The effects of minimal tillage, contour cultivation and in-field vegetative barriers on soil erosion and phosphorus loss

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Abstract

Runoff, sediment, total phosphorus and total dissolved phosphorus losses in overland flow were measured for two years on unbounded plots cropped with wheat and oats. Half of the field was cultivated with minimum tillage (shallow tillage with a tine cultivator) and half was conventionally ploughed. Within each cultivation treatment there were different treatment areas (TA). In the first year of the experiment, one TA was cultivated up and down the slope, one TA was cultivated on the contour, with a beetle bank acting as a vegetative barrier partway up the slope, and one had a mixed direction cultivation treatment, with cultivation and drilling conducted up and down

the slope and all subsequent operations conducted on the contour. In the second year, this mixed treatment was replaced with contour cultivation.
Results showed no significant reduction in runoff, sediment losses or total phosphorus losses from minimum tillage when compared to the conventional plough treatment, but there were increased losses of total dissolved phosphorus with minimum tillage. The mixed direction cultivation treatment increased surface runoff and losses of sediment and phosphorus. Increasing surface roughness with contour cultivation reduced surface runoff compared to up and down slope cultivation in both the plough and minimum tillage treatment areas, but this trend was not significant. Sediment and phosphorus losses in the contour cultivation treatment followed a very similar pattern to runoff. Combining contour cultivation with a vegetative barrier in the form of a beetle bank to reduce slope length resulted in a non-significant reduction in surface runoff, sediment and total phosphorus when compared to up and down-slope cultivation, but there was a clear trend towards reduced losses. However, the addition of a beetle bank did not provide a significant reduction in runoff, sediment losses or total phosphorus losses when compared to contour cultivation, suggesting only a marginal additional benefit. The economic implications for farmers of the different treatment options are investigated in order to assess their suitability for implementation at a field scale.

Keywords: Beetle bank, contour cultivation, minimum tillage, soil erosion, phosphorus.

Introduction

Water erosion of agricultural soils has for many years been recognised as a global environmental problem (Zuazo and Pleguezuelo, 2008). In areas of the UK where soils are light in texture and readily erodible this problem can be serious, with rates of erosion typically between 0.5 and 200 Mg ha^{-1} yr^{-1} (Chambers et al, 2000). Land in fallow and winter cereal crops are less susceptible to soil erosion than some other crops (e.g. maize and potatoes) (Evans, 2002) but, as they have bare ground or low crop cover during the autumn and winter they can still suffer large erosion losses (Chambers and Garwood, 2000).

Phosphorus (P) binds to soil particles, and losses of P associated with soil particles are often linked to soil erosion. Water erosion preferentially removes the finer fractions of the soil with which P is commonly associated. This leads to P becoming concentrated in overland flow (Quinton et al., 2001; Quinton, 2002).

Diffuse P pollution, predominantly from agricultural sources (including fertiliser and animal waste), presents a serious problem in the UK, contributing to the eutrophication of waterways and standing water bodies (Haygarth et al., 2005). Surface waters in the UK are strongly limited by P and even small additions can cause eutrophication. High inputs in the form of organic and inorganic fertilisers from agriculture have resulted in considerably higher levels of soil P than are utilised by the crop plants, thus creating an increased potential for the transfer of P to the wider environment (Haygarth et al., 1998; Haygarth et al., 2005).

Potentially high levels of excess P in soils along with increases in soil erosion have led to large amounts of P being transported to waterways. In recognition of this problem, European legislation in the form of the Water Framework Directive (2000/60/EC) requires action to reduce diffuse P pollution as part of an objective of restoring waters to good ecological status. This will require that mitigation options are introduced within fields, at field boundaries and adjacent to water bodies.

As a result of the research effort since the 1930s, there is a wide range of effective mitigation options for reducing soil erosion (see Chambers et al., 2000 for examples). Much less is known about how effective these mitigation options are for reducing the P losses that are associated with sediment. This paper considers three treatments with potential for reducing sediment and P losses associated with combinable crops: minimum tillage, contour cultivation and in-field vegetative barriers.

