Appendix 14. Soil and crop management effects on sediment and phosphorus mobilisation in surface runoff from three contrasting soil types in the Hampshire Avon catchment

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1. Introduction

Apart from the well established concern over the loss of soil as a natural resource, the transport of soil particles and associated pollutants in runoff from agricultural land causes a range of off-site environmental impacts. These include flood damage to property (Boardman et al., 1994), sedimentation of fish spawning gravels in rivers (Wood and Armitage, 1997; Acornley and Sear, 1999; Greig et al., 2005), and biological impacts on surface waters associated with agrochemicals (Cooper, 1993; Carpenter et al., 1998), including the effects of eutrophication with phosphorus (P). Phosphorus is considered by Mainstone and Parr (2002) to be the most important nutrient affecting the ecological quality of rivers in the UK. Much of the agriculturally-derived P entering waterbodies is associated with fine soil particles that are preferentially enriched with P that has been previously added in fertilizers and manures to soils (Sharpley and Smith, 1990; Edwards and Withers, 1998; Withers and Lord, 2002). Sediment-laden runoff also increases turbidity levels in rivers which can directly affect biotic processes, increase water treatment costs and local flood risk where excessive sediment accumulates in tributary channels reducing their effective transport capacity (Wood and Armitage, 1997; Harrod and Theurer, 2002). Sediment and P loads entering surface waters therefore need to be controlled to acceptable levels in order to preserve or improve good water quality, and the abundance and diversity of aquatic biota. This need is recognised, for example, in the recent introduction of the EU Water Framework Directive (European Commission, 2000) and the UK Catchment Sensitive Farming initiative (Department of the Environment, Food and Rural Affairs, 2004).

In reviewing the results from a number of catchment studies in the UK using fingerprinting techniques to trace sediment sources, Walling (2005) found that 60-96% of the suspended sediment (SS) measured in rivers during storm events is derived from surface sources as opposed to river channel banks or sub-surface sources. The highest surface soil contributions were associated with intensively cultivated lowland catchments, and it is in these areas where combinations of vulnerable soils, cultivation frequency, timing and method, and lack of crop cover during storm events most often causes significant erosion and off-site impacts (Boardman, 1990; Evans, 1990; Chambers et al., 2000). Although one of the more pragmatic technical advances in recent decades from an agronomic perspective, tramlines have also been implicated as a cause of increased surface runoff, soil erosion and transport of diffuse pollutants (Reed, 1979; Robinson and Naghizadeh, 1992; Basher and Ross, 2001; Kay et al., 2005; Silgram, 2005). Tramlines not only reduce infiltration rates due to the soil compaction created beneath the tractor wheel, but also act as a channel for any runoff that is initiated due to the indentation of the soil, especially after multiple tractor passes (Fullen and Reed, 1987). Rill erosion is therefore often associated with tramlines that run parallel with the hillslope due to the critical shear stress of water flow created by this channelling effect and subsequently encroaching on the surrounding soil (Basher and Ross, 2001).

Survey data shows that rill and gully erosion is most frequently associated with recently cultivated land that is left bare during autumn and winter storms, the presence of compacted wheelings and tramlines, and valley floor features (Reed, 1979; Skinner and Chambers, 1996;

Chambers et al., 2000). Significant amounts of fine sediment may also occur in sheetwash from soils without any visible signs that erosion has occurred (Fraser et al., 1999; Stone and Walling, 1996)). Fine sediment is preferentially enriched in P and is more likely to stay in suspension long enough to reach the watercourse (Walling, 2005). Where fields and tramlines become hydrologically connected to a waterbody, for example via a gateway and road, or farm track, then sediment and P mobilised in field runoff will enter watercourses and contribute to siltation and eutrophication. Land use management has a potentially large influence on runoff generation, sediment and P mobilisation and the proportion of the catchment area contributing sediment and associated pollutants to the watercourse (Auzet et al., 1993; Souchere et al., 1998). Hence, measures to control sediment and P loss need to be targeted at contributing fields that have both a high potential for P loss and hydrological connectivity to the watercourse. In-field ‘source’ control is therefore an important part of the integrated approach to catchment management required for diffuse pollution control (Withers and Jarvis, 1998).

A number of improved soil and crop management practices have been identified to help reduce in-field sediment and P mobilisation in the UK, often at relatively low cost. These include providing adequate crop cover during critical periods, avoidance of compaction by timely cultivations, incorporating organic matter to improve structural stability and changing cultivation method and/or cultivation and tramline direction on sloping fields (Morgan, 1992; Defra, 1999; Chambers et al., 2000; EA 2001). Most research has been directed at cultivation methods (reduced cultivations or conservation tillage) and cultivation direction in relation to the slope. Reduced cultivations includes, at least in Europe, direct drilling (no cultivation prior to drilling), shallow (<10 cm) tillage without soil inversion and deep (>10 cm) tillage without inversion (Davies and Finney, 2002). In theory, reduced cultivation techniques offer a number of benefits including lower energy (cultivation) costs, decreased susceptibility to soil structural degradation, carbon sequestration and a richer biological community in the soil (Uri et al., 1998; Holland, 2004). A large number of research studies have reported large reductions in runoff and erosion when reduced cultivations or conservation tillage techniques have been adopted (Carter, 1998; Rasmussen, 1999), with studies by Jordan et al. (2000), Chambers et al. (2000) and Quinton and Catt (2004) of relevance to the U.K.

In practice, however, reduced cultivations have led to reduced yields in some instances, and have been variably effective for erosion control because the technique must be adapted to the local soil and climatic conditions, requiring a higher degree of management skill. Particular problems in the UK have been encountered with build-up of grass weeds, poor crop establishment because of increased pest damage and/or severe topsoil compaction where the technique has been adopted on structurally unstable soils (Davies, 1988; Davies and Finney, 2002). A number of studies have also highlighted an increase in the more biologically active ‘dissolved’ fraction of P under conservation tillage due to the preferential accumulation of available P at the surface of non-inverted soils (Johnston et al., 1979; Sharpley and Smith, 1994; Gaynor and Findlay, 1995; Carter, 1998). In one study, the increase in dissolved P increased P export even though the transport of soil particulate-P was reduced (Gaynor and Findlay, 1995). Increases in leaching of other more mobile nutrients has also been recorded (Carter, 1998) These data suggest that variable effects can be produced depending on site conditions and that reduced cultivation techniques must be linked to improved crop and nutrient management to achieve lasting environmental benefits. Similarly, field studies also suggest that cultivating on the contour is not always successful due to variability in slope form, channelling effects and safety considerations (Morgan, 1992; Schonning et al., 1995; Quinton and Catt, 2004).

Whilst there is much information on the effects of reduced cultivation methods, there is virtually no information on the effects of cultivation timing on sediment and P loss risk, or on the interaction between cultivation timing and cultivation methods. Early drilling to quickly establish a crop cover has been identified as a key management option to reduce erosion risk (Morgan, 1992; Chambers et al., 2000; Quinton and Catt, 2004), yet there is very little quantitative information on the effectiveness of this technique across a range of soil types. Late cultivation under adverse soil moisture conditions was considered to be a major contributory factor for the increased incidence of erosion on the southern chalklands of England (Boardman, 1990). Martin (1999) found that late cultivations led to the highest rates of runoff and erosion in a comparative study of cultivation and cropping techniques to control 'muddy flooding' in Northern France. This report presents a comparison of cultivation method, cultivation timing and the presence of tramlines on the amounts of runoff, sediment and P generated in infiltration excess overland flow from field demonstration plots established in the Hampshire Avon catchment, which suffer the effects of diffuse pollution.

2. Materials and Methods

2.1 Site description

In 1999, a catchment management initiative called *Landcare* was started in the Hampshire Avon river basin upstream of Salisbury, England to help reduce the agriculturally-derived loads of pollutants, particularly SS and P entering the major tributaries (Huggins, 1999; Environment Agency, 2002). As part of this initiative, farmer demonstration plots were established at field sites on the three major lithologies that dominate the catchment: Upper Chalk (Wilton), Upper Greensand (Pewsey) and Kimmeridge Clay (East Knoyle). The demonstration events were organised by the Environment Agency (EA) for farmers and their advisers to encourage the adoption of more sensitive soil and land management practices required to help reduce the risk of runoff, sediment and P loss in the catchment. To supplement this demonstration activity, the field sites were monitored over two winter periods (2002/03 and 2003/04) to provide supporting data on the effects of specific land management practices on runoff generation and mobilisation of sediment and P in the runoff.

The field sites were chosen to be representative of the landscape type and contrasted strongly in soil physical and chemical characteristics (Table 1). At Pewsey, the soil had a high content of fine sand (Ardington Association) making it susceptible to sealing, or capping, of the soil surface causing increased risk of surface runoff and erosion. The site was moderately sloping (5°) and had been in continuous arable cropping for many years with low levels of organic matter (ca. 2.3%), but average levels of soil P fertility (ca. 30 mg kg^{-1}Olsen-extractable P). The arable soil at Wilton was shallow, highly calcareous and free draining (Upton Association) but with steep slopes (8°) and very low levels of Olsen-extractable P (ca.10 mg kg^{-1}) despite the high soil total P content. The heavy clay soil (Whickham Association) at East Knoyle was underdrained and contained a higher amount of organic matter than the other two sites with variably high soil P fertility (46–67 mg kg^{-1} Olsen-extractable P) reflecting a history of grass-based dairy farming and frequent manure application. The sites therefore differed markedly in their hydrological characteristics, in their inherent susceptibility to erosion and the degree of P enrichment from past fertilisation.

2.2. Treatment details

The demonstration plots were cultivated and drilled either early (E) or late (L), and adopting either traditionally cultivations (TC) or reduced cultivations (RC), providing four treatment combinations: E-TC, E-RC, L-TC and L-RC. An example of the experimental layout is given in Fig.1. The plots were not replicated but were large in size (20 m by 20 m) as required for demonstration purposes. Site management was under the control of the farmer using local cultivation practices. At Wilton in 2002/03, the farmer did not establish the late drilled treatments due to very wet weather, and at East Knoyle in 2003/04 the L-TC treatment was replaced with an E-RC headland plot (hereafter referred to as ‘headland’) due to field size restrictions. Early drilling was usually at the end of September, but late drilling varied from late October to early January depending on the weather (Table 1).

Table 1. Site characteristics and treatment details.

	Pewsey		East Knoyle		Wilton	
	02/03	03/04	02/03	03/04	02/03	03/04
Site characteristics						
Cropping	WW	WO	WW	WW	WW	WW
Slope °	5	5	1	1	7	9
Soil parent material	Greensand		Kimmeridge clay		Upper Chalk	
Soil Association	Ardington		Wickham 2		Upton	
Topsoil texture	Fine sandy loam		Clay loam		Silty clay loam	
Subsoil texture	Sandy clay loam		Clay		Chalk rubble	
Sand (%)	67	67	8	6	17	16
Silt (%)	20	19	66	56	56	54
Clay (%)	13	14	26	38	27	30
pH	7.4	7.1	7.1	6.9	8.0	8.2
O.M. ($g\ kg^{-1}$)	21	25	51	86	41	42
$CaCO_3$ ($g\ kg^{-1}$)	<5	<5	5	25	720	590
Total P mg/kg	315	332	1120	1130	985	1000
Olsen-P mg/kg	33	32	67	46	11	9
Treatment details						
Early drilling dates	24 Sept	28 Sept	26 Sept	2 Oct	20 Sept	24 Sept
Late drilling dates	10 Jan	23 Oct	24 Oct	7 Nov	-	24 Oct
Cultivations – Traditional	Plough (22 cms) Press Tine harrow and drill		Plough (15-18 cms) Cambridge roller Power harrow (x1) Combi Drill		Plough (22cm) Rolled Tine harrow and drill Rolled	
Cultivations - Reduced	Heavy discs and press Tine harrow and drill		Heavy harrow (5-8 cms) Power harrow (x1) Combi drill		Heavy discs and press Tine harrow and drill Rolled	

WW, winter wheat; WO, winter oats.

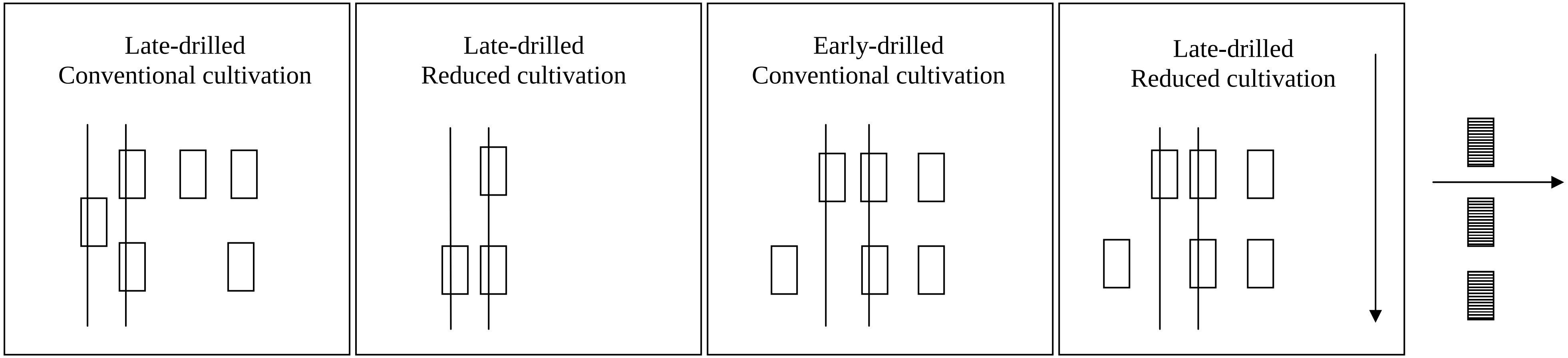

Figure 1. Layout of the experimental plots on the hillslope at Pewsey and the positioning of the runoff traps in relation to tramlines. The arrows indicate the direction of drilling. The shaded runoff traps were those located outside the plot areas where the direction of drilling was across slope.

