In England and Wales, incentive-based policy is being used to drive environmental management targeting diffuse water pollution from agriculture. Policy packages include the Entry-Level and Higher-Level agri-environment schemes (ELS and HLS). Recognizing and understanding how socio-economic factors influence the diffuse pollution management agenda is crucial, and hence the key to successful mitigation is to integrate process understanding and cost-benefit analyses of policy packages into integrated decision-making tools (McDowell *et al.*, 2001b). The DWPA User Manual (Cuttle *et al.*, 2007) draws together some of the information available on mitigation options, and provides an inventory of methods to control diffuse water pollution from agriculture. However, some of the estimates of effectiveness in the manual relating to P are based on expert judgement due to a lack of experimental data, while some other potential mitigation options are not included.

1.3. Objectives

The Mitigation Options for Phosphorus and Sediment (MOPS) project aimed to investigate the efficacy and cost-effectiveness of different in-field mitigation options which could be used to control diffuse pollution losses in surface runoff from arable fields. MOPS had four main objectives:

1. To review published literature on the effectiveness of different mitigation features for preventing the mobilisation and/or encouraging the trapping of sediment and phosphorus in problematic agricultural land forms.
2. To test the effectiveness and longevity of individual, and combinations of, control measures representing different levels of farmer intervention, in terms of mitigating sediment and P loss on three contrasting high risk sites.
3. To determine the cost-effectiveness of different approaches, and combinations of approaches, at hillslope scale to refine and update P cost curve assessments (PE0203). This will include both costs to Government (scheme grants) and farmers (profits foregone, cost of implementation and maintenance, scheme grants).
4. To provide advice to DEFRA on the potential for including the most effective P mitigation methods within existing or new agri-environment schemes (including Entry Level and Higher Tier options), and to develop mitigation practice standards for the most cost-effective methods for use by advisors and farmers.

Objective 1 is covered by the literature review appended to this report (Appendix 4). An additional review dealing with pollution swapping issues in relation to the mitigation of agricultural pollution was also partly produced under this project, and is in press (Stevens and Quinton, In press, Appendix 5). To address objective 2, the project established field trials of mitigation measures at three field sites in the UK (see Sections 3-7 of this report). The field trials focussed on winter-sown combinable crops, which were identified in the review as an important under-researched area in respect to erosion and P losses from agriculture, and as the land use covering the largest proportion of the UK arable area (winter cereals account for 70% of all cropping on arable land). Throughout the project, farm managers have been actively engaged in the design and evaluation of practical mitigation options, and assessments of the extent to which they can be incorporated into farming practices. To address objective 3, an economic analysis of each mitigation option at both farm and regional scales was undertaken (see Section 8).

Objective 4 has been addressed through meetings providing advice to farmers and Defra, and via correspondence with Defra and English Nature on revisions to the ELS and HLS agri-environment schemes. Effective knowledge transfer of practical recommendations to the farming community has been undertaken via farm open days and the farming press, in addition to publication of scientific results in peer reviewed journals (see Appendix 3).

2. Site descriptions

Three field sites were selected within the east and west midlands of the UK which have broadly comparable slopes and annual rainfalls, but differing soil types. The characteristics of each site are summarised in Table 1.

Figure 1. Location of the three field sites. 1 = Rosemaund, 2 = Old Hattons, 3 = Loddington.

2.1. *Rosemaund*

Rosemaund farm in Herefordshire has been the focus of ADAS research projects for several decades. The soils are well-structured, silty-clay-loams which are prone to surface runoff and cracking and which are widely underdrained. The site has been used in previous Defra projects PE0111 and NT1025, and the characteristics of the farm and its fields have been well described in the literature (e.g. Chapman *et al.*, 2005, Russell *et al.*, 2001, Williams *et al.*, 1996).

Table 1. Summary characteristics for three study sites.

Site	Grid reference	Long-term annual rainfall	Altitude (m AOD)	Soil series	Field name	Slope angle (°)	Slope length (m)	Organic matter (%)	Olsen P (mg l^{-1})	Land Use		
										Yr 1	Yr 2	Yr 3
Rosemaund	SO565480	660	100	Bromyard & Middleton	Holbach	5	100	2.6	34	W	W	O
Old Hattons	SJ884055	700	110	Salwick	Long Field	4	270	3.6	43	B	O	W
Loddington	SK797010	650	140	Hallsworth & Denchworth	Upper Pond North	4	67	5.2	9	W	O	W

W = winter wheat, O = winter oats, B = winter barley, R = oilseed rape, BN = winter/spring beans *Rotations as follows. Rosemaund: W O W B R (5 yr), Old Hattons: W W/B R (3 yr), Loddington: W R W BN/O (4 yr). N.B. Because of the experimental treatment design these rotations were not necessarily followed in the experimental years.

2.2. *Old Hattons*

Old Hattons farm in Staffordshire is owned by Severn Trent Water. The farm has been used for research studies for more than a decade, including for research on the effects of long term additions of sewage sludge to land (e.g. Shepherd and Smith, 2002). As a result of the addition of sludges, fields at Old Hattons have a higher organic matter and soil P status than might otherwise be expected for loamy sand soils under continuous arable production. Soils are weakly structured, erodible, and prone to surface sealing due to the effect of raindrop impact on the soil.

2.3. Loddington

The Loddington site in Leicestershire is run by the Allerton Research and Educational Trust, which seeks to demonstrate means of farming profitably with minimum environmental impact. The site has heavy clay soils, and much of the land is cultivated under minimum tillage. The site is used for other research projects, including SOWAP, and the PARIS (PE0116) and Wetting up Farmland for Biodiversity (BD1323) projects, and contains a number of novel conservation features including small ponds and vegetative strips.

3. Methods

3.1. Treatment experimental design

A broad range of practical mitigation options were explored. The mitigation treatments at each site were designed following completion of the literature review (Objective 1) and consultation with the farm managers at each site and with the project Steering Group. The treatments aimed to reduce sediment and P losses in one of three ways, either by reducing detachment of sediment and nutrients from the soil by splash erosion, by reducing the generation of surface runoff, or by reducing the volume, erosive energy and transport capacity of runoff within the hillslope. The treatments explored broadly covered tramline management, soil surface protection, slope length reduction, cultivation direction and cultivation type. The treatments used at each of the three sites over three years of monitoring are summarised in Table 2 and the experimental plans for each site and each year are shown in Appendix 1.

Table 2. Treatments and number of replicate hillslope lengths for the three study sites for each year of monitoring.

Treatment	Description	Site & Year								
		Rosemaund			Old Hattons			Loddington		
		1	2	3	1	2	3	1	2	3
P	Plough	8[1]	4			3[2]		4	3	3
P TL	Plough; Tramlines	4	4	4		4	4			4
P DTL	Plough; Disrupted tramlines	4	4	4		4	4			
P OTL	Plough; Offset tramlines		4			4				
P B	Plough; Straw baled and removed				4					
P B TL	Plough; Straw baled and removed; Tramlines				4					
P R	Plough; Residue incorporation				4					
P R TL	Plough; Residue incorporation; Tramlines				4					
P C	Plough; Contour								3	3
P C BB	Plough; Contour ; Beetle bank								3	
P MD	Plough; Mixed-direction							2[2]		
P MD BB	Plough; Mixed-direction; Beetle bank							3		
MT	Minimum tillage							4	3	3
MT TL	Minimum tillage; Tramlines			4			4			4
MT DTL	Minimum tillage; Disrupted tramlines			4			4			
MT C	Minimum tillage; Contour								3	3
MT C BB	Minimum tillage; Contour; Beetle bank								3	
MT MD	Minimum tillage; Mixed-direction							2[2]		
MT MD BB	Minimum tillage; Mixed-direction; Beetle bank							3		

[1] Paired comparisons were originally planned for the tramline areas and areas without tramlines, the areas without tramlines and the disrupted tramline areas, and the tramline areas and disrupted tramline areas, but bulking the areas without tramlines for statistical analysis provided a more robust characterisation of the site in the absence of tramlines while retaining the planned comparisons. [2] Problems in the autumn resulted in the loss of one of the experimental treatments.

Experimental hillslope lengths for each treatment were replicated at each site (Table 2). Four replicates were typically used at Rosemaund and Old Hattons. At Loddington, which had a different design because different treatments were trialled, two, three or four replicates were used. In total, 52 hillslope lengths were monitored for three years across three sites, giving a total of nine site-years for experimentation. Treatments were partially randomised, as at hillslope scale complete randomisation of the treatments and tillage operations was not always possible. This was considered acceptable as no statistically significant trends in soil chemical and physical status were identified across the slopes at any of the field sites.

3.1.1. Rosemaund

Treatments at Rosemaund focused on losses of sediment and P from tramlines, as evidence from PE0111 highlighted the importance of tramlines in influencing P losses at this site. In year 1, losses from tramlines were compared to losses from the vegetated areas between the tramlines, and to losses from disrupted tramlines. Disrupted tramlines were tramlines where the compacted surface was broken-up to 6 cm depth once after tramline establishment in the late autumn, using a cultivator fitted with a simple tine. In year 2, an offset tramline treatment was added, where losses were monitored from areas where the crop sprayer was driven over the emerging crop during the autumn, rather than driven over the unseeded tramline area. In year 3, the tramline and disrupted tramline treatments were combined with a cultivation treatment, where runoff, sediment and P losses were compared from both ploughed and minimum tillage areas.

3.1.2. Old Hattons

At Old Hattons, in year 1, a crop residue treatment was trialled. Post-harvest cereal straw residues were either chopped and incorporated using a Vaderstad Carrier (a combination cultivator with discs, tines and a crumbler roller), or were baled and removed. As there is no standard method for management of crop residues (some farmers incorporate and some bale, depending on the local market and value for baled straw, and the need for soil improvement by addition of organic matter), these methods were each compared as separate treatments. Losses from areas with and without tramlines were also monitored to determine the importance of tramlines on lighter soils. In years 2 and 3, the treatments implemented were the same as at Rosemaund.

In years 2 and 3 at Old Hattons, an additional field with a converging problematic hillslope form was monitored at its outlet into a small farm pond, in an attempt to assess whether implementing tramline disruption at a whole-field scale would reduce surface runoff and sediment and nutrient loads. However, problems with monitoring equipment meant that there are little data available for year 2. In year 3, late crop establishment due to the constraints imposed by farm operations meant that tramline disruption in the experimental field was undertaken later in the autumn, and this was followed by only two surface runoff events which were insufficient in magnitude to allow definitive conclusions to be drawn. Consequently these results are not reported with the other project results in Section 5.

3.1.3. Loddington

The experimental area was designed so that treatments could be considered both separately and in combination. In year 1, cultivation types considered were conventional plough and minimum tillage. As the field had previously been in minimum tillage, the treatment involved conversion of half of the experimental area into a traditionally-ploughed area. Cultivation type was considered separately, but also in combination with a mixed-direction treatment, and with a mixed-direction treatment and vegetative barrier. For the mixed-direction treatment, ploughing and drilling were conducted up-and-down slope, and rolling and all subsequent operations were conducted on the contour. A beetle bank, approximately 2 m wide and 50 cm high, was used as an in-field vegetative barrier on the contour, which was a raised bank seeded with a wildflower and grass mix to attract invertebrates. The beetle bank was located mid-slope, approximately 25 m above the collection tanks. In year 2, the mixed-direction treatment was changed to contour cultivation. In year 3, rather than exploring the vegetative barrier treatment further, a tramline treatment was established in order to determine whether tramline losses were important on all of the three soil types studied.

The initial field operations undertaken at each site in each year are summarised in Table 3. Where the experimental area was divided into areas of traditional cultivation and minimum tillage, the operations are shown separately. After drilling, the entire experimental area at each site was treated in the same way for fertilizer and spraying operations.

Table 3. Field operations for three study sites for each year of monitoring for ploughed areas (P) and minimum tillage areas (MT).

Site	Yr 1		Yr 2		Yr 3	
Rosemaund	P	Ploughed & power harrowed Drilled 27th September	P	Ploughed & power harrowed Drilled 26th September	P	Flatlifted, ploughed & rotospiked
					MT	Flatlifted & shallow cultivated
					P & MT	Drilled 8th October
Old Hattons	P	Disc-tine & roller cultivated x2 Drilled 4th October	P	Disc-tine & roller cultivated x2 Drilled 26th September	P	Disc-tine cultivated x2
					MT	Disc-tine cultivated
					P & MT	Drilled 5th October
Loddington	P	Ploughed, pressed & subsoiled	P	Ploughed & pressed Drilled 10th October	P	Ploughed & power harrowed
	MT	Shallow cultivated	MT	Shallow cultivated Broadcast 10th October	MT	Shallow cultivated
	P & MT	Pressed, drilled & rolled 18th-20th September			P & MT	Drilled 17th September

3.2. *Hillslope scale experimentation*

Monitoring was undertaken at the hillslope scale, using hillslope lengths. Extending the study scale from the traditionally-studied plot scale up to hillslope lengths was a key feature of this research project and means that the results are more representative of the net effect of processes to edge-of-field and of management scales. Because of the dimensions of the experimental hillslope lengths, which were 67-270 m (Table 1), hillslope lengths were unbounded except for 3 m runoff collection gutters at the base of the hillslope length (Plate 1a).

Plate 1a. Layout of hillslope monitoring equipment. Runoff from the upslope monitoring area was collected by plastic or metal gutters which channelled runoff into the piping.

Plate 1b. Piping diverted runoff downslope into the tipping- bucket sample splitters, which directed a representative subsample of runoff into covered storage tanks. The remaining runoff was directed to waste.

3.3. *Sample collection*

Surface runoff resulting from major rainfall events during the winter monitoring period (October-March) was collected from each hillslope segment. Runoff was channelled from metal or plastic collection gutters at the base of the hillslopes via plastic pipes into novel tipping-bucket sample splitters (Plate 1b). The splitters directed a user-defined proportion of the total event runoff into 400 l collection tanks, with the remainder diverted to waste. Depending on how they are configured, these devices are capable of producing representative flow-proportional samples of between one-half and one-eighth of event runoff. Each splitter was calibrated to verify that it functioned across a wide range of flow rates, and care was taken to ensure that the splitters were horizontal when installed in the field. The use of flow splitters was essential to prevent the tanks overtopping, as the total runoff volumes from the hillslope lengths could be very large. The flow splitters also allowed monitoring of runoff dynamics during individual events, as the number of tips per unit time could be logged. The bespoke design for the sample splitters was developed, and the prototypes were tested and the final products calibrated during the course of the first year of the project. The design criteria used in the development of the sample splitters ensured that they proved to be robust, suitable for unsupervised outdoor use, and resistant to blockage from stones, surface trash, and sediment.

3.4. Data analysis

Rain gauges were used on-site to characterise the intensity and duration of rainfall events. Event runoff was monitored using the measured runoff volumes in the tanks, and the logged flow-splitter data, and runoff was sampled from the collection tanks after each event. One sample was collected for each treatment replicate, and used for analysis. Samples were analysed at Lancaster University for suspended sediment (SS), Total P (TP) and Total dissolved P (TDP), and also for Total N (TN) and Total dissolved N (TDN) for each event. In year 3, samples were also analysed for Total Carbon (TC) for three events at Old Hattons and Loddington, and for two events at Rosemaund.

Upon receipt of runoff samples by the laboratory, an aliquot of sample was filtered through a pre-washed 0.45 µm Whatman GD/X syringe filter (Fisher Scientific, Loughborough, UK) incorporating a cellulose acetate membrane with a glass microfibre pre-filter. A 200 ml aliquot of unfiltered sample was reserved for the measurement of SS by evaporation at 105^{o}C (Bartram and Balance, 1996). Total P analysis was based on USEPA method 365.1 (O'Dell, 1993), which utilises classical colorimetric chemistry (Murphy and Riley, 1962) and was deemed to be the most suitable method for the sample type and analytical instrument (AQ2+ Discrete Analyser, Seal Analytical, West Sussex, UK). Total N and TC measurements were carried out by catalytic thermal oxidation using a Thermalox analyser (Analytical Sciences Ltd., Cambridge, UK). A number of soil samples were also analysed for TP, TN and TC. The TP method involved a modified Kjeldahl digest (Rowland and Grimshaw, 1985), followed by semi-automated colorimetric determination based on classical techniques (Murphy and Riley, 1962, O'Dell, 1993). Total C and TN elemental analysis by combustion was carried out using a Vario EL analyser (Elementar Analysensysteme, Hanau, Germany). A selection of samples were also used for particle size analysis, which was undertaken on a MasterSizer 2000 (Malvern Instruments Ltd., Malvern UK) after organics removal using concentrated hydrogen peroxide and dispersion with sodium hexametaphosphate.

Runoff (l) and concentration data (mg l^{-1}) were used to calculate event loads (kg), and these were combined with the area of each hillslope segment (ha) to calculate event yields for each treatment replicate (kg ha^{-1}). Data presented have been summed for all events in each year to give total overwinter yields for each treatment for each site, or averaged in the case of concentrations, and values represent the mean of all treatment replicates, with standard errors of means (SEM) also shown. Results were analysed on a treatment basis for individual sites and years using Analysis of Variance (ANOVA). Data were log-transformed for analysis where skewed. Because of the different experimental design of the three sites, slightly different analysis methods were used for the different sites, after taking statistical advice. For Rosemaund and Old Hattons, Genstat (version 10.1, 2007, VSN International) analyses were undertaken on event losses of runoff, SS, TP, TDP, TN and TDN, and flow weighted mean concentrations of SS, TP, TDP, TN and TDN for each treatment, using contrasts to discriminate ANOVA treatment effects. Data were analysed as a split-plot design at Old Hattons in year 1 and at both Old Hattons and Rosemaund in year 3. For Loddington, analysis was undertaken on event losses of runoff, SS, TP, TDP, TN and TDN, and mean event concentrations of SS, TP, TDP, TN and TDN for each treatment, using General Linear Model analysis in SPSS (v.14, SPSS Inc. 1989-2005). Two-factor ANOVA allowed the effects of the primary (cultivation) and secondary (direction, barrier, tramline) treatments to be distinguished. Further analysis of all treatments using single-factor ANOVA allowed significance levels to be calculated for differences between combinations of treatments.

A minimum of six events were monitored at each site in each winter (Table 4). The percentage of rainfall lost as surface runoff (runoff coefficient) was also calculated for each treatment for each site over each of the three years of the project (Appendix 2), in order to assist with the generalisation of treatment effects across sites and years.

Table 4. Winter rainfall and the characteristics of events monitored by site and by year.

Site	Year	Operation dates	Rainfall during monitoring period (mm)	No. of events monitored	Mean rainfall event size (mm)	Rainfall event size range (mm)
Rosemaund	1	30/10 - 15/03	293	8	37	22-41
	2	23/10 - 06/03	399	22[1]	18	6-36
	3	05/11 - 15/11	161	6	27	12-46
Old Hattons	1	27/10 - 13/03	270	8	34	10-43
	2	23/10 - 07/03	285	8	36	5-52
	3	26/10 - 21/01	140	8	18	14-42
Loddington	1	21/10 - 30/05	383	10	38	16-106
	2	17/10 - 08/03	360	10	36	24-57
	3	18/10 - 02/04	316	9	35	21-56

[1] The large number of events sampled in 2006-2007 reflects both the higher rainfall for this site, and the rainfall pattern which generated a large number of smaller runoff events, compared to the other two years.