Minimum tillage, which involves shallow tillage using a tine cultivator (Rasmussen, 1999), has the potential to conserve organic matter, promote aggregate stability, increase infiltration and reduce losses of sediment and sediment-bound pollutants (Quinton and Catt, 2004; Silgram and Shepherd, 1999). In a review of studies evaluating minimum tillage, Strauss et al. (2003) found a median effectiveness of 74% for reducing soil erosion. Although the benefits for soil erosion are well established, the potential for reducing nutrient pollution is less clear.

Contour cultivation reduces runoff by increasing surface roughness perpendicular to the slope. The increased surface roughness reduces the velocity of any flowing water, providing more time for infiltration and reducing erosion rates. Although popular as a means of reducing soil losses in many parts of the world, contour cultivation has not been widely taken up in the UK due to concerns that machinery will overturn in wet conditions (Chambers et al., 2000). Quinton and Catt (2004) demonstrated the potential benefits for reducing soil losses and runoff on sandy soils in the UK but, as with minimum tillage, although the benefits for reducing soil erosion are well known, there is less evidence available to indicate the benefits for P losses.

Vegetative barriers have frequently been used as field-edge mitigation options but can also be placed within fields along the contour, where they serve to reduce slope length and act as barriers to overland flow, thus retaining sediment from up slope. Contour grass strips have received some research attention and have been shown to reduce sediment losses. In laboratory experiments, Ligdi and Morgan (1995) found contour grass strips were effective in removing sediment on 5% and 10% slopes. In a flume experiment with different grasses and flow rates, Dabney et al. (1995) found contour grass strips to range from 15 to 79% in their effectiveness. In this study we used beetle banks as vegetative barriers. These raised banks are seeded with a wildflower and grass mix to attract invertebrates and are installed primarily for biodiversity benefits. Funding is available for farmers in the UK for the installation of beetle banks under the Environmental Stewardship Entry Level Scheme (ELS), but uptake of this option in the pilot scheme (1998–2000) was not high (ADAS, 2001).

This paper evaluates the potential for minimum tillage, contour cultivation and beetle banks to reduce sediment and P losses from combinable crops; it will also examine their cost-effectiveness.

Methods

Field Experiment

In 2005 a field experiment was established at Loddington in Leicestershire, central England (GB grid reference: SK795018). The site is run by the Game Conservancy Trust's Allerton Project, which seeks to demonstrate means of farming profitably with minimal environmental impact. Borderless hill-slope plots were established on a field with soils consisting of Hanslope and Denchworth series clays on an erodible slope with an angle varying between 2 and 6^{o}. The field was planted with wheat (*Triticum aestivum* v. Solstice) in 2005 and oats (*Avena sativa* v. Gerald) in 2006.

Eight different treatments were applied (table 1, figure 1). Half of the field was cultivated with minimum tillage using a disk cultivator with a maximum depth of 15 cm and half was conventionally ploughed using a mouldboard plough with a maximum depth of 18 cm. Each half of the field had three different cultivation treatment areas (TA). One TA from each tillage treatment was cultivated up and down the slope and a second TA was ploughed on the contour, with a beetle bank acting as a vegetative barrier part-way up the slope. In a third TA a mixed direction cultivation treatment was used in 2005/6, with ploughing and drilling conducted up and down the slope and rolling and all subsequent operations conducted on the contour. In 2006/7 this treatment was replaced with contour cultivation. Each treatment had three replicate collection tanks collecting runoff from unbounded plots (one tank had to be removed from the contour cultivation/minimum tillage/beetle bank combined treatment due to a perched water table surfacing within the plot, so this treatment was only replicated twice). Unbounded plots were 12 m wide and the length of the hill slope was an average of 67 m. Variation in slope length and angle was small so is unlikely to have a large effect on the results.

