Soil Use and Management (2004) **20**, 343–349 DOI: 10.1079/SUM2004267

The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Erosion Reference Experiment on sandy soil at Woburn, England

J.N. Quinton[1,*] & J.A. Catt[2,3]

Abstract. Over a 10-year period, runoff and soil erosion on the plots of the Woburn Erosion Reference Experiment were concentrated in periods with sparse vegetation cover: in winter after the late planting of cereals; in spring after the planting of beets; or when soils were bare after harvest. The mean event runoff of 1.32 mm from plots cultivated up-and-downslope was significantly greater ($P < 0.05$) than that from plots cultivated across-slope (0.82 mm). However, mean event soil loss was not significantly different between the two cultivation directions. No significant differences were found between minimal and standard cultivations. Mean event runoff from the across-slope/minimal tillage treatment combination (0.58 mm) was significantly less ($P < 0.01$) than from the up-and-downslope/minimal tillage (1.41 mm), up-and-downslope/standard tillage (1.24 mm), and across-slope/standard tillage (1.07 mm) treatment combinations. Runoff from the across-slope/standard treatment combination was significantly ($P < 0.05$) less than from the up-and-downslope/minimal tillage treatment. The across-slope/minimal tillage treatment combination had a significantly smaller ($P < 0.05$) event soil loss (67 kg ha^{-1}) than the up-and-downslope/standard tillage (278 kg ha^{-1}) and up-and-downslope/minimal tillage (245 kg ha^{-1}) combinations. Crop yields were significantly ($P < 0.05$) higher on across-slope plots in 1988, 1996 and 1997 than on up-and-downslope plots, and were also higher (but not significantly) on the across-slope plots in 7 of the 8 remaining years. Minimal cultivation decreased yield compared with standard cultivation in one year only. We recommend that across-slope cultivation combined with minimal tillage be investigated at field scale to assess its suitability for incorporation into UK farming systems.

Keywords: Soil erosion, soil conservation, conservation agriculture, minimal tillage, reduced tillage, runoff

INTRODUCTION

In the UK, enhanced water erosion of ploughed land was identified as early as 1868 in Norfolk (Fisher 1868). More recently, Evans (1971), Morgan *et al.* (1987), Boardman (1990) and others have recognized that water erosion of soils under arable agriculture is an increasing problem requiring attention. Its role as a carrier of soil contaminants (Quinton *et al.* 2001) has focused the attention of government departments and agencies on its control, resulting in the publication of guides for farmers (Ministry of Agriculture, Fisheries and Food 1997, Environment Agency 2001). Additionally, serious flooding in the UK during the winter of 2000 was thought to result, at least in part, from surface runoff from fields in agricultural catchments (Holman *et al.* 2002).

Sandy soils are particularly vulnerable to erosion. They tend to have low organic matter content and poor structural stability. At the soil surface this manifests itself as disaggregation under raindrop impact, with the subsequent development of a surface crust and reduction in infiltration rate and surface roughness. Runoff can then be generated at low rainfall intensities and water erosion follows, often with formation of rills on slopes and valley floors. On sandy soils in Nottinghamshire, England, Evans (1992) estimated that mean soil losses ranged from 1 m^3 ha^{-1} for soils under a winter cereal to 7.6 m^3 ha^{-1} for areas planted to sugar beet. The importance of overland flow erosion on sands was also confirmed by Morgan (1977), who found that it accounted for over 90% of the sediment moved.

[1]Department of Environmental Science, Lancaster University, Lancaster LA1 4YQ, UK. [2]Department of Geography, University College London, 26 Bedford Way, London WC1H 0AP, UK. [3]Agricultural and Environment Division, Rothamsted Research, Harpenden, Herts AL5 2JQ, UK.
*Corresponding author. Fax: +44(0)1524 593985.
E-mail: J.Quinton@ Lancaster.ac.uk

The recent downturn in profits from agriculture has forced UK farmers to search for ways to cut costs. To decrease the number of cultivations, and therefore labour and fuel costs, many farmers have adopted ploughless techniques, ranging from minimal tillage (tillage to a maximum depth of 10 cm by means of a tine cultivator) to conservation tillage with direct drilling (plant residues left on the soil surface and crops established by direct drilling into undisturbed soil) (Rasmussen 1999). Direct drilling is not thought to be suitable for sandy soils, because of problems with compaction, nor does it provide much cost saving, owing to the low draught requirements in these soils. However, some form of reduced tillage and residue management may help protect the soil surface, conserve organic matter, promote aggregate stability and thus reduce erosion.