4. Impacts of in-field management on surface runoff, sediment transport, and associated transport of phosphorus

Detailed results of all treatments applied at the three field sites over three years are shown in Appendix 2.

4.1. Effect of tramlines

In this project, losses of sediment and diffuse pollutants down tramlines were quantified at three sites in an attempt to assess the importance of this pathway over a variety of soil types and under a range of soil conditions. These losses were monitored at Rosemaund and Old Hattons in years 1 and 2 and at Loddington in year 3 (Figure 2).

At both Rosemaund and Old Hattons, there was a clear and consistent effect ($p<0.01$) of the presence of tramlines in losses of surface runoff at both sites in years 1 and 2, with 0.1-1.0% of rainfall lost as runoff in areas without tramlines compared to 2.2-15.8% of rainfall lost as runoff in areas where tramlines were present. The greater runoff coefficients in tramline areas accounted for significant increases in over-winter sediment losses ($p<0.01$). Mean losses of SS in surface runoff from tramlines were 379 kg ha^{-1} in year 1 and 4820 kg ha^{-1} in year 2 at Rosemaund, and 399 kg ha^{-1} in year 1 and 296 kg ha^{-1} in year 2 at Old Hattons, compared to losses from areas without tramlines of only 3-30 kg SS ha^{-1} at these two sites in the first two winters of monitoring. The difference in losses of SS from tramline areas compared to areas without tramlines was much greater than the difference in losses for runoff (Table 5). Losses of TP from tramlines were also significantly greater than from areas without tramlines ($p<0.01$). Overwinter losses of TP from tramline areas were 0.74-2.93 kg ha^{-1} compared to only 0.01-0.10 kg ha^{-1} from areas without tramlines at the two sites in the first two winters (Figure 2), and the increase in losses for tramline areas compared to areas without tramlines was similar to the increase in losses for SS (Table 5). Concentrations of TP in runoff were also greater in runoff from tramlines than from areas without tramlines for both sites in both years ($p<0.05$), ranging between 3.8 mg l^{-1} and 18.1 mg l^{-1} for tramline areas and 0.7 mg l^{-1} and 15.8 mg l^{-1} for areas without tramlines.

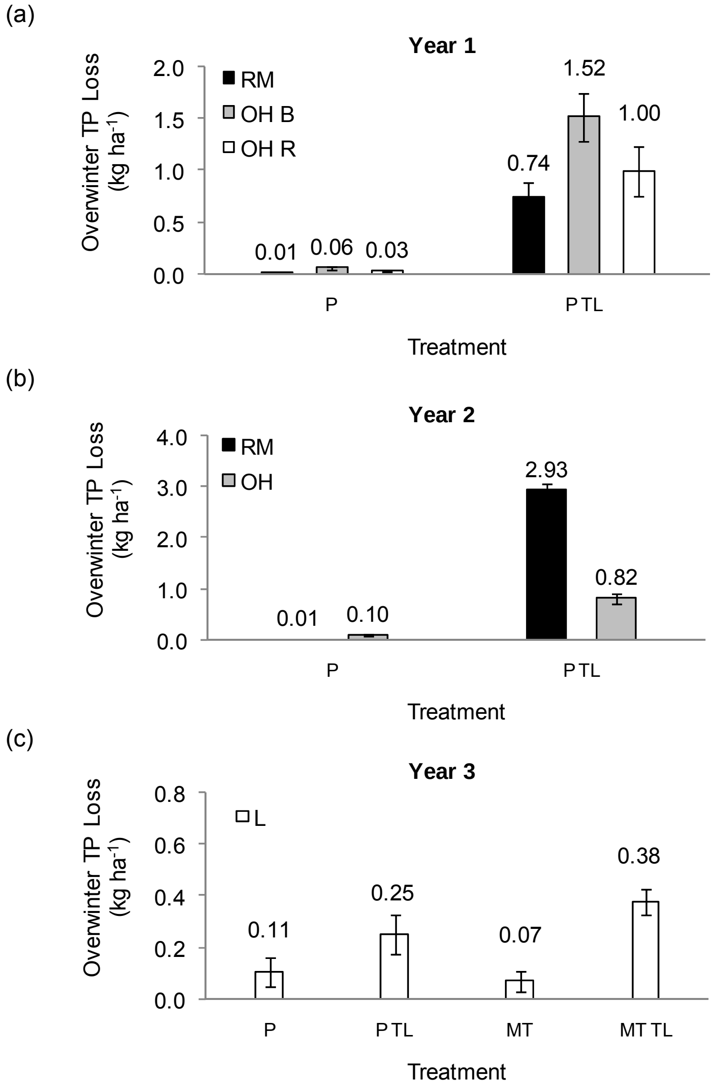

Figure 2. Overwinter TP losses from areas with tramlines (TL) compared to losses from areas without tramlines for (a) year 1 at Rosemaund (RM) and Old Hattons (OH) for areas where straw was baled and removed (B) and areas where residues were incorporated (R), (b) year 2 at Old Hattons and Rosemaund, and (c) year 3 at Loddington (L) for ploughed areas (P) and minimum tillage areas (MT). Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments. See Table 2 for treatment definitions.

At Loddington in year 3, tramlines also had a significant effect on runoff ($p<0.01$). Mean overwinter runoff under both traditional plough cultivation and minimum tillage from tramline areas was 43.5 mm compared to 15.1 mm from areas without tramlines. As for the other two sites, the increased runoff from tramline areas compared to areas without tramlines was also associated with a corresponding increase in SS and P yields ($p<0.01$), although the increase in losses was smaller than for the other two sites (Table 5). Losses of TP from tramline areas were 0.25 kg ha^{-1} for ploughed areas and 0.38 kg ha^{-1} for minimum tillage areas compared to 0.11 kg ha^{-1} and 0.07 kg ha^{-1} for areas without tramlines. However, there was no significant difference in SS or TP concentrations from tramline areas compared to areas without tramlines.

Table 5. Absolute change in overwinter loss, with multiplication factor in parentheses, for effect of tramlines on overwinter losses by year and by site. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Factor increase in overwinter loss = Treatment 2/Treatment 1. P = Plough, MT = Minimum tillage, TL = Tramline, B = Straw baled and removed, R = Residue incorporation. *p<0.05. **p<0.01.

Absolute change in overwinter loss (with multiplication factor)	Treatment 1	Treatment 2	Rosemaund				Old Hattons				Loddington	
			Yr 1		Yr 2		Yr 1		Yr 2		Yr 3	
Runoff (mm)	P R	P R TL					6.2**	(x32)				
	P B	P B TL					8.0**	(x21)				
	P	P TL	5.3**	(x19)	76.1**	(x39)			12.8**	(x5)	23.8	(x2)
	MT	MT TL									32.9**	(x5)
SS (kg ha^{-1})	P R	P R TL					287**	(x25)				
	P B	P B TL					478**	(x24)				
	P	P TL	376**	(x126)	4799**	(x230)			266**	(x10)	161	(x2)
	MT	MT TL									275**	(x6)
TP (kg ha^{-1})	P R	P R TL					0.97**	(x33)				
	P B	P B TL					1.46**	(x25)				
	P	P TL	0.73**	(x 74)	2.92**	(x 293)			0.72**	(x8)	0.14	(x2)
	MT	MT TL									0.31**	(x 5)

4.2. Tramline disruption

In year 1 losses from disrupted tramlines were compared to losses from areas with conventional tramlines at Rosemaund. Tramline disruption proved to be very effective, with results demonstrating that simple disruption of compacted tramlines could significantly (p<0.01) reduce runoff, and losses of SS and TP (Figure 3a) to levels similar to those measured in areas without tramlines (see Figure 2).

In year 2, the tramline disruption treatment was extended to Old Hattons, to investigate whether the method was also effective on lighter soils (Figure 3b). Overwinter runoff was 78.1 mm and 16.0 mm from tramline areas at Rosemaund and Old Hattons respectively, compared to 2.0 and 3.2 mm from areas without tramlines. However, disrupting the tramlines reduced runoff from tramline areas to 2.7 mm and 5.0 mm, reductions in losses of 97% and 69%. Similar reductions were also measured in losses of SS and TP (Table 6). In terms of sediment loss, the disruption of tramlines proved to be most effective at the Rosemaund site, where SS losses were 4820 kg ha^{-1} from tramline areas, but losses were reduced to 40 kg ha^{-1} after disruption, which was close to the 'background' levels measured from areas without tramlines (21 kg ha^{-1}). There were no consistent reductions in losses of runoff, sediment and TP from the offset tramline treatment at Rosemaund, where losses were greater from the offset tramline areas than from the conventional tramline areas, or at Old Hattons.

Results from year 3, where tramline disruption was applied in combination with both minimum tillage and plough treatments, differed for the two sites. Results from the Old Hattons site continued to demonstrate the significant effect (p<0.01) of tramline disruption in reducing overwinter losses of runoff, sediment and TP (Figure 3c). Tramline disruption reduced mean sediment losses for both the minimum tillage and plough treatments from 472 kg ha^{-1} to 56 kg ha^{-1}, while mean TP losses were reduced from 1.34 kg ha^{-1} to only 0.11 kg ha^{-1}. Results from Rosemaund in year 3 showed significant (p<0.05) increases in runoff from disrupted tramlines, and in overwinter sediment and P losses, compared to losses from conventional tramlines. However, this effect should be considered in relation to the low runoff coefficients (<3.4%) and sediment losses (<105 kg ha^{-1}) measured for all treatments at this site in year 3.

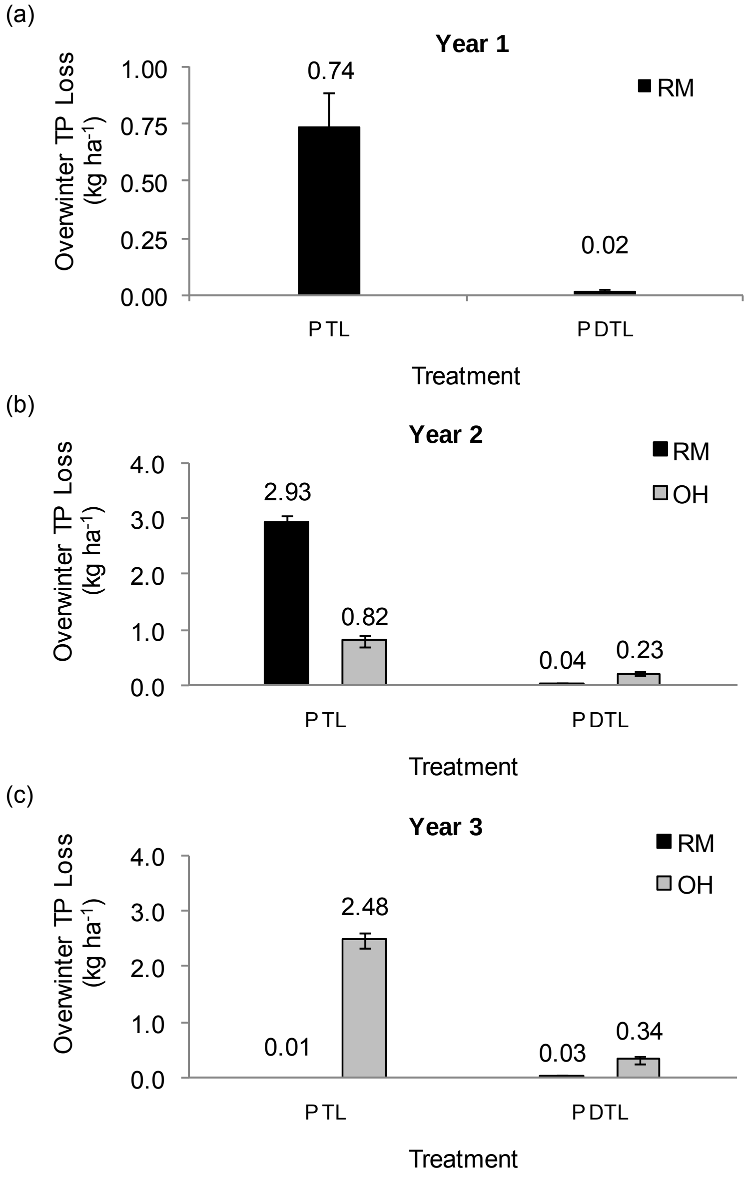

Figure 3. Effect of tramline disruption (DTL) on overwinter TP losses, compared to overwinter losses for ploughed areas (P) with tramlines (TL) for (a) year 1 at Rosemaund (RM), (b) year 2 at Rosemaund and Old Hattons (OH), and (c) year 3 at Rosemaund and Old Hattons. Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments.

Table 6. Absolute change in overwinter loss, with % relative change in parentheses, for tramline disruption treatment by year and by site. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Relative change in overwinter loss = (Treatment 2-Treatment 1)/Treatment1*100. P = Plough, MT = Minimum tillage, TL = Tramline, DTL = Disrupted tramline. *p<0.05. **p<0.01.

Absolute change in overwinter loss (with % relative change)	Treatment 1	Treatment 2	Rosemaund						Old Hattons			
			Yr 1		Yr 2		Yr 3		Yr 2		Yr 3	
Runoff (mm)	P TL	P DTL	-5.3**	-(95)	-75.4**	-(97)	0.5	(42)	-11.0**	-(69)	-9.1**	-(77)
	MT TL	MT DTL					3.4**	(243)			-3.5**	-(88)
SS (kg ha^{-1})	P TL	P DTL	-373**	-(98)	-4780**	-(99)	16	(267)	-223**	-(75)	-783**	-(88)
	MT TL	MT DTL					94**	(855)			-49	-(96)
TP (kg ha^{-1})	P TL	P DTL	-0.72**	-(97)	-2.89**	-(99)	0.02	(200)	-0.59**	-(72)	-2.14**	-(86)
	MT TL	MT DTL					0.10**	(500)			-0.19	-(95)

4.3. *Crop residues*

Losses of runoff, SS and TP were considerably reduced at Old Hattons in year 1, both within tramline areas and in areas without tramlines, by chopping and incorporating residues, rather than by baling and removing straw. Shallow incorporation of chopped straw reduced SS losses to 12 kg ha^{-1} from 21 kg ha^{-1} for straw removal on the areas without tramlines, and to 299 kg ha^{-1} from 499 kg ha^{-1} for straw removal on the areas with tramlines, representing reductions in losses of 43 and 40% respectively (Table 7). Similar reductions in losses were also found for TP (Figure 4). However, none of these differences were significant.

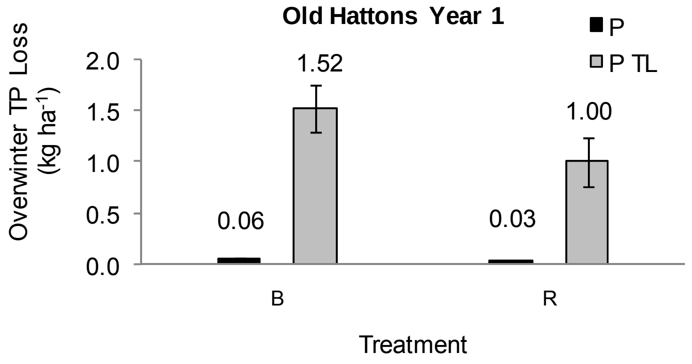

Figure 4. Effect of crop residue treatments on overwinter TP losses for year 1 at Old Hattons (OH), showing treatments where straw was baled and removed (B) and where residues were incorporated (R), for ploughed areas (P) with and without tramlines (TL). Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments.

Table 7. Absolute change in overwinter loss, with % relative change in parentheses, for residue treatments for Old Hattons in year 1. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Relative change in overwinter loss = (Treatment 2-Treatment 1)/Treatment1*100. P = Plough, MT = Minimum tillage, TL = Tramline, R = Residue incorporation, B = Straw baled and removed. *p<0.05. **p<0.01.

Absolute change in overwinter loss (with% relative change)	Treatment 1	Treatment 2	Old Hattons	
			Yr 1	
Runoff (mm)	P B	P R	-0.2	-(50)
	P B TL	P R TL	-2.0	-(24)
SS (kg ha^{-1})	P B	P R	-9	-(43)
	P B TL	P R TL	-200*	-(40)
TP (kg ha^{-1})	P B	P R	-0.03	-(50)
	P B TL	P R TL	-0.52	-(34)

4.4. Minimum tillage

Losses of runoff, sediment and P were monitored under minimum tillage in comparison to losses under traditionally-ploughed areas at all three sites, at Loddington in years 1, 2 and 3, and at Rosemaund and Old Hattons in year 3. At Loddington in year 1, losses of runoff were significantly greater (p<0.05) from areas under minimum tillage than from traditionally-ploughed areas. For areas under standard up-and-down slope cultivation, runoff was 5.1 mm for minimum tillage compared to 2.4 mm for ploughed areas. Corresponding increases in TP yields were also found to be significant (p<0.05) under minimum tillage. In year 2, the reverse was observed, and losses were lower from the minimum tillage areas than for the ploughed areas, under both contour and standard up-and-down slope cultivation in year 2, and this was also the case under standard up-and-down slope cultivation in year 3 (Figure 5).

Overwinter runoff was 55.7 mm in year 2 and 8.3 mm in year 3 for minimum tillage, compared to 87.3 and 21.9 mm for ploughed areas under standard up-and-down slope cultivation (p<0.05). Sediment and TP losses from these areas under minimum tillage were significantly (p<0.01) lower in year 2 than from the ploughed areas (Figure 5a). However, in year 3, runoff, SS and TP losses increased from the areas under minimum tillage which were cultivated on the contour (Table 8), and SS and TP losses also increased from the areas under minimum tillage which had tramlines. Overall minimum tillage significantly (p<0.05) increased losses in this year compared to traditional plough cultivation, but for standard up-and-down slope cultivation, minimum tillage decreased runoff and losses of SS and TP by 34-62% (Table 8). In year 3, as in year 1, significant (p<0.05) increases in concentrations of TP (0.83 mg l^{-1} compared to 0.73 mg l^{-1}) and TDP (0.22 mg l^{-1} compared to 0.05 mg l^{-1}) were also measured in the areas under minimum tillage compared to the ploughed areas.

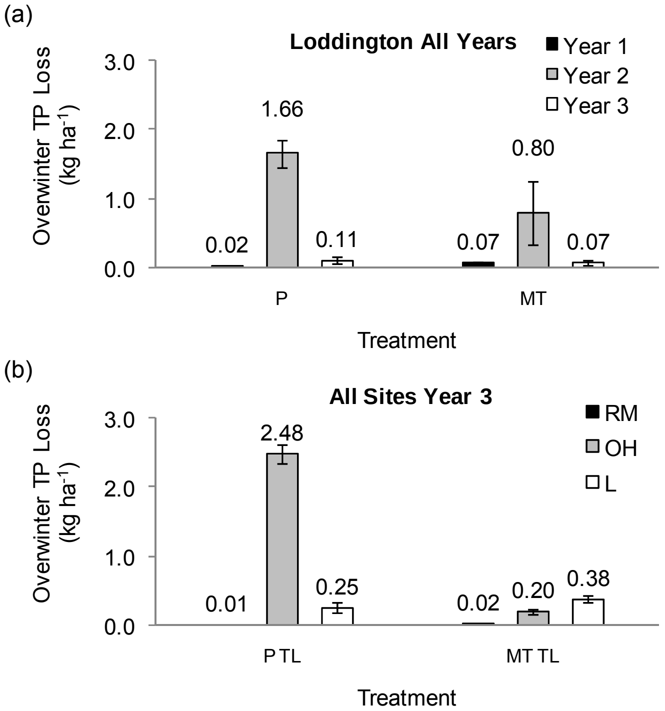

Figure 5. Effect of plough (P) and minimum tillage (MT) cultivation treatments on overwinter TP losses for (a) year 1, year 2 and year 3 at Loddington, and (b) year 3 at Rosemaund (RM), Old Hattons (OH) and Loddington (L) for areas containing tramlines (TL). Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments.