Rainfall and runoff were recorded between October and May in 2005/6 and 2006/7. Tanks were sampled after each rainfall event that generated runoff. Runoff was collected in 3 m troughs sunk into the ground so that they were flush with the soil surface. Clay soil from the site was packed around the troughs to give a smooth surface for water to flow over and to ensure water was not infiltrating at the edges of the troughs. These were placed towards the base of the slope, and water and eroded sediment ran through pipes to a splitting device located on the top of each tank. The splitting devices enabled collection of representative samples between 50% and 12.5% of the total surface runoff, which could be adjusted depending on prevailing conditions. Splitting devices were thoroughly evaluated and calibrated in the laboratory before installation. The collected runoff was stored in 500 litre tanks. On several occasions the runoff volumes filled the tanks, causing them to overflow; on these occasions a value for minimum runoff volume was measured.

Prior to sample collection, water and sediment in the collection tanks was agitated thoroughly and a mixed water and sediment sample was taken for analysis. Samples were collected as soon as possible after the rainfall event to minimise adsorption/desorption effects. Samples were kept cool prior to analysis.

Laboratory Methods

The mixed water and sediment samples collected were analysed for total P (TP) and total P <0.45 µm (TDP) using acid molybdate/antinomy with ascorbic acid reduction (USEPA, 1985) and determined spectrophotometrically (880 nm) using a Seal Analytical AQ2 analyser. Particulate phosphorus (PP) was calculated as TP minus TDP. Total suspended solids in the runoff samples were determined using a standard filtration and drying technique using Whatman GF/C filters with a pore size 1.2 µm (Bartram and Balance, 1996).

Statistical Analysis

Data were analysed using repeated-measures analysis of variance, where runoff variables were the dependant variables and treatment was the independent variable, and correlation coefficients. Post-hoc analysis was conduced using Tukey honest significant difference test. Data analysis was conducted using R (R Development

Core Team, 2007) and SPSS (SPSS Inc, 2005). All data are presented as yields per hectare for overwinter losses.

Cost-effectiveness Analysis

To determine the cost-effectiveness of the different approaches, simple spreadsheet models were constructed at the farm level. These spreadsheets calculated individual crop margins and thence an overall arable rotation margin at the farm level in the plough up and down slope treatment (control scenario). Impacts on this margin as a result of the treatments undertaken were then incorporated into the spreadsheets. 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. The data from the experimental work were collected for each treatment in each year and include (i) the field records on crop establishment, fertiliser and spray applications, harvesting and yield, and (ii) the additional operations associated with the mitigation options. Additionally, the crops grown, their areas and average yield across the whole farm were also collected for each year.

In the control scenario, 'operating' margins for each crop were calculated to reflect the costs of crop establishment, fertiliser and agro-chemical applications, and harvesting. This used crop yield and price to determine gross output. Seed, fertiliser and agro-chemical variable costs were then deducted to derive the gross margin. Finally, labour and machinery costs (which could be directly allocated to each crop enterprise, and were associated with establishment, fertiliser and agro-chemical applications, and harvesting) were deducted to derive an 'operating' margin. This operating margin goes beyond an enterprise gross margin, as it includes some fixed costs; however, it is not a true net margin, as certain building, land and general overhead costs were excluded.

To calculate gross output, average crop yields from the 2006 and 2007 harvest years were multiplied by October 2006 and 2007 market prices respectively (Farmers Weekly, 2006a,b; Farmers Weekly Interactive, 2007). Variable cost data were initially based upon standard costs taken from Nix (2005) and then amended to reflect actual practice using the field data provided. Nix provides price information on seeds, fertilisers and agro-chemicals prices, and uses these to calculate typical individual crop gross margins. Machinery and the associated labour costs were calculated based upon the number and type of operations undertaken, and as with the variable cost data, were initially based upon average farmer cost data taken from Nix (2005). The calculations take into account the work rate possible on the medium/heavy soils that occur at Loddington, and include fuel, labour requirement, repairs and depreciation but exclude the more general overhead costs.

These margins were then 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. To do this, each crop margin was multiplied by the percentage area that was grown on the farm taken from the 2006 and 2007 harvest year farm records.