Worldwide, many studies have shown that ploughless tillage can decrease runoff and erosion (e.g. Gaynor & Findlay 1995; Basic *et al.* 2001), whereas in the UK there have been few evaluations. Chambers *et al.* (2000) reported that runoff and soil losses from tine cultivation treatments were consistently, but not significantly, less than those from ploughed treatments during rainfall simulation experiments on a loamy sand soil. They attributed this to greater residue cover on the tined soil, even though the ploughed soil had a denser crop cover. They also found that ploughless tillage lessened the amount of surface crusting on medium silt and loam soils.

Contour (across-slope) cultivations are also effective in controlling soil erosion and have been adopted in mechanized agriculture in many parts of the world. However, in the UK they are usually avoided because machinery may slip downslope in wet conditions or even overturn on very steep slopes (Chambers *et al.* 2000).

In this study we assessed the impacts of minimal tillage and across-slope cultivations on runoff generation, soil erosion and yields under arable cropping using the results from 10 years of monitoring water erosion and runoff at the Woburn Erosion Reference Experiment.

METHODS

Data were collected from eight erosion plots located at Woburn Experimental Farm, Bedfordshire, UK (0°33′5″W, 52°0′45″N). Soils at the site are derived mainly from the Lower Greensand and range in texture from loamy sand to sandy loam, corresponding to the Cottenham and Lowlands series defined by Clayden & Hollis (1984). In the US Soil Taxonomy (Soil Survey Staff 1999), these correspond to Lamellic Ustipsamment and Udic Haplustept, respectively. Mean particle size distribution of the Cottenham series topsoil (loamy sand) is given in Table 1. The Lowlands series topsoil is usually similar, but its subsoil horizons are finer (sandy loam) than those of the Cottenham series. Slopes on the site range from 7 to 13%. Details of the treatments and cropping patterns are given in Tables 2 and 3. The treatments were established after harvest in 1987 and the runoff collectors installed prior to the first crop of potatoes in 1989. This was followed by two winter cereals, then sugar beet and two more years of winter cereals, a rotation common in the area. The rotation was repeated twice in 10 years, but with fodder beet replacing sugar beet in the second rotation.

Table 1. Soil particle size for the Cottenham Series soil at Woburn Experimental Farm.

Particle size	%
Coarse sand (>600 μm)	1.7
Medium sand (212–600 μm)	44.9
Fine sand (63–212 μm)	36.3
Silt (2–63 μm)	9.7
Clay (<2 μm)	5.9

Table 2. Treatments at the Woburn Erosion Reference Experiment.

Cultivation direction	Tillage[a]
Up-and-downslope (U)	Minimal (M)
Across-slope (A)	Standard (S)
Up-and-downslope (U)	Standard (S)
Across-slope (A)	Minimal (M)

[a] Minimal tillage (cultivation to 10 cm depth) with crop residues retained and standard tillage (mouldboard plough) with residues removed.

Two main treatments were used in the experiment: cultivation direction, either up-and-downslope (U) or across-slope (A), and tillage type: (i) minimal tillage (M) – for cereals straw was chopped, for potatoes and beet the haulm and tops were retained, both were partially incorporated by shallow tines or discs to 10 cm depth; (ii) standard tillage (S) – for cereals straw was baled and removed, potato haulm and beet tops were raked up and removed, and the plots were then mouldboard ploughed.

Seedbeds for cereals on all plots were formed using a rotary harrow and were drilled using a conventional seed drill. Potatoes and sugar beet were planted and harvested using standard equipment. Fodder beet was harvested by hand because of problems with finding a suitable harvester. Between crops the M plots were left in the post-harvest condition, that is stubble for cereal, and S plots were ploughed. Fallow periods were of variable duration (Table 3). Under this range of management conditions, little subsoil compaction occurred, so no subsoiling was necessary during the period of the experiment.

