Catena 191 (2020) 104557

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Efficacy of mulch and tillage options to reduce runoff and soil loss from asparagus interrows

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ARTICLE INFO

Keywords:
Asparagus
Shallow soil disturbance
Mulch
Tillage
Runoff
Erosion
Soil loss

ABSTRACT

In the UK, conventional asparagus cultivation practices on sloping land, erodible soils and increased frequency of extreme rainfall events combine to promote runoff generation and soil loss, particularly from interrows. This instrumented field study investigated the interactive effect of mulch and shallow soil disturbance (working depth of 0.175 m) on reducing runoff and soil loss. Ten treatments were installed in a commercial asparagus field near Ross-on-Wye (England, UK) during May 1st–July 17th, 2012. Straw and compost were applied to the interrows at high and low application rates (straw = 5 t ha^{-1} and 3 t ha^{-1} and compost = 18 t ha^{-1} and 8 t ha^{-1}, respectively), both with or without shallow soil disturbance (SSD and Non-SSD) as compared with a bare soil, unamended Control. Across five sampling periods, Non-SSD straw mulch applied at 5 t ha^{-1} and 3 t ha^{-1}; Non-SSD compost mulch at 18 t ha^{-1}; and straw mulch applied at 5 t ha^{-1} with SSD all significantly reduced cumulative total soil loss by 53–72% as compared with the Control. Further, mulch treatments with SSD were in general less effective at reducing total soil loss as compared to non-SSD mulch treatments. Compost application was less effective than straw, due to sub-optimal compost blanket depths as dictated by N restrictions for Nitrate Vulnerable Zones, in which the study took place. Despite an overall reduction in total soil loss of 72% (associated with Non-SSD straw mulch applied at 5 t ha^{-1}), soil erosion rates exceeded 1.4 t ha^{-1} yr^{-1}, considered to be a tolerable erosion rate in the EU. In addition, measured sediment concentrations in the runoff consistently exceeded the EU water quality guideline value of 25 mg l^{-1}. The results indicate that the efficacy of the treatments tested was not adequate to reduce soil erosion in commercial asparagus fields in the UK to tolerable rates. This may in large part be due to daily foot trafficking events that occur during the asparagus harvesting period (April–June) which disturbs and degrades the treatments applied reduing their efficacy. This study demonstrates that additional research is required in order to identify effective erosion control measures to ensure the sustainability of commercial asparagus production systems in the UK.

1. Introduction

Globally, 20% of cropped land has seen a decline in productivity (1998–2003) as a result of soil degradation (UN, 2017). Inappropriate soil and water management, generally caused by a lack of practical Best Management Practices (BMPs), can lead to accelerated soil loss which degrades farm land and threatens agricultural sustainability. Asparagus (*Asparagus officinalis* L) production is a growing industry, occupying > 2000 ha in the UK alone (Defra, 2016) and 324,405 ha globally (FAO, 2018), of which c. 60–70% is rainfed and ridged.

Agronomic practices associated with conventional rainfed, ridged asparagus on sloping land can promote the generation of surface runoff and soil erosion. Weed control practices result in prolonged periods (c. 8 months) of bare soil exposed to erosive rainfall, promoting soil aggregate breakdown and surface sealing. This encourages runoff generation from the ridged beds, with concentrated flow in the interrows (furrows). These interrow areas are trafficked by field operations including fern-topping, annual ridging, spray operations and harvesting. This can result in severe compaction to depths of > 0.5 m (Niziolomski et al., 2016). During hand-harvest of the asparagus (April to June), farm workers access interrows daily in all weather and soil conditions. This results in shallow (0.0–0.3 m depth) surface compaction and soil smearing. Combined, these practices significantly reduce infiltration and promote runoff generation and soil erosion by water.

Mechanical soil disturbance (tillage) can be an effective compaction alleviation method when implemented correctly (Batey, 2009; Spoor, 2006). Soil disturbance generates an initial reduction in bulk density and increase in infiltration that can delay runoff generation. The

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https://doi.org/10.1016/j.catena.2020.104557
Received 25 April 2019; Received in revised form 14 February 2020; Accepted 11 March 2020
Available online 01 April 2020

increased soil roughness immediately following tillage can also reduce runoff volume and velocity (Govers et al., 2000, Gómez and Nearing, 2005). However, there are limitations to the longevity of this effect; the newly created surface roughness can degrade under rainfall as a result of raindrop impacts, aggregate breakdown and slumping (Guzha, 2004; Gómez et al., 1999; Rao et al., 1998). This can result in similar or increased soil loss as compared to non-disturbed plots (Gómez and Nearing, 2005; Foster et al., 1982). The disturbed soil can also re-compact when trafficked (Unger and Cassel, 1991).

Considerable research has demonstrated the efficacy of a range of surface mulch materials to prevent soil particle detachment and aggregate breakdown by rainfall at the soil surface, so reducing erosion risk (Keesstra et al., 2016; Prosdocimi et al., 2016; Faucette et al., 2009a; Persyn et al., 2004; Risse et al., 2002). Further, surface mulches have been proven to be an effective method of erosion control in other row crops including apricot orchards (Keesstra et al., 2016), vineyards (Prosdocimi et al., 2016), persimmon plantations (Cerdà et al., 2016) and potatoes (Griffin and Honeycutt, 2009; Edwards et al., 2000; Rees et al., 2002). Faucette et al. (2009a) and Persyn et al. (2004) used both straw and compost to effectively control soil erosion on bare soil slopes prior to vegetation establishment. Surface cover can protect the soil surface from raindrop-induced soil detachment and also imparts a frictional resistance to runoff (Gholami et al., 2013). The use of a mulch for soil surface protection could prolong the beneficial effects of tillage, providing longer term runoff and erosion control. Several studies have considered combining shallow soil disturbance (SSD ($<$ 0.35 m)) with a surface mulch for controlling runoff and soil loss (Cattan et al., 2006; Iqbal et al., 2008; McGregor et al., 1990; Sharma, 1991; Silgram et al., 2010). However, few (Cattan et al., 2006; Durán-Zuazo and Rodriguez-Pleguezuelo, 2008; Holmstrom et al., 2008; Silgram et al., 2010) have studied these practices in row crops, and none have considered their use in asparagus.