Traditional cultivation included ploughing (with or without a press), and either tine harrowing or power harrowing before drilling. For the reduced cultivation treatment, the farmers adopted either heavy discs (Pewsey and Wilton), or a heavy harrow (East Knoyle) as the alternative to the plough (Table 1). At Wilton and Pewsey, the plots were drilled up and down the slope and tramlines established after drilling by one or more tractor passes. At East Knoyle, the plots were drilled across slope, except for the headland plot which was drilled parallel to the slope. Residues from the previous crop were returned to the soil and all sites grew winter cereals in both years (Table 1). At Pewsey, the same field plots were used in both years, whilst at Wilton and East Knoyle different fields were used to demonstrate the treatments each year.

2.3. Monitoring details

On each demonstration plot, three runoff traps each measuring 15m long by 2m wide were installed to monitor the mobilisation of SS and P in overland flow generated by successive storm events. At East Knoyle in 2002/03, prolonged wet weather prevented the installation of any runoff traps. The traps were hydrologically isolated by 30 cm deep stainless steel dividers driven into the ground, and each trap contained a tramline (Fig. 2a). A collecting tray was cemented in place at the bottom of each trap, and angled to direct the runoff to a 110mm-diameter pipe, which fed directly into a 500 litre covered fibreglass tank. After each major rainfall event, the runoff that had collected in the tanks was measured and recorded, and a 250 ml sub-sample taken for determination of SS and P concentrations. For some storm events where the measured volume of runoff was small, no samples were taken and the runoff was left in the tank until the next storm event. Once sampled, the tanks were emptied and cleaned in readiness for the next storm event. At the end of the monitoring period the connecting pipes were flushed through to collect any sediment retained in them. The traps were installed as soon as was practicable after drilling and removed in April to allow fertilizer and spraying operations on the field. The monitoring period for the early-drilled plots in 2002/03 was from 24 December to 12 March (10 sampled storm events) and in 2003/04 was from 5 November to 31 March (9 sampled storm events). The monitoring period for the late-drilled plots commenced on 22 January in 2002/03 and on 9 January in 2003/04, with typically 5 storm events monitored. Rainfall amount and intensity were measured at each site with an automatic rain gauge, supplemented as necessary with data from the nearest meteorological station.

To investigate separately the effect of tramlines, three additional replicate traps without a tramline were installed on selected treatments at Pewsey (Fig. 1). In the first year, traps with tramlines were installed before the traps without tramlines, which were installed only on the early-drilled treatments (E-TC and E-RC) and after the late-drilled treatments were established. The monitoring period for comparison was therefore relatively short (5 sampled storm events) from 17 January – 12 March . In the second year, the E-TC, E-RC and L-TC treatments were selected for comparison. For the early-drilled treatments, the monitoring period was from 22 October – 25 March (9 sampled events) and for the L-TC treatment, the monitoring period was from 23 December – 25 March (5 sampled events).

2.4. Soil physical measurements

A range of soil physical measurements were carried out to help explain any treatment differences in runoff observed. These measurements included: soil infiltration rate, vertical soil penetration resistance by cone penetrometer, horizontal soil shear strength by shear vane meter, bulk density, air capacity, a visual assessment of soil structure and an assessment of the degree of soil indentation created by the tranlines. The percentage bare ground was also determined at each site. Not all of these measurements were undertaken in the first year.

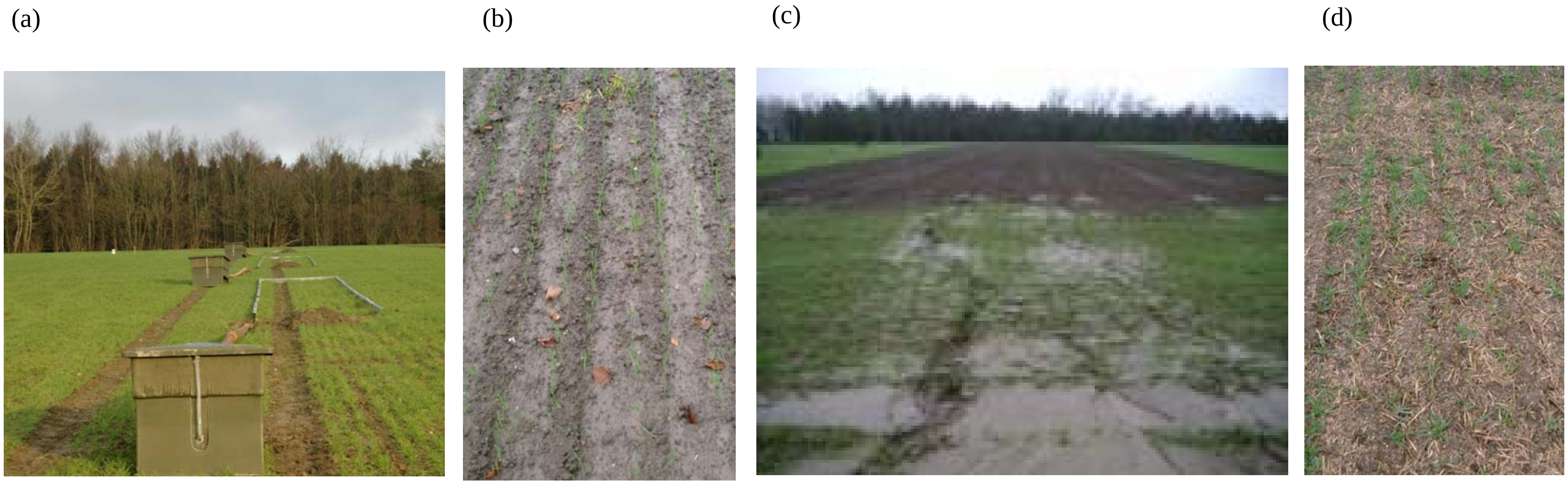

Figure 2. Experimental design at Pewsey showing (a) layout of replicate runoff traps, (b) capping of soil on traditionally cultivated treatment after heavy rain (Dec. 2002), (c) erosion on a late-drilled treatment before establishment, and (d) degree of crop cover on the reduced cultivated treatment (Dec. 2002).

Rates of water infiltration were determined using a double ring infiltrometer and a flooding technique (MAFF, 1982). Five (eight at Pewsey) replicate ring measurements were made on each demonstration plot, outside of the runoff trap area. After flooding of the inner and outer rings, the drop in water level in the inner ring was recorded every 10 minutes over a 5 hour period, and the average drop per hour over the this period was calculated as the mean infiltration rate.

Soil strength measurements carried out at constant moisture content can provide quantitative data on the degree of soil compaction (MAFF, 1982). Two assessments of soil strength were carried out: soil resistance to a horizontal shear stress using a Pilcon DR1176 Shear Vane fitted with a 19mm vane, and soil resistance to vertical stress, or penetration, using a Farnell drop cone penetrometer with a cone base area of 129 cm^2. Measurements were taken, where possible, to a minimum depth of 30 cm in either 5 cm (shear vane) or 7.5 cm (Penetrometer) increments. In the first year, shear vane measurements were taken from 12 replicate points within each trap, three of which were in the tramline. In the second year, this was increased to 15 replicate points, of which 5 were in the tramline. Penetrometer readings were taken from 30 replicate points within each runoff trap of which 10 were in the tramline.

In-tact soil cores of c. 220 cm^3 volume were taken from within the surface (0-10 cm) and sub-surface (10-25 cm) layers of the topsoil using stainless steel cylinders for determination of dry bulk density and air capacity. Five or six replicate samples were taken in May 2003 and January 2004 at each depth from each main demonstration plot outside of the trap areas. Soil structure was visually assessed according to a modification of the Pearlkamp method (MAFF, 1982), where a spadeful of soil was lifted to shoulder height and dropped, and the degree of structural disintegration was scored on a scale of 1-10 (1 = poor structure, 10 = good structure) by two separate people. The modification was based on the visual score assessment methodology developed in New Zealand (Manaaki Whenua Landcare Research, 2005). Ten measurements were taken on each demonstration plot outside of the trap areas. This was taken to be a very arbitrary but rapid assessment of coarse differences in structural stability between the treatments.

The percentage of bare ground on each treatment was assessed on 23 January and 8 April 2004 using a 0.25 m^2 quadrat divided into 25 x 0.01 m^2 sections. The assessments were undertaken at nine locations within each runoff trap, of which three were in the tramline and took into account the proportion of the trap area occupied by the tramline.

In the first year, differences in the indentation of the soil left by the tractor tyres in the tramline were assessed using a grassland ‘poaching’ meter. This meter consists of a series of free-floating metal spikes held in a horizontal bar and allowed measurements to be taken of the depth of the soil below field level at one cm intervals across the tramline. Nine replicate transects were taken along the tramline of the reduced cultivated and traditionally cultivated treatments to provide an average cross-sectional profile. In the second year, the depressions in the soil left by the tractor tyres on the early-drilled treatments were too shallow for this meter to be used effectively.

2.5. Analytical details

Particle size distribution, calcium carbonate, organic matter and pH, analyses on the soil were carried out according to standard laboratory techniques (MAFF, 1985). Soil test P was determined by the method of Olsen *et al.* (1954). Total P concentrations in soil and sediment were determined by Inductively-Coupled Plasma-Optical Emission Spectroscopy ICP-OES following aqua-regia digestion (MEWAM 1986). Runoff samples collected after each major storm event were analysed for suspended sediment (SS), molybdate-reactive P (MRP), total dissolved P (TDP) and total P (TP). Suspended solids in a known volume were weighed after passing through a 1.2 μm filter. All P fractions were determined colorimetrically according to the method of Murphy and Riley (1962), either directly (MRP) or following persulphate digestion (TDP and TP), (MEWAM 1980). TP was determined on unfiltered samples and MRP and TDP were determined after filtering through a 0.45μm filter. The difference between TP and TDP was assumed to be particulate P (PP) and the most appropriate P fraction to associate with the SS.

2.6. Statistical analyses

As there was no replication of the four main treatment combinations, data from the individual runoff traps were taken as independent treatment replicates and treatment effects analysed by a one-way ANOVA (Genstat 8 Committee, 2004). Treatment effects on mean values of measured parameters taken outside the runoff traps were determined by student t-test. The effects of the early-drilled treatment combinations (E-TC and E-RC) were evaluated over the full monitoring period. Comparisons of the late drilling treatment combinations with the early drilled treatment combinations were evaluated over the shorter monitoring period that followed the establishment of the late-drilled treatments. To enable calculation of cumulative SS and P export, a small number of erroneous or missing values were statistically interpolated. To allow better comparison between treatments, the cumulative amounts of SS and P collected over each monitoring period were adjusted according to the total runoff volume and reported as flow-weighted concentrations. In this context, flow-weighted P concentrations in mg l^{-1} are equivalent to kg P ha^{-1} per 100 mm of overland flow.

3. Results

3.1. Rainfall distribution patterns and observations after treatment establishment

The rainfall patterns after treatment establishment differed markedly between the two monitoring years providing a range of precipitation values for individual storm event sampling (Fig. 3). Prolonged heavy rain fell approximately 2 weeks after early drilling in 2002/03, and trap installation, and/or the establishment of the late treatments, was delayed or prevented. At Pewsey and Wilton, 320 mm of rain fell before the runoff traps could be installed on 4 December 2002. At the clay site at East Knoyle, soil conditions remained so wet that attempts to install the traps had to be abandoned. At Pewsey, the rain caused capping of the soil surface of the E-TC treatment (Fig. 2b), and the uncultivated plots designated for the late drilled treatments showed extensive rill erosion downslope (Figs. 2c). The E-RC plot showed little capping of the soil surface due to the presence of straw residues left from the previous cereal crop (Fig. 2d). Although, one major storm event occurred soon after the traps were installed, relatively little rain fell after the late-drilled treatments were established in early January 2003 at Pewsey (Fig. 3).

This pattern of rainfall contrasted strongly with that in the second year when very little rain fell directly after establishment of the early-drilled treatments, but heavier and more persistent rain followed the establishment of the late-drilled treatments in late October or early November 2003 (Fig. 3). Consequently, the runoff traps on the late-drilled treatments could not be installed until 23 December at Pewsey, and until 7 January at Wilton and East Knoyle. As in the first year at Pewsey, heavy rain falling onto the bare soil surface caused extensive capping, and eventually rill erosion down the tramlines on the late-drilled treatments. Gushing of runoff down tramlines was also observed on the late-drilled treatments at the more steeply sloping Wilton site, whilst increased runoff rates were observed only on the headland treatment at East Knoyle which was drilled up-and-down the slope. These effects were not observed on the early-drilled treatments in 2003/04 at any of the sites.