At Old Hattons in year 3, minimum tillage significantly ($p<0.01$) reduced losses of runoff, SS and P from tramlines, by 66-98% (Table 8). Losses of TP from minimum tillage areas with tramlines were 0.20 kg ha^{-1} compared to 2.48 kg ha^{-1} from ploughed areas with tramlines (Figure 5b). At Rosemaund in year 3, minimum tillage produced results similar to those at Loddington in year 1, with overwinter runoff, sediment, and P losses significantly ($p<0.05$) increased under minimum tillage compared to traditionally-ploughed areas. Mean sediment losses were 14 kg ha^{-1} across all ploughed treatments compared to 58 kg ha^{-1} across minimum tillage treatments. At Rosemaund this effect may be due to low rainfall (161 mm in the overwinter monitoring period) and low runoff generation (runoff coefficients 0.9-3.4%), as noted in Section 4.2.

Table 8. Absolute change in overwinter loss, with % relative change in parentheses, for minimum tillage treatment by year and by site. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Relative change in overwinter loss = (Treatment 2-Treatment 1)/Treatment1*100. P = Plough, MT = Minimum tillage, TL = Tramline, DTL = Disrupted tramline, MD = Mixed-direction, C = Contour, BB = Beetle bank. . *$p<0.05$. **$p<0.01$.

Absolute change in overwinter loss (with% relative change)	Treatment 1	Treatment 2	Rosemaund		Old Hattons		Loddington					
			Yr 3		Yr 3		Yr 1		Yr 2		Yr 3	
Runoff (mm)	P	MT					2.6	(109)	-31.6*	-(36)	-13.6	-(62)
	P MD	MT MD					-0.8	-(4)				
	P MD BB	MT MD BB					4.9	(297)				
	P C	MT C							-16.5**	-(53)	43.2**	(806)
	P TL	MT TL	0.2	(17)	-7.8**	-(66)					-4.5	-(10)
	P DTL	MT DTL	3.7**	(182)	-2.2**	-(81)						
SS (kg ha^{-1})	P	MT					17	(205)	-1133*	-(62)	-54*	-(47)
	P MD	MT MD					109	(247)				
	P MD BB	MT MD BB					27**	(944)				
	P C	MT C							-229**	-(37)	291**	(1205)
	P TL	MT TL	5	(83)	-847**	-(94)					61	(22)
	P DTL	MT DTL	83**	(377)	-107	-(98)						
TP (kg ha^{-1})	P	MT					0.05*	(211)	-0.86*	-(52)	-0.04	-(34)
	P MD	MT MD					-0.14	-(29)				
	P MD BB	MT MD BB					0.07**	(566)				
	P C	MT C							-0.25**	-(37)	0.32*	(1389)
	P TL	MT TL	0.01	(100)	-2.28**	-(92)					0.12	(50)
	P DTL	MT DTL	0.09**	(300)	-0.33*	-(97)						

4.5. Cultivation direction

In year 1, losses of runoff, sediment and P from the mixed-direction tillage treatment were significantly higher (*p*<0.01) than from standard up-and-down slope cultivation. This treatment was not continued in the following years. Cultivation on the contour was trialled at Loddington in years 2 and 3 (Figure 6). In year 2, losses of runoff, sediment, and TP significantly (*p*<0.01) decreased under contour cultivation compared to standard up-and-down slope cultivation (Figure 6a). Mean TP losses for contour cultivation treatments for both minimum tillage and ploughed areas were 0.54 kg ha^{-1} compared to 1.23 kg ha^{-1} from up-and-down slope cultivation. In year 3, the contour cultivation treatment decreased losses of runoff, sediment and P for soils in traditionally-ploughed areas, but increased losses from areas under minimum tillage, compared to standard up-and-down slope cultivation (Figure 6b). Because of the interaction of the minimum tillage and contour cultivation treatments, contour cultivation in year 2 did not significantly reduce losses overall compared to standard up-and-down slope cultivation. Over all site-years, where contour cultivation reduced losses of runoff, SS and TP, losses were reduced by 45-79% (Table 9).

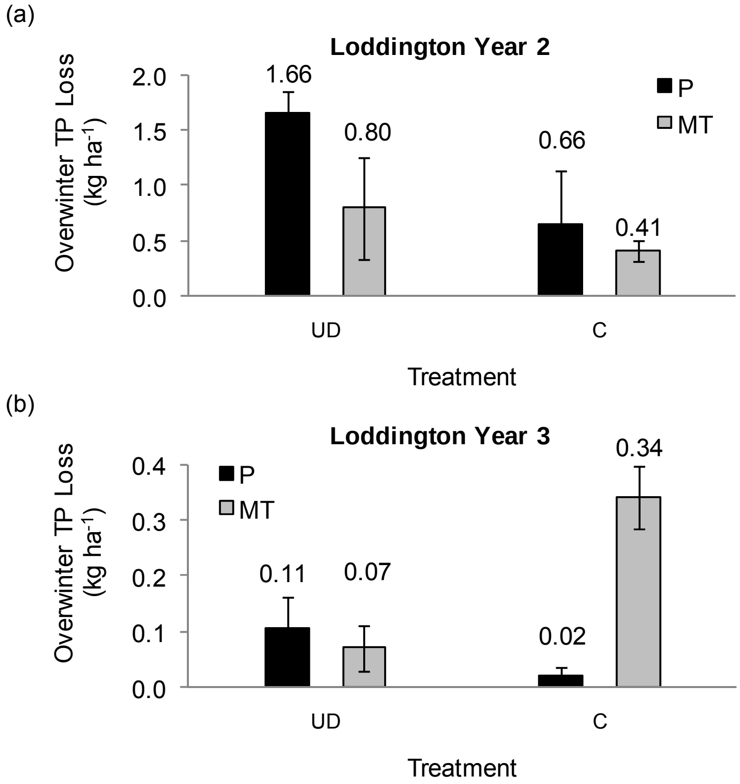

Figure 6. Effect of contour cultivation (C) on overwinter TP losses, compared to overwinter losses from up-and-down slope (UD) cultivated areas for Loddington, for ploughed areas (P) and minimum tillage area (MT) (a) year 2 and (b) year 3. Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments.

Table 9. Absolute change in overwinter loss, with % relative change in parentheses, for contour treatment for Loddington by year. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Relative change in overwinter loss = (Treatment 2-Treatment 1)/Treatment1*100. P = Plough, MT = Minimum tillage, C = Contour. **p*<0.05. ***p*<0.01.

Absolute change in overwinter loss (with% relative change)	Treatment 1	Treatment 2	Loddington			
			Yr 2		Yr 3	
Runoff (mm)	P	P C	-56.0**	-(64)	-16.5**	-(76)
	MT	MT C	-40.9	-(73)	40.2**	(483)
SS (kg ha^{-1})	P	P C	-1223**	-(67)	-90**	-(79)
	MT	MT C	-319	-(45)	255**	(424)
TP (kg ha^{-1})	P	P C	-1.00**	-(60)	-0.09**	-(79)
	MT	MT C	-0.39	-(48)	0.27**	(382)

4.6. *Vegetative barriers*

Losses from hillslope lengths containing the beetle bank, which were also cultivated on the contour, were monitored in years 1 and 2 (Figure 7). In year 1, the beetle bank significantly (p<0.01) reduced losses of runoff, SS and TP from areas under traditional plough cultivation and minimum tillage by 64-97% (Table 10). In year 1, SS losses were on average 16 kg ha^{-1} from beetle bank areas compared to 99 kg ha^{-1} from areas without the beetle bank. Mean TP losses were 0.40 kg ha^{-1} from contour cultivated areas without the beetle bank, compared to 0.05 kg ha^{-1} from areas containing the beetle bank.

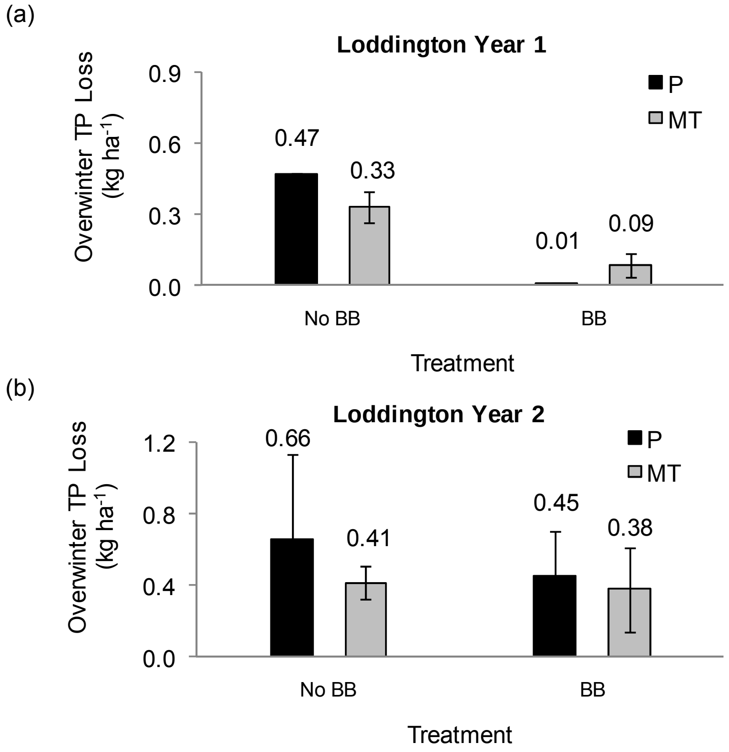

Figure 7. Effect of vegetative barriers (BB) on overwinter TP losses, compared to overwinter losses from contour cultivated areas without beetle banks, for ploughed areas (P) and minimum tillage areas (MT) at Loddington in (a) year 1 and (b) year 2. Values shown are overwinter means for replicates of each treatment, error bars are SEMs for replicates of treatments.

In year 2, the beetle bank reduced losses of runoff, SS and TP for areas under traditional plough cultivation by 32-45%, but for areas under minimum tillage, the beetle bank only decreased losses of SS and TP (by 9-16%). Overall, the beetle bank significantly reduced runoff, SS and TP losses only in year 1 (p<0.01), but was effective in both year 1 and year 2 for the traditionally-ploughed soils.

Table 10. Absolute change in overwinter loss, with % relative change in parentheses, for vegetative barrier treatment at Loddington by year. Figures are calculated by comparing mean values for treatments by year and by site. Absolute change in overwinter loss = Treatment 2-Treatment 1. Relative change in overwinter loss = (Treatment 2-Treatment 1)/Treatment1*100. P = Plough, MT = Minimum tillage, MD = Mixed-direction, C = Contour, BB = Beetle bank. . *p<0.05. **p<0.01.

Absolute change in overwinter loss (with% relative change)	Treatment 1	Treatment 2	Loddington			
			Yr 1		Yr 2	
Runoff (mm)	P MD	P MD BB	-17.6**	-(91)		
	MT MD	MT MD BB	-11.9	-(64)		
	P C	P C BB			-14.0	-(45)
	MT C	MT C BB			8.6	(58)
SS (kg ha^{-1})	P MD	P MD BB	-41**	-(94)		
	MT MD	MT MD BB	-124	-(81)		
	P C	P C BB			-228	-(37)
	MT C	MT C BB			-63	-(16)
TP (kg ha^{-1})	P MD	P MD BB	-0.45**	-(97)		
	MT MD	MT MD BB	-0.24	-(74)		
	P C	P C BB			-0.21	-(32)
	MT C	MT C BB			-0.04	-(9)

5. Impacts of in-field management on the transport of N and C in surface runoff

The effect of each of the treatments trialled in year 3 on total N (TN) losses was also assessed for each treatment for each event (see Appendix 2). At Rosemaund, N losses were principally particulate in year 1 and year 2 (73-91% and 46-75%), but dissolved N losses were more important in year 3 (PN losses only averaged 32-46%) when erosion rates were lowest. At Old Hattons, TN losses were principally particulate in all three years (90-93%, 82-92%, 41-92%). At Loddington, TN losses were principally particulate in year 2 (PN was 55-70% TN), but dissolved N losses were more important in year 1 (PN was 26-35% TN) and year 3 (PN was 26-44% TN). Despite the variability in the composition of N between sites and years, TN losses responded to the different treatments in a similar way to SS and TP.

The effects of the different treatments on total carbon (TC) losses were assessed for up to three events in year 3 for each site (Appendix 2.5). At both Rosemaund and Loddington, TC was principally transported in dissolved form, with the percentage of TC as TDC ranging between 56-81% for Rosemaund, and 58-99% for Loddington, for all samples. On the lighter soils at Old Hattons, the proportion of TC transported in dissolved and particulate form varied between events and between treatments (TC as TDC range: 8-81%). At Rosemaund, runoff from disrupted tramline areas consistently had significantly ($p<0.05$) greater mean TC and TDC losses compared to runoff from conventional tramline areas. There was an indication that losses of TC and TDC may be higher under minimum tillage compared to losses from ploughed areas, but this pattern was not consistent over the two events, and the cultivation effect was not significant in both events. At Old Hattons in year 3, tramline disruption significantly ($p<0.05$) reduced losses of TC and TDC in each event. There was also consistently less TC and TDC in runoff from areas under minimum tillage compared to ploughed areas in all three events, and this difference was significant for TC ($p<0.01$) in each event. However, at Loddington, there was no consistent effect of cultivation type (plough vs. minimum tillage) on TC or TDC losses over the three events. Losses of TC and TDC were lower from the contour treatments than from up-and-down slope cultivations for traditionally-ploughed areas, but this contour effect was not observed in the areas under minimum tillage. In each event, TC and TDC losses were higher from areas containing tramlines, but the tramline effect was not significant in all three events.

6. Use of sediment tracers to understand hillslope sediment transfer

In years 2 and 3, two tracing experiments were undertaken at Loddington, involving the application of rare earth element oxide powders to the soil surface, to determine the extent to which mitigation features act as sinks (or potential sources) for sediment and P. The results of the tracing experiment undertaken in year 2 showed that sediments are transported into tramlines from as far as 4 m each side, and that sediments can be transported at least 14 m down tramlines over the course of several events. The results of this research are published in Stevens and Quinton (2008), which is appended to this report (Appendix 5). The tracing experiment undertaken in year 3 extended this research to determine whether tramline areas and different areas of the hillslope contribute different amounts of sediment to the total eroded load, and whether the erosion rates and areas differ between treatments, through applying different tracers to different areas of the hillslope. The final samples for this part of the rare earth work were collected in April, and the results will be reported in forthcoming publications in academic journals.

7. Particle size characteristics of eroded sediment

Analysis of absolute particle size has been undertaken for a number of event samples for each site (Figure 8). The results allow comparison of the different size fractions transported in runoff from different soil types and from different treatments. Results suggest that the composition of eroded sediment is related to soil type, with the sediment at Old Hattons including a greater proportion of sand. At each site the majority of sediment eroded is silt particles, although there is a large proportion of clay. There also appears to be variation between treatments, although the patterns are not consistent. Further analysis may involve comparison of these data with soil particle size data, and calculation of enrichment ratios for the different soil types and treatments using event SS and P concentrations.

A limited number of samples have also been analysed to provide information on within-event dynamics. The results indicate that coarsening of sediment transported in runoff occurs through time, with the finest particles transported at the beginning of an event. This has implications for the transport of P and N lost in association with fine sediment, and data from within-event runoff samples also show that P and SS concentrations and loads are highest at the beginning of an event. This work provides insights into the processes controlling hillslope sediment and P transfer, and is being undertaken in association with a current NERC project (NE/E005357/1) through Lancaster, Loughborough and Cornell Universities and the USDA (see http://multisem.lboro.ac.uk/index.html).

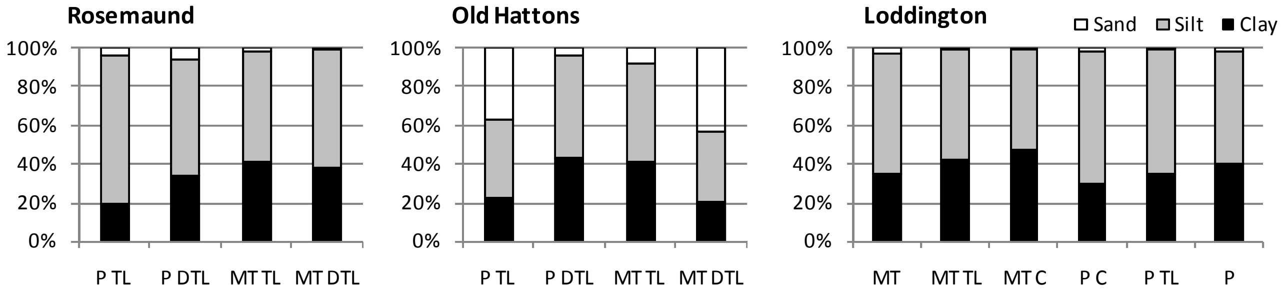

Figure 8. Results of particle size analysis undertaken on sediment collected from each treatment in events in January 2008. Data are the mean of two samples for each treatment.

8. Economic evaluation of mitigation measures

8.1. Model development

To determine the cost effectiveness of the different approaches for the mitigation of P loss, simple spreadsheet models were constructed to examine impacts on individual cereal crop margins and on the overall arable rotation. First, operating margins for each crop were calculated to reflect the direct costs of crop production (Appendix 2.6). These included: crop yield and price; seed, fertiliser and agro-chemical variable costs; and labour and machinery costs, which can be directly allocated to each crop enterprise, and which are associated with establishment, fertiliser and agro-chemical applications, and harvesting. Second, these margins were used to produce a net return per average cropped hectare for a typical arable operation, taking into account the difference in areas of crop grown. Finally, any impacts on yield, fertiliser or agrochemical requirements were incorporated, alongside the costs associated with undertaking each mitigation option, through a series of linked worksheets to demonstrate the impact on the relevant crop operating margins and the overall average net return per hectare.

8.2. Farm models

Three farm-level versions of the model were developed to represent each of the three case study farms. The models used data from the experimental work, the case study farm as a whole, and published data on prices and costs associated with each of the crop enterprises. To calculate gross output, average crop yields from each harvest year at each case study farm were multiplied by the relevant October market prices (Farmers Weekly, 2006a,b, 2007a,b; Farmers Weekly Interactive, 2007)[1]. Variable and operational costs to calculate the gross and operating margins were based upon the standard data taken from Nix (2005), linked to field records as appropriate. Machinery costs reflect the number and type of operations and the length of time required to undertake them. They include fuel, labour requirement, repairs and depreciation but exclude more general overhead costs. The calculations also take into account the differences in work rate possible on light and medium/heavy soils that occur at each of the

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[1] Yields and prices for the 2008 harvest were not available at the time of writing this report. Yields and prices were therefore assumed to be the average of the previous two years' results.

three case study farms. Average net returns per hectare were then calculated, taking into account the combinable crop rotations at each farm and the areas planted for each of the main crops. Variable and operating costs associated with each mitigation option were incorporated to demonstrate the impact on the relevant crop operating margins and overall average net return per hectare. The calculations used the data from the case study farm field records for each of the identified mitigation options and it was assumed that mitigation takes place on all fields where cereal crops are grown[2]. In reality, this would not necessarily be the case, as mitigation measures would be most effectively targeted at specific fields based on field characteristics (e.g. proximity to water course, slope, soil P status etc).