The objectives of this study were to critically evaluate the efficacy of mulch and tillage options singly and in combination to mitigate runoff and soil erosion by water from commercial asparagus fields in the UK. The study focused on the harvesting period (April–June), as it is associated with bare soil, daily trafficking and high erosion vulnerability. The current study provides for the first-time empirical data on the efficacy of practical soil management practices to mitigate runoff and soil loss from rainfed, ridged asparagus production. This data has wider applicability to both green and white asparagus production in Europe, South America, Australasia and Asia. It also applies to similarly cultivated (perennial and annual) crops including bulbs, root crops, vines, orchards and other high value horticultural crops. The results of this study extend beyond the asparagus field; control of soil erosion reduces sediment, nutrients and other agrochemicals entering water courses and drainage systems so mitigating local flood risk, improving water quality and keeping watercourses in 'good ecological status' as required by the EU Water Framework Directive (European Commission, 2000).

2. Materials and methods

2.1. Field site characteristics

Experimental plots were established in a 6.5 ha commercial asparagus field (*Asparagus officinalis* var. *Gijnlim*) near Ross-on-Wye, UK (51°89′N latitude and −2°56′E longitude), with row spacing on 1.5 m centres. Typical bed width is 1.0 m, bed height 0.35–0.4 m and interrow width 0.5 m. Normal hand harvesting and spray operations continued on the trial plots to ensure that treatments were evaluated under commercially representative conditions. Annual mean rainfall for Ross-on-Wye is 734 mm yr^{-1} (Met Office, 2014). The soil is a Eardiston soil series (Whitfield, 1971), a sandy loam equating to a Eutric Chromic Endoleptic Cambisol following the WRB 2006 notation. No significant differences were found between the experimental plots for the site parameters tested (Table 1). A penetration resistance (PR) survey to 0.5 m depth conducted (in triplicate) on four randomly selected plots indicated a zone of compaction between 0.05 and 0.35 m depth, with readings of between 3.0 and 5.0 MPa and a mean value of 3.67 (± 1.07) MPa.

Table 1
A summary of the baseline properties of the experimental plots.

Parameter	Mean	Standard deviation
Slope (degrees)	5.7	0.4
Sand (%)	69.02	1.15
Silt (%)	15.86	1.39
Clay (%)	15.12	0.39
Organic matter (LOI) (%)	1.44	0.06
Interrow bulk density (kg m^{-3})[a]	1663	137
Soil[b] moisture content (%)	16.03	1.75

[a] Taken at 0 to 0.05 m depth.
[b] Taken on 18th April 2012.

2.2. Experimental design and treatments

The experiment was established as a randomised, paired-plot design with treatments replicated in triplicate. Treatments included a Control, Shallow Soil Disturbance (SSD) and non-SSD plots with or without mulch applied at two application rates (Table 2). The SSD treatments were applied using a winged tine (45° rake angle and 30° wing inclination) mounted on a tractor frame pulled by a 170 horse power (125 kW) tractor at a working depth of 0.175 m. This implement tilled two interrows with each pass, representing the currently adopted practice. The two types of mulch tested were: wheat straw and compost (PAS 100:2005 QP compliant) applied at optimal and sub-optimal rates, with the latter used to quantify whether limited mulch availability would affect the longevity of the SSD performance. Straw application rates were based on a rate of 5 t ha^{-1} giving just over 70–75% surface cover (which is prescribed by Morgan (2005) as being sufficient to protect the soil surface from erosion) and a sub-optimal rate of 3 t ha^{-1} (representing *circa* 40% surface cover).

The high compost application rate of 18 t ha^{-1} (giving 35 mm depth of compost) was dictated by the maximum nitrogen (N) addition (250 kg ha^{-1} yr^{-1}), as permitted in a Nitrate Vulnerable Zone pre-2013 (Defra, 2013). The sub-optimal compost application rate of 8 t ha^{-1} equated to an N addition of 180 kg ha^{-1} yr^{-1} and gave a compost depth of 15 mm.

All treatments were applied exclusively to the interrows. Straw was chopped to ~40 mm length and blown onto the soil surface using a Teagle Tomahawk 5050 straw blower; compost proved too wet for mechanical application, so was applied by hand.

Table 2
A summary of the experimental treatments and their associated treatment codes.

Treatment Code[a]	Tillage	Mulch	Mulch application rate	Application rate (t ha^{-1})
Control	None	None	None	–
Non-SSD Cp^L	None	Compost	Low	8
Non-SSD Cp^H	None	Compost	High	18
Non-SSD St^L	None	Straw	Low	3
Non-SSD St^H	None	Straw	High	5
SSD No Mulch	SSD	None	None	–
SSD Cp^L	SSD	Compost	Low	8
SSD Cp^H	SSD	Compost	High	18
SSD St^L	SSD	Straw	Low	3
SSD St^H	SSD	Straw	High	5

[a] SSD = Shallow soil disturbance; Cp = Compost; St = Straw; L and H = low and high application rates for compost and straw treatments.

Table 3
Sampling period specific rainfall characteristics.

Sampling Period	Collection period (2012) 1st–3rd May	Total rainfall (mm)	Total no. collection days	No. rain days[a]	No. rainfall events[b]	Mean rainfall intensity ($mm\ hr^{-1}$)[c]	Peak rainfall intensity ($mm\ hr^{-1}$)[c]
1	4th–14th May	47.8	3	2	5	15	48
2	15th–28th May	25.8	10	4	2	14	72
3	29th May–26th June	16.8	13	3	4	12	24
4	27th June–17th July	149	28	16	16	13	48
5		149	13	13	16	15	96

[a] Rain days defined as ≥ 1.0 mm day^{-1}.
[b] Rainfall event defined as ≥ 1.0 mm rain over a 10 min period.
[c] Rainfall intensity based on 1 min logging intervals.

2.3. Runoff plots

Treatments were established in the interrows on runoff plots approximately 40 m long and 0.4 m wide, running downlope and hydrologically isolated either side by an asparagus bed (ridge). Each plot had a catchment area of approximately 40 × 1.5 m. Any generated runoff flowed into stainless steel Gerlach troughs (0.21 × 0.95 × 0.11 m) connected to 125 l tanks via plastic pipes (250 mm internal diameter). The tanks were situated approximately 9.0 m downslope of the Gerlach troughs to ensure sufficient fall height (*circa* 0.5 m) for the effective capture of runoff and eroded soil and to minimise the risk of pipe blockages.