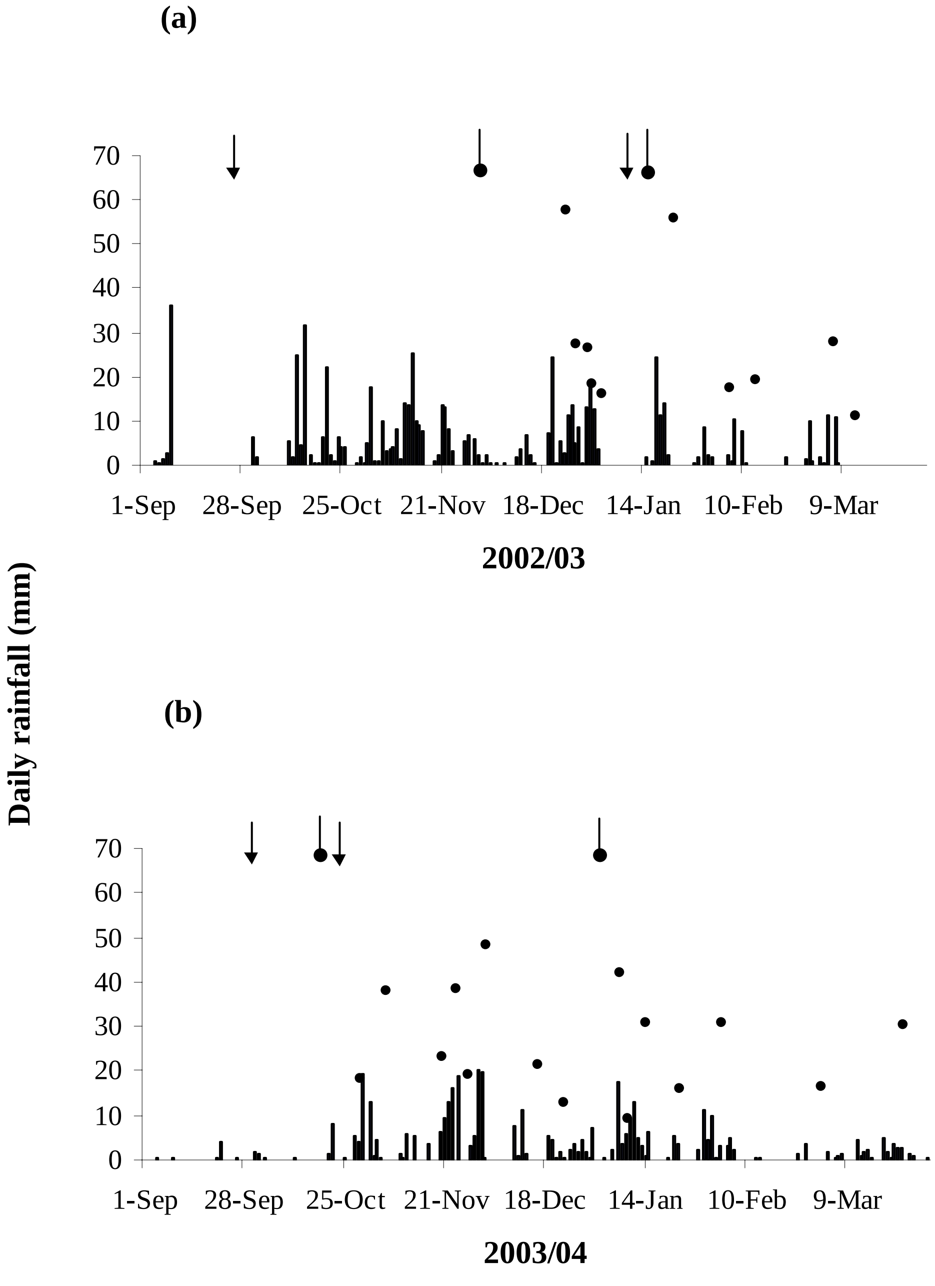

Figure 3. Daily rainfall over the monitoring periods in (a) 2002/03 and (b) 2003/04. The cumulative precipitation associated with each runoff sampling date is shown as a black circle. Arrows denote dates of treatment establishment (→) and trap installation (—●).

3.2. Runoff volumes

Treatment effects on runoff volumes were site specific and variable. At Pewsey, twice as much runoff was collected from the E-TC treatment than from the E-RC treatment in 2002/03 (Table 2). These differences were related to the degree of surface sealing of the soil which was evident on the ploughed treatment but not on the reduced cultivated treatment where cereal straw residues protected the surface. The increased runoff from the E-TC treatment was most apparent when runoff rates were high during the early part of the monitoring period. Hence, there were no differences in runoff between the E-TC and E-RC treatments when less rain fell after the late-drilled treatments were established in 2002/03 (data not shown).

Table 2. The mean effect of early-drilled treatments (E-TC and E-RC) on runoff volume, and on the losses and flow-weighted concentrations of suspended sediment (SS), total P (TP) and total dissolved P (TDP) in 2002/03 and 2003/04.

Year	Pewsey		East Knoyle		Wilton	
Measurement	E-TC	E-RC	E-TC	E-RC	E-TC	E-RC
2002/03						
Rainfall (mm)	267				287	
Runoff (mm)	19.9	10.1**	-	-	2.8	2.8
SS loss (kg ha^{-1})	476.1	90.2**	-	-	27.1	6.2**
SS concentration (g l^{-1})	2.38	0.92**	-	-	0.98	0.23***
TP loss (g ha^{-1})	386.9	104.6***	-	-	31.4	13.8***
TDP loss (g ha^{-1})	22.2	12.2	-	-	5.5	5.4
TP concentration (mg l^{-1})	1.94	1.06***	-	-	1.14	0.51**
TDP concentration (mg l^{-1})	0.11	0.12	-	-	0.20	0.20
2003/04						
Rainfall (mm)	437		478		453	
Runoff (mm)	6.6	6.2	3.1	4.7	4.4	4.8
SS loss (kg ha^{-1})	103.2	88.6	57.7	87.0	83.7	61.1
SS concentration (g l^{-1})	1.55	1.39	1.45	1.72	1.90	1.19
TP loss (g ha^{-1})	74.0	68.0	70.9	106.7	80.4	66.9
TDP loss (g ha^{-1})	9.7	10.6	17.72	25.79	9.49	6.81
TP concentration (mg l^{-1})	1.11	1.02	1.74	2.12	1.81	1.30
TDP concentration (mg l^{-1})	0.144	0.167	0.426	0.501	0.211	0.133

E, early-drilled; L, late-drilled; TC, traditional cultivations; RC, reduced cultivations. *, ** and *** denotes significance at the 5%, 1% and 0.1% level, respectively.

There was no similar significant effect of cultivation method on runoff from the early-drilled treatments in 2003/04 (Tables 2 and 3). However, in 2003/04, amounts of runoff collected from the late-drilled treatments were 5-fold greater than those obtained from the early-drilled treatments (Fig. 4). At Wilton and East Knoyle, there was no significant effect of cultivation method on runoff in either 2002/03 or 2003/04 (Table 2), but significantly increased runoff was obtained in 2003/04 on the headland at East Knoyle where the direction of drilling was up-and-down the slope (Fig. 4). Larger amounts of overland flow were also recorded from the late-drilled treatments at Wilton, and especially the L-RC treatment where water was observed gushing down compacted tramlines (Fig. 4). However, these differences were not statistically significant ($P < 0.05$) due to variable data from individual traps.

Table 3. Mean treatment effects on the loads and flow-weighted concentrations of suspended sediment (SS), total P (TP) and total dissolved P (TDP) after the late-drilled treatments were established in 2003/04

Site	Suspended sediment		Total P		Total dissolved P	
Treatment[1]	load (kg ha^{-1})	Concentration (g l^{-1})	load (g ha^{-1})	concentration (mg l^{-1})	load (g ha^{-1})	concentration (mg l^{-1})
Pewsey						
E-TC	76.5	2.30	48.1	1.45	2.6	0.075
E-RC	56.8	1.80	37.9	1.12	4.0	0.124
L-TC	650.3	4.32	547.5	3.64	30.6	0.181
L-RC	183.5	1.29	183.3	1.29	22.7	0.160
Significance	***	***	***	***	**	**
l.s.d.	128.50	1.132	107.3	0.928	17.14	0.055
East Knoyle						
E-TC	49.2	3.22	47.0	2.97	5.3	0.322
E-RC	75.4	3.28	72.4	3.17	8.8	0.386
Headland	69.5	0.71	147.8	1.41	19.3	0.224
L-RC	32.0	1.73	29.6	1.59	5.2	0.283
Significance	NS	**	NS	***	*	*
l.s.d.		1.403		0.864	9.04	0.100
Wilton						
E-TC	62.8	2.83	51.2	2.31	2.77	0.120
E-RC	43.0	1.78	39.2	1.62	1.78	0.074
L-TC	150.2	2.95	96.8	1.95	12.48	0.062
L-RC	786.7	4.57	582.8	3.43	3.06	0.095
Significance	NS	NS	NS	NS	NS	NS

E, early-drilled; L, late-drilled; TC, traditional cultivations; RC, reduced cultivations. *, ** and *** denotes significance at the 5%, 1% and 0.1% level, respectively. NS, not significant; l.s.d., least significant difference.

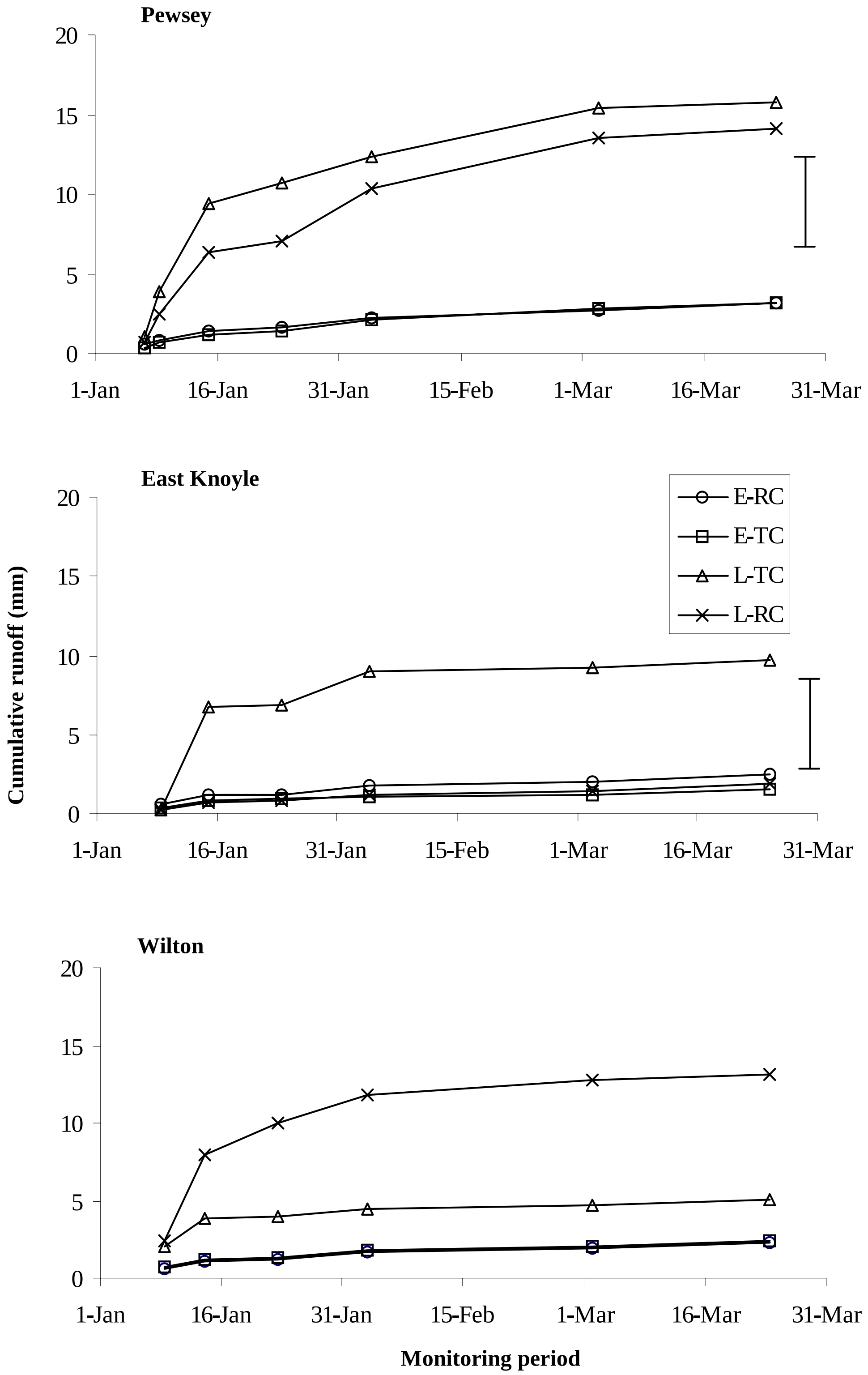

Figure 4. Cumulative runoff from successive storm events during the monitoring period following the establishment of the late-drilled treatments in 2003/04. Error bars denote least significant difference ($P < 0.05$). (At East Knoyle, the L-TC treatment was replaced by a headland area).