Finally, variable and operating costs associated with each mitigation option were then incorporated to demonstrate the impact on the relevant crop operating margins and the overall average net return per hectare. The calculations used the data from the farm field records covering (i) crop establishment, fertiliser and spray application, and harvesting and (ii) the additional costs associated with the establishment of the beetle bank for each of the identified mitigation options. It was assumed that mitigation takes place on all fields where cereal crops were grown. A more accurate picture would be to determine what percentage of the land and hence cereal crop would require implementation of the mitigation option. Average net return per hectare would therefore be somewhere between the original and new margin. This would not necessarily be the case in reality. The switch to minimum tillage and contour cultivation 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 cultivation were not included here. Consideration was also given to the establishment of the vegetative strip. There are additional costs arising from establishment and annual maintenance requirements, loss of productive land and, potentially, the increased requirement for weed control in areas at the edge of the banks 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, drill 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, slower work rate and as a result increased crop enterprise operational costs. This is dependent on farm size, arable area, field sizes, slopes and opportunity to incorporate such strips within field. In practice, areas taken for the vegetative strip would probably be less than one hectare, allowing for some reduction in cost if the area was small enough to be seeded by hand.

Results

Monitored Events

A total of 20 events were monitored from October to May 2005/6 and October to May 2006/7. Ten events were monitored in each year. Total rainfall was 382 mm in 2005/6 and 359 mm in 2006/7. The mean event size was 38 mm in 2005/6 and 36 mm in 2006/7, but variability in event size was greater in 2005/6 than 2006/7 (Figure 2). Compared to mean rainfall (1998–2007), rainfall in the first sampling season was below average for the first five months, but then exceeded the average for the remaining months. In the second sampling season, rainfall considerably exceeded averages during November, January, February and March. With the exception of April, when rainfall was very low, all other months were close to average rainfall.

Surface Runoff

Total surface runoff (Figure 3a) and the event runoff coefficients (percentage of rainfall lost as runoff) were higher in 2006/7 than in 2005/6. In year 1 there was a significant effect of treatment on runoff ($F=9.699$, $p<0.001$). Post-hoc analysis showed significantly more ($p<0.01$) runoff from the mixed direction treatment (PL mix) (1.93 mm) than the treatment ploughed up and down slope (PL) (0.24 mm). There was also significantly more ($p<0.01$) runoff with the PL mix treatment than the plough contour cultivation and beetle bank treatment (PL C BB) (0.17 mm), MT (0.51 mm) and MT C BB treatments (0.66 mm). The minimum tillage mixed direction treatment (MT mix) (1.85 mm) resulted in significantly more ($p<0.01$) runoff than the MT C BB treatment and the MT treatment.

In year 2 there was no significant effect of treatment on runoff ($F=1.97$, $p=0.16$).

Suspended Sediment

Suspended sediment losses were also greater in year 2 than year 1 (Figure 3b). In year 1 there was a significant effect of treatment on sediment losses (F=11.93, p<0.001). The mixed direction treatments PL mix (5.2 kg ha^{-1}) and MT mix (17 kg ha^{-1}) treatments were mainly responsible for this. MT mix had significantly higher (p<0.05) losses than the PL (1.1 kg ha^{-1}), PL C BB (0.4 kg ha^{-1}), MT (3.4 kg ha^{-1}) and MT C BB (3.7 kg ha^{-1}) treatments.

In year 2 there was also a significant effect of treatment on sediment loss (F=3.06, p=0.05). Post-hoc analysis showed no significant differences between individual treatments.

Total Phosphorus

Figure 3c shows variability within treatments was very large. In year 1 there was a significant effect of treatment on TP losses (F=9.86, p<0.001). This was predominantly driven by the high losses from the mixed direction tillage treatments, PL mix (0.017 kg P ha^{-1}) and MT mix (0.037 kg ha^{-1}). MT mix showed significantly higher (p<0.01) losses than the PL (0.029 kg P ha^{-1}), PL C BB (0.002 kg P ha^{-1}), MT (0.009 kg P ha^{-1}) and MT C BB (0.01 kg P ha^{-1}) treatments. Year 2 showed no significant effect of treatment on TP (F=2.21, p=0.13).

As with runoff and sediment, TP losses were much higher in year 2 than year 1 for all treatments conducted over two years.