2.4. Data collection and analysis

Runoff and sediment were sampled for each plot from five sampling periods undertaken between 1st May and the 17th July 2012. Sampling was undertaken when sufficient measurable runoff (> 50 l) was recorded in all experimental treatments. Consequently the length of time between each sampling period varies (Table 3). The performance of each treatment was compared to the Control plots. Treatment performance indicators included individual event-based hydrological response including: time to runoff initiation (min), cumulative runoff volume (l), total soil loss (kg $plot^{-1}$), sediment concentration in runoff ($g\ l^{-1}$), total oxides of nitrogen (TON) in runoff ($mg\ l^{-1}$), orthophosphate-P in runoff ($mg\ l^{-1}$) and total sediment-bound P ($mg\ kg^{-1}$).

2.4.1. Runoff sampling and analysis

Runoff volume (RV_{Total}) measurements were taken from pre-calibrated 0.5 m long Liquid Vertical Continuous Series sensors located in each of the runoff collection tanks, linked to a data logger (DT80/2). Total soil loss (TSL) was measured by combining; i) suspended sediment load derived from 3 × 0.5 l sub-samples of agitated runoff and ii) freshly deposited soil immediately upslope of and contained within the Gerlach trough. Individual tank runoff sub-samples were combined in a 2.0 l glass beaker, agitated and a 500 ml sub-sample poured out and retained. This was analysed in triplicate (50 ml) for sediment concentration (TS_{Conc}) following 'Total Solids dried at 103–105 °C' (Eaton et al., 2005). For each plot, Gerlach trough samples were dried and weighed (GT_{Total}). Total soil loss from each plot was calculated using Equation (1).

$$TSL = (RV_{Total} \times TS_{Conc}) + GT_{Total} \tag{1}$$

where TSL = Total soil loss (kg $plot^{-1}$); RV_{Total} = Runoff volume (l $plot^{-1}$); TS_{Conc} = Total sediment concentration of runoff ($g\ l^{-1}$); GT_{Total} = Total Gerlach trough soil loss (kg).

Due to experimental constraints, only the first, third and fifth sampling periods (Table 3) were analysed for chemical parameters. TON ('Automated Hydrazine Reduction Method'; Eaton et al., 2005) and orthophosphate-P ('Automated Ascorbic Acid Reduction Method'; Eaton et al., 2005) were determined using a Burkard SFA-2000 auto analyser. For each sampling period, results were analysed for statistical differences using a nested full-factorial ANOVA followed, where significant differences ($p < 0.05$) were observed by *post-hoc* Fisher LSD analysis (Statistica 13.2 Dell Inc.).

2.4.2. Individual event-driven hydrological response

Runoff hydrographs were plotted to show treatment response to individual rainfall events within each of the five sampling period. Hydrographs were generated using an automated system that linked a 0.2 mm tipping bucket rain gauge via the DT80/2 data logger to the pre-calibrated Liquid Vertical Continuous Series sensors. Data was logged at 30 min intervals until rainfall (≥0.2 mm) occurred, at which point 1 min interval data was recorded. This temporal resolution of data collection continued for 1 hr post rainfall cessation, in order to monitor the hydrological lag effects of each treatment.

Each sampling period was subdivided into rainfall events defined as > 1.0 mm rainfall within a 10 min period. The first rainfall event of each sampling period that generated runoff from > 50% of treatment plots was selected for statistical analysis. Statistical analysis was undertaken on 2 min interval data, starting from 1 min post-rainfall initiation through to rainfall cessation. This frequency is similar to that applied in other studies (Beighley et al., 2010; Faucette et al., 2004; Jasa and Dickey, 1991). Data was also analysed from 1 and 10 min post rainfall cessation. If runoff (≥1.0 l) continued, then data was analysed at additional 5 min intervals until runoff volume reached a steady state. Time to runoff initiation (min) and cumulative runoff volume (l) were analysed using two-way ANOVA followed by *post-hoc* Fisher LSD analysis (Statistica 13.2 Dell Inc.).

3. Results and discussion

3.1. Runoff volume

The results indicate that each sampling period had different rainfall characteristics (Table 3) with variable treatment responses dependent on rainfall characteristics.

Significant (two-way) interaction effects between tillage (SSD/Non-SSD) and mulch type (Compost/Straw/No Mulch) were only observed in the second sampling period. Irrespective of application rate, the compost mulch Non-SSD treatments significantly reduced runoff volume as compared with both the straw with SSD treatments and the Control. Furthermore, the compost mulch SSD and Non-SSD treatments and No Mulch SSD treatment significantly reduced runoff volume as compared with the straw mulch Non-SSD treatment. The No Mulch with SSD treatments resulted in a significant reduction in runoff volume (69%) as compared with the Control.

In sampling periods 1, 2 and 3, mulch type resulted in significant differences in runoff volume, irrespective of SSD treatment and mulch application rate. Compost mulch (at both application rates) significantly reduced runoff volume by 32, 38 and 28% as compared with the straw mulch treatments in sampling periods 1, 2 and 3 respectively.

