August 2015

Project Report No. 559

Reducing the risks associated with autumn wheeling of combinable crops to mitigate runoff and diffuse pollution: a field and catchment scale evaluation

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This is the final report of a 60 month project (RD-2007-3386) which started in March 2009. The work was funded by Sustainable Arable LINK, Defra, Scottish government and a contract for £120,000 from AHDB Cereals & Oilseeds.

AHDB Cereals & Oilseeds is a division of the Agriculture and Horticulture Development Board (AHDB).

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1. Abstract

Tramline wheelings are an important management tool for cereals, but their use for autumn spraying also increases the risk and severity of soil compaction and damage, surface runoff, erosion, and nutrient/sediment loss to water bodies (GAEC 5). Recent ADAS research shows most runoff from cereals occurs down these bare, compacted tramline wheelings when soils are wet.

Research evaluated tramline management options over four years at four sites with contrasting soil types and slopes in England and Scotland using replicated hillslope sections. Results showed the most practical cost-effective tramline management options included:

- Correctly-inflated Very Flexible (VF) tyres – operating at half the pressure of conventional tyres
- A novel self-propelled rotary harrow unit attached to the rear of the crop sprayer in autumn. This punctures the soil in several places across a wheeling, increasing infiltration without affecting traction. It is self-cleaning, easy to use (hydraulically controlled from the cab), has very low (9 hp) draft requirements, and works on both self-propelled and trailed sprayers.
- A novel surface profiler-roller unit attached to the rear of a tractor, and used once after autumn spraying. This creates a convex soil surface which sheds water back into the crop rather than channelling it into the concave tyre imprint usually created by farm traffic.

VF tyres and rotary harrow both proved versatile and cost-effective, significantly reducing (p<0.05) runoff and erosion on a range of soil types (although data on clays was limited). Surface runoff was reduced by up to 75% using VF tyres, 85% using surface profiler-roller and up to 95% using the rotary harrow, compared to control tyres. The surface profiler required a separate pass and so proved less practical in a winter cereal crop situation, although other ADAS research has demonstrated its practicality and cost-effectiveness in row crop systems. For cereals, the slightly greater initial cost of VF compared to conventional tyres was more than offset by their reported longer lifespan, resulting in a net gain of £2/ha across a 300ha farm. The rotary harrow cost £12/ha if applied to only 20% of a 300ha farm (but costs could be lower as allied research confirms efficacy across crop rotations). Supported by this research, capital grants towards tramline management tools are now available under the Higher Tier of Countryside Stewardship in England (RP31).

Other tramline management practices to avoid the risk of compaction, runoff and erosion include:

- Increase tramline spacing (e.g. moving from 18m to 24m or more)
- Correct tyre inflation pressure for the tyre, field operation and axle load (i.e. don’t over-inflate)
- Careful timing of autumn spraying operations to avoid very moist soil conditions
- Avoid establishing tramlines on loose “fluffy” seedbeds or when soils are very moist

- Use an extra headland tramline at the lowest end of the field, and disconnected from the other tramlines, so the area between the two tramlines acts as a buffer strip to most of the field
- Re-orientate crop drilling (and hence spraying) so tramlines do not follow the steepest slope

However, results showed that drilling tramlines which will be receiving traffic (and spraying using GPS) is not a solution, because soils will still be compacted by sprayer traffic in autumn when soils are often wet and vegetation cover is limited, and so the risk of runoff and erosion remains.

2. Introduction

2.1. Project Background and Purpose

This project addresses the need for practical, affordable, and targeted management of fields with combinable crops to help reduce the risk of soil compaction, erosion, and losses of soil, phosphorus (P) and nitrogen from land to water courses. This is to support sustainable and profitable farming, achieve the requirements for cross-compliance and Good Agricultural and Environmental Condition (GAEC 5) (Defra, 2015), and support catchment management water quality objectives.

Tramline wheelings are the narrow, concave, unvegetated areas which often run up and down the steepest slope, and which are used as bout markers for spray operations in autumn when soils are moist and prone to soil compaction from farm traffic. Previous Defra-funded research projects [NT1033 (Silgram, 2001), PE0111 (Silgram, 2005; Silgram *et al.*, 2006) and PE0206 ('MOPS' - Mitigation of Phosphorus and Sediment: Quinton *et al.*, 2007, 2008)] revealed that these unvegetated and compacted tramline wheelings were a major transport pathway for surface runoff and associated losses of sediment and phosphorus (P) from winter cereals on moderate slopes. These effects were evident over several winters on both lighter and heavier textured soils and on moderate 4–5° slopes, representing a large proportion of the 4.6 million hectares of cropped land in Great Britain.

These findings concur with the results of a survey of 146 arable fields which found that tramline wheelings were a major causal factor in 34% of fields where erosion occurred (Chambers *et al.*, 2000). That conclusion has been supported by more recent evidence (Withers *et al.*, 2006; Silgram *et al.*, 2007; Deasy *et al.*, 2009, 2010a,b; Silgram *et al.*, 2010), which has confirmed that losses of runoff, sediment and P down tramlines are often specifically associated with the autumn spraying of cereals. It is recognised that autumn spraying of cereals is an economic necessity in many farming circumstances. Nonetheless, the unforeseen potential effects of autumn spraying on soil compaction, surface runoff, erosion, and loss of sediment and P can pose a potential risk to sustainable profitable farming. Risks include deteriorating soil structure, undesirable soil hydraulic impacts (affecting porosity, drainage etc.), and the loss in runoff of fertile topsoil which is rich in organic matter, fertiliser and surface-applied plant protection products.

Such impacts can also pose an environmental risk associated with the protection of water bodies, given estimates that agriculture contributes around 25% of the total P load and around 70% of the sediment load entering surface freshwater systems in England (Collins *et al.*, 2009a,b; Natural England, 2011; Environment Agency, 2012). Sediment eroding from fields can smother sensitive river beds, hindering the ability of fish to spawn on river gravels (e.g. Armstrong *et al.,* 2003); while agronomically-insignificant loads of P (*c.*1kg/ha) can pose ecological problems, promoting eutrophic status in receiving waters, stimulating toxic algal blooms and reducing dissolved oxygen concentrations, even with riverine P levels as low as 0.1mg/l.

In response to these agricultural and environmental risks, this project aimed to develop and evaluate the relative merits of cost-effective, practical solutions for managing autumn spraying of winter cereals to protect farmers' valuable and limited soil resources, promote sustainable land management practices, help farmers achieve cross-compliance objectives (GAEC 5) and support environmental protection objectives.

2.2. Project Objectives

The overall objectives of this project were:

1. To design, prototype and evaluate the efficacy of practical and novel engineering solutions for reducing the risk of soil compaction, surface runoff and associated diffuse pollution from tramline wheelings used for autumn spraying in combinable crops across a range of UK soil types and slopes.
2. To use this, and other, research evidence (i) to develop, test, and refine novel modelling approaches to estimate the effectiveness of different mitigation techniques over a wide range of sites and environmental conditions, and (ii) to upscale mitigation results to estimate impacts of the targeted introduction of such measures at sub-catchment scale.
3. To evaluate the cost-effectiveness of integrating the use of different mitigation tools into commercial farm operations.
4. To provide robust evidence, advice and recommendations concerning alternative management methods for tramlines in autumn cereals, both to inform government agri-environmental policy needs, and to support sustainable, cost-effective best practices compatible with profitable arable farming.

2.3. Project Approach

Project Objective (1) was achieved by developing and testing several novel yet practical methods for managing tramlines in autumn cereals. The use of both conventional and novel soil physical methods, new equipment attachments and low impact tyres were included in this evaluation. The development and selection of these tramline mitigation methods are outlined in Section 3.1. The effect of different tramline management methods on soil physical parameters (e.g. soil compaction, trafficability for autumn spraying), and their efficacy in reducing surface runoff and associated losses of sediment and P, were evaluated across a range of soil types and climatic conditions in replicated, statistically-robust hillslope trials (rather than less representative and scaleable small plot studies). The effect of tramline management on crop yield was also investigated. The methodologies for the experimental trial activities are described in Chapters 3.2–3.6 inclusive, and results are reported in Chapter 4.1 (Impacts on soil properties) and Chapter 4.2 (Impacts on surface runoff, sediment and P loss).

Project Objective (2) used hillslope-scale rainfall-runoff data from previous Defra-funded projects including PE0111 and PE0206, to incorporate the use of tramlines in cereals in the field-scale ADAS Pollutant Transfer (APT) model developed in Defra project WQ0128 (Collins *et al.*, 2012). Results from the experimental hillslope trials outlined under Objective (1) were then used to identify model parameters and develop novel model functions to characterise the effectiveness of these alternative tramline mitigation methods across a range of soils and climatic conditions at whole-field scale. These impacts were then up-scaled to infer the potential impacts of implementing the alternative tramline management methods across larger areas, considering three sub-catchments in the West Midlands as case study examples. The project’s modelling outcomes are presented in Chapter 4.3.

Project Objective (3) used results from the hillslope trials from Objective (1) which quantified the efficacy of tramline mitigation methods, coupled with estimates of field-scale and catchment-scale efficacy of these methods based on modelling results from Objective (2), to derive cost-effectiveness assessments for each tramline mitigation method. These assessments considered implications for different operational sprayer configurations (e.g. tractor mounted versus self-propelled sprayers). Broader issues associated with the alternative tramline management methods evaluated under Objective (1) were also considered, such as their carbon footprints (e.g. fuel use), adoption incentives, catchment-scale outcomes and policy impacts. The economic and practical assessment of alternative tramline management methods are reported in Chapter 4.4.

Objective (4) used the approach outlined above to integrate experimental and modelling results, and thereby demonstrate the efficacy and limitations of different practical approaches for tramline management at field and sub-catchment scale. Project outputs have provided targeted evidence to inform agri-environmental policy needs (e.g. Defra’s Countryside Stewardship scheme), together with robust guidance to the farming industry on the most practical and cost-effective options for incorporating tramline management methods into best practice to support future commercial farming operations. A discussion of project outputs and recommendations to the industry are presented in Chapter 5, and a large number of Knowledge Transfer activities associated with this project are documented in chronological order in Appendix 1.

3. Materials and methods

3.1. Site and treatment selection

3.1.1. Site selection

Sites were selected to evaluate tramline management methods on light, medium and heavy textured soils with long, linear slopes with slope angles of 4–9 degrees under cereal rotations. Long slopes are at inherently greater risk of runoff, due to the larger volumes of runoff which can potentially be transmitted downslope without a gravitational hindrance or physical barrier. Slope angle was chosen to encompass the majority of slopes on which cereals are grown and where surface runoff would be both a potential risk and have the potential to be mitigated by practical management solutions. The characteristics of the field sites are shown in Table 1. The original intention was for these field sites to be monitored in Year 1 (winter 2009-10), Year 2 (winter 2010-11) and Year 3 (winter 2011-12).

Table 1. Field sites for experimental evaluation of tramline management methods. Ordnance Survey Grid References (OS GR) are shown.

Site	Location	Soil type	Mean Slope Angle (°)	Altitude (m)	OS GR
Hattons	Staffordshire	Loamy Sand	4	120	SJ887046
Gatley	Herefordshire	Silty Clay Loam	9	250	SO442677
Loddington	Leicestershire	Clay Loam	5	130	SK789023
Balruddery	Perthshire	Sandy Loam	6	100	NO305329

A third party error associated with the analysis of some laboratory samples in Year 1 facilitated a repeat of these treatments in an additional Year 4 of the field campaign (winter 2012-13), at no additional cost to funders. This had the effect of postponing the planned economics and modelling activities by 12 months (as they depended on the experimental results), and so (with the funders' agreement) the final project end date became 31 March 2014. The Hattons site was operated by Severn Trent Water plc, the Gatley site was privately managed, and the Loddington site was operated by the Game and Wildlife Conservation Trust.

Separate complementary funding was obtained from the Scottish government at the end of Year 1, and as a consequence a further site was established at Balruddery in Scotland which was used in monitoring Years 2–4 inclusive (Table 1). This site was operated by the James Hutton Institute. Sites had not received organic amendments in the three years prior to the project's inception. All four field sites were managed as commercial crops of winter cereals, including the usual cultivations, drilling, spraying, fertilisation and harvesting operations determined by each Farm Manager.

3.1.2. Treatment selection

A wide variety of tramline mitigation techniques were considered by the project team. However the final selection for the development and field testing phase was based on individual concepts satisfying a total of eight challenging design criteria before methods were deemed “fit for field testing”. Tramline management methods had to:

- Be practical for use in a commercial rotation drilling autumn cereals
- Be effective – Increasing surface roughness and/or infiltration over-winter, reducing soil surface compaction; or otherwise reducing surface runoff and erosion risk
- Be potentially useable on both trailer-mounted and self-propelled sprayers
- Be low-cost
- Have negligible impact on trafficability in later autumn or in spring (i.e. leave wheelings amenable to further traffic in case a subsequent spray operation is needed)
- Have no negative effect on yield along crop edges beside wheelings
- Be self-cleaning (low adhesion)
- Be useable at conventional sprayer speeds with no significant loss of traction (i.e. wheelslip and/or fuel use)

Following dialogue with industry partners, an assessment of recent applied science and engineering literature, the following mitigation methods (Figure 1) were selected:

- **Drilling tramlines**. This option is used in Australia and was advocated by some UK industry partners, as the spraying operations can be positioned using GPS instead of using the bare undrilled tramlines as bout markers.
- **Very Flexible (VF) tyres**. These VF tyres were designed to operate at much lower ground pressures compared to conventional tyres – typically around 10 psi (69 kPa) instead of 20psi (138 kPa) for conventional tyres. These VF tyres were also designed to retain traction whilst operating at normal sprayer speeds, and by operating at much lower pressures they were able to distribute the sprayer axle weight over a greater surface area in contact with the soil surface, which should cause less soil compaction (and hence runoff risk). Although such tyres were already on the market in 2009, there was very little information available about their impacts on soil physical conditions (such as compaction), surface runoff, or practical advice on their use.
- **Self-propelled rotary harrow unit.** This was invented during the course of this project, and comprised a novel self-propelled rotary harrow device with very low (<9 hp) draft requirements, attached to the rear of a trailed or self-propelled sprayer unit and hydraulically linked to the tractor cab. The rotary harrow unit was designed by Wright Resolutions Ltd. for trailed sprayers in conjunction with Simba UK Ltd (now Great Plains UK Ltd.), and modified for self-propelled sprayers by Housham Sprayers Ltd.) The unit was designed to be self-cleaning, with short

offset spikes to loosen the top 5–7cm of compacted topsoil which were deliberately arranged diagonally to avoid losing traction (in case a subsequent spray operations were required).

- **Surface profiler**. This was a novel surface profiler-tine-roller unit which created a convex soil surface, as opposed to the usual concave cross-section created by a tyre imprint, which tends to promote the channelling of water down tramlines. The unit's resulting convex soil imprint was instead designed to shed water away from the compacted wheeling and back into the growing crop. This unit, developed by independent engineer Charles Creyke, was a two-piece unit incorporating an angled tine to loosen compacted wheelings preceding a newly-designed roller with a novel cross-sectional profile and diagonal rippled surface made from a patented polymer with self-cleaning properties.

Figure 1. Experimental treatments: VF tyre (left), rotary harrow (middle), and surface profiler (right)

3.1.3. Experimental treatments for different sites and years

The mitigation treatments chosen for study varied from year to year, based on results from the previous season, and the development and availability of equipment within the project.

Year 1 (winter 2009/10)

The experiment was established using a randomised design in a two-way factorial design with four replicates. In this, and all other years of the project, treatments were imposed using vehicles driven in an upslope direction at 10 km h^{-1}. In this first season, the treatments imposed at the three English sites were:

- Conventional bare undrilled tramline wheelings (baseline control treatment), compared to drilling the area used for wheeling with GPS used to guide spray operations ("fuzzy" or "furry" tramlines). The whole field was drilled in an identical fashion, the only treatment difference being that GPS was used to guide spraying operations and hence tramline wheelings were imposed during the spraying operation itself using conventional tyres (see below).

- Optimally-inflated “Very Flexible” (VF) tyres compared to conventional tyres inflated to road pressure – to assess any effect on runoff, sediment and P losses when VF tyres are used for autumn spraying.

Year 2 (winter 2010/11)

Four replicates of four treatments were studied in a randomised block design. This allowed three methods to be compared against the control (typical practice) treatment at the three English sites and the Scottish site:

- Tyres inflated to conventional road pressure: Conventional (control tyre) treatment (CT)
- Optimally-inflated “Very Flexible” (VF) tyres
- Novel rotary harrow unit (on hydraulic toolbar attached to back of sprayer)
- Novel surface profiler roller-tine roller unit

The vehicle and tyre configuration were identical to that used in the first year of the study. The rotary harrow unit was used on the conventional tyre configuration (so as to separate out any harrow effect from any VF tyre effect). The surface profiler roller-tine unit required a separate pass operation after the autumn spray had taken place: this separate pass was done with the unit attached to the rear of the tractor (with conventional tyre pressures).

Year 3 (winter 2011/12)

In the third year of the trial, a randomised design with four replicates of four treatments were imposed at the three English sites and the Scottish site, exploring the effect of tyre and harrow treatments separately and in combination:

- Conventional control tyre (CT)
- Conventional control tyre (CT) + rotary harrow
- Optimally-inflated VF low ground pressure tyre
- Optimally-inflated VF low ground pressure tyre + rotary harrow

Year 4 (winter 2012/13) – repeat of year 1 due to third party error

A third party error facilitated a repeat of the treatments imposed in Year 1 of the study in an additional Year 4. The Scottish site was unaffected by this issue (as monitoring began there in Year 2), and treatments compared drilled tramlines with both VF and conventional CT tyres (similar to Year 1 at the English sites), but also included an assessment of the rotary harrow as this had not previously been assessed in Scotland.

Across all sites and years, tramlines were imposed using a Massey Ferguson 7480 tractor weighing 6729 kg (AGCO Ltd., Kenilworth) or similar, towing a full Guardian 3500 litre spray-tanker

(Chafer Machinery Ltd., Lincolnshire), unloaded weight 3950 kg (Figure 2). The tyres used were Michelin Agribib and Xeobib agricultural tyres (Michelin Tyre PLC, Stoke-on-Trent). Tyre pressures were set by the Michelin engineer on the day based on knowledge of the tractor, sprayer, axle weight distribution and sprayer loading (water volume): typical tyre inflation pressures are shown in Figure 2, together with their configuration on the vehicles under conventional and Very Flexible (VF) tyre treatments. The rotary harrow unit was designed by Wright Resolutions Ltd. in conjunction with Simba UK Ltd. (now Great Plains Ltd.), and the surface profiler roller-tine unit was designed by independent engineer Charles Creyke.

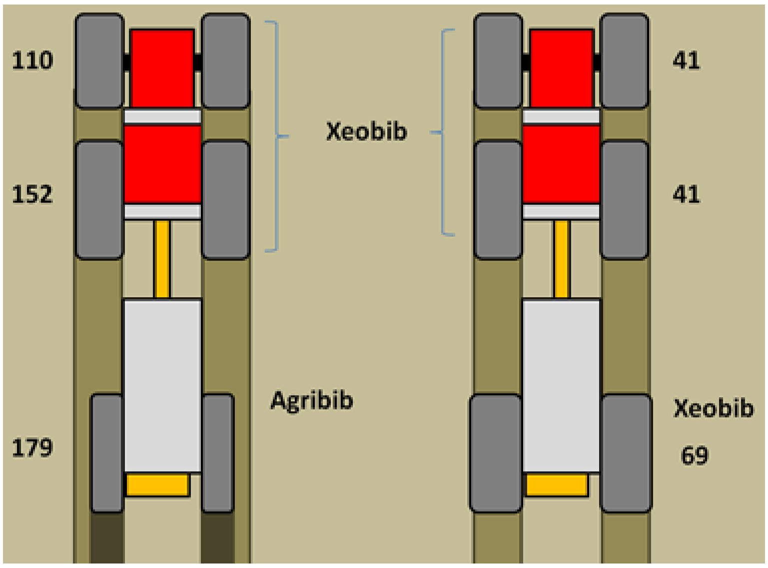


Figure 2. Plan view of conventional ground pressure (left) and Very Flexible (VF) low ground-pressure (right) vehicle configurations for a Massey Ferguson 7480 tractor (upper vehicle) pulling a trailed Chafer Guardian sprayer (lower vehicle). Tyre inflation pressures are shown in kPa.

A summary of the various treatments investigated in different sites and years is shown in Table 2. Results from this hillslope-scale evaluation of the alternative tramline mitigation treatments are presented in Chapter 4.2.

Table 2. Summary of tramline mitigation treatments investigated in different sites and years. An “X” denotes treatments were studied. Black rows denote a site was not used in that year.

Year	**Site**	**Conventional tyres**				**VF tyres**		
		Not drilled	**Drilled tramline**	**Rotary harrow**	**Roller**	**Not drilled**	**Drilled tramline**	**Rotary harrow**
2009/10	Hattons	X	X			X	X	
	Gatley	X	X			X	X	
	Loddington	X	X			X	X	
	Balruddery							
2010/11	Hattons	X		X	X	X		
	Gatley	X		X	X	X		
	Loddington	X		X	X	X		
	Balruddery	X		X	X	X		
2011/12	Hattons	X		X		X		X
	Gatley	X		X		X		X
	Loddington	X		X		X		X
	Balruddery	X		X		X		X
2012/13	Hattons	X	X			X	X	
	Gatley							
	Loddington							
	Balruddery	X	X	X			X	

3.2. Experimental and equipment design

3.2.1. Rotary harrow design

The principle of the rotary harrow evolved as a system to disrupt compacted tramlines, loosening the surface soil, increasing surface roughness and promoting infiltration of ponded and runoff water. In addition to promoting localised infiltration of water ponding in tramline wheelings, the resulting pattern created by the harrows creates a chevron pattern of shallow indentations (Figure 3) which encourages water away from the centre of the tramline towards the uncompacted cropped areas either side.

The specific design of the rotating harrow was developed to allow for high speed (10 to 16kph) operation with low soil movement, low draft requirement, and without adversely affecting traction (in case a further spray event should be required). Consequently, unlike conventional tines, the rotary harrow's operation was compatible with a sprayer in terms of its low power requirement and soil disturbance at speed. Harrow pressure and cutting angle could be varied to suit soil conditions and minimise soil throw.

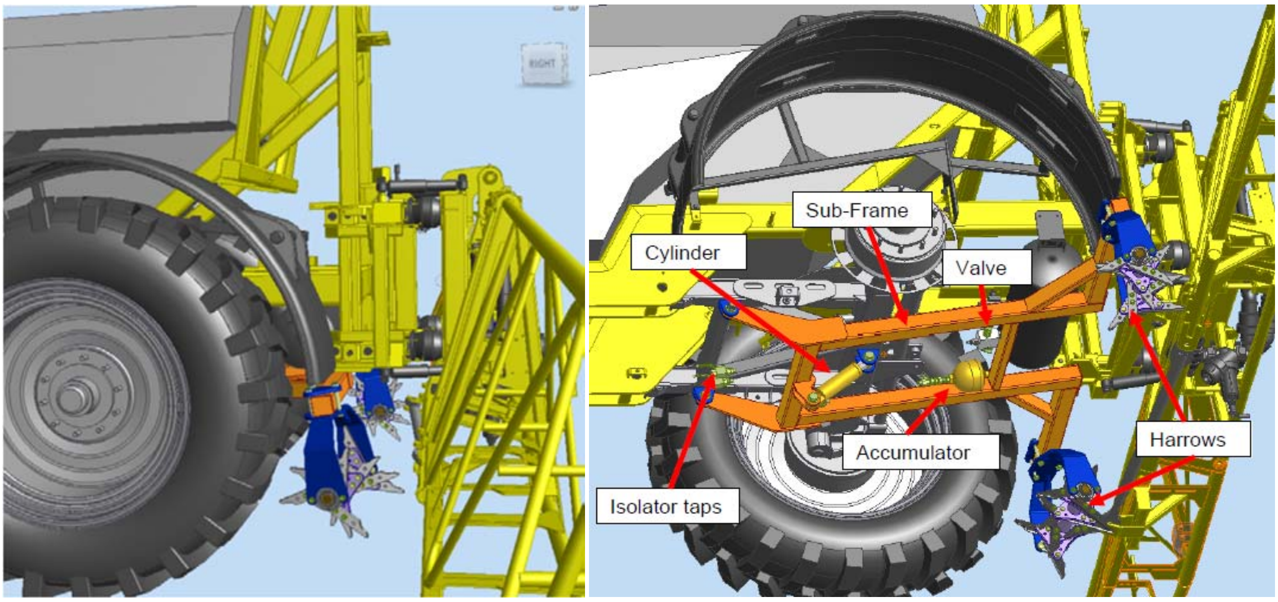


Figure 3. Rotary harrow design plan showing attachment to rear of sprayer unit (left), and underside view showing sub-frame and hydraulic control system (right)

The harrow units were designed during the project and comprised three main parts (Figure 3):

- Harrows – the rotary harrow assemblies themselves. These were clamped to a sub-frame or frames which were part of the sprayer, and the design of which was specific to each sprayer model. The harrows were (wherever possible) a generic design of simple, replaceable tines on a rotor axle held by bearings onto a small carrier frame. This carrier was bolted to the sprayer sub-frame, and the rotors could thus be aligned to wheel track width, or removed as required when not needed.

- Sub-Frame – made specifically to suit the sprayer. Could be a single part (as above) or units fitted to wheel motors of a self-propelled sprayer.
- Hydraulic control – comprised a cylinder for raise/lower, a pressure setting valve, and an accumulator and isolators to set and maintain ground engaging pressure. A pre-set pressure was set in the down side of the circuit (via pressure setting valve), and this was then locked in. An accumulator provided cushioning and contouring to the harrows, maintaining the pre-set pressure. Raising to clear the ground surface when turning or when not required was effected by pressuring the sub-frame up, the accumulator holding excess oil generated and the harrows could be isolated in this up position when not required. They return to the pre-set operating position and pressure when the isolator was opened and the oil was allowed back to the tractor or sprayer hydraulics when spraying commenced.

Operational notes

The operating pressure of the harrows comprising the final designed unit (Figure 4) could be adjusted for different field conditions. If ground conditions required it, more or less pressure could simply be set as needed. The harrow circuit itself was pressured to raise clear of work, allowing it to be isolated in this position if needed when the harrows were not required. Returning the circuit to float or lower allowed the harrows to engage the ground and follow contours at the pre-set pressure as needed via the accumulator.

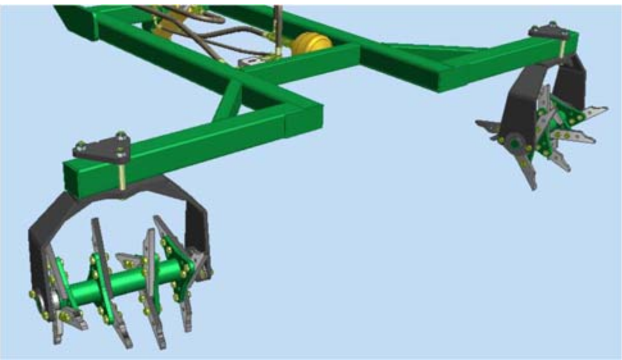


Figure 4. Final rotary harrow design, with four harrows per arm, with one arm set to disrupt each tramline wheeling.

In terms of maintenance:

- Bearings – these are pre-sealed for life and require no maintenance
- Rotor Tines – provided these are kept tight, maintenance is limited to replacement or reversal when worn.

- Overall – the device comprised a simple set of units which could be pre-set and operated when needed, or left clear of work. Removal of the rotors was a quick 15 minute operation for two people. Removal of the sub-frame (for example when spraying established tall crops) depends on the fittings, but was usually a two persons operation taking between 30 minutes and two hours depending on the machine – typically done only once per season.

The unit was designed to function not only on cereals, but also on row crops (and has been successfully tested in a separate Defra-funded project WQ0127 led by ADAS called MOPS2 (Silgram *et al.*, 2015). This versatility and multi-functionality renders the purchase of such a unit much more cost-effective, as it can have multiple applications to reduce near-surface soil compaction and runoff risk on different land uses across a whole farming system.

3.2.2. Experimental site layout

At each site in each year, experimental treatments aimed at mitigating soil compaction, surface runoff and erosion were imposed using a statistically robust randomised block design, typically encompassing four replicates of four treatments. Randomised plots, typically 100–300m long and 3m wide spanning adjacent pairs of tramline wheelings were studied on these loamy sand, sandy loam, silty clay loam and clay soils over four years. In this way, the sampled area in each “plot” was, in reality, more akin to a true hillslope “segment”, typically measuring 300–900m^2. This was a deliberate attempt to avoid the (valid) edge effects and lack-of-representativeness criticisms which can be levelled at small plot-scale field experiments where plots are often less than 100m^2 in size (for example, Kay *et al.*, 2005; Withers *et al.*, 2006) and fail to consider the cumulative effect of saturation building up within a hillslope. Runoff generated upslope may not be able to infiltrate into soil further downhill because that soil lower down will often be wetter, the effect of which can be to exacerbate how much runoff reaches the base of the slope.

However, this novel hillslope-scale experimental design, which was intended to promote more robust measurements less prone to the usual constraints inherent in small plot studies, created the difficulty that very large volumes of runoff could be generated, even from these relatively modest hillslope segments. For example, a rainfall event of 5mm/h lasting for two hours may generate 2mm of surface runoff. This equates to (2mm x 600m^2=) 1200L of runoff water which must be sampled. The largest practically sized fibreglass storage tanks which could be used at these field sites had a capacity of only 500L each, and therefore a method was required to take a flow-proportional sample of the runoff as it arrived in the tramline wheeling at the base of the hillslope. A novel piece of equipment – a sample splitter – was required to achieve this aim.

3.2.3. Sample splitter design

ADAS had developed a prototype means for taking representative sub-samples of runoff using a flow-proportional sample splitter (Deasy *et al.*, 2009) in a previous Defra-funded project PE0206, Mitigation of Phosphorus and Sediment (MOPS). This was based on the tipping bucket concept commonly used in rain gauges, but in MOPS this equipment was only developed to collect runoff subsamples from relatively small plot areas. The MOPS design concept therefore required significant upscaling and redesign in order to sample the much larger volumes of sediment-laden runoff (not clear rainwater) and much higher rates of runoff flowing from the larger catchment areas proposed in this project of up to 900m^2.

This objective was constrained by the electronics, which used a specialised reed switch to register each individual tip (and its timing) with a connected datalogger. Reed switches can only record completed electrical circuits (i.e. tips) up to a finite temporal frequency, which therefore imposes inherent limits on the number of tips per minute which can be recorded, and hence on the maximum flow rate (in litres per minute) which can be measured. It was essential this inherent electronic constraint did not limit the recording of the runoff flow rates which were anticipated in this study, which was one reason why the volume per tip had to be increased.

To illustrate the potential range of runoff flow rates which would be required in this study, Table 3 shows the relationship between the size of the monitoring area in each hillslope segment (“catchment area”), the rainfall intensity, the proportion of rainfall lost as surface runoff (typically 5–10%) based on losses from conventional undrilled tramlines monitored in earlier ADAS work (Silgram, 2005, 2006), and the flow rate of runoff reaching the tipping bucket sample splitter units at the base of the slope.

Rainfall events in excess of 5mm/hr would normally be classed as intense in lowland UK situations, but could occur for short periods of time such as during a thunderstorm. The calculations underpinning Table 3 were therefore critical to the design criteria for the upscaled tipping bucket sample splitters, as they defined the range of tipping bucket flow rates which were required to capture runoff from rainfall events with differing intensities.

Table 3. Relationship between runoff rate reaching the monitoring equipment at base of slope, hillslope monitoring area, rainfall intensity, and proportions of rainfall lost as surface runoff.

Catchment area m2	Surface run-off as % rainfall	Rainfall mm/hr				
		2	4	6	8	10
		Flow l/min				
300	5	0.5	1.0	1.5	2.0	2.5
600	5	1.0	2.0	3.0	4.0	5.0
900	5	1.5	3.0	4.5	6.0	7.5
300	10	1.0	2.0	3.0	4.0	5.0
600	10	2.0	4.0	6.0	8.0	10.0
900	10	3.0	6.0	9.0	12.0	15.0
300	15	1.5	3.0	4.5	6.0	7.5
600	15	3.0	6.0	9.0	12.0	15.0
900	15	4.5	9.0	13.5	18.0	22.5
300	20	2.0	4.0	6.0	8.0	10.0
600	20	4.0	8.0	12.0	16.0	20.0
900	20	6.0	12.0	18.0	24.0	30.0

Based on Table 3, it was clear the tipping bucket sample splitters were needed to operate routinely over a range of runoff flow rates up to at least 30l/min, and potentially at higher rates over short intense periods such as thunderstorms. The original MOPS design for sample splitters was therefore modified to satisfy this project's operational criteria that the resulting units were able:

- To monitor runoff flow from moderate slopes ≥4° whilst allowing a 2° angle to maintain water flow (and avoid backing up) in pipes transferring collected runoff into sample storage tanks
- To have straightforward, low-cost manufacturing cost, compact design (especially height), and installation method for mounting immediately above 500L sample storage tanks
- To separate and store a flow-proportional sample containing representative concentrations of sediment and potential pollutants
- To increase the capacity of units to around 1L per tip, to sample higher intensity runoff events
- To increase speed per tip to enable the operating range to be extended to record runoff arriving at the sampler at up to at least 30 l/min (Table 3)
- To remain functional and relatively maintenance-free while left unattended in relatively remote locations for extended time periods. This required improvement to the lid strength, entry flow direction and speed, with manufacturing material chosen to resist physical damage in normal working conditions (i.e. unit must be robust and durable over a four year project lifecycle)
- To provide an overflow outlet in case the fibreglass runoff tanks became full, in spite of this subsampling strategy
- To reduce the likelihood of surface trash (i.e. soil clods, crop residues, stones) clogging or blocking the flow inlet in order to maintain accurate flow measurement and representative sampling whilst handling sediment-laden run-off
- To provide a practical, rapid means to modify the proportion of total surface runoff collected in storage tanks (with the remainder diverted to waste), depending on the prevailing soil, ground cover, and weather conditions

- To improve the precision with which the central pivot line was drilled, to ensure the unit was balanced and produced near-equal volumes per tip from both left hand and right hand sides of the tipping bucket (tested and verified through intensive calibration – see below)

The penultimate criterion listed above was solved by using four compartments located on one side of the splitter box, with each compartment having a drainage hole in the base which could be left open, or blocked. This allowed the proportion of the total runoff which was sampled to be manually varied between 12.5% and 50% of the total runoff volume, depending how many of the four compartments were left open to drain into the storage tank below. This decision was subjectively determined on an event basis, depending on the antecedent weather conditions, visual extent of topsoil saturation, and local three-day weather forecast.

The final design criterion listed above, requiring both sides of the tipping bucket to have a similar volume per tip, was verified by calibrating left and right hand sides of the tippers separately. This was essentially a Quality Control (QC) exercise to avoid introducing unnecessary errors into subsequent field measurements. Plain water was used for the calibration as it was not possible to incorporate sediment continuously at a stable concentration, although it was recognised that the slightly higher specific gravity with a mixture of water and sediment, simulating field situations (+0.6% at maximum expected sediment concentrations of 10,000 mg/l, assuming dry sediment at 2.5 g/cc), might increase the tipping rate marginally.

Analysis revealed a general trend toward slightly greater errors between replicate measurements at higher flow rates, but an acceptable level of error (coefficient of variation <10%, where cv is defined as standard deviation/mean *100) was consistently achieved with the final prototype equipment. Figure 5 illustrates an analysis of field kit prior to installation, with mean tipping bucket capacities for this batch of 16 units destined for an individual field site ranging from 1.03–1.28 l/tip with a 95% confidence interval of ±0.11%. The availability of such individual calibration coefficients for each unit negated the need to introduce additional errors by using a single default value for volume per tip.

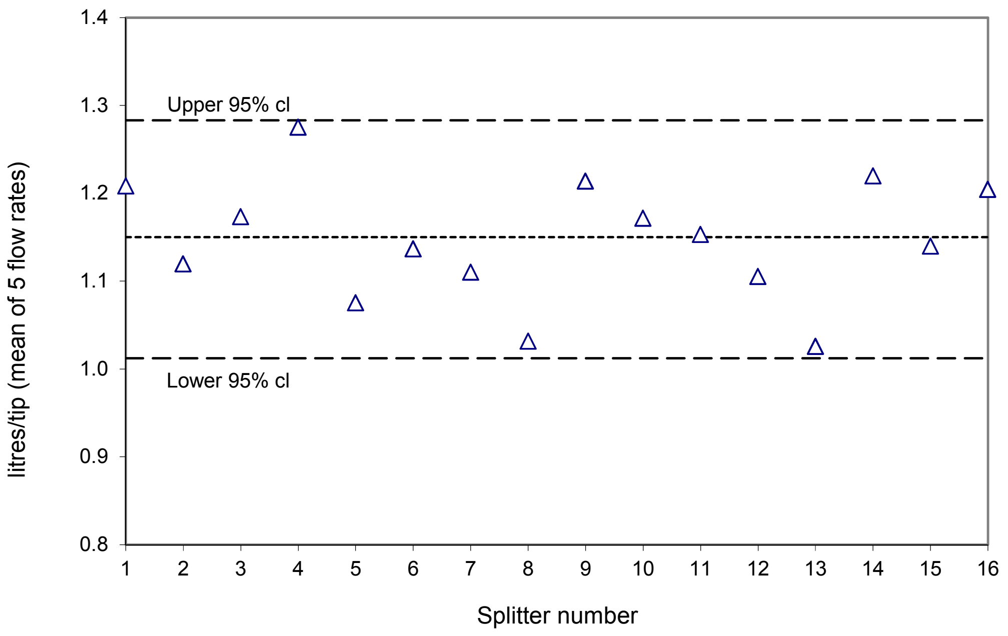


Figure 5. Calibration of a batch of 16 sample splitters for a single site, showing variations in litres per tip (which were taken into account via individual splitter conversion equations). Upper and lower 95% confidence intervals are shown.