The switch to minimum tillage and contour cultivation and the offsetting of tramlines is included in the model within the relevant crop operating margins, specifically in terms of impacts on yield, fertiliser and agrochemical costs, and changes to operational costs. Additional capital costs associated with the purchase of new alternative equipment to undertake minimum tillage are not included here. The costs of straw chopping, undertaken at harvest, and straw incorporation during subsequent crop establishment were also included within the relevant operating margins and are not identified as a separate cost. The costs for the baling and removal of straw, based upon the length of time taken for the operation and associated labour and machinery costs, are shown as additional deductions from the relevant cereal crop operating margins. Similarly, the additional time spent in the field disrupting tramlines in cereal crops following the last autumn spray operation is identified as an additional cost deducted from the relevant crop operating margins. Given the similar equipment used, it was assumed that the labour and machinery costs would be similar to those of spring tine harrowing.

Consideration was also given to the establishment of the vegetative strip. There are additional costs as a result of establishment and annual maintenance requirements, loss of productive land, and potentially the increased requirement for weed control in areas at the edge of the beetle bank that cannot be cultivated. The initial cost for the establishment of a vegetative strip covers land preparation, sowing of grass seed and cutting in the first year. A fully mechanised operation with plough, seedbed cultivation, drilling and rolling is assumed. In subsequent years, regular topping of the vegetation may be required. As a one-off capital cost, the initial cost of establishment is not included within the crop enterprise operating margins. The costs associated with the reduction in arable area are more difficult to calculate. In addition to the direct loss of arable land, there are potential costs associated with reduced field size and slower work rate, and as a result of increased crop enterprise operational costs. These are dependent on farm size, arable area, field sizes, slope characteristics, and opportunity to incorporate vegetative strips within fields. In practice, areas taken for the vegetative strip would probably be less than 1 ha, allowing for some reduction in cost if the area was small enough to be seeded by hand. It is also likely that the creation of a contour vegetative strip would also require cultivation to be undertaken on the contour.

8.3. Regional models

The next stage of the analysis was to extrapolate the results beyond the farm level to generic farm typologies at a regional level. The regional models were constructed around three key cereal crops, wheat, barley and oats, and two break crops: oilseed rape and beans. Defra June Survey data (2006) were used to define typical farms and cropping patterns. Financial returns used as the baseline level of the analyses were calculated using financial crop enterprise data for the regions taken from the relevant Farm Business Survey (2007a,b; pers. comm.) for the 2006 harvest year. Average net returns per hectare were calculated, taking into account the percentage area of crops grown within a region using the same survey data. Impacts at the farm level were then incorporated within the regional model for the different crops for which data are available using the results from the three years. The costs were incorporated in two ways. For the minimum tillage and offset tramline treatments, impacts on yield, and

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[2] A more accurate picture would be to determine what percentage of the land and hence cereal crop area would require implementation of the mitigation option. Average net return per hectare would therefore be somewhere between the original and new margin.

variable and operating costs were incorporated as percentage impacts for each crop enterprise margin using a series of linked worksheets, while for the straw residue and tramline disruption options, the additional associated costs were subtracted, as with the farm model, from the individual crop margins.

8.4. *Model Results*

The results presented here cover both the farm and regional levels. Table 11 illustrates, for each case study farm in each year, an average operating margin per hectare and the financial impact, at the farm level, of the introduction of the relevant mitigation options on the net return per average cropped hectare.

Table 11. Additional costs and impact of mitigation options on rotational operating margin at the farm level, 2006-08

Site	Year	Mitigation Option	Impact on Rotational Operating Margin (£ ha^{-1})	
Rosemaund	2006	P (control)	£183	Margin
		P DTL	-£4	See note a
	2007	P (control)	£522	Margin
		P DTL	-£4	See note a
		P OTL	£0	
	2008	P (control)	£355	Margin
		P DTL	-£3	See note a
		MT	+£44	See note b
		MT DTL	+£41	See notes a, b
Old Hattons	2006	P (control)	£202	Margin
		P B	-£1	See note c
	2007	P (control)	£623	Margin
		P DTL	-£2	See note a
		P OTL	£0	
	2008	P (control)	£498	Margin
		P DTL	-£2	See note a
		MT	+£50	
		MT DTL	+£48	See notes a, b
Loddington	2006	P (control)	£201	Margin
		P MD	£0	See note d
		P MD BB	- £2	See notes d, e
		MT	+ £46	See note b
		MT MD	+ £46	See notes b, d
		MT MD BB	+ £44	See notes b, d, e
	2007	P (control)	£502	Margin
		P C	£0	See note d
		P C BB	- £5	See notes d, e
		MT	+ £45	See note b
		MT C	+ £45	See notes b, d
		MT C BB	+ £40	See notes b, d, e
	2008	P (control)	£365	Margin
		P C	£0	See note d
		MT	+ £47	See note b
		MT C	+ £47	See notes b, d

[a] Tramline disruption costs £38 ha^{-1} at Rosemaund (heavy soil) and £18 ha^{-1} at Old Hattons (light soil) relating to the time spent setting up the machinery and the operation itself. The high cost is associated with the small experimental areas and 12m tramline spacing. Rosemaund has a much greater cost due to the smaller area covered in the experiment (a scale issue) and the slower work rate on the heavier soil. With 24 m tramline spacing across a greater area, it is envisaged that on light soils, up to 12 ha hr^{-1} could be achieved at a cost of £2 ha^{-1}. Figures quoted here assume a work rate of 10 ha hr^{-1} on light soil (£3 ha^{-1} per crop), and 5 ha hr^{-1} on heavier soil (£5 ha^{-1} per crop). These costs are reduced further when incorporated within the rotational margin, as it is assumed that tramline disruption does not take place in every crop in every year.

[b] This figure assumes no impact on the resultant agronomy of the crop. However, problems with increased weed burdens, pest and disease problems and compaction can have a negative impact. Similarly, there are also agronomic implications as a result of timing of establishment, and climate and soil conditions. Guidance provided by the Environment Agency (2003) suggests savings may be as little as £10-25 ha^{-1}.

[c] The baling and removal of cereal straw residues amounts to a cost of £1 ha^{-1} per crop and therefore has minimal impact on the overall margin when incorporated within the rotation (less than £1 ha^{-1}) as it is assumed that this option is only applied to cereal straw residues. It should be noted that there would be potential for additional revenue from this option (rather than a cost) were a market available for baled straw. A farmer moving from baling and removal to chopping and incorporation may also face additional costs, of £5 ha^{-1} per crop when combined with harvesting rising to approximately £25 ha^{-1} if chopping is undertaken as a separate operation (Nix, 2005). To some extent this is dependent on the age and specification of the combine harvester, and whether or not the equipment is attached in the standard specification or is available as an extra.

[d] Although the impact on rotational margin is given here as £0, working across the contour can reduce ground speed, incurring increased costs, or conversely can improve fuel use, and this is dependent on slope characteristics, but extra costs may be around £5 ha^{-1} (D'Arcy and Frost, 2001).

[e] The vegetative strip took approximately 1% of the field area out of production. The impact on the margin is dependent on (i) the level of the crop margin (a combination of yields, prices and input costs), and (ii) field size. Higher margins intuitively result in a greater reduction per hectare from taking land out of production. Similarly, reductions are greater/lower on smaller/larger field sizes. For these reasons, the ongoing annual maintenance costs, which for Loddington would be approximately £2 ha, are not included in the table.

In terms of the impact on yield, fertiliser and agro-chemical applications, field records from the three years show that no differences occurred as a result of the implementation of the mitigation options. In the longer term this may not be the case. Table 12 shows the financial impact, at the regional level, of the introduction of the various mitigation options on the net return per average cropped hectare.

The reduction in margin as a result of the additional tramline disruption operation reflects the labour and machinery cost of the additional pass required to disrupt the tramlines in the late autumn. In determining the cost of tramline disruption, a number of assumptions were made. First, the operation is assumed to be similar to spring tine harrowing, estimated at £15 ha^{-1} (Nix, 2005). Second, the actual costs incurred (see Table 10, note a) were not used as these were indicative of the experimental situation, i.e. small plot width and 12 m tramline spacing. In reality, the upscaled per hectare work rate will be greater due to gains from economies of scale. Additionally, in commercial practice, tramline spacing of 18 m, 20 m and 24 m is far more common. These considerations were taken into account in the calculations. Finally, no additional equipment costs were calculated, as it can be safely assumed that on the majority of farms, the type of equipment required would already be available and in use for conventional operations. Offsetting tramlines does not give rise to any additional operational costs. There may be implications for resultant crop yield but initial results suggest that this has not been the case.

In terms of residue management, the costs of baling and removing straw had only a minimal impact on the overall rotational margin, although this does not include additional potential revenue from the sale of the straw. Other impacts associated with straw incorporation, including improved organic matter content giving rise to improved yields and increased weed and disease problems, were not evident primarily as a result of the trialing of this option in one first year of the project.

The switch to minimum tillage, as is to be expected, reduced establishment costs and thereby substantially increased the operating margin. However, minimum tillage can increase weed burdens and pest and disease problems, giving rise to increased agro-chemical costs. There may also be problems with compaction, although this was not case at the case study sites across the years of the project.

The change to operating across the contour from up-and-down slope cultivation was not explicitly costed. In reality, additional time spent in the field as a result of the reduced work rate may increase the operational costs per hectare associated with crop establishment, and potential costs of fertiliser applications and spraying of agrochemicals. Many farmers are reluctant to cultivate on the contour because of the difficulties with cultivation and spraying operations, and because of its suitability to only a limited number of slopes.

The costs of the vegetative strip include a one-off capital cost for establishment (£163 ha^{-1}, or £3-£5 per 100 m of 2 m width barrier) and an ongoing annual maintenance cost for topping the vegetation (£21 ha^{-1} of area in the strip, or £0.5-0.6 per 100 m of 2 m width barrier), which are not included in Table 11, and a further cost associated with reduced field size and increasing operational complexity, which is dependent on the opportunity cost associated with the value of the crop that the vegetative strip replaces. Higher crop prices result in a greater opportunity cost and, therefore, a greater impact on the rotational margin.

Table 12. Additional costs and impact on margin at the regional level of mitigation options, 2006

Region	Mitigation Option	Resultant Operating Margin (£ ha^{-1})
East Midlands	P	£68
	P C	£0
	P C BB	-£2
	MT	+£68
	MT C	+£68
	MT C BB	+£66
	P DTL	-£2-3
	P OTL	£0
	P B	-£1
	P R	-£16
West Midlands	P	£58
	P C	£0
	P C BB	-£2
	MT	+£70
	MT C	+£70
	MT C BB	+£68
	P DTL	-£2-4
	P OTL	£0
	P B	-£2
	P R	-£19

N.B. Regional farm business survey data for 2007 and 2008 was not available at the time of report preparation.

9. Discussion

9.1. Erosion and transport of diffuse pollutants

The data from field trials on different soil types indicate that mean event runoff, sediment and P losses vary between sites and depend on soil type and soil management. The percentage of rainfall generated as runoff was lowest for the sand site at Old Hattons (0.1-5.5%), and highest for the clay soils (Rosemaund: 0.5-19.1%, Loddington 0.6-24.3%). Runoff generation was lower in year 1 (0.6-4.8%) than for years 2 and 3 for Loddington, and for year 3 (0.9-3.4%) compared to years 1 and 2 for Rosemaund, but was similar in each year for Old Hattons. Runoff losses were highest from the clay soils, with Loddington generating the highest runoff (mean treatment overwinter runoff 25.2 mm), followed by the silty-clay-loam site (Rosemaund: 17.5 mm) and the loamy sand site (Old Hattons 5.7 mm). The overwinter runoff generated is comparable to runoff recorded in other hillslope studies. Defra project PE0111 reported lower overwinter runoff values for Rosemaund, from a field with a steeper 7° slope, ranging between 4.5 mm and 6.6 mm from tramline areas, and 0.7-3.7 mm for vegetated areas without tramlines, while Defra project PE0203 reported overwinter runoff values of 2.0- 13. 2 mm for runoff from tramline areas on chalk soils, 3.2-14.1 mm from sandy soils and 1.5-9.7 mm from clay soils. The variability in the reported ranges, and the differences in the contributions from various soil types, reflect differences in overwinter rainfall amounts and intensities, the length of the winter monitoring period, the number of monitoring seasons, contributing slope length (scale of monitoring), and the effect of different management and mitigation treatments operating at each site.

The pattern of sediment losses measured in this project differs slightly from that of runoff, with the highest losses from Rosemaund (mean event loss 1070 kg ha^{-1}), and the lowest losses from Old Hattons (201 kg ha^{-1}). Although Loddington had higher runoff losses, the clay soils are more cohesive than the silty soils, and although the poorly structured soils at Old Hattons are easily eroded, the lower runoff meant that sediment was not as easily transported from hillslopes as it was at the wetter sites. Average UK erosion rates for different soil types reported in the literature range widely between <8-16000 kg ha^{-1} for plot studies, and 0-6300 kg ha^{-1} for field surveys (Brazier, 2004), and the data recorded within this project fall within this range. Erosion rates, as for runoff, are again higher for Rosemaund than data reported in PE0111, where SS losses were 116-205 kg ha^{-1} for tramline areas and 9.2 kg ha^{-1} to 42.3 kg ha^{-1} for areas without tramlines, but are within the range reported in PE0203, where recorded SS losses were 77-650 kg ha^{-1} for sandy soils, 32-75 kg ha^{-1} for clay soils, and 63- 787 kg ha^{-1} for soils on chalk.

The pattern of TP losses differs from the pattern of SS losses, with TP losses being highest from Rosemaund (mean event loss 0.70 kg ha^{-1}), and lowest from Loddington (0.36 kg ha^{-1}). This partly reflects the pattern of SS loss, but also reflects the topsoil P values, which were low at Loddington compared to the other sites, and were higher at Old Hattons due to previous applications of sewage sludge. Losses of TP at Rosemaund in PE0111 were much lower at 0.08-0.17 kg ha^{-1} for tramline areas, and 0.004-0.03 kg ha^{-1} for areas without tramlines, reflecting the lower runoff and SS losses. Values recorded in PE0203 for TP loss were more similar, at 0.04-0.55 kg ha for sandy soils, 0.04-0.8 kg ha^{-1} for soils over chalk, and 0.03-0.15 kg ha^{-1} for clay soils.

Mean concentrations of sediment in runoff were higher for the erosive sandy soils at Old Hattons than for the other sites (3319 mg l^{-1} compared to 2680 mg l^{-1} at Rosemaund, and 894 mg l^{-1} at Loddington), and the same pattern was also observed for TP concentrations (Rosemaund 3.46 mg l^{-1}, Old Hattons 10.0 mg l^{-1}, Loddington 1.37 mg l^{-1}). These values are similar to those in the literature; SS concentrations for Rosemaund reported in PE0111 ranged between 854 mg l^{-1} and 3036 mg l^{-1}, and mean TP concentrations were between 0.52 mg l^{-1} and 2.31 mg l^{-1}. Values reported in PE0203 for SS losses were 1300 mg l^{-1} to 4300 mg l^{-1} for the greensand, 2800 mg l^{-1} to 4600 mg l^{-1} for the chalk, and 700 mg l^{-1} to 3300 mg l^{-1} for the clay sites used in PE0203, while TP concentrations were 1.1 mg l^{-1} to 3.6 mg l^{-1}, 1.6 mg l^{-1} to 3.4 mg l^{-1} and 1.4 to 3.2 mg l^{-1} respectively.

Losses of P from cereal fields in this project were principally particulate (overwinter means for the proportion of TP as PP for each treatment were 71-95% for Rosemaund, 88-98% for Old Hattons, and 58-95% for Loddington), although there was greater variability for the clay site. Therefore treatments which reduce erosion, either by reducing detachment through rainsplash, by reducing runoff and sediment transport through increased infiltration or storing of water on the soil surface, or by trapping particulate material on the hillslope by promoting deposition, all have potential for reducing sediment and diffuse pollution losses from winter-sown combinable crops.

9.2. Tramline management

9.2.1. Importance of tramlines

The results of the field trials indicate that at all three of the study sites, most surface runoff, fine sediment and P was transported down in-field tramlines rather than from the vegetated areas between tramlines. These hillslope-scale results support the findings of NT1033 and PE0111 at Rosemaund, and those of Withers *et al.* (2006) in the Hampshire Avon catchment, and provide strong evidence of the need for forms of practical tramline management which can be targeted to reduce pollution losses from cereal fields. The difference in sediment and nutrient loads from tramline areas compared to no-tramline (i.e. conventionally drilled) areas was highly significant for each year and for each site ($p<0.01$), but the importance of the tramlines as a transport pathway varied between the three sites. In years 1 and 2, at Rosemaund, on silty-clay-loam soils, SS and TP losses from tramlines were up to 300 times greater, and at Old Hattons on coarser sandy soils, SS and TP losses were between five and 30 times greater, than from areas without tramlines. At Loddington, on heavy clay soils in year 3, SS and TP losses from tramline areas were between two and five times greater than from areas without tramlines. The absolute magnitude of losses from tramlines varied by site and by year, but results indicated that tramlines consistently represented the dominant surface transport pathway for runoff and associated pollutants.

The importance of tramlines is due to two factors. Firstly, the compaction effect of farm traffic reduces the bulk density and porosity of tramline soils and results in reduced infiltration in tramline areas. Secondly, the lack of vegetation cover means that rainfall and sediment cannot be intercepted in these areas, and reduced surface roughness leads to increased runoff velocities and an increase in the mass of transported material. The net effect of both the compaction and lack of vegetation cover is a build-up and channeling of runoff, which can gather momentum as it moves downslope and which therefore has a relatively high capacity to erode and transport entrained material. Visual observation of the offset tramline areas at Old Hattons indicated that runoff down tramlines resulted predominantly from compaction as opposed to lack of vegetation cover.

Tramlines are pathways for runoff, and their zone of influence can also extend beyond the tramline area. Results of the initial tracer experiments undertaken in this project show that at the Loddington site on clay soils, material can enter the tramline from as far as 4 m away, although the contributing area is likely to depend on the slope characteristics and existence of small-scale topographical features resulting from tillage and other management practices.

At Rosemaund and Old Hattons, runoff volumes were consistently and significantly ($p<0.01$) larger from tramline areas, compared to areas without tramlines, in all four site-years when comparisons were made. Concentrations of SS and TP in runoff were also consistently and significantly greater ($p<0.05$) for the tramline areas compared to areas without tramlines, except at Old Hattons in year 2 for SS. However, at the Loddington site, although tramlines significantly ($p<0.01$) increased runoff and SS and TP loads relative to areas without tramlines, there was no significant effect on concentrations of SS and TP in runoff. There is therefore no evidence to suggest that the importance of tramlines at Loddington is due to increased erosion and transport within the tramlines. The differences between the sites reflect the different soil types, and the cohesiveness of the clay soil in comparison to the sand and silty-clay-loam soils at the other two sites.