3.3. Sediment concentrations and loads

At all sites, SS concentrations in runoff during individual storm events varied from <0.1 – ca. 8 g L^{-1}. Concentrations measured under low flow were very variable, and high SS values were associated with small as well as large runoff volumes (Fig. 5). A significant relationship between flow and SS concentration was observed only on the L-RC treatment at Wilton, when water gushing down the tramlines mobilised additional sediment (Fig 5). Such relationships were not readily apparent at the other sites. For example, at Pewsey increased SS concentrations were observed for only modest increases in runoff, and at East Knoyle, increased runoff on the headland plot was accompanied by a significant decrease in SS concentrations compared to the other treatments (Table 3). At Pewsey in both years, and at Wilton in 2002/03, flow-weighted SS concentrations were significantly ($P < 0.05$) lower under reduced cultivation than under traditional cultivation (Tables 2 and 3). The greater sediment mobilisation on the L-TC treatment was also clearly evident as rill erosion in the tramlines. The greater sediment mobilisation on the L-RC treatment at Wilton was not statistically significant ($P > 0.05$).

Mean cumulative sediment loads in runoff ranged up to 650 kg at Pewsey, 787 kg at Wilton and 87 kg at East Knoyle, with significant treatment effects obtained at Pewsey in both years, and at Wilton in the first year (Tables 2 and 3). The much larger loads of SS from the E-TC treatment in 2002/03 and L-TC treatment in 2003/04 at Pewsey, reflected both greater runoff volumes and increased flow-weighted concentrations in the runoff. Similar effects were observed on the L-RC treatment at Wilton in the second year, but the variability between plots was too high to show a significant treatment effect. The significantly reduced SS load from the E-RC treatment at Wilton in 2002/03 was due solely to decreased susceptibility to particle detachment rather than to any decrease in runoff (Table 2). At East Knoyle, SS loads were not increased on the headland treatment despite the increased runoff volumes because flow-weighted SS concentrations were significantly decreased (Table 3).

3.4. Phosphorus concentrations and loads

Cumulative TP losses and flow-weighted TP concentrations followed the same general patterns as for SS, since the majority (60-97%) of TP was in particulate (> 0.45 μm) form at all three sites. Concentrations typically varied from between 0.1 and ca. 6 mg TP L^{-1} for individual storm events and runoff traps, and cumulative TP losses ranged up to 0.6 kg P ha^{-1} at Pewsey and Wilton, and up to 0.15 kg P ha^{-1} at East Knoyle (Tables 2 and 3). Significantly increased TP losses were obtained on the E-TC plots at Pewsey and at Wilton in 2002/03, and on the late-drilled treatments at Pewsey in 2003/04. As with SS, flow-weighted TP concentrations were consistently lower when the soil was not inverted, except for the L-RC treatment at Wilton where water gushing down the compacted tramline generated additional particulate P (Tables 2 and 3).

Statistically significant ($P < 0.05$) treatment effects on dissolved P concentrations were generally absent, except at Pewsey and East Knoyle in 2003/04. At Pewsey, TDP concentrations were increased where runoff volumes were greater, whilst at East Knoyle the reverse was obtained (Table 3). The molybdate reactive form was dominant (>95% of TDP), and flow-weighted averages of MRP over the respective monitoring periods were notably greater at East Knoyle (ca. 0.22-0.50 mg L^{-1}) compared to Pewsey (0.08-0.18 mg L^{-1}) and Wilton (0.06-0.21 mg L^{-1}). Hence, flow-weighted concentrations of TDP were very similar at Wilton and at Pewsey despite the large differences in their soil P fertility (Table 1).

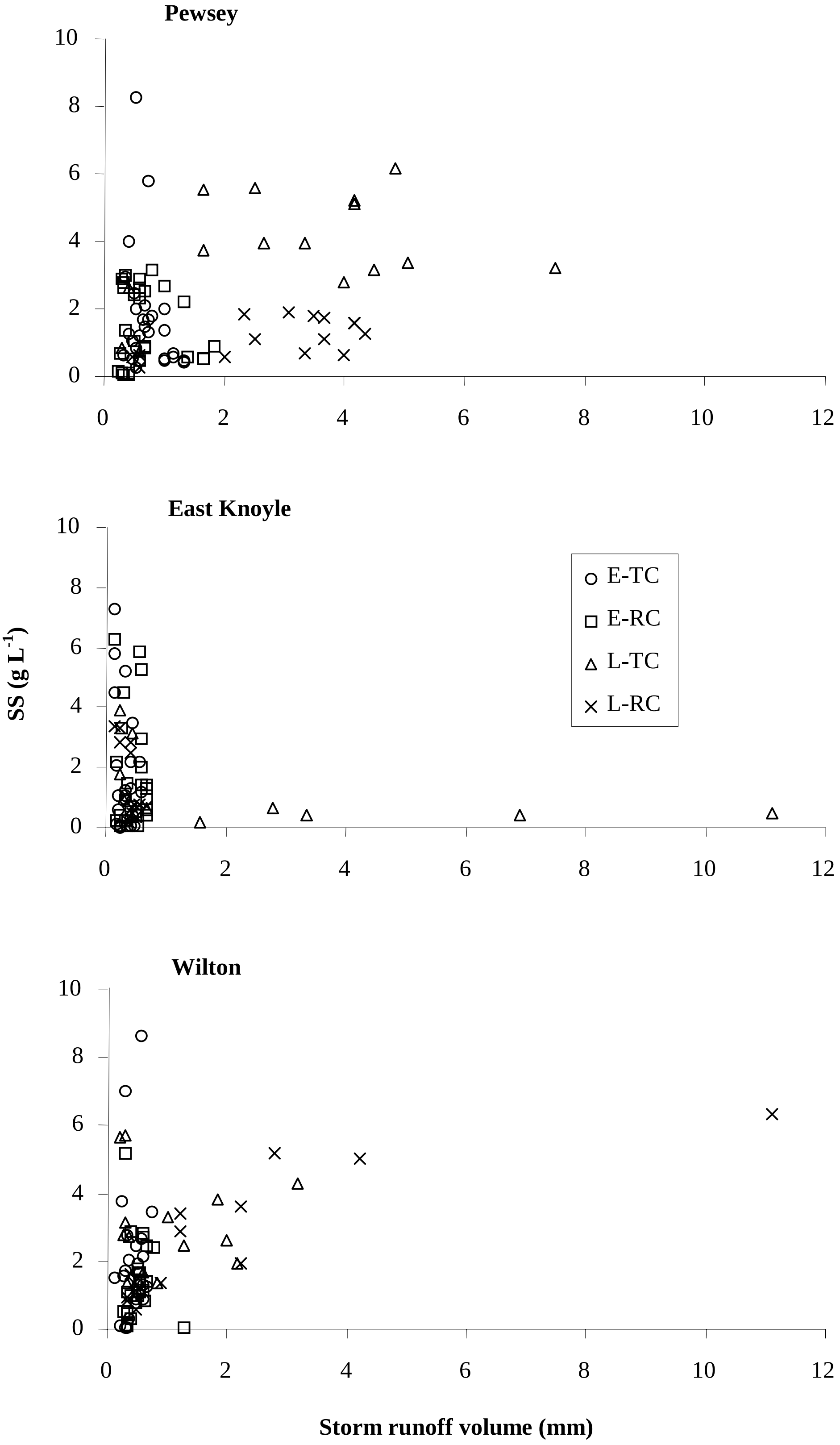

Figure 5. Concentrations of suspended sediment (SS) in relation to the amounts of runoff generated in 2003/04. (At East Knoyle, the L-TC treatment was replaced by a headland area).

3.5. Soil physical quality

The range in soil physical measurements undertaken all showed that at Pewsey and Wilton, reduced cultivation resulted in a more consolidated topsoil structure than when the soil was ploughed. Measurements meaned over 30 cm depth are given in Table 4. Not all the differences were significant at the 5% level, but were generally significant at the 10% level. This consistent soil cultivation effect was obtained at both drilling dates, although the magnitude of the difference was generally greater at the later drilling dates. Soil strength measurements indicated that treatment effects were most pronounced between 5 and 25 cm depth (Figs. 6 and 7). At Pewsey, there was evidence of a plough pan below 25 cm depth and at both sites, differences in soil strength disappeared at 30 cm depth. In contrast, there were no significant differences in soil physical quality between any of the treatments at East Knoyle, except for the E-RC plot which showed better soil structure and slightly increased air capacity compared to the other treatments (Table 4). However, these differences were not detected by the other techniques. Soil shear strength data taken in May in year 1 (data not shown) also showed greater consolidation on RC treatments; values for the E-TC and E-RC treatments were 55.4 and 80.9, 77.3 and 90.0 and 59.0 and 83.9 kPa at Pewsey, East Knoyle and Wilton, respectively. However, no significant treatment differences in soil bulk density and air capacity were detected in year 1 at any site.

Infiltration rates were more variable than other soil physical measurements and the apparent treatment differences were not statistically significant ($P > 0.05$). Any differences between treatments were relatively small compared to the differences between sites, with very low rates measured at Pewsey compared to the other two sites (Table 4, Fig. 8). Similar data were obtained in year 1; for example mean infiltration rates over 4 hours on the E-TC and E-RC treatments at Pewsey in February 2003 were 15.5 and 18.7 mm hr^{-1}, respectively compared to 65.1 mm hr^{-1} on the E-TC treatment at East Knoyle. At Pewsey, there was virtually no infiltration of water at some measuring points due to capping of the soil surface by fine particles dispersed by raindrops. Infiltration was particularly low on the late-drilled treatments and on reduced cultivated treatments at Pewsey (Fig. 8), although these differences were significant only at the 10% level. Infiltration rates were also slightly lower on RC treatments than on TC treatments at both Wilton and East Knoyle, but the differences were too small to be statistically significant (Table 4). At all sites, the lowest infiltration rates were measured on the L-RC treatments (Fig. 8). This treatment also tended to show the highest bulk density, the lowest air capacity, the lowest structure score and the highest soil strength, particularly at Pewsey and Wilton (Table 4). In contrast, soil physical quality was generally best on the E-TC treatment, although infiltration rates were not consistently highest on this treatment.

3.6. Crop cover

Measurements of crop cover are available for only two dates in 2004, although some general observations of treatment differences in crop cover were also noted from the first year. As expected, the residues left by the previous crop helped to provide a greater degree of crop cover where the soil was not inverted (Fig. 2d). Visual differences in the degree of crop cover were most pronounced at Wilton in 2002/03 and at Pewsey in both years. At East Knoyle, the previous crop was maize providing a residue of coarse stems spaced widely apart and differences were not so readily apparent. Measured data for the second year are shown in Table 5. At Pewsey, the RC treatments had 40% (early-drilled) and 25% (late-drilled) more crop cover than the corresponding TC treatments. In contrast, the E-RC plots at Wilton and East Knoyle had only 8-9% greater crop cover than the E-TC plot. By April, differences in crop cover became less apparent and crop growth was noticeably more abundant at East Knoyle than at the other two sites, perhaps reflecting the better soil structure (Table 4).

Table 4. Mean treatment effects on soil physical quality and on the percentage of bare ground in 2003/04.

Site	Dry bulk density		Air capacity		Structure	Soil strength[2]		Infiltration	Bare ground	
Treatment	Topsoil	Subsoil	Topsoil	Subsoil	Score[1]	Vertical	Horizontal	Rate[3]	23 Jan	9 Apr
	(g cm^{-3})		(%)			(N m^{-2})	(kPa)	(mm)	(%)	
Pewsey										
E-TC	1.15	1.08^{a}	14.3^{bc}	18.1^{b}	7.6^{c}	35	37	19.1	78	41
E-RC	1.19	1.17^{a}	8.8^{a}	14.8^{b}	4.7^{a}	70	59	12.3	36	23
L-TC	1.21	1.14^{a}	11.5^{ab}	18.4^{b}	6.7^{b}	49	39	6.6	85	40
L-RC	1.23	1.32^{b}	7.9^{a}	10.2^{a}	5.2^{a}	90	80	3.6	60	47
Significance	NS	**	***	**	***	***	***	NS	***	***
l.s.d.						8.1	6.2		6.0	4.5
East Knoyle										
E-TC	0.86	0.84	18.8^{a}	17.9	5.2^{a}	46	64	62.2	71	8
E-RC	0.82	0.81	21.6^{b}	18.8	6.9^{b}	49	64	55.4	62	8
Headland	0.83	0.93	17.8^{a}	13.3	4.6^{a}	50	69	79.2	66	14
L-RC	0.88	0.85	18.3^{a}	14.4	4.7^{a}	47	57	47.7	86	38
Significance	NS	NS	*	NS	***	NS	NS	NS	**	***
l.s.d.									10.9	6.0
Wilton										
E-TC	0.88^{a}	0.94^{ab}	27.3^{b}	25.3^{b}	6.9^{b}	29	41	76.0	79	44
E-RC	1.01^{b}	1.04^{ab}	20.9^{a}	23.1^{ab}	5.4^{a}	35	54	67.6	71	31
L-TC	0.95^{ab}	0.97^{a}	27.1^{b}	20.7^{ab}	6.2^{b}	34	49	102.0	85	52
L-RC	1.05^{b}	1.08^{b}	19.8^{a}	17.3^{a}	5.2^{a}	73	72	58.5	82	50
Significance[5]	*	*	*	*	***	***	*	NS	***	***
l.s.d.						10.5	18.4		5.3	7.4

E, early-drilled; L, late-drilled; TC, traditional cultivations; RC, reduced cultivations. *, ** and *** denotes significance at the 5%, 1% and 0.1% level, respectively. Values with different letters are significant from one another. NS, not significant; l.s.d., least significant difference from Genstat analysis. [1]Score out of ten, 1 = poor, 10 = good. [2]Mean values over a depth of 30 cms. [3]Mean values over 5 hrs.

