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Optimising soil disturbance and mulch attenuation for erosion and runoff control in asparagus crops.

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ABSTRACT

Exposure of bare soil for long periods and onsite compaction create soil and water problems in asparagus production. This project aims to develop a cost effective and practical runoff and soil erosion management system. Two field trials (Phase 1 running from April - July 2012 and Phase 2 running from May - November 2013) tested different combinations of shallow soil disturbance (SSD) and mulch (straw and compost) application for soil erosion control. Cranfield University's soil bin was used to test the effect of different tine configurations on soil disturbance. The results of this research corroborated observations that asparagus production can result in levels of unsustainable soil loss that will contribute to the degradation of the existing soil resource.

The field trials demonstrated that a straw mulch applied at 6 t ha^{-1} significantly improved key performance indicators (KPIs, i.e. runoff initiation, volume and rate; total soil loss; sediment concentration; total oxides of nitrogen; orthophosphate-P; and sediment-bound P) as compared with the Non-SSD Control. In general, SSD (irrespective of tine configuration) was ineffective at improving key performance indicators as compared with the Non-SSD Control.

In the soil bin work, different tine configurations generated varying degrees and extent of SSD, with the modified para-plough giving the greatest soil disturbance for the least draught force. However, the differences in SSD observed in the soil bin had no effect on the KPI's tested in the Phase 2 field trial.

The effective treatments observed in the field trials only yielded cost savings to the farmer/grower when a high level of soil loss occurred. This research highlights the need to develop erosion control measures in asparagus fields, with wider implications to other row crops. However caution is needed, given the observed variation in effectiveness and reliability of in-field mitigation measures, especially during 'extreme' rainfall events.

Keywords: Compaction, straw, compost, infiltration, tillage.

Sponsors: EPSRC, Douglas Bomford Trust and Cobrey Farms.

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Finally, I would like to dedicate this thesis to two people who have been particularly important in my life, with whom I will not be able to otherwise share this achievement: Joan Lee and Jemma Brownlee.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
Cp	Compost
Cp^H	Compost applied at a high applicate rate
Cp^L	Compost applied at a low application rate
D_{AG}	Above ground / surface disturbance
DASY	Data acquisition system
D_{BG}	Below ground disturbance
Defra	Department for Environment, Food and Rural Affairs
EA	Environment Agency
EORT	Extended octagonal ring transducer
EU	European Union
FYM	Farm yard manure
MPP	Modified para-plough
N	Nitrogen
Non-SSD	Without shallow soil disturbance
NSLT	Narrow with shallow leading tines
NT	Narrow tine
NVZ	Nitrate Vulnerable Zone
P	Phosphorus
QP	Quality Protocol
RE_1	The initial Rainfall Event of each Sampling Period
SD	Specific draught
SD_D	Specific draught for D_{BG} and D_{AG} soil disturbance
SR	Surface roughness
SR_I	Surface roughness in-line with the tine run
SR_P	Surface roughness perpendicular to the tine run
SSD	Shallow soil disturbance
St	Straw
St^H	Straw applied at a high applicate rate
St^L	Straw applied at a low application rate
TON	Total oxides of nitrogen
TSL	Total soil loss
WFD	Water Framework Directive
WSLT	Winged with shallow leading tines

WT	Winged tine

1 INTRODUCTION

Inappropriate soil and water management, generally caused by a lack of adoptable and practical options, can lead to accelerated soil erosion. Soil erosion degrades agricultural land, threatening agricultural sustainability. Runoff and soil erosion is the costliest and most damaging consequence of conventional agriculture. In England and Wales 2.2 million tonnes of topsoil is lost annually (SSLRC, 2000), costing the farming industry between £180 and £280 million (Graves et al., 2011). However, the impacts are much wider as soil is key to ecosystems services that include food production, flood management, water filtration, carbon storage and climate regulation (Defra, 2011). This total cost of soil degradation (as a result erosion, compaction and loss of organic matter) has been estimated to cost the UK economy £1.2 billion a year (Defra, 2011). In order to address global degradation Rio+20 has set a target for a land degradation neutral world by 2030 that includes a sub-target of a 50 % reduction in erosion by wind and water (Defra, 2011). However, in order to tackle this, the effectiveness, feasibility and practicality of in-field measures that control erosion to an ‘acceptable’ rate must be understood (Defra, 2014a). The large degree of variability in the effectiveness of in-field measures on erosion control makes this difficult (Defra, 2014a). Furthermore, there is a knowledge gap in the effectiveness of in-field measures under extreme weather events that are predicted to become more frequent with climate change (Rickson et al., 2010).

Agricultural erosion and runoff is accelerating with the increased frequency of ‘extreme’ rainfall events and the increased susceptibility of soil to erosion. This increased susceptibility is due to increased compaction, reducing soil pore space resulting in poor soil structure and a reduced infiltration potential, as well as the loss of soil organic matter. Soil susceptibility is further worsened by land management. Asparagus when grown on erodible soils and sloping land can, under extreme rainfall, generate high rates of runoff and soil erosion, and thus is the focus of this project. Asparagus is a growing British industry covering >2000 ha and worth approximately £30 million (Defra, 2014b). It is an intensive cropping system grown as a continuous monoculture stand for up to 15 years. Grown as a row cropping system it leaves areas of bare vulnerable soil exposed to rainfall for up to 6-months per year. In addition, the uncropped areas or ‘wheelings’ act as channels, concentrating runoff further increasing erosion risk. The addition of polythene cloches used to promote early harvesting creates impermeable layers further increasing runoff coefficients and directing rainfall to wheelings.. In order to ensure the economic and environmental sustainability of asparagus production in the light of the increased frequency of extreme rainfall events, runoff and erosion must be controlled.

Many erosion control studies have been carried out under both construction site and agriculture conditions. Some studies have been undertaken on erosion control in row crops (Holstrom et al., 2008; Edwards et al., 2000; Döring et al., 2005; Rees et al., 2002). However, erosion control in asparagus production has not been studied in published literature. Fewer still have considered the interaction effects between shallow (<350 mm) soil disturbance and mulch application (Holstrom et al., 2008). Both individually and in combination, shallow soil disturbance and mulching has been proven in other agricultural systems such as cereals to be an effective control of erosion and runoff. This study aims to test the effectiveness of a range of currently adopted and commercially available tines to generate shallow soil disturbance in combination with/without mulch on sloping asparagus fields as a cost effective and practical method to control runoff and erosion management. Two field trials (Phase 1 running from April - July 2012 and Phase 2 running from May - November 2013) undertaken at Cobrey Farms, Ross-on-Wye, UK, tested different combinations of shallow soil disturbance (SSD) and mulch (straw and compost) application for soil erosion control. In addition, the Cranfield University’s soil bin was used to test the effect of the selected tine configurations on above and below ground soil disturbance and draught efficiency. The results of this study will contribute much needed empirical data on the effectiveness of simple and affordable land management practices to control runoff and erosion control for asparagus.

This thesis is divided into 8 chapters. Chapter 2 presents the relevant literature that led to the formation of the research hypotheses that are outlined in Chapter 3. Chapter 4, 5 and 6 document the experimental programmes undertaken to address the research hypotheses. In Chapter 7, the conclusions of each experimental programme are brought together in a synthesis. An economic appraisal is undertaken to establish the cost effectiveness of erosion control treatments and final conclusions drawn. Chapter 8 discusses the wider implications of the research and potential opportunities for further work.

2 LITERATURE REVIEW

2.1 Soil erosion

2.1.1 Processes

Water induced soil erosion is a three stage process consisting of; detachment, entrainment and transport (Figure 2.1). As a raindrop strikes the soil it creates a small amount of compaction on the soil surface, this seals some of the soil pores. Raindrop splash leads to some soil becoming detached. Some of the raindrops infiltrate into the soil whilst the remainder runs off downslope. This runoff builds up speed and volume, and entrains any detached sediment and transports it downslope. The magnitude of each of these stages depends upon rainfall and runoff erosivity and soil erodibility. Erosivity pertains to the potential of rainfall and runoff to cause erosion (Morgan, 2005). Soil erodibility is the degree to which soil is susceptible to erosion by eroding agents (Morgan, 2005).

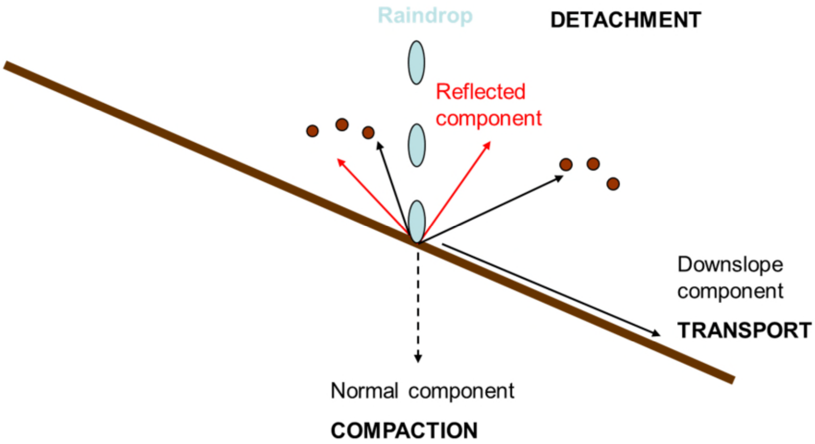


Figure 2.1. The three stage rainfall induced erosion process on a slope. Modified from: Simmons (2011).

2.1.1.1 Soil detachment

Soil detachment is the critical component in the erosion process. Rainfall is the key agent in soil detachment as very fine sand requires an erosion velocity of 30 cm s^{-1}

(Figure 2.2) that is rarely attained by overland flow (Evans, 1980). The probability of soil particles or even small aggregates detaching during a rainfall event is determined by both rainfall erosivity and soil erodibility (Figure 2.4).

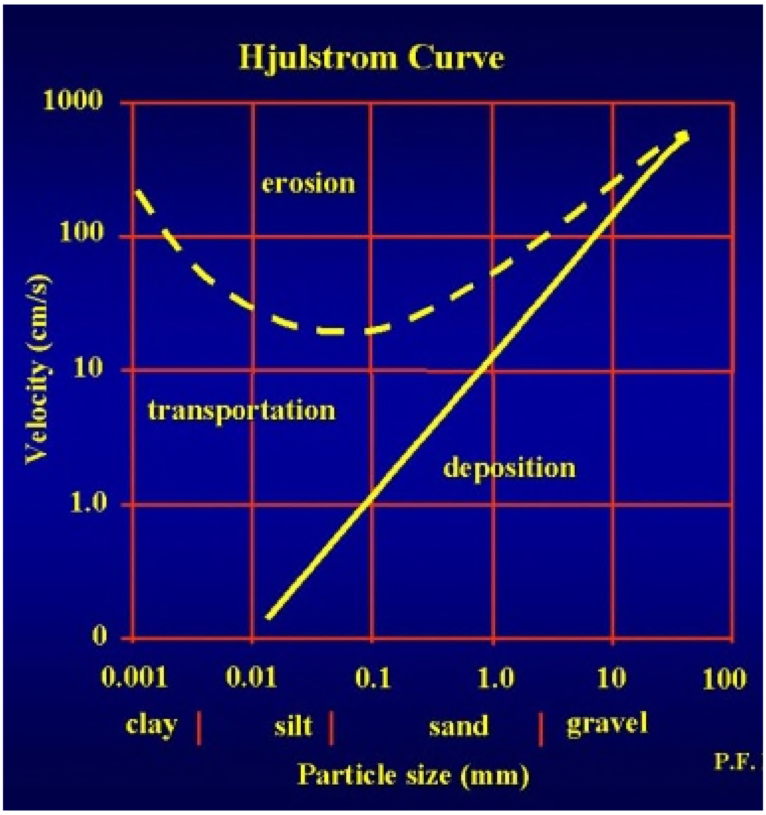


Figure 2.2. Hjulstrom curve demonstrating required flow velocity for soil particle erosion, transportation and deposition. Source: http://www.utexas.edu/depts/grg/hudson/grg338c/schedule/3_erosion_sed/sediment_transport_suspended.html (2014).

The erosivity of rainfall is dependent upon rainfall kinetic energy, this is determined by individual rain drop characteristics such as drop size, mass and fall velocity. The intensity and duration of the storm also has an effect (Morgan and Duzant, 2008). Raindrop impact can alter the soil surface (Figure 2.5). It can compact the soil creating a dense, low permeability layer of soil at the surface, commonly known as a structural seal when wet, and a crust when dry (Bradford et al., 1987). Soil aggregates are broken down (creating easily detachable material) by raindrop impact, or through slaking (Assouline, 2004). In this process soil wetting weakens the cohesion within soil aggregates causing them to collapse (Morgan, 2005). The resulting soil particles are dispersed by the splash jets of impacting raindrops (Figure 2.3) and are then deposited back onto the soil surface where they can clog soil pores. This sedimentation process also forms a surface seal (Assouline, 2004). Consequently, soil infiltration is reduced increasing the risk of runoff and crop yield impacts.

In addition to rain splash detachment, soil can become detached by the scouring action of rainfall-induced surface overland flow (Hillel, 2008). When infiltration is reduced as a result of poor soil structure or land becomes saturated, water begins to flow over the surface. When slope gradient is $>0^{\circ}$, the velocity of this water increases resulting in kinetic energy which is expended to detach unstable soil. This process results in the formation of micro-rills, rills and gullies.

Figure 2.3. The action of a falling raindrop striking the soil surface.

Soil erodibility is determined by soil properties that affect their susceptibility to erosion. Stable, well-structured soils are not generally easily detached. Soil stability originates from the internal bonds existing within aggregates reinforced by clay particles, organic matter, microorganisms and plant roots (Hillel, 2008). Soils with a restricted clay content of < 30 % are considered to be the most susceptible to erosion (Evans, 1980). Organic matter addition can be a catalyst to improved soil structure. It is able to bond with soil particles directly, and encourage microbial communities that further increase particle bonding (Hillel, 2008). Low organic matter soils (> 2 %) therefore are more prone to detachment (Fullen, 2000). Field cultivation can also increase the likelihood of soil detachment as it creates a loose and unstructured soil layer (Reed, 1983).