9.2.2. Tramline disruption

At Rosemaund in year 1 and year 2, losses of sediment and P from areas containing tramlines which were disrupted using a simple tine were significantly ($p<0.01$) and consistently reduced to close to 'background' levels from conventional tramline areas. This mitigation effect was also significant at Old Hattons in years 2 and 3. Disrupting compacted tramlines in these four site-years was able to reduce runoff by 69-97%, losses of SS by 75-99% and losses of TP by 72-99%, compared to losses from the conventionally wheeled tramlines. In the fifth site-year, on the silty soils at Rosemaund under low winter rainfall conditions, disruption using a simple tine increased tramline losses of runoff by at least 40%, and more than doubled losses of SS and TP. Reducing the compaction in tramlines by disrupting them using a simple tine is likely to have been successful in four out of five site-years, because disruption allowed greater infiltration of rainfall (by removing compaction in the near-surface zone) and greater surface water storage (associated with increased surface roughness). The potential for surface erosion and associated pollutant transport processes was therefore reduced.

Although an expensive treatment when considered at the experimental field scale (between £18 and £38 ha^{-1}), tramline disruption at the farm scale, assuming a work rate of between 5 and 10 ha hr^{-1} per hour depending on soil type and 24 m tramline spacing, is associated with a only a small cost of between £2 and £4 per ha. The importance of tramline losses as demonstrated in this report means that some form of tramline management would be a very effective way to reduce sediment and P losses from arable land under combinable crops. The potential effectiveness of the tramline disruption treatment undertaken once in the autumn, in combination with its relatively low cost at the farm scale, means that disruption of tramlines has considerable potential as a mitigation option. However, the type of disruption equipment required may vary for different soil types and conditions, and operationalising tramline management solutions now requires further work (see Section 9.6). This may include developing an engineering solution whereby a tramline disruptor could be attached to a sprayer so that a separate pass for disruption is not required. Tramline disruption may also be less effective in some tillage systems, for example under minimum tillage where the soil bulk density and associated hydraulic properties in the compacted tramline wheeling may not differ markedly from those of the surrounding vegetated soil area.

9.3. Tillage treatments and residue management

Minimum tillage was effective at Loddington in years 2 and 3, reducing runoff losses by 36-62%, SS losses by 47-62% and TP losses by 34-52%, for soils cultivated up-and-down the slope. These reductions were significant in year 2. These results support the findings of the EU-LIFE SOWAP project, where practicing conservation tillage reduced soil loss by up to 98%, and TP and TN losses were also reduced compared to ploughing (see www.sowap.org/results/soilandwater.htm). In year 1, where runoff, SS and TP losses increased by two to three times under minimum tillage the minimum-tillage area was pressed before drilling, which may have compacted the surface soil and destroyed some of the soil structure usually preserved under reduced cultivation. The effect of minimum tillage in improving soil structure and permitting drainage through macropores may therefore not have been operational in year 1. On sandy soils at Old Hattons in year 3, minimum tillage proved highly effective (p<0.01) in reducing runoff, and diffuse pollution losses compared to traditional plough cultivation by 66-98%. However, the effectiveness of the minimum tillage treatments at Loddington and Old Hattons contrasts with results from the heavier textured Rosemaund site in year 3, where minimum tillage was not effective. These results should be considered in the context of only six events monitored in a relatively dry winter monitoring period (161 mm), during which the absolute magnitude of all losses was low. Results from other studies considering the effectiveness of different cultivation treatments also show high variability in event data (e.g. Quinton *et al.*, 2001), and it is often difficult to draw robust conclusions regarding treatment effects when absolute losses are low.

Minimum tillage significantly reduced losses of runoff, SS and P in three site-years out of five, and the effectiveness of minimum tillage is dependent on autumn cultivation conditions and farm management operations. The figures reported here are much greater than those reported in the DWPA manual (Cuttle *et al.*, 2007), where the soil component of P loss is estimated to result in only a 5% reduction of the soil component of P loss from clay loam soils. In addition, the DWPA manual assumes that the method is not applicable to sandy loam soils, but the results presented here indicate that minimum tillage can be effective even on very light sandy soils.

The results of this project show that minimum tillage is associated with increased cost savings at the farm scale of £44 to £50 ha^{-1}, although this figure does not include the costs of purchasing equipment, but assumes the change in cultivation will be made when new equipment needs to be replaced, or that equipment will be owned cooperatively. These cost estimates are well within the range reported in the DWPA manual (£30 to £50 ha^{-1}). Disadvantages of minimum tillage to the farmer are increased weed burdens and pest and disease problems, giving rise to increased agro-chemical costs, and potential problems with soil compaction. Compaction is frequently overcome with a form of sub-soiling or ploughing operation undertaken one year in four or one year in five. At Loddington, where minimum tillage was trialled for all of the three project years, additional cultivation to counteract compaction did not take place, so the cost of this is not reflected in the rotational margin. Guidance provided by the Environment Agency (2003) suggests minimum tillage may generate savings of £10-£25 ha^{-1}. Taking into account the potential effectiveness and potential cost savings of minimum tillage, it is a recommended mitigation treatment for arable land under combinable crops where appropriate.

The data from Old Hattons in year 1 suggest that shallow incorporation of crop residues may be an effective mitigation option, reducing SS and TP losses by 34-50%, and it is likely that this was due to the increased surface cover, which may also have contributed to the effectiveness of minimum tillage in reducing SS and P losses at Loddington. Chopping and incorporation of straw may be the default practice where there is no ready use or market for baled straw, and may incur little cost to the farmer when undertaken as part of normal harvesting and subsequent crop establishment practices. Costs arise through lost revenue when there is a market for the straw, and where chopping is undertaken as a separate operation to harvesting (£25 ha^{-1}). Furthermore, there may be other impacts associated with moving to straw incorporation, although improved organic matter content may give rise to improved yields, it may also result in increased weed and disease problems. The DWPA manual does not explicitly cover residue incorporation, but refers to it as a possible cover crop, where the cover effect would be expected to reduce the soil component of P loss by 25-30%. The results reported here indicate that this figure may be higher (34-50%) on sandy soils which are susceptible to erosion due to poor soil structure.

9.4. *Cultivation direction and vegetative barriers*

Losses from the mixed-direction tillage treatment, where ploughing and drilling were conducted up-and-down the slope, and rolling and all subsequent operations were conducted on the contour, were between four and 20 times greater than from standard up-and-down slope cultivation. It is thought that these results are due to the different cultivation directions altering local topography and affecting runoff pathways on the hillslope. The effects of this cultivation are discussed in more detail in Stevens *et al.* (Submitted).

Cultivation on the contour under traditional ploughing was an effective mitigation treatment on the clay soils at Loddington in both the years it was trialled, reducing TP losses by 48-79%, which is higher than the figure of 25-35% reported in the DWPA manual, although this effect was only significant in year 2. Contour cultivation is likely to be only associated with a small cost, for example, D'Arcy and Frost (2001) suggest extra costs associated of £5 ha^{-1}, while the DWPA manual reports costs of £3 ha^{-1}, due to a slower work rate in operations on the contour. If farmer resistance can be overcome, contour cultivation has the potential to be an effective mitigation option on the shallow to moderate uniform slopes where it can be implemented, although contour cultivation needs to be undertaken carefully to avoid concentrating runoff in hillslope hollows and promoting rill and gully erosion.

Including a 2 m wide vegetative barrier on the contour can reduce losses by a further 9-97%, which suggests reductions may be higher than the 40% reduction in soil P loss reported in the DWPA manual. The effectiveness of the barrier at Loddington is likely to be due to both the trapping effect of the raised, vegetated barrier, and the reduction in slope length. At Loddington slope length contributing to the runoff gutter was reduced by 63%, from 68 m to 25 m. Results reported here indicate that vegetative strips are associated with only a small cost of £2 to £5 ha^{-1}, although a maintenance cost of £21 ha^{-1} is also applicable to the area of the barrier. At Loddington the barrier represented only 1% of the 8 ha field area, which represents an additional annual cost of around £2, and the results suggest that beetle banks are likely to be effective with only small areas of the field taken out of production. This is in contrast to the DWPA manual, which assumes a much greater area of the farm is put into barriers (10%), and so calculates a much higher figure of £32 ha^{-1}, as more land is taken out of production, and ongoing maintenance costs increase. As vegetative strips may have further biodiversity benefits, and promote cultivation on the contour and so combine two mitigation treatments, in-field vegetative barriers are therefore recommended as a mitigation option where their use is preferred by the farmer. However, in-field barriers may also cause inconvenience, and many farmers may not wish to take up this option. In addition, as for contour cultivation, the length and placement on the contour of the vegetative barrier must be carefully considered if it is to be effective at field scale. Observational evidence from Loddington suggests that runoff trapped by the beetle bank may have been channelled around the end of the barrier.

9.5. *Treatment interactions*

Field trials of combinations of different treatment options has allowed assessment of the effectiveness of different treatments when they are applied to hillslopes which are not cultivated under traditional plough cultivation up-and-down the slope. The results reported in this project suggest that there are interactions between some of the treatments. There was no significant interaction between the residue treatments and the tramline treatments at Old Hattons in year 1, which suggests that residue treatments could be applied in addition to tramline management mitigation options to further reduce runoff, sediment and P losses. Minimum tillage appears to reduce the effectiveness of contour cultivation under some conditions. There was a significant interaction effect ($p<0.05$) between minimum tillage and tramline disruption at Rosemaund in year 3 for runoff, and the cultivation-disruption interaction effect was also significant for Old Hattons for runoff, SS and TP ($p<0.01$) in year 3, although it did not affect the significance of the different treatments at these sites. Cultivation on the contour under minimum tillage was only effective in one of the two years this treatment was trialled (year 2), and the minimum tillage effect in year 3 meant that contour cultivation did not significantly reduce runoff and diffuse pollution losses compared to standard up-and-down slope cultivation. In year 2, losses of TP decreased by 48%

under contour cultivation, but in year 3 losses of TP were nearly four times greater for areas under contour cultivation than for traditionally ploughed areas. It appears that contour cultivation is more effective under traditional plough cultivation than under minimum tillage, and that the two treatments may interact to produce detrimental increases in runoff and erosion under certain conditions. It is possible that the observed increases in losses were specific to the design of the mitigation trials, but without further study it is not possible to explain the interaction effect. As each of these mitigation treatments is separately effective under different conditions, it is not recommended that they be applied in combination without further trials.

9.6. Further work

The following further work is planned:

- Improving the evidence base for diffuse pollution mitigation: A follow-on project (MOPS2, WQ0127) will address further aspects of diffuse pollution mitigation which have not been covered in MOPS 1. There are two aspects to the work. The first aspect is to investigate the use of farm ponds and wetlands to control agricultural diffuse pollution losses from both surface runoff and from tile drains inputs to streams at a range of sites across the UK. The second aspect of the work is to consider in-field mitigation options for spring-sown crops such as potatoes.
- Operationalising tramline management options for controlling diffuse pollution: A Sustainable Arable LINK project will focus on operationalising options for tramline management following on from the promising ‘proof of concept’ tramline disruption results obtained within MOPS 1. This work is currently planned with a broad consortium involving farming and engineering partners, which is essential to ensure engagement with the agricultural industry so that all practical and agronomic issues are adequately considered.

We also recommend that Defra consider funding future research into:

- Exploiting MOPS 1 data: Modeling tools used for policy support are only as good as the underlying parameters and functions contained within the models. Data generated by projects such as PEDAL (PE0113), BUFFERS (PE0205) and MOPS 1 can be used to help define key parameters and develop/refine specific functions for use in scenario modelling to explore the effect of implementing mitigation measures at field and catchment scale. The data can also be used in policy support tools such as the PSYCHIC model (Davison *et al.*, 2008) and EUROSEM (Morgan *et al.*, 1998). The MOPS dataset also provides an excellent resource for the evaluation of models allowing estimates of uncertainty to be placed around model predictions.
- In-field mitigation of subsurface pathways: This is difficult since at present little is known about the risk factors, sources and mobilisation mechanisms for subsurface soil loss, and about the mechanisms by which sediment and pollutants reach subsurface drains. As a result it is difficult to propose appropriate in-field mitigation measures. In addition, it is not clear whether reducing surface losses means that incident rainfall is still transferred to the stream by an alternative subsurface pathway (e.g. via drainflow). There is therefore a need to support work of a more fundamental nature in this area, which can underpin the development of new mitigation measures for use within the field.
- Scaling-up mitigation trials: We have demonstrated in MOPS 1 that many mitigation measures can be effective at the hillslope scale. However, for certain measures, particularly the use of tramline disruption, contour cultivation and vegetative barriers where the practicalities of imposing the mitigation measure may cause it to be ineffective, there is a need to evaluate their success at the farm scale.

10. Conclusions

Field monitoring over three years and on three different soil types, together with the development of simple spreadsheet models, has allowed the cost-effectiveness of different mitigation treatments to be assessed. In terms of the impact on yield, fertiliser and agro-chemical applications, field records from the three years show that no differences occurred as a result of the implementation of the mitigation options.

The results suggest that minimum tillage has the potential to reduce runoff, sediment and P losses from arable land under combinable crops by 4-98%, if establishment conditions are favorable. Aside from the initial high capital investment, minimum tillage is associated with high ongoing annual cost savings of £44-50 ha^{-1}, and rising fuel costs may encourage more farmers to consider this option. Contour cultivation, with limited applicability, is likely to be more costly, due to reduced work rates and an associated increase in costs. However, contour cultivation has been shown to be effective in two years of monitoring, reducing SS and P losses by 45-79%. Promotion of cultivation on the contour is also one of the major benefits of using in-field contour vegetative barriers, and results suggest that for a small cost of approximately £2 to £5 ha^{-1}, further reductions in SS and P loss of 9-97% can be realised, although at some inconvenience to the farmer. Residue management may not be as cost-effective a mitigation treatment as the other options identified, especially as the crop residue treatment did not show statistically significant effects when compared to straw baling and removal.

Tramlines are important pathways of runoff, sediment and associated nutrient transfer on arable land under combinable crops, with measured losses of SS and TP from tramline areas between two and 300 times greater than losses from vegetated areas without tramlines, depending on soil type and conditions. Tramline management treatments such as tramline disruption, which can be achieved for a low cost of £2-4 ha^{-1} assuming 24 m tramline spacing and a 3-5 yr rotation, therefore have the potential to be attractive mitigation options. Tramline disruption reduced losses of SS and TP by 72-99% in four out of the five site-years in which it was trilled on silty-clay loam and sandy-loam soils.

Tramline disruption was ineffective in one of the five site-years in which the treatment was trialled, hence the type of disruption required is likely to be specific to soil type and antecedent moisture conditions at the time of the tramline disruption activity. The tine used here to demonstrate ‘proof of concept’ may not be well-suited to more medium and heavy soil textures, and different tramline disruption methods may be required for different soil types and tillage systems. Further work is now required to investigate the most suitable method of operationally managing tramlines and to quantify how the effects of tramline management are affected by soil physical properties.

Within the project, the success of all of the mitigation options depended to a large extent on farmer attitude and willingness to implement each option. The uptake and success of each of the options at farm scale also depends to some extent on farmer perceptions, adoption costs (e.g. equipment, training), potential risks (e.g. on disease, pests, yield), and how mitigation management practices can be practically and cost-effectively integrated into conventional farming operations.

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12. References

Bartram J and Balance R, 1996. *Water Quality Monitoring; A practical guide to the design and implementation of freshwater quality studies and monitoring programmes. UNEP/WHO publication.* TJ Press Ltd, Cornwall.

Bradford JM and Huang CH, 1994. Interrill soil erosion as affected by tillage and residue cover. *Soil & Tillage Research* **31**: 353-361.

Catt JA, Quinton JN, Rickson RJ and Styles PDR, 1994. Nutrient losses and crop yields in the Woburn Erosion Reference Experiment. In *Conserving soil resources: European perspectives*. Rickson RJ (Editor). CAB International, Wallingford, United Kingdom: pp. 94-104.

Chambers BJ, Davies DB and Holmes S, 1992. Monitoring of water erosion on arable farms in England and Wales: 1989-1990. *Soil Use and Management* **8**: 163-170.

Chambers BJ and Garwood TWD, 2000. Monitoring of water erosion on arable farms in England and Wales. 1990-94. *Soil Use and Management* **16**(2): 93-99.

Chapman AS, Foster IDL, Lees JA and Hodgkinson RA, 2005. Sediment delivery from agricultural land to rivers via subsurface drainage. *Hydrological Processes* **19**(15): 2875-2897.

Clarke S and Wharton G, 2001. Sediment nutrient characteristics and aquatic macrophytes in lowland English rivers. *The Science of the Total Environment* **266**: 103-112.

Collins A, Walling D and Leeks G, 2005. Storage of fine-grained sediment and associated contaminants within the channels of lowland permeable catchments in the UK. In *Sediment Budgets 1. IAHS Publication No. 291*. DE W and A H (Editors). IAHS Press, Wallingford: pp. 259-268.

Collins AL and Walling DE, 2004. Documenting catchment suspended sediment sources: problems, approaches and prospects. *Progress in Physical Geography* **28**(2): 159-196.

Cuttle SP, Macleod CJA, Chadwick DR, Scholefield D, Haygarth PM, Newell-Price P, Harris D, Shepherd MA, Chambers BJ and Humphrey R, 2007. *An Inventory of Methods to Control Diffuse Water Pollution from Agriculture. DWPA User Manual.* Defra London

D'Arcy B and Frost A, 2001. The role of best management practices in alleviating water quality problems associated with diffuse pollution. *The Science of the Total Environment* **265**: 359-367.

Dabney SM, Liu Z, Lane M, Douglas J, Zhu J and Flanagan DC, 1999. Landscape benching from tillage erosion between grass hedges. *Soil and Tillage Research* **51**(3-4): 219-231.

Davison PS, Withers PJA, Lord EI, Betson MJ and J S, 2008. PSYCHIC - A process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments. Part 1: Model description and parameterisation. *Journal of Hydrology* **350**: 290-302.

Deasy C, 2007. *Effects of Scale on Phosphorus Transfer in Small Agricultural Catchments*. PhD Thesis, University of Sheffield, June 2007

Defra, 2002. *Agriculture and water: a diffuse pollution review*Department for Environment, Food and Rural Affairs, London

Defra, 2006. The June Agricultural Survey [online]. Available at: http://farmstats.defra.gov.uk/cs/farmstats_data/DATA/soa_data/repop_query.asp. Accessed 31 July 2006.

Dickey EC, Shelton DP and Jasa PJ, 1986. *Residue mangement for soil erosion control*, University.

EA, 2003. *Best Farming Practice: Profiting from a Good Environment. R&D Publication 23.* Environment Agency, Bristol

Edwards AC and Withers PJA, 1998. Soil phosphorus management and water quality: a UK perspective. *Soil Use and Management* **14**: 124-130.

Environment Agency, 2000a. *Aquatic eutrophication in England & Wales: Management strategy*, University, Bristol, UK.

Environment Agency, 2000b. *Focus on biodiversity*, University, Bristol, UK.

European Commission, 2001. *Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000, establishing a framework for Community action in the field of water policy.* Official Journal L 327 of 22.12.2001,

Farm Business Survey, 2007a. Crop production in England 2005/2006. Rural Business Unit, Department of Land Economy, University of Cambridge.

Farm Business Survey, 2007b. Government Office Region Reports 2006/07 [online]. Rural Business Research. Available at: www.farmbusinesssurvey.co.uk/regional/index.asp. Accessed 27 March 2008.