The eight plots were arranged in two blocks, each with all four combinations of the two treatments. Each plot measured 25 m by 35 m (0.0875 ha) and was isolated from the rest of the slope by a low earth bund. Water and soil flowing down each plot were channeled to a collecting trough and through a pipe to two 2000 litre tanks where they were stored until sampled. The amounts of runoff and soil loss from each plot were measured as soon after each runoff event as practically possible and usually within 48 hours.

Yield data were collected at harvest from each of the plots. They were also collected in the year prior to the experiment, when treatments had been imposed on the site but runoff collectors were not yet in place.

Statistical analyses of the sediment and runoff data were by STATISTICA (Statsoft 1997) and the yield data were analysed using GENSTAT (Lawes Agricultural Trust 2001).

Table 3. Planting and harvest dates, crop, rainfall, number of rain days and the maximum number of runoff events of the Woburn Erosion Reference Experiment from 1988 to 1998.

Year	Planting date	Harvest date	Crop	Rainfall (mm)	Rain days	Maximum number of erosion events
1988	30 Mar 1988	17 Aug 1988	Spring barley			
1989	10 May 1989	10 Oct 1989	Potatoes	153	47	1
1989			Fallow	45	12	1
1989/90	31 Oct 1989	17 Aug 1990	Winter wheat	459	105	13
1990			Fallow	37	12	0
1990/91	22 Sep 1990	6 Aug 1991	Winter barley	512	152	2
1991/92			Fallow	335	96	1
1992	9 Apr 1992	16 Nov 1992	Sugar beet	597	118	10
1992			Fallow	172	42	9
1992/93	26 Jan 1993	19 Aug 1993	Winter wheat	350	91	2
1993			Fallow	201	36	0
1993/94	15 Oct 1993	26 Jul 1994	Winter barley	493	152	7
1994/95			Fallow	495	144	2
1995	12 Apr 1995	19 Sep 1995	Potatoes	227	53	1
1995			Fallow	42	13	1
1995/96	9 Oct 1996	16 Aug 1996	Winter wheat	43	128	5
1996			Fallow	48	19	0
1996/97	2 Oct 1996	19 Aug 1997	Winter barley	429	148	2
1997/98			Fallow	326	99	1
1998	19 Mar 1998	29/10–10/11/98	Fodder beet	561	146	5

The total number of events was determined by those occurring on Plot 7 of the experiment, which produced runoff and erosion whenever it occurred anywhere on the site.

RESULTS

Temporal patterns of soil loss and runoff

The distribution of monthly rainfall, runoff and soil loss between 1988 and 1998 is given in Figure 1 for one plot with each treatment combination. Runoff and soil loss generally occurred in the winter months, when the ground had a sparse vegetation cover and the soils usually had water contents close to field capacity. In the 10 years of the experiment there were four major periods of runoff and soil loss: 1989/90; 1992/93; 1995/96 and 1998. In 1989/90 and 1995/96, winter wheat was planted later than usual leading to a sparse vegetation cover. This exposed the soil surface to raindrop impact, which caused structural degradation and the formation of a surface crust. Combined with greater than average rainfall, this led to runoff and erosion. Periods of erosion in mid-winter 1992/93 and autumn 1998 were associated with the sugar and fodder beet crops, which were planted in the late spring and harvested in the late autumn. Sugar beet is well known for leaving soils vulnerable to soil erosion: it is planted in rows, which act as channels for overland flow, and its canopy develops slowly, leaving large areas of soil exposed to rainfall when intense convectional storms are frequent. Heavy machinery used during the harvesting of beet crops can compact the topsoil leading to lower infiltration rates, and therefore more runoff and erosion. The effects of slow canopy development and localized topsoil compaction during harvesting were both observed in 1992 and 1998. Figure 1a also shows that the magnitude of individual event losses was very variable and not always explained by monthly rainfall. Instead, individual event losses probably depended on the complex interaction of antecedent soil conditions, storm rainfall intensity patterns and development of the crop canopy.