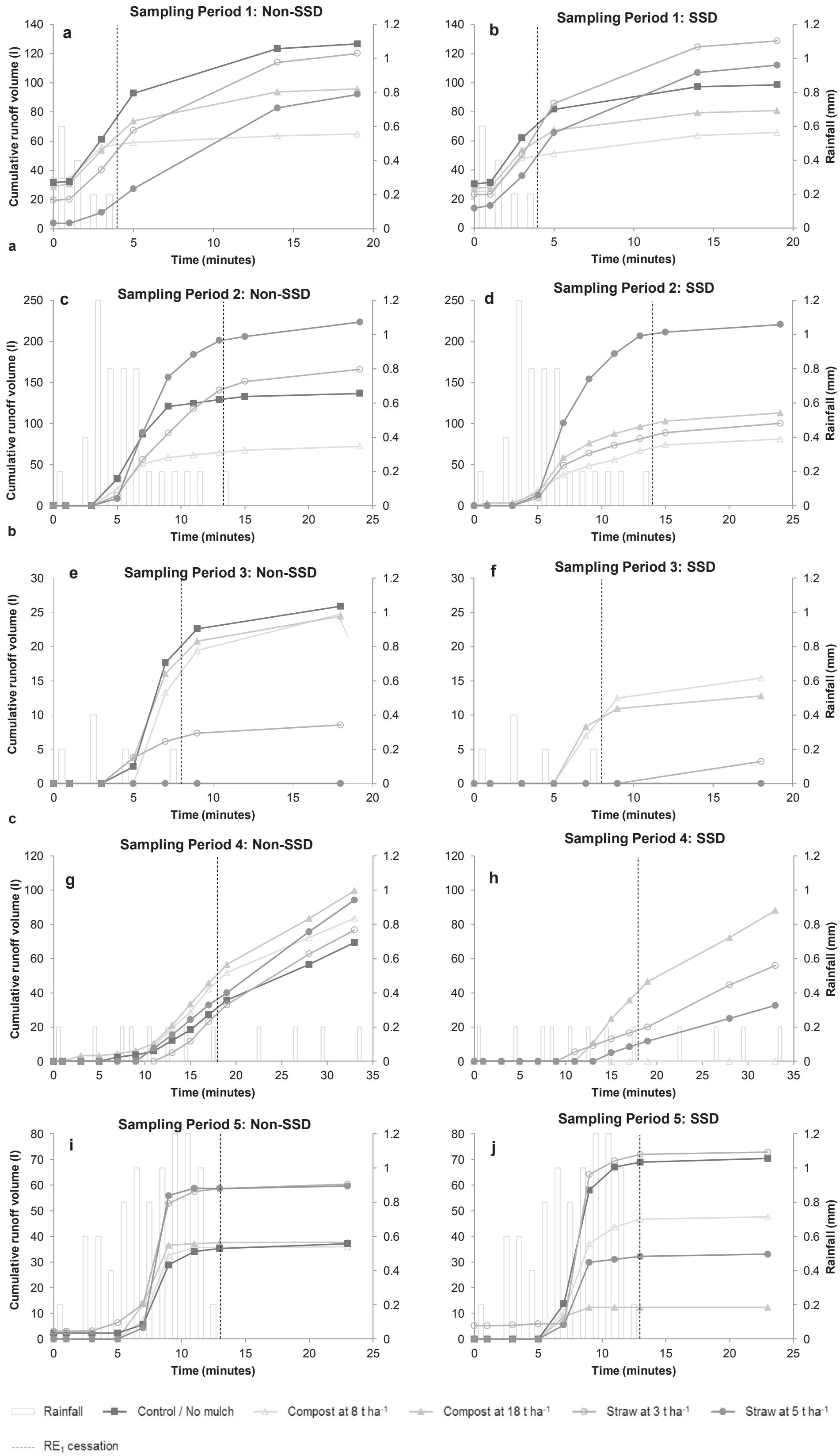

Fig. 1. Runoff hydrographs for treatments with and without SSD for the RE_1 for sampling period 1 (a and b), period 2 (c and d), period 3 (e and f), period 4 (g and h) and period 5 (i and j). Cumulative runoff volume (solid lines) and rainfall (shaded bars) are shown at set intervals during RE_1 as well as 1 and 10 min(s) post rainfall cessation (indicated by the dashed line). Treatments shown are without and with SSD (left and right respectively), control (■, darkest line), straw at 5 t ha^{-1} (●), straw at 3 t ha^{-1} (○), compost at 18 t ha^{-1} (▲) and compost at 8 t ha^{-1} (Δ, lightest line). N.B. Vertical axis vary between sampling periods.

No significant differences in runoff volume were observed between treatments in sampling period 4 and 5. This may have been due in part to the runoff generated by the extreme rainfall events at this time exceeding the surface depression storage generated by the shallow soil disturbance. A total of 388 mm of rainfall was recorded on-site during the sampling period as compared with the 30 year average for May to mid-July (1981–2010) of 268 mm (Met Office, 2014).

Table 4
Mean cumulative TSL (kg plot^{-1}) for each treatment across all sampling periods.

Treatment[a]	Cumulative TSL (kg plot^{-1})	% Significant reductions in cumulative TSL compared to the Control[b]	Extropolated Cumulative TSL (t ha^{-1})[c]
Control	131 (± 20) cd	/	21.8
SSD No mulch	124 (± 20) cd	ns	20.7
Non-SSD Cp^L	147 (± 20) c	ns	24.6
Non-SSD Cp^H	52.7 (± 16) ab	− 59.6	8.79
Non-SSD St^L	56.7 (± 16) ab	− 56.6	9.44
Non-SSD St^H	36.5 (± 16) a	− 72.0	6.08
SSD Cp^L	148 (± 20) c	ns	24.7
SSD Cp^H	92.2 (± 20) bcd	ns	15.4
SSD St^L	72.5 (± 20) abd	ns	12.1
SSD St^H	61.8 (± 16) ab	− 52.7	10.3

[a] SSD = Treatments with shallow soil disturbance; Non-SSD = Treatments without shallow soil disturbance; Cp = Compost; St = Straw; L and H = low and high application rates (Ref. Table 2) for compost and straw treatments.
[b] ns denotes treatments with cumulative TSL not significantly different from the Control.
[c] For the 2.5 month (May to mid-July) sample collection period. Values in parentheses indicate ± 1 S.E. Results followed by different letters are significantly different ($p \leq 0.05$) following one-way factorial ANOVA and *post-hoc* Fisher LSD analysis.

3.2. Individual event-driven hydrological response

Runoff hydrograph data for the first rainfall event of each sampling period that generated runoff from > 50% of treatments (RE_1) showed significant differences in the hydrological response between treatments (Fig. 1a–j).

3.2.1. Time to runoff initiation

Significant differences in time to runoff initiation between treatments were only observed in the first and third sampling periods. For the first sampling period, the high application rate (5 t ha^{-1}) straw mulch without SSD exhibited a significant delay in runoff initiation as compared with all other treatments (Fig. 1a and b). This was probably because of increased surface roughness imparting friction to the flow and increased depression storage associated with the straw micro-dams that were observed to initially hold back runoff.

In the third sampling period, for RE_1 no runoff was generated by the high application rate (5 t ha^{-1}) straw mulch with SSD or No Mulch with SSD treatment (Fig. 1e and f). The RE_1 for the third sampling period was associated with only 1.0 mm of rainfall, with a mean intensity of 7.5 mm hr^{-1} peaking at 24 mm hr^{-1} (n = 8). This suggests that only high intensity, longer duration events resulted in runoff generation from these treatments, as confirmed by runoff observed for the RE_1 in the first, second, fourth and fifth sampling periods (Section 3.2.2). Furthermore, in the third sampling period, the both application rates of compost with SSD treatments significantly delayed time to runoff initiation by approximately 2 and 1.5 min, as compared with the Control respectively (Fig. 1e and f). For both the compost and straw mulch treatments, time to runoff initiation may have been reduced through direct interception of rainfall and the formation of mulch micro-dams which impeded runoff generation and promoted infiltration.