Farmers Weekly, 2006a. Markets: Grain, Oilseeds and Pulses. Farmers Weekly, 27 October 2006, p123.

Farmers Weekly, 2006b. Markets: Grain, Oilseeds and Pulses. Farmers Weekly, 3 November 2006, p127.

Farmers Weekly, 2007a. Markets: Grain, Oilseeds and Pulses. Farmers Weekly, 26 October 2007.

Farmers Weekly, 2007b. Markets: Grain, Oilseeds and Pulses. Farmers Weekly, 2 November 2007.

Farmers Weekly Interactive, 2007. Prices and Trends [online]. Available at http://www.fwi.co.uk/Prices/Prices.aspx?sPage=List&pList=front. Accessed March 2007.

Heathwaite AL, Quinn PF and Hewett CJM, 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. *Journal of Hydrology* **304**(1-4): 446-461.

Kronvang B, Jeppesen E, Conley DJ, Søndergaard M, Larsen SE, Ovesen NB and Carstensen J, 2005. Nutrient pressures and ecological responses to nutrient loading reductions in Danish streams, lakes and coastal waters. *Journal of Hydrology* **304**(1-4): 274-288.

Leeds-Harrison PB, Quinton JN, Walker M, Harrison KS, Gowing DG, Tyrrel SF, Morris J, Mills J and Harrod T, 1996. *Buffer zones in headwater catchments. MAFF-English Nature Buffer Zone project CSA 2285*, University.

Ligdi EE and Morgan RPC, 1995. Contour grass strips: a laboratory simulation of their role in soil erosion control. *Soil Technology* **8**(2): 109-117.

McDowell R, Sharpley A and Folmar G, 2001a. Phosphorus export from an agricultural watershed: Linking source and transport mechanisms. *Journal Of Environmental Quality* **30**(5): 1587-1595.

McDowell RW, Sharpley AN, Condron LM, Haygarth PM and Brookes PC, 2001b. Processes controlling soil phosphorus release to runoff and implications for agricultural management. *Nutrient Cycling In Agroecosystems* **59**.

Morgan RPC, 2005. *Soil Erosion and Conservation*. Blackwell, Oxford, 304 pp.

Morgan RPC, Quinton JN, Smith RE, Govers G, Poesen JWA, Auerswald K, Chisci G, Torri D and Styczen ME, 1998. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms* **23**(6): 527-544.

Moss B, Stephen D, Alvarez C, Becares E, Van De Bund W, Collings S, Van Donk E, De Eyto E, Feldmann T, Fernández-Aláez C, Fernández-Aláez M, Franken R, García-Criado F and Gross E, 2003. *The determination of ecological status in shallow lakes - a tested system (ECOFRAME) for implementation of the European Water Framework Directive*,

Murphy J and Riley JP, 1962. A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* **27**: 31-36.

Nix J, 2005. *Farm Management Pocketbook 36th Edition*. Imperial College London, Wye Campus. The Andersons Centre.

O'Dell J, 1993. *Determination of Phosphorus by Semi-Automated Colorimetry. Method 365.1*. US Environmental Protection Agency, Ohio.

Pierzynski GM, Sims JT and Vance GF, 2000. *Soils and environmental quality*. CRC Press, Boca Raton, Florida, 424 pp.

Quinton JN and Catt JA, 2004. The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Soil Erosion Experiment on a sandy soil in England. *Soil Use and Management* **20**: 343-349.

Quinton JN and Catt JA, 2007. Enrichment of Heavy Metals in Sediment Resulting from Soil Erosion on Agricultural Fields. *Environ. Sci. Technol.* **41**(10): 3495-3500.

Quinton JN, Catt JA and Hess TM, 2001. The selective removal of phosphorus from soil: Is event size important? *Journal of Environmental Quality* **30**(2): 538-545.

Robinson DA and Naghizadeh R, 1992. The impact of cultivation practice and wheelings on runoff generation and soil erosion on the South Downs: some experimental results using simulated rainfall. *Soil Use and Management* **8**: 151-156.

Rowland AP and Grimshaw HM, 1985. A wet oxidation procedure suitable for total nitrogen and phosphorus in soil *Communications in Soil Science and Plant Analysis* **16**: 551.

Russell MA, Walling DE and Hodgkinson RA, 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. *Journal of Hydrology* **252**(1-4): 1-24.

Schreiber JD, 1999. Nutrient leaching from corn residues under simulated rainfall. *Journal of Environmental Quality* **28**: 1864-1870.

Schwab GO, Fangmeier DD and Elliot WJ, 1996. *Soil and Water Management Systems*. John Wiley and Sons, New York.

Sharpley AN, 1980. The enrichment of soil phosphorus in runoff sediments. *Journal of Environmental Quality* **9**: 521-526.

Sharpley AN, Foy RH and Withers PJA, 2000. Practical and innovative measures for the control of agricultural phosphorus losses to water. An Overview. . *Journal of Environmental Quality* **29**: 1-9.

Shepherd MA and Smith KA, 2002. *Integrating organic amendments as nutrient sources in arable crop rotations. Final project report, Defra SAPPIO LINK research programme (LK0904, HGCA1674).* Defra, London

Silgram M and Chambers BJ, 2002. Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. *Journal of Agricultural Science* **139**: 115-127.

Stevens CJ and Quinton JN, 2008. Investigating source areas of eroded sediments transported in concentrated overland flow using rare earth element tracers. *Catena* **74**(1): 31-36.

Stevens CJ, Quinton JN, Bailey AP, Deasy C, Silgram M and Jackson B, Submitted. The effects of minimal tillage, contour cultivation and in-field vegetative barriers on phosphorus and sediment yields. *Soil and Tillage Research*.

Tyrrel SF and Quinton JN, 2003. Overland flow transport of pathogens from agricultural land receiving faecal wastes. *Journal of Applied Microbiology* **94**: 87S-93S.

White PJ and Hammond JP, 2006. *Updating the estimates of the sources of phosphorus in UK waters. Defra Final Report for Project WT0701CSF.* Available at: http://randd.defra.gov.uk/Document.aspx?Document=WT0701CSF_4159_FRP.pdf. Accessed 19th July 2007.

Williams RJ, Brooke DN, Clare RW, Matthiessen P and Mitchell RDJ, 1996. *Rosemaund pesticide transport study 1987-1993*, University, Wallingford.

Withers PJ and Sharpley AN, 1995. Phosphorus Fertilizers. In *Soil Amendments and Environmental Quality*. Rechcigl JE (Editor). CRC Press, Boca Raton, Florida: pp. 65-107.

Withers PJA, Hodgkinson RA, Bates A and Withers CM, 2006. Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. *Soil Use and Management* **22**(3): 245-255.

Withers PJA and Jarvis SC, 1998. Mitigation options for diffuse phosphorus loss to water. *Soil Use and Management* **14**: 186-192.

Appendices

Appendix 1. Site plans
1.1. Rosemaund
1.2. Old Hattons
1.3. Loddington

Appendix 2. Data tables
2.1. Rosemaund data (a) year 1, (b) year 2 and (c) year 3
2.2. Old Hattons data (a) year 1, (b) year 2 and (c) year 3
2.3. Loddington data (a) year 1, (b) year 2 and (c) year 3
2.4. Comparison of overwinter mean treatment losses for the three field sites
2.5. Effect of treatments applied at the three sites on total carbon (TC) losses for events in year 3
2.6. Cropping area and operating margins, 2006, 2007 and 2008
2.7. Summary tables of effectiveness of each treatment

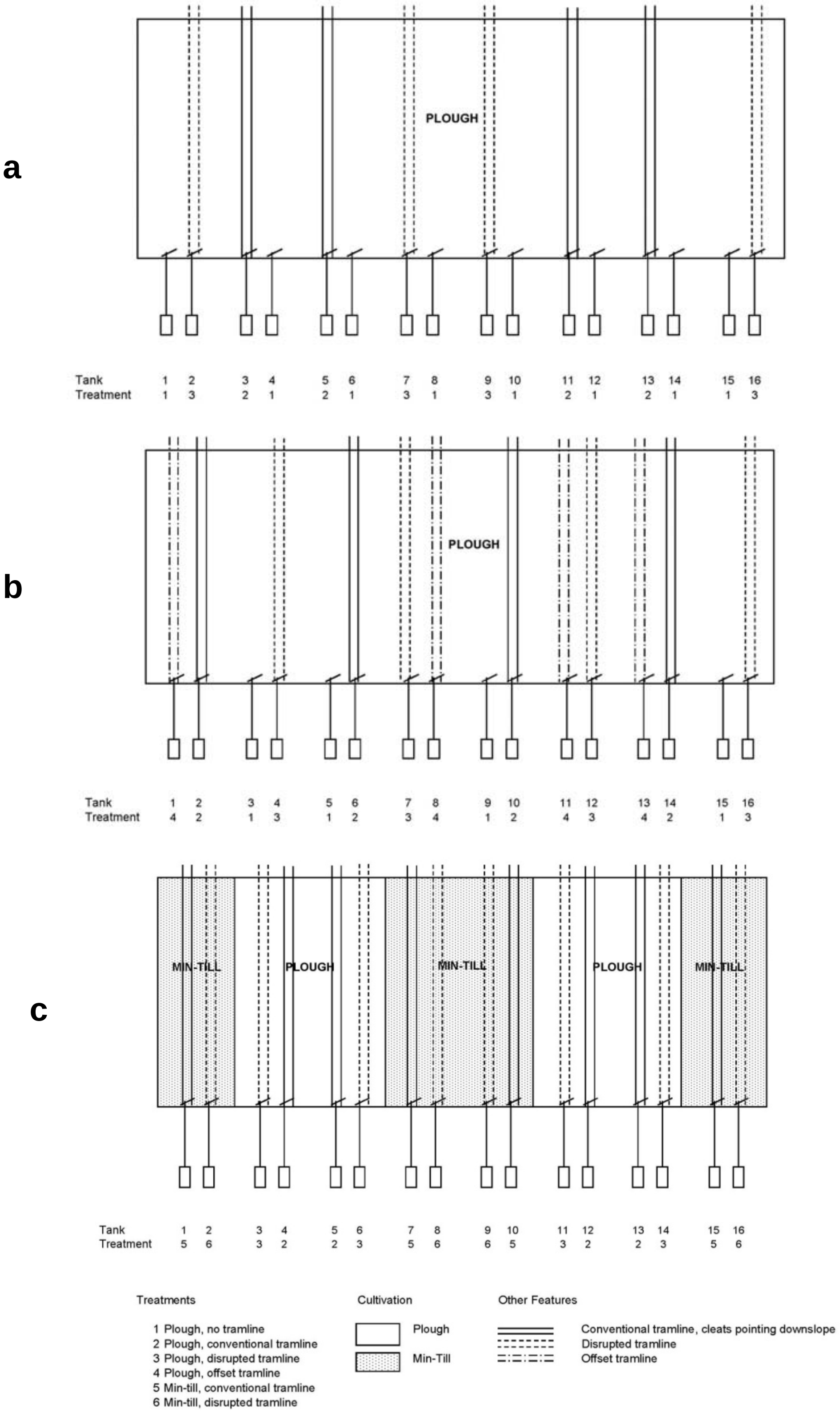
Appendix 3. Lists of publications and other outputs
3.1. Journal papers
3.2. Journal papers in preparation
3.3. Published conference papers
3.4. Unpublished conference papers
3.5. Poster presentations
3.6. Knowledge transfer

Appendix 4. Literature review

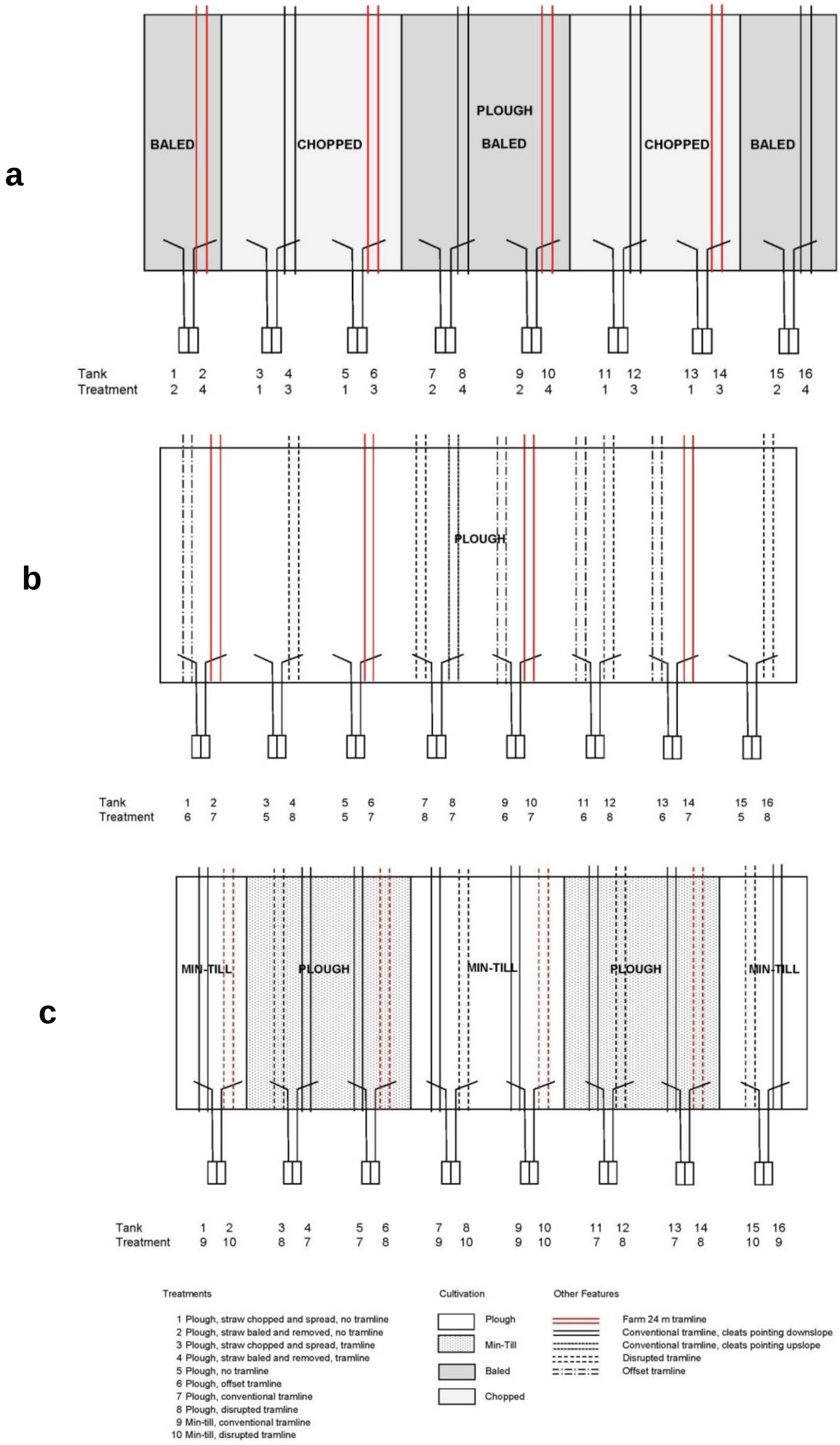
Appendix 5. Published papers
5.1. Journal papers
    5.1.1: Stevens and Quinton, 2008
    5.1.2: Stevens and Quinton, In press (a)
    5.1.3: Stevens and Quinton, In press (b)
5.2. Conference papers
    5.2.1: Bailey *et al.* 2007
    5.2.2: Bailey *et al.* 2007 (b)
    5.2.3: Deasy *et al.* 2008
    5.2.4: Quinton *et al.* 2007
    5.2.5: Silgram *et al.* 2007
    5.2.6: Stevens *et al.* 2006

Appendix 1. Site plans

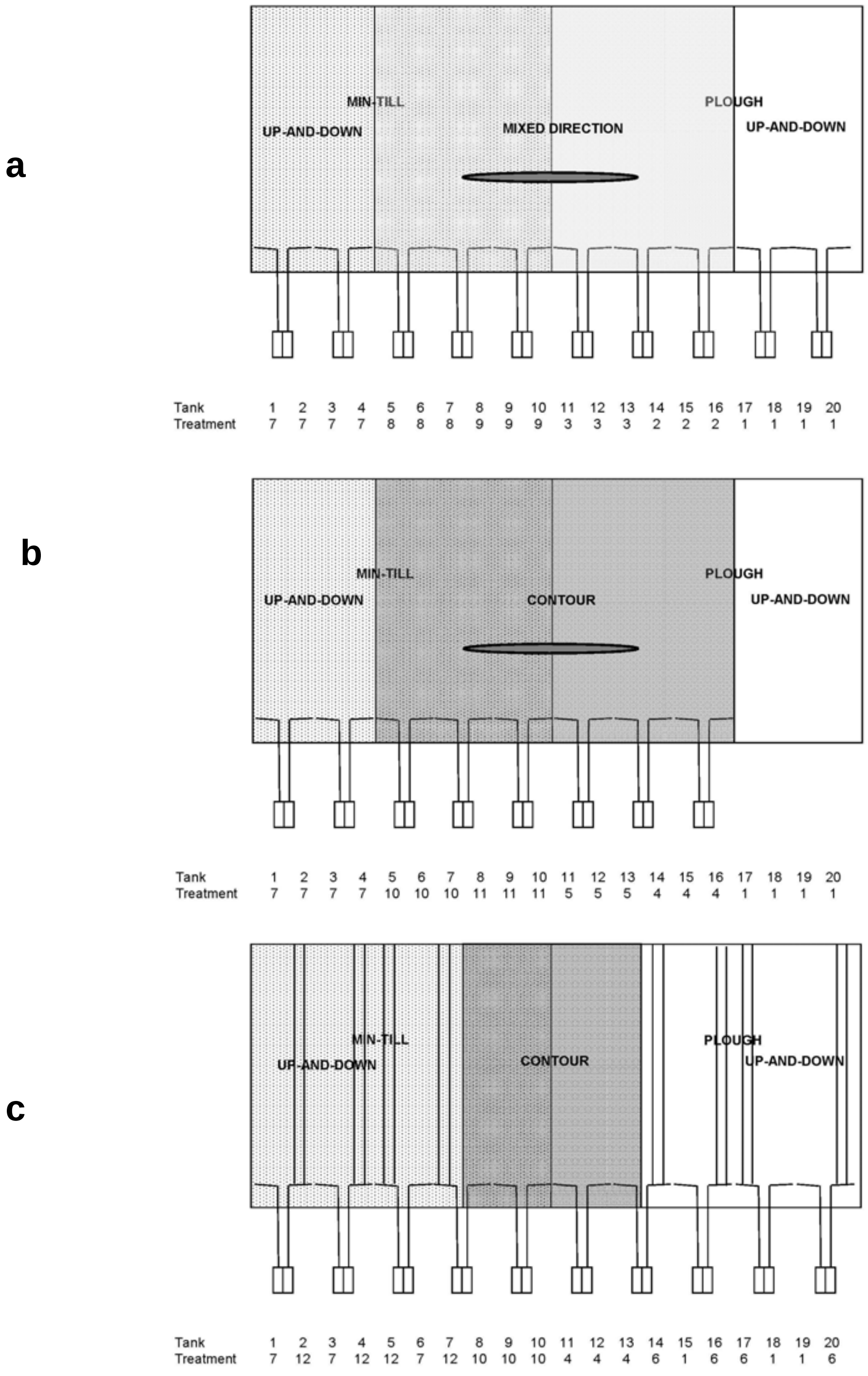
Appendix 1.1. Design of Rosemaund experimental treatments in (a) year 1, (b) year 2 and (c) year 3.