Effect of treatments on event soil loss and runoff

The mean event soil loss from the across-slope (A) plots (148 kg ha^{-1}) was less than that (262 kg ha^{-1}) from the up-and-downslope (U) plots (Table 4), but the difference was not statistically significant ($P > 0.05$). However, the volume of runoff from the A plots (0.82 mm) was significantly less ($P < 0.01$) than from the U plots (1.32 mm). Minimal tillage (M) decreased both runoff and soil loss compared with standard tillages, but the differences were not significant ($P > 0.05$). When the treatments were combined there was a strong interaction between A and M, resulting in a significantly smaller soil loss ($P < 0.05$) from AM plots than either UM or US, and significantly smaller runoff ($P < 0.01$) from AM than for all other treatments.

Over the 10 years of the experiment a mean of 16.5 t ha^{-1} of soil was lost from the U plots, compared with a mean of 6.4 t ha^{-1} from the A plots (Table 5); M plots lost 9.8 t ha^{-1} and S plots 13.1 t ha^{-1}, but no difference was significant. Mean cumulative runoff followed a similar pattern, with the most runoff from the U plots and the least from the A plots, although differences were not significant. Differences in runoff between the combined treatments were also not significant. The cumulative soil loss and runoff from the plots were largest from the UM and US combinations, and the AM plots produced the lowest soil loss and runoff.

The mean number of events yielding sediment (Table 5) was significantly fewer ($P < 0.01$) on the A plots (33) than the U plots (52). There were no other significant differences in the number of events, although the AM (34) and AS (32) treatments both had fewer erosion events than the UM and US (52 for both).

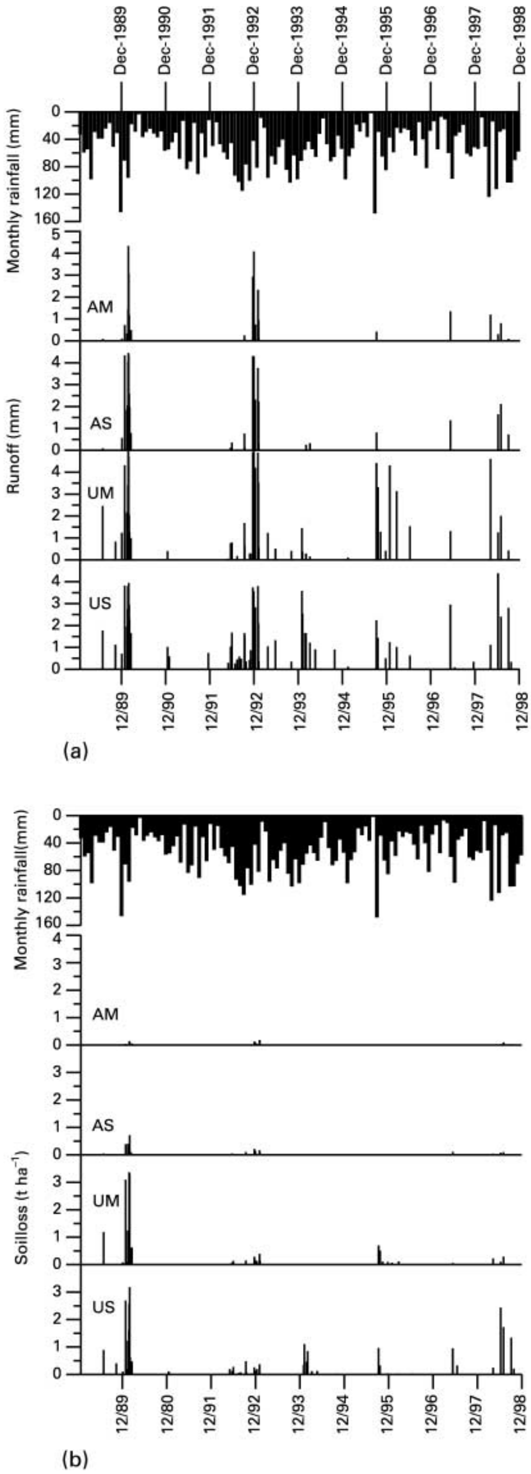

Figure 1. Distribution of (a) monthly rainfall and event runoff and (b) monthly rainfall and event soil losses for one plot from each combination of treatments at the Woburn Erosion Reference Experiment. Treatment key: U, cultivations up-and-downslope; A, cultivations across-slope; M, minimal tillage with crop residues retained; S, standard tillage with residues removed.