Unplasticised polyvinyl chloride (UPVC) was the material chosen for construction because it is strong and durable and can be easily machined to fine tolerances. Alternative materials such as aluminium or stainless steel were discounted on cost grounds. Welding using specialised heat equipment provides strong bonded joints capable of withstanding the force of impact of the tipping bucket. The axle under the tipping bucket was initially mounted in plastic bearings inside the box, but excess friction caused by sediment ingress led to the axle being routed through the sides of the box into sealed bearings on the outside on later models.

Following the development and testing of five different prototypes for the splitter unit during the initial year of the project, a final sample splitter unit and an example calibration curve are shown in Figure 6. This calibration curve shows the operating range over which a robust calibration curve used to convert tips/min (recorded by the datalogger) to runoff flow (in litres/min) renders the unit capable of successfully subsampling runoff at flow rates of up to 40 l/min. The actual volume of runoff collected in the storage tanks was then reduced by a factor of 12.5–50.0% depending on how many stoppers were opened at the base of the sample splitter unit, with the remainder diverted to waste.

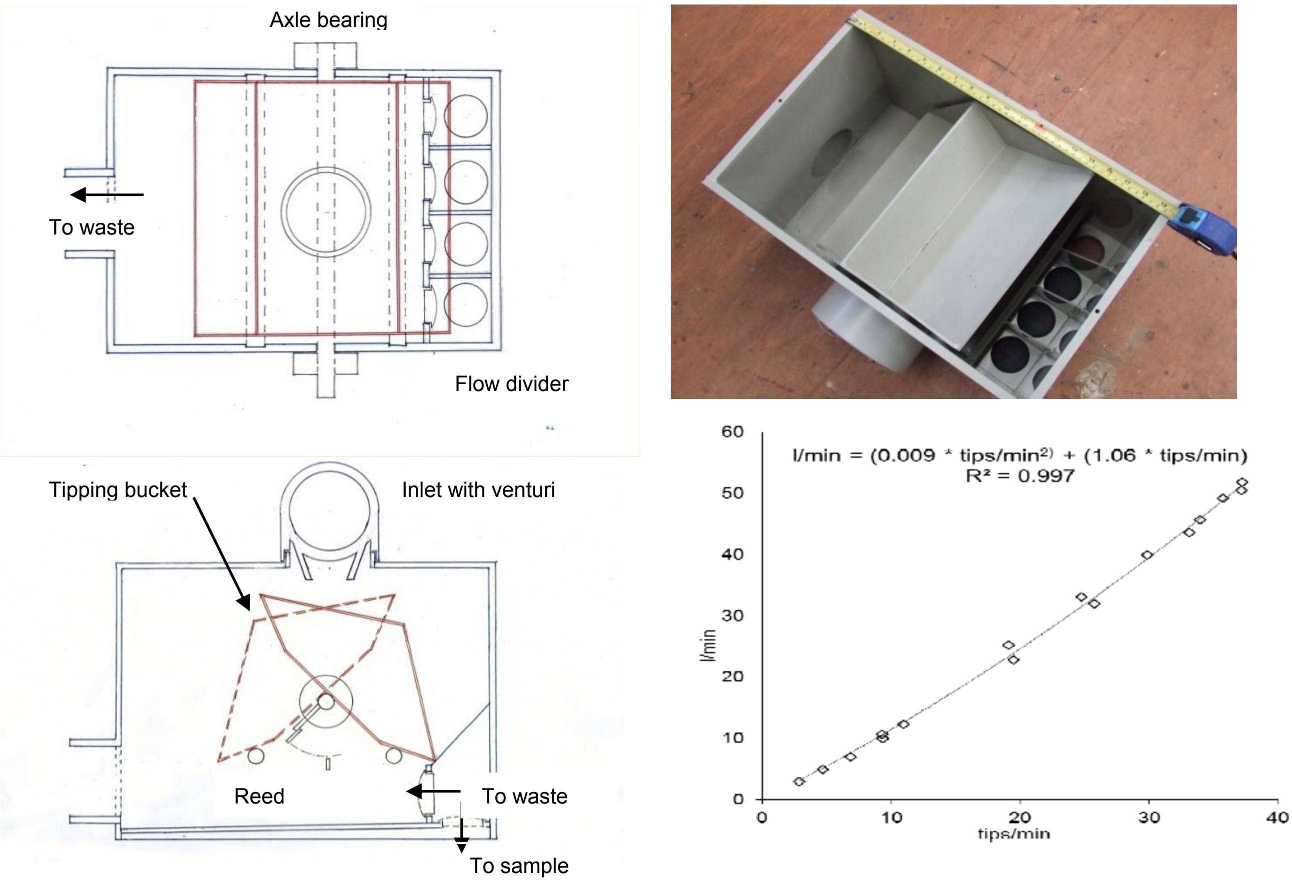


Figure 6. Novel flow-proportional sample splitter for runoff, showing plan design view (top left and top right), and side view (bottom left). The plan views show the internal compartments used to modify the proportion of flow collected. The bottom right image shows a calibration curve to convert tipping frequency to volume flow rate, with quadratic equation and ‘goodness of fit’ statistic.

3.3. Field installation

After treatments were imposed in each of the 4 replicates of the 4 treatments i.e. across a total of 16 hillslope segments, equipment was installed to collect surface runoff from each individual segment. Runoff water was collected using 3m lengths of domestic metal or plastic guttering installed across individual pairs of tramline wheelings, dug into the soil at an angle of 120^{o} to the long plot edge in order to increase downward slope angle and minimise the risk of sediment build up in the guttering. A flange on the leading edge against the plot, was bent down to 45^{o} to facilitate backfill compaction, thus minimising the possibility of water undercutting the gutter. The runoff was then transmitted downslope using drainpipes (supported by wooden trestles), into the sample splitters where a chosen proportion of the runoff was allowed to enter the 500L runoff storage tanks below whilst the remainder was diverted to waste.

Typically, 6m lengths of 110mm drainpipe were used, and positioned to ensure an adequate minimum downslope angle (≥2°) relative to the sloping soil surface. The pipe length needed to obtain the required vertical drop to maintain runoff flow was calculated as:

$$L = \frac{H \cos \theta_f}{\sin(\theta_f - \theta_p)}$$

where L is drainpipe length, H is installation height, θ_p is the downslope angle on pipe, and θ_f is the slope of the field's soil surface.

Based on practical experience in the previous MOPS project, wherever possible runoff storage tanks were sited on top of the soil surface. This increased material cost on pipework and trestles but decreased labour costs for installation. This method was preferable because the alternative of burying tanks in holes increased the risk of them floating as the holes filled with water: this would cause sampling apparatus to fail, and could occur at the base of slopes if subsoil saturation developed (due to prolonged wet weather causing wetness to build up from depth, and/or by subsoil compaction leading to a perched water table developing at plough pan depth).

An example of the resulting experimental installation is shown in Figure 7 below.

Figure 7. Rills in tramline wheelings at silty clay loam site following autumn spraying (top left); gutter collecting runoff from tramline wheeling during rainfall event at loamy sand site (top right); monitoring equipment in situ on two adjacent plots with orange pipework, white sample splitters, black runoff collection tanks with red lids, and blue wastepipes (bottom left); and aerial view of 16 plot experiment monitoring tramline treatments (bottom right).

3.4. Runoff sampling strategy

Stokes's law – originally identified over 150 years ago – dictates that particle size is a key factor controlling settlement times, with larger sand-sized particles (>2mm) in runoff settling out almost immediately while clay sized fractions (<2µm) in runoff will stay in suspension for much longer. Consequently it was important that tanks were thoroughly stirred prior to sub-samples of runoff being taken for analysis for sediment and P contents (see later). For this same reason it was also very important to avoid the tanks from over-topping as this would create a decanting effect which would artificially increase the sediment concentration in the sample and hence distort results.

This was one reason for connecting dataloggers to the tipping bucket units, so that in the unfortunate event that tanks did over-top then at least data would be recorded to relate rainfall to runoff timing and volume, even if sediment and chemical data may be unreliable due to the decanting effect. However, to minimise the risk of over-topping occurring at all, a rule-set was developed as a guide to sampling frequency which prompted a field visit if local rainfall exceeded 4mm/hour in intensity, or reached a total of 30mm in any single 24 hour period.

When an event was identified, based on these sampling criteria, the depth of the total runoff accumulated in each tank was measured and converted to a volume using a tank depth calibration (as a QC check on total runoff volume). Care was then taken to ensure complete suspension of soil particles by agitating the tank contents using a hand-held pump output hose directed at the bottom of the tank, prior to taking a representative subsample for laboratory analysis. Each tank was then emptied using an engine-driven pump to prime the equipment ready for the next event.

When totalled over entire individual monitoring events, the total of runoff volumes recorded every 15 minutes by the dataloggers connected to the tipping bucket sample splitters should equate to those back-calculated from volumes derived from depth measurements taken in the 500L runoff storage tanks (after the number of open stoppers had been taken into account). This proved to be a useful QC check, as obvious outliers due to equipment or installation failures could be easily identified, while more moderate variability due to minor errors (e.g. tipping buckets not being quite level) could be assessed as background or residual error within analysis of variance.

A comparison of corresponding values from the two methods is shown in Figure 8 for 35 measurements across two contrasting soil textures, one sandy and one a heavier clay loam. This confirms the validity of this approach, highlighting consistent performance across the two soil types, and illustrating the typical precision possible using such equipment. The strong linear relationship also serves to validate the derived calibration coefficients.

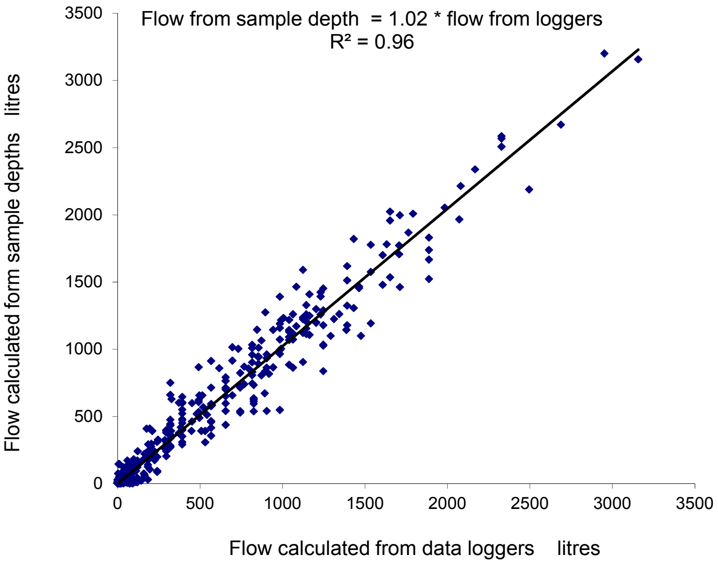


Figure 8. Relationship between total event-based runoff volume from dataloggers and that back-calculated from depths measured in runoff storage tanks (n=35 events across two sites)

Runoff was collected from individual rainfall events over the winter period. Experimental equipment took around a week to install and prime following cereal drilling. The effect of over-winter rainfall events were typically monitored between early November and the end of January in most sites and years. The exact monitoring periods varied from site to site and year to year, as they were wholly depended on prevailing weather conditions, soil conditions (which had to be amenable to autumn spraying in the first place) and cereal drilling dates identified by the host farmers based on the schedule for their own farming operations. Rainfall “events” which were sampled for analysis were regarded as periods of time lasting between 1–3 days which generated runoff (in reality, this could comprise one intense rainfall event, or several low-intensity drizzly events, as either could produce saturated topsoils and hence surface runoff). Meteorological data, including rainfall (usually hourly or sub-hourly resolution) was collected from an automated weather station (AWS) installed nearby, and used to compare with runoff data.

The final experimental design and runoff sampling methodology therefore collected runoff samples at different sites in different years using 16 sets of gutters, pipes, flow-proportional samplers and runoff storage tanks per site (Figure 7), with runoff volumes timed and recorded using dataloggers and with the samples analysed for suspended sediment (<0.45µm), total dissolved phosphorus (TDP) and total phosphorus (TP) contents based on standard laboratory methods (MAFF, 1986).

3.5. Runoff data analysis

Tipping bucket calibrations (described earlier) were applied to runoff data, taking account of the number of stoppers left open in the sample splitter units, and results were matched to incident rainfall data to permit calculations of the percentage of rainfall lost as runoff in each individual event. Laboratory analysis of sediment and P concentrations from runoff samples taken from individual storage tanks were matched to runoff volumes from each event to calculate event-based loads of sediment and P which had been lost to the base-of-slope in surface runoff.

Results for runoff and loads were expressed per unit area (e.g. mm or kg/ha) rather than on a per plot basis, in order to assist with upscaling. Exploratory data analysis was undertaken for monitored or derived variables on each sampling occasion and also on the cumulative totals aggregated across the over-winter sampling period using ANOVA in the statistical software Genstat (VSN International, 2011). The variables analysed included runoff volume as well as the mass, concentration and loads of suspended sediment, dissolved P and total P contained in surface runoff. In the few instances where data were skewed, log-transformed data were not used instead as they did not improve the distribution about the mean. Other variables, such as wheelslip, fuel use, and soil physics data associated with soil compaction were analysed where possible using pairwise t-tests, also using Genstat.

3.6. Soil monitoring strategy

3.6.1. Underlying principles

Surface runoff occurs when precipitation rate exceed the infiltration capacity of the soil and soils become locally saturated. This may be the result of wetting up from beneath (for example, due to a perched water table building up above a plough pan at 25–30cm depth), or due to rainfall landing at the soil surface faster than it can infiltrate into the soil surface. In both cases, surface runoff is promoted by soils becoming compacted either at depth (e.g. due to a plough pan) or in the near-surface area (e.g. due to heavy machinery traffic). Compaction reduces infiltration into soils, and hydraulic conductivity within soils. As the volume of air is reduced, this restricts the volume of water which soils can hold against gravity (i.e. field capacity), the total volume of air-filled pore space (i.e. porosity), and the proportion of the largest pores which are responsible for transmitting the majority of drainage water. Loading the soil with vehicle traffic reduces soil porosity and causes soil compaction which is exacerbated by the weight of vehicles (load); the length of time over which compaction takes place (duration); the number of traffic events; the extent of shearing that accompanies the uniaxial load; and the soil conditions at the time of loading (as wetter soils are structurally weaker and hence more prone to compaction).

Measuring surface runoff in this project therefore assesses the effect of the autumn spray event, which in turn depends on local rainfall conditions in the weeks after spraying. Consequently, if post-spraying conditions are dry, then monitoring results may show little runoff and fail to discriminate the effect of tramline mitigation treatments. For this reason, and to help understand the reason behind any experimental treatment effects on surface runoff, this project also characterised soil conditions associated with different tramline mitigation methods.

3.6.2. Soil physics measurements: overview

In addition to measuring the impact of tramline mitigation treatment on surface runoff, soil physical measurements were taken. These measurements varied between sites and years as the project developed, but typically included:

1) Topsoil bulk density
2) Hydraulic conductivity
3) Wheelslip and fuel use (from tractor cab)
4) Non-destructive methods for characterising soil compaction

The first variable above was assessed using standard methods with bulk density tins. Saturated hydraulic conductivity was measured in soil cores (see later Electrical Resistivity section for sampling details) by immersing them in de-ionised water for one week, and the constant head method described by Bohne (2005) used to determine the saturated hydraulic conductivity (K_s). In addition, the use of x-ray computer tomography (CT) scanning was investigated to characterise differences in soil structure and air-filled pore space under contrasting tramline treatments which may have different soil compaction (see later).

Problematically, both of the first two measurements listed were invasive and/or destructive, and risk modifying the soil structure and therefore affecting the very variables being measured. Consequently, this project also considered an additional category of method: alternative contemporary and novel non-invasive methods for assessing soil compaction (and, by inference, surface roughness). A detailed literature review of non-invasive methods for assessing soil compaction was undertaken in this project: findings from this review are reported in Shanahan (2013) and so are not repeated here.

Following that review, the most promising methods identified for characterising soil surface roughness (micro-topography) included:

- pin meter
- electrical resistivity (ER)

- high resolution photogrammetry

The pin meter and high resolution photogrammetry techniques involved constructing a Digital Terrain Model (DTM) of tramline wheeling areas under different experimental treatments, and, like the ER method, were non-destructive. These three methods are considered below. Much of the information and results related to measurements of electrical resistivity and high resolution photogrammetry have been reported in Shanahan (2013).

3.6.3. Pin meter method

The pin meter method has been used successfully by researchers including Jester and Klik (2005) and Botta *et al.* (2008). This method has the advantage of being non-destructive, but it is relatively time-consuming and, as noted by Withers *et al*. (2006), it may not be capable of recording very shallow wheelings if the spatial resolution is limited.

A bespoke version of this equipment was designed and constructed by ADAS (Figure 9). It comprised a series of 100 lightweight vertical pins with felt ends, each sited 1cm apart and suspended in an aluminium frame. The frame was sited across a tramline wheeling in an experimental treatment area, and the pins were gently lowered onto the soil surface. The height of each pin was then recorded using an attached digital camera attached to the frame and configured at a fixed location, field of view and focal length. The resulting set of pin profile depth data were used to construct a cross-sectional (two-dimensional) slice across the soil surface encompassing a tramline wheeling. By repeating this process every few centimetres upslope and downslope, it was possible to create three-dimensional profiles of the soil surface, at a resolution of around ±0.5cm, which was used to compare the effect of different tramline mitigation treatments.

Figure 9. ADAS staff taking soil surface roughness measurements using the bespoke pin meter unit. The horizontal bar at the top of the unit was attached to a digital camera (out of shot), which recorded the height of individual pins across the tramline.

Data characterising the tramline wheeling area which could be derived using this method included:

- mean depression depth (potentially useful for defining parameters in runoff models)
- total depression area
- total depression volume

The first type of derived data is defined as the distance along the soil surface, and is compared to the distance perpendicular to the soil surface. The ratio of these two values provides a dimensionless index which characterises the tortuosity of the soil surface. The last three types of derived data are potentially useful for defining parameters in runoff models.

3.6.4. Electrical resistivity

Geophysical techniques provide an opportunity to investigate the soil subsurface without disturbance (Allred *et al.*, 2008). This study used electrical resistivity (ER) geophysics to investigate the potential for reduced compaction along tramlines of Low Ground Pressure (LGP) traffic compared to conventional higher ground pressure traffic. Electrical resistivity (ER) imaging determines soil electrical resistivity (the inverse of electrical conductivity) for a 2D space below the soil surface. ER therefore measures the resistance imparted to current flow through the soil, and is a geophysical aspect which can be applied to studies of compacted soils. The method uses metal spikes inserted into the soil, with an electrical current applied to the spikes utilising the principle that soil water and air space have different electrical conductivity properties compared to solid mineral soil, and so spatial variations in the volume proportion of these constituents act like the dielectric in a capacitor. The resulting pattern of return data, derived by inversion modelling, can reveal zones of the soil where there is reduced electrical resistivity (i.e. increased electrical conductivity) which may be associated with reduced porosity and increased soil compaction, such as locations beneath tramline wheelings. However, spatial variations in stoniness, mineralogy and/or organic matter content can confound such inferences concerning patterns in subsurface soil compaction.

Details concerning the method as reviewed for this project are contained in Shanahan (2013), so only a brief summary based on those findings is included here. Corwin and Lesch (2005) reviewed the use of the ER method in field surveying to further develop precision cultivation, highlighting the complexity of determining apparent electrical resistivity (ER) due to edaphic, anthropogenic, biological and meteorological factors, but concluding that the method does have potential in soil compaction studies. Binley and Kemna (2005) demonstrated the application of Wenner and dipole-dipole surface electrical imaging configurations of surveying equipment with a square-wave DC current. At depths between 1m and 5m, the Wenner configurations display better horizontal resolution of resistivity changes over dipole-dipole whereas the dipole-dipole configuration displayed better vertical resolution. As tramlines are relatively narrow features, a dipole-dipole survey will best determine variances in soil resistivity under wheelings due to the compressive effects on porosity (i.e. water content).

Besson *et al.* (2004) produced 2D maps of soil structure below and around compacted wheelings when using electrical resistivity imaging. For a sandy loam in northern France the authors conducted a Wenner survey perpendicular to the travel of a heavy (81.4kN) tractor with rear tyres of 0.65m width and 200 kPa pressure. Their results show significant reduction in soil electrical resistivity in the compacted wheeled soil. Besson *et al.* (2004) conclude that a 3D survey would determine more detail about soil structure, especially clod distribution, as demonstrated by Tabbagh *et al.* (2000) and Séger *et al.* (2009). Besson *et al.* (2004) and Séger *et al.* (2009) only used a single tyre type, tyre pressure, and axle load, with only one tractor speed with no mention of number of passes. The authors did not use the dipole-dipole technique as explored by Binley and Kemna (2005) and Samouëlian *et al.* (2005) which would improve vertical resolution to soil structural changes.

Based on this assessment of published literature, electrical conductivity was considered a suitable method for use in this project. In this project, in autumn 2009, PVC tubes 0.15m in length and 0.065m outer diameter were used to extract cores of wheeled and non-wheeled soil of the tramline conventional and Very Flexible (VF) treatments. The two cores for each wheeled location were from the tyre cleats and casing depressions generated by the trailer tyres and a single non-wheeled soil core was extracted adjacent to the wheeled cores, 0.1–0.2m beyond the wheeling edge (Figure 10).

Figure 10. Locations of cleat, casing and no-wheel soil core extraction sites (Hattons, 2011)

On later inspection of the soil cores, it was found that the Loddington samples were of poor quality, with many broken or shaken loose during extraction and transport, therefore only Gatley and Hattons samples were analysed. The soil datum used for the cores was the soil surface in the unwheeled areas.

The resulting soil cores were measured for electrical conductivity (EC). The cores were saturated with increasing concentrations of sodium chloride (NaCl) solution (between 0.01 and 0.5M). The cores were removed from the NaCl solution at each concentration and connected via electrodes applied to the soil to an Iris Syscal Junior electrical resistivity meter (Iris Instruments, Orleans, France). Current passing through the soil, or bulk electrical conductivity (EC_{bulk}), is a function of the saturating solution electrical conductivity ($EC_{soultion}$), the porosity (φ) of the cores (determined by drying) and tortuosity or connectivity of the pores (τ). This is known as Archie's Law (Archie, 1942):

$$EC_{bulk} = \left(\frac{1}{\tau}\right) \times EC_{solution} \times \varphi^{m}$$

Where m is the cementation index used by Archie for porous sedimentary rocks (1.8–2.0), with 1.2 used for the soils of this study.

In autumn 2010, measurements of apparent electrical resistivity (ρ_a) of wheeled and non-wheeled soil was conducted using a Wenner-type mobile array: 4 electrodes, equally spaced at 30cm. Measurements of soil ρ_a were made at 1m intervals along 50m lengths of the conventional and VF tramlines.

In autumn 2011, soil ρ_a was measured with a mobile 48 electrode array, with 0.02m pins equally spaced at 0.01m, a total length of 4.7m. The array was laid across the conventional and VF tramlines at three locations in lower, mid and upper slope sections. Measurement of soil ρ_a was achieved with a Syscal Pro resistivity meter (Iris Instruments, Orleans) using a skip-0 sequence of dipole-dipole measurements. Dipole-dipole measurement was selected for the best signal to noise ratio for the soil textures and for the best vertical spatial resolution of soil ρ_a (Binley and Kemna, 2005). Inversion processing then calculated true soil electrical resistivity (ρ) for a 2-D area below the tramlines.

3.6.5. CT scanning

Sets of soil cores described in the previous Electrical Conductivity section were maintained at the moisture content at the time of extraction, and placed inside an x-ray computer-tomography (CT) imager (CT160Xi, X-Tek Systems Ltd., Tring). Analysis of the radiographs was conducted with the radiographic image analysis software ImageJ (National Institutes of Health, USA). The distribution of grey scale values for the individual radiographs (0=black, 255=white) were analysed. These grey scale values were converted to values of bulk density using a technique adapted from Bresson and Moran (1998) by scanning soil cores of a known bulk density and measuring the mean grey scale value (e.g. 180=1.8g cm^{-3}). Values of bulk density were determined for each of the radiographs at 5mm intervals.

3.6.6. High resolution photogrammetry

This section explores the application of photogrammetry at close-range in the study of the tramline wheelings. The aim was to improve the accuracy of measurement of soil deformation by heavy farm traffic at the plot scale using an appropriate non-invasive technique over conventional techniques available to soil scientists. Photogrammetry, the technique of deriving quantitative measurements from 2-D imagery, has been successfully used in Earth Sciences for mapping topography over large scales (e.g. catchments) (Wolf and Dewitt, 2000), and at close range or plot scale (Chandler, 1999; Heng *et al.*, 2010). In this study, the principles of data acquisition was adapted for capturing digital images of tramline wheelings across three soil types over areas of ~1 m^2 at the field sites, and produce representative models of the surface at a spatial resolution (<0.003 m).

In November 2010 and 2011 digital photographs were taken of the wheeled soil surfaces at the three field sites using the Canon EOS 540D SLR camera (Canon Inc., New York) fitted with a 28 mm lens. Images were taken in two overlapping pairs of 60–80% overlap, and with three replicates per wheeling location (Figure 11). The camera and lens were calibrated using PhotoModeler (Eos Systems Inc., Vancouver).

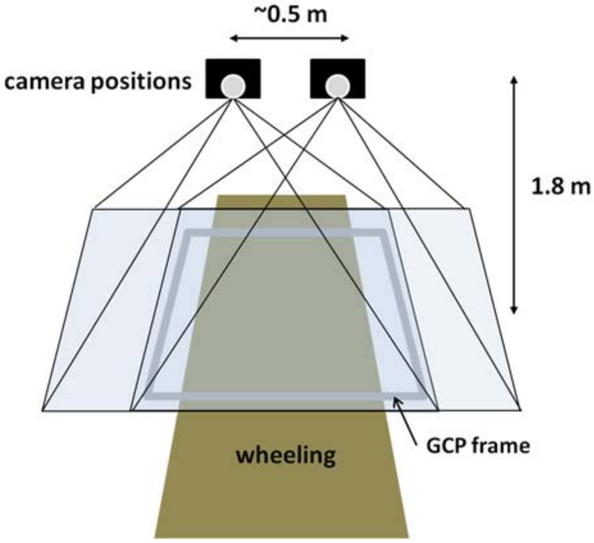


Figure 11. Schematic of photogrammetric principles applied to recording overlapping digital images of a tramline wheeling.

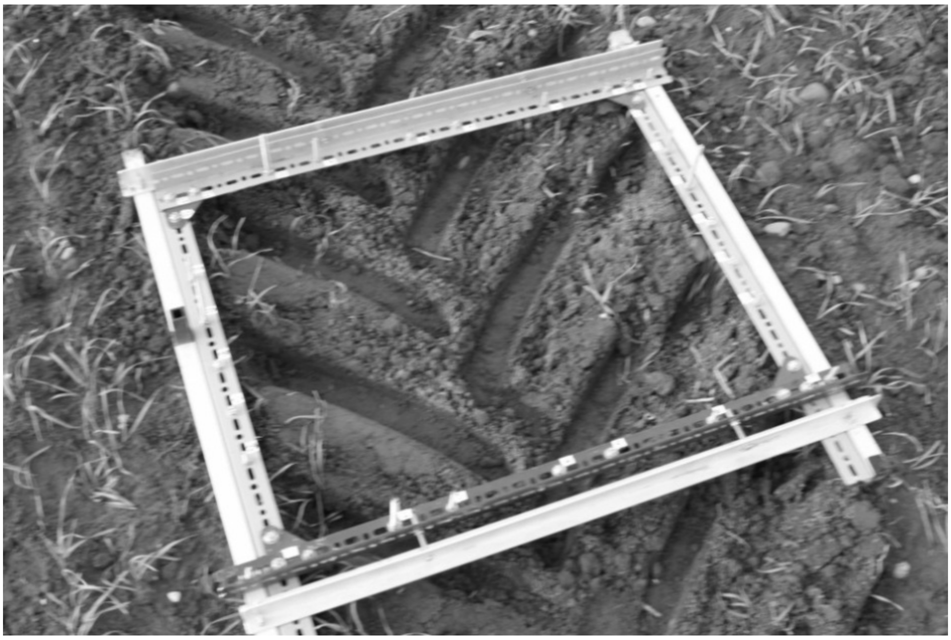


Figure 12. The GCP frame set around a wheeling at the Loddington site in autumn 2010.

Twenty-eight ground control points (GCPs) mounted along a 0.7m by 0.6m frame provided ground co-ordinates for the images, for use in determining the camera orientations by the photogrammetry software (see below). This GCP frame was laid down on the non-wheeled soil surface and framed the tramline wheeling within (Figure 12). Two overlapping photographs of the wheeled surface and GCP frame were taken of the wheeling treatments. The generation of digital terrain models (DTMs) of the wheeling surfaces was achieved with the use of Erdas photogrammetry software (Leica Photogrammetry Suite). The distribution of the full soil surface elevation data was analysed with R statistics (R Foundation).

Each tramline wheeling was photographed at three locations along their length: 10m, 35m, and 60m up-slope from the line of runoff monitoring equipment installed by ADAS. In pairs, overlapping by 60–80%, the digital photographs showed a single tramline wheeling, with ground-referencing coordinates. These photographs formed the basis of photogrammetry and 3D models of tramline wheelings. DTMs were generated with Erdas eATE imaging software. Pin meter measurements collected by ADAS were used for comparison to the DTMs generated.

In addition to the traditional and novel soil physical methods described here, an alternative approach to quantifying tyre impressions on soil was investigated using the Moiré technique. This method and the associated results are reported separately in a manuscript (McKenzie *et al.*) currently undergoing peer review with the journal *Soil & Tillage Research*.

4. Results

4.1. Impacts on soil properties

This section includes results from the various experimental methods use to characterise the effect of tramline management (treatments) on soil physical properties, most notably soil compaction, surface roughness and hydraulic behaviour.

4.1.1. Tyre imprint characterisation: Pin meter

Results from the pin meter data comprised 100 depth measurements (one from each pin, spaced 1cm apart) on a 1m transect across a tramline wheeling, and these measurements were repeated every 2cm along the wheeling for a total of 1m, resulting in 5000 individual pin metre measurements per treatment, captured using a digital camera. Data were too numerous for manual processing, so images were processed using a bespoke GIS algorithm developed in the project which analysed images and derived depths for each individual pin relative to a reference datum at the top of the device frame. Data were divided into “cleat” and “casing” elements based on a combination of semi-automated and visual analysis of image data. Data were corrected to reference their datum as the uncompacted cropped soil surface using image reference points. Resulting data derived from these pin meter measurements included:

- Spatial distribution of pin elevation data
- Mean depth of tyre imprint: tyre cleat (cm)
- Mean depth of tyre imprint: tyre casing (cm)
- Standard deviation of tyre imprint depth data (cm)
- Area of tyre imprint (cm^2)
- Volume of tyre imprint (cm^3)

The first of these data provide spatial patterns which allowed micro-topographic surfaces to be visualised: effectively creating a Digital Terrain Model (DTM) on a miniature scale. Figure 13 (top right) shows an example of such a surface profile image, with central browny-red areas identifying tyre imprint with areas labelled to aid calculation of surface statistics; hatched blue areas denoting casing area; and peripheral pale blue and white areas denoting uncompacted (higher elevation) soil. The remaining variables listed above allowed the control conventional tyre (CT) treatment to be compared directly against the optimal tyre (VF) treatment at each of the three sites when treatments were imposed in autumn 2010. Resulting data are shown for mean tyre imprint depth, tyre imprint area and tyre imprint volume for CT and VF tyres for each of the three sites in Figure 13. Total tyre imprint areas (bottom left plot) ranged from 1000–6000cm^2 and therefore represented 500–3000 individual pin measurements (i.e. one pin every 2cm^2).

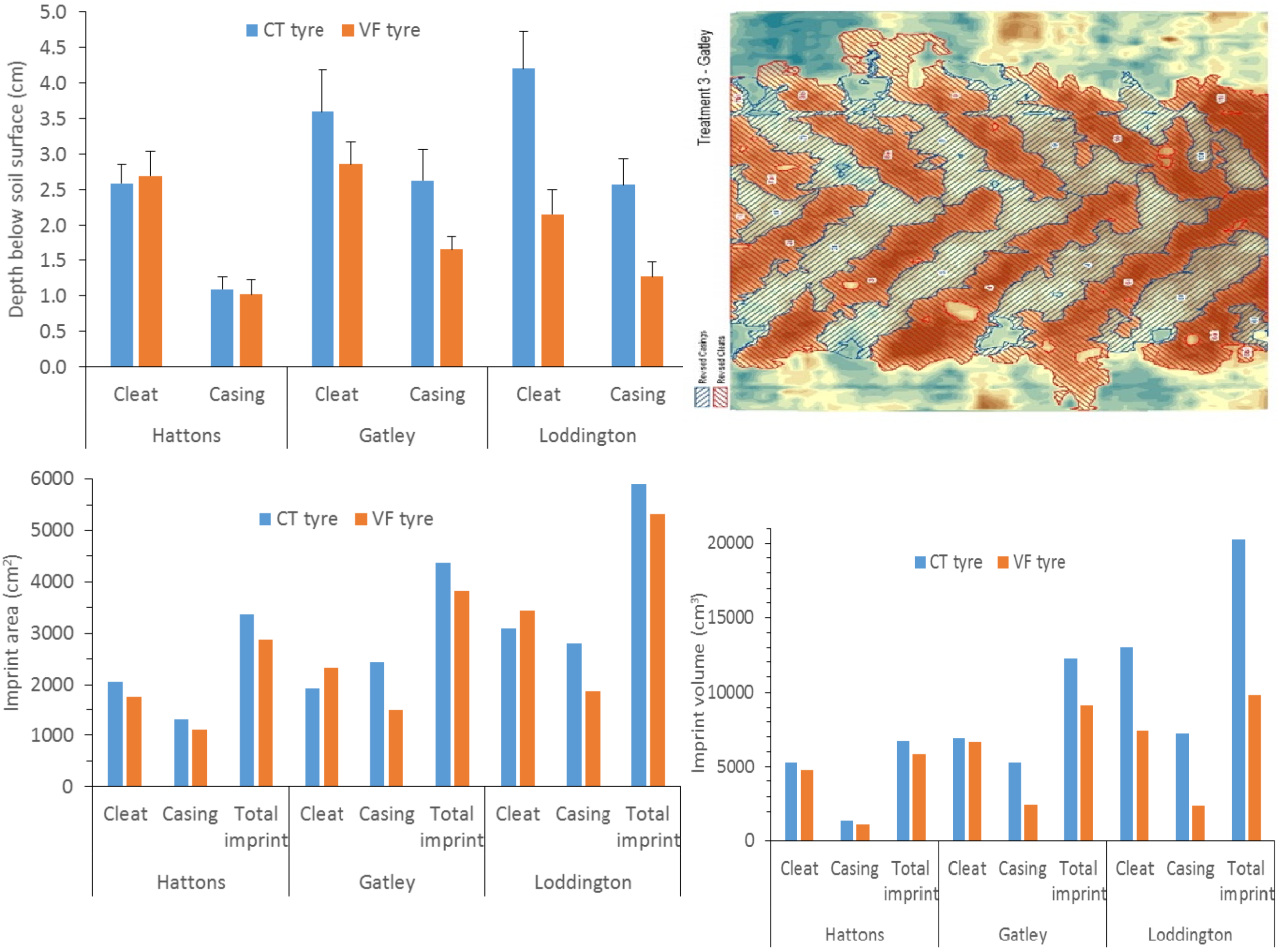


Figure 13. Pin meter data shortly after treatments imposed in autumn 2009. Charts show mean tyre imprint depth (top left with standard error bars), tyre imprint area (bottom left) and tyre imprint volume (bottom right) for cleat and casing tyre elements, showing effect of CT and VF tyre treatments. The top right hand image shows an example surface DTM derived from pin meter data.

Figure 13 (top left plot) shows deeper tyre imprint depths from cleat areas compared to casing areas (as would be expected), but with a clear pattern for shallower imprints from VF tyre treatments compared to CT treatments at both the Loddington and Gatley sites. Corresponding results for the Hattons site appear similar between tyre treatments, which reflects the different soil texture (loamy sand) which although it is friable and prone to detachment and erosion, the solid sand particles mean it is less prone to compaction *per se*. The associated tyre imprint area results (bottom left plot) reveal smaller compacted tyre imprint areas from the VF tyres compared to the CT tyres at all three sites. The corresponding tyre imprint volume results (bottom right plot) also show this same pattern but in a more marked fashion, with the VF tyres reducing tyre imprint volumes by 51.7% (Loddington), 12.7% (Hattons) and 25.4% (Gatley) i.e. the greatest benefit from the VF tyres in reducing soil compaction was found at the Loddington site. Loddington also had the greatest potential for mitigation in this season, as it had the largest tyre imprint volume (i.e. the greatest compaction) across all sites from the control treatment CT tyres, and this reflects the higher clay content at this site which (when moist) renders this soil at relatively greater risk of soil deformation from pressure such as farm traffic.

4.1.2. Topsoil bulk density

Measurements of bulk density were taken using both standard methods, and also independently derived from the information from the soil cores taken for the CT scans. The standard method was applied to topsoil only at all four sites, whereas soil cores for the novel radiographic method were only collected from the Hattons and Gatley sites. Both sets of data are reported here.

Results using standard methods for bulk density are shown in Figure 14, derived using bulk density tins (around 23cm deep) with known volumes which were weighed before and after sampling, and then oven-dried before being re-weighed. Reference values for the cropped area are also shown: these areas were vegetated, uncompacted and had not received traffic. The bulk density results show that the optimally-inflated VF tyres resulted in notably less compaction than the conventional CF tyre treatment (i.e. VF tyres, with bulk density values closer to the reference field values). It is notable that this effect was consistent in tyre imprints associated with both cleat and casing elements, and was consistent across all four sites with their contrasting loamy sand, silty clay loam and clay soil textures. Such results support the conclusion that VF tyres prove effective across all soil types, given suitable soil moisture conditions at the time they receive farm traffic.