Appendix 1.2. Design of Old Hattons experimental treatments in (a) year 1, (b) year 2 and (c) year 3.



Appendix 1.3. Design of Loddington experimental treatments in (a) year 1, (b) year 2 and (c) year 3.



(a)

Tank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Treatment	7	7	7	7	8	8	8	9	9	9	3	3	3	2	2	2	1	1	1	1

(b)

Tank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Treatment	7	7	7	7	10	10	10	11	11	11	5	5	5	4	4	4	1	1	1	1

(c)

Tank	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Treatment	7	12	7	12	12	7	12	10	10	10	4	4	4	6	1	6	6	1	1	6

Treatments

1	Plough, up-and-down slope
2	Plough, mixed direction
3	Plough, mixed direction, beetle bank
4	Plough, contour
5	Plough, contour, beetle bank
6	Plough, tramline
7	Min-till, up-and-down slope
8	Min till, mixed direction
9	Min till, mixed direction, beetle bank
10	Min-till, contour
11	Min-till, contour, beetle bank
12	Min-till, tramline

Cultivation

☐	Plough
▨	Min-till
▨	Mixed direction
▨	Contour

Other Features

●	Beetle Bank
═	Tramline

Appendix 2. Data tables

Appendix 2.1. Results of treatments applied at Rosemaund in (a) year 1, (b) year 2 and (c) year 3. Data are treatment means of hillslope segment replicates for overwinter yields, and event means for concentrations/flow weighted mean concentrations. Tables show the significance of the treatment effect ($p<0.05$).

(a)

Year 1 Rosemaund		Treatment						
Variable		P		P TL		P DTL		*p*
		Mean	SEM	Mean	SEM	Mean	SEM	
Rainfall as runoff	%	0.5		11.3		0.5		
Runoff	mm	0.3	0.0	5.6	1.2	0.3	0.0	<0.01
SS	kg ha^{-1}	3	1	379	117	6	4	<0.01
TP	kg ha^{-1}	0.01	0.00	0.74	0.15	0.02	0.01	<0.01
TDP	kg ha^{-1}	0.001	0.000	0.020	0.003	0.001	0.000	<0.01
TN	kg ha^{-1}	0.03	0.01	1.36	0.33	0.06	0.02	<0.01
TDN	kg ha^{-1}	0.010	0.001	0.130	0.044	0.010	0.001	<0.01
SS	mg l^{-1}	876	258	7684	1808	1589	786	<0.01
TP	mg l^{-1}	3.5	0.5	13.6	1.7	6.0	1.3	<0.01
TDP	mg l^{-1}	0.29	0.04	0.34	0.02	0.39	0.06	N/S
TN	mg l^{-1}	11.1	1.3	26.6	4.7	16.9	3.2	<0.01
TDN	mg l^{-1}	2.9	0.3	2.3	0.3	3.4	0.3	N/S
PP as TP	%	90.8	1.5	97.4	0.2	91.6	3.0	N/S
PN as TN	%	72.8	1.6	91.4	2.8	77.0	5.3	0.01

(b)

Year 2 Rosemaund		Treatment								
Variable		P		P TL		P DTL		P OTL		*p*
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	
Rainfall as runoff	%	0.5		15.8		0.6		19.1		
Runoff	mm	2.0	0.3	78.1	4.8	2.7	0.6	94.7	3.6	<0.01
SS	kg ha^{-1}	21	7	4820	334	40	21	6360	411	<0.01
TP	kg ha^{-1}	0.01	0.00	2.93	0.12	0.04	0.02	3.74	0.14	<0.01
TDP	kg ha^{-1}	0.003	0.001	0.156	0.016	0.005	0.001	0.204	0.023	<0.01
TN	kg ha^{-1}	0.05	0.01	5.42	0.35	0.11	0.06	6.50	0.20	<0.01
TDN	kg ha^{-1}	0.030	0.003	1.370	0.092	0.050	0.026	1.630	0.137	<0.01
SS	mg l^{-1}	1070	295	6180	287	1215	467	6709	261	<0.01
TP	mg l^{-1}	0.7	0.1	3.8	0.1	1.1	0.4	4.0	0.0	<0.01
TDP	mg l^{-1}	0.10	0.01	0.20	0.02	0.20	0.01	0.20	0.02	N/S
TN	mg l^{-1}	2.3	0.2	7.0	0.4	3.4	1.0	6.9	0.2	<0.01
TDN	mg l^{-1}	1.3	0.1	1.8	0.1	1.6	0.4	1.7	0.1	N/S
PP as TP	%	81.0	3.6	95.0	0.5	80.0	6.5	95.0	0.5	0.01
PN as TN	%	46.0	2.9	75.0	2.0	52.0	1.4	75.0	2.3	<0.01

(c)

Year 3 Rosemaund		Treatment								p		
Variable		P TL		P DTL		MT TL		MT DTL				
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Cultivation (MT vs. P)	Disruption (DTL vs. TL)	Interaction*
Rainfall as runoff	%	0.9		1.2		1.0		3.4				
Runoff	mm	1.2	0.22	1.7	0.65	1.4	0.26	4.8	0.81	<0.01	0.01	0.04
SS	kg ha^{-1}	6	1.5	22	17.3	11	7.1	105	31.5	0.03	0.02	N/S
TP	kg ha^{-1}	0.01	0.002	0.03	0.020	0.02	0.008	0.12	0.035	0.03	0.02	N/S
TDP	kg ha^{-1}	0.002	0.001	0.004	0.002	0.004	0.002	0.014	0.005	0.01	N/S	N/S
TN	kg ha^{-1}	0.04	0.020	0.07	0.036	0.05	0.01	0.20	0.029	0.04	0.01	0.03
TDN	kg ha^{-1}	0.030	0.017	0.040	0.022	0.030	0.006	0.100	0.012	N/S	<0.01	0.01
SS	mg l^{-1}	444	44.4	842	391.0	618	300.5	2248	569 4	N/S	0.01	N/S
TP	mg l^{-1}	0.6	0.08	1.0	0.45	1.2	0.42	2.6	0.59	N/S	0.01	N/S
TDP	mg l^{-1}	0.10	0.03	0.20	0.06	0.40	0.22	0.30	0.04	N/S	N/S	N/S
TN	mg l^{-1}	3.1	0.83	3.4	0.78	3.8	1.01	4.2	0.31	N/S	N/S	N/S
TDN	mg l^{-1}	2.2	0.79	2.3	0.66	2.2	0.64	2.3	0.20	N/S	N/S	N/S
PP as TP	%	75.0	3.4	77.0	5.6	71.0	8.8	87.0	4.7	N/S	N/S	N/S
PN as TN	%	32.0	4.3	37.0	5.5	43.0	1.9	46.0	3.3	N/S	N/S	N/S

Appendix 2.2. Results of treatments applied at Old Hattons in (a) year 1, (b) year 2 and (c) year 3. Data are treatment means of hillslope segment replicates for overwinter yields, and event means for concentrations/flow weighted mean concentrations. Tables show the significance of the treatment effect ($p<0.05$).

(a)

Year 1 Old Hattons		Treatment								*p*		
Variable		P B		P B TL		P R		P R TL		Residue (R vs. B)	Tramline (TL)	Interaction
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM			
Rainfall as runoff	%	0.1		2.8		0.1		2.2		N/S	<0.00	N/S
Runoff	mm	0.4	0.0	8.4	1.2	0.2	0.1	6.4	1.2	N/S	<0.01	N/S
SS	kg ha^{-1}	21	3	499	57	12	5	299	82	N/S	<0.00	N/S
TP	kg ha^{-1}	0.06	0.01	1.52	0.23	0.03	0.01	1.00	0.24	N/S	<0.01	N/S
TDP	kg ha^{-1}	0.001	0.000	0.045	0.006	0.001	0.000	0.029	0.006	N/S	<0.01	N/S
TN	kg ha^{-1}	0.09	0.01	1.83	0.28	0.04	0.02	1.16	0.29	N/S	<0.01	N/S
TDN	kg ha^{-1}	0.006	0.001	0.157	0.031	0.004	0.001	0.078	0.013	N/S	0.05	N/S
SS	mg l^{-1}	5286	288	5994	234	5461	534	4517	430	N/S	N/S	N/S
TP	mg l^{-1}	15.8	0.5	18.1	0.5	14.1	1.4	14.9	0.7	N/S	<0.01	N/S
TDP	mg l^{-1}	0.25	0.05	0.54	0.03	0.23	0.03	0.42	0.01	N/S	N/S	N/S
TN	mg l^{-1}	22.2	1.8	21.8	1.3	19.7	1.7	16.5	1.2	N/S	N/S	N/S
TDN	mg l^{-1}	1.7	0.2	1.9	0.3	2.0	0.2	1.2	0.1	N/S	0.01	N/S
PP as TP	%	98.4	0.3	97.0	0.2	98.3	0.3	97.2	0.1	N/S	0.01	N/S
PN as TN	%	92.1	1.3	91.5	0.9	89.4	1.7	93.0	0.7	N/S	N/S	N/S

(b)

Year 2 Old Hattons		Treatment								
Variable		P		P TL		P DTL		P OTL		*p*
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	
Rainfall as runoff	%	1.0		5.5		1.7		3.5		
Runoff	mm	3.2	0.9	16.0	0.7	5.0	0.3	10.1	2.1	<0.01
SS	kg ha^{-1}	30	7	296	49	73	15	133	37	<0.01
TP	kg ha^{-1}	0.10	0.02	0.82	0.10	0.23	0.03	0.42	0.11	<0.01
TDP	kg ha^{-1}	0.010	0.001	0.030	0.002	0.010	0.001	0.020	0.005	<0.01
TN	kg ha^{-1}	0.11	0.02	1.12	0.12	0.29	0.06	0.48	0.15	<0.01
TDN	kg ha^{-1}	0.020	0.005	0.090	0.005	0.030	0.003	0.060	0.015	<0.01
SS	mg l^{-1}	991	80	1822	232	1455	249	1279	146	N/S
TP	mg l^{-1}	3.2	0.2	5.1	0.4	4.7	0.5	4.0	0.3	0.03
TDP	mg l^{-1}	0.20	0.03	0.30	0.02	0.20	0.02	0.20	0.02	N/S
TN	mg l^{-1}	4.2	1.0	7.0	0.5	5.9	1.2	4.7	0.8	0.03
TDN	mg l^{-1}	1.0	0.1	0.8	0.0	0.9	0.1	0.8	0.1	N/S
PP as TP	%	94.0	0.8	96.0	0.4	96.0	0.2	95.0	0.4	N/S
PN as TN	%	82.0	1.8	92.0	0.5	88.0	2.1	86.0	1.5	<0.01

(c)

Year 3 Old Hattons		Treatment								p		
Variable		P TL		P DTL		MT TL		MT DTL				
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Cultivation (MT vs. P)	Disruption (DTL vs. TL)	Interaction
Rainfall as runoff	%	4.5		1.3		2.0		0.3				
Runoff	mm	11.8	0.08	2.7	0.28	4.0	0.46	0.5	0.06	<0.01	<0.01	<0.01
SS	kg ha^{-1}	892	85.5	109	22	51	7.6	2	0.2	<0.01	<0.01	<0.01
TP	kg ha^{-1}	2.48	0.13	0.34	0.06	0.20	0.03	0.01	0.0004	<0.01	<0.01	<0.01
TDP	kg ha^{-1}	0.050	0.002	0.010	0.001	0.010	0.001	0.000	0.0001	<0.01	<0.01	<0.01
TN	kg ha^{-1}	1.07	0.14	0.16	0.03	0.14	0.03	0.01	0.001	0.01	<0.01	<0.01
TDN	kg ha^{-1}	0.080	0.001	0.020	0.003	0.030	0.003	0.010	0.001	<0.00	<0.01	<0.01
SS	mg l^{-1}	7226	716.8	3960	477.5	1300	114.2	538	46.6	0.01	<0.01	0.01
TP	mg l^{-1}	20.8	1.17	12.5	1.25	5.0	0.49	1.8	0.26	<0.00	<0.01	0.01
TDP	mg l^{-1}	0.40	0.02	0.40	0.03	0.30	0.01	0.20	0.03	0.01	0.02	N/S
TN	mg l^{-1}	9.1	1.21	0.6	0.60	3.5	0.26	2.8	0.31	0.02	<0.01	0.03
TDN	mg l^{-1}	0.7	0.01	0.9	0.03	0.8	0.04	1.6	0.1	<0.01	<0.01	0.01
PP as TP	%	98.0	0.1	97.0	0.2	95.0	0.4	88.0	1.0	<0.01	<0.01	<0.00
PN as TN	%	92.0	0.9	85.0	1.9	76.0	3.1	41.0	4.8	<0.01	<0.01	<0.01

Appendix 2.3. Results of treatments applied at Loddington in (a) year 1, (b) year 2 and (c) and (d) year 3. Data are treatment means of hillslope segment replicates for overwinter yields, and event means for concentrations/flow weighted mean concentrations. Tables show the significance of the treatment effect (*p*<0.05).

(a)

Year 1 Loddington		Treatment												*p*			
Variable		P		P MD		P MD BB		MT		MT MD		MT MD BB					
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Cultivation (MT vs. P)	Direction (MD)	Barrier (BB)	Interaction
Rainfall as runoff	%	0.6	0.1	3.4	2.0	0.4	0.1	1.3	0.2	4.8	0.2	1.7	0.9				
Runoff	mm	2.4	0.4	19.3	7.1	1.7	0.6	5.1	0.9	18.5	0.7	6.6	3.4	0.01	<0.01	<0.01	NS
SS	kg ha^{-1}	8	4	44	22	3	1	25	8	153	39	29	20	NS	<0.01	<0.01	NS
TP	kg ha^{-1}	0.02	0.01	0.47	0.01	0.01	0.00	0.07	0.02	0.33	0.07	0.09	0.05	0.02	<0.01	<0.01	NS
TDP	kg ha^{-1}	0.006	0.001	0.027	0.001	0.005	0.001	0.011	0.003	0.015	0.000	0.010	0.003	NS	<0.01	<0.01	NS
TN	kg ha^{-1}	0.3	0.1	3.0	1.4	0.1	0.0	0.8	0.3	4.2	0.5	0.6	0.4	<0.01	<0.01	<0.01	NS
TDN	kg ha^{-1}	0.3	0.1	2.3	1.3	0.1	0.0	0.7	0.2	3.8	0.6	0.5	0.4	0.01	<0.01	<0.01	NS
SS	mg l^{-1}	182	33	371	66	144	42	267	52	576	132	306	53	0.01	<0.01	<0.01	NS
TP	mg l^{-1}	0.71	0.09	1.81	0.30	0.80	0.16	1.35	0.21	1.72	0.28	1.32	0.19	<0.01	<0.01	<0.01	NS
TDP	mg l^{-1}	0.24	0.04	0.28	0.06	0.26	0.06	0.63	0.19	0.25	0.05	0.39	0.13	0.01	NS	NS	NS
TN	mg l^{-1}	5.05	1.17	9.35	1.65	4.35	1.03	8.90	1.68	11.94	2.39	6.93	1.41	0.01	0.01	<0.01	NS
TDN	mg l^{-1}	4.13	1.16	6.94	1.45	3.44	0.98	6.49	1.51	9.06	2.41	5.22	1.26	<0.01	NS	0.02	NS
PP as TP	%	62.1	4.9	76.2	4.3	66.3	3.1	58.0	4.3	79.7	5.8	70.8	8.4	NS	<0.01	NS	NS
PN as TN	%	25.5	1.51	29.1	1.49	30.8	5.82	28.6	1.2	34.8	4.5	29.6	1.1	NS	NS	NS	NS

(b)

Year 2 Loddington		Treatment												*p*			
Variable		P		P C		P C BB		MT		MT C		MT C BB					
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Cultivation (MT vs. P)	Direction (MD)	Barrier (BB)	Interaction
Rainfall as runoff	%	24.3	4.4	8.7	6.6	4.8	2.8	15.5	9.4	4.1	1.0	6.5	4.7				
Runoff	Mm	87.3	15.9	31.3	23.5	17.3	10.0	55.7	33.9	14.8	3.8	23.4	17.0	0.03	<0.01	NS	0.0
SS	kg ha^{-1}	1836	392	613	442	385	204	704	398	384	84	322	200	0.02	<0.01	NS	NS
TP	kg ha^{-1}	1.66	0.20	0.66	0.47	0.45	0.25	0.80	0.46	0.41	0.09	0.38	0.24	0.02	<0.01	NS	NS
TDP	kg ha^{-1}	0.032	0.005	0.010	0.007	0.007	0.003	0.022	0.014	0.005	0.001	0.011	0.008	0.02	<0.01	NS	NS
TN	kg ha^{-1}	3.6	0.5	1.3	1.0	0.9	0.5	2.7	1.6	0.9	0.2	0.9	0.6	NS	<0.01	NS	NS
TDN	kg ha^{-1}	0.9	0.1	0.3	0.2	0.2	0.1	0.9	0.5	0.1	0.0	0.2	0.2	NS	<0.01	NS	NS
SS	mg l^{-1}	1874	243	2171	313	1709	240	1283	192	2473	361	978	195	NS	NS	0.02	NS
TP	mg l^{-1}	1.77	0.24	2.54	0.35	2.10	0.28	1.51	0.22	2.91	0.44	1.23	0.21	NS	0.02	NS	NS
TDP	mg l^{-1}	0.04	0.00	0.06	0.01	0.09	0.02	0.09	0.02	0.07	0.01	0.07	0.01	NS	NS	NS	NS
TN	mg l^{-1}	3.96	0.40	4.63	0.52	4.76	0.47	4.69	0.48	5.77	0.63	2.99	0.51	NS	NS	NS	0.0
TDN	mg l^{-1}	1.03	0.25	1.06	0.18	1.31	0.19	1.64	0.19	1.08	0.10	0.89	0.11	NS	NS	NS	0.03
PP as TP	%	94.8	0.2	93.6	2.9	90.5	3.0	88.1	4.1	94.5	1.3	88.6	4.7	NS	NS	NS	NS
PN as TN	%	68.7	1.07	64.1	6.36	61.5	4.89	54.6	1.89	70	1.64	56.1	11.0	NS	NS	NS	NS

(c)