3.2.2. Cumulative runoff volume

In the first sampling period (Fig. 1a and b), significantly lower cumulative runoff volumes were observed for high application rate (5 t ha^{-1}) straw mulch Non-SSD (88, 88 and 82%); high application rate (5 t ha^{-1}) straw mulch with SSD (57, 52 and 42%); and low application rate (3 t ha^{-1}) straw mulch Non-SSD (38, 37 and 34%); as compared with the Control at 0, 1 and 3 min post runoff initiation respectively. The effectiveness of the high straw application rate with SSD over the low straw application rate is likely due to the higher percentage cover (> 70%) preventing detachment and soil surface slumping within the interrows, thus maintaining the SSD-induced surface roughness and surface depression storage. At 1 and 3 min, the 82 and 88% reduction in runoff volume associated with the high application rate straw mulch Non-SSD was significantly greater as compared with all other treatments.

For the second sampling period, (Fig. 1c and d), all mulch treatments generated significantly lower cumulative runoff volumes at 5 min post rainfall initiation as compared to the Control. These reductions ranged from 74% (high application rate straw mulch Non-SSD) to 39% (Non-SSD low application rate compost) and are likely to be a result of increased infiltration made possible through the mulches providing obstructions to the flow (microdams), so reducing runoff velocity (and volume). The reduced efficacy of all mulch treatments by the second sampling period could be attributed to the saturation of the available surface depression storage and/or treatment degradation, due to daily foot traffic.

In the third sampling period, (Fig. 1e and f), all straw and the high application rate compost mulch with SSD treatments significantly reduced cumulative runoff volume at 7, 9 and 10 min post rainfall initiation as compared to the Control. As already discussed, both the ‘NonSSD high application rate straw mulch’ treatments did not generate runoff throughout the RE_1 of the third sampling period. Further, the low application rate straw mulch with SSD only initiated runoff 10 min post rainfall initiation with rainfall cessation at 18 min (Fig. 1f), resulting in significantly less runoff (88%) as compared with the Control. The relative ineffectiveness of the low application rate straw mulch with SSD suggests that the combination of a sub-optimal surface cover combined with SSD is less effective as compared to other straw mulch treatments.

By the fourth sampling period (Fig. 1g and h), fewer significant reductions in cumulative runoff volume between treatments were observed. The low application rate compost with SSD significantly reduced runoff by 100% at both 28 and 33 min post rainfall initiation, with no runoff throughout the RE_1. In the fifth sampling period (Fig. 1i and j), the high application rate compost with SSD significantly reduced cumulative runoff volume by 67% at 23 min (10 min post-rainfall cessation) as compared to the Control. This difference in mulch response suggests that as the mulch is degraded by foot traffic during harvest, compost retains its ability to control runoff better than straw. A similar finding was observed by Persyn et al. (2004). Significantly higher cumulative runoff volumes as compared with the Control were observed for the RE_1 of the fifth sampling period. The low application rate Non-SSD straw treatment was associated with 180, 83 and 69% higher runoff volume ($p < 0.05$) at 5, 9 and 11 min post-rainfall initiation respectively as compared with the Control. At 9, 11 and 23 min post-rainfall initiation, the low application rate straw with SSD treatment significantly increased runoff by 122, 104 and 96% respectively. The No Mulch with SSD also generated higher runoff (101, 96 and 90% respectively) as compared to the Control. Significant increases in cumulative runoff volume as compared to the Control suggest that although initially the mulch treatments were hindering runoff generation,