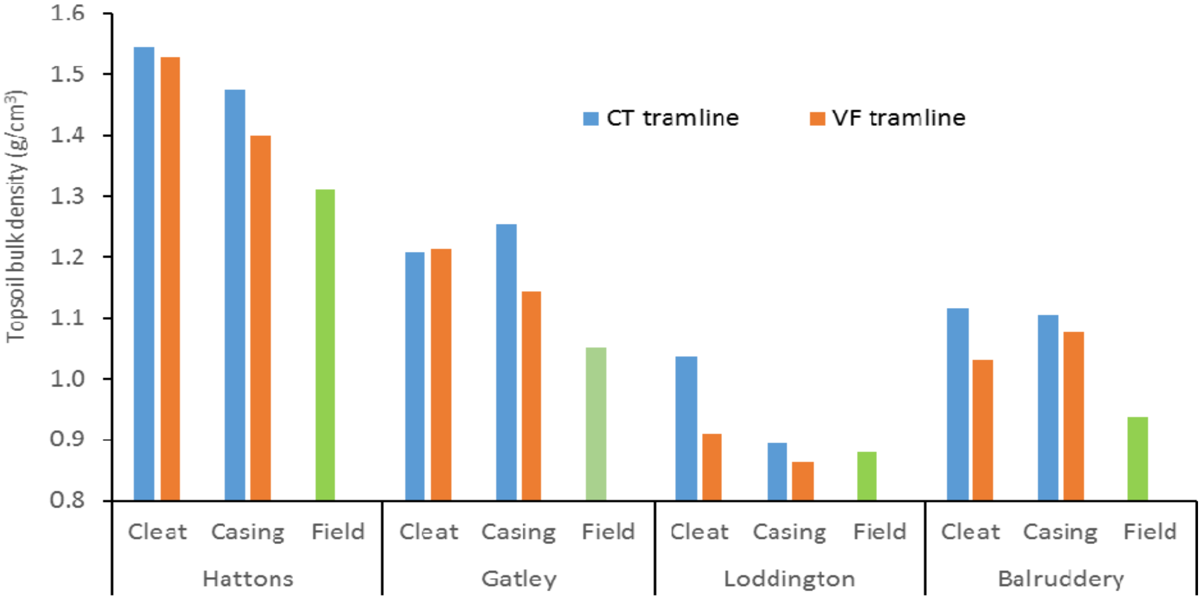


Figure 14. Topsoil bulk density measured using standard methods, for cleat and casing tyre imprint areas for CT and VF tyre treatments at the three sites in autumn 2009. Field values measured in the cropped area which did not receive any spray traffic are also shown. Topsoil stone contents were 5.0% (Hattons), 10.7% (Gatley) and 12.4% (Loddington) by volume.

Whole-profile bulk density values were derived using the novel radiographic measurement for the Gatley and Hattons cores for cleat, casing and non-wheeled soil of conventional (CT) and VF tyre treatments, and are shown in Figure 15. The 0.005m depth resolution was sufficient to demonstrate the variation in bulk density through the core depths whilst also considering the degree of error imposed by the pixel value to bulk density value conversion. This degree of error can always be expected due to the discrepancy between the physically measured soil properties and the estimated values from radiographs (Baveye *et al.*, 2010).

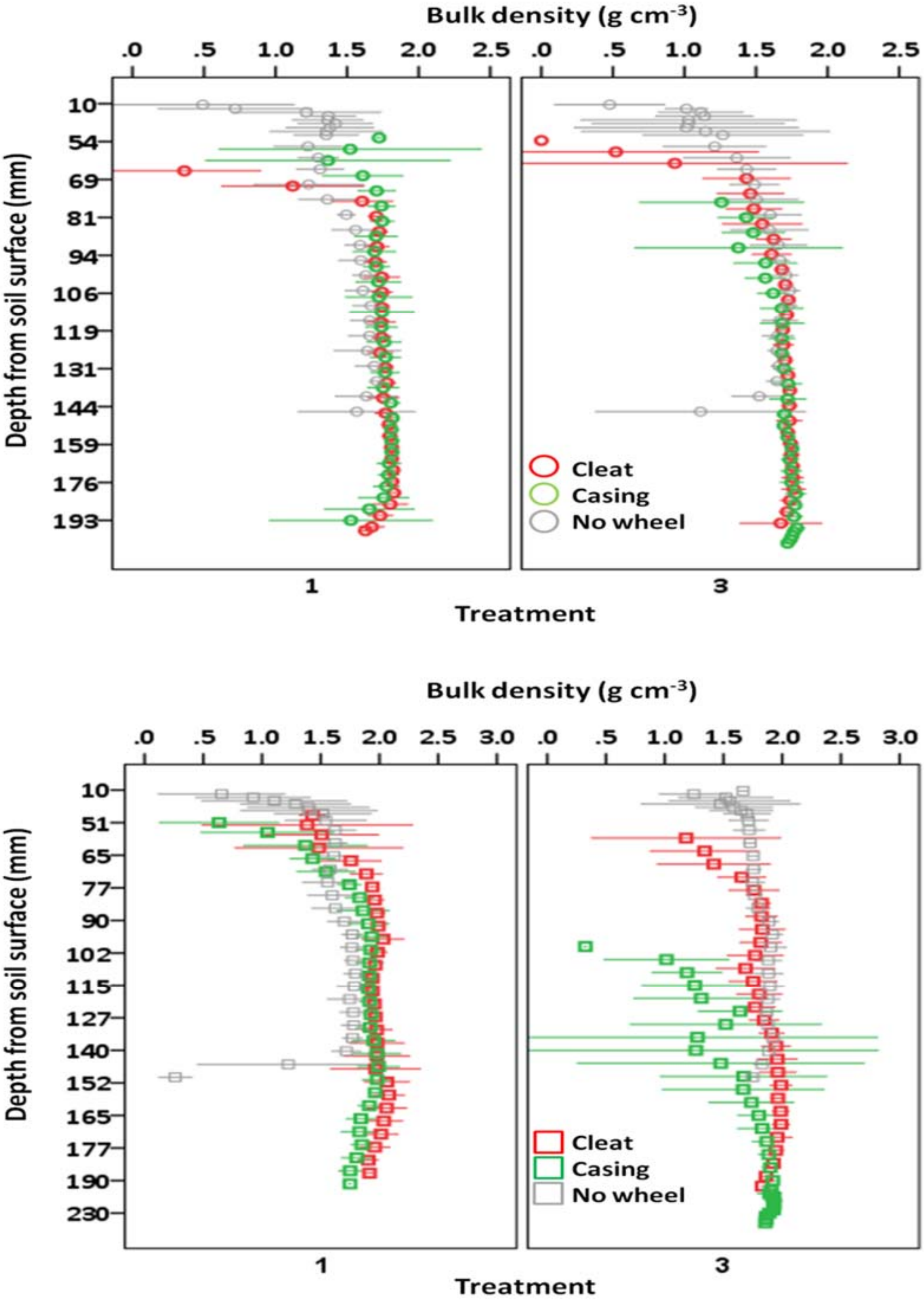


Figure 15. Bulk densities for cleat, casing and non-wheeled soil profile cores at Gatley (top) and Hattons (bottom) sites in autumn 2010. Treatment 1 (CT tyres; n=12, except no-wheel n=10) and Treatment 3 (VF tyres; n=12) treatments, at 5mm depth intervals. Error bars represent 2 standard deviations.

At Gatley, comparing CT and VF plots (Figure 15) shows, there is some evidence of greater bulk density values in the near-surface data (i.e. cleat and casing data usually appear higher than the reference grey no-wheel data under the CT treatment), illustrating the compaction caused by such traffic, whereas all three data classes often appear to overlap under the VF treatment – illustrating the reduced (and sometimes negligible) compaction observed under the VF tyres. At Hattons, data in Figure 15 show similar behaviour to Gatley for the CT tyres, but the effect of the VF tyres is much more pronounced, with substantially reduced bulk densities found in both cleat and casing areas.

Although these differences in bulk density were not statistically significant ($p>0.05$), results for all soils do show an increase in bulk density with depth: this is most pronounced for the cleat cores at Gatley and in the casing cores and Hattons. However, at both sites it is clear that the surface of the no wheel treatment (i.e. the cropped non-tramline area) was also compacted from historic traffic events – which illustrates graphically that soil compaction can readily persist from one season to the next unless remedial action is taken to remove it.

The results compare well to the findings of Alakukku (2003), who demonstrated that machine induced stresses decrease with depth due to increasing soil resistance to deformation, therefore limiting pressure distributions to the upper soil surface. The bulk density characteristics of the non-wheeled soil are similar to the findings of Mooney and Morris (2008), where a highly porous (30%) upper region of a cultivated soil significantly reduced with depth. It was expected that the cleats would display clearly greater bulk densities compared to the casing bulk densities because of the greater pressure and deformation they create, and this was observed at Hattons but not at Gatley probably due to the latter's stronger soil structure associated with its greater clay content combined with the drier soil conditions at the time of spraying in this particular season. Such findings support comments by Alakukku (2003) that the contact area under tyres is the net result of complex association of stresses between the tyre and soil.

4.1.3. Saturated hydraulic conductivity (K_s)

The results for the measurement of K_s for the wheeled and non-wheeled soil cores from the 2009 field treatments at Gatley and Hattons are given in Table 4. As expected, Analysis of Variance (ANOVA) showed a significant decrease in K_s from the cores taken from the wheeled treatments compared to cores from the non-wheeled reference area at both sites. At Gatley, there was evidence of lower K_s in cores from both cleat and casing areas of tyre imprints under the CT treatment when compared to the VF treatment, and this difference was statistically significant

($p<0.05$) in the casing area. At Hattons, there was no significant effect of tyre treatment on K_s in the casing area, but rather surprisingly, K_s appeared higher under VF tyres compared to CT tyres in the cleat area ($p<0.05$). However, as a soil variable, hydraulic conductivity data are notorious for demonstrating particularly wide spatial variability in their magnitude (Chappell and Ternan, 1997), partly due to the relatively small soil cores used, and this effect will be exacerbated when sampling at a sub-field scale. This suggests that such data should be interpreted with caution given their intrinsically high spatial variability.

Table 4. Mean K_s values for Gatley and Hattons wheeled and non-wheeled soil cores from CT and VF treatments. Different letters identify significant difference ($p<0.05$); same letters at individual sites indicate no significant difference.

		Gatley K_s (mm hr^{-1})			Hattons K_s (mm hr^{-1})		
Treatment	Core	Mean	Std. Dev	n	Mean	Std. Dev	n
CT tyres	Cleat	40^a	47	9	26^a	19	9
	Casing	24^a	31	9	31^a	25	9
	No wheel	1023^b	929	9	200^c	133	9
VF tyres	Cleat	22^a	23	6	92^c	52	9
	Casing	0.2^d	0.7	9	46^a	17	9
	No wheel	2576^b	2411	9	143^c	28	9

4.1.4. Electrical resistivity

Winter 2010–11

The winter 2010–11 apparent electrical resistivity (ρ_a) data for wheeled and non-wheeled soil at the Gatley, Hattons and Loddington sites are shown in Figure 16. The Loddington soils had the lowest ρ_a which was a function of the higher silt and clay content. The highest ρ_a values were found at the Hattons site due to the sandy texture. It is clear from Figure 16, that at all sites with no wheel treatments had a higher ρ_a at all slope positions, indicating that the method was able to determine the presence of soil compaction. A degree of variation in ρ_a was revealed at the field scale, the cause being a combination of soil moisture, bulk density, and soil textural variability, which was to be expected from electrical geophysical surveys on cultivated loamy soil (Allred *et al.*, 2008; Besson *et al.*, 2010). The effect of VF versus CT tyre treatments is less clear, since although at Gatley and Loddington the VF treatment appeared to yield lower values than for the CT treatment, when the VF results are compared relative to the no wheel area adjacent to the treatment the results for the two treatments were rather similar (perhaps indicating the compaction caused by VF tyres is negligible on such medium and heavier textured soils in drier winters).

Linear regression was performed on the results of ρ_a from the autumn 2010 surveys against treatment and tramline distance. For the Gatley, Hattons and Loddington soil the results show a significant decrease ($p<0.001$) in ρ_a as a result of traffic, and tramline distance had a significant effect ($p<0.001$) on ρ_a. In summary, soil electrical resistivity significantly reduced when compacted, and that slope over which the tramline passed also had a significant effect on electrical resistivity as shown in the plots of ρ_a for the three sites. Results showed the clear effect of traffic on uncompacted (no wheel) drilled crop area compared to wheelings receiving spray traffic, but no effect of VF tyre versus CT tyre could be established.

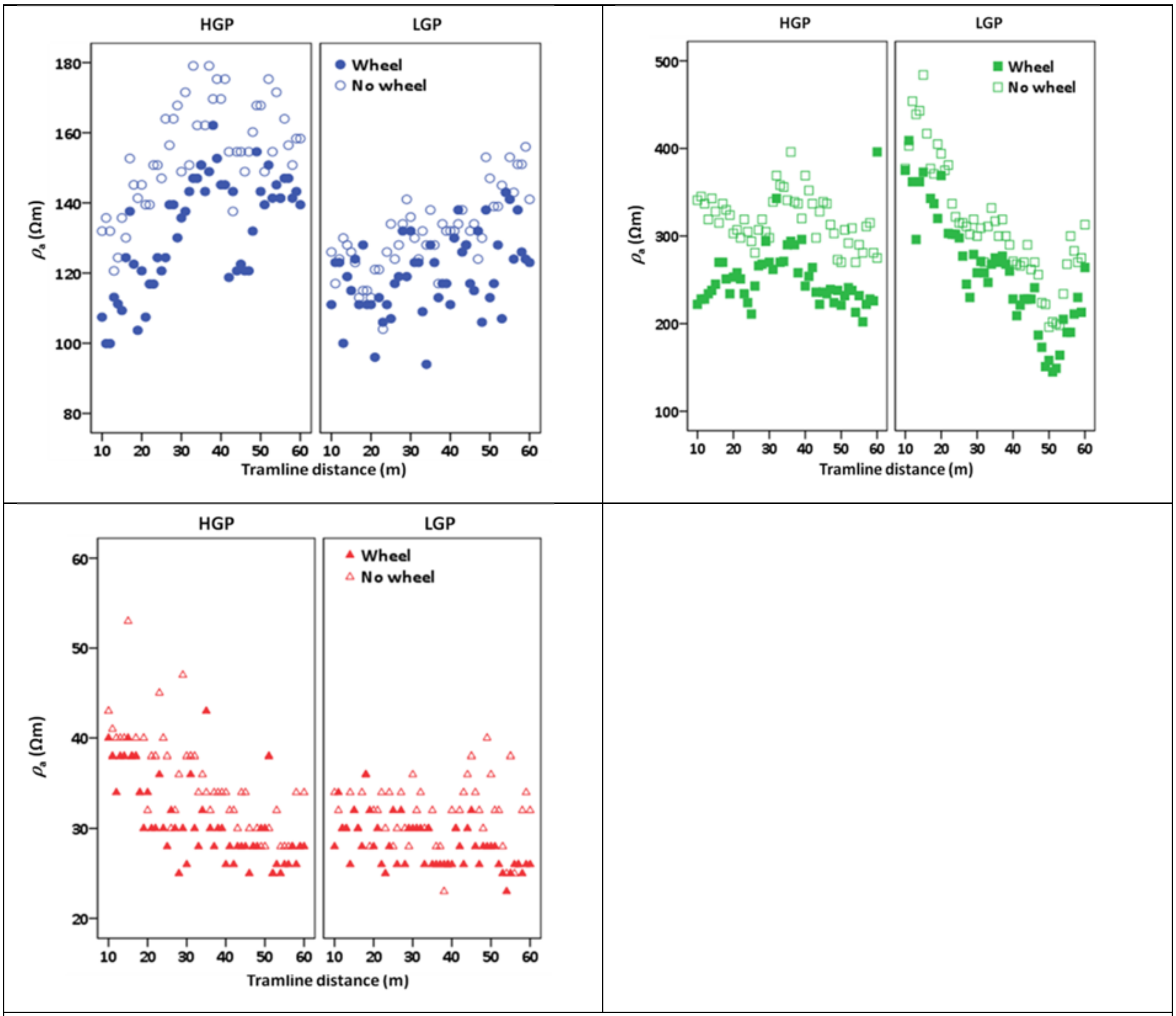


Figure 16. Apparent electrical resistivity for a) Gatley (top left), b) Hattons (top right) and c) Loddington (bottom) wheeled and non-wheeled soil, November 2010. Soil ρ_a determined along 50 m transect with a Wenner array and RM4 resistance meter.

Winter 2011–12

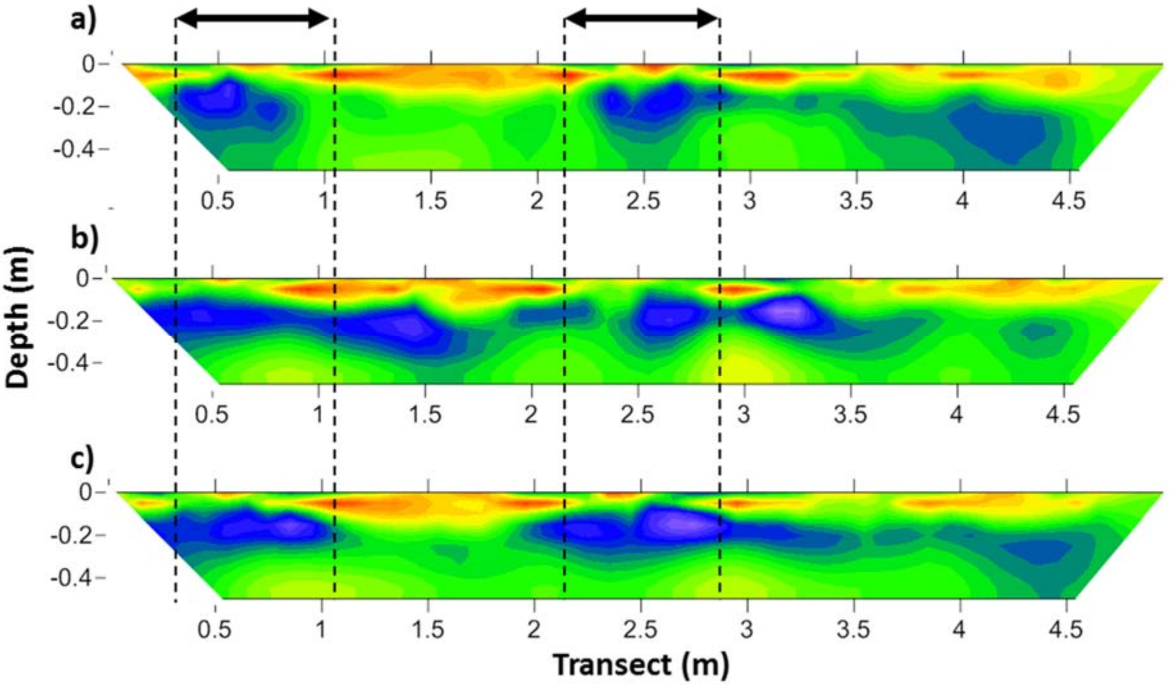
For the autumn 2011, Figures 17–19 shows *ρ* data for CT and VF tramlines at Gatley, Hattons and Loddington, respectively. The plots reveal the spatial distribution of *ρ* over the tramline wheeling transects (taken as 0.7m width) and non-wheeled soil to a depth of 0.5m.

Electrical resistivity (ERT) is a measure of how much the soil resists the flow of electricity. This in turn is a function of its mineralogy, organic matter content, and water content (as water is an excellent conductor). As ERT is sensitive to water content, it can be useful for inferring the effects of soil compaction, which compresses soil and reduces the relative volume available for air and water compared to the volume of solid mass. The Gatley soil's electrical resistivity (ERT) data reveal zones of higher *ρ* relative to the deeper soil at the soil surface which would be the result of drier, more aggregated soil conditions. Increasing resistivity is apparent between the wheelings of the Gatley soil. Below the surface a zone of lower *ρ* is apparent the first 0.3m of the soil, tallying with the depth of the ploughed horizon. In comparison, soil at depths below 0.3m show higher *ρ* which would result from higher pore tortuosity in the denser subsoil, changes in mineralogy, and cooler temperatures increasing resistivity.

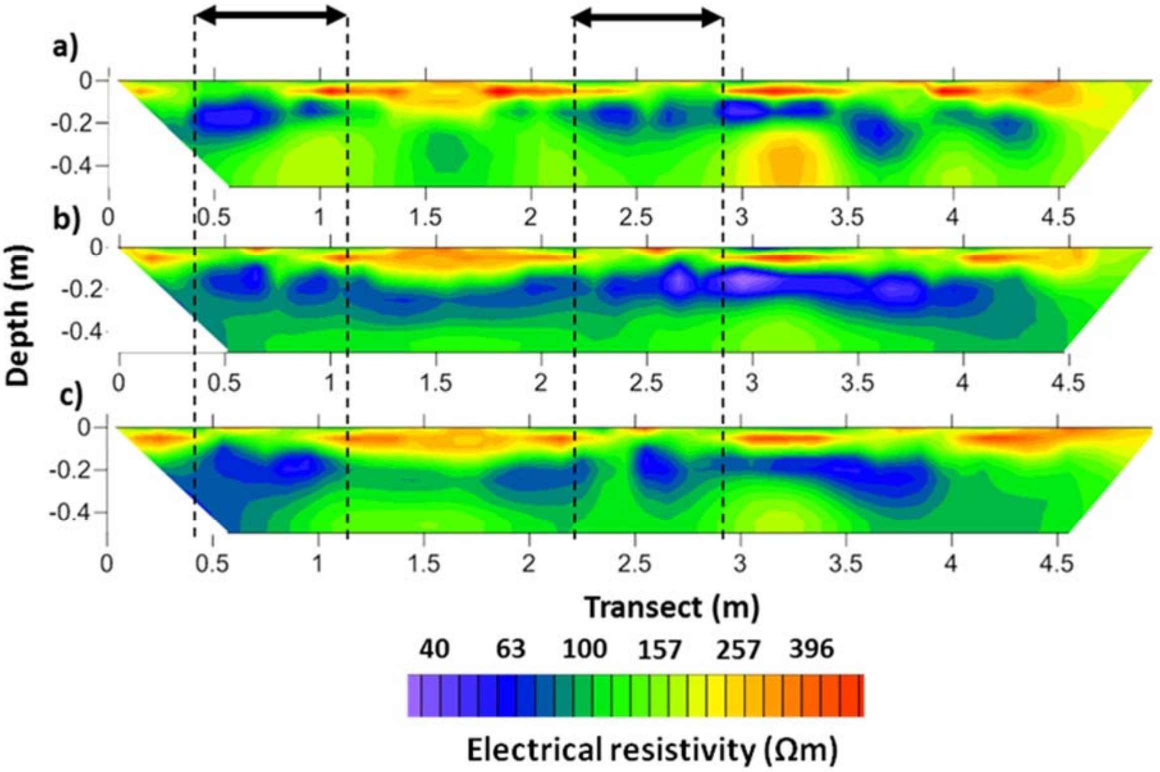
The Hattons soil ERT data (Figure 18) show a higher degree of variability in *ρ*. Higher values of *ρ* are still evident at the surface, though more discontinuous than at Gatley. Lower values of *ρ* are found through the ploughed topsoil (Ap soil horizon layer) with a rather abrupt change to higher values below 0.3m. The patchiness of the results may be a result of the sandy soil at Hattons providing a poorer electrical conductor to the electrodes compared to the other sites. The signal to noise ratio was, therefore, lower at the Hattons site.

At Loddington soil ERT data (Figure 19) show high variation in values across the transects. However, the higher values of *ρ* observed at the other two sites in not present. Instead, the Ap horizon has generally lower ρ than the soil below.

In summary, the ERT data in winter 2010–11 was successful in revealing spatial variations in soil electrical conductivity as a result of farm traffic. The findings support those of Besson *et al*. (2004) who reported that wheeled soil retained more rainfall due to reduced drainage and evaporation. What is apparent is the reduced impact the VF treatment has on *ρ* at depth, which indicates relatively better soil drainage and aeration under this treatment compared to the CT treatment. Time-lapse observations of soil EC during rainfall events and subsequent soil drying would provide further evidence to corroborate this explanation. Extensive electromagnetic-induction (EMI) techniques would also allow for further investigation of tramline soil EC at the hillslope and field scale.

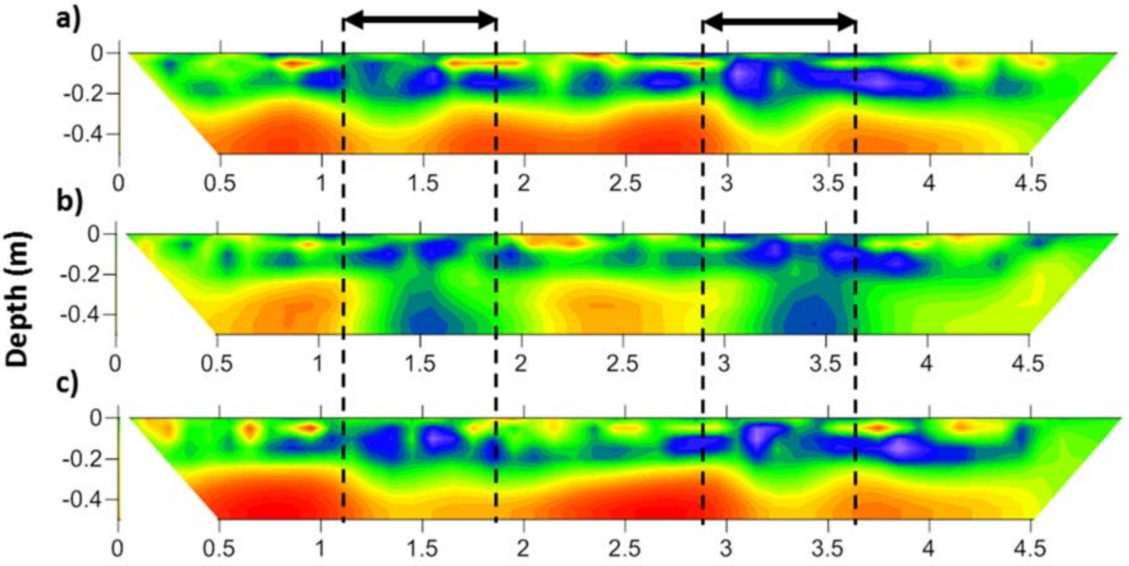


CT

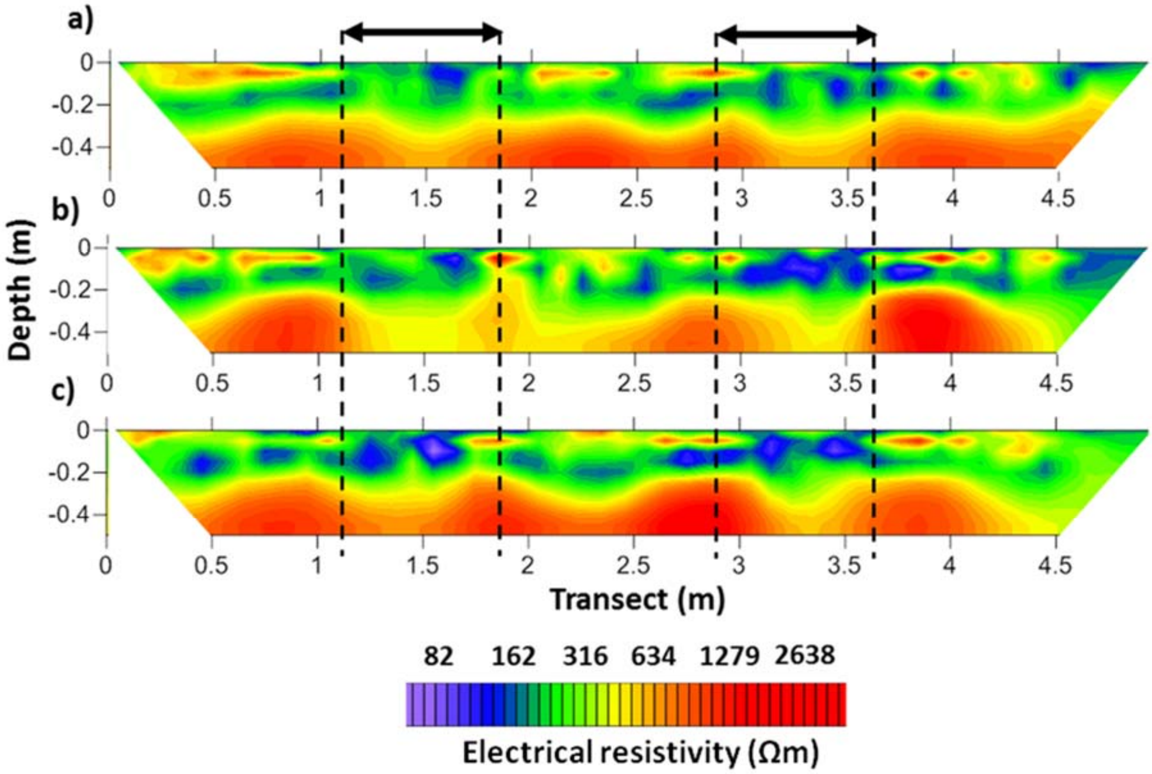


VF

Figure 17. Computed electrical resistivity for Gatley under CT (top) and VF (bottom) tyre treatments. Plots a), b) and c) are replicates from 9, 22 and 77m upslope of the runoff collection gutter in the CT treatment; and 5, 56 and 77m upslope of the runoff collection gutter in the VF treatment. Plots describe the electrical resistivity in $\log_{10}$ scale, with true values on the scale bar. The extent of tramline wheelings (0.7m wide) are shown by black arrows and dashed lines.

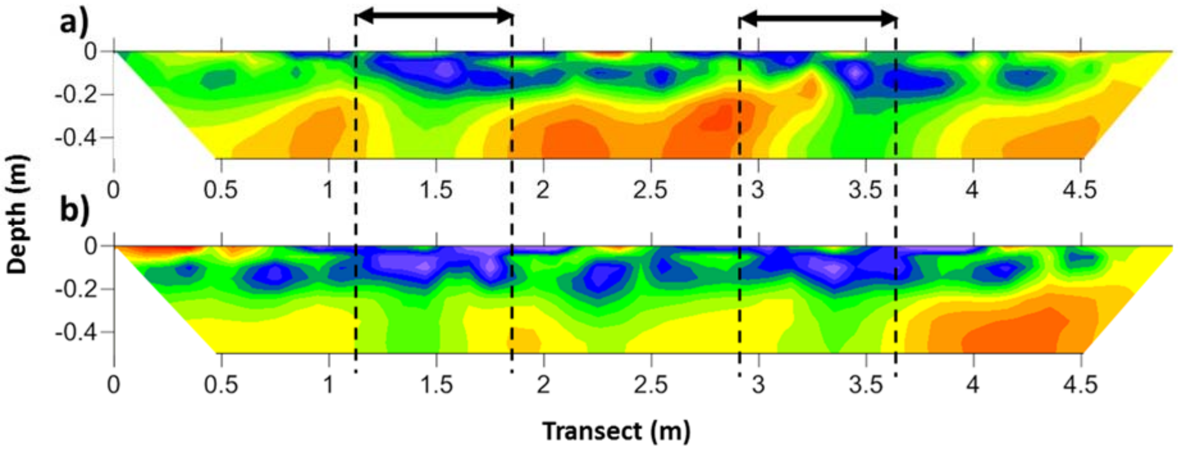


CT

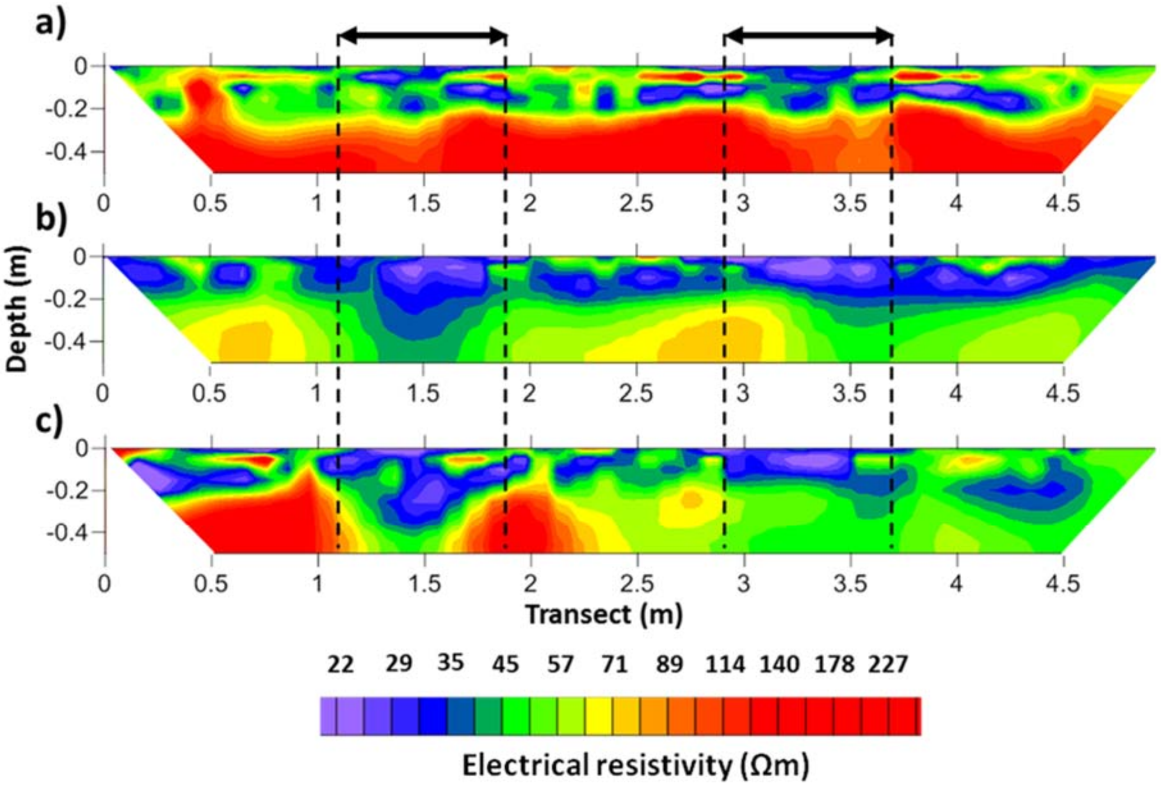


VF

Figure 18. Computed electrical resistivity for Hattons under CT (top) and VF (bottom) tyre treatments. Plots a), b) and c) are replicates from 27, 57 and 77m upslope of the runoff collection gutter in the CT treatment; and 5, 66 and 69m upslope of the runoff collection gutter in the VF treatment. Plots show electrical resistivity in $\log_{10}$ scale, with true values on the scale bar. The extent of tramline wheelings (0.7m wide) are shown by black arrows and dashed lines.



CT



VF

Figure 19. Computed electrical resistivity for Loddington CT (top) and VF (bottom) tyre treatments. Plots a), b) and c) are replicates taken from 15 and 37m upslope of the runoff collection gutter in the CT treatment; and 5, 40 and 70m upslope of the runoff collection gutter in the VF treatment. Plots show electrical resistivity in $\log_{10}$ scale, with true values on the scale bar. The extent of tramline wheelings (0.7m wide) are shown by black arrows and dashed lines.

4.1.5. Photogrammetry, derived DTMs & surface roughness indices

The Digital Terrain Models (DTMs) generated from the photographs taken in autumn 2010 provided an accurate representation of the wheelings created by the traffic treatments. Figure 20 shows an example of a DTM for the Hattons CT wheelings, the direction of the chevron marks indicating the direction down slope. The tyre casings caused less change in soil elevation as shown by the lighter shades. The spatial resolution of the DTMs had mean accuracy of 0.003m and demonstrates the ability of photogrammetry as a tool for capturing detailed topographic information relating to soil surfaces in the field. The results compare well to the study of Chandler (1999) who used photogrammetry at close-range to measure surface roughness change of cultivated soil as a result of simulated rainfall erosion, and to Jester and Klik (2005) who found that photogrammetry provides quick data capture for measuring soil surface micro-morphology.

Figure 20. Example DTM developed for the Hattons CT wheeling in 2010 using Erdas eATE. The cleat impressions are darkest, representing approximately 0.06m depth from the soil surface. The field of view is 0.8m.

Data from the DTMs acquired in 2010 provided accurate measurements of soil surface roughness. A Roughness Index (Jester and Klik, 2005) was calculated for each wheeling DTM by:

$$RI = \left(\frac{3D\ surface\ area}{2D\ area}\right) - 1$$

The range of Roughness Index (*RI*) values for the three replicate DTMs at each site is presented in Table 5. These results reveal that for the Gatley and Loddington DTM area data, VF tyre wheelings had significantly ($p<0.05$) higher surface roughness than conventional tyre treatment wheelings. The DTM area data for Hattons show a significantly rougher surface area ($p<0.001$) for the conventional tyre treatment wheelings compared to the VF tyre treatment wheelings.

Visual field observations confirmed that increased RI values for Gatley and Loddington VF tyre treatment wheelings were due to an increased prevalence of surface aggregates that were destroyed under the greater compaction resulting from conventional tyre treatment traffic (i.e. by the passing of the narrower, higher pressured Agribib tyre). The relatively high clay content of the soils at the Gatley and Loddington sites allow for stable aggregates to form. The high sand content at the Hattons soil means it does not tend to form stable soil aggregates, and the soil surface rapidly settles and slumps after deformation from traffic – as a result the treatments did not contribute to the RI values observed with photogrammetry. The increased surface area of soil under conventional tyre treatments at Hattons therefore indicates increased compaction as a result of the narrow Agribib tyres fitted to the trailer unit on the conventional tyre treatment.