Total Dissolved Phosphorus

The difference in losses between years 1 and 2 is less than that observed for other runoff variables. Variability in the data is much lower than other runoff variables

(Figure 3d). Differences in TDP losses were proportionally much lower than differences between TP losses.

Examining year 1 data shows a significant effect of treatment on TDP losses ($F=6.74$, $p<0.05$). Significantly higher losses ($p<0.05$) were found from the PL mix (0.0026 kg P ha^{-1}) treatment compared to the PL C BB (0.0006 kg P ha^{-1}) and PL (0.0008 kg P ha^{-1}), MT (0.0014 kg P ha^{-1}) and MT C BB (0.0012 kg P ha^{-1}) treatments.

In year 2 there was no significant effect of treatment on TDP losses ($F=2.06$, $p=0.14$).

Particulate Phosphorus

PP losses were higher in year 2 than in year 1. Results for PP losses were similar to sediment losses. In year 1 there was a significant effect of treatment on PP ($F=13.118$, $p<0.001$). As with sediment losses, the MT mix (0.0322 kg P ha^{-1}) treatment was mainly responsible for this, with significantly higher ($p<0.05$) losses than the PL (0.0016 kg P ha^{-1}), PL C BB (0.0009 kg P ha^{-1}), PL (0.0015 kg P ha^{-1}) and MT C BB (0.0077 kg P ha^{-1}) treatments.

In year 2 there was no significant effect of treatment on PP loss ($F=2.21$, $p=0.12$). .

Cost-effectiveness Analysis

Table 2 illustrates the 2006 and 2007 cropping areas and, based upon this, an average ‘operating margin’ per hectare for the case study farm. Table 3 shows the financial impact of the introduction of the various mitigation options on the ‘operating’ margin in each year. Field records from both years show that no changes in terms of fertiliser or agro-chemical applications were required and that there were no impacts on yield. In the long term, this may not be the case.

The switch to a minimum tillage system, as is to be expected, reduces establishment costs and thereby increases the operating margin. However, it can increase certain weed burdens, giving rise to increased agrochemical costs. This has not been the case so far.

The change to operating across the contour has not been explicitly costed. In reality, additional time spent in the field as a result of a reduced work rate will increase the operational costs per hectare associated with crop establishment, and, potentially, fertiliser application and spraying of agrochemicals. Many farmers are reluctant to adopt contour cultivation because of the difficulties with cultivation and spraying operations. Furthermore, it would only be possible on a limited number of slopes.

Provisional estimates for the establishment of the vegetative strip suggest a cost of establishment of £163 ha^{-1} and ongoing annual maintenance cost of £21 ha^{-1}. The costs associated with reducing field size and increasing operational costs amount to between £1 and £2 ha^{-1} and are incorporated within the resultant operating margin.

Discussion

Monitored events

Total surface runoff, losses of sediment and losses of TP were generally much higher in year 2 than in year 1. The large variation between years demonstrates the need for longer term monitoring. There was also large variability between plots and events within treatments.

In year 1 overwinter losses of sediment (range for treatment means 0.4-17 kg ha^{-1}) were lower than the average losses for tillage land in England and Wales reported by Chambers et al. (2000) (160–123,000 kg ha^{-1}). Losses of sediment in year 2 of this experiment (33-184 kg ha^{-1}) were closer to the range reported by Chambers et al.

(2000). P losses from the experiment in year 2 (0.04–0.16 kg P ha^{-1}) were lower than average losses from agriculture-dominated catchments in the UK (Ulén et al., 2007) (0.5 kg P ha^{-1}) and at the lower end of the range for reported losses from tillage land in England and Wales (0.16–94 kg P ha^{-1}) (Chambers et al. 2000), although in year 1 losses were lower (0.002–0.03 kg P ha^{-1}).