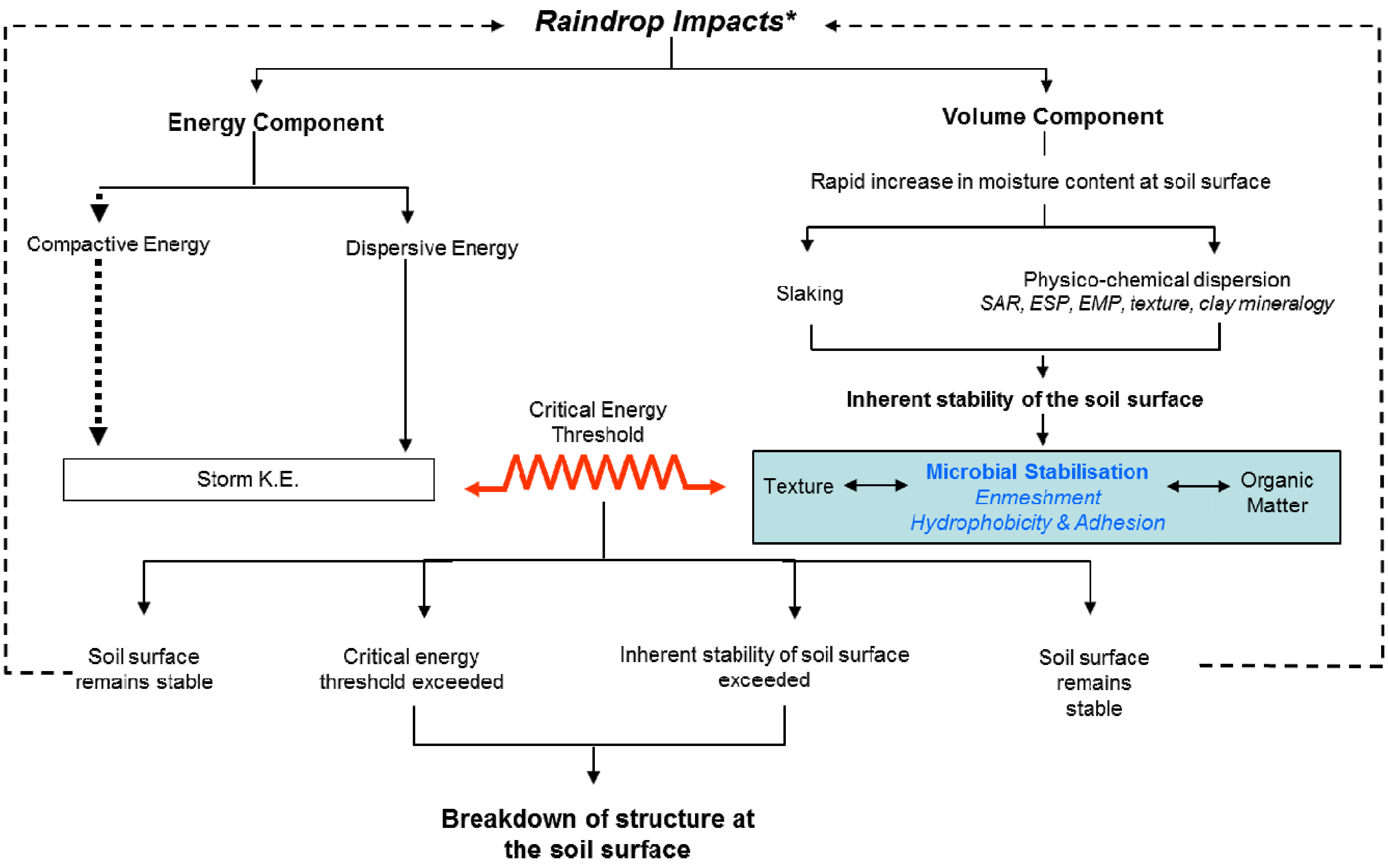


Figure 2.4. The consequences of raindrops on the soil surface. Source: Modified from Simmons (1998).

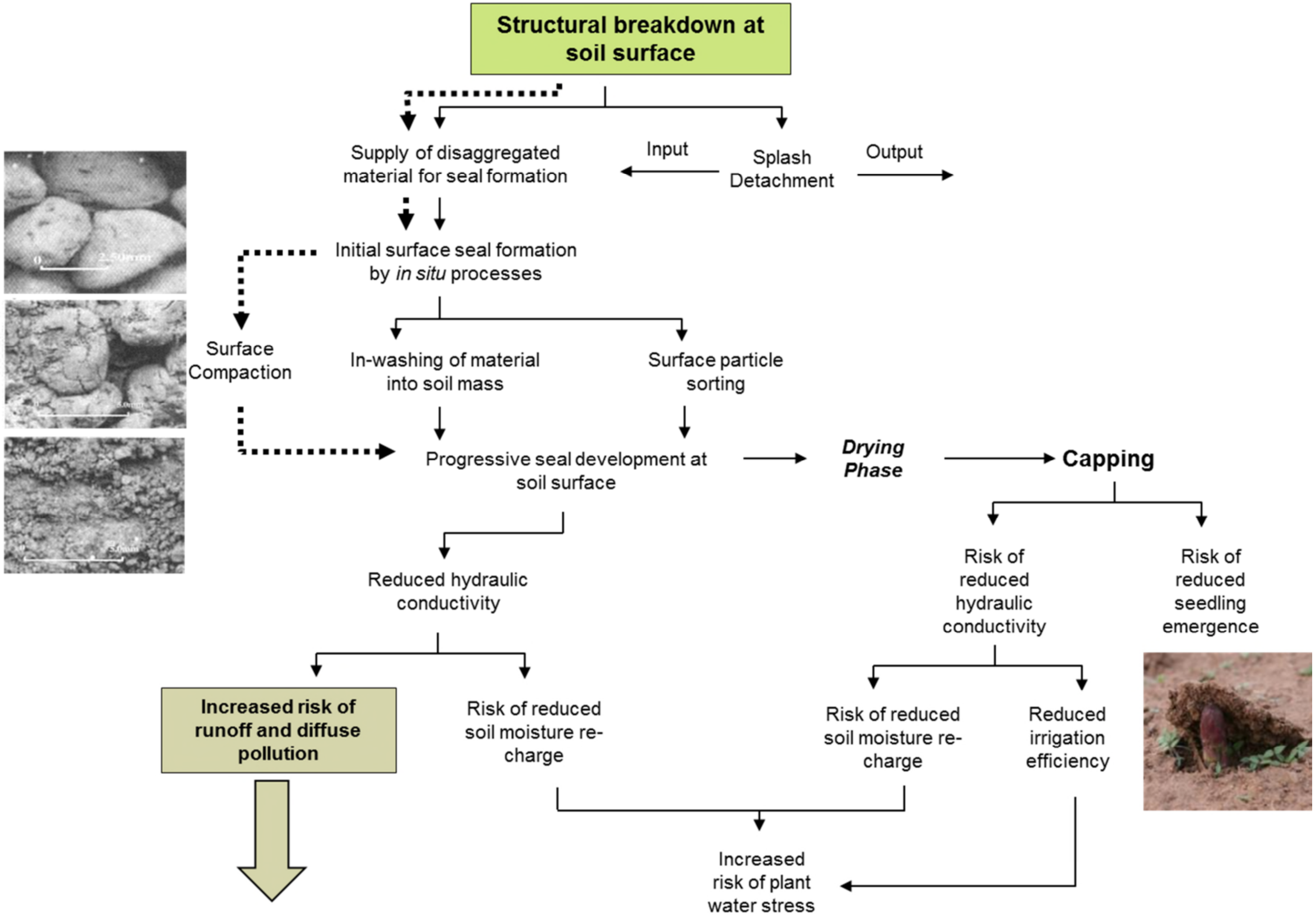


Figure 2.5. The soil surface response to raindrop impact and resulting effects. Modified from Simmons (1998).

In row crops, the probability of soil detachment by rainfall is high due to the large extent of bare soil between crops that facilitate various field operations. Furthermore some field operations, such as de-stoning in potato crops and harvesting in carrot production, produce a large layer of disturbed, structure-less soil, which is highly susceptible to detachment, often resulting in the formation of rills and gullies. Compaction between rows from field operations also reduces soil structure and increases the generation of surface flow, making the soil more susceptible to detachment.

2.1.1.2 Sediment entrainment

Detached soil particles can become entrained within the splash jets of raindrops impacting on the soil surface and within runoff. For the latter, entrainment is dependent upon the volume and velocity of runoff and the size of the detached soil particles. Runoff of a moderate velocity will first entrain smaller non-cohesive particles such as silts and fine sands (Quinton et al., 2001), extending to larger particles if the velocity is increased (Figure 2.2).

Steeper slope gradients increase the likelihood of entrainment as runoff velocity is increased (Table 2.1). In some raised-bed row crop systems, cultivation follows the predominant slope fall line, in order to avoid water ponding. This is also the case where harvest operations are impaired by the slope gradient when cultivated across slope making it necessary to cultivate up and down slope (EA, 2007). This generates long down-hill runs where high runoff velocities can be generated, thus enabling more energy with which to entrain detached sediment. Compaction between row crops as a result surface sealing and trafficking further facilitates high runoff volume and velocity, as these conditions create a relatively smooth channel-like surface over which the runoff can flow easily without hindrance.

2.1.1.3 Sediment transport

The degree to which detached soil is transported depends upon the runoff volume and runoff velocity, which is often determined by the gradient of the land. Runoff volume determines the carrying capacity of detached soil, with greater volumes capable of transporting more soil. Meanwhile, runoff velocity dictates the particle size that can be transported. When velocity is slowed, the heavier particles are the first to be deposited (Figure 2.2).

Today, row crops are grown without interruption over large open areas of land over which water can flow and gain speed. Finer fractions including clay and organic matter are transported away from where they are most needed, leaving behind coarser low-nutrient soil particles (Dalzell et al., 1987).

Table 2.1. Risk associated with erosion based on soil type and slope gradient. Source: DEFRA (2005).

Soils	Steep slopes >7 degrees	Moderate slopes 3 – 7 degrees	Gentle slopes 2 – 3 degrees	Level ground < 2 degrees
Sandy and light silty soils	Very high	High	Moderate	Lower
Medium and calcareous soils	High	Moderate	Lower	Lower
Heavy soils	Lower	Lower	Lower	Lower

2.1.2 Impacts

2.1.2.1 Soil degradation

Soil loss is often not an immediate concern for farmers as significant losses of soil, fertiliser and crops do not occur (Boardman and Evans, 2006), but it can result in long-term impacts. As discussed above, lighter soil particles are the most easily detached during soil erosion, leaving behind coarser materials (Dalzell et al., 1987). However, organic matter is also sufficiently light to become easily eroded, and is found in high concentration in eroded soil (Schwab et al., 1957). Rees et al. (2002) reported eroded soil to contain 2.3 times the organic matter content found in the in-situ, un-eroded soil. Soil organic matter improves soil water holding capacity, soil structure and tilth, and provides a carbon substrate for soil microorganisms (Lal, 2004). Without organic matter water is less able to infiltrate making the soil more susceptible to erosion and therefore at a greater risk of further degradation. Soil erosion also reduces soil depth. This can have an impact on crop yields as less growing media is available (Table 2.2).

As soil becomes displaced the nutrients and organic matter lost needs to be replaced. As well as the cost implications of inputting these components back into the soil, some nutrient inputs are becoming scarcer and so in the future could become irreplaceable. Whilst nitrogen-based fertilisers are in abundance, the commercially viable reserves of rock phosphate are limited (Rosemarin et al., 2010). Reserves are currently estimated to last between 48 to 235 years depending on the agricultural production of the developing world (Rosemarin et al., 2010). This reinforces the need to control agricultural losses in order to preserve the longevity of our existing phosphorus reserves.

Further to a reduction in soil quality and health, large erosion events result in rill and gully formation (Figure 2.6). These damage agricultural land, expose plant roots and interrupt farming operations, so need to be filled in to maintain crop production.

Figure 2.6. Gully formation from asparagus wheelings. Runoff from the compacted wheelings forms deep rills in the relatively less-compacted track way. These rills run downslope, and merge to form one deep gully.

Table 2.2. Impact of past erosion and resulting differences in soil depth on crop yields (European data). Source: den Biggelaar et al. (2004).

Crop	No of records	Mean duration of experiments (yr)	Mean of mean experimental crop yield (Mg ha^{-1})	Erosion-induced yield loss			Source
				Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Kg ha^{-1} Mg^{-1} soil erosion	% Mg^{-1} soil erosion	
Wheat	8	4	3.5	0.026 ((-0.058) to 0.097)	0.17	0.00	Burnham and Mutter, 1993; Duck, 1974; Evans and Nortcliff, 1981; Krisztian et al., 1987; Krumov and Tzvetkova, 1998; Tikhonov, 1960; Vernander et al., 1964
Barley	11	3	2.5	0.052 ((-0.023) to 0.174)	0.35	0.01	Biot and Lu, 1993; Duck, 1974; Dzhadan et al., 1975; Evans and Nortcliff, 1978; Krisztian et al., 1987; Lu and Biot, 1994; Tikhonov, 1960; Xu and Biot, 1994

Crop	No of records	Mean duration of experiments (yr)	Mean of mean experimental crop yield (Mg ha^{-1})	Erosion-induced yield loss			Source
				Mg ha^{-1} cm^{-1} soil erosion, mean (range)	Kg ha^{-1} Mg^{-1} soil erosion	% Mg^{-1} soil erosion	
Millet	2	4	0.3	0.011 (0.005 to 0.018)	0.08	0.02	Tikhonov, 1960
Soybeans	1	10	0.6	0.020 (n/a)	0.13	0.02	Krisztian et al., 1987;
Potatoes	2	5	11.4	0.084 (0.018 to 0.150)	0.56	0.00	Krumov and Tzvetkova, 1998; Tikhonov, 1960;

2.1.2.2 Off-site impacts

Agricultural runoff contains soil, agrochemicals, minerals and fertilisers. Two nutrients most commonly found in agricultural runoff are nitrogen and phosphorus. Together with soil, these make up the three largest contributions of agriculture to water pollution (Figure 2.7). Soil contained within runoff can have negative off-site effects. For water companies, additional costs in water treatment can be incurred to achieve necessary drinking water quality standards. Sediment can also reduce reservoir storage capacities and increase the risk of river flooding. Deposited sediment can smother fish spawning grounds, reduce food supply to aquatic organisms and promote large growths of aquatic vegetation that may further increase flood risks by decreasing watercourse capacity (Defra 2009). As a result of the effects of detached soil on river ecosystems a guideline of 25 mg l^{-1} has been provided for annual suspended sediment levels in rivers (Collins et al., 2008).

One of the common pollutants derived from nitrogen is nitrate. This is formed from the mineralisation of ammonia fertiliser (Merrington et al., 2002). Nitrate is very soluble and remains in the soil solution, so that it is easily available to crops (Merrington et al., 2002). However, once in contact with a water course it can, depending on its concentration, kill fish, cause eutrophication (e.g. excessive algae growth with high biological oxygen demand), and lead to untreatable sources of drinking water (Defra, 2009). Nitrate removal in drinking water has been estimated to have cost England and Wales £ 184 million between 2004 and 2009 (NAO, 2010). The Water Framework Directive (WFD, 2000) in its drive for 'good ecological status' within rivers and other water bodies has stipulated a nitrate concentration limit of 25 mg l^{-1}.