Table 5. Roughness Indices for Gatley, Hattons and Loddington tramline areas, autumn 2010.

Site	Conventional (CT) tyres treatment	Correctly-inflated VF tyre treatment
Hattons	0.57–0.90	0.41–0.51
Gatley	0.40–0.47	0.46–0.54
Loddington	0.55–0.79	0.71–s0.97

4.1.6. Wheelslip and Fuel use

Measurements of wheelslip and fuel use were taken from the display on the tractor cab when treatments were being imposed at the four sites. Typically around 30 readings of wheelslip were taken while traversing tramlines in the experimental hillslope segment areas when treatments were imposed in the autumn. Readings were separated for analysis based on slope location derived from a cross-section analysis of each hillslope conducted using a detailed GPS survey (Figure 21).

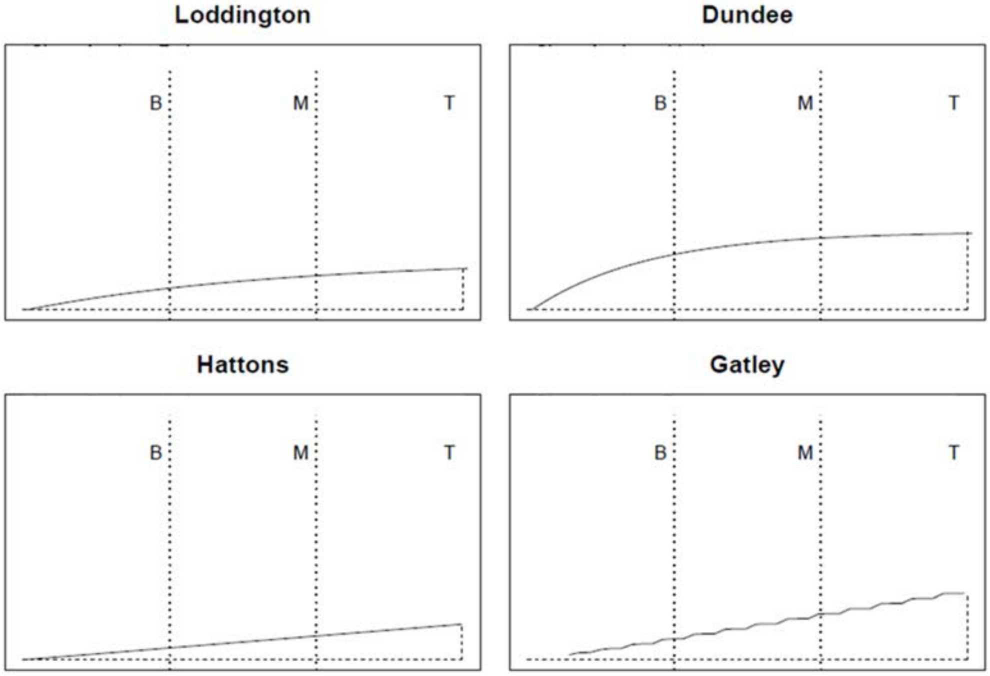


Figure 21. Illustration of the relatively planar slope form at the four experimental sites, based on detailed GPS survey. Bottom (B), middle (M) and top (T) of each hillslope segment are identified.

The results of the measurements at the four sites are shown in Figure 22. Wheelslip measurements typically lay within the manufacturer's recommended range of 4–12% (Michelin, pers. comm.) which was consistent with more generic published assessments (Grisso *et al.*, 2006; Wulfsohn *et al.*, 2009). The experiment's design allowed the effect of drilling tramlines to be analysed separately from the effect of tyre treatment. There was no significant effect of whether tramlines were undrilled or drilled on wheelslip from sprayer traffic with either CT or VF tyres, and so for conciseness, those results are not presented here. In marked contrast, Figure 22 shows that the VF tyre treatment had significantly lower wheelslip at all hillslope positions at Hattons (*p*<0.01), Gatley (*p*<0.001) and Balruddery (*p*<0.001), although results were reversed at the clay-rich Loddington site (*p*<0.001). However, treatment differences were typically relatively small (<3%).

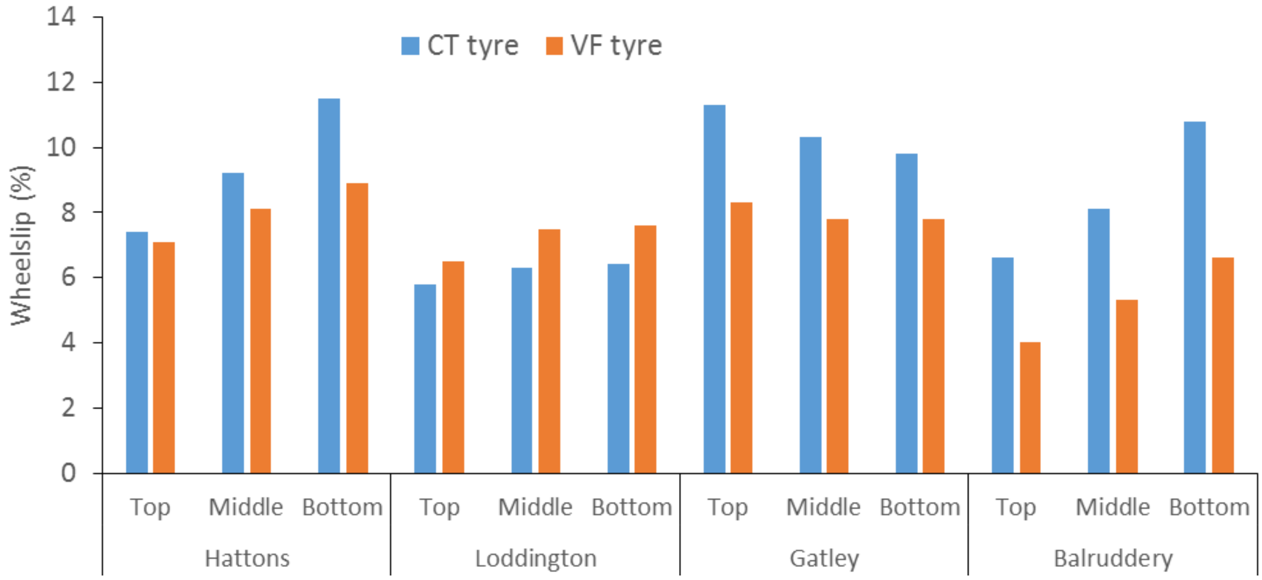


Figure 22. Summary wheelslip measurement results for CT and VF tyres taken as treatments were imposed. Readings are separated into top, middle and bottom third of the hillslope segment at each site. Statistics are discussed in the text.

Although sites were selected to have as planar a slope form as possible, results provide some evidence of a positional effect within slopes, with data shown separately for the bottom, middle and top sections of the hillslope segments (Figure 23). Wheelslip increased as the sprayer moved upslope at Hattons. At Loddington, the slope angle was similar for both bottom and middle sections of slope with a noticeable plateau at the top of slope. At Gatley, surface topography indicated the land had been contour ploughed in the past, leaving an uneven but fairly planar slope angle. As a result, wheelslip measurements did not show the same pattern between segments of the slope at this site. In contrast, the Balruddery site was notably steeper in the bottom third of the slope (Figure 21), and this resulted in wheelslip consistently and significantly (*p*<0.001) increasing as the sprayer moved progressively upslope.

However, in spite of the statistically significant effect of tyre treatment, differences were small in absolute terms (typically varying by <3%) and consistently lay within manufacturer's recommended ranges. Fuel use (measured in litres per 100m in the experimental hillslope area) was not significantly different between the two tyre treatments at all of the four sites. Such measurements may differ from manufacturer's estimates and from whole-field values, because (for consistency with treatment imposition) they were measured travelling upslope only on consolidated tramlines and ignored turning at the end of a sprayer run.

4.1.7. Implications for Crop Yield

This project focused on the management of the uncropped part of cereal fields i.e. the area left undrilled and used to provide access for field management operations, including spraying, along tramline wheelings. Consequently, it was not expected that there would be any impact on crop yield in the main cropped part of the field area.

The only possible effect which was considered was associated with the VF tyres, given their lower pressure and different sidewall structure compared to conventional control tyres. The much lower recommended operational pressure for VF tyres is typically half of that used for conventional tyres i.e. 16-26 psi (100–179 kPa) for CT tyres compared to 6-10 psi (41–69 kPa) for VF tyres in this project; see Figure 2). This lower pressure used in VF tyres is associated with a wider tyre imprint and a characteristically larger area of tyre being in contact with the soil. For example, the control tyre had a width of around 30cm, whereas the optimally-inflated VF tyre had a width of 36cm.

It was postulated that, in theory, traffic with wider tyres used to conduct autumn spraying could compact the recently-drilled crop rows immediately adjacent to the tramline wheeling. Although this was very early in the season, and agronomic experience indicates that the crop would recover, it was necessary to demonstrate that there was no long-term impact of VF tyres on resulting crop yield. Consequently, on each of the four experimental treatments in Year 1 (winter 2009/10), measurements were taken of the number of ears, grains per ear, dry grain weight, dry thousand grain weight (TGW), and green grains in the harvested crop in 2010. These measurements were taken in six different locations: the centre of the tramline (C), and then in five crop rows (positions P1 to P5) moving perpendicular to (and out of) the wheeling, progressively into the uncompacted crop area.

Results from the Hattons site (Figure 23) show a modest compensatory effect in increasing dry grain weight and the number of cereal ears at locations immediately adjacent to the tramline areas in both CT and VF tyre treatments. This phenomenon occurs due to the greater incidence of solar radiation in locations immediately adjacent to tramline wheelings. Most importantly, the results (Figure 23) confirm the expectation that there was no effect of tyre treatment on any of the cereal harvest variables which were assessed in the areas spanning the tramline wheeling. Similar data were found at the other three sites, and so for brevity are not reported here.

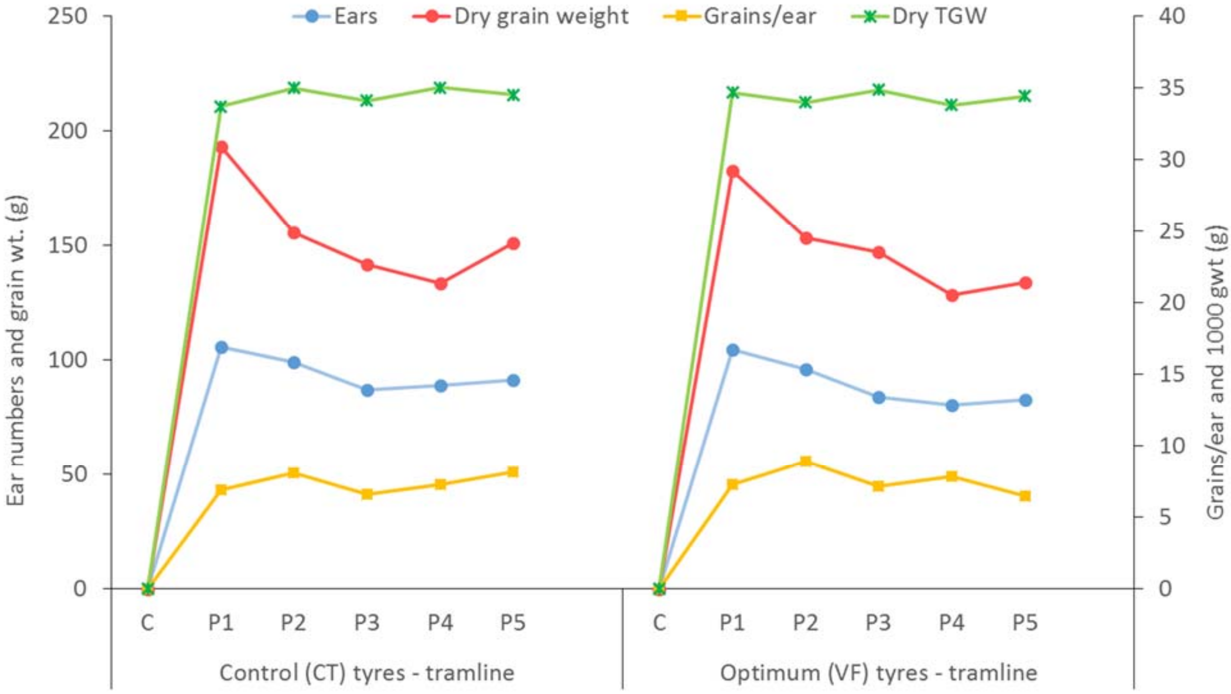


Figure 23. Harvest statistics, Hattons 2010. Number of ears, dry grain weight, grains per ear and dry thousand grain weight (TGW) in Control and VF tyre treatments at the centre of the tramline (C) and at locations moving perpendicular out into the uncompacted cropped area (P1–P5).

4.2. Impacts on surface runoff, sediment and P loss

This section reports results from experiments monitoring surface runoff and associated losses of suspended sediment and P from tramline areas on hillslope segments at three sites. Treatments evaluated at different sites and in different years were summarised in Table 2 in Chapter 3.1.3.

Results are expressed both as mm of runoff (to compare directly to mm of rainfall), and also as litres of runoff, to illustrate the very large volumes associated with relatively narrow (3m wide) widths of slope traversing tramline wheelings which have received sprayer traffic. Sediment and P results are reported both as concentrations, and also as volume-weighted loads which take account of the different amounts of runoff associated with the losses. These loads are reported as kg/ha and specifically relate to the monitored hillslope segment areas (i.e. 3m wide x hillslope length): these loads therefore do not represent losses averaged over the entire field area (as most of the field will not have tramlines). However, such results can be readily upscaled to whole-field given (i) reference data showing very little loss from the cropped areas without tramlines – which do not receive traffic (e.g. Silgram, 2005; Silgram *et al.*, 2010), and (ii) when assumptions concerning the number of tramlines per field and hillslope length are taken into account. Such equivalent up-scaled whole-field losses are considered later during field and catchment scale modelling activities (Chapter 4.3). In the graphs in Section 4.2.1, care should be taken to note the different scales used for different sites and different years, which illustrate losses from control treatment areas, the efficacy of tramline mitigation treatments, and the mediating effect of site (soil texture, slope) and weather (experimental year).

4.2.1. Year 1 (winter 2009/10)

In Year 1, treatments included a control treatment with conventional tyres (CT) in tramlines, the optimal (VF) tyres in tramlines, and the effect of drilling tramlines which then received traffic with either CT or VF tyres. Over-winter results for surface runoff and sediment measurements are shown in Figures 24–26, and a commentary with statistical results for each site is included below. Data from P analyses are not reported due to the laboratory issue identified in Chapter 3.1.1. Reported losses from all three sites were relatively low in this first experimental monitoring period.

Hattons

There was 125mm of rainfall during the monitored events, and runoff as a percentage of incident precipitation was 0.7% (CT tyres; drilled tramline), 1.0% (CT tyres; tramline), 0.4% (VF tyres; drilled tramline) and 0.4% (VF tyres; tramline). There was a significant effect of tyre treatment (i.e. VF tyres < CT tyres) in reducing runoff ($p<0.001$), sediment concentrations ($p<0.05$) and sediment loads ($p<0.001$). In contrast, there was no significant effect ($p>0.05$) of drilling tramlines on any reported variable.

Gatley

There were many missing values due to site and logger issues affecting five runoff storage tanks (out of 16), so results only relate to a single event with 50.9mm rainfall and should be treated with caution. Runoff as a percentage of incident precipitation was 0.3% (CT tyres; drilled tramline), 0.6% (CT tyres; tramline), 0.1% (VF tyres; drilled tramline) and 0.1% (VF tyres; tramline). There was a significant effect of tyre treatment (i.e. CT tyres compared to VF tyres) in reducing runoff ($p<0.001$) and sediment loads ($p<0.01$). In contrast, there was no significant effect ($p>0.05$) of drilling tramlines on any reported variable.

Loddington

There was 149mm rainfall during the monitored events. Runoff expressed as a percentage of incident precipitation was 2.9% (CT tyres; drilled tramline), 4.3% (CT tyres; tramline), 1.9% (VF tyres; drilled tramline) and 2.0% (VF tyres; tramline). There was a significant effect of tyre treatment (i.e. CT tyres compared to VF tyres) on runoff ($p<0.01$), sediment concentrations ($p=0.05$) and sediment loads ($p<0.01$). In contrast, there was no significant effect ($p>0.05$) of drilling tramlines on any variable.

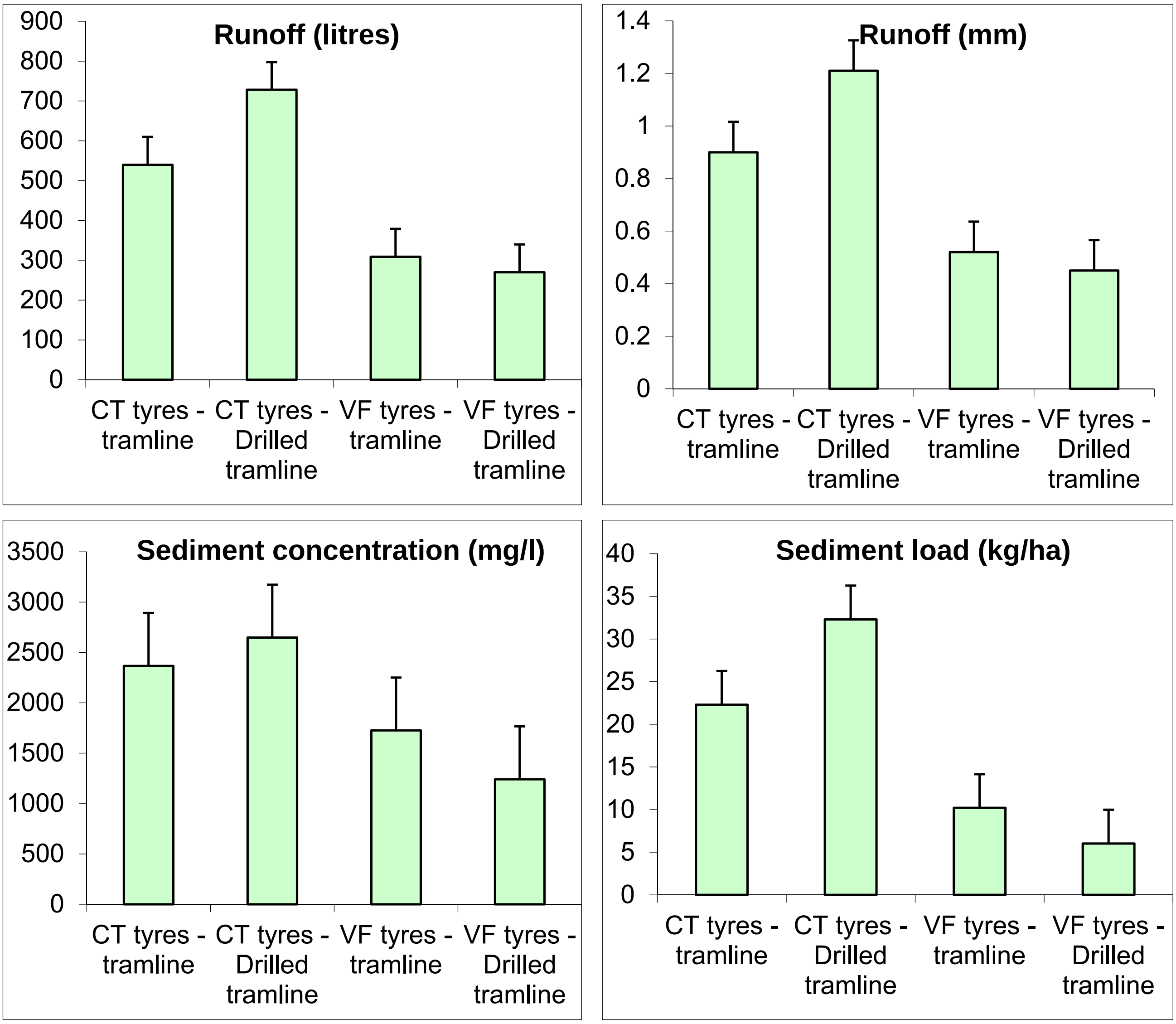


Figure 24. Hattons, winter 2009-10. Over-winter total surface runoff (l and mm), mean sediment concentration and total loads for different treatments. Standard errors are shown.

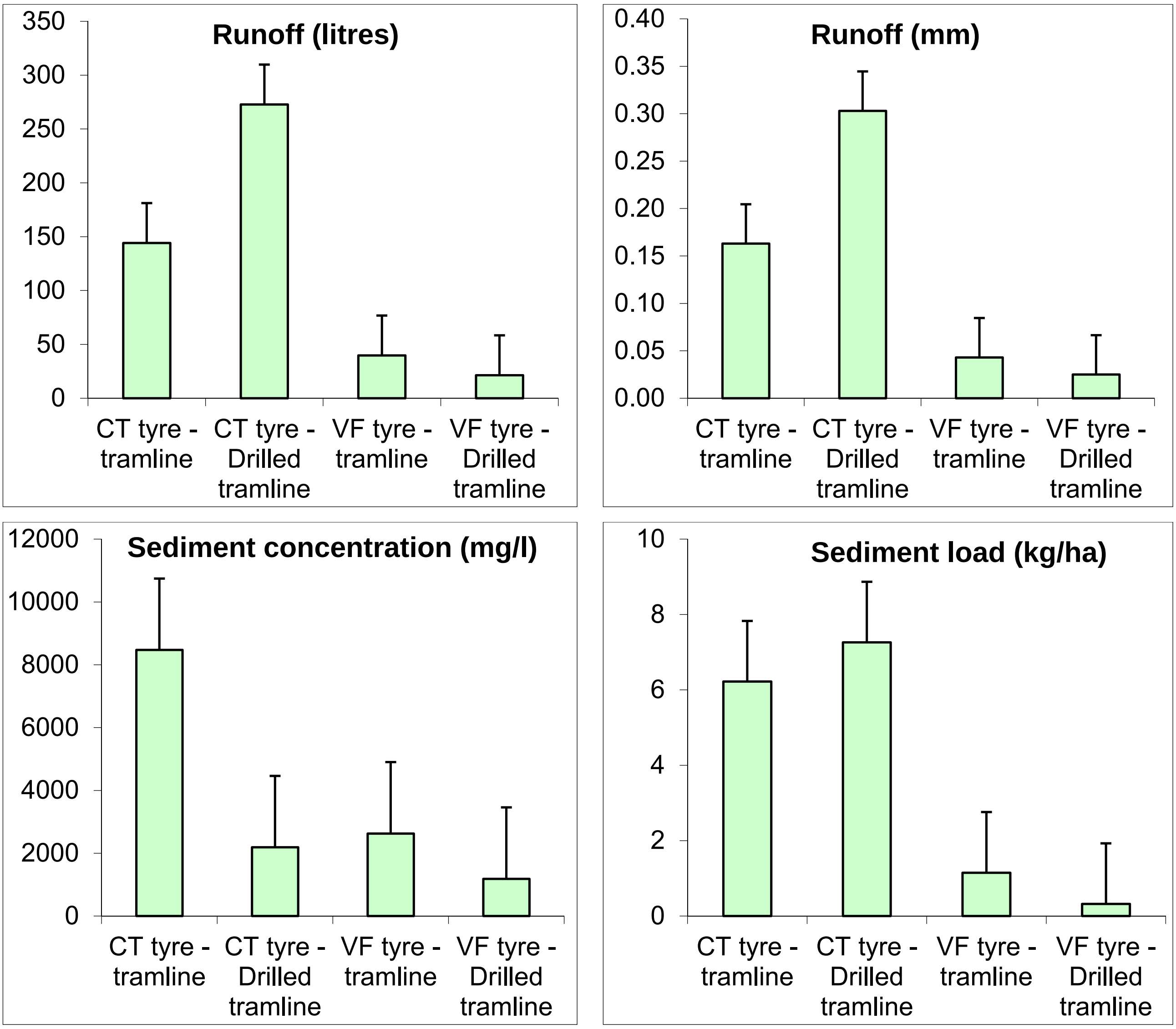


Figure 25. Gatley, winter 2009-10. Over-winter total surface runoff (l and mm), mean sediment concentration and total loads for different treatments. Standard errors are shown.

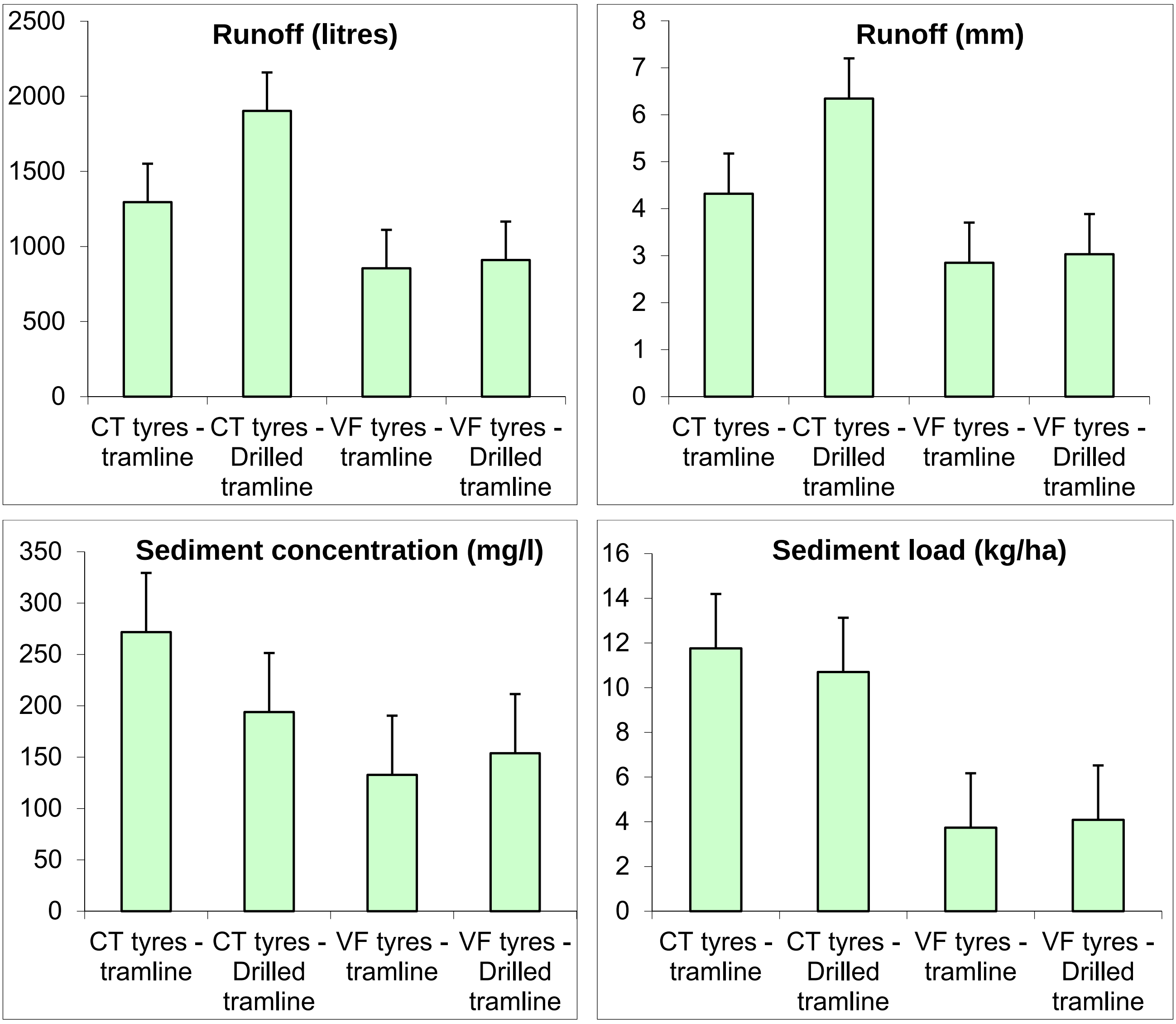


Figure 26. Loddington, winter 2009-10. Over-winter total surface runoff (l and mm), mean sediment concentration and total loads for different treatments. Standard errors are shown.

4.2.2. Year 2 (Winter 2010/11)

The Year 1 results demonstrated the importance of tramline wheelings as transmission pathways for surface runoff, sediment and P loss; and dismissed the idea of drilling tramlines as a potential tramline mitigation option. Year 2 studies explored the potential value of alternative mitigation option ideas for managing cereal tramlines, including the use of VF tyres (which had showed promising results in Year 1), as well as novel rotary harrow and surface profiler solutions. Over-winter results for surface runoff, sediment and P measurements at all four sites are shown in Figures 27–30, and a commentary with statistical results for each site is included below. Recorded losses from experimental treatments in this second winter were low at Hattons and Loddington sites, but were notably much higher at Balruddery and at the more steeply sloping Gatley site.

Hattons

There was 123mm of rainfall during the monitored events, with the greatest runoff, and concentrations and loads of sediment from the control tyre treatment. Runoff (and consequently sediment and P losses) were very small compared to those observed at the Gatley site in this season, and runoff only represented <1% of incident precipitation on all four treatments. All three tramline mitigation treatments proved effective, substantially reducing surface runoff, and resulting loads of sediment, TDP and TP. There was a statistically significant effect of tramline treatment on surface runoff (p=0.001), and on loads of sediment (p<0.05), TDP and TP (both p<0.05). Surprisingly, TDP concentrations appeared higher on VF tyre and surface profiler treatments, although this was more than matched by inverse pattern for particulate phosphorus, such that the overall results for TP showed the more typical pattern with reduced loads from all three non-control treatments.

Gatley

There was only 32mm of rainfall during the monitored events, with control tyre treatments yielding the highest losses of runoff, TDP and TP. In spite of the low rainfall, it was notable that runoff losses were much greater than that observed at either of the other two sites (where rainfall had been considerably greater), and the steeper slope angle at this site may have been a contributory factor. Overall, runoff represented as much as 25.5% of incident precipitation on control tyre treatment plots, but this was reduced to only 7.3% under the optimum VF tyre treatment, 5.8% under the rotary harrow treatment and 3.6% under the surface profiler treatment. All three mitigation treatments proved highly effective, dramatically reducing runoff with resulting loads of sediment and P limited to negligible levels. Consequently there was a highly statistically significant effect of tramline mitigation treatment on surface runoff (p<0.001); concentrations of sediment (p=0.05), TDP (p<0.05) and TP (p<0.05); and loads of sediment (p=0.05), TDP (p<0.001) and TP

($p<0.05$). Gatley was the only one of the three sites to record substantial runoff, sediment and P losses in winter 2010/11, with total over-winter losses of 488kg/ha sediment and 0.48kg/ha total P in runoff from the control CT tyre treatment tramline area.

Loddington

There was 101mm of rainfall during the monitored events, with runoff representing a small proportion (1.1–1.5%) of incident precipitation, resulting in very small losses of only 1.4–2.5 kg/ha of sediment and only 0.009–0.012 kg/ha TP. There was no statistically significant effect of tramline mitigation treatment on runoff, sediment or phosphorus concentrations or loads. The lack of any treatment effect at this site contrasts markedly with results from the other two sites, and reflects the contrasting, clay soil texture at Loddington and the notably dry antecedent weather conditions in the weeks prior to autumn spraying. On this structurally stronger clay-rich site, these dry conditions would have meant the soil had not reached its plastic limit, and so soil compaction would not have been a risk when spraying took place i.e. there was no compaction problem to mitigate.

Balruddery

There was 90mm of rainfall across the first three events which comprise the summary results reported here (events 4–6 are not reported due to icing of equipment). Surface runoff from the replicated 300m^2 hillslope areas represented 17.9% of rainfall under the control CT tyre treatment, but was only 6.5% of rainfall under the VF tyre, 4.5% of rainfall under the rotary harrow, and 1.4% of rainfall under the surface profiler treatments, respectively. All three tramline mitigation treatments therefore proved effective, significantly reducing surface runoff ($p<0.05$) and associated concentrations of sediment ($p<0.01$), TDP ($p<0.001$) and TP ($p=0.001$). Consequently, these tramline management methods also had a significant effect in reducing loads of sediment ($p<0.05$), TDP ($p<0.01$) and TP ($p<0.01$) lost to the base of the hillslope. The three mitigation methods reduced over-winter runoff and mean sediment, TDP and TP concentrations by 64–92%, 58–85%, 30–58%, and 44–83%, respectively, compared to the control CT tyre treatment. The comparable effect of mitigation treatment on loads were reductions of 85–99%, 77–97% and 82–99% for sediment, TDP and TP, respectively.