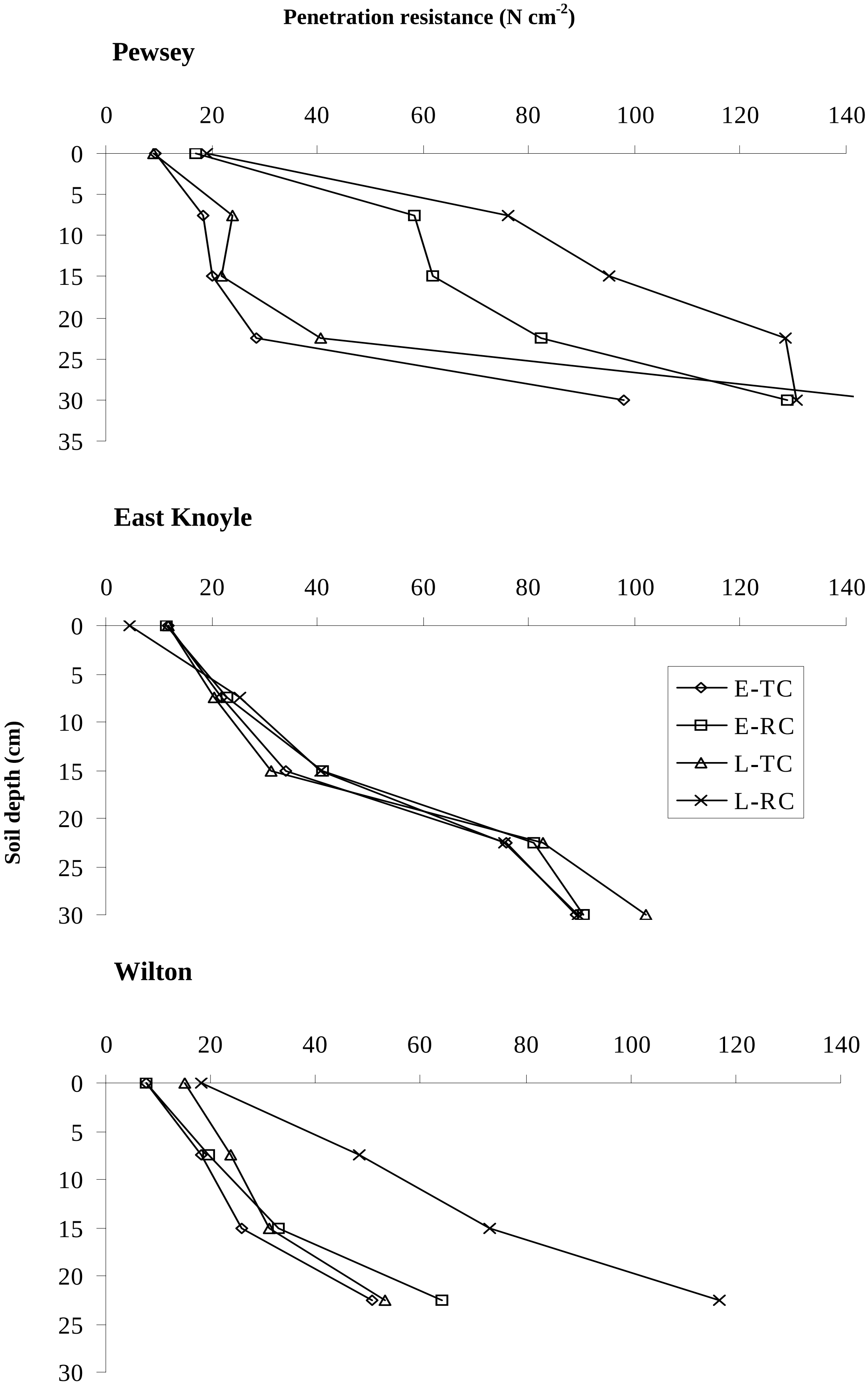

Figure 6. Treatment effects on changes in soil penetration resistance with increasing soil depth down to 30 cm at each site in January 2004. (At East Knoyle, the L-TC treatment was replaced by a headland area).

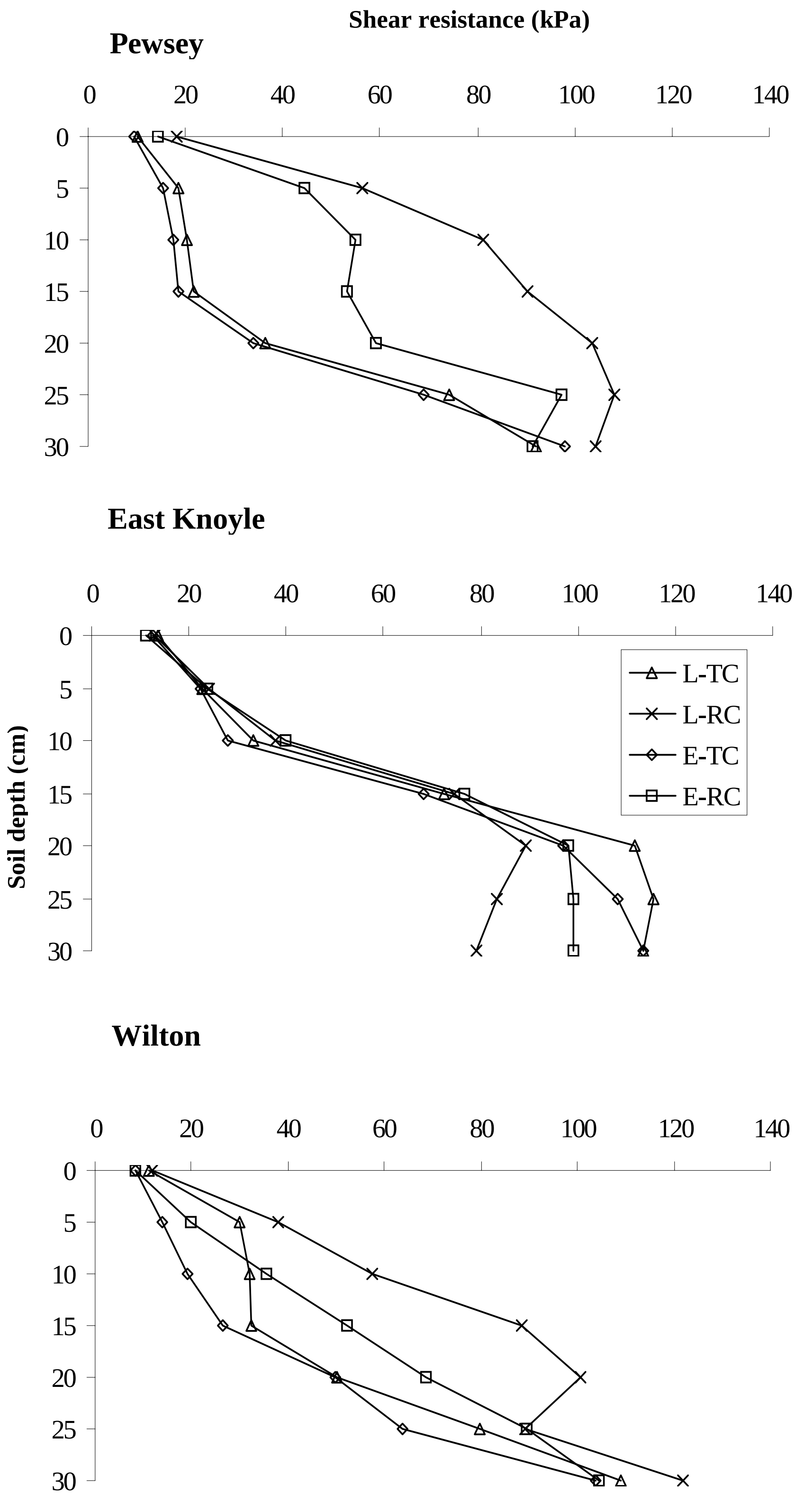

Figure 7. Treatment effects on changes in soil shear strength with increasing soil depth down to 30 cm at each site in January 2004. (At East Knoyle, the L-TC treatment was replaced by a headland area).

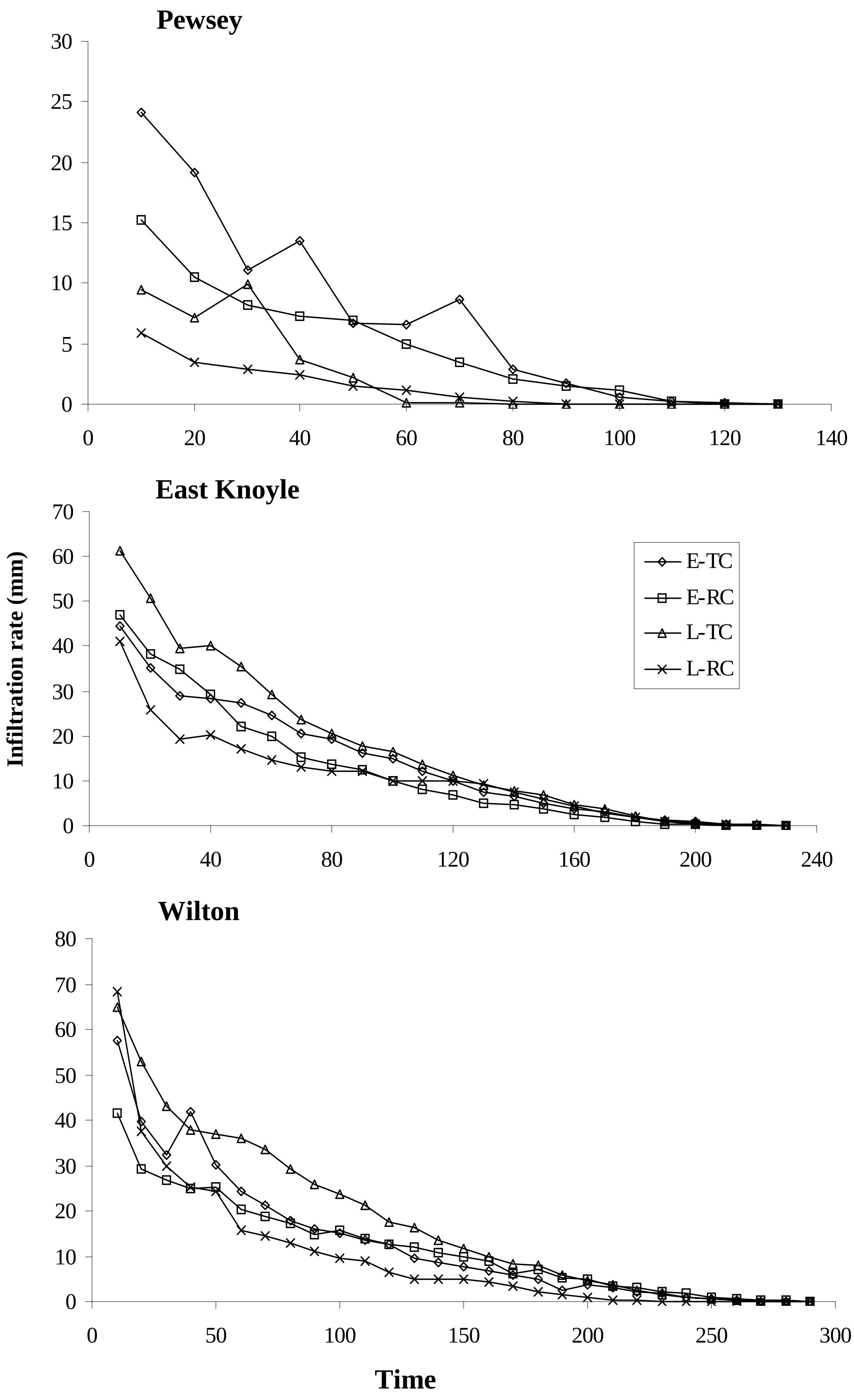

Figure 8. Treatment effects on infiltration of water over a 5-hour period at each site in January 2004. Note the different scales and times to reach saturation (zero infiltration). (At East Knoyle, the L-TC treatment was replaced by a headland area).