Effect of treatments on crop yields

In most years the treatments had no significant effect on crop yields (Table 6). However, in 1988, 1996 and 1997 cereal yields were significantly ($P < 0.05$) less on the U plots than on the A plots, and in 1991 winter barley yields were significantly ($P < 0.05$) less on the M plots ($6.32\,t\,ha^{-1}$) than on the S plots ($8.29\,t\,ha^{-1}$). The only year when a significant difference was found between the combined treatments was in 1988, the year before the installation of the runoff traps, when the US combination produced a significantly lower spring barley yield ($4.62\,t\,ha^{-1}$) than UM ($5.18\,t\,ha^{-1}$), AM ($5.25\,t\,ha^{-1}$) and AS ($5.53\,t\,ha^{-1}$). The UM yield was significantly less than the AS yield.

Although there were few significant differences between yields, it is worth noting that A plots had higher yields than U plots in 10 of the 11 years, and in 7 years the S plots were higher yielding than the M plots. This is reflected in the treatment combinations, as AS and AM were the highest yielding plots in seven and four years, respectively. The combinations with the lowest yields were UM (6 yr), US (4 yr) and AM (1 yr). Averaged over the 10 years of the experiment, the yields of the A plots were 15.7% greater than those of the U plots, and those of the M plots were 6% less than those of the S plots.

DISCUSSION

Soil and water conservation

Our results show that soil erosion at Woburn is normally associated with periods of sparse or zero crop cover and that across-slope cultivation can significantly decrease soil erosion, especially where it is combined with minimal tillage. Planting winter crops as soon as practically possible so that a dense cover is obtained early in the season is a well known erosion control strategy, and is recommended by the Environment Agency (2001) and the Ministry of Agriculture, Fisheries and Food (1997). Avoiding periods of sparse cover is more difficult with spring sown row crops as their canopy tends to develop slowly and they are harvested late, either leaving bare ground through the winter or forcing the late establishment of a winter cereal with associated poor cover development. We agree with the Environment Agency (2001) and the Ministry of Agriculture, Fisheries and Food (1997) in recommending not to plant row crops, such as sugar beet, on steep slopes. After late harvests we suggest that fields should be left in stubble or ploughed to produce a rough surface to impede overland flow. Where soils are compacted, as may occur locally after harvesting beet crops, drainage can be aided by subsoiling below the depth of compaction (Batey 1989). However, we rarely encountered this problem.

Our results also suggest that crops should be planted across-slope using minimal tillage, where practically possible. Across-slope cultivations produce a barrier to surface runoff, reducing its velocity and giving it more time to infiltrate, thus reducing runoff and erosion. Also, crop yields appear to be improved, possibly because of better water conservation in drought-prone sandy soils. Runoff may also be reduced on the minimal plots by the partial incorporation of crop residues, which helps protect the soil surface from raindrop impact. It is widely believed that minimal cultivation is of less value with sandy than finer textured soils because of decreased crop yields compared

Table 4. Effect of cultivation direction and tillage type and their combinations on the mean event soil loss and runoff ± one standard deviation at the Woburn Erosion Reference Experiment from 1988 to 1998.[a]

Treatment[b]	Event soil loss (kg ha^{-1})	No. of plot events	Event runoff (mm)	No. of plot events
U	262 ± 566	252	1.32 ± 1.35cc	248
A	148 ± 774	252	0.82 ± 1.26cc	248
M	156 ± 437	252	0.99 ± 1.31	248
S	253 ± 855	252	1.15 ± 1.35	248
UM	245 ± 571a	126	1.41 ± 1.50ddg	124
US	278 ± 563b	126	1.24 ± 1.19ee	124
AM	67 ± 202ab	126	0.58 ± 0.92ddeeff	124
AS	229 ± 1072	126	1.07 ± 1.49ffg	124

[a]Data marked with one and two letters the same are significantly different at $P < 0.05$ and $P < 0.01$, respectively.
[b]Treatment key: U, cultivations up-and-downslope; A, cultivations across-slope; M, minimal tillage with crop residues retained; S, standard tillage with residues removed.

with conventional tillage. However, we recorded a significantly lower yield with minimal tillage in only 1 of the 10 years, and the mean yield penalty over the 10 years was just 6%. The decreased value of crops with minimal tillage would be offset, at least partly, by decreased cultivation costs.