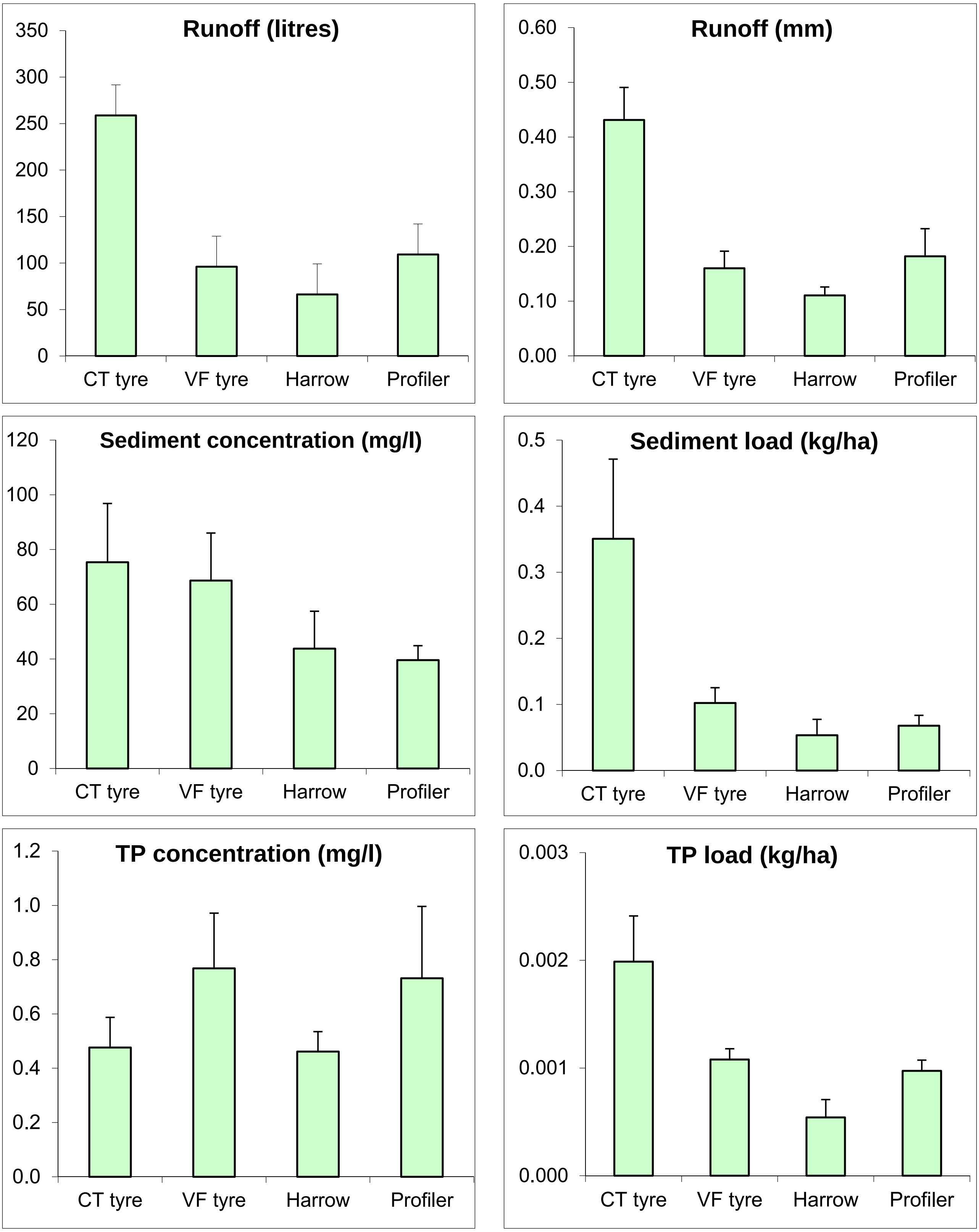


Figure 27. Hattons winter 2010–11. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

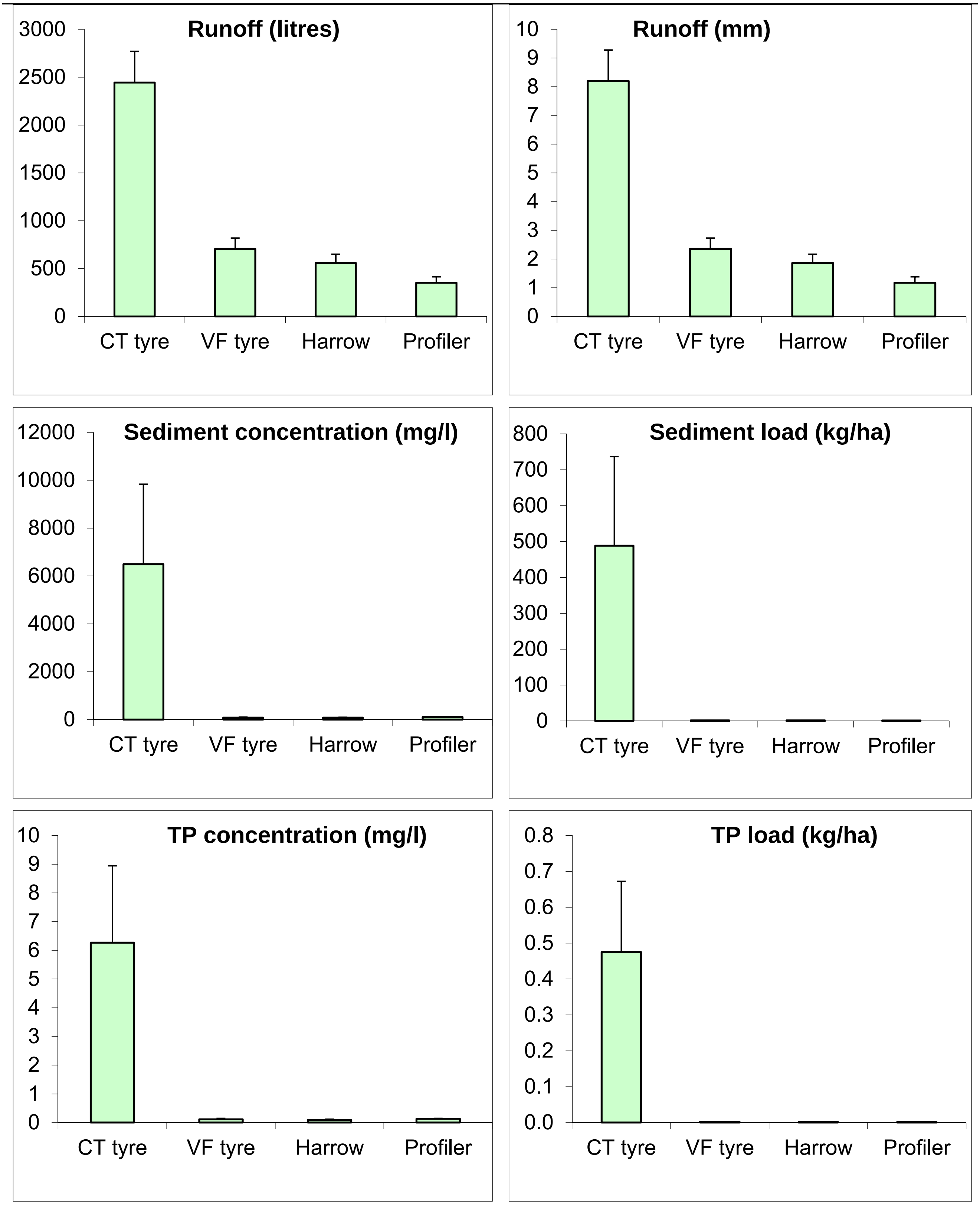


Figure 28. Gatley, winter 2010–11. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

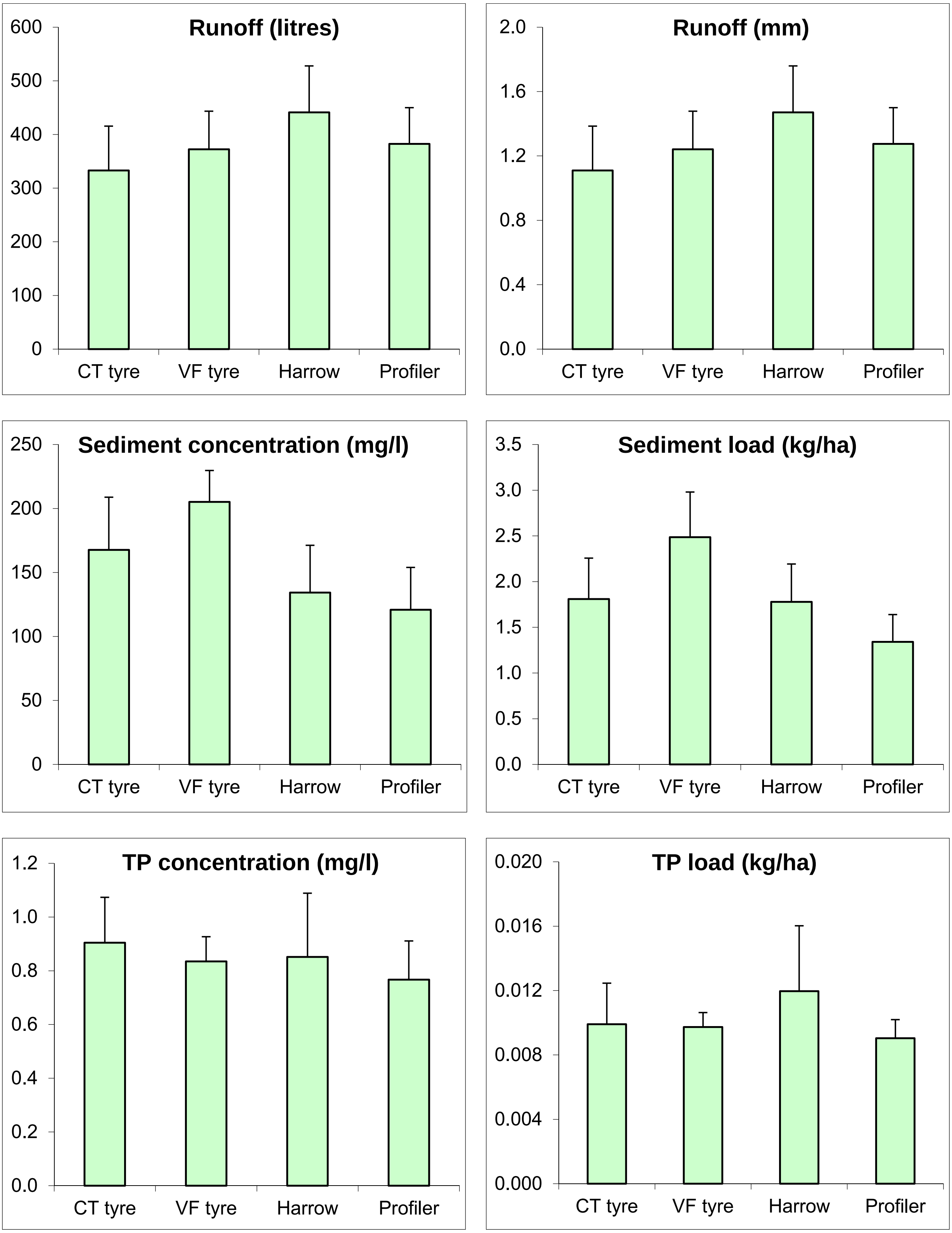


Figure 29. Loddington, winter 2010–11. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown. Note scale: sediment and P values were much lower than corresponding Hattons and Gatley data from this winter.

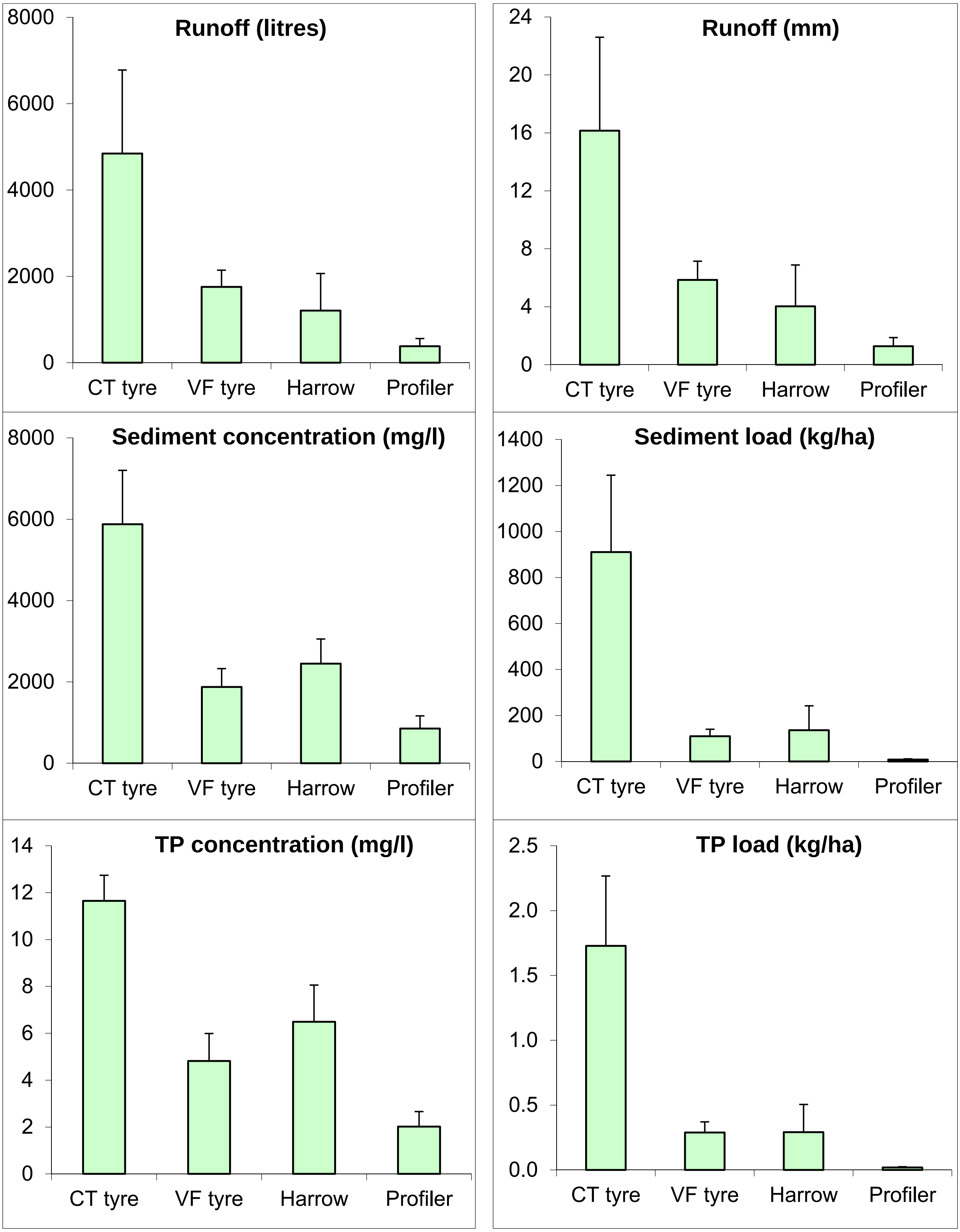


Figure 30. Balruddery, winter 2010–11. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

4.2.3. Year 3 (Winter 2011/12)

Year 3 studies incorporated the most promising elements from the tramline mitigation treatments explored in the earlier years of this project. Treatments therefore focused on gathering further evidence of the potential mitigation benefits from use of the VF tyres and the rotary harrow unit as part of the autumn spray operation. These two elements were studied separately, and in combination to see if there was any additive effect from using both methods simultaneously. Over-winter results for surface runoff, sediment and P measurements are shown for all four sites in Figures 31–34, and a commentary with statistical results for each site is included below. Across all the experimental sites, recorded losses of runoff, sediment and P down tramlines were notably much higher in this third winter when compared to those reported from the previous two winters.

Hattons

It was a wet winter in 2011–12 with a total of 156mm rainfall recorded during the monitoring period. This resulted in large volumes of runoff, with over 8000 litres recorded in each of the control CT treatment areas (each measuring 3m by 100m). There was a highly statistically significant effect of the use of the VF tyre ($p<0.001$) and the use of the harrow ($p<0.001$) in reducing surface runoff. The percentage of rainfall lost as runoff was 11.5% from the control CT tyre treatment, but this was substantially reduced under the CF tyre + harrow treatment (0.4%), the VF tyre treatment (7.0%), and the VF tyre + harrow treatment (0.2%).

Sediment losses in runoff were very high, with mean concentrations of over 7000 mg/l and total over-winter losses of 1200 kg/ha from the control CT tyre treatment areas. Both the VF tyre and the rotary harrow proved very effective as mitigation methods. The VF tyre had a highly significantly and consistent impact in reducing loads of sediment ($p<0.001$), TDP ($p=0.001$) and TP ($p<0.001$). The harrow treatment had a highly significant and consistent impact in reducing sediment concentrations ($p<0.001$) and loads ($p<0.001$); TDP concentrations ($p<0.001$) and loads ($p<0.001$); and TP concentrations ($p<0.001$) and loads ($p<0.001$).

The harrow treatment was responsible for the most notable reduction in losses of both sediment and P losses, when compared to the VF tyre treatment. The combination of both VF tyre and harrow mitigation treatments resulted in the largest reduction in both sediment and P loss, demonstrating that there was a beneficial additive effect of using both mitigation methods together. Total over-winter loads of sediment and TP from lost down tramline wheelings at this site were very high, equivalent to 1226kg/ha sediment and 2.93kg/ha of total P from the control CT tyre treatment area.

Gatley

This season was rather wet at Gatley, with 97mm of runoff across 11 rainfall events during the monitoring period from 23 November 2011 until 30 January 2012. Several of these events occurred within a few days of each other in mid-November (i.e. 35mm of rainfall fell in the 12–15th November period alone). This meant that the ground remained at or close to saturation for much of the time, and consequently the percentage of rainfall lost as runoff was relatively high at 21.0% for the control treatment CT tyres. However, the mitigation treatments proved effective in substantially reducing these relative losses (p<0.05), with losses of only 9.5% for the CT tyre + harrow, 11.8% for the VF tyre, and 10.0% for the VF tyre + harrow treatments, respectively. However, measured volumes of runoff were very high, with an average of over 6000 litres of runoff recorded from each of the replicate control treatment areas (each 3m wide by 300m long), which demonstrates that the mitigation methods appeared capable of reducing runoff even under relatively extreme rainfall conditions.

There were significantly higher concentrations of sediment (p<0.05) and TP (p<0.01) (but not TDP) in runoff from the two treatments which included the harrow, but this was not reflected in overall loads of sediment or TP reaching the base of the hillslope. Total over-winter loads of sediment and TP lost down tramline wheelings at this site were very high, equivalent to 989kg/ha sediment and 1.23kg/ha of total P from the control CT tyre treatment area.

Lodddington

Only two events in winter 2011/12 had usable data from this site, due to runoff tanks over-topping during two other events. Total rainfall across the two reported events was 43mm, with 3.8% of rainfall lost as runoff from the control CT tyre treatment area. The tramline mitigation treatments proved effective in significantly reducing (p<0.05) this loss to only 0.4% of rainfall (CT tyre + Harrow), 2.9% of rainfall (VF tyre) and 0.4% of rainfall (VF tyre + Harrow).

As noted at the Hattons site during this same winter (2011/12), the harrow treatment alone accounted for the largest reduction in runoff (p<0.01), sediment and P loss, rather than the tyre treatment, although there appeared to be an additive benefit of applying both treatments together. Consequently, the harrow tramline mitigation treatment had a highly significant effect in reducing concentrations of sediment (p<0.001), TDP (p<0.05) and TP (p<0.001) in runoff; and in reducing runoff loads of sediment (p<0.01), TDP (p<0.01) and TP (p<0.01). The VF tyre tramline mitigation treatment reduced concentrations of sediment (p<0.05) and TP (p<0.07) in runoff; and reduced loads of sediment and TP (although these effects were not statistically noteworthy).

Total over-winter losses of sediment and P were much lower from this sites than those reported for the other two sites this winter because only two events are reported, but the pattern of loss and the impact of the tramline mitigation treatments were broadly consistent across all four sites.

Balruddery

There was 92mm of rainfall over two events at the Balruddery site in winter 2011–12. This rain fell over a period of 41h with a peak intensity of 2mm/h and resulted in a peak runoff rate of 14.5l/min. Runoff lost as a proportion of this rainfall was 15.7% from the control CT tyre treatment, but only 0.7% from the CT tyre + Harrow treatment, 10.5% from the VF tyre treatment, and 0.15% from the VF tyre + Harrow treatment areas, respectively.

All three tramline treatments had a beneficial mitigating effect. The harrow significantly reduced runoff (p<0001), concentrations of sediment (p<0.001), TDP (p<0.001) and TP (p<0.001). Consequently, mitigation methods had a significant effect in reducing loads of sediment (p<0.001), TDP (p<0.001) and TP (p<0.001) reaching the base of the hillslope.

The VF tyre treatment also reduced runoff, and concentrations of sediment, TDP and TP, and consequently reduced loads of sediment, TDP and TP reaching the base of the hillslope, but these effects were not statistically significant. Results show that by far the greatest benefit in terms of the mitigation of losses of runoff, sediment and P losses was gained from the use of the rotary harrow, although there was some small additional additive benefit of using this in conjunction with the VF tyres. This conclusion is consistent with the comparable results presented from both Hattons and Loddington from this winter, but not with data from the much wetter and steeper Gatley site.

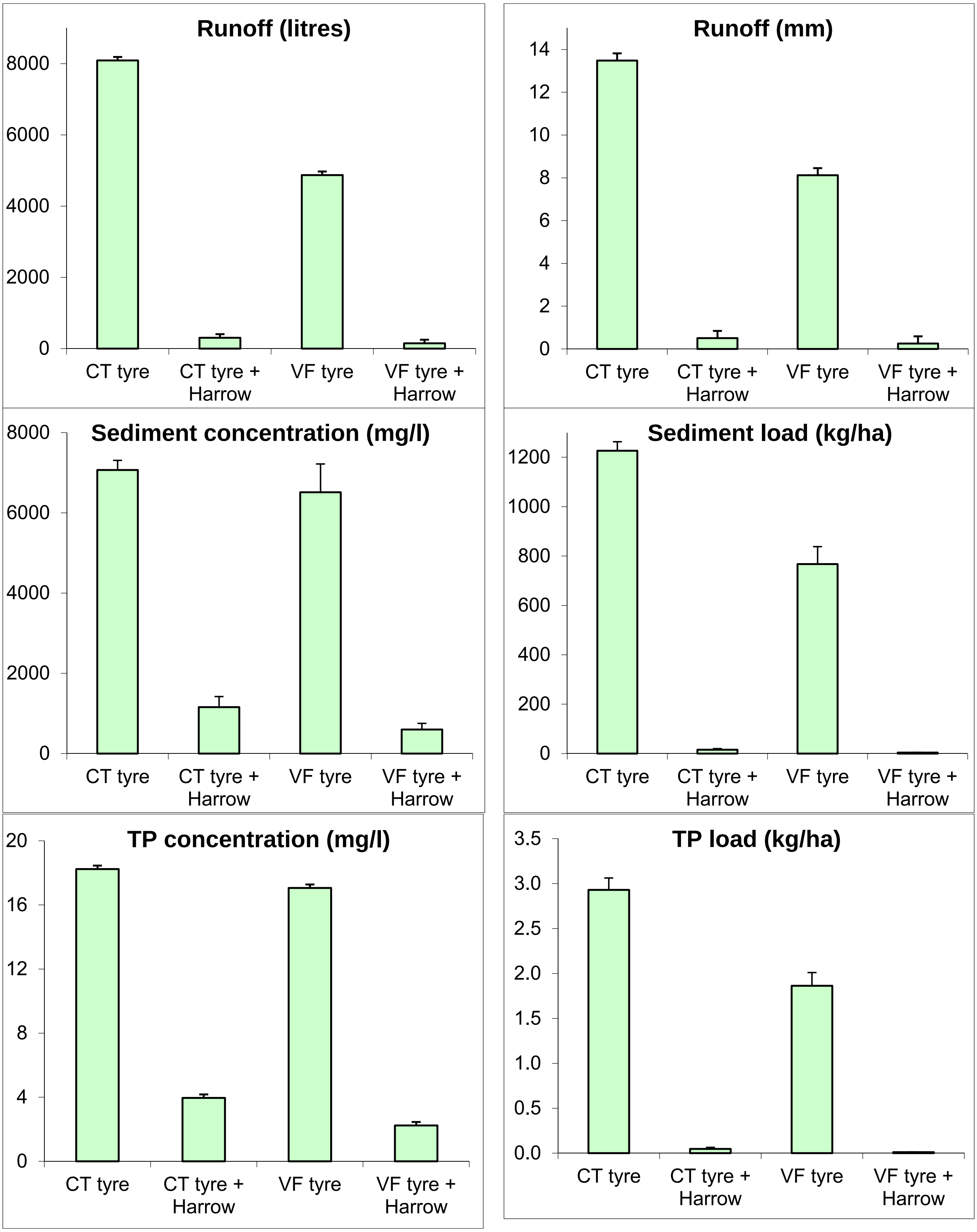


Figure 31. Hattons, winter 2011–12. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

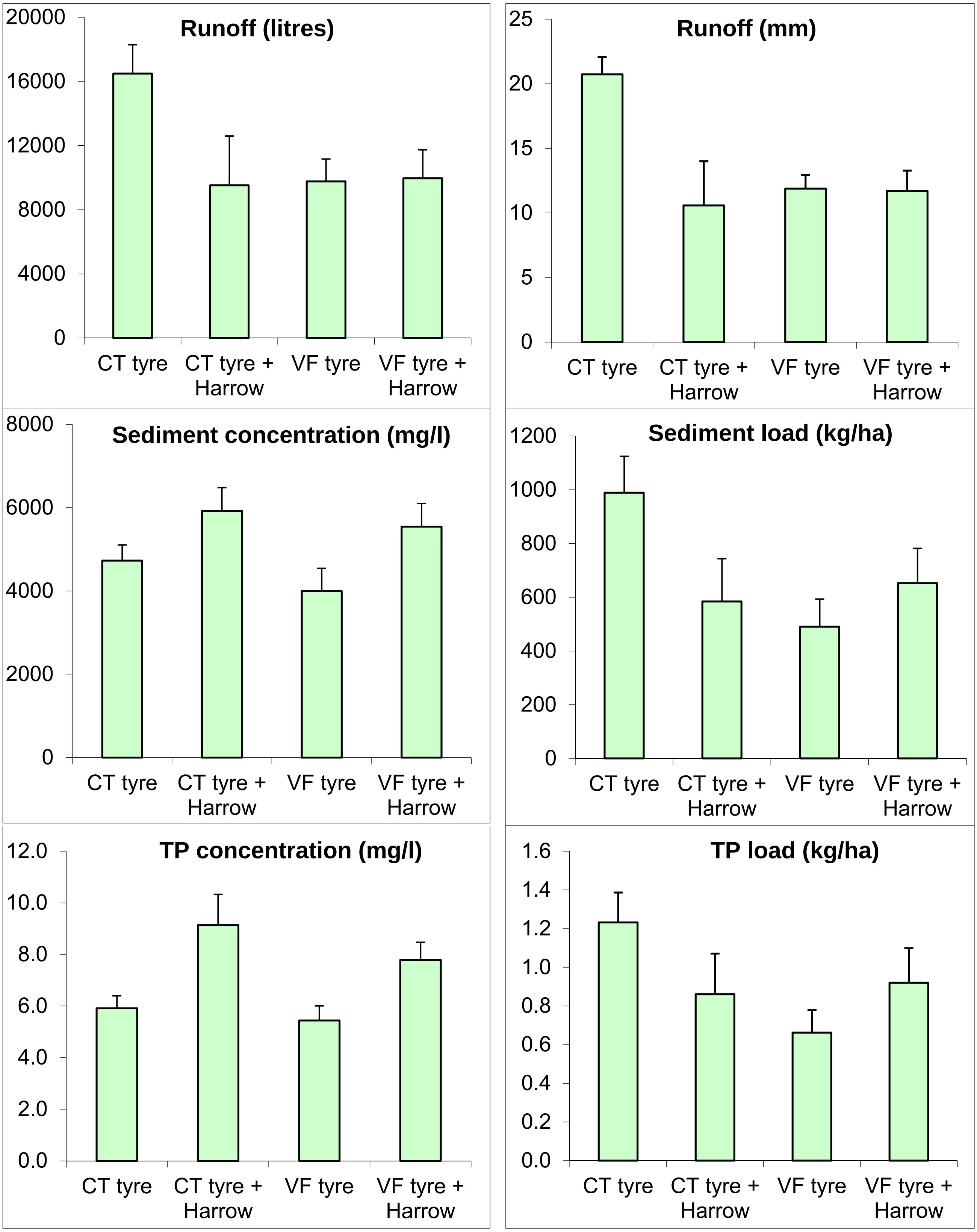


Figure 32. Gatley, winter 2011–12. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

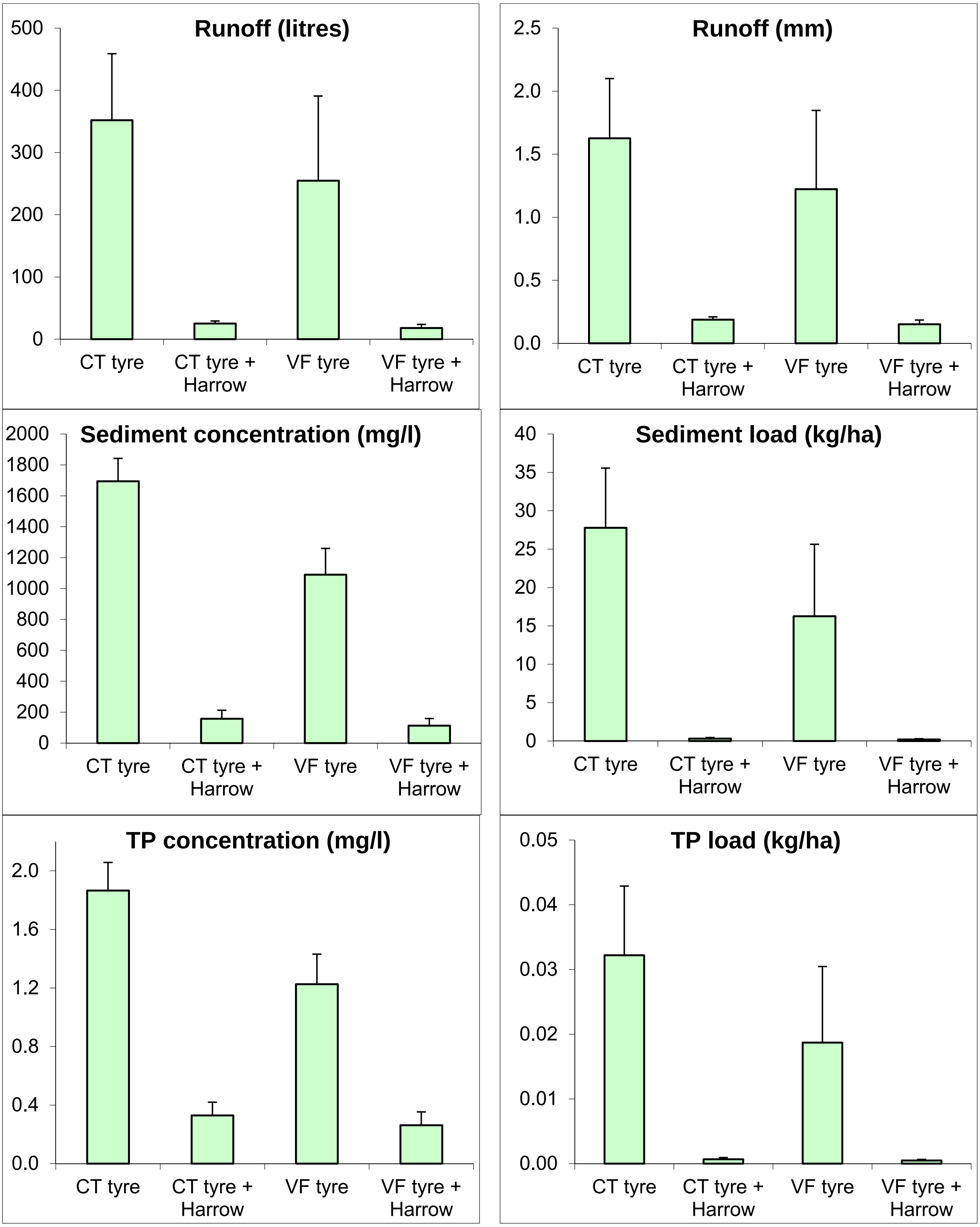


Figure 33. Loddington, winter 2011–12 (only 2 events). Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

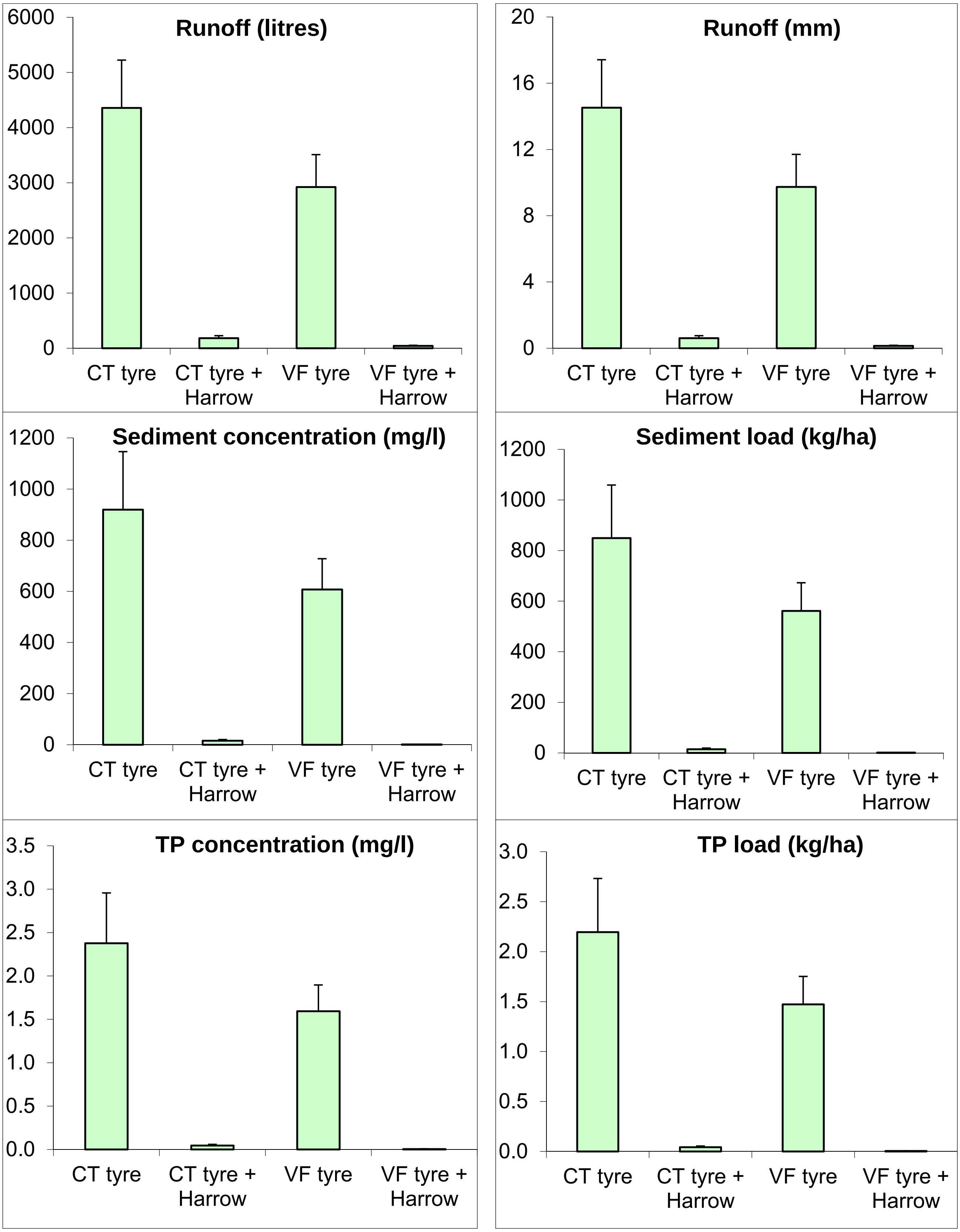


Figure 34. Balrudddery, winter 2011–12. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

4.2.4. Year 4 (Winter 2012/13)

Year 4 monitoring involved a repeat of the Year 1 treatments. However, unfortunately the Gatley site was not available for this year of the study. In addition, the weather at the Loddington site was so wet throughout the entire autumn period that this heavy clay soil remained saturated throughout November, and the farm manager decided that this field (together with half of the rest of the cereal crop area) was unsuitable for crop spraying throughout this period (it was sprayed in the spring instead). Indeed only half of the farm area due for drilling in autumn 2012 was actually drilled on this clay site, due to this persistent wet weather, and the crop failed in half of the area which was drilled, requiring re-drilling in spring.

Consequently, only results for the Hattons and Balruddery sites are presented here. Over-winter results for surface runoff, sediment and P measurements are shown in Figures 35–36, and a commentary is included below.

Hattons

Crop drilling was possible at this site given its much lighter, better-drained soil texture compared to the other two sites in England. Nonetheless, it was a particularly and abnormally wet winter with 313mm rainfall, and, as a result, the Hattons field remained close to, or at, saturation throughout much of the monitoring period. This resulted in the runoff tanks over-topping during many events, rendering the chemistry data unusable due to a decanting effect. A perched water table also occurred periodically above the plough pan which also limited the collection of useable field data.

Consequently, results are presented for events 1 and 2 only (out of a total of 17 events), as these were the only events for which complete runoff and chemistry data were all available for all four replicates of all four treatments. Over events 1 and 2, a total of 32.4mm rainfall fell over 30.7h. During those storms, rainfall intensity peaked at 8mm/h, and surface runoff peaked at 34.5 l/min in tanks collecting runoff from the monitored 3m wide x 200m long tramlines. Runoff represented 31.4% of incident rainfall from the control CT treatment and 28.2% from the CT tyre + Drilled tramline treatment, but was reduced to only 16.3% and 19.1% of rainfall from the VF tyre and VF tyre + Drilled tramline treatments respectively.

There was evidence of a treatment effect with the VF tyre treatment tending to reduce surface runoff (p=0.07) and sediment loads (p=0.05), as well as a pattern for reduced loads of TDP and TP (although these results were not statistically noteworthy). In contrast, there was no effect of the drilled tramline treatment on surface runoff, although there did appear to be an effect in reducing concentrations of sediment (*p*=0.06) and TP (*p*<0.05), but due to the lack of any effect on runoff volumes there was no effect of drilling tramlines on loads of sediment, TDP or TP lost in runoff. This demonstrates that controlling the volumes of surface runoff lost from fields is the most important objective, as this is the vector responsible for transporting sediment and P to edge of field (and ultimately losses to water courses). Only tramline management methods which reduce soil compaction and/or reduce runoff and encourage surface infiltration will therefore be effective management tools for this purpose.

Although chemistry data for other events were not available, the logger data for surface runoff meant it was possible to calculate total over-winter runoff for all treatment replicates over the entire very wet period spanning 17 events from 19 November 2012 to 14 February 2013 inclusive. Total over-winter runoff during this period was 85.4mm (CT tyre treatment), 97.9mm (CT tyre + Drilled tramline), 60.7mm (VF tyre) and 67.4mm (VF tyre + Drilled tramline). Expressed as a percentage of the 313mm of rainfall which fell during the whole winter period, runoff losses were therefore 27.3% for the control CT tyre treatment, 31.3% for the CT tyre + Drilled tramline treatment, but only 19.4% for the VF tyre treatment and 21.6% for the VF tyre + Drilled tramline treatment.

Such results highlight the very high volumes of runoff which can occur over a full three month winter period from relatively narrow (3m wide) areas spanning a single pair of tramline wheelings. Total over-winter hillslope losses at Hattons were measured as 51225 litres (CF tyre), 58718 litres (CF tyre + Drilled tramline), 36448 litres (VF tyre) and 40467 litres (VF tyre + drilled tramline). Such very large volumes of runoff, which are channelled into very narrow, compacted, concave-shaped and unvegetated area on a hillslope, will clearly have considerable erosive potential and the ability to transport large loads of sediment and P (and other surface-applied plant protection pollutants) to the base of the hillslope and into any adjacent water course.

When totalled over the entire winter period, this pattern of runoff loss between treatments appears broadly comparable to that shown in Figure 35 for events 1+2 alone, with less surface runoff measured where the VF tyre treatment was used rather than the control CT tyre treatment, but with no significant effect of drilling tramlines on surface runoff. These results from winter 2012–13, although relatively limited, do nonetheless corroborate the earlier findings from Year 1 (winter 2009–10) of this study. The fact that, unlike the VF tyre treatment, the use of drilled tramlines did not consistently reduce runoff losses in either of these two project years means that this cannot be considered a practical method for mitigating erosion risk and associated losses in commercial cereal crops on shallow or moderate slopes.

Balruddery

In winter 2012–13, treatments at Balruddery were different from the Hattons site, and compared the control CT tyre against the CT tyre with a drilled tramline, the VF tyre with a drilled tramline, and the CT tyre with the rotary harrow. Combined results from events 2, 3, 5 and 9 are reported here, as results from other events were confounded by tanks over-topping, frozen soils, or a localised perched water table causing runoff tanks to become dislodged.

There was 40mm rainfall over these events, which resulted in a peak runoff rate of 18 l/min associated with the replicate 3m wide x 100m hillslope segments which traversed a pair of tramline wheelings. Mean runoff expressed as a percentage of rainfall was 23.8% under the control CT tyre treatment and 19.3% under the CT tyre + drilled tramline treatment, but only 6.8% under the VF tyre + drilled tramline treatment, and 3.5% under the CF tyre + harrow treatment. Runoff volumes were therefore substantial – with nearly 3000 litres lost from the control CT tyre treatment.

Runoff results indicate that the VF tyre treatment had a statistically significant effect ($p<0.05$) in reducing surface runoff, concentrations of sediment and TP, and loads of sediment, TDP and TP. The combination of VF tyres + drilled tramlines substantially reduced ($p<0.05$) surface runoff and associated concentrations and loads of sediment and TP, whereas the drilled tramlines alone had a much more marginal effect. This evidence suggests that the vast majority of any benefit in reducing these losses was associated with using the VF tyres during spraying rather than drilling the tramlines beforehand. It was the rotary harrow alone (i.e. using conventional tyres) which proved the most effective of all three mitigation treatments, having a highly significant impact ($p<0.05$) in reducing runoff and loads of sediment, TDP and TP.

These results from winter 2012–13 corroborate the findings from Year 1 (winter 2009–10) of the study regarding the absence of any significant benefit from drilling tramlines and the results from earlier years demonstrating the benefit of both the VF tyre and rotary harrow mitigation treatments, in reducing runoff, sediment and P losses from compacted tramline areas.