Minimum tillage

A review of the literature comparing minimum tillage to ploughing suggests minimum tillage commonly results in a significant reduction in surface runoff and sediment losses (Strauss et al., 2003), but reductions were not observed at this site. There were no significant reductions in runoff or sediment losses in the minimum tillage treatments compared to plough treatments, in the plots ploughed up and down, in those ploughed on the contour, or in those ploughed on the contour with a beetle bank. Examination of the data did not reveal any apparent, but non-significant differences. TP and PP losses also showed a very similar pattern. As losses of TP across all treatments were strongly driven by sediment losses across all treatments (r^2=0.92, $p<0.01$), this is not surprising. Losses of TDP showed a slightly different result, with a trend towards higher losses of TDP from the MT treatment than the plough treatment in year 1. In year 2 this was not the case with no significant difference between treatments. The higher losses observed in year 1 could be due to P concentrating at the surface of the soil and an increase in organic matter (Bertol et al., 2007; Saveedra et al., 2007). Saavedra et al. (2007) found significantly higher organic matter contents in soils under minimum tillage than those under conventional tillage. They also found higher TP, Olsen P and organic P concentrations, but these differences were not significant. A small plot study study with intense rainfall in

Brazil on a Hapludox soil (68% clay, 21% silt, 11% sand) showed P concentrations in the upper 0–0.025 m of a soil with no-tillage cultivation were over five times those in the conventional tillage after four years of treatment (Bertol et al., 2007).

The reduced establishment costs associated with minimum tillage may make this option more appealing to farmers. However, at higher prices for output (as was seen in 2007) moving to minimum tillage has less of a percentage impact than at lower prices, although the actual (absolute) change is the same. The lack of a significant reduction in P and sediment losses with minimum tillage means that although costs are not increased overall, this cultivation is not cost-effective.

Mixed direction tillage

The mixed direction tillage treatment presents an advantage over contour cultivation: it avoids conducting the tillage and drilling across the slope, which many farmers feel presents a risk of vehicles slipping down slope or tipping over. The mixed direction tillage treatment resulted in significantly higher losses of runoff, sediment and PP compared to all other treatments. Losses of TP and TDP were significantly higher from the mixed direction minimum tillage treatment and there was a clear trend for higher losses in the plough mixed direction tillage, although this was not significantly different from other plough treatments (Figure 3d). However, it is possible that longer may be required for the treatment to have an effect.

Although mixed direction tillage offers some advantages for farmers over contour cultivation, it is clearly not beneficial to controlling soil erosion or nutrient losses. Farmers working on similar soils would be better using up and down slope cultivations than using the mixed direction tillage. These high sediment and P losses are likely to be a result of the contour rolling following up and down slope tillage which formed a series of slightly raised, loose soil micro-ridges on the soil surface. Crop alignment encouraged water movement down slope as in the up and down slope cultivations, but these micro-ridges were too small to impede flow, instead providing a source of easily erodible soil. This measure would not be cost-effective given increased losses and increased labour costs in cultivating across the slope.

Contour cultivation

The contour cultivation treatment was established in year 2 of the experiment. Contour cultivation did not result in a significant reduction in surface runoff when compared to up and down cultivation in either the plough or minimum tillage plots. However figure 3a shows that there was quite a large difference between the treatments, with a mean reduction of 72.2% although this ranged from 9 to 98%. Sediment losses followed a very similar pattern to runoff (Figure 3b), This was the same for TP, TDP (Figures 3c and d) and PP. Although the results were not statistically significant, the strong trends in the data suggest that there are benefits to be gained from using contour cultivation to reduce runoff sediment and P losses. There are additional costs associated with contour cultivation tillage, primarily additional time spent in the field which will increase operational costs compared with traditional cultivation. Many farmers are reluctant to adopt contour cultivation because of difficulties with cultivation and spraying operations (Quinton and Catt, 2004), but with the right incentive this measure could be cost-effective.

Beetle Bank

Data collected from the beetle bank and contour cultivation treatment did not show a significant reduction in surface runoff compared to up and down slope cultivation.

There was no significant difference between runoff from the beetle bank plots than from the contour cultivation plots. Figure 3a shows that this difference is small and variability was large. Sediment losses, TP and PP losses again show a similar pattern to surface runoff. In both years there was no significant difference between TDP losses from the beetle bank treatment and the plough treatment and figure 3d shows that the mean loss was actually slightly higher from the beetle bank plots than the up and down slope cultivation in year 1.