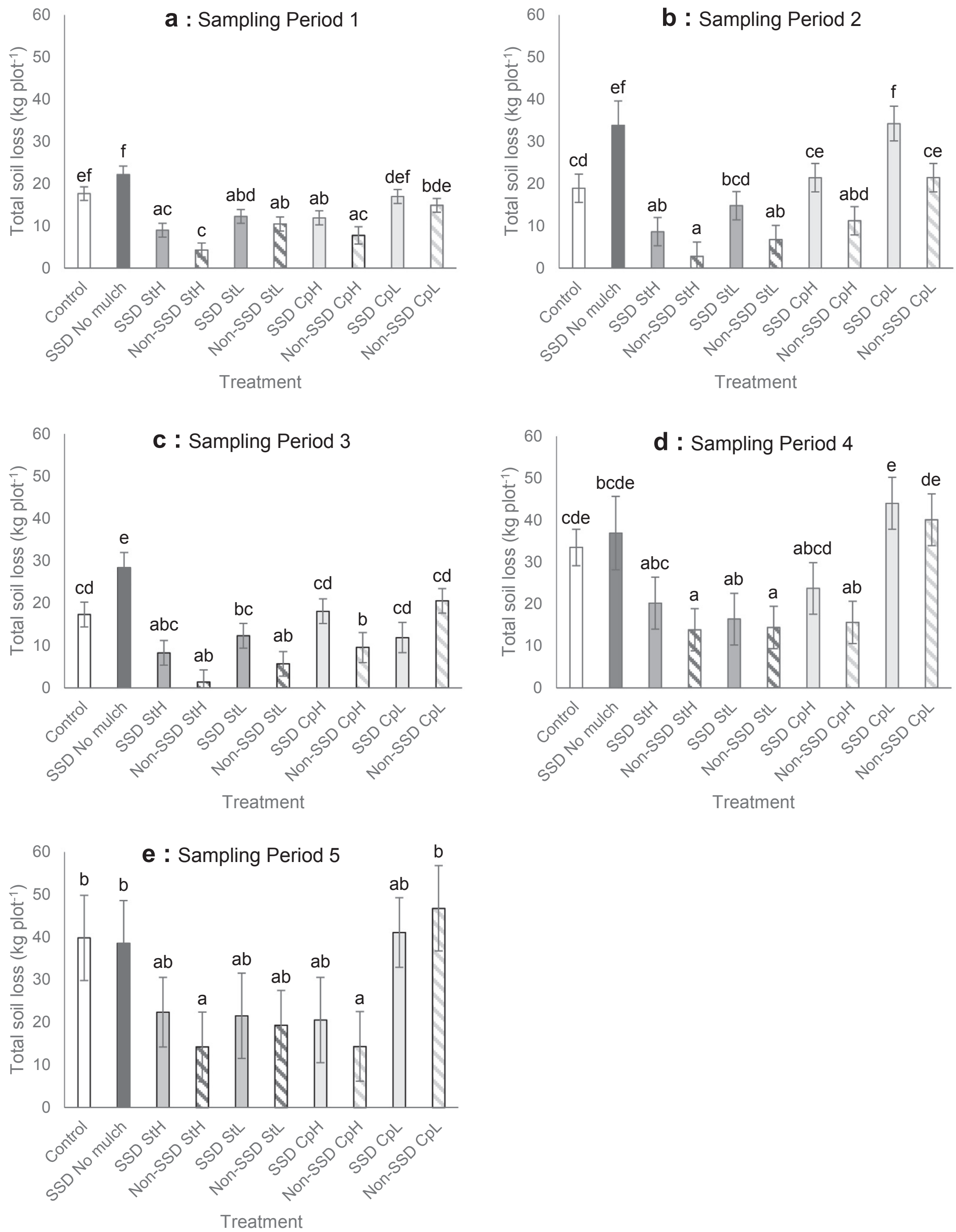

Fig. 2. Mean soil loss (kg plot^{-1})) for sampling period 1 (a), period 2 (b) period 3 (c), period 4 (d) and period 5 (e). Error bars show ± 1 Standard Error. SSD: Treatments with shallow soil disturbance, Non-SSD: Treatments without shallow soil disturbance, CpL: Compost applied at 8 t ha^{-1}, CpH: Compost applied at 18 t ha^{-1}, StL: Straw applied at 3 t ha^{-1}, StH: Straw applied at 5 t ha^{-1}. For each sampling period, bars with the same letter are not significantly different ($p \leq 0.05$) following one-way factorial ANOVA and *post-hoc* Fisher LSD analysis.

they were overwhelmed during the most intense period of rainfall observed across all RE_1s (Fig. 1i and j), resulting in a significant release of runoff.

3.3. Total soil loss (TSL)

Across all sampling periods, the high application rate straw Non-SSD and SSD; high application rate Non-SSD compost; and low application rate Non-SSD straw treatments all significantly reduced cumulative TSL compared to the Control (Table 4). This may in large part result from the protective effect of the straw and compost mulch which reduces soil detachment by raindrop impact. The mulches also reduce runoff volume through the formation of micro-check dams. The frictional component imparted to runoff by the straw and compost mulch will also reduce runoff velocity and hence rates of flow detachment and transport capacity. Critically, even with the observed significant reductions in soil loss, extrapolated TSL (t ha^{-1}) exceeds the tolerable annual soil erosion rate for Europe estimated at 1.4 t ha^{-1} (Verheijen et al., 2009) and the rates set by the FAO Intergovernmental Technical Panel on Soils (FAO and ITPS, 2015). With this in mind, the magnitude of soil loss observed over the 2.5 month experimental period must be regarded as unsustainable.

The high application rate straw mulch Non-SSD treatmentgave the greatest significant reductions in TSL as compared with the Control