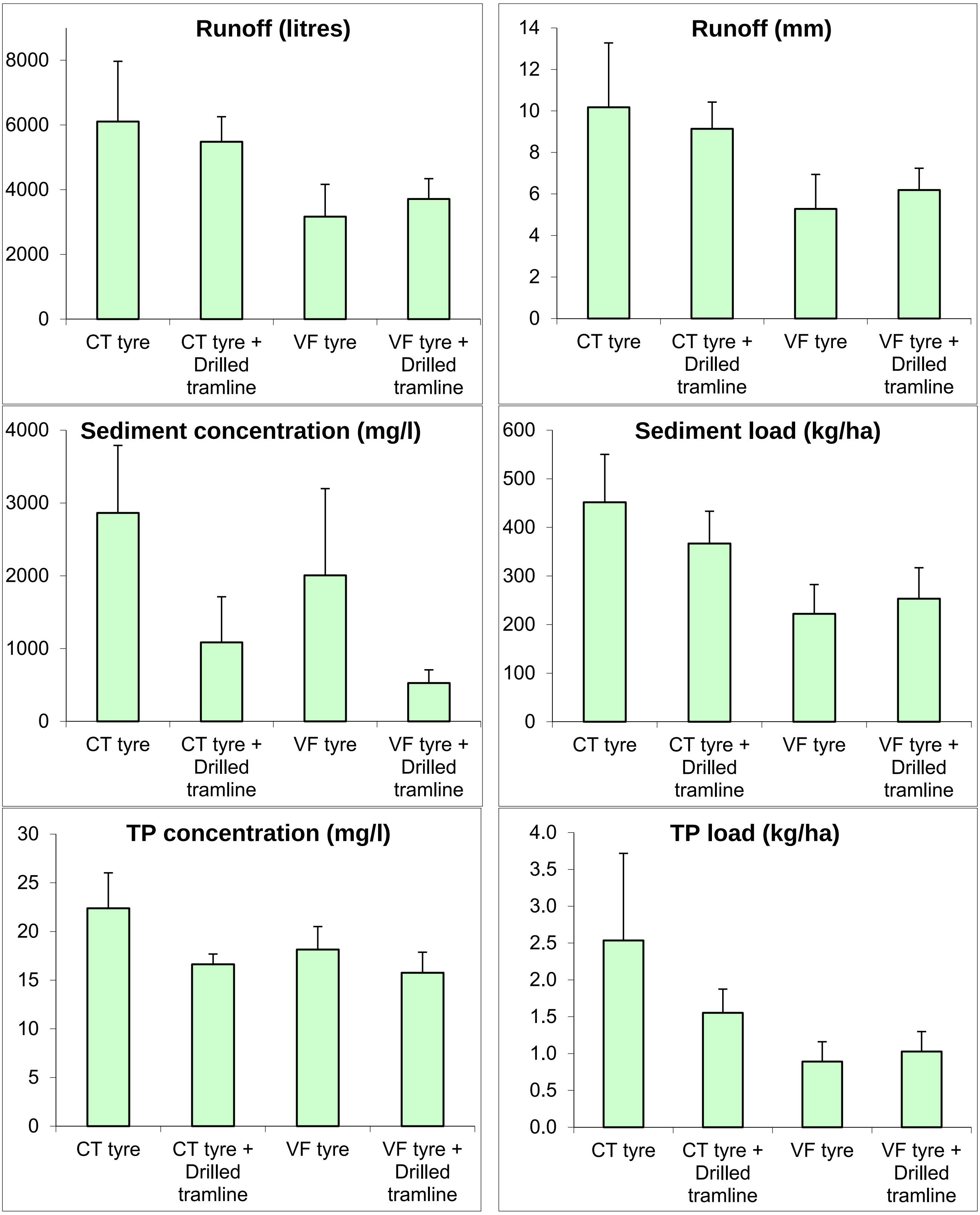


Figure 35. Hattons, winter 2012–13. Event 1+2 results. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

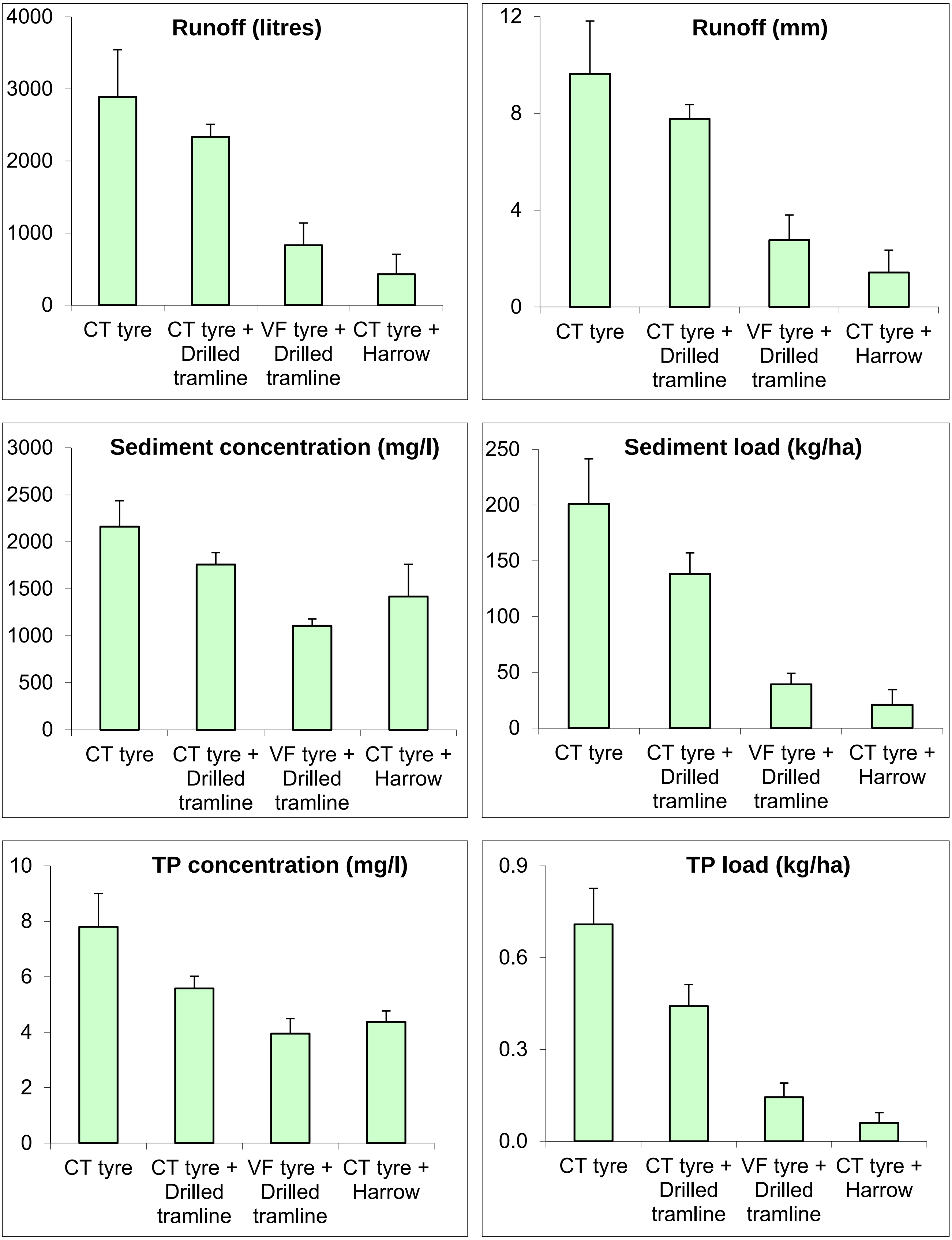


Figure 36. Balruddery, winter 2012–13. Over-winter total surface runoff (l and mm), mean sediment concentration and total load, and mean total phosphorus (TP) concentration and total load for different treatments. Standard errors are shown.

4.3. Field and Catchment Modelling

4.3.1. Approach

Experimental results, although focused on relatively large hillslope-scale segments, were nonetheless limited to a small number of field sites with their particular slope angles, soil types and locations. In order to generalise results in terms of their impact on surface water quality, it was necessary to apply field and catchment scale models. Such models have been specifically developed for assessing the impact of land management options at a variety of scales, with functions and parameters derived from field experimental data. Within the UK, ADAS in particular has been at the forefront of the development and application of such models for policy support for central and regional government, government agencies, and private sector organisations such as water companies, driven by EU legislation including the Water Framework Directive, Nitrates Directive and Habitats Directive. A particular body of ADAS work has focused on developing, testing and applying models to assess the impacts of land management on water quality to inform Defra's implementation, evaluation and reporting associated with agri-environment schemes and the location and rules implemented in Nitrate Vulnerable Zones (e.g. Lord *et al.*, 2007; Hodgkinson *et al.*, 2013).

The Phosphorus and Sediment Yield Characterisation in Catchments (PSYCHIC) decision support tool was developed to enable catchment stakeholders to target options to mitigate suspended sediment and phosphorus loss within catchments (Collins *et al.*, 2007; Davison *et al.*, 2008; Stromqvist *et al.*, 2008; Collins and Anthony, 2008; Collins *et al.*, 2009a,b). It has since been incorporated into the updated ADAS Pollutant Transfer (APT) pressure modelling tool which was successfully applied in Defra project WQ0128 (Collins *et al.*, 2012), to assess the potential impacts of delaying tramline establishment at national scale. More recently, its estimation of sediment, total phosphorus, and nitrate loadings have been used to evaluate the agricultural contribution for a cross-sector screening work in Defra project WQ0223 (as detailed in Zhang *et al.*, 2014). As a result, APT was considered to be the natural successor of PSYCHIC and selected as the pressure modelling tool for use in this project.

Compared with the PSYCHIC model, APT operates at a daily time step and has a common hydrology module for all pollutants being simulated. It can be run at either field or catchment scale. One significant change of the modelling approach is the adoption of Soil Conservation Service (SCS) curve number approach (USDA-SCS, 1972) for the estimation of surface runoff (Q):

$$Q = \frac{(R - I_a)^2}{R - I_a + S}$$

$$S = \frac{25400}{CN} - 254$$

where R is rainfall amount, I_a is initial abstraction accounting for vegetation interception, surface depression and similar, S is the water storage capacity in soil and CN is a soil type and hydrological condition specific curve number. Similar approaches have already been implemented in other existing water quality models, such as Generalised Watershed Loading Function (GWLF) (Haith *et al.*, 1987), Agricultural Non-Point Source Pollution model (AGNPS) (Young *et al.* 1989) and Soil and Water Assessment Tool (SWAT) model (Neitsch *et al.*, 2011). While tramline presence and their disruption will have impacts on both I_a and S, the most significant change will be to the latter.

The Soil Conservation Service (SCS) runoff curve-number (CN) approach was chosen for the representation of tramlines and their mitigation in pressure modelling. The SCS CN approach is an empirical model that describes runoff as a function of total rainfall and a potential maximum storage parameter. The approach predicts total storm response runoff, which may include surface and sub-surface flow paths. The storage parameter reflects infiltration and ponding capacity. This approach has obvious advantages including fewer parameters for calibration, flexibility of using observed daily weather data and the ability to produce more temporally comparable flow and pollutant estimates for comparison with monitored results which are generally daily or event-based. The limitation of the daily timestep approach is that it does not represent the influence of changes in rain intensity at the sub-daily temporal scale, for example rain events that would be shown in 15 minute rainfall monitoring.

In this project, experimental assessments of the effect of different tramline management methods on surface runoff, sediment and P loss were up-scaled to infer the potential impacts at (i) whole-field and (ii) sub-catchment scale. This involved:

- Calibrating the updated APT pressure model to represent the effect of tramlines at hillslope-segment scale (based on experimental monitoring data)
- Developing novel functions to represent the impacts of the different tramline mitigation methods at hillslope-segment scale (based on experimental monitoring data)
- Up-scaling impacts of different tramline management methods to whole-field scale
- Up-scaling impacts of different tramline management methods to sub-catchment scale for three exemplar catchments.

4.3.2. Representation of tramlines in APT modelling framework

Tramlines are represented as an explicit source area in the APT modelling framework. They are parameterised in the model framework using the following properties:

- Tramline presence (true / false)

- Tramline spacing
- Establishment date
- Tramline length
- Adjustment to water storage capacity (*S*) relative to the cropped area of the field
- Adjustment to soil cohesion modifier (*m*) relative to the cropped area of the field

To derive representative parameter values for different soil types being considered, monitored runoff and pollutant data from control plots (i.e. those without mitigation measures) were used to calibrate the water storage capacity and soil cohesion parameters in the tramline area relative to the cropped area during the monitored periods. This is an adjustment to the default APT parameters used previously, and allows the model to replicate better the pollutant losses and measured impacts observed in field experiments.

Site-specific data were used from the monitored sites, including continuous daily rainfall, field and crop management practices (e.g. crop type, plough date, drilling date, tramline establishment date). Using separate water storage capacity settings and water balances, daily surface runoff from both the tramline and cropped area were defined, and then combined, to calculate an overall flow depth for the monitored area. The water storage capacity in the tramline area (relative to the cropped areas) was optimised to match the total flow depths calculated from multiple control plots. As an example, comparison of simulated and measured runoff for two reference sites (Figure 37) shows that simulated daily flow depths were significantly correlated to measured daily runoff flow depths. Across all calibration sites, the associated correlation coefficient varied from 0.794 to 0.823 and was notably stronger under conditions with relatively high runoff. A summary of calibration across multiple sites and multiple years suggests that the water storage capacity (S) in the tramline area relative to the cropped area for different soil types varies from 0.60 to 0.89 for clay soils and from 0.09 to 0.27 for sandy soils.

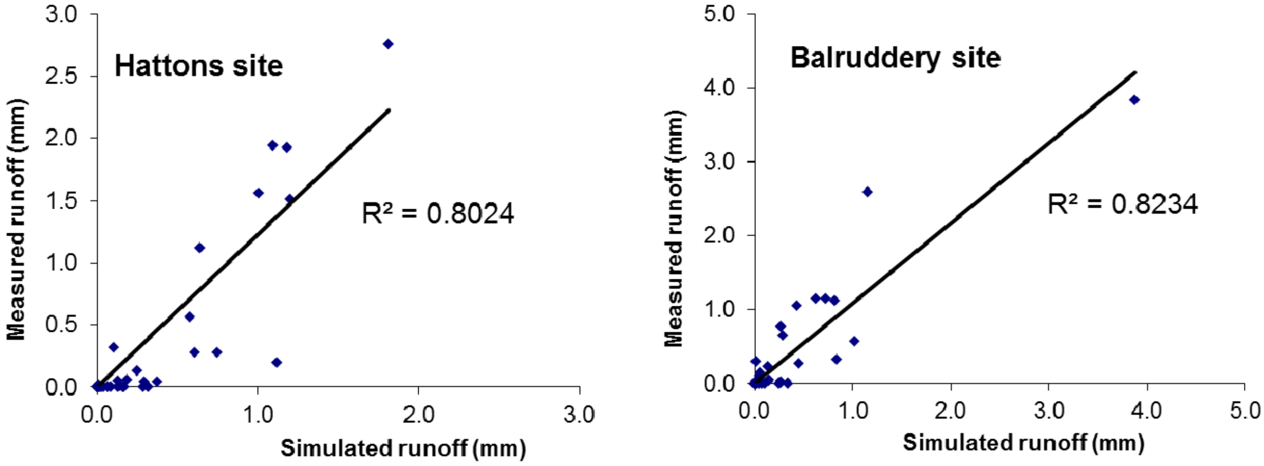


Figure 37. Calibrated modelled daily surface runoff plotted against measured daily surface runoff from tramlines in control plots at two field sites.

4.3.3. Representation of tramline management options in APT modelling framework

The implementation of the experimental mitigation measures, including optimally-inflated Very Flexible (VF) tyres on spraying equipment used in the autumn, attaching a self-propelled rotary harrow device to the rear of the sprayer in the autumn, and the Creyke surface profiler/roller unit, were expected to alter the hydrological response and pollutant loadings from tramline areas. To quantify treatment effects on runoff generation and pollutant delivery in the APT modelling framework, the same calibration procedures were undertaken to estimate the water storage capacity (*S*) in tramline areas relative to cropped areas with and without mitigation using the assembled datasets from treatment plots where different mitigation options were systematically trialled. The calibrated values for different soil types and mitigation options are shown in Table 6.

Table 6. Impact of mitigation treatment on water storage capacity in tramline wheelings, expressed relative to that in the cropped area

Soil type	Optimally inflated VF Tyre	Rotary Harrow	Roller*
Medium/Heavy	0.73	0.91	0.79
Light	0.78	0.88	

* limited data available for roller mitigation measure

As there were limited experimental data available, no satisfactory calibration were achieved on the use of the roller. Therefore, its effects were not implemented in the APT modelling framework and their impacts at catchment scale were not assessed.

Considering the inevitably short temporal scale and limited weather conditions associated with the monitoring periods, attempts were made to assess the broader potential impacts of tramline mitigation in reducing surface runoff amounts under future climate change scenarios. Assuming the "medium" emissions level scenario in the UKCP09 climate change projections (Murphy et al. 2009), a distribution of daily weather predictions for 2050 at the monitored sites were generated and used as inputs into the APT model.

Model outputs including the use of the rotary harrow suggest that this mitigation method will reduce the annual total runoff during the over-winter monitoring period by at least 20% in future 2050 scenario weather conditions at the Hattons site. The climate inputs are a distribution of simulated years, the effects in the wet years (wettest 10 years) and dry years (driest 10 years) are shown in Table 7. Results suggest that tramline mitigation will be more effective in relatively drier years, compared with very wet years. This may appear counterintuitive, but is likely to be because any mitigation option has a limit on the conditions under which it can operate effectively, and so it is possible that the potential beneficial effects of the rotary harrow unit could be overwhelmed by extremely persistent wet weather conditions. Nonetheless, under more typical conditions, the overall mitigation impact of the rotary harrow is impressive and, considering the lower and upper quartile predictions, results in an overall reduction in surface runoff to edge of field of 15–56% over the winter period when compared to the control tramline scenario (Table 7).

Table 7. Impact of rotary harrow on total runoff from the whole field area in 2050 using UKCP09 “medium” scenario projection*. Q1 and Q3 refer to lower and upper quartile values, respectively.

Scenario	Statistics	% Reduction
Dry years	Median	36
	Q1	18
	Q3	56
Wet years	Median	21
	Q1	15
	Q3	27

* based on using the rotary harrow unit when autumn spraying compared to control situation with conventional tramlines receiving sprayer traffic at the Hattons site.

To assess the impacts of tramline mitigation on the sediment delivery from the monitored sites, measured sediment concentrations associated with different mitigation options were analysed. Sediment concentrations from mitigation plots were compared with corresponding control plots to estimate the relative change in sediment concentrations measured in runoff. A summary of results is shown in Table 8 exploring the impact of both the VF tyres and rotary harrow mitigation measures. A bold font indicates that limited data were used to derive the values.

Table 8. Modelled impact of tramline mitigation measures on sediment concentrations

Mitigation measure	Soil group	Slope Angle (°)	Ratio to control *
Optimally inflated VF tyres	Sandy	≤ 7	0.95
	Silt	≤ 7	0.72
	Clay	≤ 7	**0.68**
Rotary Harrow	Sandy	≤ 7	0.25
	Silt	≤ 7	0.62
	Clay	≤ 7	0.90
Optimally inflated VF tyres	Sandy	>7	**0.85**
	Silt	>7	0.77
	Clay	>7	**0.60**
Rotary Harrow	Sandy	>7	0.35
	Silt	>7	0.50
	Clay	>7	**0.95**

* i.e. 0.95 means a 5% reduction relative to control

While the total phosphorus concentrations lost in runoff differed between monitoring sites, at a given site the adoption of mitigation measures had no statistically significant (*p*>0.05) impact on the relationship between sediment concentration and total phosphorus concentration in runoff. As a result, no modification was deemed necessary to account for mitigation treatment effects on phosphorus speciation in the APT modelling framework.

4.3.4. Field-scale impacts of mitigation methods

Having parameterised and calibrated the APT model to reflect the hillslope segment experiment results, the model was applied under typical field conditions and management practices to examine the impact of alternative tramline management options on losses at a whole field scale. The detailed results at this scale focused on sediment loss. Since particulate P was the dominant form of P at all study sites, these results should also give a good indication about the particulate P loss, as this attaches to the sediment and so is driven by sediment loss (Heathwaite *et al.*, 2005).

The key parameters for these model application scenarios included:

- Crop: a field sown with continuous winter wheat for a 20 year period
- Soil type: sand, silt, clay
- Slope: using the categories for shallow (3°) and steep (8°) slopes
- Field drains: (moles, tiles, none). The spacing and drain efficacy variables were based on those used in previous national scale APT modelling applications (e.g. Hodgkinson *et al.*, 2013, Zhang *et al.*, 2014)
- Average annual rainfall: low (575mm), medium (740mm), high (1150mm)

The average annual sediment loss from the field (in kg/ha) was modelled under three scenarios: a control scenario (no tramline mitigation with autumn spraying), a scenario using the rotary harrow after autumn spraying, and a scenario using optimally-inflated Very Flexible tyres on the autumn sprayer. Reductions in sediment loss due to the two mitigation measures were calculated, both in absolute terms and re-expressed as a percentage relative to the loss under the control scenario. To evaluate the sensitivity of mitigation measures to site-specific conditions, model results were summarised by key field conditions represented in APT (i.e. average values of all different combinations of individual variables including rainfall, soil type, drain type and slope angle).

Results (Table 9) show that in all modelled scenarios except for clay soils, the harrow mitigation measure produced greater reductions in sediment loss than the optimally inflated VF tyres. Both mitigation measures were highly effective compared to the baseline scenario, with mitigation of the order of 50%, and substantial average reductions in sediment loss of around 500 kg/ha. The greatest impacts in percentage terms were under the low rainfall scenarios, but the greatest impacts in terms of mass of sediment loss mitigated were on the high rainfall scenario where the baseline losses were also much higher.

Table 9. Modelled field-scale mitigation impacts on sediment loads lost to edge of field

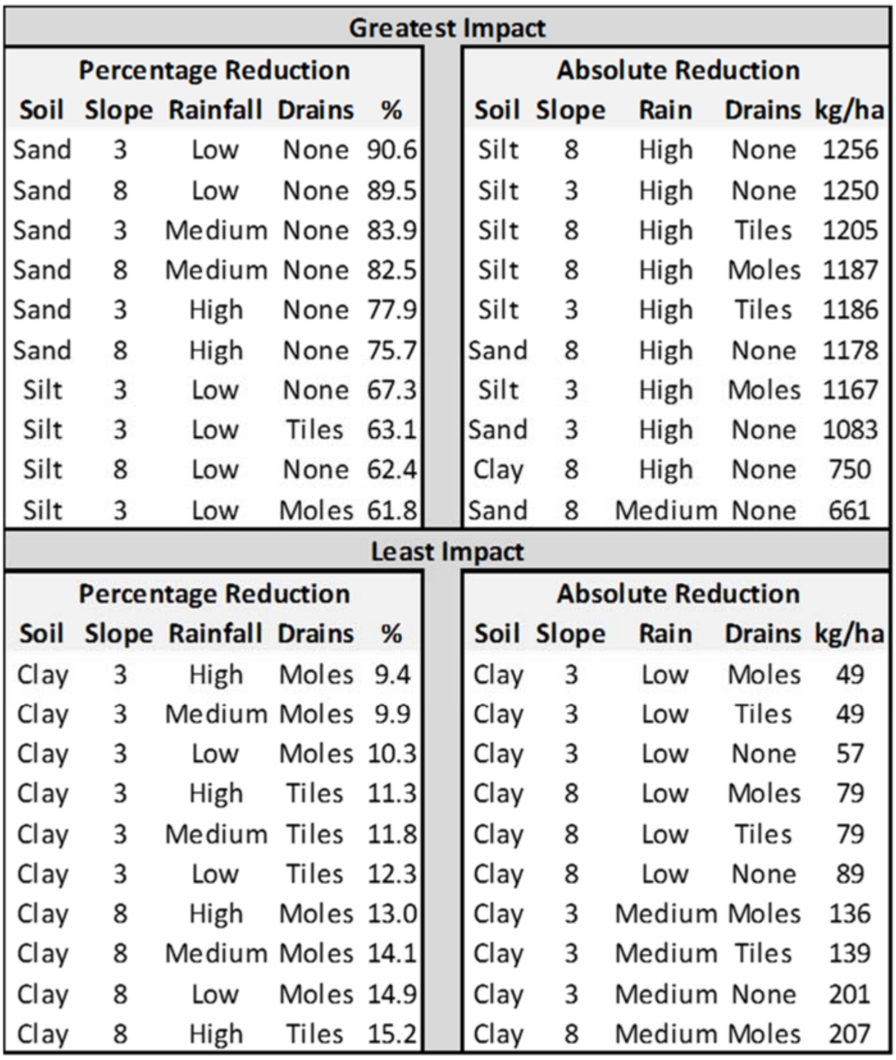
		% Reduction relative to control		**Absolute reduction (kg/ha) relative to control**	
Treatment		**Optimally inflated VF tyre**	**Rotary Harrow**	**Optimally inflated VF tyre**	**Rotary Harrow**
Rainfall	**Low**	57	61	214	228
	Medium	51	55	479	518
	High	45	51	937	1027
Soil Type	**Sand**	83	94	685	795
	Silt	52	61	699	841
	Clay	17	11	245	137
Drain Type	**None**	55	59	576	610
	Tiles	49	54	530	584
	Moles	48	53	524	579
Slope gradient	**3 degrees**	51	56	510	553
	8 degrees	51	55	577	629
All Scenarios		51	56	543	591

Table 10. Largest and smallest impact scenarios: rotary harrow mitigation method

Greatest Impact									
Percentage Reduction					**Absolute Reduction**				
Soil	**Slope**	**Rainfall**	**Drains**	**%**	**Soil**	**Slope**	**Rain**	**Drains**	**kg/ha**
Sand	3	Low	None	97.7	Silt	8	High	None	1680
Sand	8	Low	None	96.1	Silt	8	High	Tiles	1599
Sand	3	Medium	None	95.6	Silt	8	High	Moles	1579
Sand	3	High	None	93.9	Silt	3	High	None	1408
Sand	8	Medium	None	93.0	Sand	8	High	None	1401
Sand	8	High	None	90.1	Silt	3	High	Tiles	1329
Silt	8	Low	None	73.6	Silt	3	High	Moles	1310
Silt	3	Low	None	72.4	Sand	3	High	None	1306
Silt	8	Low	Tiles	69.9	Silt	8	Medium	None	831
Silt	8	Medium	None	68.9	Silt	8	Medium	Tiles	795
Least Impact									
Percentage Reduction					**Absolute Reduction**				
Soil	**Slope**	**Rainfall**	**Drains**	**%**	**Soil**	**Slope**	**Rain**	**Drains**	**kg/ha**
Clay	8	High	Moles	5.9	Clay	3	Low	Moles	44
Clay	8	High	Tiles	6.8	Clay	3	Low	Tiles	46
Clay	3	High	Moles	6.9	Clay	8	Low	Moles	49
Clay	8	Medium	Moles	6.9	Clay	8	Low	Tiles	51
Clay	3	Medium	Moles	7.5	Clay	3	Low	None	58
Clay	8	High	None	7.6	Clay	8	Low	None	60
Clay	3	High	Tiles	8.2	Clay	8	Medium	Moles	102
Clay	8	Medium	Tiles	8.7	Clay	3	Medium	Moles	103
Clay	8	Low	Moles	9.2	Clay	8	Medium	Tiles	111
Clay	3	Low	Moles	9.3	Clay	3	Medium	Tiles	113

Resource constraints and cost-benefit ratios means there is always a need for spatial targeting in the use of mitigating diffuse pollution, i.e. such mitigation methods should be targeted at the highest risk locations (which may vary between years, for example as cropping patterns change). Tables 10 and 11 summarise the combination of soil drainage and slope conditions which resulted in the most and least effective modelled impacts of using the rotary harrow and VF tyre mitigation methods. Such results may help target the use of such mitigation methods at landscape areas where they have the potential to have the greatest beneficial effect in reducing the risk of sediment loss.

Table 11. Largest and smallest impact scenarios: optimally-inflated VF tyre mitigation method



Greatest Impact									
Percentage Reduction					Absolute Reduction				
Soil	Slope	Rainfall	Drains	%	Soil	Slope	Rain	Drains	kg/ha
Sand	3	Low	None	90.6	Silt	8	High	None	1256
Sand	8	Low	None	89.5	Silt	3	High	None	1250
Sand	3	Medium	None	83.9	Silt	8	High	Tiles	1205
Sand	8	Medium	None	82.5	Silt	8	High	Moles	1187
Sand	3	High	None	77.9	Silt	3	High	Tiles	1186
Sand	8	High	None	75.7	Sand	8	High	None	1178
Silt	3	Low	None	67.3	Silt	3	High	Moles	1167
Silt	3	Low	Tiles	63.1	Sand	3	High	None	1083
Silt	8	Low	None	62.4	Clay	8	High	None	750
Silt	3	Low	Moles	61.8	Sand	8	Medium	None	661
Least Impact									
Percentage Reduction					Absolute Reduction				
Soil	Slope	Rainfall	Drains	%	Soil	Slope	Rain	Drains	kg/ha
Clay	3	High	Moles	9.4	Clay	3	Low	Moles	49
Clay	3	Medium	Moles	9.9	Clay	3	Low	Tiles	49
Clay	3	Low	Moles	10.3	Clay	3	Low	None	57
Clay	3	High	Tiles	11.3	Clay	8	Low	Moles	79
Clay	3	Medium	Tiles	11.8	Clay	8	Low	Tiles	79
Clay	3	Low	Tiles	12.3	Clay	8	Low	None	89
Clay	8	High	Moles	13.0	Clay	3	Medium	Moles	136
Clay	8	Medium	Moles	14.1	Clay	3	Medium	Tiles	139
Clay	8	Low	Moles	14.9	Clay	3	Medium	None	201
Clay	8	High	Tiles	15.2	Clay	8	Medium	Moles	207

Results in Tables 10 and 11 are only directly applicable to the crop being modelled i.e. winter wheat. It is clear, however, that the rotary harrow mitigation method is very effective in relative terms on sandy soils and least effective on clay soil with drains. The VF tyres yield slightly higher relative reductions in losses from clay soils with drains when compared to mitigation using the rotary harrow method. As would be expected, in absolute terms, the most effective locations to target the mitigation methods would be on steeper sloping fields in higher rainfall environments.

These modelled relationships between tramline effects with key controlling factors for sediment loss are broadly consistent with the observed patterns seen in the experimental monitoring data. This verification exercise confirms that the modified version of the APT model developed in this project, parameterised with hillslope-scale experimental data, can be used to assess the impacts of the rotary harrow and optimally-inflated VF tyre mitigation methods at a broader catchment scale where spatial variability between field conditions are more marked.

4.3.5. Catchment-scale impacts of mitigation methods

To up-scale impacts of these methods for mitigating losses from tramline wheeling areas to a sub-catchment scale (of interest to those responsible for spatial targeting policy such as national and regional government, government agencies, water companies etc.), three Environment Agency Water Framework Directive water bodies were selected to assess the potential impact of the mitigation methods at catchment scale using the modified APT modelling framework.

These areas were selected based on the following criteria:

- low level of confounding factors contributing to water pollution pressures (i.e. low proportion of urban areas and waste water treatment plants, and high proportion of agricultural land)
- known diffuse pollution pressures related to sediment and phosphorus concentrations in surface waters
- significant proportion of agricultural land planted to winter cereal cropping
- similar slope angles and soil types compared to the experimental field sites
- dominance of surface water pathways for delivering pollutants to water bodies.

The selected water bodies are all headwater sub-catchments in two priority catchments and their locations are shown in Figure 38. Summary information on the three selected sub-catchments is shown in Table 12.

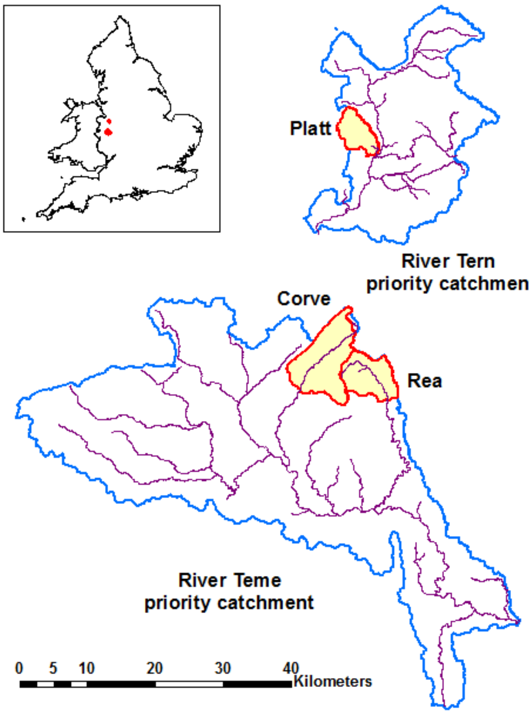


Figure 38. Locations of the three test sub-catchments

Table 12. Physical attributes and winter cereal distribution in exemplar sub-catchments

Short Name **EA Waterbody ID**	**Platt** GB109054050210	**Rea** GB109054044281	**Corve** GB109054049110
Area (km^2)	25.05	42.79	64.36
Average slope angle (°)	1.3	3.7	4.7
Maximum slope angle (°)	27.5	21.3	27.4
Dominant soil series	Bridgnorth (silty loam)	Bromyard (loamy sand)	Munslow (silty loam)
Secondary soil series	Clifton (clay loam)	Middleton (clay loam)	Bromyard (loamy sand)
SAAR[1] (mm)	674	810	784
SPR[2] (%)	26.25	41.54	31.66
BFI[3]	0.656	0.539	0.583
Drainage density[4] (km/km^2)	1.003	2.056	1.695
Winter cereal area (ha)	897.6	1130.7	2152
% of catchment area	35.4	26.2	28.1

[1] Standard (1961–1990) Average Annual Rainfall

[2] Standard Percentage Runoff (reflecting the importance of flashy surface loss pathways compared to slower subsurface drainage pathways as contributors to river flow hydrographs)

[3] Base Flow Index (a hydrological index reflecting the importance of base-flow as a proportion of overall river flow hydrographs)

[4] River length divided by the catchment area, which characterises the density of the surface water drainage network. This density defines the relative proximity of fields to water bodies for water quality impacts.

To estimate baseline pollutant loadings and quantify the mitigation impacts associated with different tramline management options, a large amount of catchment scale input data and assumptions are required to fully parameterise the model. The following key input data layers and assumptions were made:

- Land use based on the ADAS 2010 land use database (derived from Agricultural Census 2010 and mapped to a 1km grid according to the methodology described by Comber *et al.* (2008))
- Daily weather conditions based on daily weather data interpolated using the ADAS Irriguide model (Bailey and Spackman, 1996; Silgram *et al.*, 2007) and UK Met Office weather station data from 1990 to 2010.
- Soil properties based on National Soils Research Institute (NSRI) NatMap 1000 soils database
- Tramline presence: Cereal crops were assumed to have uncropped tramline areas as standard management practice, with tramline width, spacing and establishment dates as used in the previous national APT model applications (Collins *et al.*, 2012; Zhang *et al.*, 2014).
- Field and crop management practices, including fertiliser and manure application rates and timings, sowing / ploughing / harvest dates etc. were based on those used in previous national scale model applications (Collins *et al.*, 2012; Zhang *et al.*, 2014).

Although the APT model generates daily estimates of sediment, dissolved, total phosphorus and nitrate loads, for simplicity only aggregated annual loads of sediment and total phosphorus are presented here.

Table 13 shows that in the Rea and Corve sub-catchments, the optimally-inflated VF tyres (“Optimal”) and rotary harrow (“Harrow”) mitigation measures led to a 7–9% reduction in surface runoff. In contrast, in the Platt sub-catchment, with its heavier soil texture (Table 12), the impact of these mitigation methods on surface runoff was large when expressed on a percentage basis (Table 13). Table 14 shows the modelled average annual sediment loss from fields to adjacent tributaries of the selected sub-catchments under the control (CT tyre), optimal (VF) tyre and harrow tramline management scenarios, with results presented both in terms of absolute losses (in tonnes) and expressed on a mass per unit area basis (kg/ha). The modelled estimates in Tables 13 and 14 predict notable differences in baseline loadings, with the Platt sub-catchment having a much lower rate of sediment loss, which is likely to be due to its lower average annual rainfall, generally shallower slopes and lower drainage density which results in less surface runoff compared to the other two sub-catchments.

Table 13. Percentage reductions in annual surface runoff due to tramline management methods

	Rea		Corve		Platt	
	Optimal VF tyre	Rotary Harrow	Optimal VF	Rotary Harrow	Optimal VF tyre	Rotary Harrow
Oct-Mar	7	8	7	9	40	43
Annual	8	9	7	9	48	52

Table 14. Average annual sediment loss by sub-catchment and tramline management method

	Annual Average Sediment Loss (t)			Annual Average Sediment Loss (kg/ha)		
	Control CT tyre	Optimal VF tyre	Rotary Harrow	Control CT tyre	Optimal VF tyre	Rotary Harrow
Rea	1736	1464	1436	434	366	359
Corve	1978	1623	1596	335	275	271
Platt	95	60	51	42	26	22

Table 15 re-presents the data in Table 14, but expresses the impacts of mitigation measures in reducing sediment loss in absolute terms (tonnes mitigated), on a mass per unit area basis (kg/ha mitigated), and as an overall percentage reduction in sediment loss at sub-catchment scale. It is noticeable that the specific (absolute) loading reduction and percentage reductions at the sub-catchment scale were much smaller than those modelled in the field-scale scenarios. This is to be expected because field scenarios are focused solely on cereal fields, whereas at sub-catchment scale there are inevitably large areas of the landscape which are not suitable for such mitigation options to be applied (e.g. due to different cropping, flat fields, other land uses such as woodland, urban etc.). As these other areas do not benefit from the mitigation method, when averaged over the entire sub-catchment area the overall mitigation impact appears to be much lower.