Year 3 Loddington		Treatment												p			
Variable		P		P C		P C TL		MT		MT C		MT C TL					
		Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Cultivation (MT vs. P)	Direction (MD)	Barrier (BB)	Interaction
Rainfall as runoff	%	6.9	4.8	1.7	1.3	14.4	4.3	2.6	1.5	15.4	4.5	13.0	2.5				
Runoff	Mm	21.9	15.2	5.4	4.2	45.7	13.7	8.3	4.9	48.6	14.2	41.2	7.8	0.01	NS	<0.01	<0.01
SS	kg ha^{-1}	114	65	24	20	275	88	60	38	315	55	335	41	<0.01	NS	<0.01	<0.01
TP	kg ha^{-1}	0.11	0.06	0.02	0.01	0.25	0.07	0.07	0.04	0.34	0.06	0.38	0.05	<0.01	NS	<0.01	<0.01
TDP	kg ha^{-1}	0.010	0.007	0.005	0.002	0.019	0.006	0.006	0.002	0.021	0.006	0.031	0.003	<0.01	NS	<0.01	<0.01
TN	kg ha^{-1}	1.4	1.1	0.4	0.4	2.7	1.2	0.4	0.3	2.9	0.8	1.8	0.3	<0.01	NS	<0.01	<0.01
TDN	kg ha^{-1}	1.2	1.0	0.4	0.4	2.3	1.0	0.3	0.2	2.2	0.8	1.1	0.2	0.02	NS	<0.01	<0.01
SS	mg l^{-1}	638	59	477	58	494	57	518	67	817	129	820	102	NS	NS	NS	<0.01
TP	mg l^{-1}	0.73	0.08	0.86	0.16	0.51	0.07	0.83	0.15	0.94	0.16	1.07	0.12	0.01	NS	NS	<0.01
TDP	mg l^{-1}	0.05	0.01	0.18	0.03	0.06	0.01	0.22	0.07	0.07	0.01	0.20	0.06	0.01	NS	NS	<0.01
TN	mg l^{-1}	4.10	0.81	3.02	0.67	3.38	0.72	4.16	0.76	5.25	1.32	4.37	0.84	0.03	NS	NS	NS
TDN	mg l^{-1}	3.05	0.75	2.33	0.61	2.65	0.69	2.84	0.68	3.67	1.22	2.77	0.64	NS	NS	NS	NS
PP as TP	%	90.0	0.4	74.3	8.2	80.1	5.5	68.9	4.2	88.0	1.1	79.3	3.1	NS	NS	NS	<0.01
PN as TN	%	34.7	4.51	26.3	2.42	29.1	3.25	36.7	3.75	44.2	2.22	40.8	1.48	<0.01	NS	NS	NS

Appendix 2.4. Comparison of mean overwinter losses for all treatments for the three sites

Site	Variable	Mean	SEM
Rosemaund	Runoff (mm)	17.5	10.3
	SS (kg ha^{-1})	1070	683
	TP (kg ha^{-1})	0.70	0.40
	TDP (kg ha^{-1})	0.04	0.02
	SS (mg l^{-1})	2680	829
	TP (mg l^{-1})	3.46	1.14
	TDP (mg l^{-1})	0.25	0.03
Old Hattons	Runoff (mm)	5.7	1.4
	SS (kg ha^{-1})	201	77
	TP (kg ha^{-1})	0.60	0.22
	TDP (kg ha^{-1})	0.02	0.00
	SS (mg l^{-1})	3319	673
	TP (mg l^{-1})	10.00	1.93
	TDP (mg l^{-1})	0.30	0.03
Loddington	Runoff (mm)	25.2	5.4
	SS (kg ha^{-1})	313	102
	TP (kg ha^{-1})	0.36	0.09
	TDP (kg ha^{-1})	0.01	0.00
	SS (mg l^{-1})	894	168
	TP (mg l^{-1})	1.37	0.16
	TDP (mg l^{-1})	0.18	0.04

Appendix 2.5. Effect of treatments applied at the three sites on total carbon (TC) losses in events in year 3, showing the significance of the treatment effect for each event (p<0.05).

Site			TC (kg ha^{-1})				TDC (kg ha^{-1})			
		Treatment	14/01/2008	15/01/2008		Mean	14/01/2008	15/01/2008		Mean
Rosemaund	P	TL	0.09	0.02		0.06	0.05	0.02		0.03
	P	DTL	0.29	0.02		0.15	0.23	0.02		0.12
	MT	TL	0.18	0.01		0.10	0.15	0.01		0.08
	MT	DTL	1.53	0.08		0.81	0.88	0.05		0.46
	p value	Cultivation	<0.01	N/S			<0.01	N/S		
		Tramline	<0.01	<0.01			0.02	0.01		
		Interaction	0.02	<0.01			N/S	0.02		
		Treatment	11/01/2008	12/01/2008	16/01/2008	Mean	11/01/2008	12/01/2008	16/01/2008	Mean
Old Hattons	P	TL	0.73	2.64	0.80	1.39	0.09	0.35	0.18	0.21
	P	DTL	0.03	0.80	0.33	0.39	0.01	0.06	0.04	0.04
	MT	TL	0.03	0.75	0.12	0.30	0.02	0.14	0.04	0.06
	MT	DTL	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	p value	Cultivation	<0.01	<0.01	<0.01		0.01	<0.01	N/S	
		Tramline	<0.01	<0.01	0.02		<0.01	<0.01	<0.01	
		Interaction	<0.01	0.01	N/S		<0.01	0.04	<0.01	
		Treatment	14/01/08	16/01/08	24/01/08	Mean	14/01/08	16/01/08	24/01/08	Mean
Loddington	P		2.01	1.66	0.50	1.39	1.42	1.38	0.44	1.08
	P	C	0.33	0.30	0.03	0.22	0.29	0.24	0.02	0.18
	P	TL	3.22	7.57	2.65	4.48	2.10	5.97	2.52	3.53
	MT		0.80	1.78	0.08	0.89	0.71	1.23	0.08	0.68
	MT	C	4.16	4.65	1.60	3.47	3.55	3.15	1.43	2.71
	MT	TL	4.30	6.63	1.28	4.07	4.05	4.80	1.16	3.34
	p value	Cultivation	N/S	N/S	N/S		N/S	N/S	N/S	
		Secondary treatment	N/S	<0.01	N/S		N/S	<0.01	N/S	
		Interaction	N/S	N/S	N/S		N/S	N/S	N/S	

Appendix 2.6. Cropping area and ‘operating’ margins, 2006, 2007 and 2008, and, based upon this, an average operating margin ha-1 for each region (2006) and case study farm (2006 to 2008).

Region	Site	Year	Cropping Area (%)					Operating Margin (£ ha^{-1})
			Wheat	Barley	Oats	Oilseed Rape	Beans	
West Midlands	Region	2006	53	16	6	12	5	£58
	Rosemaund [b]	2006	38	16	21	17	0	£183
		2007	40	15	13	23	0	£522
		2008	39	16	17	20	0	£355
	Old Hattons	2006	41	33	0	26	0	£202
		2007	32	33	6	30	0	£623
		2008	63	12	0	25	0	£498
East Midlands	Region	2006	56	11	2	18	6	£68
	Loddington	2006	51	0	7	20	14	£201
		2007	45	0	12	23	11	£502
		2008	47	0	9	22	15	£365

[a] Yields and prices for the 2008 harvest were not available at the time of writing this report. The calculation of the operating margin for each case study farm therefore assumes that yields and prices were the average of the previous two years results.

[b] In 2007, ADAS Rosemaund was sold to Tyrells and the majority of fields not under trials were put down to potatoes. For the purposes of the project cropping areas were taken as the mid-point of the previous two years cropping.

Appendix 3. Lists of publications and other outputs

Appendix 3.1. Journal papers

Stevens, C.J. and Quinton, J.N., 2008. Investigating source areas of eroded sediments transported in concentrated overland flow using rare earth element tracers. *Catena* **74**(1): 31-36.

Stevens, C.J. and Quinton, J.N., In press (a). Policy implications of pollution swapping. *Physics and Chemistry of the Earth, Parts A/B/C*: doi:10.1016/j.pce.2008.1001.1001

Stevens, C.J and Quinton, J.N. In press (b). Diffuse pollution swapping in arable agricultural systems. *Critical Reviews in Environmental Science and Technology*.

Stevens, C.J, Quinton, J.N., Bailey, A.P., Deasy, C., Silgram, M. and Jackson, R., Submitted. The effects of minimal tillage, contour cultivation and in-field vegetative barriers on phosphorus and sediment yields. *Soil and Tillage Research*.

Appendix 3.2. Journal papers in preparation

Deasy, C. and Quinton, J.N. Effectiveness of rare earth oxide tracers for determining the sources, transfer and rates of sediment eroded from hillslopes.

Deasy, C. and Quinton, J.N. Temporal variation in erosion source areas and sediment transfer between tillage treatments.

Deasy, C., Quinton, J.N., Silgram, M., Jackson, R., Bailey, A.P. and Stevens, C.J. Mitigation options for sediment and phosphorus losses from winter-sown arable crops.

Deasy, C., Quinton, J.N., Silgram, M., Jackson, R. Event dynamics of sediment loss from arable hillslopes.

Silgram, M., Collins, A., Quinton, J.N, Bailey, A.P., Deasy, C. and Stevens, C.J. Practical options for limiting phosphorus and sediment loss from winter–sown crops: a review of contemporary methods. *Advances in Sustainable Agriculture.*

Silgram, M., Jackson, R., Quinton, J.N., Bailey, A.P., Deasy, C. and Stevens, C.J. The role of tramline wheelings as diffuse pollution pathways, and potential mitigation strategies. *Agronomy for Sustainable Development.*

Silgram, M., Jackson, R., Quinton, J.N., Bailey, A.P., Deasy, C. and Stevens, C.J. Controlling soil erosion and nutrient loss from cereal crops: the effectiveness of land management strategies. *Soil Use and Management.*

Silgram, M., Jackson, R., Quinton, J.N., Deasy, C. and Stevens, C.J. Impact of pollution mitigation strategies on event-based runoff, sediment and nutrient losses from winter cereal crops.

Appendix 3.3. Published conference papers

Bailey, A.P., Quinton, J.N., Silgram, M., Stevens, C.J. and Jackson, R. Mitigation of Phosphorous and Sediment (MOPS): Is there a cost-effective solution? In Heckrath, G. Rubaek, B. Kronvang, B. (Eds). *Diffuse Phosphorus Loss. Risk Assessment, Mitigation Options and Ecological Effects in River Basins.* Proceedings of the 5th International Phosphorus Workshop (IPW5), 3-7 September 2007, Silkeborg, Denmark, *Plant Science*, 130, 309-311.

Bailey, A.P., Quinton, J.N., Silgram, M., Stevens, C.J. and Jackson, R. Determining the cost effectiveness of solutions to diffuse pollution: the case of in-field mitigation options for phosphorous and sediment loss. In: *Proceedings of the 16th International Farm Management Association Congress, A Vibrant Rural Economy – The Challenge for Balance, Peer Reviewed Papers, Volume II,* 16-20 July 2007, University College Cork, Cork, Ireland, 657-664.

Deasy, C., Quinton, J.N., Stevens, C.J., Silgram, M., Jackson, R., and Bailey, A.P. Mitigation options for phosphorus and sediment (MOPS): Reducing pollution in surface runoff from arable fields. In Crighton, K and Audsley, R. *Agriculture and the Environment VII. Land Management in a Changing Environment.* Proceedings of the SAC/SEPA Biennial Conference, 26-27 March 2008, Edinburgh, Scotland, 114-119.

Quinton, J.N., Deasy, C., Stevens, C.J., Silgram, M., Jackson, R., and Bailey, A.P. Mitigation options for phosphorus and sediment (MOPS): Tillage treatments and the use of vegetative barriers. In Heckrath, G. Rubaek, B. Kronvang, B (Eds). *Diffuse Phosphorus Loss. Risk Assessment, Mitigation Options and Ecological Effects in River Basins.* Proceedings of the 5th International Phosphorus Workshop (IPW5), 3-7 September 2007, Silkeborg, Denmark, *Plant Science*, 130, 295-7.

Silgram, M., Jackson, R., Quinton, J., Stevens, C.J., and Bailey, A.P. 2007. Can tramline management be an effective tool for mitigating phosphorus and sediment loss? In Heckrath, G., Rubaek, B., Kronvang, B. (Eds). *Diffuse Phosphorus Loss. Risk Assessment, Mitigation Options and Ecological Effects in River Basins.* Proceedings of the 5th International Phosphorus Workshop (IPW5), 3-7 September 2007, Silkeborg, Denmark, *Plant Science*, 130, 287-290.

Stevens, C.J. and Quinton, J.N. Field testing of mitigation options for phosphorus and sediment (MOPS). In: Gairns, L, Crighton, K and Jeffrey, B. (Eds.). *Agriculture and the Environment VI. Managing Rural Diffuse Pollution.* Proceedings of the SAC/SEPA Biennial Conference, 5-6 April 2006, Edinburgh, Scotland. 244-248.

Appendix 3.4. Unpublished conference papers

Bailey, A.P., Quinton, J.N., Silgram, M., Stevens, C.J. and Jackson, R. Determining the cost effectiveness of solutions to diffuse pollution: developing a model to assess in-field mitigation options for phosphorous and sediment loss. Paper presented at the *81st Agricultural Economics Society Conference*, 2-4 April 2007, University of Reading, UK

Bailey, A.P., Quinton, J.N., Silgram, M., Stevens, C.J., Deasy, C. and Jackson, R. Mitigation Options for Phosphorous and Sediment (MOPS): Determining the cost effectiveness of in-field mitigation options at the farm and regional level. Paper presented at the *82nd Agricultural Economics Society Conference*, March 31-April 2 2008, Royal Agricultural College, Cirencester, UK

Deasy, C., Quinton, J.N., Stevens, C.J., Silgram, M., Jackson, R. and Bailey, A.P. Mitigation options for phosphorus and sediment (MOPS): Reducing pollution in surface runoff from arable fields. Paper presented at the *15th International Congress of ISCO*, 18-23 May 2008, Budapest, Hungary

Deasy, C., Quinton, J.N., Silgram, M, Jackson, R. and Bailey, A.P. Controlling Sediment in Arable Landscapes, Experiences from the United Kingdom. Presented at the *Final Cost 634 International Conference, On- and Off-site Environmental Impacts of Runoff and Erosion,* 30 June – 4 July 2008, Aveiro, Portugal

Quinton, J.N., Silgram, M., Deasy, C., Stevens, C.J., Jackson, R., Bailey, A.P. and Heathwaite, A.L. Mitigation options for phosphorus and sediment (MOPS): Overview and results of the first two years. Paper presented at the *European Geosciences Union General Assembly*, 15-20 April 2007, Vienna, Austria

Quinton, J.N. Silgram, M, Deasy, C, Stevens, C.J., Jackson, R., Bailey, A.P. and Heathwaite, A.L. Mitigation options for phosphorus and sediment (MOPS): Overview and results of the first two years. Paper presented at the *Meeting of COST 869 Working Group 3*, 27-29 November 2007, Devon, UK

Quinton, J.N. and Deasy, C. How do soil and tillage practices regulate surface pollutant losses? Paper presented at the *European Geosciences Union General Assembly*, 13-18 April 2008, Vienna, Austria

Silgram, M., Jackson, R.J., Quinton, J.N., Stevens, C.J. 2006. Practical mitigation options for controlling sediment and phosphorus loss at hillslope scale. Paper presented at the *BHS 9th National Hydrology Symposium, Land Management and the Protection of the Water Environment: Understanding the Impact of New Legislation,* 10-13 September 2006, Durham, UK

Silgram, M., Jackson, R., Quinton, J.N., Stevens, C.J. and Bailey, A.P. Tramlines. Paper presented at the *European Geosciences Union General Assembly*, 15-20 April 2007, Vienna, Austria

Appendix 3.5. Poster presentations

Bailey, A. P., Quinton, J.N., Silgram, M., Deasy, C., Stevens, C.J. Jackson, R. and Heathwaite, A.L. Mitigation Options for Phosphorus and Sediment (MOPS): determining cost effectiveness. Poster presented at the *IPSS/SCI meeting on Soil and Water Protection through Integrated Catchment Management,* 16 October 2007, London, UK

Deasy, C., Quinton, J.N. and Silgram, M. Hillslope monitoring approaches to assess pollution losses from arable land. Poster presented at the *International Workshop on Agriculture, Water Management and Climate Change*, 4-6 March 2008, Bath, UK

Deasy, C. and Quinton, J.N. Monitoring techniques to assess soil erosion and nutrient loss from arable land to water within the Mitigation of Phosphorus and Sediment (MOPS) project. Poster presented at the *European Geosciences Union General Assembly*, 13-18 April 2008, Vienna, Austria

Quinton, J.N., Silgram, M., Bailey, A. P., Deasy, C., Stevens, C.J., Jackson, R. and Heathwaite, A.L. Mitigation Options for Phosphorus and Sediment (MOPS). Poster presented at the *IPSS/SCI meeting on Soil and Water Protection through Integrated Catchment Management,* 16 October 2007, London, UK

Silgram, M., Jackson, R., Quinton, J.N, Bailey, A. P., Stevens, C.J. and Heathwaite, A.L. Can tramline disruption mitigate against phosphorus and sediment loss in surface runoff? Poster presented at the *IPSS/SCI meeting on Soil and Water Protection through Integrated Catchment Management,* 16 October 2007, London, UK

Silgram, M., Jackson, R., Quinton, J.N., Bailey, A. P., Stevens, C.J. and Heathwaite, A.L. Mitigation options for phosphorus and sediment: residue management on erodable sandy soils. Poster presented at the *IPSS/SCI meeting on Soil and Water Protection through Integrated Catchment Management,* 16 October 2007, London, UK

Stevens, C.J. and Quinton, J.N. Field testing of mitigation options for phosphorus and sediment (MOPS). Poster presented at the *European Geosciences Union General Assembly*, 2-7 April 2006, Vienna, Austria

Appendix 3.6. Knowledge transfer

A number of open days have been held at Loddington for farmers**:**

Date	Group	No. of Visitors
31/01/05	Simba	30
03/02/05	HGCA	40
17/02/05	LEAF event	31
12/04/05 – 13/04/05	British Ecological Society	65
19/04/05	Yara	18
29/06/05	NFU	30
20/07/05	Natural England	70
02/11/05	Oxey Farm + guests	40
21/11/05	BIAC	30
31/01/06	Bayer CropScience	57
15/05/06	Monsanto	15
01/06/06	ADAS	50
31/07/06	Defra	8
19/09/06	FWAG	20
20/09/06	Smiths Gore	16
28/09/06	Crown Estates	12
10/10/06	Norton & Gaulby Young Farmers Club	25
20/11/06	Velcourt	11
05/12/06	Simba visit, Eastern European farmers	30
18/12/06	Gwyn Morgan-Jones	12
21/03/07	Simba visit	30
18/04/07	Simba visit	30
05/06/07	HGCA event with farm tour	42
15/06/07	Land Trusts Association	15
25/06/07	Visit by Parker Farms	25

- Presentations have been given at numerous conferences over the three years of the project, including meetings organised by the European Geosciences Union, the International Soil Conservation Association, the University of Aarhus, University College Cork, the Royal Agricultural College, the SAC and SEPA, the IPSS and the SCI, the Agricultural Economics Society, the British Hydrological Society, the University of Reading, and COST Actions 634 and 869.
- The project was involved in hosting the Defra Phosphorus Coordination Meeting field visit to Loddington, 3rd July 2006, which included poster presentations on the other two sites.
- Meetings describing the project findings have been held with the Defra Catchment Sensitive Farming Team.
- MOPS was featured in an article on Minimising Phosphate Loss, *Farmers Weekly*, 21st July 2006, p.60
- Reference was made to MOPS research in *Blueprint for a Green Economy.* Submitted to the Shadow Cabinet. Quality of Life Policy Group, Chairman, Rt Hon John Gummer MP Vice-Chairman, Zac Goldsmith, September 2007, p.235
- The project operates a website hosted by Lancaster University to update interested parties on progress and disseminate research findings. A copy of this final report and published papers are available from the website: www.lec.lancs.ac.uk/cswm/mops.htm.