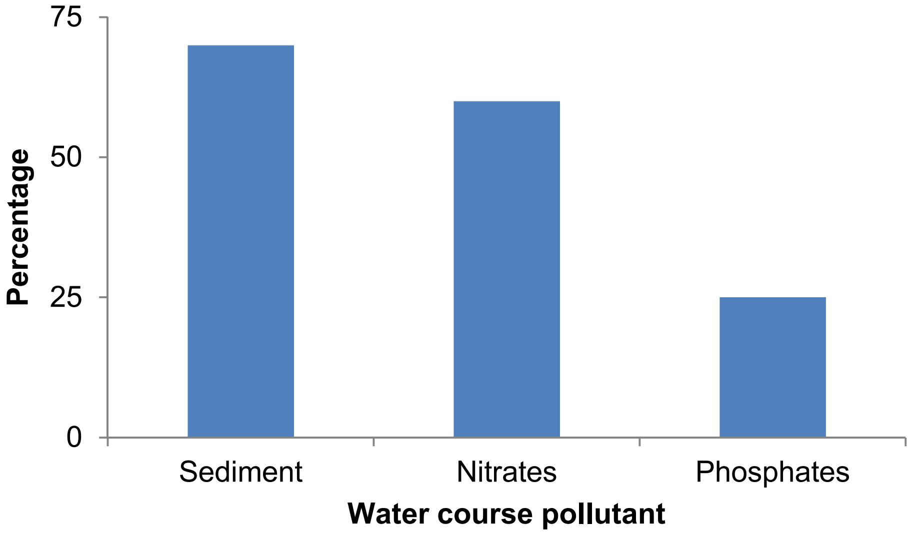


Figure 2.7. Agriculture's contribution to total sediment, nitrate and phosphate pollutants found in English water courses. Data source: NAO (2010).

Phosphorus is less soluble than nitrogen (Balana et al., 2012). Whilst present in soil solution in a small amount, it is strongly absorbed onto soil surfaces and can be lost in both the entrained soil particles and surface runoff (Cherry et al., 2008). Only 30 % of the phosphorus added as fertiliser is retained within the soil (Rosemarin et al., 2010). High levels of phosphorus in watercourses can, as with nitrogen, lead to eutrophication. As a result, the WFD (2000) has stipulated limits for soluble reactive P of between 0.04 and 0.12 mg l^{-1} dependent upon water body alkalinity and elevation.

2.2 Compaction

Compaction, alongside soil erosion, is the costliest and most environmentally damaging consequence of conventional agriculture (FAO, 2003). Graves et al. (2011) estimated the cost of soil compaction in England and Wales at £472 million a year. This figure includes the on-site cost of nutrient and productivity loss, the increase fuel required to work compacted soils and the environmental cost of nutrient and sediment pollution as well as greenhouse gas losses. In Europe alone it is believed to be responsible for the degradation of 33 million hectares (Hamza and Anderson, 2005), of which 3.9 million hectares is deemed at risk in England and Wales (Graves et al., 2011).

Compaction can increase the risk of erosion as a result of increasing soil bulk density and decreasing void spaces (Hamza and Anderson, 2005). This decreases infiltration rates and lowers thresholds at which rainfall becomes erosive (Fullen, 2000), as the inter-locking forces between particles decrease, making the soil more susceptible to detachment. The reduced infiltration also increases runoff generation, which on sloped land can result in overland flow (Batey, 2009). Therefore, where soil detachment has occurred, compaction can facilitate the entrainment and transport of soil. Silgram et al. (2010) studied tramline runoff in cereal fields, finding that such areas of compaction are important pathways for phosphorus and sediment.

Compaction can be caused by any degree of loading applied to the soil surface. The extent of the compaction depends upon the nature of the loading and the physical properties of the soil at the point where and when the load is applied. The complex interactions between these factors can make compaction very difficult to predict (Larson et al., 1980).

2.2.1.1 Susceptible soil types

Some soil types have properties that pre-dispose them to compaction. These properties fall into two categories; frictional resistance and cohesion (Jones et al., 2003). Stable soils with good aggregate stability, particle size distribution, soil organic matter and low soil moisture content, have both frictional resistance and cohesion.

Clay soils are the most susceptible soil type to compaction, and silt soils the least (Graves et al., 2011). The percentage of soil organic matter affects a soils frictional resistance to compaction, as organic matter holds the soil open, creating voids, reducing the impact of soil loading (Davies et al., 2001). Organic matter also increases the cohesion between soil particles increasing soil strength and reducing deformation. Soil moisture content can affect cohesion. High soil moisture content can weaken the cohesive forces between soil particles (Mouazen et al., 2002) making it more likely to deform under loading (Hamza and Anderson, 2005). Soils that have been recently loosened are also particularly vulnerable to compaction as soil aggregates have been re-organised and require time to stabilise into an improved profile (Spoor, 2006). Compaction following tillage has been found to decrease hydraulic conductivity beyond the pre-tilled conditions (Unger and Cassel, 1991).

2.2.2 Causes of compaction

In row crops, factors affecting soil compaction include loading by agricultural machinery (tractors, trailers etc.), and where crops are hand-harvested, human trampling (foot traffic). Research has been predominantly undertaken on vehicle-based compaction, known as trafficking, as load mass and distribution can be easily manipulated to reduce compaction risk, such as the use of low ground pressure tyres or tracks as an alternative to tyres.

2.2.2.1 Agricultural machinery induced compaction

Agricultural machinery induced compaction can occur by two methods; soil loading and compaction form cultivation implements. Agricultural machinery has high axle loadings that in turn apply massive force onto the soil surface. All agricultural machines used today exert ground contact pressures that can induce compaction (Hetz, 2001). The total force exerted is dependent upon the total axle weight and the soil surface contact area. The resulting compaction radiates from the wheel contact area affecting both the topsoil and sub-soil, and can lead to surface rut formation (Hamza and Anderson, 2005, Figure 2.8).

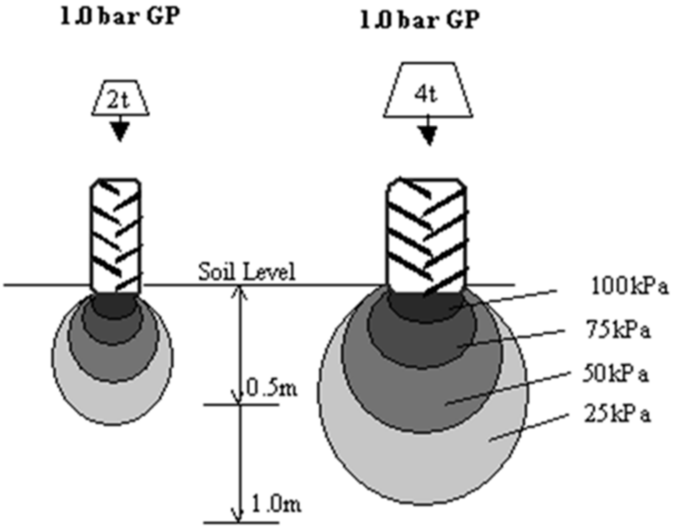


Figure 2.8. Distribution of pressure stresses beneath a lightly loaded small tyre and a heavily laden large tyre exerting similar ground pressures. Source: Forristal (2003).

The degree of the resulting compaction depends upon several factors. These pertain to both the machine; the total axle load, wheel type, tyre dimensions, tyre pressure and number of passes, and the soil; soil type and moisture content. Greater axle loads cause greater subsoil compaction (Botta et al., 1999). Tracks as opposed to tyres are known to better distribute axle loads resulting in less compaction. When using tyres wider treads equate to a better distribution of load resulting in reduced compaction, as do lower tyre pressures. The frequency of vehicle passage over the soil will also affect compaction extent. Whilst it could be assumed that with more vehicle passes compaction will increase, laboratory research suggests that the first pass of a vehicle causes the most soil deterioration of up to 90 % of the total increase in density, subsequent trafficking further degrades soil condition but to a lesser extent (Davies, et al., 2001, Figure 2.9).

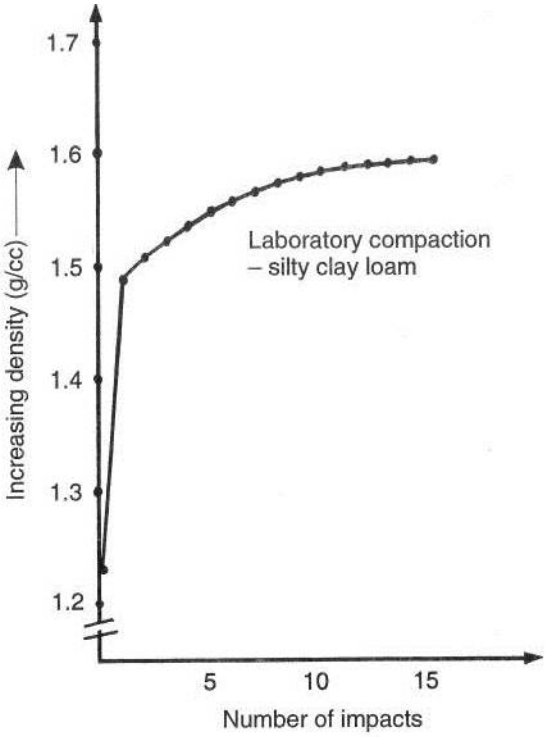


Figure 2.9. The impact of the first wheeling and subsequent wheelings on soil density. Source: Davies et al. (2001).

In addition to machinery tyres, cultivation equipment can cause compaction. This compaction occurs below the depth of cultivation, and can be referred to as a plough pan. Considering tillage operations, a tine, if used too deep can cause compaction. As the working depth increases so too do the compressive forces operating on the tine. This results in inhibited soil failure, where only a leg slot is created whilst the foot-soil interface compresses the soil compacting it to the sides and below (Spoor, 2006). The point at which forces become compressive is referred to as critical depth. Due to the inherent variation in soil properties, critical depth is not something that is easily ascertained in the field; however, it can be observed by assessing the degree of disturbance following the first tine pass (Spoor, 2006, Figure 2.10).

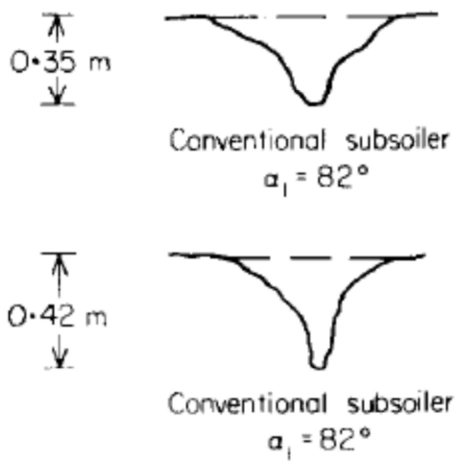


Figure 2.10. Soil disturbance patterns of a conventional subsoiler both above (0.35 m) and below critical depth (0.42 m). Source: Spoor and Godwin (1978).

2.2.2.2 Foot trafficking/human trampling

The soil response to foot trafficking has been little investigated in an agricultural setting. However, research on military training areas and recreational land has been undertaken, and has demonstrated that foot trafficking does result in compaction. These findings, particularly from recreational land can be applied to on-farm, in-field foot-trafficking, as the processes operating between crop rows are not dissimilar to those on unsurfaced footpaths.

Quinn et al. (1980) investigated the trampling forces exerted by the foot when walking upslope (Figure 2.11). The foot exerts a maximum compressive force at heel strike followed by lesser compressive forces from the toe prior to the foot being lifted off. The force of the toe pushing off the ground also exerts a shear stress force. From this, Quinn et al. (1980) deduced that whilst heel strike would result in compaction and vegetation damage, pressure from the toe would wear vegetation and damage the footpath surface. Resulting heel strike compaction has been observed in the top 3 to 5 cm's of soil (Kuss 1983).

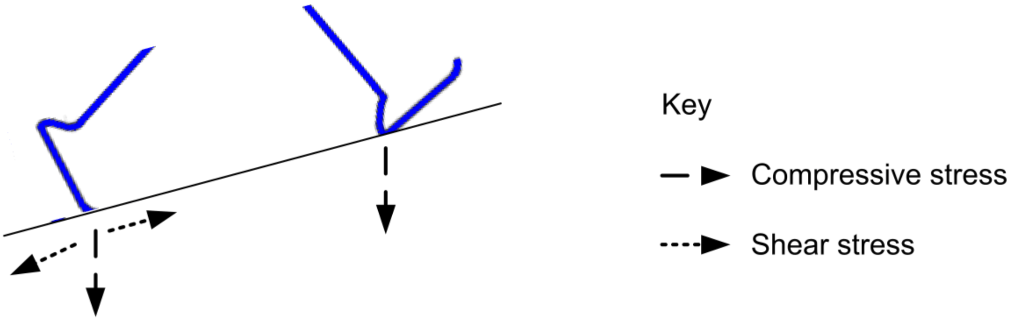


Figure 2.11. The forces exerted on the soil surface whilst walking upslope. Based on experimental results from Quinn et al. (1980).

Monti and Mackintosh (1979) support this observation. On boreal forest soils, increasing foot traffic intensity first removes surface organic matter, and then forms a thin compacted mineral layer. This led to an increased bulk density, a reduction in macro-pore area of up to 60%, and reduced infiltration rates to less than 0.1 cm min^{-1}. Post-construction changes in the degradation of recreational footpaths occur with initial or low levels of use (Leung and Marion, 1996). Changes then diminish with increasing use. This suggests, as with vehicle compaction, that soil degradation occurs from the first passes even with low intensity traffic.

The toe-pressure imparted by foot traffic responsible for wearing vegetation could result in the downslope displacement of soil, as it loosens and detaches soil particles (Quinn et al., 1980). This detached material can later be transported downslope by overland flow. However, Quinn et al. (1980) found that with rainfall, soil loss was not initiated until 900 passes. Whilst runoff was initially high, it levelled off with increasing passes due to the surface depression storage created by foot print indentations. Kuss (1983), compared two different trampling intensities and found that the sediment yield in runoff increased with higher intensities, and remained (all be it at a lower level) 41 days after trampling had ceased.

2.3 Asparagus agronomy

Asparagus is a perennial crop that can grow for approximately 15 years in a single rotation (Hamel et al., 2005). It is a high value crop, requiring a lot of initial financial investment. Asparagus (*Asparagus officinalis*) exhibits autotoxicity, meaning that with time asparagus crops lead to *fusarium* build-up in the soil that can lead to its own decline (Batish et al., 2001). Therefore once asparagus decline has fully set-in a new asparagus crop cannot be successfully re-grown in the same field. This makes initial crop management very important. An overview of asparagus agronomy is provided in Figure 2.12.

Asparagus is grown on a raised bed system in order to prevent beds from becoming water logged as rainwater is channelled into the wheelings that are situated in between each bed. Following initial plantation, the crop is not suitable for harvest until the second year. The rhizome root mass, known as the crown, sends shoots upwards that come through the soil surface as asparagus spears. Once the spears are of a marketable size, they are hand-harvested, by pickers on foot and cut just below ground. The typical UK asparagus season runs from April 23rd to June 23rd, but harvest can be extended using plastic cloches installed over the beds to create hospitable temperatures for crop emergence. After harvest, the asparagus plants develop into ferns that naturally senesce and are later chopped and incorporated into the beds to prevent disease from *Stemphylium vesicarium* .