Table 15 illustrates that the estimated range of reduction in sediment loss due to the VF tyre and rotary harrow mitigation methods were broadly similar (15–68kg/ha reduction from VF tyres; 19–75kg/ha reduction from rotary harrow), and that these benefits equate to reductions in losses of 16–37% (VF tyre) and 17–46% (rotary harrow). The greatest absolute annual reductions of 355–382t sediment lost from land to adjacent water courses due to tramline mitigation treatments were modelled in the Corve sub-catchment. Such results illustrate that the efficacy of tramline management methods at sub-catchment scale is determined by (i) site-specific baseline sediment loadings (reflecting inherent risk of loss from a particular landscape type due to factors such as soil, slope, and proximity to watercourses), (ii) the effectiveness of different mitigation methods, and (iii) land use patterns (i.e. the proportion and location of fields in the landscape where the mitigation method is applicable).

Table 15. Impact of tramline mitigation method on annual reduction in sediment loss for three sub-catchments

	Absolute reduction (t)		Reduction (kg/ha)		Reduction (%)	
	Optimal VF	Harrow	Optimal VF	Harrow	Optimal VF	Harrow
Rea	272	300	68	75	16	17
Corve	355	382	60	65	18	19
Platt	35	44	15	19	37	46

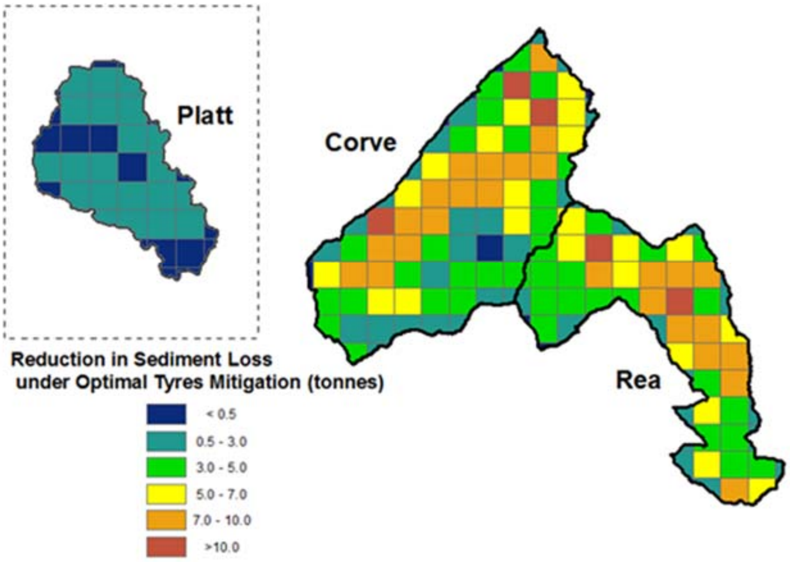


Figure 39. Reductions in catchment-scale sediment loss (t/km^2) under optimal (VF) tyre treatment

The spatial variability in baseline loading and land use are significant. However, within the sub-catchments there are contiguous areas where the mitigation methods prove particularly effective because there is a cluster of fields with moderate or high inherent risk and where the land use renders that tramline mitigation methods are relevant. Figures 39 and 40 show how the spatial patterns of mitigation effectiveness within a sub-catchment can vary (squares represent individual km^2), with patterns driven mainly by spatial variations in land use and crop type, and influenced by soil, slope angle and rainfall (factors shown to be important in the field scenario analysis).

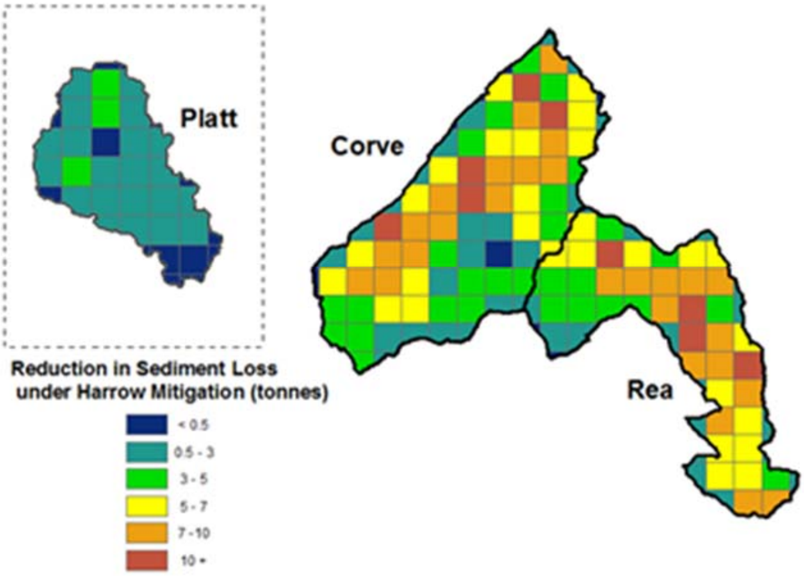


Figure 40. Reductions in catchment-scale sediment loss (t/km^2) under Rotary Harrow treatment

Table 16 shows the effect of tramline mitigation methods on average phosphorus losses and mitigation impacts, and Table 17 shows these data re-expressed in absolute terms. The Platt sub-catchment had the highest percentage reductions associated with tramline mitigation treatments, but the lowest overall phosphorus loading in absolute terms. Table 17 indicates that, as found for sediment (Table 15), the percentage reductions in P loss due to the VF tyre and rotary harrow mitigation methods were broadly similar (7–26% for VF tyre; 8–28% for rotary harrow). The greatest absolute annual reductions of 304–322kg P lost from land to adjacent water courses due to tramline mitigation treatments were modelled in the Corve sub-catchment.

Table 16. Average annual P loss by sub-catchment and tramline management method

	Annual Average Phosphorus Loss (kg)			Annual Average Phosphorus Loss (kg/ha)		
Catchment	Control	Optimal VF	Harrow	Control	Optimal VF	Harrow
Rea	3269	3024	3003	0.82	0.76	0.75
Corve	3535	3231	3213	0.60	0.55	0.54
Platt	400	296	287	0.18	0.13	0.13

Table 17. Impact of tramline mitigation method on annual reduction in P loss for three sub-catchments

	Total Absolute Reduction (kg)		Reduction (kg/ha)		Reduction (%)	
	Optimal VF	Harrow	Optimal VF	Harrow	Optimal VF	Harrow
Rea	244	266	0.06	0.07	7	8
Corve	304	322	0.05	0.05	9	9
Platt	105	113	0.05	0.05	26	28

The spatial distribution of mitigation impacts on total phosphorus losses under optimal tyre and harrow mitigation treatments are shown in Figures 41 and 42, respectively. In general, the spatial patterns of mitigation impacts on sediment and phosphorus are quite similar, which reflects the dominance of particulate P associated with sediment (rather than dissolved P in solution) in the runoff water and the areas targeted as high erosion risk.

The application of the modified APT framework to exemplar water bodies has shown that the efficacy associated with alternative tramline management at sub-catchment scale are moderated by catchment characteristics affecting intrinsic pollutant risk (e.g. soil type, slope angle, slope length, proximity to water body), the land area potentially amenable to particular mitigation methods, hydrological flow pathways and connectivity to points of impact. In practice, implementation of tramline management options to the entire potential catchment area is not a cost-effective or practical option. However, by spatially targeting such land mitigation activities to focus on high risk areas where the greatest impacts may be realised is a pragmatic means of constraining implementation costs whilst maximising the benefits in terms of mitigation on a per hectare basis (and thereby optimising overall cost-benefit effects).

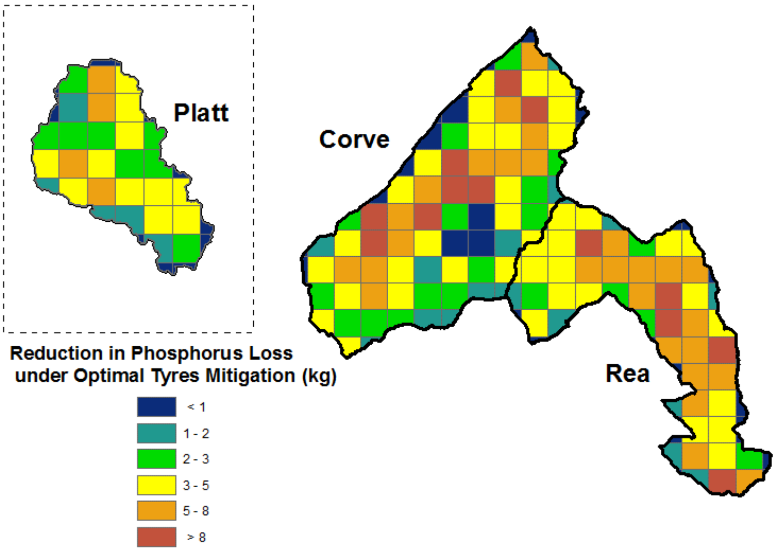


Figure 41. Reduction in Catchment Phosphorus Loss under Optimal VF Tyres treatment (kg/km^2)

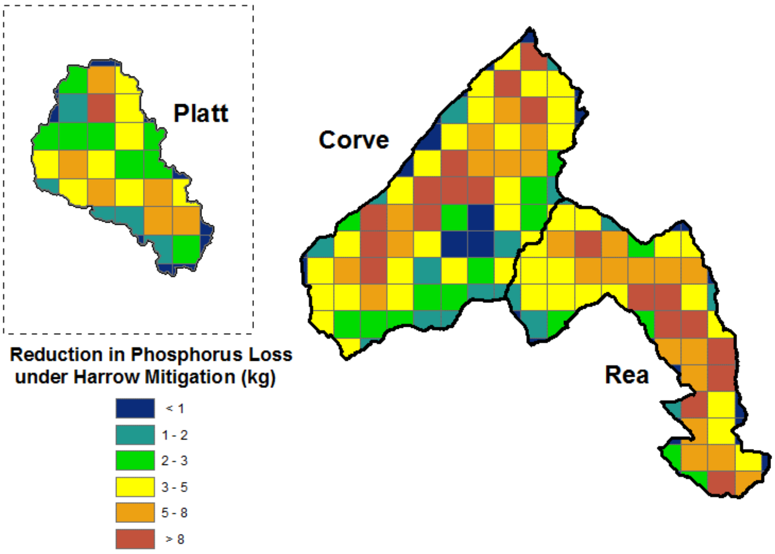


Figure 42. Reduction in Catchment Phosphorus Loss under Rotary Harrow treatment (kg/km^2)

4.3.6. Spatial Targeting of Mitigation Measures

Land management practices which are locally highly-effective at a field-scale, can appear (potentially misleadingly) to be less effective when viewed at larger sub-catchment scale as a consequence of averaging efficacy across the entire catchment area. This effect can be acute even when considering widely-known and highly effective mitigation measures. For example, cover crops can be used over-winter to conserve unused soil mineral nitrogen which would otherwise be lost via leaching during winter. Although evidence shows they can reduce losses from individual fields by 50% or more, at a catchment scale their impacts can often be less than 5% purely because the area of land on which they can be used is limited by crop rotations and soil types (see, for example, Lord *et al.*, 2007). Such results should not be interpreted as meaning such mitigation methods are a waste of time – on the contrary they appear highly effective when correctly spatially-targeted at relevant locations at a sub-catchment scale, and methods such as those assessed in this project have a potentially important role to play contributing to integrated management strategies at field, farm and catchment scale.

Spatial targeting of tramline mitigation at national scale would involve the selection of Environment Agency Water Framework Directive (WFD) water bodies based on the overall ecological status of receiving water bodies, consideration of site-specific pollutant pressures, non-agricultural contributions and field-to-river catchment connectivity. Selection of these test catchments as examples have, to some extent, taken these factors into consideration. Policy-level implementation could use spatial targeting within the recently-introduced Countryside Stewardship scheme in England as a starting point to identify potential candidate areas for the targeted mitigation activities demonstrated in this project.

Tramline mitigation for the reduction of pollutant loading requires capital investment and could affect the farmer’s field management practices (see Economics chapter). As demonstrated in the previous section, although highly effective at a local field and farm scale, the mitigation methods explored in this project have been focused on winter cereal crops only. The VF tyres and rotary harrow unit do have broader potential applicability at a farm scale on other land uses, but those were not assessed as part of this project. Consequently, modelled impacts reported here focus solely on the impact on losses from areas of winter cereals within the broader sub-catchment landscape, and will tend to under-estimate the actual environmental benefit when such techniques are applicable to other land uses at sub-catchment scale.

Within a given catchment, there is therefore a need to select specific areas where most cost effective benefits could be achieved. This has been analysed by examining the effects of implementing mitigation only in the locations where the localised reduction in pollutant loss is above threshold values. While the choice of these threshold values should be based on the magnitude of the pollutant reduction required, a series of speculative values were used here for demonstration purposes only. They are 10,8,6,4,2,1 tonnes per km^2 for sediment and 10,8,6,4,2,1 kg per km^2 for phosphorus, respectively.

Table 18 shows the impacts for sediment and phosphorus mitigation (O is optimal VF tyre and H is rotary harrow treatment). Tabulated rows relate to different target areas in the three sub-catchments: for example, targeting only the areas where a mitigation of 8t/km^2 or more of sediment loss is possible. Data show the percentage of the catchment affected, the percentage of the total sediment or phosphorus mitigation achieved, and the actual mass of mitigation. Such modelled scenarios demonstrate that, even by targeting only a relatively limited proportion of the total catchment area, significant reductions in sediment and phosphorus loss from cereal tramlines to adjacent watercourses can be achieved.

Table 18. Modelled impacts of optimal VF tyre (O) and rotary harrow (H) tramline mitigation treatments on sediment (top) and phosphorus (bottom) losses from cereal fields to water courses in the three sub-catchments. See text for details.

SEDIMENT		**% of Catchment Affected**						**% of Total Sediment Mitigation Achieved**						**Actual Sediment Mitigated (t)**					
Catchment		Rea		Corve		Platt		Rea		Corve		Platt		Rea		Corve		Platt	
Mitigation Method		**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**
Mitigation Target Level (t/km^2)	**10**	3	6	3	6	0	0	8	15	11	17	0	0	22	45	39	65	0	0
	8	13	18	13	17	0	0	30	42	32	41	0	0	83	126	112	157	0	0
	6	26	29	23	26	0	0	56	61	50	56	0	0	153	182	177	212	0	0
	4	44	47	44	45	0	0	80	83	77	79	0	0	216	248	274	302	0	0
	2	61	63	65	65	15	24	93	94	93	94	42	62	254	283	331	357	15	27
	1	69	71	80	80	32	37	97	97	99	99	73	79	264	293	350	377	26	35

TOTAL P		**% of Catchment Affected**						**% of Total Phosphorus Mitigation Achieved**						**Actual Phosphorus Mitigated (t)**					
Catchment		Rea		Corve		Platt		Rea		Corve		Platt		Rea		Corve		Platt	
Mitigation Method		**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**	**O**	**H**
Mitigation Target Level (t/km^2)	**10**	0	4	1	5	0	0		12	4	14	0	0	0	31	13	46	0	0
	8	7	13	9	13	0	2	19	32	25	33	0	8	46	84	76	107	0	8
	6	22	25	20	20	10	10	51	56	48	49	27	28	125	150	145	156	28	30
	4	39	40	38	43	22	27	75	77	70	77	49	57	183	204	213	249	51	61
	2	58	61	64	64	56	56	92	94	93	93	89	89	226	250	283	300	93	94
	1	69	69	75	76	68	68	97	97	98	98	95	95	238	259	296	315	100	101

4.3.7. Summary

The valuable datasets on rainfall, flow, sediment, phosphorus from controlled experiment plots generated during this project and its precursor Defra-funded studies led by ADAS and Lancaster University have together provided a unique opportunity to improve the quantification of tramline effects and the effect of different methods to mitigate losses from tramlines at field and catchment scale using the APT modelling framework. Taking advantage of the site and treatment specific information available, key parameters which represent the effects of tramline and its disruption on flow generation, sediment delivery and phosphorus loading have been derived. With calibrated parameters, simulated flow showed generally good agreement with measured flow at a daily temporal scale. The relationships tend to be less impressive for small rainfall events, likely because the daily time step of the model means we cannot capture short intense sub-daily rainfall events which may produce runoff. These intense rainfall events can be captured in measured 15 minute rainfall data, but when rainfall intensities are averaged across a whole day in a model, this may not be significant enough for the model to predict create runoff. Increasing the temporal resolution of the model may allow better representation of these events, but this would come at the cost of spatial and temporal scale – there is a trade-off between increasing resolution and being able to run the mode nationally for 30 or more years at a time.

Limited climate change scenario runs undertaken in this project suggest that tramline mitigation will still be an effective option in reducing surface runoff volume into the foreseeable future (2050). It is notable that that the mitigation techniques studied in this project are only necessary and appropriate when soils are vulnerable to compaction (i.e. when autumn spraying occurs when soils are at or above their plastic limit) but are not completely saturated. Spraying in a timely fashion when soils are below their plastic limit is not likely to result in substantial soil compaction risk in the first place (as noted at the clay site in one experimental season), while any mitigation method will have limited efficacy when soils are close to saturation (and good farming practice would preclude autumn spraying operations from taking place).

The updated APT modelling framework has been applied at the field scale and at catchment scale in three example areas to assess the mitigation potentials of different methods in different areas. Scaling up from the experimental plot scale to a modelled field of winter wheat, the mitigation methods were still found to have positive impacts, although the level of impact varied greatly depending on soil type, slope and climate.

The modelled impacts at catchment scale were more modest, due to the localised field-scale mitigation effect being “diluted” in calculations of catchment-scale averages by the presence of land uses (non-cereal crops, woodland) and landscape locations (e.g. flat land) which were not considered as part of this project. Inputs of sediment and nutrients from other non-agricultural sources (septic tanks, urban) further compound assessments of impacts over such larger sub-catchment areas. Nonetheless, within larger catchment areas there are still km^2 where the mitigation has very significant impacts, in some places greater than 10 tonnes of sediment loss is mitigated per km^2. It was notable that the heavier textured soils in the Platt catchment resulted in the mitigation methods reducing runoff by the greatest percentage compared to two catchments with lighter textured soils. However, the Platt catchment was characterised by much lower sediment and P losses under current (control) conditions, and therefore the absolute mass (not percentages) of sediment and P reductions due to mitigation measures were modest compared to the other two test catchments. These responses highlight the importance of spatial targeting such mitigation measures both within and between catchments to ensure the most cost-effective catchment-scale outcomes.

4.4. Economics assessment

The economics assessment in this project included:

(i) a study of the carbon footprint associated with different tramline management options,
(ii) a cost-effectiveness assessment,
(iii) a commentary on adoption incentives,
(iv) a discussion on catchments-scale outcomes, and
(v) implications for policy implementation and impacts.

4.4.1. Carbon Footprint

In this project, the ‘carbon footprint’ under consideration is that of the *operational* carbon footprint without the *embedded* carbon emissions involved in machinery manufacture. This approach was taken because of the uncertainty of embedded carbon in any commercial product yet to be finalised and the limited range of tractors available to the project compared with those available to farmers generally, leading to significant uncertainties in the value of any embedded carbon component.

The *operational* carbon footprint is influenced by soil type, soil conditions such as degree of consolidation and degree of wetness and slope. It should be noted that measurements on fuel use, wheelslip and treatment efficacy related to operations were conducted in an uphill direction – where fuel use would be greater than downhill work. In contrast, in an operational context, each direction (uphill and downhill) would have represented half of the sprayer traffic.

Fuel usage imposed using different tramline mitigation treatments was recorded as around 400m per litre of diesel fuel at the time when treatments were imposed. Using a sprayer with a 24m width would mean that approximately one hectare of the field could be sprayed for each litre of fuel consumed (this figure is used in the section below). Whilst it is difficult to compare this with a value for continuous field operation due to the number of variables (tractor power, speed, soil conditions etc.), a plausible rate for a whole field operation might be 1.25 l/ha (B. Basford, pers. comm.) but that ballpark figure includes turning at the field edge (not considered in our project).

Rotary harrow

The additional cost for the use of the rotary harrow would be close to zero since it added very little to the draft of the equipment (around 9 hp) and was used during the sprayer operation (whereas the surface profiler required a separate pass operation after spraying).

Surface profiler / roller

The toolbar with roller and tines was used on its own in an additional pass, using approximately one litre of fuel per 400m, which at a cost of 72p/l equates to £0.72 per hectare treated. The variations due to wheelslip and rolling resistance were small, as were typical variations in recorded fuel use, and so these factors would have a negligible impact on total fuel cost.

Carbon emissions for fuel are published by the Department for Energy and Climate Change in ‘Updated short-term traded carbon values used for UK public policy appraisal’ (DECC, 2012), and shown in Table 19.

Table 19. Updated short-term traded carbon values (DECC, 2012)

	£/tCO$_2$e		
Year	Updated low	Updated central	Updated high
2012	0	5.76	11.98
2013	0	5.98	12.42
2014	0	6.24	12.88
2015	0	6.45	13.36

In terms of greenhouse gas emissions and the carbon footprint, reference was made to ‘Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting’ Annex 1. This provides values for the greenhouses gas emissions from burning various fuels. In this case, the figures for 100% mineral oil, diesel oil, and diesel average biofuel blend have been used (Table 20).

Table 20. GHG emission factors (Defra, 2012a)

kg CO_2e/litre	CO_2 only	CO_2, CH_4 & N_2O		
Diesel	Direct	Direct	Indirect	Grand total
100% mineral diesel	2.6569	2.6769	0.5644	3.2413
Average biofuel blend	2.5636	2.5837	0.5837	3.1674

These data show carbon dioxide alone and all three greenhouse gases (carbon dioxide, methane and nitrous oxide) emitted during direct combustion, together with the indirect emissions associated with the extraction and transport of primary fuels together with the refining, distribution, storage and retail of finished fuels. Assuming 100% mineral diesel, the greenhouse gas emissions would be 2.6769 kg/litre (direct only) and 3.2413 (total) kg/litre of fuel burnt.

Continuing with the assumption that around one litre of fuel is used per hectare, then the carbon footprint for the surface profiler / roller would be 3.2413 kg/ha. Then the carbon footprint cost based on £5.98/tCO_2e in 2013 (Table 19) would be **£0.0194 CO_2e/ha**. Accounting for fuel costs in the range of +/-10% would give a range of £0.0213 CO_2e/ha to £0.0174 CO_2e/ha. This carbon footprint estimate is close to the independent AHDB Cereals & Oilseeds Carbon Calculator figure which suggests the surface profiler / roller footprint is £0.0160 CO_2e per hectare for feed wheat on heavy land with a yield of 9t/ha.

4.4.2. Cost-effectiveness assessment

This section provides efficiency estimates for tramline disruption on commercial farms using reported costs related to the tramline management treatments, and considers how the cost-effectiveness of mitigation methods evaluated in this project compare with those previously reported, almost ten years ago now and based on more limited experimental data, in Defra's Diffuse Pollution Inventory Manual (Cuttle *et al.*, 2006).

The following calculations are based on experimental results together with a wide range of trade information on tyre specification and prices, machinery specifications and manufacturing costs, which have varied during the life of the project (and may do further subject to final design, manufacturing costs, raw material costs and competitive factors). All prices are for supplying brand new equipment, which avoids difficulties associated with the costs of upgrading existing sprayer units or accounting for the value of part-used tyres being traded-in for VF tyre units.

Challenges in assessing economic implications

Both rotary harrow and surface profiler techniques were designed as part of this project, which means that some costs are based on best estimates and these in turn are influenced by the cost of raw materials, energy and other inputs. These costs are further modified by commercial decisions on price. These techniques are most likely to be used on the part of a farm where there is a higher risk of runoff due to intrinsic risk factors (such as soil type or slope) and the use of tramlines in combinable crops. On higher risk land, the tramline mitigation operation would take place post-emergence of the crop in the late autumn associated with the autumn spraying operation.

In addition to the question of the area of the farm that the technique applies to, a further issue is that costs are generally expressed as a unit, for example as £/ha. Such a figure is usually available for existing machinery from standard reference material and contractor rates, but in this case, the lack of data means that an estimate needs to made by comparison with similar operations or to divide the annual cost by an average-sized farm where there are many views on what that size may be, depending on the machine in question. In addition to deciding on the average area of a farm likely to purchase tramline disruption equipment, the area treated in any given year may vary due to weather conditions and which crop is on the higher risk land as well as the degree to which the crop develops before growth slows.

With regard to tyres, the project compared conventional radial tyres with the VF (Very Flexible) tyre type. VF tyres are currently produced by a limited number of companies including Michelin and Bridgestone although others offer an IF (Improved Flexion) option. However, non-VF tyres do not have the same performance characteristics for road and field work, and focus on low inflation pressure to reduce the risk of soil compaction in the field. VF tyres can operate at low pressure on both field and road, whereas other tyre makes often require farmers to change inflation pressures manually between road and field (which may often not happen). Associated price data are subject to market conditions and competition, and it is recognised that suggested prices are very general and individual purchasers may obtain different prices depending on their relationship with the dealer.

With regard to the area of application, unlike the tramline disruption techniques, tyres are likely to be used across the whole farm for a wide range of operations, including primary cultivations. In this case, differences between VF and other specifications could come into play in terms of differences in fuel use and wheelslip. In the field experiments, although there were statistically significant differences detected in wheelslip between the CT and VF tyres, in absolute terms these differences lay within the normal reported operating range and were typically relatively small (<3%). Fuel use was not found to be significantly different between treatments. Consequently, both wheelslip and fuel use are not considered as mediating factors in subsequent discussions regarding costs. A potentially significant further point is the potential reduction in sub-soiling costs resulting from the use of VF tyres, which may also influence timeliness of operations and overall work rates across the whole farm as a consequence.

In terms of presentation, calculations of the costs of the various pieces of equipment can be carried out on a per farm, per hectare or per hour basis. All three approaches have their own advantages and disadvantages, and emphasise different issues depending on the context. For example the objective may be to find the most effective operating cost to the farmer or to consider the level of uptake and implementation where capital costs may be a stronger influence on adoption than overall costs per hectare.

Machinery

For different tramline mitigation methods, estimated costs are in addition to the current farm system. The costs of these tramline mitigation techniques are based on small production runs, and any potential 'economies of scale' associated with larger production runs are ignored in the assessments reported here, given likely differences in sprayer specifications and the individual parts of the toolbar with roller and tines, and material (steel) costs.

Because of the limited area of the farm where either techniques may be used, annual costs are difficult to translate into per hectare costs, but to allow comparison between methods, it has been assumed that 20% of the land on a given farm may benefit from tramline disruption. As an illustration, the costs per hectare of the machines is shown below for a typical 200ha farm and a 300ha farm. Clearly, a larger farm would reduce the cost on both a per hectare and a per hour basis. On farms with a greater area of higher risk land, for example, more fields with slopes of over 3^{o} and or higher risk soils, costs would again be lower on a per hectare or per hour basis.

Rotary harrow unit

Manufacturing costs were supplied by Great Plains Simba, Chafer and Househam, and figures are based on 50 to 100 units in a production run (Table 21). Capital costs would not be expected to fall much with increased production due to the large range of sprayer models, each with its own requirements for fitting rather than a universal design and the cost of steel. In addition to steel components, hydraulic hoses and connections would be required. The Great Plains Simba machine was fitted to a Chafer trailed sprayer and the Househam unit was fitted to a self-propelled machine. Costs shown are amortised over 10 years at 7% interest.

Table 21. Annual cost of rotary harrow (amortised capital costs *)

	Chafer		Househam	
		Annual cost *		Annual cost *
Capital cost (£)	4,615	655	3,640	517
Repairs (£)	5.00%	231	5.00%	182
Fitting (£)		30		30
Annual total (£)		916		729
Annual cost (£/ha) (20% of 200ha farm)	Area used 40 ha	22.90		18.22
Annual cost (£/ha) (20% of 300ha farm)	Area used 60 ha	15.27		12.15

The fitting cost would be in two parts. There would be an initial cost of mechanical and hydraulic fittings to the sprayer to attach the rotary harrow and frame, classed as part of the manufacturing process. For subsequent on-farm use, a fitting would be expected to be carried out by farm staff and to take half an hour, based on observations and discussions with Simba Great Plains and Wright Resolutions. A charge of £30 was included to cover this cost per fitting where, once fitted, the rotary harrow would typically remain on continuously or would be removed once each year. Repair costs for the rotary harrow were assumed at 5% of original capital cost. The additional operational cost of using the rotary harrow was assumed to be zero, since it was attached to the sprayer and field measurements indicated negligible additional draft requirements and consequently no notable impact on fuel use.

Surface profiler (comprising novel roller and tines)

Manufacturing costs were supplied by Charles Creyke (Table 22). Capital costs may fall if sufficient volumes were to allow economies of scale to be achieved, and an allowance of 25% was made for this. Fitting costs would simply be hitching the tool bar with roller and tines to the three point linkage, for which a time of 15 minutes was allowed at a cost of £15 per fitting. Repair costs for the toolbar with roller and tines were assumed at 7.5% of the original capital cost, which is higher than the rotary harrow due to the likely wear on the leading tines on the toolbar.

Table 22. Annual cost of tool bar with roller and tines (amortised capital costs*)

		Annual cost * (£)
Capital cost (£)	4,125	586
Repairs	7.5%	309
Fitting		15
Annual total		910
Additional operational cost	£/ha	15
Annual cost on 200ha farm £/ha	Area used 40ha	38.98
Annual cost on 300ha farm £/ha	Area used 60ha	30.99

Use of the surface profiler toolbar with roller and tines required an additional field operation and the cost for this was assumed to be £15/ha based on values from Nix (2015). The cost of fitting the toolbar was less than the rotary harrow because it is on a three point linkage. With the cost of the additional field operation, the total costs were £38.98/ha pa and £30.99/ha pa on the two farm sizes, respectively, for a single use of the machine in the autumn.

Tyres

For the tyre comparisons, the whole farm area was used, since such tyres would be used across the farm and not limited to the 20% of the land where the tramline disruption techniques were used. It was notable that the VF design allows a greater load to be carried at a lower inflation pressure than conventional tyres and for the vehicle to travel at road speed without increasing inflation pressure above that used in the field. Many farmers have to use roads to access some of their fields and others, particularly contractors, travel significant distances prior to entering the field. For conventional tyres, a higher tyre pressure is required for the road due to the higher speed of travel compared with operations on the land, but a lower inflation pressure is required in the field to avoid compacting the soil. For conventional tyres, typical road inflation pressures will be around 1.7 bar to 2 bar, whereas field inflation rates substantially below this would be desirable to reduce risk of soil compaction and rutting.

This ability to use the lower inflation pressure in the field and on the road is an important design feature, since farmers may otherwise compromise on an inflation pressure between the different road and field pressures to save time deflating and re-inflating their tyres. Such a compromise results in a greater degree of compaction than if the correct inflation pressure were used in the field, and increased tyre wear on the road due to greater heating from the tyre being under-inflated.

The costs of the Michelin tyres were compared with the closest low ground pressure comparison tyres from Goodyear, Trelleborg and Firestone with prices obtained from national or European technical specialists or nominated supplier in each respective company (Table 23).

Table 23. Tyre cost comparison (VF = Very Flexible; LGP = Low Ground Pressure)

	Tyre cost (£)				
	Michelin conventional	Michelin VF	Goodyear LGP	Trelleborg LGP	Firestone LGP
Front axle	1,650	2,226	1,600	1,400	1,851
Rear axle	3,400	4,096	3,200	2,600	3,487
Sprayer	3,400	4,096	3,200	2,600	3.487
Overall total	8,450	10,418	8,000	6,600	8,824

Costs were obtained for a full set of tyres for the tractor and sprayer and it was assumed that the sprayer uses the same tyre as the rear tractor tyre. This may vary in practice, but trade advice was that costs would vary little if this were the case. For simplicity and comparability, tyre costs were considered for new tyres in all cases, with no account taken of any trade-in against conventional tyres. The costs derived in Table 24 illustrate commercial prices to farmers for a set of six tyres (four on the tractor and two on the trailed sprayer), including rims and fitting.

Table 24. Capital costs (with no account for differences in reported tyre life)

		Cost
Capital cost basis	Conventional tyres (£)	8,450
	VF tyres (£)	10,418
	Difference (£)	1,968
	200ha farm (£/ha)	9.84
	300ha farm (£/ha)	6.56
Annualised capital cost basis	Amortised values	
	Difference	480
	200ha farm (£/ha)	2.40
	300ha farm (£/ha)	1.60

Data in Table 25 assumes the usual method of determining the cost of tyres, which is to amortise them (i.e. write them off) over a period of 5 years at an annual rate of 7% interest. The additional purchase cost of a full set of VF tyres over conventional tyres is therefore £1,968. Without taking into account differences on tyre life, when written off over a period of five years this results in a greater cost for VF tyres of £480 per annum. Considering an example 200ha farm, this cost would be spread over the whole farm, giving a capital cost of £9.85/ha or £2.40/ha when annualised. On a 300ha farm, the equivalent figure is £6.56/ha in capital cost or £1.60/ha annualised.

Table 25. Tyre cost: conventional tyres adjusted pro rata to equalise longer life of VF tyres

		Cost
Capital cost basis	Conventional tyres (£)	12,675
	VF tyres (£)	10,418
	Difference (£)	-2,257
	Difference (£/ha, 200ha farm)	-11.29
	Difference (£/ha, 300ha farm)	-7.52
Annualised capital cost basis	Amortised difference (£/year)	-551
	Amortised difference (£/ha/yr, 200ha farm)	-2.75
	Amortised difference (£/ha/yr, 300ha farm)	**-1.84**

N.B. This option adds 50% to the cost of conventional tyres (using 6,000hrs conventional vs 9,000hrs VF)

Conventional tyres can be expected to last around 6,000hrs, but manufacturers report that VF tyres can be expected to last up to 9,000hrs, which means that the costing above is unfairly biased in favour of conventional tyres. By increasing the cost of conventional tyres on a *pro rata* basis to equal the lifetime cost of the VF tyres, the comparison between the two tyre types becomes a more reasonable one, and the consequent net savings in costs for VF tyres is shown in Table 25. An alternative simpler approach based on the cost/hour shows that the difference between tyre types would result in a saving of around 25p per hour in favour of the VF tyres (Table 26).

Table 26. Tyre costs based on lifetime in hours

	Tyre life (hours)	Capital cost (£)	Cost (£/hour)
Conventional tyres	6000	8450	1.41
VF tyres	9000	10418	1.16
Difference	***3000***	***1968***	***-0.25***

4.4.3. Adoption incentives

Incentives for farmers to implement certain practices are normally given in terms of an assessment of income foregone due to market failure. The value of income foregone is based on the assumption that whichever practice is undertaken, it will be a divergence from normal commercial practice that is likely to result in increased costs or reduced productivity or both. Environmental Stewardship (Countryside Stewardship in England from April 2015) is an example of a policy operating along these lines, where farmers can pick from a range of options that provide a given number of points based on the extent of income foregone for each option. The points go towards their target number in order for them to claim support payments.

However, tramline management and associated pollution risk mitigation do not fit well into this conceptual ‘profit foregone’ framework, as the area being managed is not drilled with crop, so there is no direct profit to forego. However, there are other clear direct benefits (as shown in this study), which include reduced soil compaction, promoting good soil structure, drainage and improved crop rooting; retention of valuable nutrients on the field; and avoidance of fines by environmental agencies for sediment erosion reaching roads and water courses. In addition, a further difficulty is that any payment per length of tramline treated, or related to the proportion of the field represented by tramlines, would vary greatly due to the difference in tramline widths (which could range from 12-36m) from farm to farm depending on the equipment used.

Furthermore, on a capital basis, although it would be relatively straightforward to demonstrate that a machine was on a farm, it may be less easy to demonstrate it had been used in a given field at the time of autumn spraying. Fortunately, the rotary harrow is intended to be fitted to a sprayer at the beginning of the season and to be left attached for use when required, and as it does not require a separate field operation it would be entirely possible for the purchase and use of this equipment to be considered within a capital cost basis.

In the case of tramline disruption, this practice is likely to retain nutrients and sediment on the field that would otherwise be lost in erosion and runoff. The overall costs of implementing such methods would comprise:

- Capital cost of tyres
- Capital cost of tramline disruption technique
- Changes to fuel costs
- Changes to repair costs
- Changes to working time

These changes may lead to additional costs or financial savings (negative costs), for example in the direct costs of tyres over a period of time, or indirect costs such as savings in fertiliser costs due to reduced nutrient losses. If manufacturers' results are correct across a wide range of soil types and conditions, then savings in tyre costs, fuel use and sub-soiling may be significant.

Hence in the case of tramline disruption techniques, the outcome may be a change to land management costs rather than income foregone. This may manifest itself over a number of years in the case of the capital cost of tramline disruption machinery and tyres rather than, for example, a reduction in fertiliser costs in any given year. The incentive to adopt these practices therefore appears to be largely a market incentive, although to achieve the benefits of tramline disruption requires the commitment of capital investment which will be spread over a number of years.

The magnitude of the benefits provided will also depend on the individual season, as follows:

- Costs will be the same over a range of seasons regardless of rainfall
- The benefit (i.e. reduction in nutrient and sediment losses) will be greater in autumns with moist soil conditions – very dry autumns would not have notable runoff risk, whereas very wet autumns would mean soils conditions may be unsuitable to allow autumn spraying.
- The collateral benefits suggested by Michelin and Bridgestone (pers. comm. Barry Coleman) – reduced fuel use, tyre costs and reduced sub-soiling costs – will be seen across the whole farm each year and will be greater in wet years.