For all of the runoff variables considered there were only minor reductions in losses provided by the beetle bank treatment compared to the contour cultivation treatment. In order for a beetle bank to be placed on the contour, contour cultivation needs to be used. Beetle banks are potentially problematic for farmers, not only requiring contour cultivation, but also resulting in a loss of land and potentially introducing weeds in the areas at the end of banks that cannot be cultivated. They also result in additional cost to the farmer both through increased operational costs and a loss of productive land. Installing beetle banks as a measure to improve water quality may not seem very beneficial, but they do have a proven benefit for invertebrate diversity (Thomas et al., 2002). If beetle banks are going to be installed as a conservation measure to enhance invertebrate diversity, placing them on the contour combined with contour cultivation is likely to have increased benefits for water quality when compared to contour cultivation alone. Given the additional costs associated with their installation and the minimal reduction in erosion losses, beetle banks are only cost-effective for farmers to install where there are gains for biodiversity.

Conclusion

Minimum tillage did not reduce or increase diffuse pollution when compared to the control, although it may be beneficial in other situations and reduces operating margins.

Mixed direction tillage resulted in increases in surface runoff, sediment and P losses and is not recommend as a mitigation option. Contour cultivation gave much more positive results: although differences were not significant, mean sediment and P losses were much lower. However, the additional time input required for cultivations and safety concerns mean that this option may not be popular with farmers.

The beetle bank generates additional costs for the farmer and although it provides significant reductions in runoff variables compared to up and down slope cultivation, there is only a marginal benefit compared to contour cultivation alone. The additional biodiversity benefits of beetle banks mean that there is potential for their installation to benefit water quality if they are placed on the contour.

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Table 1. Treatments applied during October 2005 and 2006: PL is plough, MT is minimum tillage, C is contour cultivation, mix is mixed direction cultivation and BB is beetle bank. Plot numbers refer to Figure 1.

Treatment	Plot number	2005/6 (wheat)	2006/7 (Oats)
MT	1, 2, 3	✓	✓
MT C	4, 5, 6		✓
MT mix	4, 5, 6	✓	
MT C BB	7, 8, 9	✓	✓
PL C BB	10, 11, 12	✓	✓
PL mix	13, 14, 15	✓	
PL C	13, 14, 15		✓
PL	16, 17, 18	✓	✓

Table 2. Cropping and 'Operating' Margin, 2006 and 2007

Year	Wheat % area	Oats % area	Rape % area	Beans[1] % area	Set aside % area	Margin £/ha
2006	51	7	20	14	9	201
2007	45	12	23	11	9	502

[1] In 2006 winter beans were grown; in 2007 spring beans were grown.

Table 3. Mitigation Options: Impact on Farm Rotational Operating Margin, 2006 and 2007

Year	Mitigation option	Operating margin
2006	Plough	£201 per ha
	Contour plough	£201 per ha
	Contour plough with beetle bank	£199 per ha
	Minimum tillage	£247 per ha
	Contour minimum tillage	£247 per ha
	Contour minimum tillage with beetle bank	£245 per ha
2007	Plough	£502 per ha
	Contour plough	£502 per ha
	Contour plough with beetle bank	£497 per ha
	Minimum tillage	£547 per ha
	Contour minimum tillage	£547 per ha
	Contour minimum tillage with beetle bank	£542 per ha

Figure 1. Plan of experimental plots. Bold number shows plot treatments as outlined in Table 1. Plot lengths and dimensions of the beetle bank are shown in metres. Contour lines are placed every metre.

Figure 2. Daily rainfall between October and May from 2005 to 2007 (mm). Mean event runoff (all treatments) is shown with a closed circle.

Figure 3. Mean overwinter a) surface runoff (mm), b) sediment losses (kg ha^{-1}), c) TP losses (kg P ha^{-1}) and d) TDP losses (kg P ha^{-1}). Error bars show standard deviation. Grey bars show data collected during 2005/6 and white bars data collected during 2006/7.