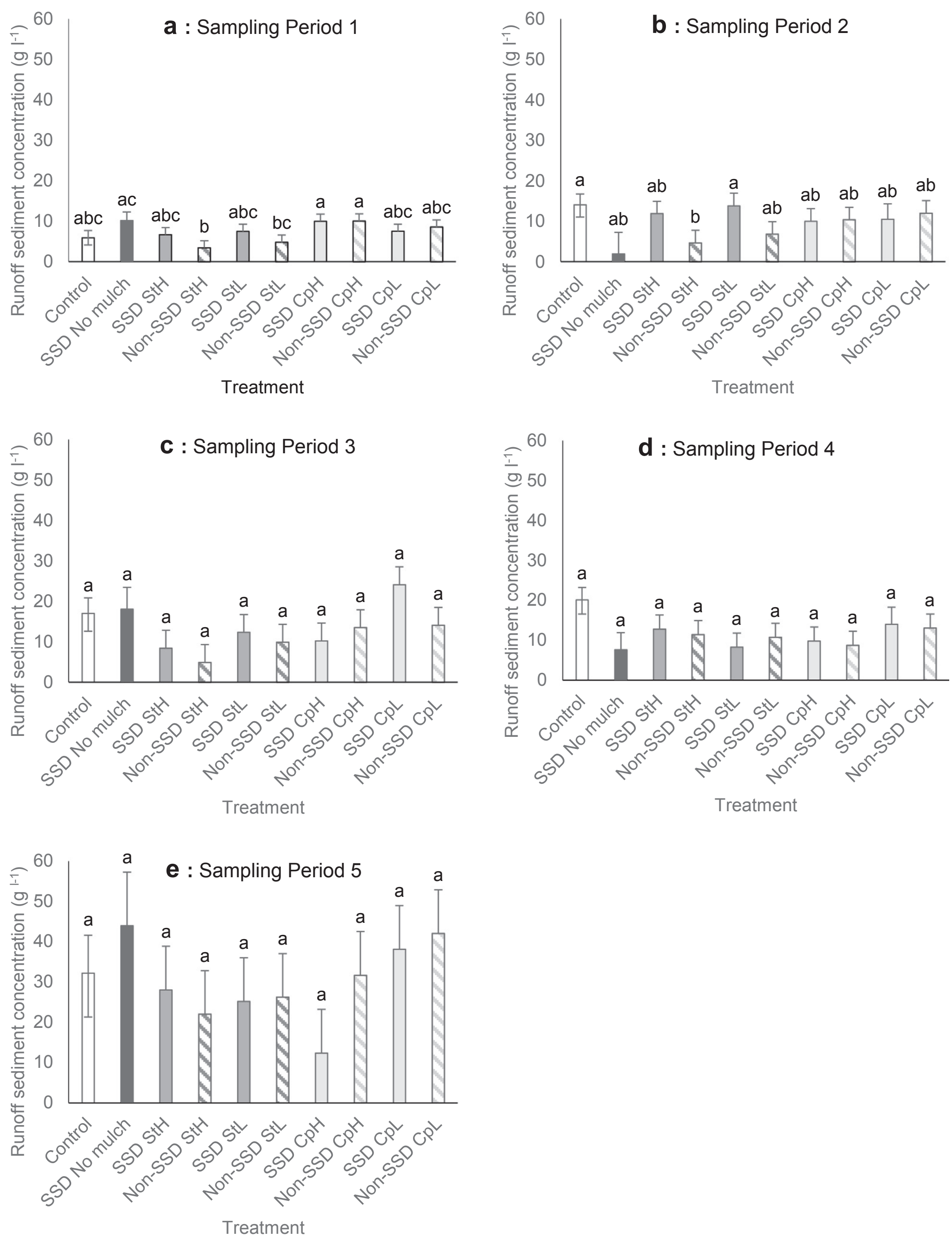

Fig. 3. Mean runoff sediment concentration (g l^{-1}) for sampling period 1 (a), period 2 (b) period 3 (c), period 4 (d) and period 5 (e). Error bars show ± 1 Standard Error. SSD: Treatments with shallow soil disturbance, Non-SSD: Treatments without shallow soil disturbance, CpL: Compost applied at 8 t ha^{-1}, CpH: Compost applied at 18 t ha^{-1}, StL: Straw applied at 3 t ha^{-1}, StH: Straw applied at 5 t ha^{-1}. For each sampling period, bars with the same letter are not significantly different ($p \leq 0.05$) following one-way factorial ANOVA and *post-hoc* Fisher LSD analysis.

(Fig. 2a–e) of 76, 85 and 59% for sampling periods 1, 2 and 4 respectively. Further, the low application rate straw mulch without SSD treatment also significantly reduced TSL by 41, 64 and 57% in sampling periods 1, 2 and 4 respectively as compared with the Control (Fig. 2a–e). Significant differences in TSL between high and low application rate straw mulch without SSD were only observed in sampling period 1 (Fig. 2a–e). The general trend for the better performance of high application rate straw mulch without SSD could be attributed to the enhanced soil surface protection afforded by the higher mulch application rate, preventing soil detachment, and subsequent entrainment and transport.

At higher application rates, straw can become repeatedly mobilised and rearranged by the runoff (Berg, 1984), forming micro-dams (Brown et al., 1998; Kwaad et al., 1998) that impede runoff allowing entrained soil particles to drop out of suspension. The straw can also impart a frictional component to the flow and increase the Manning's n coefficient, thus reducing the velocity of runoff, its kinetic energy and thus its ability to detach, entrain and transport soil particles/aggregates (Styczen et al., 1995) A similar trend was observed by Berg (1984), Brown and Kemper (1987), Döring et al. (2005) Holmstrom et al. (2008), Prosdocimi et al. (2016) and Rees et al. (2002). The lack of significant differences between the two straw (Non-SSD) treatments could be due to the effect of foot traffic during wet weather harvesting operations which may have reduced the initial efficacy of the mulch treatments.

The high compost application rate (18 t ha^{-1}) Non-SSD treatment

Table 5
Mean (n = 3) runoff TON, Orthophosphate-P concentrations for sampling periods 1, 3 and 5. Within each sampling period, values followed by different letters are significantly different (p ≤ 0.05) following factorial nested ANOVA and *post-hoc* Fisher LSD.

Treatment code[a]	TON (mg l^{-1})			Orthophosphate-P (mg l^{-1})		
	1	3	5	1	3	5
Control	1.87bdef	4.18a	117a	0.69ab	0.83a	0.63a
SSD No mulch	2.45f	4.37a	106ab	0.98d	0.95a	0.25a
Non-SSD Cp^L	1.92def	3.17a	102ab	0.78abd	0.86a	0.22a
Non-SSD Cp^H	1.39abd	3.47a	128a	0.81abd	0.62a	0.73a
Non-SSD St^L	1.21ac	3.74a	93.4ab	0.62ac	0.72a	0.35a
Non-SSD St^H	0.67c	3.18a	105a	0.47c	0.63a	0.46a
SSD Cp^L	2.01ef	2.74a	134a	0.84bd	0.79a	0.67a
SSD Cp^H	1.57abde	4.70a	50.0b	0.68abc	0.69a	0.24a
SSD St^L	1.26abc	3.30a	85.9ab	0.70ab	0.79a	0.58a
SSD St^H	1.26abc	3.34a	98.1ab	0.63abc	0.78a	0.70a

[a] SSD = Treatments with shallow soil disturbance; Non-SSD = Treatments without shallow soil disturbance; Cp = Compost; St = Straw; L and H = low and high application rates (Ref. Table 2) for compost and straw treatments.

Table 6
Aggregated mean orthophosphate- P concentrations (mg l^{-1}) over sampling periods 1, 3 and 5. Within each sampling period for mulch/tillage type, results followed by a different letter are significantly different (p ≤ 0.05) following factorial nested ANOVA and *post-hoc* Fisher LSD.

Treatment[a]	Sampling period 1	Sampling period 3	Sampling period 5
Mulch			
Compost (n = 4)	0.78a	0.74a	0.53a
Control (n = 2)	0.84a	0.89a	0.44a
Straw (n = 4)	0.60b	0.73a	0.52a
Tillage (n = 5)			
Non-SSD	0.68a	0.76a	0.48a
SSD	0.81b	0.83a	0.51a

[a] SSD = Treatments with shallow soil disturbance; Non-SSD = Treatments without shallow soil disturbance.

significantly reduced TSL by 66% as compared with the Control in sampling period 1, but did not differ significantly from either of the straw Non-SSD treatments (Fig. 2a–e). Persyn et al. (2004) observed that compost mulch blankets have the same efficacy at reducing soil loss as straw blankets. Faucette et al. (2009a) also observed no significant difference between compost blankets as compared with straw-geotextile treatments. In this study, no significant differences in TSL were observed between straw and compost treatments for the majority of the sampling periods (Fig. 2a–e), as well as in cumulative TSL across all sampling periods. This similarity in findings between the present study and Persyn et al. (2004) and Faucette et al. (2009a) is despite differences in the experimental conditions (i.e. concentrated flow vs sheet flow; unanchored mulch vs mulch contained within netting).