Typically asparagus consumed in the UK market originates from Peru where the climate is favourable and the production costs low. However, concerns over the detrimental environmental impacts of excessive 'air miles' and the demand for home grown produce mean that suitable conditions are being developed in the UK where asparagus can grow. Consequently, home-grown asparagus is increasingly seen on supermarket shelves.

2.3.1 Soil impacts of asparagus production

A ‘typical’ asparagus production year has several potential environmental and economic impacts that revolve around soil and water management (Figure 2.12). Compaction and soil erosion are big on-site issues witnessed on some asparagus producing fields. Both issues are worsened by cultivation practices, including minimal surface cover, low organic matter, cloching, and a poor soil legacy (Figure 2.13).

2.3.1.1 Soil erosion

Asparagus production is typically undertaken on sandy free-draining soils. Such soil types have a very low clay and organic matter content making them initially susceptible to erosion (MAFF 1969). Furthermore, asparagus cultivation up and down slope gives inclined and long slopes over which runoff could potentially entrain and transport detached soil.

Asparagus practices (Figure 2.12) are synonymous with extremely low vegetative cover on the soil. Approximately 65% of a typical asparagus production year sees fields with negligible surface cover. This leaves the susceptible soil exposed to the full kinetic energy of erosive rain drops and is thus vulnerable to erosion (Figure 2.4). This can lead to the formation of a surface crust that reduces the infiltration of the soil increasing runoff into the wheelings (Figure 2.13). Both raised beds and wheelings are left bare over winter when rains are deemed to be most erosive. In early spring, spears offer little soil protection on the beds, and wheelings remain bare until fern development. Plastic cloches installed over the beds for 5 months of the year provide an impermeable rainfall barrier. This diverts rainfall onto the bare wheelings, further exposing them to erosion risk (Figure 2.13). In late summer, asparagus fern intercepts rainfall protecting the bed and to some extent the wheelings from direct rainfall impact.

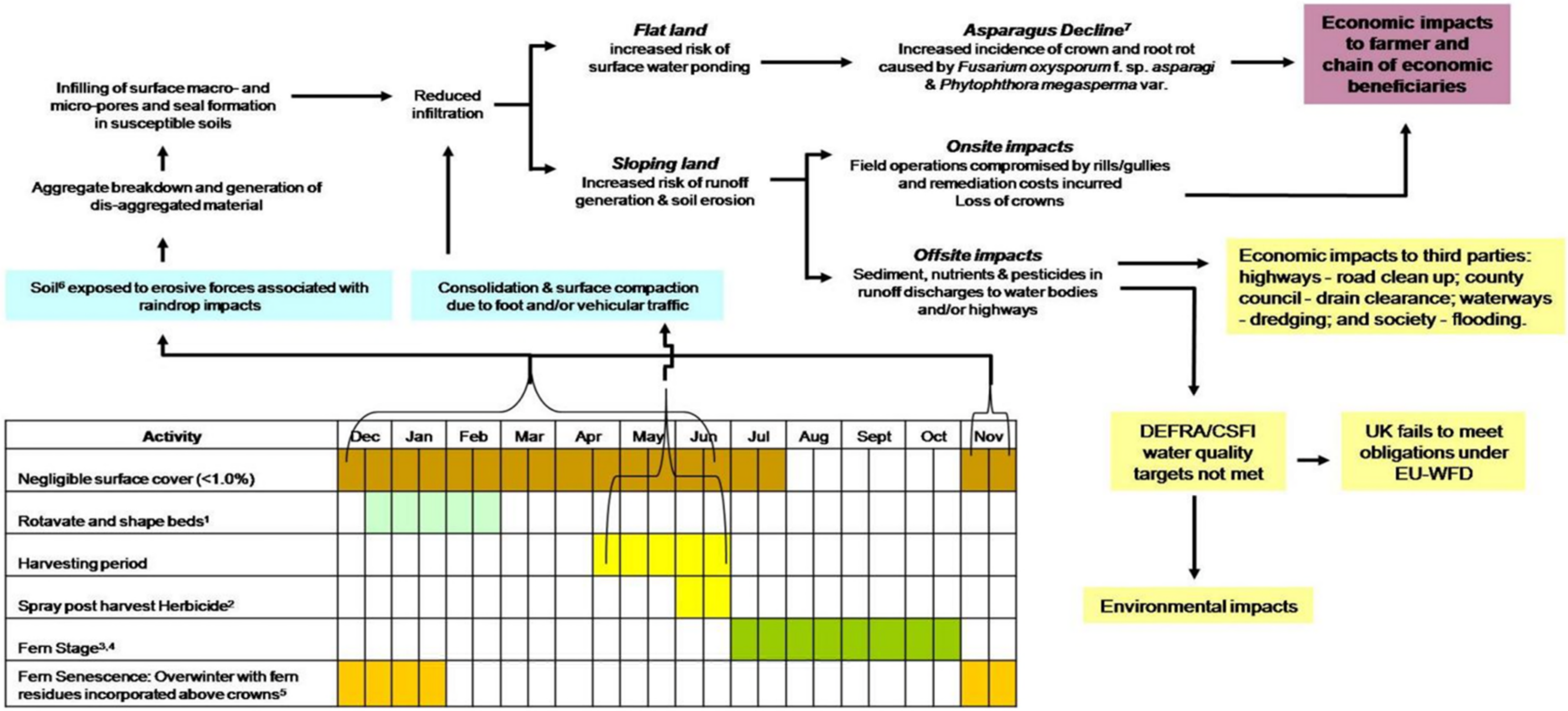
2.3.1.2 Compaction

Compaction is a significant problem in typical asparagus production systems. This is a result of poorly structured soil, multiple machinery passes and the requirement to access land daily during harvest.

Current asparagus agronomy can consist of many different field operations with varying breadths of operation; bed forming, subsoiling, plastic cloche hoop and plastic laying, spraying, fern topping and incorporation. Consequently every asparagus wheeling is trafficked. Furthermore, during the harvest season harvest workers that hand-pick the asparagus will walk the wheelings as often as twice daily, irrespective of weather conditions. This further contributes to compaction and in wet weather increases the risk of soil smearing. When soil is smeared it seals over any open pores at the surface inhibiting water infiltration (Morgan, 2005).

2.3.1.3 Soil legacy

Every field has a soil legacy, namely the soil condition that exists following the previous land use and its management. The nature of the previous crop will determine initial soil properties. In the UK, fields available for new crops such as asparagus tend to be former potato fields that are no longer suitable as a result of a high Potato Cyst Nematode (PCN) index. Following potato cultivation, a legacy exists of intensively cultivated soil to depth, probable compaction and low stone content (Chow et al., 1990). When compounded with subsequent asparagus agronomy, this legacy results in an increased erosion risk.



Activity	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
Negligible surface cover (<1.0%)	■	■	■	■	■	■	■	■				■
Rotavate and shape beds[1]	■	■	■									
Harvesting period					■	■	■					
Spray post harvest Herbicide[2]							■					
Fern Stage[3,4]								■	■	■	■	
Fern Senescence: Overwinter with fern residues incorporated above crowns[5]	■	■										■

[1]Weed control: Residual pre-emergence herbicide (Sencorex; Flexidor; Stomp 400SC); [2]Weed control: Post harvest herbicide (Sencorex & Centium); [3]Control Purple Spot (*Stemphylium vesicarium*) and Botrytis: Up to 6 sprays (Mancozeb, Plover, Signum, Amistar); [4] Control asparagus beetle: Spray Insecticide (Cypermethrin); [5]Control of *Pleospora allii* (sexual stage of *Stemphylium vesicarium*); [6]Asparagus prefers well drained sandy light textured erodible soils; [7]Incidence of crown and root rot tends to be associated with 'active' and not 'dormant' crowns.

🟦 Primary stage of management intervention

Figure 2.12. Potential environmental and economic impacts associated with 'traditional' asparagus cultivation methods. Source: Simmons (2010).

2.3.2 Importance of soil and water conservation

Sound soil and water management is not just pertinent to soil protection. In asparagus production, poor soil and water management can lead to disease and crop decline (Figure 2.12). Disease control is particularly critical to ensuring a good yield over the full length of the asparagus production cycle (approximately 15 years). Asparagus crops are threatened by several pests and diseases: Purple spot, *botrytis*, and asparagus beetle. Most of these can be managed using chemicals, however, *fusarium* and *phytopthora*, both soil borne diseases, pose a constant threat that instead requires careful environmental management.

Fusarium can invade the roots/crown of asparagus early-on and reside as a parasite (Nigh, 1990). Once the plant becomes stressed, the parasite becomes pathogenic, causing crown and root rot (Hamel et al., 2005, Damicone, 1987)). Stressors can include; poor soil drainage, drought, weed competition, tillage and soil compaction (Nigh, 1990; Drost, 1999; Wilcox-Lee and Drost, 1991). According to Nigh (1990), *fusarium* risk can only be managed by first minimising the risk of early-on infection of the crown/roots. After that, careful environmental management to minimise stress to the asparagus is required. *Phytophthora* survives in the soil as oospores, producing asexual sporangia under wet conditions (Snowdon, 1991). Infection results in reduced asparagus yield and plant death (Snowdon, 1991). Fungicide application can help control *phytophtora* (Snowdon, 1991); however, field conditions also have an effect. After heavy and prolonged periods of rain, sporangia are mobilised and invade the crowns, so infecting the asparagus (Snowdon, 1991).

On-site soil and water management can help maintain a healthy asparagus stand, and will dramatically reduce the risk of crown and root rot. MAFF (1969) verifies this, documenting that wet soil during winter is especially known to cause crown rot, resulting in serious yield losses. Falloon et al. (1986) also demonstrate higher yield losses from *phytophthora* when field conditions were cool (15°C soil temperature) and wet, as opposed to warm (27°C soil temperature) and dry. If water is unable to infiltrate into the soil it will either runoff on slopes, or pond on the surface (Reed, 1983). Runoff risks depleted soil health, however in asparagus water ponding increases risk of disease generating favourable conditions for *phytophthora* and *fusarium* infection. In order to prevent ponding, asparagus ridges and cultivations are oriented downslope, increasing the risk of soil erosion.

The ability to improve infiltration and reduce runoff and erosion from asparagus fields will also further deliver multiple benefits both on and off site, over several timescales. In the short term, on-site labour costs could be reduced. This could occur as a result of a reduction in field operations required to fill gullies and large rills that affect land accessibility and future field operations. The development of a new erosion control method could also result in less field operations (e.g. subsoiling operations) than currently carried out to address the problem. Furthermore, improved traffickability as a result of improved soil moisture status could improve the timeliness of field operations and reduce subsequent compaction. An improved soil moisture status could also improve picker efficiency and fatigue. In the short-term off site issues and associated costs could also be reduced as a result of a reduction in watercourse pollution events from entrained soil particles and nutrients. This will not only reduce the risk of financial penalties (e.g. EA fines) but will also help maintain a good level of ecological health within the water body as required by the WFD. In the long term an improvement in infiltration will reduce nutrient loss in runoff, together with organic matter and finer soil fractions, maintaining a degree of soil fertility and reducing input costs. Furthermore the improvement of soil moisture re-charge will improve plant nutrient uptake, reduce plant water stress and reduce the need for supplementary irrigation. This could also improve the re-charge of root carbohydrates during the fern stage. Over the profitable asparagus production period (10-12 years) this could result in an increase in yields without increasing inputs.

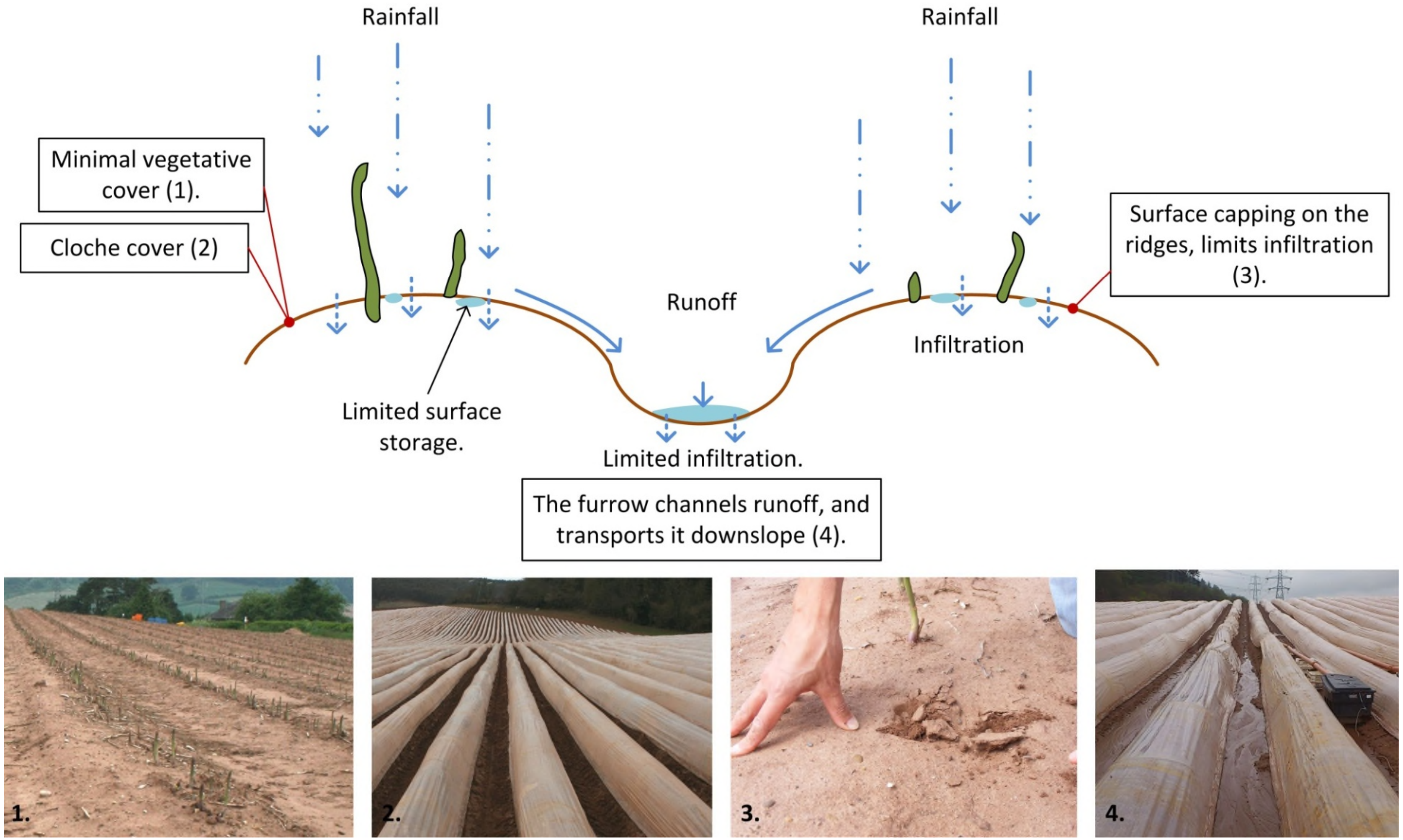


Figure 2.13. Agronomic factors of asparagus production contributing to soil erosion, compaction and runoff.