3.7 Effects of tramlines

Tramline effects (2002/03)

Soon after the early drilling treatments were established in the first year, observations of flow rates from the traps with tramlines during storm events indicated that the tramlines might be having a significant impact on the amount of runoff collected from the traps. Runoff was being initiated in the tramlines sooner than from non-tramline areas, and twice as much runoff was generated from the E-TC treatment, where the tramlines not only appeared deeper and more incised than on the E-RC treatment, but also had tyre lugs pointing in a downward ∨ rather than in an upward ∧ direction. Maximum tramline depth was 10 mm greater on the E-TC treatment than on the E-RC treatment, and with a more irregular surface as a result of the depressions left by the tractor tyres and/or the effects of the runoff water (Fig. 9).

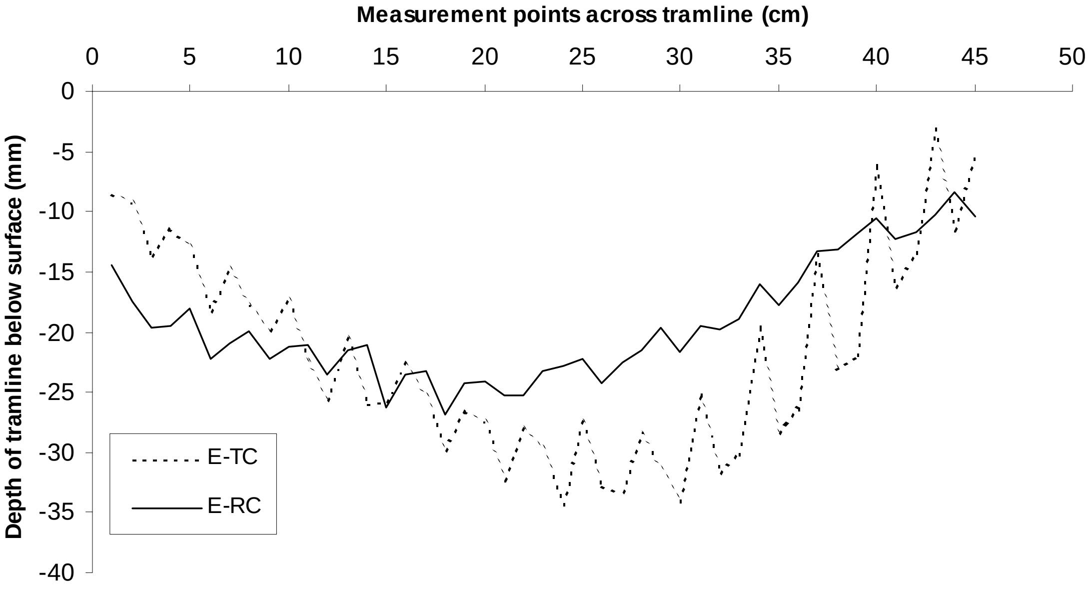

Figure 9. Tramline cross-sectional profiles for the traditionally cultivated (E-TC) and reduced cultivated (E-RC) treatments in June 2003.

After the traps with no tramlines were installed in January 2003, the cumulative amounts of runoff collected from the traps on the E-TC treatment over the 5 monitored storm events were 40% less than from the traps with a tramline (Table 5). Much of this significant difference (P <0.01) occurred in the first heavy storm event although runoff volumes were always greater where a tramline was present. This additional runoff caused significantly greater mobilisation of soil particles as evidenced by large increases in the flow-weighted concentrations of both SS and TP (Table 5). However, the extra runoff was too small to generate any rill erosion down the tramlines and did not increase concentrations of dissolved P (TDP), which consequently represented a smaller proportion of the total P lost. Losses of SS and TP on the E-TC treatment were 4-5 fold greater where tramlines were present than where they were not present, reflecting both increased runoff and increased concentrations of SS and TP in the runoff (Table 5). The reduction in SS and TP mobilisation by not having tramlines was ca. 75%.

Table 5. Effects of tramlines on the cumulative mean volumes of runoff, and associated loads and flow-weighted concentrations of suspended sediment (SS) and total P (TP) and dissolved P (TDP) in 2002/03.

Treatment[1]	Runoff	Losses			Flow-weighted concentrations		
	(mm)	SS (kg ha^{-1})	TP (g ha^{-1})	TDP (g ha^{-1})	SS (g L^{-1})	TP (mg L^{-1})	TDP (% of TP)
E-TC	2.37	69.8	58.4	2.22	2.86	2.39	3.8
E-TC-NT	1.44	14.1	14.8	1.88	0.91	0.94	12.0
P value	**	**	**	NS	**	**	*
l.s.d	0.44	22.8	17.7		0.90	0.84	6.3
E-RC	1.92	19.3	18.9	3.09	0.98	0.96	16.5
E-RC-NT	2.55	22.9	29.5	4.15	0.86	1.11	14.4
P value	NS	NS	NS	NS	NS	NS	NS

[1] Early-drilled (E), late-drilled (L), traditional cultivations (TC), reduced cultivations (RC), no tramline (NT). *, ** and *** denotes significance at the 5%, 1% and 0.1% level, respectively. NS – not significant (P >0.05), l.s.d – least significant difference

In contrast, there was no statistically significant (P >0.05) effect of tramlines on runoff, or on the concentrations and losses of SS and TP, from the plots that had been reduced cultivated (Table 5). However, it was observed that the runoff volumes from one replicate trap on the E-RC treatment which contained a tramline that became partially crop covered was 50% less than for the other two replicates where the tramlines were bare (Fig. 10). The degree of crop cover on the tramline is illustrated in Fig 11a, and the effect on runoff was consistent over the extended monitoring period covered by the main study.

Tramline effects (2003/04)

In the second year, the effects of tramlines on runoff, SS and TP loss from the early-drilled treatments were compared over a longer period, and the cumulative volumes of runoff were greater (ca. 5 mm, Table 6). Also in this year, a comparison was made with an E-TC treated area outside the main plots where the tramline direction was running across the slope (offplot) rather than up and down the slope. As in the first year, runoff was initiated in the tramline (Fig 11b). However, in contrast to the first year, the soil was not greatly indented when the tramlines were established. Two or three passes of the tractor wheel were required simply to establish a visible tramline both on the E-TC and the E-RC treatments reflecting a dry and stable soil structure. On the E-TC treatment, there was a significant (P <0.05) reduction in runoff of 26% where there was no tramline, and a 31% reduction in runoff where the tramline and drilling direction was across the field slope (Fig 12). However, there was no accompanying reduction in mobilisation of soil particles because flow-weighted concentrations of SS and TP tended to increase rather than decrease when runoff volumes were lower (Table 6). However, this trend was significant at the 10% level only. Flow-weighted concentrations of TDP were significantly (P <0.05) lower on the E-TC traps with a tramline running up and down the slope. Similar reductions in runoff (ca. 2mm) were obtained on the E-RC treatment where tramlines were absent but this was not significant even at the 10% level. Neither was there any significant effect of tramlines on the concentrations, or cumulative loads of SS, TP and TDP on the reduced cultivated treatment (Table 6).

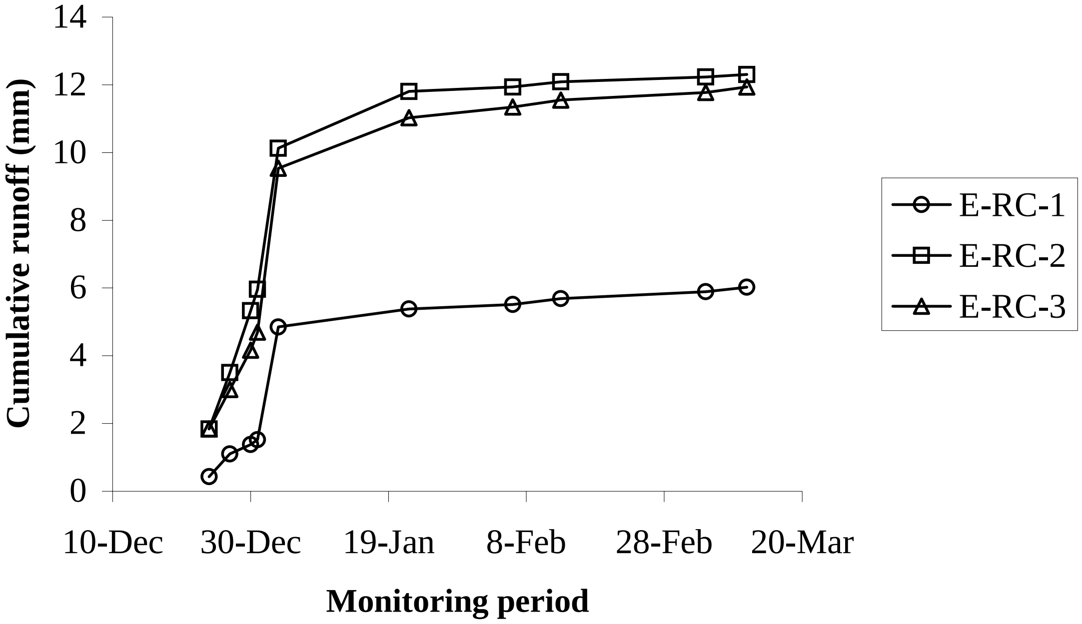

Figure 10. Cumulative runoff from replicate traps on the early-drilled reduced cultivated (E-RC) treatment during the 2002/03 monitoring period. E-RC-1 is the replicate trap with partial crop cover as shown in Fig 11a.

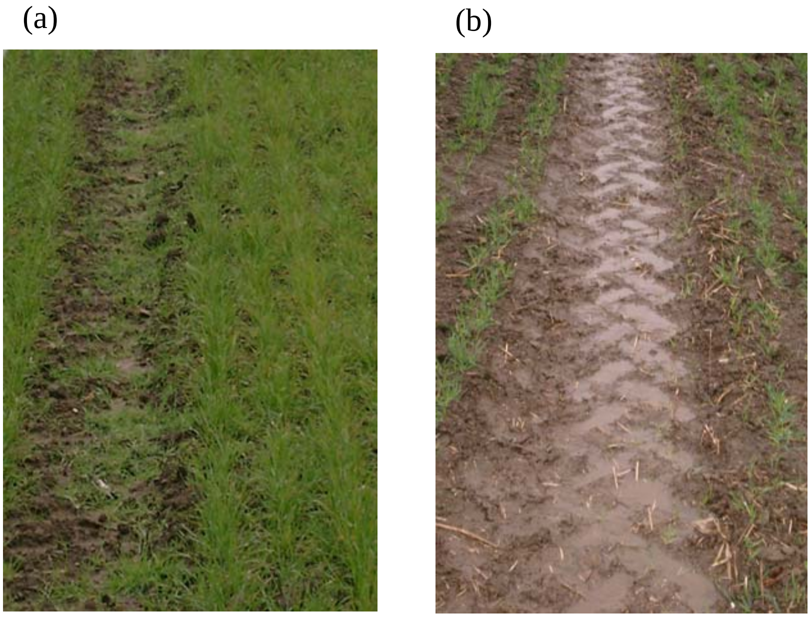

Figure 11. (a) Extent of partial crop cover in the tramline in December 2002 and (b) runoff is generated in the tramline before non-tramlined areas (November 2003). Tyre lugs were positioned in a downward ∨ direction encouraging flow.

Table 6. Effects of tramlines on the cumulative mean volumes of runoff, and associated loads and flow-weighted concentrations of suspended sediment (SS) and total P (TP) and dissolved P (TDP) in 2003/04.

Treatment[1]	Runoff (mm)	Losses			Flow-weighted concentrations		
		SS (kg ha^{-1})	TP (g ha^{-1})	TDP (g ha^{-1})	SS (g L^{-1})	TP (mg L^{-1})	TDP (% of TP)
E-TC	6.56	103.2	74.0	9.67	1.55	1.11	13.0
E-TC-NT	4.83	93.8	55.1	9.83	1.95	1.14	17.9
E-TC-Offplot	4.54	97.3	69.3	10.73	1.90	1.37	15.4
P value	*	NS	NS	NS	NS	NS	**
l.s.d.	1.49						2.5
E-RC	6.24	88.6	68.0	10.6	1.39	1.02	16.7
E-RC-NT	4.62	75.1	47.4	7.2	1.57	0.99	15.2
P value	NS	NS	NS	NS	NS	NS	NS
L-TC	15.8	650.3	547.5	30.6	4.32	3.64	5.4
L-TC-NT	14.1	269.9	210.1	11.0	1.89	1.46	5.2
P value	NS	**	**	NS	*	*	NS
l.s.d.		220.5	195.2		1.67	1.45	

[1] Early-drilled (E), late-drilled (L), traditional cultivations (TC), reduced cultivations (RC), no tramline (NT).

*, ** and *** denotes significance at the 5%, 1% and 0.1% level, respectively. NS – not significant ($P > 0.05$), l.s.d – least significant difference.