Although we would expect erosion to decrease if across-slope cultivation were more widely used by farmers, there are barriers to adoption of this practice. There are concerns about the effectiveness and stability of farm equipment when working across steeper slopes (Morgan 1992, Chambers *et al.* 2000). There is also a potential risk of concentrating runoff in slope concavities and thus increasing the severity of erosion when the concavities overflow (Morgan 1992). The United States Department of Agriculture gives detailed guidance for contour (across-slope) farming (Natural Resources Conservation Service 2000), but suggests that it is not suitable on slopes greater than 10% or on rolling topography. Particular difficulties are likely to be encountered with heavy sugar-beet harvesters which can slip down the slope in wet conditions. Although we accept these difficulties with across-slope cultivation, we suggest that further evaluation at field scale in the UK is desirable, given the yield increases and the reductions in runoff and erosion that we observed.

Table 5. Effect of the cultivation direction and tillage type and their combination on the sum ± one standard deviation of the soil loss and runoff at the Woburn Erosion Reference Experiment from 1988 to 1998.[a]

Treatment	Sum of soil loss (t ha^{-1})	Sum of runoff (mm)	Number of erosion events[b]	No. of plots
U	16.48 ± 10.48	82 ± 23	52 ± 8aa	4
A	6.42 ± 5.70	51 ± 20	33 ± 6aa	4
M	9.82 ± 7.70	62 ± 31	42 ± 13	4
S	13.07 ± 11.98	72 ± 23	43 ± 13	4
UM	15.46 ± 5.43	87 ± 13	52 ± 5	2
US	17.49 ± 17.20	77 ± 36	52 ± 13	2
AM	4.18 ± 4.57	36 ± 9	32 ± 8	2
AS	8.66 ± 7.52	66 ± 11	34 ± 4	2

[a]Data marked with two letters the same are significantly different at the $P < 0.01$ level. [b]The number of erosion events is the number of events where a recordable amount of sediment was collected.
For treatment key, see Table 4.

Soil erosion rates

If the total soil loss values over the 10 years of the experiment (Table 5) are recalculated to give mean annual rates, the range of soil loss (0.41–1.7 t ha^{-1} yr^{-1}) is of the same order as estimated rates of 0.62 and 0.89 t ha^{-1} yr^{-1} (1973–79) on the same site prior to establishment of the experiment (Morgan *et al.* 1987), though lower than the upper end of the range 0.3–44.4 t ha^{-1} yr^{-1} found under similar land uses in the neighbouring area by the same authors. Evans (2002) gave eroded volumes of 1–5 m^3 ha^{-1} yr^{-1} for a range of different crops grown in the UK based on aerial photograph interpretation and field survey. Converted to volumes, the amounts measured at Woburn (0.3–1.24 m^3 ha^{-1} yr^{-1}) are near the lower the lower end of this range. Our results may have been artificially reduced by the use of bunds; the measurements by Morgan *et al.* (1987) were for open plots and the field survey results of Evans (2002) were for slopes of variable length. The effect of plot boundaries on reducing runoff and erosion is an inherent problem with the field plot method of measuring soil erosion. However, it provides the most precise method of comparing treatment effects and is therefore a reliable basis for recommendations to farmers.

CONCLUSIONS

Our results show that erosion on sandy soils can be minimized at source without recourse to edge-of-field solutions to erosion control, such as buffer strips. Many sandy soils in the UK are low in organic matter and have weak surface structure, which makes them vulnerable to surface sealing. Once sealed, infiltration rates are greatly reduced and runoff and erosion often follow. We support the advice currently given to farmers to plant autumn sown crops as early as possible to minimize erosion, and not to plant crops such as sugar beet, which lead to a high erosion risk, on steep slopes. Our work shows that cultivation across the slope and minimal tillage can be valuable additional tools for decreasing the amounts of runoff and erosion from these sandy soils. The minimal cultivation used in this study retained and incorporated residues from the previous crop, and this probably increased the infiltration rate. By using shallow cultivations during autumn we were able to avoid the worst compaction, which can be a problem on

Table 6. Mean crop yields (t ha^{-1}) ± one standard deviation at the Woburn Erosion Reference Experiment for the years 1988 to 1998. Cereal yields are given as grain at 85% dry matter, potatoes as clean tubers, and fodder and sugar beet as the mass of clean wet beet averaged from a harvest across-slope and up-and-downslope.