2.4 Soil erosion management measures

Soil erosion can be managed by manipulating variables known to influence erosion rates. These variables include slope (length and gradient), surface water storage, surface protection, surface roughness and soil compaction. Table 2.3 reviews existing erosion and runoff control measures relative to the perceived suitability for adoption in asparagus production. No previous erosion studies have been found on soils under asparagus production. The erosion and runoff control measures that appear most suitable for application in asparagus production are considered to be surface mulch application and shallow soil disturbance.

2.4.1 Surface cover

Surface cover both protects the soil surface and imparts a degree of surface roughness (Dalzell et al., 1987; Foster et al., 1982). Rainfall can be intercepted by surface cover that protects the soil surface from the compacting and detaching energy of rain splash (Dalzell et al., 1987; Morgan, 1979). This can protect a soil surface from sealing (Zuzel et al., 1990) and maintain infiltration thus reducing entrainment and transport. Following rainfall interception, the cover can collect and absorb some of the rainfall depth (Persyn et al., 2004) thus reducing runoff volume and the associated entrainment and transport of eroded material. This intercepted rainfall could be permanently excluded from runoff generation through later evaporation (Duran-Zuazo and Rodriguez-Pleguezuelo, 2008). An increased surface roughness can reduce runoff velocity affecting the entrainment and transport capacity of runoff, so reducing soil erosion rate. As velocity decreases, less entrainment will occur, and runoff has a greater opportunity to infiltrate, thus reducing the runoff volume available to transport detached particles (Persyn et al., 2004). Manning’s n typically expresses the effect of surface roughness in soil conservation studies (Morgan, 2005).

Table 2.3. A review of existing erosion and runoff control measures and their suitability to current asparagus production.

Control type	Key references	Erosion/runoff control function	Suitability to asparagus production.	
Field Layout				
Grassed strips	Shipitalo et al., 2010	Reduces runoff velocity forcing deposition of entrained soil particles.	Not suitable for established asparagus fields.	
Slope management				
Terraces	Morgan, 2005	Shortens steep slopes, reducing runoff velocity, entrainment and transport capacity.	Slopes are not steep enough to benefit.	-
Bunding	Morgan, 2005	Reduces runoff velocity forcing deposition of entrained soil particles.	Not suitable for furrow trafficking.	-
Cross contour cultivation	Stevens et al., 2009	Reduces slope gradient reducing runoff velocity, entrainment and transport capacity.	Water ponds in between furrows causing asparagus decline.	-
Increase surface storage				
Tied ridging	Roose, 1996	Reduces runoff volume, when full with water it protects the soil surface from detachment.	Puts asparagus at disease risk. In downslope cultivation storage ponds are susceptible to breaching. Not suitable for hand-harvest practices.	-
Soil cover				

Control type	Key references	Erosion/runoff control function	Suitability to asparagus production.	
Crop residue	Shock et al., 1997	Protects soil from detachment by rainfall. Reduces soil entrainment and transport using surface roughness and storage. Adds organic matter to the soil reducing soil erodibility.	Asparagus has little crop residue. The residue that it has is already incorporated into the soil above crowns for disease control.	-
Cover crops	Brainard et al., 2012	Intercepts rainfall protecting the soil from detachment. Root mass further prevents soil detachment.	Concern of water and nutrient competition. Current herbicide regime Weed kill rate too high to support this.	-
Surface mulch	Silgram et al., 2010	Same function as crop residue.	Suitable if applied to furrows where most erosion is observed.	+
<u>Soil conditioners</u>				
Polyacrylamides	Lentz et al., 1994	Acts as an adhesive between soil particles reducing detachment.	Leaves soil exposed to rainfall.	-
<u>Compaction alleviation</u>				
Controlled traffic farming	Chamen et al., 1992; Chamen, 2006	Reduces runoff volume and velocity by reducing compacted tramlines.	Many operations are currently undertaken on different wheelings, with some machinery being specifically designed on-site. Loss of land to wheel tracks is not an issue as furrows are not planted.	-

Control type	Key references	Erosion/runoff control function	Suitability to asparagus production.	
Soil disturbance	Sharma, 1991.	Increases soil porosity, increasing infiltration reducing runoff volume and velocity with surface roughness and storage.	Sub-surface cultivation is already routinely undertaken to improve infiltration, as are other cultivations such as asparagus bed formation that result in soil disturbance.	+

Mulch is a suitable option for asparagus production. Crop residues are not typically available due to mono-culture cropping systems and the adoption of disease prevention practices with the small amount of existing asparagus residue. In the literature many mulch types have been applied for erosion control in construction and agricultural applications; straw, wood chips / shavings, compost (green waste, municipal solid waste, poultry waste, bio solids and food waste) and geotextiles such as coconut fibre blankets (Table 2.4). Despite this, few mulch types have been studied in a UK horticultural context, particularly in row crop systems. Of all the mulch types, straw has been studied the most. This section will focus on two mulch types that are easily sourced in the UK; cereal straw and compost materials which have become more abundant recently because of improved recycling of green waste.

2.4.1.1 Cereal straw

Studies in irrigation furrows and under rainfall (both natural and simulated) have found straw to be an effective means of reducing soil loss, and to some extent runoff volume (Table 2.5). Furthermore, the addition of straw has had additional benefits to soil condition.

Such benefits include increased soil moisture, increasing the water available for crop uptake (Shock et al., 1997, Brown and Kemper, 1987 and Berg, 1984). In compacted furrows this has been achieved through increased lateral wetting as the straw holds back the water allowing a greater wetting front (Shock et al., 1997 and Berg, 1984). This increased water uptake often results in increased yields (Holstrom et al., 2008, Brown and Kemper, 1987, Berg, 1984). Straw can also add organic matter to the soil; however, its high isohumic factor means that this effect is only seen in the longer term as compared with additions of manure and leguminous crops (Morgan, 1979).

Table 2.4. A summary of studies investigating the effectiveness of a range of mulches in runoff and erosion control. Adapted from Persyn et al. (2004).

Citation	Application	Media	Slope	Rainfall (simulated/irrigated/natural)	Mulch
Agassi et al., 1998	Arid/semi arid bare soil	Laboratory runoff rig.	5%	Simulated rainfall: 40mm h^{-1}.	Solid waste compost.
Block, 2000	Construction	Road construction site.	50%	Natural rainfall.	Composted yard waste, wood mulch and straw.
Brown et al., 1987	Agriculture	Dry bean furrows.	Year 1: 2.4%, 3.9% and 1.9%. Year 2: 2.4%, 4.4% and 2.4%.	Irrigated: 15.2 l min^{-1} for 8 hour periods (yr 1) and 12 hour periods (yr2).	Straw mulch 45 g m-1 (yr1), 30 g m-1 (yr2).
Brown et al., 1998	Agriculture	Sweet corn furrows.	2.3%, 2.4% and 4.4%	Irrigated: 11 l min^{-1} for 12 hour periods.	Straw mulch 780 kg ha-1 and cottage cheese whey.
Demars et al., 2000	Construction	Bare soil field slope.	50%	Natural rainfall.	Wood waste materials.
Faucette et al., 2004	Construction	Laboratory runoff rig.	10%	Simulated rainfall: 160 mm h^{-1} for 60 minute periods.	Seven different compost mixes from various feedstocks and 3 different grades of wood mulch.

Citation	Application	Media	Slope	Rainfall (simulated/irrigated/natural)	Mulch
Faucette et al., 2009	Construction	Laboratory runoff rig.	50%, 33% and 25%.	Simulated rainfall: 60 minute periods split into 3 different intensities 50 mm h^{-1} (20 min), 100 mm h^{-1} (20 min) and 150 mm h^{-1} (20 min).	Green waste compost blankets (1.25, 2.5 and 5 cm depths), straw blankets (single and double), coconut fibre blanket, wood fibre blanket, tackifiers and PAM.
Meyer et al., 1971	Agriculture	Cotton furrows	12%	Simulated rainfall: 63 mm h^{-1}.	Straw mulch of 2.3 t ha-1, 10cm topsoil application.
Reinsch et al., 2007	Agriculture		33%	Natural rainfall and simulated rainfall: 64 mm hr^{-1} for 50 minute periods.	Yard waste and straw mats.
Risse et al., 2002	Construction		10%	Simulated rainfall: 167 mm h^{-1}.	Compost, wood mulch, poultry litter at 5 cm depths.
Shock et al., 1997	Agriculture	Onion furrows	3%	Irrigated	Wheat straw 900 kg ha-1.
Storey et al., 1996	Recreational paths		33%	Simulated rainfall: 1, 2 and 5 year storm events.	Compost and wood mulch with synthetic chemical tackifiers applied between 76 to 101 mm depth.

Some adverse effects of straw mulch have also been noted in the literature. Döring et al. (2005) observed that straw at 10 t ha^{-1} gave a pronounced decrease in soil temperature, leading to a reduction in potato yield. In carrots, Holstrom et al. (2008) noted an increase in nematodes with straw mulch treatments, although the effects on nematode populations can vary. The addition of straw can also affect nutrient concentrations. Döring et al. (2005) acknowledge straw to be a nitrogen immobiliser post-potato harvest, as it decreases N concentrations in runoff. Rees et al. (2002) observed a greater increase in phosphorus in runoff from straw mulch applied at 9 t ha^{-1} as compared with straw applied at 2.25 and 4.5 t ha^{-1}.

Foster et al. (1982b) describes the effectiveness of mulch cover in terms of shear stress of overland flow. With the addition of a surface mulch, there are two types of shear stress applied to flow; mulch shear stress and soil shear stress. Both are dependent on their irrespective properties, similar to the properties that deem soil to be erodible. A high rate of mulch application can reduce the flow shear stress imparted to soil, thus protecting it from erosion. In unanchored corn straw, Foster et al. (1982a) observed three types of mulch failure; piece by piece movement, floating and en-masse mulch movement. Piece by piece movement was observed at the lowest application rate of 0.2 kg m^{-2} (2 t ha^{-1}), whilst mulch floating was observed at rates greater than 0.4 kg m^{-2} (4 t ha^{-1}). En-masse failure of sections of up to 1 m length was observed upon reaching a critical discharge point in flow rate. These sections moved downslope where they were re-deposited, resulting in bare soil sections interspersed with bunched up corn stalk. This bunching up effect results in the creation of mini dams, which effectively increases the wetted perimeter of the mulched area. This results in the slowing down of advancing irrigation water (Kwaad et al., 1998; Brown et al., 1998; Berg, 1984), giving the runoff more time to infiltrate.

Table 2.5. A summary of results from straw mulch studies in agriculture.

Study	Slope (%)	Straw application rate (t ha^{-1})	Runoff reduction (%) †	Sediment loss reduction (%)
Berg (1984)‡	1.5, 4, 7	0.6, 1.2 and 2.2.	Improved infiltration; 0 to	65 to 97, 79 to 98 and 85 to

Study	**Slope (%)**	**Straw application rate (t ha^{-1})**	**Runoff reduction (%)** †	**Sediment loss reduction (%)**
			100, 0 to 109 and 0 to 172.	100.
Brown and Kemper (1987)‡	Mixed slope profile	3 and 4.5.	21 and 33.	74 to 92 and 83 to 99.
Brown et al. (1998)‡	2.3, 2.4, 4.4	7.8	-21 to 49.	46 to 99
Döring et al. (2005)	5-6	1.25, 2.5 (cut and uncut) and 5.0.	/	98, 97 (92 uncut) and 98.
Edwards et al. (2000)*	2.6, 4.6, 5.4	4	/	49
Holstrom et al. (2008)		2.25* and 3.5.	-2.6 to 12 and -17 to 32.	23 to 45 and 61 to 74.
Rees et al. (2002)‡	8, 11	2.25, 4.5 and 9.	-0.5 to 57, -0.3 to 78 and 76.	55 to 86, 75 to 93 and 98.
Shock et al. (1997)	3	9		95
Silgram et al. (2010)*	4	2.5	23 to 50	40 to 43
Tatham (1989)		2.5		82

*Straw was incorporated. †Negative numbers indicate a runoff increase. ‡Percentage ranges result from data merged from different slope conditions.

Within straw treatments, different erosion control properties will exist depending upon the means of straw application. In particular, the straw application rate, straw length and whether the straw is incorporated into the soil or left on the surface will all have an impact. Higher mulch application rates increase the effectiveness of soil erosion prevention. The studies summarised in Table 2.5 show that where straw is applied at different rates, the higher rates achieve higher reductions in soil loss, as well as less variability within the results. Morgan (2005) suggests that this effectiveness relates to percentage cover, stating that a cover of 70-75% is sufficient to protect the soil surface from erosion. This is because as straw rates increase, a greater percentage surface cover is achieved, although this is dependent on the density of the straw applied. This will boost the erosion properties of the mulch such as protecting the surface from raindrop and runoff impact (as well as sealing processes), increase surface roughness and increase the critical flow threshold (Foster et al., 1982a) at which the mulch may become displaced. A high rate of straw application does risk negative consequences on runoff properties such as increased nutrient pollution; however, this is rarely cited in the literature.

Studies of chopped and un-chopped straw have shown a difference in soil loss reduction. Döring et al. (2005) compared chopped and un-chopped straw at 2.5 t ha^{-1} applied to potato ridges on a loamy soil with an 8% slope. Chopped straw treatments reduced soil loss by 97 % as compared with the control, whilst un-chopped straw resulted in a lower (92 %) reduction. Similar results were observed in runoff sediment concentrations, with chopped straw sediment reductions of 97 % as compared with the control, compared with just 85 % from un-chopped straw treatments. In both treatments, straw was observed to move from the ridges into the furrows to form mini dams and retain surface water. Berg (1984), whilst not directly testing different straw lengths, observed that shorter straw pieces tended to float down and bunch up with the first application of irrigation water, whilst longer pieces stuck to the side of the furrow and became embedded. Furthermore, Berg (1984) observed that straw effectiveness in erosion control reduced after the first irrigation as the combined dispersion and settling of the straw allowed water to channel around it. This suggests that un-chopped straw would make a more effective surface cover.