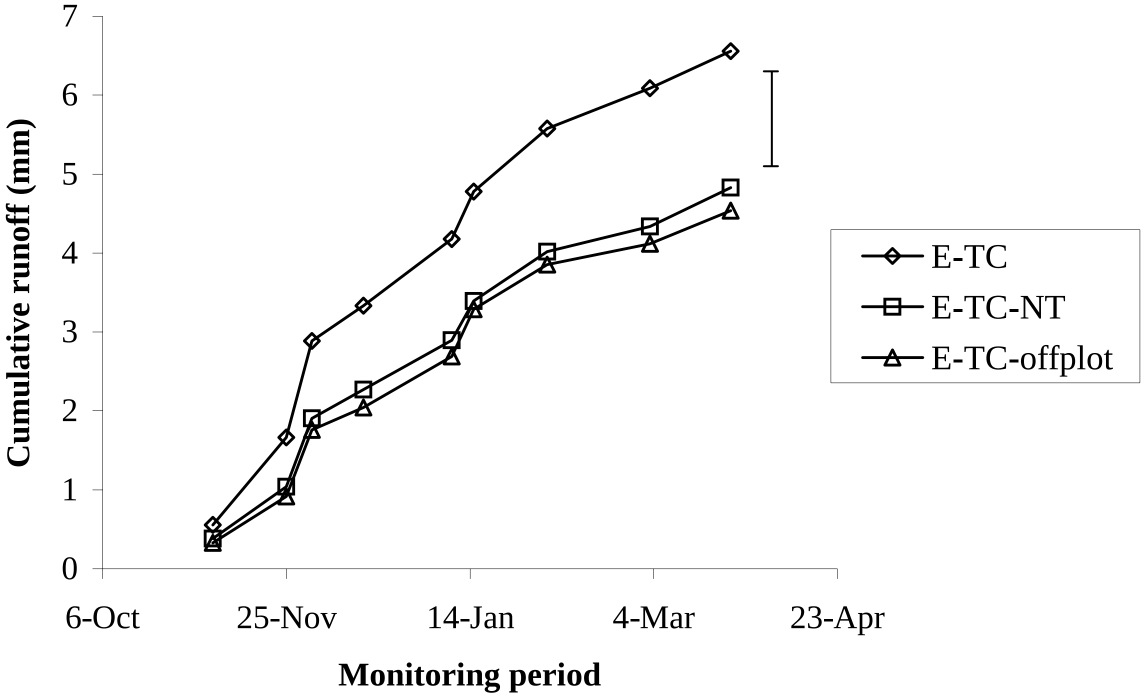

Figure 12. Pattern of cumulative runoff from replicate traps on the early-drilled traditionally cultivated treatment in 2003/04 either with a tramline (E-TC), without a tramline (E-TC-NT) or with tramlines running across slope (E-TC-offplot). Error bars represent the least significant difference.

Cumulative losses of SS and TP were also much lower from the trap that contained the partially covered tramline. For example, cumulative losses of SS were 64, 95 and 112 kg ha^{-1}, and cumulative losses of TP were 69, 114 and 131 g ha^{-1} for the three replicate traps respectively, where the first trap was partially crop covered. These differences in losses were solely due to differences in runoff, and SS, TP and TDP concentrations were quite similar across all the three traps.

After establishment of the L-TC treatment, there was a marked increase in the amounts of runoff generated irrespective of whether a tramline was present or not. Runoff volume was greater on the tramlined areas (+ 1.7 mm), but not significantly so indicating there was substantial runoff occurring on the non-tramline area within the trap with a tramline. However, the flow-weighted concentrations of SS, TP and TDP significantly decreased by ca. 60% where the tramlines were absent (Table 6). Cumulative loads of SS, TP and TDP from traps with tramlines were consequently ca. 2.5 times greater than from traps without tramlines. During the monitoring period the tramlines became progressively more incised as rills developed during consecutive storm events.

Combining all the data for the early-drilled treatments in both years, there was a significant relationship between rainfall and runoff for traps with and without a tramline (Fig 13). The gradient of the relationship was shallower for traps without a tramline, resulting in an increasing divergence in runoff rates between tramlined and non-tramlined areas as rainfall increased. For traps with a tramline, 1.9% of incoming rainfall occurred in runoff, whilst the corresponding figure for traps without a tramline was 1.3%. Tramlines therefore increased runoff on average by 46% when crops were drilled early. There was no relationship between rainfall and runoff on the late-drilled treatments reflecting the greater sensitivity of the capped soil surface to rainfall intensity. For the L-TC treatment, runoff averaged ca. 7% of rainfall (range up to 13%) from traps without a tramline and ca. 8% (range up to 18%) from traps with a tramline. Considerable amounts of runoff were clearly travelling down inter-tramline areas as well as down tramlines.

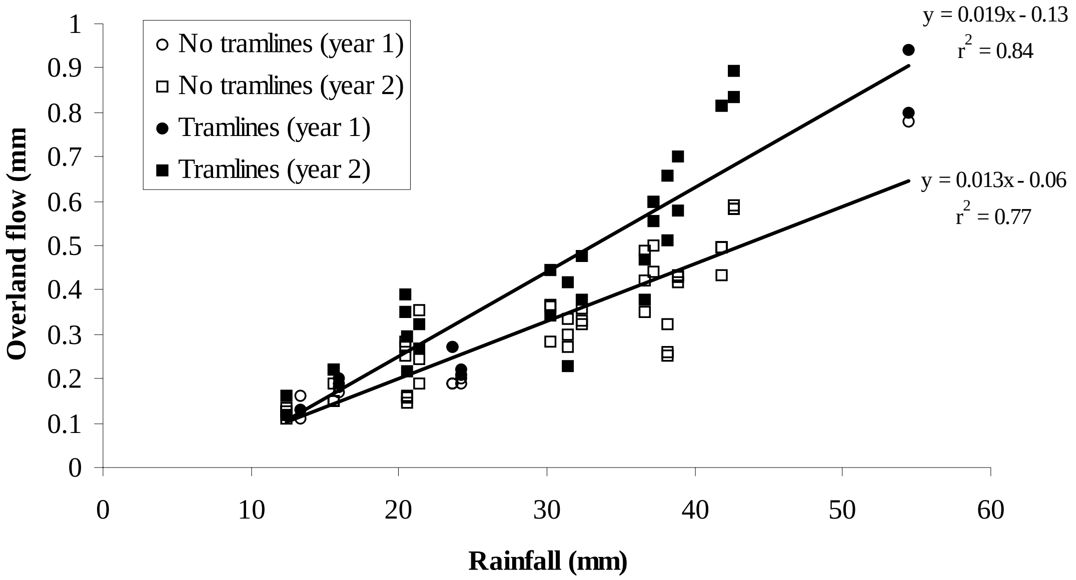

Figure 13. Rainfall-runoff relationships for traps on the early-drilling treatments with and without tramlines, and including traps with tramlines running perpendicular to the field slope. Data points represent individual replicate traps in each year.

Soil compaction in tramlines

Soil shear strength and penetration resistance values were almost always greater in the tramlines than in non-tramlined areas but the differences were generally only statistically significant ($P<0.05$) on the traditionally cultivated treatments in 2003/04 (Table 7, Fig. 14). Penetrometer readings suggested that the soil under the tramlines on the E-TC treatment was significantly more compacted throughout the top 30 cm, but differences in soil penetration resistance on the E-RC treatment were not sufficiently large to be statistically significant (Fig 14). Similarly, significant differences in soil shear strength were obtained only at the soil surface (0-10 cm) of traditionally cultivated treatments (E-TC and L-TC), whilst the increases on the tramlines of the E-RC treatment tended to be smaller and not significant. The differences between tramlined and non-tramlined areas were also small in relation to the much larger differences in both shear strength and penetration resistance between the two cultivation treatments. The reduced cultivated plots were considerably more consolidated at 5 cm depth, and below, than the traditionally cultivated plots. Hence differences in measured values under the tramlines of the E-RC treatment would have to be proportionally larger to show a significant effect.

Table 7. Changes in soil shear strength with increasing soil depth to 30 cm on tramlined and non-tramlined areas for the early-drilled and late-drilled treatments in January 2004.

Soil depth (cm)	E-TC			E-RC			L-TC		
	No tramline k Pa	Tramline % increase	Significance	No tramline k Pa	Tramline % Increase	Significance	No tramline k Pa	Tramline % Increase	Significance[1]
0	9.4	21	NS	14.4	59	NS	10.0	45	**
5	15.4	59	*	44.6	17	NS	18.6	35	*
10	17.6	66	**	54.8	14	NS	20.3	14	NS
15	18.6	56	NS	53.3	20	NS	21.8	32	NS
20	34.0	4	NS	59.3	56	**	36.3	44	NS
25	69.1	22	NS	97.3	10	NS	74.3	18	NS
30	97.9	11	NS	91.2	-2	NS	92.1	6	NS

[1] Significance at the 5%, 1% and 0.1% level is denoted by * ** and ***, respectively. NS not significant.

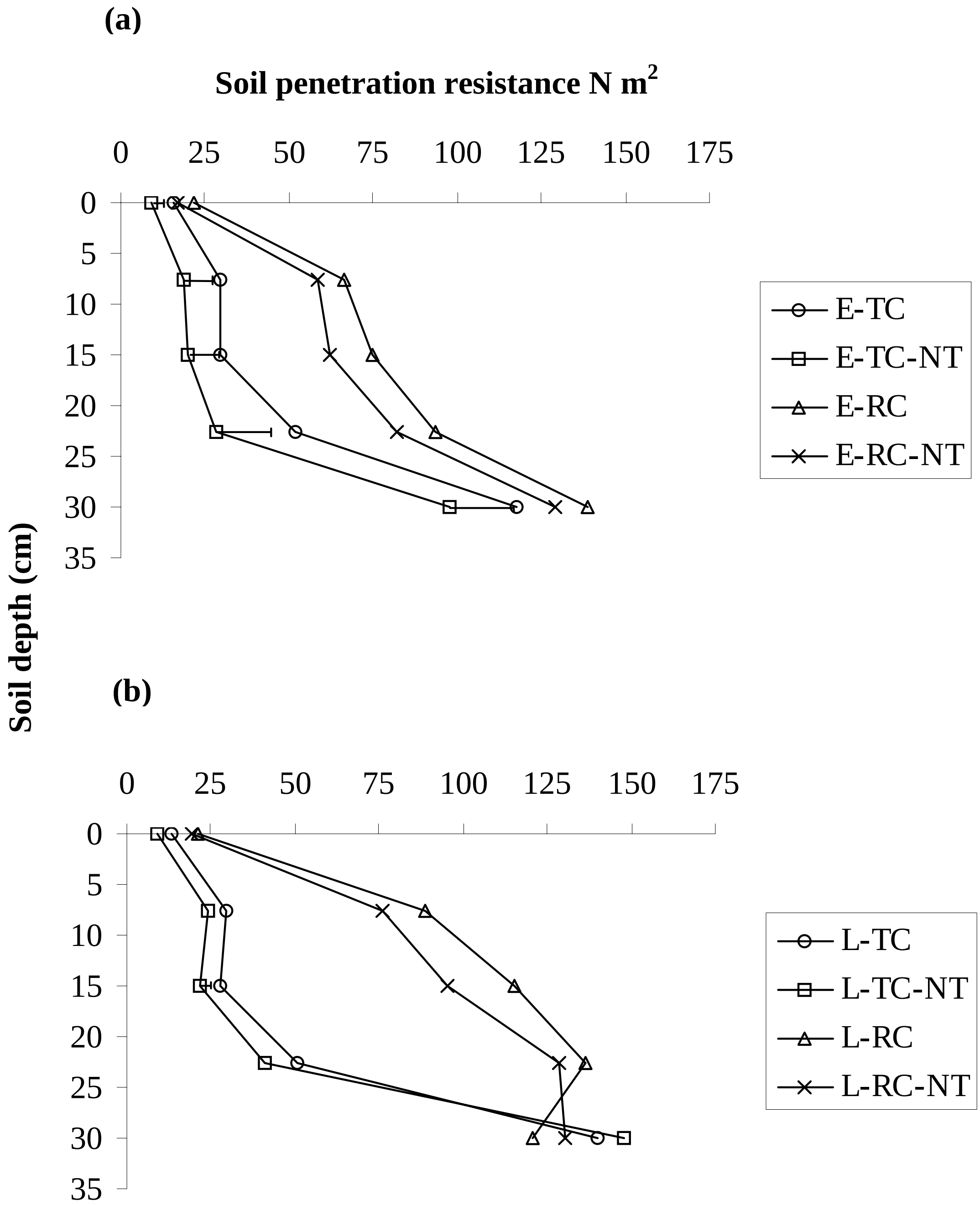

Figure 14. Effects of tramlines on soil penetration resistance with increasing soil depth down to 30 cm on (a) early-drilled treatments and (b) late-drilled treatments in January 2004. Error bars represent the least significant difference ($P < 0.05$). The lack of an error bar means there was no significant difference in soil strength at that depth.