Shallow soil disturbance and mulch interactions were mainly associated with reductions in TSL (Fig. 2a–e) at the beginning of the field trial (sampling periods 1 and 2). This is likely due to the degradation of the SSD when subjected to rainfall (Guzha, 2004, Gómez et al., 1999; Rao et al., 1998), natural soil slumping and soil poaching by harvest workers. The high and low straw mulch with SSD treatments significantly reduced TSL during sampling periods 1 and 2 by 49–54% and 30–51%, respectively (Fig. 2a and b). In contrast, the high application rate compost mulch with SSD treatments significantly reduced TSL (by 33%) as compared with the Control in sampling period 1 only. Further, this was not significantly different from either of the straw with SSD treatments.

Unexpectedly, TSL from the low application rate compost with SSD significantly exceeded the TSL of the Control in sampling period 2 (Fig. 2b). This ties in with field observations that compost fines (from both high and low application rate treatments) had been partially washed off prior to sampling period 1. This meant that on low application rate compost with SSD plots, insufficient mulch was left protecting the SSD from the short and intense rainfall events of sampling period 2. This is further supported by the fact that measured TSL from compost treatments was not significantly different from the No Mulch with SSD in sampling period 2.

Treatment TSL results for sampling period 5 showed a high degree of variability (Fig. 2e). This was due to slumping of the SSD (resulting in reduced surface roughness and surface depression storage) as a result of cumulative rainfall and repeated foot trafficking during harvest. The rainfall events leading up to this sampling period were also the most intense during the study duration(Table 3).

3.4. Runoff sediment concentration

All treatments andsampling periods runoff sediment concentrations exceeded the suspended sediment concentration guideline value of 1000 mg l^{-1} (1.0 g l^{-1}), considered to have potentially major (Category 1) effects on receiving water bodies (Environment Agency, 2016) (Fig. 3a–e). Therefore, all runoff events sampled are potentially polluting, if there is hydrological connectivity between the field and adjacent watercourse. This suggests that under the present land use, these in-field BMPs must be combined with effective 'end of pipe' sediment control BMPs such as grassed water ways, riparian buffer strips, filter socks and/or compost berms (Faucette et al., 2009b; Fiener and Auerswald, 2003; Owens et al., 2007) to prevent sediment-laden runoff entering a watercourse.

3.5. Total oxides of nitrogen (TON) in runoff

Significant differences in TON were observed between treatments in sampling periods 1 and 5 (Table 5). In sampling period 1, irrespective of application rate or SSD, straw treatments significantly reduced TON in runoff by 50% as compared to No Mulch treatments (including the Control) and by 35% as compared with the compost treatments (Table 5). This could result from greater N mobilisation in the No Mulch treatments, as the runoff carries both suspended and soluble fractions. Further, across both mulch types, treatments without SSD significantly reduced TON in runoff by 18% in sampling period 1 as compared with SSD treatments (Table 5). It is important to note that TON levels in sampling period 1 were < 25 mg l^{-1}, which is the nitrate guideline set by the EU Directive 75/440/EEC.

In contrast, all treatments in sampling period 5 (including the Control) produced TON concentrations up to 5 times greater than the nitrate guideline value (EU Directive 75/440/EEC) (Table 5). These elevated TON concentrations coincided with an on-site application of ammonium nitrate fertiliser on the 12th July 2012. This was followed by a brief but intense rainfall event on the 13th July 2012 (22 min duration, maximum intensity = 36 mm hr^{-1}; mean intensity = 19.8 mm hr^{-1}). The TON results indicate that a proportion of the applied N-fertiliser was washed off, without time for it to dissolve and infiltrate into the compacted interrows.

3.6. Orthophosphate-P in runoff

Orthophosphate-P concentrations in runoff from all treatments (Table 5) exceeded the WFD annual mean range for soluble reactive P (0.04–0.12 mg l^{-1}), as prescribed for rivers to be in good ecological status across all alkalinity and elevation classifications (UKTAG, 2008). The high orthophosphate-P concentrations are due to the soil in the trial field having a RB209 P index of 4 (56 mg l^{-1}) which exceeds the critical P soil index (26–45 mg l^{-1}) for vegetable farming systems (Defra, 2010).

The high straw application rate Non-SSD was the only treatment to significantly reduce orthophosphate-P concentration (by 32%) as compared to the Control, across all tested sampling periods (Table 5). This could be a result of the initial surface protection imparted by the straw, preventing soil aggregate breakdown and reducing the amount of P becoming dissolved from the soil into runoff. In contrast, the No mulch with SSD treatment significantly increased orthophosphate-P concentration by 30% as compared to the Control (Table 5). In sampling period 1, all straw treatments irrespective of application rate gave significant (29%) reductions in runoff orthophosphate-P concentrations as compared with No Mulch treatments, and by 23% as compared with compost treatments (Table 5). Across all mulch types and application rates, Non-SSD treatments significantly reduced orthophosphate-P by 16% as compared with the SSD treatments (Table 6).

4. Conclusions

This study demonstrates for the first time that conventional ridged asparagus production systems on sloping land and erodible soils can result in high levels of soil, water and nutrient losses. The interrow application of straw at 5 t ha^{-1} without SSD most consistently reduced TSL and runoff sediment concentration as compared to all other treatments. This was followed by straw applied at 3 t ha^{-1} without SSD, and straw at 5 t ha^{-1} with SSD. Compost application was less consistent due to sub-optimal compost blanket depths as dictated by N restrictions for Nitrate Vulnerable Zones, in which the study took place.

Despite the straw treatments giving significant reductions in both sampling period specific and cumulative TSL, soil erosion still exceeded tolerable rates of soil loss by an order of magnitude. This has the potential to degrade the natural capital of the farm, reducing onsite productivity, increasing private and public costs, polluting local watercourses and resulting in financial penalties from environmental regulators. The results of this study suggest that until more effective interrow management approaches are identified for asparagus, mulch-based treatments must be combined with effective 'end of pipe' sediment control measures. These include grassed water ways, riparian buffer strips, filter socks and/or compost berms to prevent sediment and nutrient laden runoff entering a watercourse. Further work is also required to improve treatment effectiveness and interrow management, along with other emerging best management practices such as companion cropping. This work is on-going under the AHDB funded project FV450 (AHDB, 2018).

Funding

This study was supported by the Engineering and Physical Science Research Council (EPSRC), The Douglas Bomford Trust, Cranfield University and Cobrey Farms Ltd. All data supporting this study are openly available from the Cranfield University repository at https://doi.org//10.17862/cranfield.rd.3574053.

Data availability

All data supporting this study are openly available from the Cranfield University repository at https://doi.org/10.17862/cranfield.rd.3574053.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104557.

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