It is generally agreed in the literature that mulch is a more effective erosion control measure when applied to the surface as compared with when it is incorporated into the soil (Raper, 2007; Wischmeier and Smith, 1965). In studies where straw is incorporated, the soil loss reduction is less than the equivalent surface applied straw (Table 2.5). Holstrom et al. (2005) and Silgram et al. (2010) observed greater soil loss with incorporated straw (applied at 2.25 t ha^{-1}) than Rees et al. (2002) observed when surface applied. Similarly, Edwards et al. (2000) observed at least 25% more soil loss from 4 t ha^{-1} incorporated than from 4.5 t ha^{-1} surface applied straw (Rees et al., 2002; Brown and Kemper, 1987). Despite this, incorporated residue can still be considered to be an effective erosion control measure (Silgram et al., 2010; Holstrom, 2008; Edwards et al., 2000; Tatham, 1989). Tatham (1989) compared both surface applied and incorporated straw in the same study. The surface application of straw (at 2.5 t ha^{-1}) resulted in the greatest reduction of soil loss as compared with the control and incorporated straw treatment. However, the incorporated treatment also reduced soil loss when compared with the control. Silgram et al. (2010) looked at the effect of chopping and incorporating 2.5 t ha^{-1} of straw in a moderately sloping (4 degrees) cereal field on and between designated tramlines. Due to the differences in response between tramline and non-tramline rows, no significant differences were found between the straw and no straw treatments. However, straw did reduce surface runoff, soil loss, total phosphorus and nitrogen by approximately 50% on no-tramline rows and sediment, total phosphorus and nitrogen by over 35% on tramline rows. Edwards et al. (2000) applied straw to potatoes prior to planting, which was then partially incorporated following potato ridging. He observed a significant (49 %) reduction in soil loss and a 6 % increase in soil moisture that could benefit the crop in dry years. Holstrom et al. (2005) applied straw prior to several tillage operations pre carrot planting on a 5-6% slope on a shallow sandy soil. In all instances the mulched treatments produced less sediment (23 to 45 %), with significantly less sediment observed at one of two testing sites. Despite this success, grower feedback stated that the mulch treatments negatively impacted the quality of raised beds for seed planting. Consequently non-cultivated, post-planting alternatives were developed instead.

The results of the incorporated straw studies discussed confirm that surface application of mulch is the most effective erosion control measure. However, when necessary field operations incorporate straw soil loss is still reduced as compared with no mulch treatments.

2.4.1.2 Compost

In addition to agricultural studies, mulches have also been effectively applied in the prevention of erosion on engineered slopes. In this application, mulch is required to temporarily stabilise slopes against erosion whilst vegetation is established (Block, 2000). Compost has the added benefit of inputting nutrients to degraded soils, facilitating vegetation establishment (Table 2.6). Persyn et al. (2004) postulated that a compost blanket is expected to have the same effect as a straw blanket. In UK agriculture there is an increased drive from organisations including the Waste and Resources Action Programme (WRAP) to make use of compost. Consequently several studies exist on the crop benefit of compost application; however, little literature evidence exists to support the claim of potential erosion control properties.

Table 2.6. Typical nutrient content of compost. Source: WRAP (2007).

	Nitrogen	Potassium	Phosphorus
Kg t^{-1}	8	6	3

When directly compared with straw, studies show compost to be the most effective erosion control measure of the two. Faucette et al. (2009) compared green waste compost blankets at 1.25, 2.5 and 5 cm depths with and without netting and single-net and double-net straw blankets on varying slopes of 25, 33 and 50%. Over a simulated rainfall event of 20 minutes (16.5 mm total rainfall) all treatments significantly reduced soil loss. After 40 minutes (50 mm total rainfall) and a further 60 minutes (100 mm total rainfall), the 5 cm compost blanket depth with netting reduced significantly more soil loss as compared with the single-net straw. Beighley et al. (2010) investigated the runoff characteristics of the treatments and rainfall conditions used by Faucette et al. (2009) on a 50% slope. Double-net straw generated less runoff than single net straw following 20, 40 and 60 minutes of rainfall. However, compost at all three thicknesses best reduced runoff as compared with the double-net straw following 20 minutes of rainfall. At 40 and 60 minutes the double-net runoff reduction was less than the compost treatments at 2.5 and 5 cm depths.

Reinsch et al. (2007) compared runoff volume and total soil loss from a single-net straw mat and 5 cm depth, yard waste compost. The compost blanket outperformed the straw mat on both runoff and soil loss reduction. Compost reduced runoff by 96 % and straw by 29 % as compared with control plots. Soil loss was a closer comparison with compost reducing sediment by 99 % and straw by 93 % as compared with control plots.

There is some evidence in the literature that compost is a more effective erosion control measure when applied in combination with netting. The application of compost on top of netting reduces the failure potential of the compost by sliding downslope or lifting off the soil surface (Beighley et al., 2010). When tested under laboratory conditions, compost applied on top of a 5 mm polypropylene net with 19 mm openings generates less sediment and runoff (Faucette et al., 2009 and Beighley et al., 2010). Faucette et al. (2009) observed an improvement in soil loss reduction of between 0.1 to 46 % as compared with the control, with the greatest improvement evident on the shallowest blanket depth (1.25 cm). Netted blankets also demonstrated a better mean performance and decreased variability on runoff reduction (Beighley et al., 2010).

Compost blanket thickness is also an important erosion control property to consider. Thicker blankets tend to result in more effective erosion control results (Table 2.7). Beighley et al. (2010) demonstrated that blanket depths only played an important role in initial runoff rates after which little difference between depths were observed. At 5 cm thick the compost blanket showed the most reduction initially, followed by the 2.5 cm thick treatment. This suggests that a key mechanism in compost effectiveness is initial water storage, thus reducing initial runoff (Beighley et al., 2010). From the same study, Faucette et al. (2009) demonstrated a noteworthy (but not significant) reduction in sediment with a thicker compost blanket irrespective of netting. Compost at 5 cm depth is the most effective in reducing sediment after 20 minutes by 99.8 %, and then 66.8 and 71.9 % after 40 and 60 minutes respectively as compared with the control. Little difference (+/- 6 %) is observed between 5 and 2.5 cm depth. The greatest difference is observed between the 1.25 and 5 cm compost blanket, with the extra 3.75 cm depth improving soil loss reductions by up to 48 %.

Table 2.7. A summary of results from compost erosion studies.

Study	Compost thickness (cm)	Runoff reduction as compared to the control (%)	Sediment loss reduction as compared to the control (%)†
Faucette et al. (2009) and Beighley et al. (2010)	1.25, 2.5 and 5	Netted: 15 to 60, 34 to 92 and 38 to 95. Un-netted: 10 to 58, 25 to 88 and 28 to 94.	Netted: 30 to 58, 61 to 99 and 67 to 100. Un-netted: 45 to 98, 68 to 100, 69 to 100.
Glanville et al. (2004)	5 and 10	100 (mean of two depths)	100 (mean of two depths)
Reinsch et al. (2007)	5	96	99
Simmons et al. (2011)	2.5 and 5	58 to 97 (5 cm)	99 (5 cm)

†Percentage ranges result from data merged following different rainfall durations. Percentages are rounded up to the nearest whole integer.

2.4.2 Soil disturbance

Soil disturbance (also known as tillage or soil loosening) is the only means by which compacted areas can be broken up quickly and in time for the next field operations. It requires the loosening or disturbance of compacted areas generally using a tine. Compaction can be ameliorated by brittle or tensile forces applied through an upward movement of soil initiated 25-40 mm beneath the compacted layer (Spoor, 2006). This breaks up the soil into smaller units, creating cracks, increasing porosity, enabling water to infiltrate (Figure 2.14), roots to penetrate and biological activity to stabilise the area (Spoor, 2006). This can delay runoff generation as well as reduce runoff volume (Rao et al., 1998) thus reducing the amount of detached soil transported. With soil disturbance a rough soil surface is generated as loosened soil is left on the soil surface (Figure 2.14). This surface roughness can store water in surface depressions (Idowu et al., 2002) further reducing runoff volume. The generated surface roughness can also reduce runoff velocity as it imparts a frictional component to the flow (Figure 2.14).

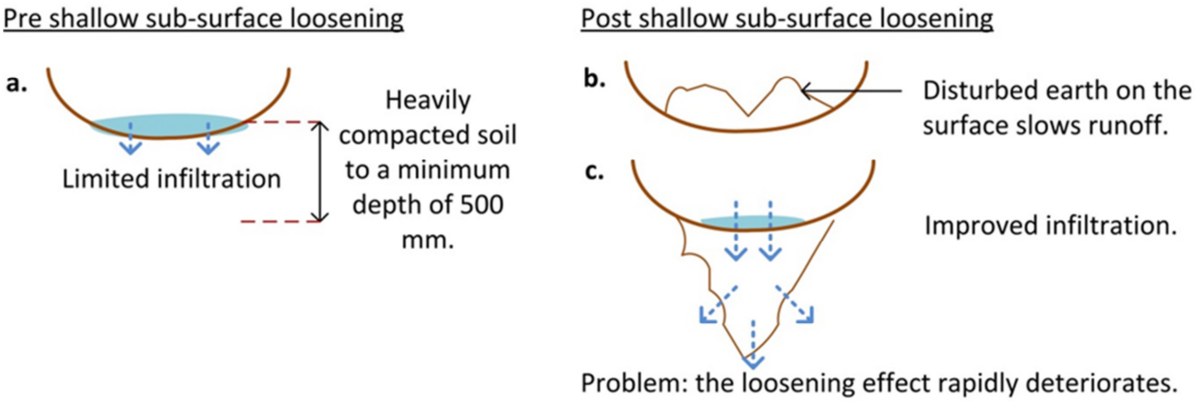


Figure 2.14. A cross sectional area of a compacted wheeling both pre and post shallow soil disturbance.

The type of soil disturbance conducted in the field depends upon several factors; subsequent land use requirements, extent of compaction, availability of machinery/implements and cost of operation. Research has shown that optimum loosening operations occur at 300 – 350 mm depth, with deeper operations being less successful (Spoor, 2006). Subsequent land use requirements such as those for root crops would mean that thorough loosening would be required to enable normal crop development (Spoor, 2006). For compaction extent, farmers are encouraged to regularly assess compaction problems to ensure that the correct loosening needs are addressed. Cost can be managed by ensuring that specific draught –force required per area disturbed- is necessary for the loosening achieved. Many farmers undertake soil loosening but without being fully informed of the risk associated with the practice. These risks are that soils left in a very loose, open condition following tillage are particularly susceptible to re-compaction (Spoor, 2006). Furthermore, working below critical depth (the maximum working depth to which a tine will continue to loosen the soil) may not alleviate existing compaction but risks worsening it. To improve soil loosening success, tillage implements geometries and arrangements can be modified to suit individual requirements.

2.4.2.1 Implements

Tines are designed in such a way that soil is forced upward and forwards by the angled tine foot resulting in failure and slip along a plane (Figure 2.15).

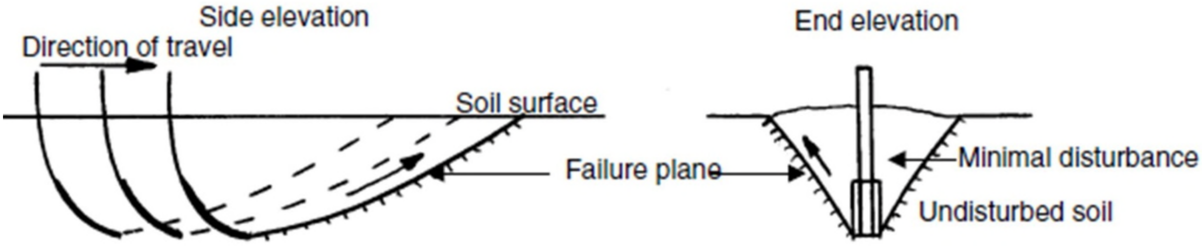


Figure 2.15. Brittle soil disturbance with a narrow tine. Source: Spoor (2006).

The extent of disturbance caused by a tine can be manipulated through tine design and, in wider operations, tine arrangement. Considering typical asparagus systems, tine spacing is limited by wheeling width between beds, therefore some tine arrangement factors such as spacing between main tines will not be considered here. Soil disturbance can be increased by working well above the critical working depth. This is the depth at which loosening operations are limited by confining forces that prevent the upward movement of the soil (Spoor and Godwin, 1978). This means that at the critical depth the tine is no longer loosening and is instead compacting. The critical depth can be increased by widening the tine point or with the addition of wings. This increases the strain exerted on the soil by the tine increasing the confining forces required to prevent upward soil movement. Soil disturbance with winged tines is greater as tension cracks develop as soil flows up and over the wings (Figure 2.16). With wings, disturbance can be further manipulated by altering wing lift, with higher lift height resulting in greater disturbance.

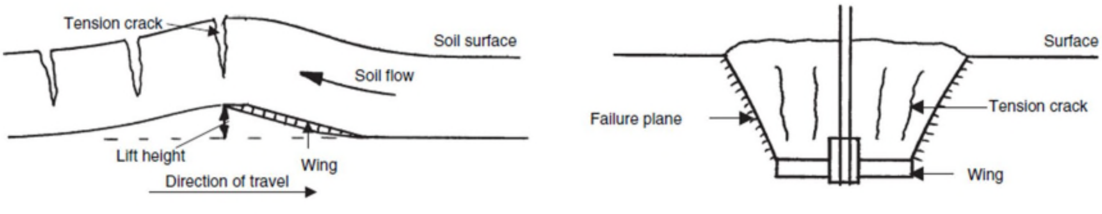


Figure 2.16. Tensile soil disturbance with a winged tine. Source: Spoor (2006).

The use of shallow leading tines can also increase the critical working depth and degree of disturbance (Spoor, 2006). As the shallow leading tine first passes through the soil it reduces the confining resistance applied on the deeper tine (Spoor, 2006). The deeper tine is then only disturbing a shallower area of soil, resulting in greater disturbance, for least force.

Considering more novel tines, Tatham (1989) experimented with an innovative implement called a 'tramline drainer' (Figure 2.17). This targets drainage improvements in wheel ruts by loosening the outside of a compacted wheeling rut thus allowing water to infiltrate around it. Whilst this does not directly alleviate compaction it does alleviate the effects of compaction. Given the high proportion of wheelings occurring in row crop systems this could be an appropriate implement with which to control runoff through diversion around the compacted area.

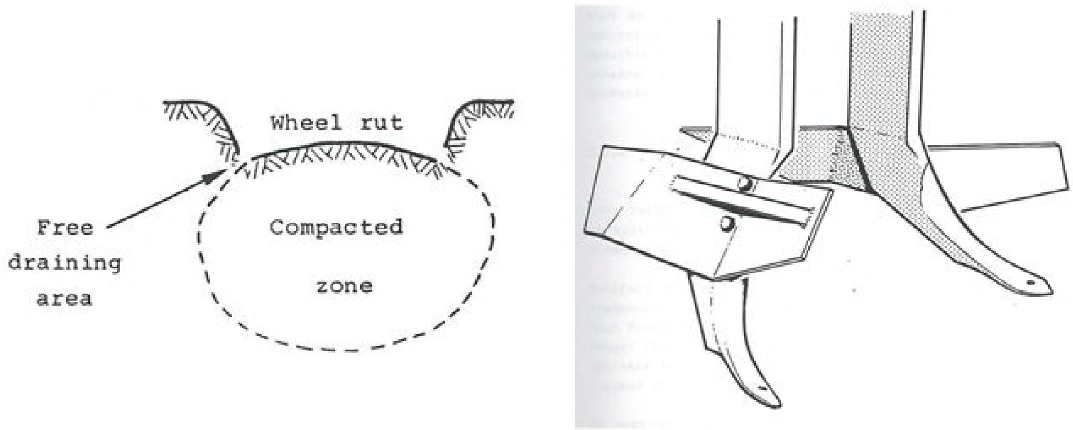


Figure 2.17 The tramline drainer. Source: Tatham (1989).