4. Discussion

4.1 Main cultivation and drilling treatments

Treatment effects on runoff and subsequent entrainment of soil particles and associated P were site specific depending on soil and site characteristics, and were variable between years depending on weather patterns. At Pewsey, the inherent vulnerability of the fine sandy soil to surface sealing when there was little crop cover was the main factor causing increased runoff and erosion. In the first year, the surface sealing occurred when heavy rain fell within two weeks of drilling, and there was little the farmer could have done to prevent this using traditional ploughing. However, in 2003/04, it did not rain appreciably until after the late-drilled treatments were established, and under these circumstances, the beneficial effects of early drilling were considerable. Late cultivation increased runoff 5-fold and increased SS and P mobilisation by an order of magnitude. These data provide the first quantitative evidence of the effects of capping and late drilling on runoff, and the resulting impacts on the mobilisation of suspended sediment and P. Our results show that early-drilling as a management technique to reduce the risk of sediment and P loss may not always be successful on this vulnerable Greensand soil. Similarly the adverse consequences of late-drilling on runoff, SS and P loss risk may only occur in some years depending on rainfall patterns. However early drilling can clearly be an extremely effective management technique for reducing runoff and erosion and has other benefits for crop yield.

The inherent vulnerability of the Pewsey soil to structural degradation from raindrop impact was generally absent at the other two sites due to the more stable soil structure resulting from their higher clay, organic matter and/or calcium carbonate contents. For example, the heavy rain that fell after the establishment of the early-drilled treatments in 2002/03 did not increase runoff rates on the steeply sloping site at Wilton, even though this soil is prone to capping due to its high silt content (Boardman, 1990). Our observations suggested that any capping that occurred on the Chalk soil tended to disintegrate between storm events. In the second year, late cultivation did increase runoff rates by causing soil compaction on the L-RC treatment, especially in the tramline which acted as an efficient conduit for the runoff which was generated. Hence, the key factors influencing runoff rates on the chalkland site were timeliness of cultivation and the presence of tramlines running up and down the slope, which concentrated the flow. These factors were also identified by Boardman (1990) in his review of erosion problems on the Chalklands in Southern England.

The comparatively low runoff volumes and associated loads of SS and P measured at East Knoyle were surprising in view of the heavy texture of the soil. Recent subsoiling will have helped to maintain good infiltration rates to the tile drains, but it is also likely that the drilling of the crop across the slope on the early-drilled and L-RC treatments also helped to reduce runoff, sediment and P losses to a minimum. Significantly larger amounts of runoff were obtained on the headland where the soil was cultivated up and down the slope. Since soil physical measurements did not indicate that the headland was any more compacted than the other treatments, the direction of drilling was probably the main factor influencing runoff rates despite the slight slope. The larger runoff rates actually reduced sediment mobilisation on the headland, which may reflect the more stable soil structure associated with a well-fissured clay soil with long-term grass in the rotation. Similar effects have been noted in other work where increased runoff is not always associated with increased erosion because of the lack of loose soil to become entrained (Robinson and Naghizadeh, 1992; Martin, 1999; Chambers et al., 2000).

The consistent beneficial effects of non-inversion cultivation methods in reducing runoff, and/or SS and P mobilisation under heavy rain at Pewsey and Wilton support earlier work (Carter, 1998). The effects were obtained despite evidence from a range of soil physical measurements that the reduced-cultivated soils were structurally more consolidated, although treatment differences in infiltration rates were not sufficiently large to be statistically significant. Limited soil moisture measurements (data not shown) also indicated that reduced cultivated soils initially contained more moisture than the ploughed soils. This apparent contradiction may be related to the differences in the continuity and size of the pores in the soil under the two cultivation techniques. Previous work has shown that greater bulk density and lower total porosity in reduced-cultivated soils are offset by a greater continuity of medium sized pores and a firmer surface for trafficing (Hill et al., 1985; Davies, 1988; Rasmussen, 1999; Tebrugge and During, 1999). The lack of indentation by the tramlines on the reduced cultivated treatment was also beneficial in reducing SS and P mobilisation that would otherwise have occurred through channelling of flow down the tramline.

Increased crop cover on the reduced cultivation treatments was also clearly a factor at Pewsey (both years) and at Wilton in 2002/03. Hence the beneficial environmental effects of reduced cultivations presented here reflect both better crop cover and improved resilience to trafficing after drilling. The lack of any effect of reduced cultivation on the heavier clay soil at East Knoyle, despite its suitability to this cultivation technique (Davies, 1988), may be related to the lack of any major differences in crop cover. Maize is a widely spaced crop that leaves single coarse stems and therefore does not provide a good crop residue cover.

Contrary to previous work, there was no indication of higher dissolved P concentrations under reduced cultivation. This probably reflects the short-term nature of this study and the lack of P fertilisation during the study periods. Since the runoff would have remained in the tank for the duration of the storm event, dissolved P concentrations would reflect equilibrium conditions and the P sorption properties of the SS rather than the soil in situ. It is therefore likely that dissolved P will decrease when finer clay particles are preferentially transported, since they have a larger P sorption capacity. Hence the tendency for TDP concentrations to decrease on the headland treatment at East Knoyle is consistent with the lower sediment entrainment, while the tendency for TDP concentrations to increase with increasing runoff and soil loss at Pewsey reflects P release from coarser soil particles.

4.2 Effects of tramlines

The Pewsey site is located in a headwater area of the Hampshire Avon catchment where sediment deposition is a particular problem (Wheeldon 2003). The soil is classed by Evans (1990) as moderately vulnerable to erosion and fans of deposited soil are frequently seen at the bottom of tramlines where the hillslopes level out into the riparian zone, or which connect to roads and tracks. The observations and measurements presented support earlier studies showing that tramlines running parallel to the slope can increase volumes of overland flow and/or the entrainment of soil particles and associated P transfer (Basher and Ross 2001; Kay et al. 2005; Silgram 2005). In our study, runoff volumes were increased by up to 65% and SS and TP loads were increased up to 5-fold and 4-fold, respectively. Earlier initiation of runoff, the lack of any crop cover to protect the soil and the channelling effect created by the depth and pattern of indentation left by the lugs of the tractor wheel were key contributory factors. These factors were also identified by Reed (1979; 1986), and by Fullen (1985), in studies on erosion-prone sandy soils in the West Midlands. The effect of tramlines on P transfer was very similar in magnitude to that obtained by Silgram (2005) on a similar length of plot (10 m). As in that study, there was a very strong relationship between concentrations of SS and

TP (and PP) in the runoff at Pewsey (Withers et al. 2006). However, we found variable effects of tramlines on dissolved P concentrations rather than the consistent decrease observed by Silgram (2005).

However, as noted by Robinson and Naghizadeh (1992) in a similar experiment on chalk soils, there was considerable variation in the impact of tramlines depending on the extent to which these key factors were represented. Most obvious in our data was the significant difference in tramline effects between the traditionally cultivated and reduced cultivated treatments in the first year, and the lack of such differences between cultivation type in the second year. In the first year it was noted that the tramlines were shallower and smoother on the reduced cultivated treatment, where the topsoil structure was much more consolidated than on the ploughed treatment; for example in the soil strength data reported here. A looser ploughed soil has a greater vulnerability to the force exerted by the tractor tyre and hence the lugs of the tractor tyres caused a deeper, more irregular and slightly more compacted surface on the ploughed treatments than on the more consolidated reduced cultivated treatments. The greater depression left under ploughed soil may also have been accentuated by wet weather that occurred soon after drilling in autumn 2002.

The greater cross-sectional area of the tramline on the ploughed area in the first year therefore acted as an effective channel for increased mobilisation of sediment and P as runoff was initiated. Robinson and Naghizadeh (1992) also found higher rates of sediment mobilisation from tramlines on ploughed as compared to shallow cultivated soil, and suggested this occurred when the tyre treads or lugs broke up the soil rather than simply compressed the soil. However, contrary to our data, these authors found that runoff was lower on ploughed plots where the soil in the tramlines had broken up, and suggested that this was due to ponding of runoff water in the depressions left by the tractor treads allowing greater time for infiltration. This difference may be related to the direction of the treads which pointed in a downward V shape in this study, and also to the tendency for the lug depressions to fill up with silt detached by splash erosion during rainfall. Contrary to data obtained by Fullen (1985), the soil compaction created by the tractor tyres was relatively minor in relation to the differences between the cultivation methods. The markedly increased soil strength on the reduced cultivated treatments also did not cause increased runoff. This suggests that the channelling effect of the tramlines was a much more important contributory factor than soil compaction in increasing runoff generation.

In the second year, the ploughed soil was not deeply incised by the tramline, which was not visibly different to the tramline channel left in the reduced cultivated plot. Indeed, in contrast to the first year, the farmer had to make 2 or 3 tractor passes to establish a tramline on both cultivation treatments after early drilling when soil conditions were much drier. Hence, although there was slightly more runoff generated on the tramlined areas (+35% on both early-drilled treatments), flow-weighted sediment and P concentrations tended to be lower than on non-tramlined areas. Dilution of sediment concentrations with increasing runoff in tramlines was also noted at East Knoyle where the soil surface of the tramline was not greatly disturbed and there was less loose soil material available for entrainment. In contrast, on the late-drilled treatments which became severely capped after heavy rain, much larger amounts of sediment and P (2.5 fold greater) were mobilised from the tramlines despite small differences in runoff, reflecting the lack of crop cover in the tramlines and high runoff velocities. These data strongly suggest that the timing of tramline establishment in relation to antecedent soil moisture conditions can have an important influence on the risk of increased runoff and erosion from these soils.

A number of management techniques to reduce the risk of increased runoff and erosion along tramlines have been suggested (Armstrong et al., 1990; Defra, 1999; Chambers et al., 2000). These include: delaying tramline establishment until >25% crop cover has been established, establishing tramlines perpendicular, rather than parallel, to the hillslope, and drawing a tine behind the tractor wheel to disrupt any compaction caused by the tractor wheel. Although not specifically tested here, the observations on some replicate traps on the E-RC treatment in 2002/03 suggest that providing some crop cover was effective in reducing runoff volumes. The lack of any accompanying reduction in sediment and P concentrations may be related to the more stable nature of the tramline surface under reduced cultivation, as indicated by the tramline profiles. The offplot traps with drill lines and tramlines running across the field slope produced the same amounts of runoff as traps with drill lines running parallel to the slope but without a tramline.

However, these management options are not always practical to the farmer who needs to apply a herbicide to control weeds in early autumn, or on slopes where concerns over safety take priority. In some fields, ponding of water in tramlines running perpendicular to the slope can reach sufficient proportions to cause breakthrough down slope. Nevertheless they will be suitable for adoption at many sites. The use of tines behind the tractor wheels was not tested here but was found by Basher and Ross (2001) to be very effective in reducing runoff and erosion on a clay soil in intensive horticultural areas where crops are grown in raised beds. However, Chambers et al., (2000) found that this technique increased erosion on sandy soils because the tine smeared the soil at the depth of operation and the loosened soil became more vulnerable to entrainment by the runoff.

The data presented here also suggest that an additional important measure to reduce sediment and P mobilisation is to avoid establishing tramlines on ‘puffy’ seedbeds or in wet conditions that will cause deep channelling and irregular tramline profiles. Ensuring tractor lugs are pointing in an upward V rather than a downward V is not a practical option for the farmer who needs to travel in both directions across the field. No-one technique is likely to be suitable to all site conditions, and in-field controls may need to be integrated with other control practices which seek to prevent sediment and P-laden runoff entering waterbodies directly (Withers and Jarvis, 1998). However these results support earlier studies that more sensitive management of tramlines is required on soils vulnerable to runoff and erosion in areas suffering from diffuse pollution, and that such management would be effective in reducing the risk of flooding and diffuse pollution.

5. Conclusions

These plots were established by the Environment Agency and host farmers to demonstrate the importance of soil management on the risk of mobilisation of sediment and associated pollutants in agricultural runoff that may be contributing to declines in river water quality across the Hampshire Avon catchment. Although the treatments were not replicated, the deployment of replicate run-off traps allowed some statistical evaluation of selected cultivation and crop management practices under contrasting site and rainfall conditions. Quantitative evidence is presented of capping and cultivation timing effects on runoff, and subsequent entrainment of soil particles and associated P across three soils differing in both hydrological characteristics and past P fertilisation. Although not always reliable on erosion vulnerable soils due to variations in precipitation, early drilling of crops to quickly establish a crop cover, and timeliness of cultivations to avoid compaction, have been shown to be key management techniques to help reduce the potential risk of runoff, erosion and P loss. The greater susceptibility to runoff and erosion when crops are necessarily sown late can be minimised by adoption of reduced cultivation techniques. Reduced cultivated soils provided greater crop residue cover, were less susceptible to sealing (or capping) at the soil surface and provided a firmer surface for tractor wheelings due to their more consolidated and uniform soil structure. Tramlines were also important vectors of runoff causing increased mobilisation of sediment and P and need to be managed carefully. The greatest impact of tramlines was obtained where they caused significant indentation of the soil surface after traditional inversion cultivation or where erosion rills developed in the tramline. Lowest losses were obtained when tramlines were established on more consolidated reduced-cultivated soil, or under dry soil conditions, when any increase in runoff generation was compensated by a decrease in sediment entrainment. Establishment of partial crop cover in the tramline, and establishing tramlines across the slope rather than up and down the slope, were also effective in reducing runoff and/or entrainment of sediment and P. The data support the adoption of improved soil management practices on farms in the catchment area, and will be used to help develop the catchment-based decision support tools required to predict the impact of management change on sediment and P loads as part of river basin management planning.

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