Treatment	1988 S. Barley	1989 Potatoes	1990 W. wheat	1991 W. barley	1992 Sugar beet	1993 W. wheat	1994 W. barley	1995 Potatoes	1996 W. wheat	1997 W. barley	1998 Fodder beet
U	4.90 ± 0.33a	28.40 ± 4.18	4.57 ± 1.74	7.03 ± 1.44	61.00 ± 2.55	6.19 ± 0.51	2.94 ± 1.27	14.50 ± 1.30	3.48 ± 1.55 g	0.62 ± 0.61h	59.09 ± 13.19
A	5.39 ± 0.21a	35.38 ± 3.68	5.04 ± 0.83	7.50 ± 1.22	65.33 ± 7.44	6.25 ± 0.52	2.57 ± 1.43	15.48 ± 3.23	4.65 ± 1.13 g	1.88 ± 0.93h	73.49 ± 6.88
S	5.07 ± 0.53	32.38 ± 6.44	4.85 ± 0.82	8.29 ± 0.68f	65.18 ± 3.83	6.33 ± 0.29	3.45 ± 0.82	13.78 ± 0.76	4.02 ± 1.41	1.30 ± 1.01	69.71 ± 6.10
M	5.21 ± 0.13	31.40 ± 4.63	4.76 ± 1.78	6.23 ± 0.65f	61.15 ± 6.98	6.11 ± 0.64	2.06 ± 1.34	16.20 ± 2.87	4.11 ± 1.60	1.20 ± 1.13	62.86 ± 17.06
UM	5.18 ± 0.11bc	29.30 ± 6.22	4.43 ± 2.81	5.86 ± 0.83	60.05 ± 3.89	6.10 ± 0.76	2.43 ± 1.36	15.45 ± 0.07	3.63 ± 2.04	0.43 ± 0.34	51.50 ± 17.04
US	4.62 ± 0.00bddee	27.50 ± 3.25	4.72 ± 1.04	8.20 ± 0.24	61.95 ± 0.92	6.28 ± 0.42	3.45 ± 1.40	13.55 ± 1.20	3.34 ± 1.70	0.82 ± 0.93	66.68 ± 1.24
AM	5.25 ± 0.19dd	33.50 ± 2.83	5.09 ± 1.11	6.61 ± 0.10	62.25 ± 11.24	6.12 ± 0.81	1.69 ± 1.73	16.95 ± 4.74	4.60 ± 1.61	1.98 ± 1.14	74.23 ± 8.17
AS	5.53 ± 0.12cee	37.25 ± 4.31	4.99 ± 0.92	8.39 ± 1.14	68.40 ± 1.27	6.39 ± 0.25	3.45 ± 0.21	14.00 ± 0.28	4.70 ± 1.10	1.78 ± 1.12	72.75 ± 8.56

[a]Data marked with one and two letters the same are significantly different at $P < 0.05$ and $P < 0.01$, respectively.
For treatment key, see Table 4.

direct drilled sandy soils (Ministry of Agriculture, Fisheries and Food 1983). The yield decrease with minimal cultivation was small (6%) when averaged over the 10 years of the experiment and significant in only one year (with winter barley). In terms of practical farming, the decreased value of crops would be partly offset by the lower cost of soil cultivation.

Across-slope crop cultivation forms a second line of defence: if soil and water are already moving over the surface, the barriers formed by the across-slope tillage and crop rows can slow their progress. However, there is a danger that on complex slopes water will accumulate in low points, and then break through to form large rills or gullies. There are also problems with the stability of machinery working across the slope. These problems will need to be addressed before more widespread adoption of across-slope cultivation is encouraged. For this reason we recommend that across-slope cultivations and reduced tillage with residues partially incorporated into the topsoil are evaluated at field scales on various soil types and slope configurations to resolve these problems. Our results also suggested a small (15.7%) mean yield benefit from across-slope compared with up-and-downslope cultivation, which should encourage farmers to adopt this technique.