2.4.2.2 Erosion control application

Many studies have assessed different tillage practices and their impacts on soil erosion and runoff. Francia, et al. (2006), Silgram et al. (2010) and Tatham (1989) have all found tillage to aid erosion and runoff control. Francia et al. (2006) tilled plots using a mouldboard plough to 150 mm depth and found soil erosion reduced by 79 % and runoff 67 % as compared to the control. Silgram et al. (2010) conducted a study of tramlines on moderate sloping arable fields. In one treatment, a single tine was run behind a cultivator wheel to a 600 mm depth, disturbing the soil. Silgram et al. (2010) found that losses of soil, nitrogen, phosphorus and water were reduced by 86 – 97 %, as compared with undisturbed tramlines in the same field. This suggests that soil disturbance could be used in reducing runoff and losses from heavily compacted areas. Tatham (1989) compared the effect of four different tramline treatments for physical soil changes and runoff. The treatments applied were an 80 % cover straw surface mulch; a tramline drainer; a tramline drainer over a straw surface mulch; and a horizontal ripper. With the tramline drainer, bulk density in the central rut increased, whilst in the loosened area, infiltration rates were 6 times that of the control. This can be accounted for by the flow pathways observed; surface water drained into the loosened zones instead of favouring rut-free tramline centres. In the extent of soil lost, 'drained' tramline rates were second highest to untrafficked soil conditions.

Other studies have shown variable effects of tillage. Holstrom et al. (2005) compared a mouldboard plough, disk and chisel plough at 15 – 20 cm depth in combination with straw mulch at 2.25 t ha^{-1}. No difference in relative soil erosion was observed between the tillage methods used. Foster et al. (1982a) tilled plots using a roto-tiller at 100 mm depth. Tilled plots were more susceptible to erosion generating >185 % more soil loss as compared with untilled plots. Jasa and Dickey (1991) found sub-soiling at approximately 360 mm to reduce runoff by 38 % as compared to control plots but increase soil loss by 116 %. Unger and Cassel (1991) reviewed the effect of different tillage mechanisms on soils, finding that water retention increased but not in coarse textured soils. Tillage conducted on soil with unstable aggregates found a negative impact of rapid soil dispersion and surface sealing, decreasing the infiltration rate (Unger and Cassel, 1991).

The effectiveness of soil disturbance on runoff and erosion control can vary over time. Soil disturbance can slump resulting in a reversion to pre-existing conditions particularly if the area is wheeled, as demonstrated by Unger and Cassel (1991). Furthermore, rainfall received shortly after tillage can result in a change in surface roughness as soil particles are detached and transported (Burwell et al., 1966). This can affect infiltration rates. Unger (1984) states that soil disturbance is effective at improving infiltration when precipitation is sufficiently low. This has been shown in several studies where soil disturbance effectiveness was reduced with increasing rainfall; 85 mm rainfall (Gomez et al., 1999) and 155 mm rainfall (Rao et al., 1998).

2.4.3 Soil disturbance in combination with surface mulch

Surface cover on soil disturbance can protect the soil surface from crust development, thus increasing the longevity of the disturbance effect on runoff and erosion (Rao et al., 1998). Furthermore, it can prevent the soil slumping back into the same position. Of the erosion control studies found, few have considered the interaction effects between soil disturbance and mulch application. Those that have are outlined in (Table 2.8).

The addition of mulch to the tramline drainer by Tatham (1989) increased infiltration rates after 30 minutes as compared with the tramline drainer alone. The presence of the surface mulch also lowered runoff and soil loss rates on ‘drained’ tramlines. Surface mulch when applied alone caused the lowest runoff and soil loss rates out of all other treatments. These results suggest that whilst disturbance improves infiltration, it is the effects of the mulch that further optimises the outcomes. Holstrom et al. (2005) found mulching reduced soil loss significantly by 45 % on one of two sites both with and without tillage as compared with un-mulched plots. However, Rao et al. (1998) found no difference between tilled and untilled plots with the same mulch amendment. McGregor et al. (1990) observed a significant difference between average soil loss from wheat residue and fallow disked plots. This was a reduction of 84 % from wheat mulch plots as compared with fallow. However, one contributing factor could have been that fallow plots were disked 40 mm deeper than wheat plots potentially providing more loose sediment for entrainment. Wheat tilled plots also reduced total runoff by 26 % as compared with un-mulched tilled plots. However, significant differences in runoff volume were only observed in the first 60 minutes of rainfall. This suggests a deterioration in the soil loosening effect.

Vegetation has also been considered as a solution in human trampling studies. Monti and Mackintosh (1979) found that organic leaf litter acted as a barrier to initial footpath erosion process. This led them to conclude that organic leaf litter plays an important role in protecting the soil surface from negative changes; suggesting that conserving or maintaining a surface cover is key to footpath management. Further to this the breakdown of organic leaf litter by foot traffic was seen to initially be beneficial. Monti and Mackintosh (1979) observed that each foot fall initiates the decomposition of surface organic matter, as soil macro-fauna would, increasing the surface area and accelerating rates of microbial activity. This suggests a wider benefit of vegetative cover as a means of compaction mitigation, not just maintaining soil physical properties but increasing soil health through microbial activity.

Leung and Marion (1996) support the use of vegetation in soil protection, stating that in areas of low trampling intensities, vegetation of a high trampling resistance and resilience can be used, resulting in minimal degradation. However, on grassland, Quinn et al. (1980) found that soil degradation occurred before changes in vegetation cover had been observed. This suggests vegetation to be more of a cover-up than protector, and that visual vegetation damage is an insufficient indicator for the initiation of soil degradation. Although, before this theory can be considered the work by Quinn et al. (1980) requires further validation, as the experiment was carried out under controlled laboratory conditions with very high intensities of rainfall.

Table 2.8. A summary of studies investigating the interaction of mulch and soil disturbance. Adapted from Persyn et al. (2004).

Citation	Investigation	Conditions
Sharma, 1991	Water use, growth and yield of fodder maize.	Crop: fodder maize. Plot size: 6 x 6 m. Duration: 2 years. Natural rainfall with irrigation. Tillage type: minimum, reduced and conventional. Treatment: surface residues presence (5 t ha^{-1}) and absence. Normal (75 kg ha^{-1}) and high (150 kg ha^{-1}) N application
Iqbal et al., 2008	Crop grain yield, growth parameters and soil physical properties.	Crop: maize. Plot size: 10 x 10 m. Duration: 2 years. Natural rainfall with irrigation. Tillage type: zero, minimum, conventional and deep tillage. Treatment: wheat straw mulch at rates of zero, 2, 4 and 6 mg ha^{-1}.
Roozeh et al., 2011	Sediment loss, runoff nitrate concentration, N losses and N recovery.	Crop: wheat. Plot size: Slope: 0.5%. Duration: 3 irrigations. Tillage type: conventional tillage; mouldboard plough and 2 disks (3 passes), mouldboard plough and power harrow (2 passes), reduced tillage; stubble cultivator only. Treatment: PAM at rates of 0, 10 and 20 mg l^{-1}.
Silgram et al., 2010	Whether tramline management and/or crop residue can reduce erosion, loss of sediment and P.	Crop: cereals. Plot size: 3.5 x 270 m, Slope: 4 degrees. Duration: 2 years at time of publishing. Natural rainfall. Tillage type: a 6cm deep tine following behind the wheel of the cultivator. Treatment: effect of baled and removed, and chopped and spread cereal straw residue. In addition to tine disruption.

Citation	Investigation	Conditions
Holstrom et al., 2008	Tillage regimens on soil erosion, nematodes and carrot yield.	Crop: carrots. Plot size: Slope: 5 - 6%. Simulated rainfall. Tillage type: Experiment 1 (pre-planting): no fall tillage, full mouldboard plough, fall disked, fall chisel ploughed -all to 15-20 cm. Treatment: Timothy Hay mulch at 2.25 t ha (pre-planting exp.) and 3.5 t ha (post-planting exp.).
Tatham, 1989	Wheel rut drainage and erosion control	Crop: unknown. Plot size: Unknown. Natural and simulated rainfall. Tillage type: Tramline drainer and horizontal ripper. Treatment: Surface straw application (0.25kg m).
Cattan et al., 2006	Runoff control under Banana crops	Crop: Banana. Plot size: Slope: 12%. Natural rainfall Tillage type: Cross-contour disc ploughing followed by harrowing and furrowing. Treatment: bare soil (cycle 1), mulch with harvest residues in every other interrow, mulch with harvest residues in every interrow.
Rao et al., 1998	Rainfall infiltration and runoff from tilled systems.	Crop: Sorghum bicolour and orr Zea mays. Plot size: 28.5 x 8 m. Slope: 2 %. Bulk density: 1.4 to 1.6 g cm^3. Natural rainfall. Tillage type: no tillage, shallow tillage (duck foot tine 10 cm depth, annual), deep tillage (duck foot tine 20 cm depth, annual). Mulch: Farmyard manure 15 Mg ha^{-1}, Rice straw 5 Mg ha^{-1}.

3 RESEARCH OBJECTIVES

Based on a detailed literature review, it was found that little work has been done to alleviate the soil and water management problems identified. In order to address this, this study aims to:

Develop a cost effective and practical runoff and soil erosion management system for asparagus production.

Main hypothesis:

Shallow soil disturbance and mulch application are cost effective and practical methods to control runoff and soil erosion from asparagus fields.

In order to test the hypothesis the following sub-hypotheses have been developed.

a. Shallow soil disturbance alone can significantly reduce runoff volume and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no shallow soil disturbance.
b. The application of mulch materials (defined by type and rate) can significantly reduce runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no mulch application.
c. The application of mulch materials (defined by type and rate) in combination with shallow soil disturbance can significantly reduce runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no mulch application and no shallow soil disturbance.
d. Tine configuration (geometry, arrangement and depth of operation) can significantly change the degree and extent of soil disturbance and affect implement dynamics (draught force) as compared with the currently adopted tine.
e. Tine configuration (geometry and arrangement) can significantly affect runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no soil disturbance.
f. Tine configuration (geometry and arrangement) in combination with mulch can significantly affect runoff volume, and associated nutrient and sediment

loads in an asparagus production system, as compared with control plots with no soil disturbance and no mulch.

These sub-hypotheses will be tested using three different experimental programmes that are detailed in the subsequent chapters (Table 3.1). Once all sub-hypotheses have been tested the final sub-hypothesis will further test the main hypothesis.

g. Adopting the most effective soil erosion measure will result in cost benefits.

Table 3.1. The experimental programmes to be used to test the sub-hypotheses.

Sub-hypothesis	Experimental programme
a, b, c	Phase 1 field trials (Chapter 4)
d	Soil bin work (Chapter 5)
e, f	Phase 2 field trials (Chapter 6)

4 PHASE 1 FIELD TRIALS

4.1 Methodology

In order to test the research hypotheses (Chapter 3) the following methodology was developed.

The Phase 1 experimental programme took place between February and July 2012 at Cobrey Farms, Coughton, Ross on Wye (SO619218) in a field that had been under asparagus production for 7 years. Replicated field runoff plots were setup in which shallow soil disturbance (SSD) and mulch treatment combinations were tested (Section 4.1.1 and 4.1.2). Runoff rate, volume and associated nutrient and sediment loads were measured from each plot and subsequently analysed to ascertain the effective erosion control of each treatment.

4.1.1 Treatment selection

Experimental treatments were selected based on a detailed literature review (Chapter 2) as well as an assessment of their feasibility within an asparagus production system and practical adoptability relative to material sourcing and costs. This also involved consultation with the grower. Table 4.1 shows the treatments tested in this experiment namely:

- two types of soil disturbance (SSD (0-175 mm) and non-SSD);
- three mulch options (straw, PAS 100:2005 compost, and a bare soil control). The mulch treatments were applied at two different application rates (low and high). Straw was applied at 6 and 3 t ha^{-1} and compost at 15 and 7 t ha^{-1}.

The economics of the treatments are discussed later in Chapter 7.

Table 4.1. A summary of Phase 1 experimental treatments, and their associated reference codes.

Treatment number	Shallow soil disturbance†	Mulch type‡	Application rate*	Treatment code
1	Non-SSD	Cp	L	Non-SSD Cp^{L}
2	Non-SSD	Cp	H	Non-SSD Cp^{H}

Treatment number	Shallow soil disturbance[†]	Mulch type[‡]	Application rate*	Treatment code
3	Non-SSD	N/A	N/A	Non-SSD Control
4	Non-SSD	St	L	Non-SSD St^L
5	Non-SSD	St	H	Non-SSD St^H
6	SSD	Cp	L	SSD Cp^L
7	SSD	Cp	H	SSD Cp^H
8	SSD	N/A	N/A	SSD No Mulch
9	SSD	St	L	SSD St^L
10	SSD	St	H	SSD St^H

[†]Non-SSD = Without shallow soil disturbance; SSD = With shallow soil disturbance (Winged tine at 175 mm depth). [‡]Cp = Compost; St = Straw. *Compost application rates; Low (L) = 7 t ha^{-1}, High (H) = 15 t ha^{-1} Straw application rates; Low (L) = 3 t ha^{-1}, High (H) = 6 t ha^{-1}.

4.1.1.1 Shallow soil disturbance

Currently, on-site shallow soil disturbance (SSD) is undertaken post-harvest in the asparagus wheelings using a modified single winged tine with a tine rake angle of 65 degrees (Figure 4.1). The depth of cultivation is 175 mm, kept shallow to minimise damage to asparagus roots. These wheelings are defined here as the bare soil areas situated between the raised asparagus beds and make up the treatment areas for each experimental plot.

Figure 4.1. The currently adopted single winged tine.

4.1.1.2 Compost

The PAS 100:2011 Quality Protocol compliant green waste compost utilised in Phase 1 was sourced from a certified local compost supplier; Rose Hill Recycling (Table 4.2). The product was of a 20 – 40 mm grade, with sufficiently reduced fines to ensure adequate erosion control (Mantovani, 2010) Potentially toxic elements (PTE) were below the upper limit set for general compost application (WRAP, 2011).

Table 4.2. Physical and chemical characteristics of the Rose Hill Compost. Means are derived from triplicate analysis. *Property determined from fresh.