The lack of a specific direct annual short-term benefit for a specific medium-term cost may prove to be a barrier to adoption for some farmers. Therefore, there may be a case for supporting the purchase of the equipment to encourage uptake in area of high risk of soil erosion in order to encourage a wider uptake without support as the benefits of tramline disruption become more widely appreciated. The next consideration would be settling on a rate of support, which would need to be high enough to encourage a farmer to buy the machine and/or VF tyres, but not so high that value for public money was deemed to be poor. This may be particularly appropriate in areas of high risk crops on high risk soils (e.g. potatoes on sloping fields with light sandy and silty soils).

Ensuring that farmers actually use the machine once purchased may be another barrier. In policy terms, a pragmatic approach would be to see such environmentally friendly activities as a marketing opportunity for the food industry, perhaps as part of a farm assurance scheme.

4.4.4. Catchment scale outcomes

This activity up-scales the public benefits of tramline disruption to a sub-catchment level, based on the Platt, Rea and Corve sub-catchments considered in the modelling work (Chapter 4.3).

The cost/benefit of tramline disruption in each of these three catchment areas is the product of cost-effectiveness per hectare of treatment multiplied by the size of the catchment (Table 27). For simplicity, an average figure was used to allow for the two brands of rotary harrow and the two hypothetical farm implementation sizes. For the tyres, the difference between the two approaches on a capital cost basis was close to zero. Since the lifetime of each type of tyre was not tested in this project, this was not taken into account in the figures presented in Table 27.

Table 27. Catchment-scale costs/benefits of rotary harrow and VF tyre tramline mitigation methods

	Platt	**Rea**	**Corve**
Catchment area km^2	25.05	42.79	64.36
Average slope	1.3°	3.7°	4.7°
Dominant Soil Type	Silty loam	Loamy sand	Silty loam
Area treated @ 20% of catchment (ha)	501	855	1,287
Rotary harrow			
Average cost (£/ha)	17.14	17.14	17.14
Cost of treatment per catchment (£)	8587	14668	22062
Benefit of reduction in P & sediment loss			
P (£/ha)	1.28	1.80	1.28
Sediment (£/ha)	5.80	22.91	19.85
Total benefit (£/ha)	7.09	24.71	21.14
Net benefit (£/catchment)	**4209**	**22128**	**12420**
VF tyres			
Saving (£/ha)	0.03	0.03	0.03
Saving of treatment per catchment (£)	626	1,070	1,609
Benefit of reduction in P & sediment loss			
P (£/ha)	1.28	1.54	1.28
Sediment (£/ha)	4.58	20.77	18.33
Total benefit (£/ha)	5.87	22.31	19.61
Net benefit (£/catchment)	**2955**	**19121**	**25284**

Total benefits in pollutant reduction per hectare were similar from the use of both the harrow and VF tyres, although the costs of the treatments were very different from a mean of £17.14/ha for the harrow to a saving of £0.03/ha for the tyres. This small saving is, however, a somewhat artificial figure, since whilst it is assumed here that the harrow will only be used on 20% of the catchment area, the tyres are unlikely to be changed between operations and will be used over the whole farm. However, to make 'fair' comparison, the savings have been applied to only the 20% likely to benefit from the harrow. Note the £0.25/h saving for the VF tyres is per hour, and the rate used above is per hectare assuming an average work rate of 12ha/h.

4.4.5. Policy impacts

This section explores the potential policy impacts of incorporating tramline disruption into existing policy instruments, such as Defra's new Countryside Stewardship scheme. The above sections highlight three major issues for policy formulation:

(i) Policy is normally based on income foregone and in this instance there is no evidence that farm incomes would be reduced by using tramline disruption machinery and VF tyres. It is more likely that farmers will enhance their income, although there would be the initial capital outlay for both tramline disruption techniques and the VF tyres.

(ii) There may be an issue with the capital nature of the investment required to carry out tramline disruption. Farmers would need to commit a significant amount of capital to implement tramline disruption methods. Similar support has been given through the Catchment Sensitive Farming Capital Grant Scheme for a range of interventions aimed at reducing diffuse pollution.

(iii) The magnitude of losses of phosphate and sediment avoided by tramline disruption is variable subject to the soil type, slope and volume and intensity of rainfall, and is therefore variable from close to zero on low risk locations up to environmentally significant figures.

These factors add up to a significant challenge as:

- There is no apparent market failure to address
- A proportion of farmers may consider the capital outlay unjustified on its own for potentially zero or uncertain returns.

On the one hand, without a market failure, there is no justification for support whilst on the other, farmers may be reluctant to invest with such an uncertain return. However, if this remains the case, it does nothing to address the fact that the great majority of losses from arable land are due to losses as runoff down tramline wheelings. However, as the rotary harrow has demonstrated it is highly effective but requires capital investment, and (unlike the VF tyres) is specifically focused on mitigating the risk of compaction and runoff, erosion and diffuse pollution from tramlines, Defra have recently included a partial capital grant in a spatially targeted element of the Higher Tier section of the new Countryside Stewardship (CS) scheme which launched in spring 2015. This will provide a capital sum to support the cost of tramline disruption techniques. That decision was directly facilitated by the outputs from this project, which were summarised in a policy document to Natural England in 2013–14, at their request, for consideration when the details of the new CS scheme were being formulated.

In the document 'Estimating Damage Costs for Major English Water Pollutants' (Defra, 2012b), the damage from agricultural diffuse pollution is assessed in terms of the following categories:

- Drinking water quality (surface and groundwater)
- Improved river water quality (amenity)
- Improved fishing
- Freshwater and marine eutrophication
- Bathing water quality
- Ecosystems, natural habitat impacts – rivers and wetlands

The cost of this pollution is given in Table 28.

Table 28. Damage cost for major English water pollutants (Defra, 2012b)

	£/tonne			
	Minimum	**Average**	Maximum	Std. Dev
Nitrate	121.03	**169.87**	221.11	20.05
Phosphorus	20,657.89	**25,691.14**	30,479.32	2,055.77
Sediment	234.63	**305.45**	376.64	31.18

The values of reductions in losses of both total phosphorus and suspended sediment are shown in Table 27 assuming applications to 20% of each of the three modelled catchments. In areas where the losses of sediment and P are relatively high, the cost of the tramline disruption machinery is more likely to be overcome by the benefit associated with reductions in these P and sediment losses. Using these estimated farm-scale figures as a guide to proportions, at a catchment scale, reductions in losses of 0.06 kg/ha of P and 32 kg/ha of sediment would be sufficient to achieve break-even costs in the case of the rotary harrow and 0.07 kg/ha of P and 66 kg/ha of sediment for the surface profiler-tine-roller unit.

4.4.6. Summary

In terms of additional costs associated with the tramline disruption techniques, there were capital costs for purchasing the machines and the additional cost associated with adaptations to the sprayer during its manufacture. The average net cost of the rotary harrow was £17/ha compared with £35 for the surface profiler unit with roller and tines. These costs would be lower on larger farms and those with larger areas of land at risk. In terms of operational costs, for carrying out the work, there was no additional cost for the rotary harrow (since it was mounted on the sprayer and there was no evidence of any impact on fuel use), but there was a cost of £15/ha for the surface profiler with roller and tines (since it required an additional field operation).

With regard to tyres, there were two aspects of cost: capital costs associated with purchasing the VF tyres, and any differences in operational costs as a result of their use. In terms of capital, the VF tyres were significantly more expensive than conventional tyres, but this calculation does not account for manufacturer’s data which indicates a significantly longer working life compared with conventional tyres. On a simple substitution basis, there would be an increase in annual costs when the capital cost is amortised of £2.40/ha on the example 200 hectare farm. However, by taking into account the manufacturer’s reported longer life of the VF tyres, then a net saving of £2.75/ha could be achieved. A third alternative would be if the cost was calculated per hour of use, in which case the same data suggests an overall net saving in favour of the VF tyres of £0.25/hour.

With regard to operational costs, there were no consistent significant differences in fuel use or rolling resistance between the control treatment and the two tramline disruption machines or tyres, and so there were no additional costs associated with these aspects of the field operations. The major difference between the two tramline disruption machines was therefore the additional pass required for the tool bar with roller and tines. Any co-benefits associated with reduced fuel use or sub-soiling operations with the VF tyres were not examined within this project.

5. Discussion

5.1. Experimental methods

A combination of traditional methods (e.g. topsoil bulk density, pin meter) and emerging novel methods (e.g. photogrammetry, electrical resistivity, DTMs) were used in this project to characterise the soil physical effects associated with alternative approaches to the sustainable management of tramline wheelings in winter cereals. Application of non-invasive techniques to the assessment of soil compaction within arable tramlines found that novel photogrammetric methods were capable of sufficient resolution to generate accurate digital terrain models of the soil surface beyond the capability of the traditional pin-meter surface profiling; while the use of novel near-surface electrical resistivity imagery revealed soil hydrological properties altered by heavy farm traffic which would have involved extensive and destructive conventional soil surveying (Shanahan, 2013). These assessments were supplemented by operational measurements (e.g. wheelslip, fuel use) to provide practical information which complemented field and laboratory determinations of soil physical properties.

In theory, laboratory-based soil bins have the potential to provide more controlled conditions (i.e. soil particle grain and aggregate size, moisture content) which may assist in measuring the distribution of stress under tyres and tracks (Ansorge and Godwin, 2007). However, these comprise soil which has been removed from the field, sieved and standardised and then “re-packed” in very small volumes (typically a few m^3) at known bulk densities in an attempt to represent undisturbed *in situ* soil (minus macropores, stones, earthworm channels, soil aggregates etc.). Furthermore, such controlled indoor experiments typically rely on rainfall simulators, which often have raindrop sizes, velocities, and intensities which are unrealistic of natural rainfall conditions in the UK – for example, Armstrong *et al.* (2011) reported nutrient losses from controlled indoor runoff experiments using simulated rainfall intensities of 47mm/h when typical UK rainfall would be considered <10mm/h).

Consequently, in spite of their real-world variability, field trials can produce a more realistic basis for measurements (provided sufficient replication), as in laboratories it is very difficult to mimic realistically the effect on soil of farm traffic involving moving tyres with different designs and tread patterns, axle weights, speeds and operational configurations (i.e. tractors, sprayers, mitigation equipment) with contrasting draft requirements. This assessment is especially pertinent when attempting to mimic land with contrasting slope angles subject to operational farm conditions. Such reasoning vindicates the use of hillslope-scale segments (300–900m^2) in this project, from which it was possible to derive large-area assessments of the impacts of tramline management options on soil physical variables, surface runoff, and associated losses of suspended sediment and phosphorus, free from the constraints (e.g. unrepresentative small areas, edge effects, short slope lengths) inherent in studies reported by researchers using small plots (typically ≤100m^2) (e.g. Withers *et al.*, 2006).

Assessments of related hydrological impacts on surface runoff were therefore explored in this project at hillslope scale using a methodology originally developed by ADAS in Defra project PE0206 (Silgram *et al.*, 2006, 2007; Deasy *et al.,* 2009), but which was substantially developed and refined in this project to accommodate much longer, hillslope-scale areas of up to 900m^2 which traverse tramline wheelings generating runoff from tramlines at up to 40l/min. This novel methodology involved a flow-proportional sample splitter capable of sampling 12.5%–50.0% of the runoff from a hillslope area, and was an extension of some of the concepts used by Bonilla *et al.* (2006), who described a passive sampling system to measure run-off, sediment and chemical losses from agricultural areas ranging from 400–5000m^2 in southern USA. This concept was adopted after an alternative approach using a Coshocton wheel connected to a flume (e.g. Parker & Busch, 2013) was discounted, as this was deemed too large and semi-permanent a structure to allow for 16 replicate units to be installed in commercial field situations.

5.2. Results synthesis

Soil compaction is one of the major problems facing modern agriculture as farm vehicle axle weights have increased inexorably over the past five decades (Hamza & Anderson, 2005). It is widely accepted that soil compaction can significantly reduce farm yields and profits by restricting plant root growth, soil aeration, porosity, drainage, soil organic carbon and nitrogen levels, and biological activity at both macro and micro scales (e.g. Schjønning *et al.*, 2009; Hoorman *et al.*, 2011). Attempts to develop practical, cost-effective means for minimising the risk of soil compaction associated with farm traffic – such as the methods developed and evaluated in this project – are therefore highly relevant to the drive for more sustainable farm practices and the need for improved environmental protection. These objectives are consistent with the need to achieve and maintain cross-compliance, specifically GAEC 5 on minimising the risk of soil erosion (Defra, 2015). This project's results have demonstrated the negative impact of farm traffic on a variety of soil physical properties, and the same principles associated with avoiding and/or mitigating soil compaction underpin broader approaches to land management such as Controlled Traffic Farming (e.g. Chamen, 2011; Gasso *et al.*, 2013).

Even though tramline wheelings may only represent around 5% of a typical cereal field (Regan *et al.,* 2012), there is now strong evidence that the compacted soil in this area can serve as the major pathway for loss of surface runoff, soil sediment, nutrients such as nitrogen and phosphorus (e.g.

Withers *et al.*, 2006), and surface-applied products including herbicide and pesticide sprays (Klöppel *et al.*, 1997; Evans, 2009) and veterinary antibiotics contained in livestock slurry (Kay *et al.*, 2005). If such losses from land reach water courses, the sediment can smother river beds, adversely affecting fish spawning (e.g. Armstrong *et al.*, 2003), while the nutrient enrichment can promote eutrophic status resulting in toxic algal blooms, reduce dissolved oxygen levels, and breach water quality standards laid down in the EU Water Framework Directive. Loads of P of only 1kg/ha lost from land to water courses would be regarded as very high, because even though such amounts are agronomically insignificant, they would be highly significant ecologically with EU water quality standards for P in rivers of the order of around 0.1mg/l.

This project has shown that a variety of practical methods are available to promote sustainable management of tramlines in winter cereals, with no effect on overall crop yield, but with the potential to reduce the risk of soil compaction, surface runoff, and associated losses of sediment and P from land towards vulnerable water bodies. In particular, reported results have highlighted the reduced soil compaction associated with correctly-inflated VF tyres, which were characterised by lower mean tyre imprint depth, area and volume of compacted soil compared to the control CT tyres (Figure 13). The corollary to this impact is the evidence showing correspondingly lower topsoil bulk density associated with the VF tyres compared to the control CT tyres (Figure 14). The combined effect of these complementary soil physical responses logically means that the soil under VF tyres will therefore typically have more air-filled pore space, higher porosity (i.e. water holding capacity), improved surface infiltration rate and hydraulic conductivity (i.e. drainage), and hence be less prone to surface ponding of incident water (which could generate runoff), when compared to the control CT tyre. This is consistent with evidence that operating vehicles with lower ground pressure can significantly decrease soil compaction (e.g. Ridge, 2002).

Hillslope-scale evaluations of the effect of alternative mitigation methods for managing tramlines investigated the concept of drilling tramlines in an attempt to stabilise topsoil and provide a physical vegetative barrier to promote interception storage and drainage of water, and thereby hinder the occurrence of surface runoff. This concept has variations including “fuzzy” tramlines (intermittently sown, creating a “dashed” effect), “sown” tramlines (as investigated in this study) and “furry” tramlines (using chaff diverted during the previous harvest), all of which are used commercially in areas such as Western Australia (Webb *et al.*, 2004). However, results reported in Chapter 4.2 consistently showed that this approach was not successful, as drilling tramlines had no significant effect ($p>0.05$) on surface runoff or on associated loads of sediment and P lost down hillslopes. This was an interesting, perhaps counterintuitive finding, which reflects the very limited vegetation cover provided by emerging cereals during the cold and wet winter months in the UK, coupled with the fact that in a drilled tramline scenario the autumn spraying operations will still be at risk of causing soil compaction at this time. From these results, we can conclude that under UK conditions, it is the soil compaction caused by the autumn sprayer traffic, and not the lack of vegetation cover over-winter, which is the primary cause of tramlines being a major rapid transmission pathway for surface runoff from winter cereal fields on moderate slopes.

In contrast, the VF tyres proved highly effective in significantly reducing ($p<0.05$) these same variables, and this effect was highly consistent across all four sites and four years (Chapter 4.2), with the exception of a very dry site-year when soil compaction was not a risk (Loddington, winter 2010-11). Even when exceptionally high rainfall and wet soil conditions occurred after autumn spraying had taken place (Hattons, winter 2012–13), the VF tyres still proved effective in reducing surface runoff, indicating their versatility across a wide range of demanding weather and soil conditions. The use of VF tyres resulted in reductions in surface runoff of up to 75% compared to the control CT tyres, and it is this runoff which is the vector driving (or constraining) losses of sediment, P and other potential pollutants (e.g. nitrogen, surface applied plant-protection products).

The novel rotary harrow unit, which was specifically designed and prototyped during this project, used the concept of a small self-propelled unit, hydraulically linked to the tractor cab, with several small offset spikes to create shallow (5cm deep) indentations in the tramline wheeling. These indentations were intended to break any surface soil “cap” and promote surface infiltration, while their diagonal configuration avoided any impact on traction. Results from the hillslope-scale evaluation (Chapter 4.2) showed that the harrow was highly effective ($p<0.05$) in reducing surface runoff down tramlines and reducing the associated concentrations and loads of both sediment and P. This efficacy was consistent across all four sites and monitoring years 2–4 inclusive, illustrating this unit’s flexibility across a wide range of soil types and conditions. Again, the only exception to this impressive performance was the dry site-year at Loddington in 2010–11 when compaction was not a risk at the time of autumn spraying. Results reveal that using the rotary harrow resulted in reductions in surface runoff of up to 95% compared to the control (no mitigation) treatment.

The novel surface profiler-roller-tine unit created a convex soil surface which shed water back into the crop rather than channelling it into the concave tyre imprint usually created with farm traffic. The device was self-cleaning, using a patented polymer material and featuring a rippled surface. The hillslope-scale evaluation (Chapter 4.2) in Year 2 (winter 2010–11) showed the unit was highly effective at reducing ($p<0.05$) runoff, sediment and P losses at three sites, the only exception again being at the dry Loddington site where compaction was not a problem. Results indicated the use of the surface profiler reduced surface runoff by up to 85% compared to the control (no mitigation) treatment.

5.3. Operational aspects

Operationally, experimental data indicated the VF tyres had marginally (but significantly) lower wheelslip (Figure 22) and little effect on fuel use. They also have the flexibility to be used on other land use types (not just cereals) and for other purposes around the farm, rendering their use cost-effective and a practical 'win-win' option to mitigate compaction in (and losses from) tramlines receiving spray traffic. However, VF tyres are associated with substantially greater amortised annual costs of £1.60/ha (based on the whole of a 300ha farm; Chapter 4.3). Fortunately, these costs are more than offset by the VF tyre's reportedly greater lifespan (9000h versus 6000h), which means that – in addition to the environmental benefits reported here – over an entire lifecycle there is a modest amortised annual benefit of £1.84/ha when their use is considered over the whole of a 300ha farm (Table 25).

From a practical and operational perspective, the rotary harrow unit's amortised annual costs were estimated at around £12/ha to use on 20% of a 300ha farm (Chapter 4.4.2). Bearing in mind the effect of inflation on fuel and labour prices, this contemporary cost estimate compares favourably to the nine year old cost estimate of £10/ha for tramline disruption in Defra's Diffuse Pollution Inventory manual back in 2006 (Cuttle *et al.,*2006). The novel harrow unit has the advantage of being a "single pass" tool, which can be used at the same time and at the same speed as conventional spraying takes place. It is also self-cleaning, has very low draft requirements assessed at around 9hp, has no significant effect on traction, and has the potential to be attached (via a toolbar frame) to both self-propelled and trailed sprayer units. Although evaluated on a trailed Chafer sprayer unit in this project, this flexibility was demonstrated during the final year of the project as Househam demonstrated this harrow unit was compatible with their self-propelled sprayers at Cereals 2014. Furthermore, although this report's economics section (Chapter 4.4) only consider the unit's costs relative to its use on cereal crops, in practice other allied ADAS-led research provides evidence that the unit may also be highly effective on row crops as a way to mitigate compaction and reduce runoff, erosion and losses of sediment and P on light and medium textured soils: see for example, 'Practical ways to reduce runoff', Farmers' Weekly, 18 February 2011, pp66-67; and ADAS final reports for Defra project WQ0127 (Silgram *et al.*, 2015). The harrow unit therefore has the potential for a broader role in supporting a range of farming operations on other land use types, and this versatility would reduce the relative operational cost of this unit at a whole-farm scale (per hectare basis) compared to the costs reported here. Using the harrow on other land uses would also increase the resulting sub-catchment-scale impacts associated with the implementation of this mitigation method.

Although effective as a mitigation tool, the novel surface profiler-roller-tine unit required a separate pass after the spraying operation itself, with associated implications for fuel use and resource requirements. This resulted in higher costs of around £31/ha for application to 20% of a 300ha farm. Due to these factors, this unit appeared less attractive to land managers in subsequent workshop discussions on tramline mitigation methods, compared to the alternative VF tyre and rotary harrow tramline mitigation methods. However, those discussions focused on cereals only and – like the rotary harrow – this unit has also proved effective in mitigating losses from row crops in other ADAS-led research (Silgram *et al.*, 2015). The economics associated with high-value crops such as potatoes may mean that this tool is therefore better suited for use in managing such row crop systems, rather than managing cereal tramlines.

5.4. Field and catchment modelling

This project successfully developed the APT multipollutant model framework beyond its earlier application which only considered the effect of the delayed establishment of tramlines in cereals in Defra project WQ0128 (Collins *et al.*, 2012). This new development considered the efficacy of a range of novel tramline mitigation methods across contrasting soil types, slopes and weather scenarios at both whole-field and sub-catchment scale. Modelled assessments of whole-field impacts suggest the harrow and VF tyre mitigation methods are most effective on lighter soils in terms of percentage reduction in losses, and on silty soils in higher rainfall areas in terms of absolute reductions in losses (Chapter 4.3.4). This is a plausible conclusion, but such inferences implicitly reflect the more limited field data from clay-rich soils which were available to calibrate the APT model, both from historic data and from data generated within this project.

At sub-catchment scale, modelling suggested the VF tyre and rotary harrow mitigation methods were capable of reducing runoff by 7–9% (Rea, Corve) and 40-52% (Platt); reducing sediment losses by 16–37% (VF tyre) and 16–46% (rotary harrow); and reducing P loss by 7–26% (VF tyre) and 8–28% (rotary harrow) (Tables 13, 15 & 17). Such anticipated mitigation efficacies at sub-catchment scale are very impressive when compared to the more limited impact of some other diffuse pollution control measures, such those explored with scenario modelling in Nitrate Vulnerable Zones (e.g. Lord *et al.*, 2007; Hodgkinson *et al.*, 2013). Modelled assessments of the impact of tramline mitigation methods in the Rea, Corve and Platt sub-catchments reveal notable differences in losses under both control conditions (i.e. without mitigation) and under the alternative tramline mitigation methods. This reflects differences in the spatial distribution of intrinsic risk which is associated with different landscapes (as affected by slope, weather and proximity to water courses), and differences in the spatial distribution of management-related risk (as affected by factors such as land use, field geometry, cultivation direction etc.). In the case of the Platt sub-catchment, for example, the much lower rate of sediment loss without mitigation is likely to be due to its lower average annual rainfall, generally shallower slopes and different soil type distribution compared to the other two sub-catchments (Table 12).

The observation that the efficacy of different mitigation methods is highly spatially variable is of great importance, as it underpins the principle that for maximum benefit, such land management practices must be implemented in a spatially targeted manner across the landscape. Modelling can help in this regard, by helping to focus mitigation methods on areas with high intrinsic and/or management-related risk in ecologically sensitive sub-catchments. For example, modelled results in this project suggest that targeting VF tyre or rotary harrow mitigation method on only 13-18% of the area in the Rea, Corve and Platt sub-catchments may be capable of achieving 30-42% of the maximum potential mitigation of sediment (Table 18).

5.5. Policy implications

The VF tyres, rotary harrow and surface profiler unit all proved effective approaches to managing cereal tramlines during the vulnerable winter months, and their use supports the requirement to maintain cross-compliance, specifically GAEC 5 on minimising the risk of soil erosion (Defra, 2015). From a policy perspective, although these tools proved effective as methods to reduce compaction risk and/or mitigate runoff, erosion and sediment and P losses, because they focus on the uncropped tramline area within cereal fields it has been shown that their use has no effect on crop yield. Unfortunately, the “profit foregone” principle underpinning many incentives in government-endorsed agri-environment schemes does not therefore apply to these mitigation methods. However, an alternative approach to support more widespread adoption of such sustainable land management methods would be to support them on a capital purchase basis, perhaps with a partial grant.

At the requests of Natural England and Defra for England, and SEPA and RESAS for Scotland, results from this project were summarised and submitted in 2013-14 for consideration regarding future agri-environment schemes. As a result, in the new Countryside Stewardship scheme introduced in England in April 2015, there is now – for the first time - a partial capital grant available (of up to £1500) for purchasing equipment to manage tramlines in cereals to reduce soil compaction, erosion and diffuse pollution risk in spatially-targeted higher risk locations associated with vulnerable water bodies. This grant (RP31) is only available in the Higher Tier scheme “in areas targeted for the reduction of water pollution from agriculture on farms with crops of field identified as at risk of soil erosion in the farm environment record” (https://www.gov.uk/countryside-stewardship-grants/equipment-to-disrupt-tramlines-in-arable-areas-rp31). This recent policy development demonstrates the link between (and strong value of) the evidence emerging from applied, practical agricultural research such as this project, sustainable farming practice, and spatially-targeted agri-environment policy.

5.6. Further work

The experimental work reported here has focused solely on developing sustainable methods for managing tramline traffic and spraying operations in the autumn related to winter cereals. Management of traffic and spraying operations in the spring, when soils are still moist and ground cover still limited, remains a pertinent topic for future research and the development and evaluation of practical management techniques. Furthermore, this study focused solely on cereals, and there is potential to explore the management of other land uses: for example, only a limited assessment of the rotary harrow and surface profiler has currently been undertaken in a separate Defra-funded project focusing on the management of row crops such as potatoes (Silgram *et al.*, 2015). Further work is now needed to evaluate the suitability of other novel land management methods (including several emerging since the project was funded in 2009) with respect to their value in supporting sustainable farming practices by reducing the risk of soil compaction, mitigating erosion and constraining diffuse pollution risk. This future work should focus on expanding assessments of novel, practical land management practices which mitigate soil compaction, runoff and diffuser pollution risk whilst promoting sustainable and profitable farming, so that they cover a wider range of land uses – this could include (environmentally) higher risk land uses such as maize (building on Defra project WQ0140), field vegetables and soft fruit.

Field and catchment modelling has a key role to play in upscaling such experimental results to consider the impacts of land management treatments at whole-field, farm and sub-catchment scale. Any model, of course, is only as good as the experimental data on which it has been derived and calibrated. There are inevitably a limited number of experimental field sites, soil types, slopes, and monitoring years (weather) providing data from which such model parameters and functions are derived. Although this project has provided results covering a broad range of soil types, there were noticeably limited data on the efficacy of tramline mitigation methods at the clay site (Loddington), as this site was dry in Year 2 (2010/11) so there was no compaction to mitigate, but was too wet in Year 4 (2012/13) such that autumn spraying could not occur.

This data limitation reflects not only weather variability, but also the real-world difficulty in managing such heavier soils, which rapidly wet up in autumn and reach their plastic limit. Further data on the efficacy of mitigation treatments on runoff and associated losses from heavier-textured soils are therefore needed. Such data would improve the confidence placed on the (currently more tentative) conclusions regarding the efficacy of tramline mitigation methods on clay soils, strengthen the resulting recommendations to land managers, and improve the robustness of field and catchment scale model predictions used for policy support. As all four field sites had slope angles of 4–9°, additional assessments on shallower or steeper slopes would be of similar benefit.

5.7. Industry recommendations

Some of the Industry advice emerging from this project has been included in guidance issued by Natural England (Natural England, 2011). Tramline management to reduce the risk of soil compaction, runoff and erosion in autumn is most effectively targeted on higher risk fields, such areas with long shallow and medium slopes in proximity to water courses, gateways or farm tracks. Such tramline management activities can help achieve the requirement to maintain cross-compliance, specifically GAEC 5 on minimising the risk of soil erosion (Defra, 2015) by retaining fertile topsoil and surface-applied products on cereal fields.

Research assessed practical cost-effective management options over four years and four sites with contrasting soil types and slopes in England and Scotland. The most straightforward recommendations include:

- Increase tramline spacing (e.g. move from 18m to 24m)
- Use the correct tyre inflation pressure for the tyre, field operation and axle load (i.e. don’t over-inflate)
- Avoid establishing tramlines on loose “fluffy” seedbeds or when soils are very moist (careful timing is critical to avoid or minimise the risk of compaction, runoff and erosion)
- Use an extra headland tramline which is disconnected from the other tramlines, positioned on the lowest end of the field. The area between the two tramlines can then serve as a buffer strip to the major part of the field
- Consider re-orientating crop drilling (and hence spraying) direction so that tramlines do not follow the line of steepest slope

Research undertaken in this project shows that drilling tramline areas which will be receiving traffic (and then spraying using GPS) is not a solution, because vegetation cover will be very limited in the vulnerable winter months and soil will still be compacted by sprayer traffic – hence the risk of runoff and erosion remains unchanged. Omitting autumn spraying entirely (as advocated by Defra (2005)) may be possible, but is often not a practical or an economically viable option in a commercial farm setting.

New experimental evidence from this project also identified novel methods which reduced soil compaction, runoff and erosion from winter cereals by 50% or more, with no effect on crop yield, and applicable across a range of soil types and on both shallow to medium slopes:

- **Correctly-inflated Very Flexible (VF) tyres** – which typically operate at half the pressure of conventional tyres
- **A small self-propelled rotary harrow** – attached to the rear of the crop sprayer in autumn. This punctures the soil in several places across a wheeling, increasing infiltration without affecting traction. It is self-cleaning, easy to use, has very low draft requirements (9 hp), and works on both self-propelled and trailed sprayers. This equipment was developed for trailed sprayers by Simba Ltd (now Great Plains Ltd), and modified for self-propelled sprayers by Housham Ltd – and both organisations now have the opportunity to commercialise this product. A partial (£1500) capital grant towards the cost of such tramline management equipment is now available under the Higher Tier of the new Countryside Stewardship scheme in England (RP31) – see https://www.gov.uk/countryside-stewardship-grants/equipment-to-disrupt-tramlines-in-arable-areas-rp31

VF tyres proved versatile and highly cost-effective at reducing compaction, runoff, and erosion risk on a wide range of soil types (light, medium and heavy textured soils). Their slightly greater initial cost was more than offset by their greater lifespan, resulting in a net gain of around £2/ha across a 300ha farm.

The rotary harrow proved highly effective as a tramline management tool on light and medium textured soils, costing around £12/ha if applied to 20% of a 300ha farm. Results from clay soils also showed benefits from the rotary harrow, but data were more limited: such soils are inherently structurally stronger and more able to withstand axle loads when dry (and hence are less prone to compaction problems in dry autumns), but quickly smear and rut when wet (suggesting it is preferable that – where possible – traffic is avoided when soils are wet). This highlights the importance of careful timing of autumn spray operations on these more difficult-to-manage heavier textured soils.

Both the rotary harrow and an alternative novel surface profiler/roller unit have also been evaluated on row crops and both proved highly effective in reducing compaction and erosion in those situations – they therefore represent practical management tools across crop rotations.

Acknowledgements

This work was part of projects funded by Department for Environment, Food and Rural Affairs (Defra), LINK and AHDB Cereals & Oilseeds, and managed by Dr Martyn Silgram (ADAS). This project would not have been possible without previous Defra-funded projects which identified the importance of tramline wheelings as pathways for surface runoff, erosion and loss of sediment and phosphorus to water courses i.e. projects NT1033 (Silgram, 2001), PE0111 (Silgram, 2005; Silgram *et al.*, 2006) and PE0206 ('MOPS' – Mitigation of Phosphorus and Sediment: Quinton *et al.*, 2007, 2008).

Funding from the Sustainable Arable LINK programme, Defra, AHDB Cereals & Oilseeds, and the Scottish government is gratefully acknowledged. Our sincere thanks are extended to the managers of the experimental sites: Alastair Leake, Phil Jarvis and Chris Stoate of the Game and Wildlife Conservation Trust; Gary Powell of Severn Trent Water; Stuart Hutchins (Gatley site); and Bob Jackson and Hugh Edwards (ADAS). The authors acknowledge the invaluable input from John Lapworth (ADAS) and Ken Loades (JHI) in field installation, sampling and data handling activities. Experimental and data processing support from Katrina Morrow, Adele Hulin and Phil Edgington is also acknowledged. Mark Edwards (Edwards Plastic Fabrications Ltd., Unit 44, Chapel Street Industrial Estate, Tipton, DY4 8JB) contributed invaluable design and construction initiatives regarding the novel tipping bucket sample splitters.

In addition to the co-authors of this report and the project funders, special thanks are given to all the industrial partners in this project, who gave both their time and other resources in support of the work described here. The project partners and associated stakeholder organisations included Agco Ltd., AHDB Cereals & Oilseeds, Allerton Trust, Chafer Machinery Ltd., Defra, Environment Agency, Househam, LEAF, Michelin Group Products, Mylnefield Research Services, NFU, Scottish government, Scottish Society for Crops Research (SSCR), Severn Trent Water Ltd., Simba Great Plains Ltd., The Bulmer Foundation, and Wright Resolutions Ltd. The initiative from Househam in modifying and demonstrating the rotary harrow unit's compatibility with self-propelled sprayers is also very much appreciated. The co-operation of the Farm Managers and operators at all four field sites (by including the experimental treatments into field management regimes) is gratefully acknowledged.

The invaluable guidance, advice and support provided by all the members of the project Steering Committee, including Arthur Hill (chair), Huw Philips, Julian Hasler, Bill Basford, Charles Creyke and Shamal Mohammed is gratefully acknowledged.

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Appendix 1. Knowledge Exchange activities

Presentations

- TV interview, “Farming Sunday” SKY channel 280, Mar 10
- YouTube interview, AHDB Cereals & Oilseeds workshop (2012)
- CSF training on diffuse pollution control, Loddington, Mar 10
- Stand, talk and practical demo at Tillage Live 2011 as a required stop on the “soils knowledge trail”
- Agricultural Engineers Association presentation, Oct 11
- High Mowthorpe Farmers’ Association presentation, Dec 11
- Presentation as part of 'Developments in Crop Production' Level 3 Agricultural Business Management degree students at Hartpury College (University of West of England), 5th Dec 10
- Defra IWAM WQ0109 CSF CPD Diffuse pollution related to arable land, Loddington, Mar 10
- International Phosphorus Workshop (IPW6), Seville, Sep 10
- CSF training day, Telford, Aug 10
- ‘Farming Futures’ event, Loddington, 11 Nov 2010, 80 participants: speaker & field tour
- CSF meeting –- mitigating risk of pesticides in water, Ledbury, Jan 11
- Rosemaund Open Day, Summer 11
- Invited speaker and practical demonstrator in two sessions at Soil & Water Management Day, Harper Adams, Feb 12, www.harper-adams.co.uk/video/201594
- Seminar to Environmental Management Group, Cranfield University, Jan 12
- Boxworth Farming Association meeting, Feb 12
- Series of 5 AHDB Cereals & Oilseeds industry events with farm walks & presentations (Mar 13)
- Talk and field walk at “Farm Water Pathway management” CSF event (Nov 13)
- Presentation at NIABTAG farm event (Summer 13);
- Demonstration / stand / poster at Cereals event (Jun 2010–14)
- “Repairing damaged soils of 2012” soil compaction workshop, Harper Adams (Feb 13);
- Presentation at Soil management workshop, Loddington (Jan 13)
- Cereals in Practice (Jul 13)
- Series of 3 AHDB Cereals & Oilseeds/SRUC winter industry events (Jan 14)

Papers & press articles

- ‘Focus on wheelings to cut surface runoff and diffuse pollution risk’, Famers’ Guardian, 11 Dec 09, p16.
- ‘Seeking practical measures to cut tramline surface loss’. Crops magazine, 13 Mar 10, pp26-27.
- ‘Soft rubber beats autumn erosion’, Farmers’ Weekly, 19 Nov 10, p47.
- ‘Innovative kit can take care of pesticide runoff’, Farmers’ Weekly, 23 Sep 11, pp58-59.
- ‘Correct tyre choice relieves tramline pressures’, Farmers1st (www.atlasfram.co.uk), 20 June 11, p18.
- H2OK “Catchment news”, Voluntary Initiative newsletter, Autumn 10, p7.
- ADAS Environmental Digest article, Nov 10
- Crop Protection Magazine – Tillage 2011 article, Oct 11
- Farmers Weekly article on Harper Adams soil and water management day, Mar 12
- Article – NIABTAG Landmark Bulletin Issue 12, Summer 13
- Internal paper requested by Defra / NE to support review of agri-environment policy, Jul 2013
- “Spiked harrow eases problem”. The Courier press article, Jul 13
- McKenzie BM Silgram M, Baxter C, Lewis TD, Hawes C, Neilson R & Rowan JR 2013. Managing the surface structure of arable soil to control erosion and maintain ecosystem services. *International Workshop on “Soil Structure and its Functions in Ecosystems 8-10th September 2013 Nanjing, China.*

Online only

- AHDB Cereals & Oilseeds website + YouTube article, Sep 11
- UK-ADAPT website and email alert article (Dec 11)
- James Hutton website (summer 13)
- ADAS website (summer 13)

Posters

- Open Farm Sunday, Jun 10 – Jun13
- EGU Vienna, May 10

- European Geosciences Union (EGU) annual meeting, Vienna, May 10
- Royal Welsh Smallholders and Garden Festival, Royal Welsh showground, May 11
- Three Counties Show, Malvern, Jun 11
- Bulmer's Orchard and Machinery Day, Jul 11
- Malvern Farming Conference, Nov 11
- EUROSOIL conference, Summer 12
- Tillage 2012 – Demonstration plot, two posters, and equipment display area
- ISTRO, Sep 12
- Nordic Association of Agricultural Sciences meeting, Helsinki Mar 12