ACKNOWLEDGEMENTS

We thank the staff of Woburn Experimental Farm for maintaining the plot treatments, the Soils Laboratory of the National Soil Resources Institute for technical support, Alan Todd for statistical help with the yield data, and the financial support the European Commission (EV4VI*1591 and PL900247).

REFERENCES

Basic F Kisic A Butrac O Nestroy O & Mesic M 2001. Runoff and soil loss under different tillage methods on Stagnic Luvisols in central Croatia. Soil and Tillage Research 62, 145–151.

Batey T 1989. Soil husbandry: a practical guide to the use and management of soils. Soil and Land Use Consultants Ltd, 125 Blenheim Place, Aberdeen AB25 2DL UK.

Boardman J 1990. Soil erosion on the south Downs: a review. In: Soil erosion on agricultural land, eds J Boardman IDL Foster & JA Dearing, Wiley Chichester UK pp 87–105.

Chambers BJ Garwood TWD & Unwin RJ 2000. Controlling soil water erosion and phosphorus losses from arable land in England and Wales. Journal of Environmental Quality 29, 145–150.

Clayden B & Hollis JM 1984. Criteria for differentiating soil series. Soil Survey Technical Monograph No. 17, Soil Survey of England and Wales, Rothamsted Experimental Station Harpenden Herts AL5 2JQ UK. Obtained from NSRIC, Cranfield University Silsoe Campus Bedford MK45 4DT UK

Environment Agency 2001. Best farming practices: profiting from a good environment. R&D Publication 23, Environment Agency, Rio House Aztec West Almondsbury Bristol BS32 4UD UK.

Evans R 1971. The need for soil conservation. Area 3, 20–23.

Evans R 1992. Rill erosion in contrasting landscapes. Soil Use and Management 8, 170–175.

Evans R 2002. An alternative way to assess water erosion of cultivated land – field-based measurements and analysis of some results. Applied Geography 22, 187–208.

Fisher MA 1868. On the denudations of Norfolk. Geological Magazine 5, 544–558.
Gaynor JD & Findlay WI 1995. Soil phosphorus loss from conservation and conventional tillage in corn production, Canada. Journal of Environmental Quality 24, 734–741.
Holman IP, Hollis JM & Thompson TRE 2002. Impact of agricultural soil conditions on floods – autumn 2000. R&D Technical Report W5B-026/TR, DEFRA/Environment Agency Rio House Aztec West Almondsbury Bristol BS32 4UD, UK.
Lawes Agricultural Trust 2001. GENSTAT 4.21. Rothamsted Experimental Station Harpenden Herts AL5 2JQ UK.
Ministry of Agriculture, Fisheries and Food 1983. Soil examination for autumn cultivations. MAFF Leaflet 802, Ministry of Agriculture, Fisheries and Food, Lion House Willowburn Estate Alnwick Northumberland NE66 2PF UK.
Ministry of Agriculture, Fisheries and Food 1997. Controlling soil erosion. MAFF Publications, ADMAIL 6000 London.
Morgan RPC 1977. Soil erosion in the United Kingdom: field studies in the Silsoe area. National College of Agricultural Engineering, Cranfield Institute of Technology Silsoe Bedford MK45 4DT UK.
Morgan RPC 1992. Soil conservation options in the UK. Soil Use and Management 8, 176–180.
Morgan RPC, Martin L & Noble CA 1987. Soil erosion in the United Kingdom: a case study from mid-Bedfordshire. Occasional Paper No. 14, Silsoe College Cranfield Institute of Technology Silsoe Bedford MK45 4DT UK.
Natural Resources Conservation Service 2000. Contour farming. Code 330, United States Department of Agriculture, Natural Resources Conservation Service Washington DC.
Quinton JN, Catt JA & Hess TM 2001. The selective removal of phosphorus from soil: Is event size important? Journal of Environmental Quality 30, 538–545.
Rasmussen KJ 1999. Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. Soil and Tillage Research 53, 3–14.
Soil Survey Staff 1999. Soil Taxonomy. a basic system of soil classification for making and interpreting soil surveys, 2nd edition. United States Department of Agriculture, Natural Resources Conservation Service Washington DC.
Statsoft 1997. STATISTICA 5.1. Statsoft Tulsa OK.

Received September 2003, accepted after revision May 2004.