Property	Unit	Mean	Standard deviation	Upper limit for PAS 100 compost
Dry matter*	%	78.2	0	N/A
Moisture*	%	21.9	0	N/A
pH*	pH units	8.9	0	N/A
Organic Matter LOI	% w/w	54.4	± 2.90	N/A
Organic Carbon	% w/w	31.6	±1.70	N/A

Property	Unit	Mean	Standard deviation	Upper limit for PAS 100 compost
Electrical Conductivity*	µS cm^{-1}	1325	± 142	N/A
Total soluble N	mg kg^{-1}	900	± 140	N/A
Total N	mg kg^{-1}	22967	± 759	N/A
Total P	mg kg^{-1}	4621	± 58.0	N/A
Total Cu	mg kg^{-1}	57.3	± 0.26	200
Total Zn	mg kg^{-1}	195	± 14.4	400
Total Pb	mg kg^{-1}	97.6	± 21.3	200
Total Cd	mg kg^{-1}	0.44	± 0.01	1.5
Total Hg	mg kg^{-1}	0.15	± 0.01	1
Total Ni	mg kg^{-1}	16.1	± 0.39	50
Total Cr	mg kg^{-1}	24.3	± 0.99	100

N/A; No upper limit set within the PAS 100 Compost Quality Protocol.

Compost application rates were calculated based upon the pre-2013 Nitrate Vulnerable Zones (NVZ) Directive limiting annual nitrogen (N) application to 250 kg ha^{-1} (Defra, 2013). This limit formed the basis of the highest compost rate used in this experiment (15 t ha^{-1}, giving a compost depth in the wheelings of 35 mm). This application rate was then halved for the low application rate (7 t ha^{-1}, compost depth of 15 mm). Due to a change in compost supplier and a subsequent delay in N content analysis, the resulting N content in the high compost rate exceeded the maximum permissible limit (Table 4.3). However, this application rate is below the current revised (post 2013) NVZ guidelines which allow 500 kg N ha^{-1} to be applied over a two-year period, when compost is the only organic fertiliser applied (Defra, 2013). Compost rate calculations are presented in Appendix A.1, Figure_Apx A-1 and Figure_Apx A-2.

Table 4.3 Details of PAS 100:2011 compost treatments.

Application rate (t ha^{-1})	Compost depth (cm)	Total fresh N (kg ha^{-1})
7	1.5	168
15	3.5	391

4.1.1.3 Straw

Wheat straw, grown locally was selected for use in the straw treatment. Unlike compost application to land, the use of straw mulches is not restricted by legislation. Therefore, application rates were based on existing guidance on effective erosion control mulch cover. Morgan (2005) reports that a 70-75% surface cover (≈ 5 t ha^{-1}) is sufficient to protect the soil surface from erosion. This rate was rounded up to 6 t ha^{-1} for the high straw application rate. The low rate used was half this at 3 t ha^{-1}. This provided a less adequate cover for erosion control (approximately 35 – 40 % cover), but represents a lower cost of application and offers more soil protection than the bare soil control. Straw cover calculations are presented in Appendix A.1, Table_Apx A-1.

4.1.2 Experimental setup

Figure 4.2. Overall view of the Phase 1 experimental area. N.B Photo taken on the 12th April 2012, at which time the asparagus beds were under plastic cloches.

4.1.2.1 Design

Each treatment was replicated three times, and included an untreated control (Non-SSD Control) to which no mulch was applied (Table 4.4). Treatment allocation to each plot was based on a randomised split-plot design. The experimental area was first divided into paired plots that were randomly assigned to the SSD and non-SSD treatment. This took into account the two-wheeling breadth of operation of the SSD machine. Mulch treatments were then randomly allocated to individual plots.

Table 4.4 Phase 1 experimental design with treatment codes.

Plot #	Treatment Code	Plot #	Treatment Code	Plot #	Treatment Code
1	Non-SSD Cp^L	11	Non-SSD Cp^H	21	SSD No mulch
2	Non-SSD Control	12	Non-SSD St^L	22	SSD Cp^L
3	SSD St^H	13	Non-SSD St^L	23	Non-SSD St^H
4	SSD St^L	14	Non-SSD Cp^H	24	Non-SSD Cp^H
5	Non-SSD St^H	15	SSD St^L	25	Non-SSD Control
6	Non-SSD Control	16	SSD St^H	26	Non-SSD St^L
7	SSD Cp^H	17	Non-SSD St^H	27	SSD Cp^L
8	SSD St^L	18	Non-SSD Control	28	SSD No mulch
9	SSD St^H	19	SSD Cp^H	29	Non-SSD Cp^L
10	SSD Cp^H	20	SSD Cp^L	30	Non-SSD Cp^L

SSD = Shallow soil disturbance, Cp = Compost, St = Straw, ^{L} = low application rate, ^{H} = High application rate.

Typical field operations of harvest, cloche removal, fertiliser, herbicide, fungicide (Botrytis and Purple Spot Control) and insecticide (Asparagus beetle control) application continued on the field trial area throughout the experimental period. To facilitate access by machinery for routine spray operations, two wheelings were left bare in the middle of the experimental area.

4.1.2.2 Treatment application

Treatments were only applied in the wheelings, as this was where the greatest erosion had previously been observed. Furthermore, wheeling application minimised potential damage to the asparagus crown and impacts on spear yield and yield quality. SSD and Non-SSD treatments were applied on the 24th February 2012. Shallow soil disturbance was undertaken to a depth of approximately 175 mm using a single winged tine described in Section 4.1.1.1. Plots with the mulch / SSD combination treatment had mulch applied first. Subsequently, SSD was undertaken in one pass with a leading serrated disc coulter opening the soil surface directly ahead of a winged tine, followed by a separate 8-bar crumbler of approximately 300 mm diameter, placed approximately 850 mm behind the tine (Figure 4.3). This avoided the mulch being dragged by the leading edge of the tine and accumulating at the bottom of the slope. Mulch treatments were applied to the entire 40 m plot within the wheelings to a width of 0.4 m. Straw was chopped to approximately 400 mm and machine blown onto the wheelings using a Teagle Tomahawk 5050 Straw Blower. The machine speeds required for the prescribed high and low straw application rates were 8 km hr^{-1} and 16 km hr^{-1} respectively. Compost proved too wet to be machine blown and so had to be applied by hand on a kg m^{-2} basis.

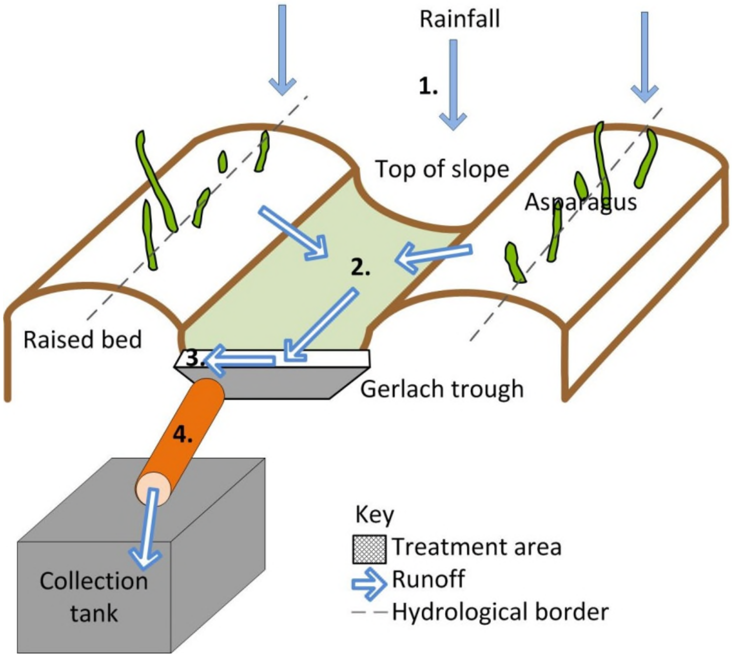
Figure 4.3 The customised cultivator used for shallow soil disturbance following mulch application.

4.1.2.3 Runoff plots

Experimental plots were 40 m in length situated between two asparagus beds set on 1.5 m centres (Figure 4.4). Each plot included a wheeling (0.4 m width). It was assumed that 50 % of the rainfall hitting the asparagus beds was shed to the upslope and downslope wheeling, forming the crest line acting as the hydrological border of the plots (Figure 4.4). Furthermore, upslope plot boundaries were positioned at the top of a slope feature preventing additional runoff onto each plot.

The methods used to capture runoff and soil loss in the field trials are similar to erosion plots used in other documented field-based soil loss experiments (Unger 1984; Zöbisch et al., 1996; Silgram et al., 2010). Furthermore, the methods adopted have been tried and tested in an initial proof of concept study (Niziolomski, 2011).

The experimental area consisted of in-wheeling runoff plots feeding into stainless steel Gerlach troughs (0.21 x 0.95 x 0.11 m) that were connected via 110 mm diameter PVC-u waste drainage pipe to 250 litre capacity household water tanks (Figure 4.4 and Figure 4.5). The Gerlach troughs were bedded in with cement and set with a slight drop towards the pipe outlet. The plot and trough interface was carefully cemented and sealed to ensure that all runoff was collected. Sedimentation within the pipe was avoided by keeping a good fall on the pipe network from the Gerlach trough to the collection tank.



1. Raindrops strike the raised beds and wheelings and, where infiltration does not occur, runoff is generated.
2. Runoff flows downslope onto the treatment area and towards the trough.
3. Once in the trough runoff flows into the pipe.
4. The pipe leads to the tank where the runoff is collected and sampled. It is discharged via a bung after sampling.

Figure 4.4 A raised bed-wheeling experimental runoff plot.

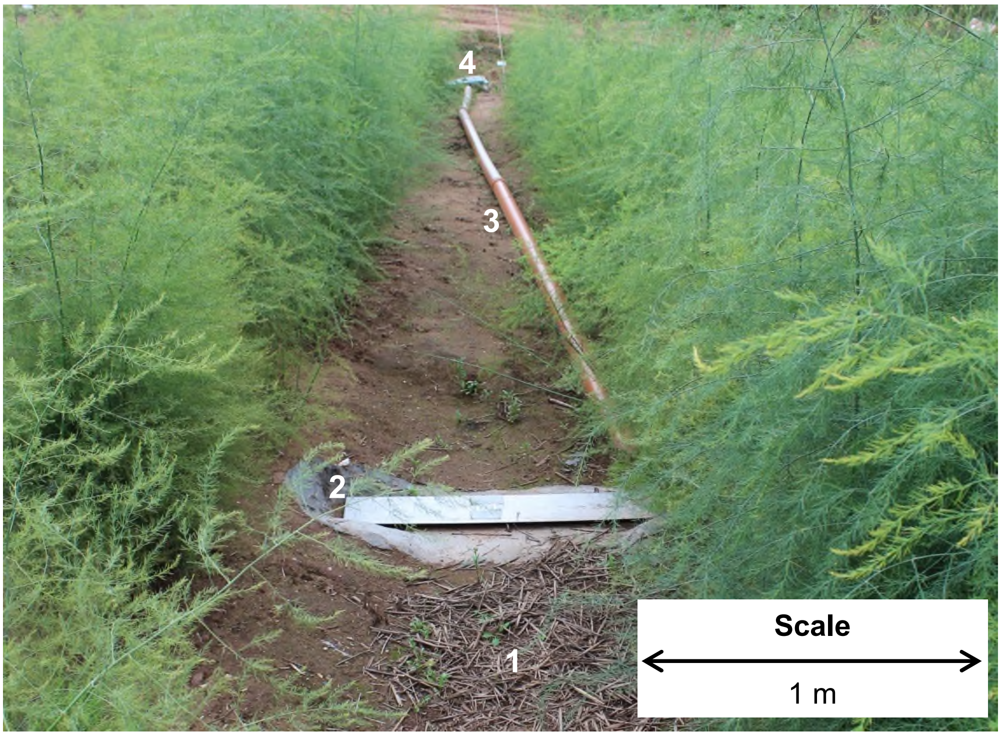


Figure 4.5. In-field experimental plot set-up (looking downslope from the treatment area). 1. Treatment area; 2. Gerlach trough; 3. Pipe; 4. Collection tank.

4.1.3 Data collection and analysis

4.1.3.1 Runoff sampling

The persistent nature of on-site rainfall meant that individual rainfall event-based runoff and erosion monitoring was not possible. Instead, runoff and sediment accumulated over multiple rainfall events. This accumulated runoff and sediment was sampled on five separate occasions that are hereafter referred to as Sampling Periods.

Runoff and soil loss from the experimental plots were collected in two forms; i) three 500 ml sub-samples of the water collected in the tanks, after agitation to ensure the collected sediment was entrained in each sub-sample, ii) sediment contained within and deposited around the Gerlach Trough ($GT_{Samples}$). Three sub-samples were taken per tank to minimise the risk of under calculation of tank suspended sediment (Zöbisch et al., 1996). Tank runoff depth was measured to validate the values obtained from the linear level sensors.

4.1.3.2 Runoff analysis

The triplicated tank runoff samples collected from each plot were hand shaken to ensure sample homogeneity and combined into a 2 litre glass beaker. The combined sample was then stirred for 30 seconds using a wide stirrer in order to bring the sediment into suspension. Immediately after stirring, 500 ml of the sample was poured into a pre-labelled bottle. This sample was tested in triplicate for Total Sediment Load (TSL) ('Total Solids dried at 103°C - 105°C'; Eaton et al., 2005). Alternate Sampling Periods (Periods 1, 3 and 5) were also analysed for chemical parameters. This was not carried out on all Sampling Periods due to the time taken to carry out and interpret the analyses. Total Oxides of Nitrogen (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. Total sediment-bound-P was determined using a maximum 0.5 g sub-sample of the total solids retained after oven drying. The solids were carefully brushed from the bottom of the beaker and prepared using an *aqua-regia* microwave digest (BS EN 7755 Section 3.13:1998). Results from these analyses enabled runoff water quality to be assessed in relation to water quality guidelines and a sub-total of soil loss from each runoff plot to be calculated (Equation 1).

For each Sampling Period, plot specific $GT_{Samples}$ were collected, air dried and weighed. Later methodology refinements meant that samples were collected into a bucket and weighed on-site. Each bucket was then sub-sampled and placed into a pre-weighed container. The sub-sample was later air dried and re-weighed to determine the Dry Matter Content (DMC) of sediment deposited in and around the Gerlach trough (BS EN 7755: Section 3.1:1994) (GT_{Total}). This enabled a total soil loss (TSL_{Total}) to be calculated from the plot when added to the total sediment load calculated from tank runoff samples (Equation 1).

$$TSL_{Total} = (RV_{Total} \times TS_{Conc}) + GT_{Total} \qquad \textbf{(Equation 1)}$$

Where TSL_{Total} = total soil loss (g); RV_{Total} = total Runoff Volume (l); TS_{Conc} = concentration of sediment in the Tank (g l^{-1}); GT_{Total} = total Gerlach Trough Sediment Load (g).

All experimental data was put into STATISTICA version 12 and checked for normal distribution (using residual analysis). If required the data was transformed by calculating the log (log n or log 2n) of each value and outliers were identified and removed as appropriate. Data was then analysed for statistical significance ($p < 0.05$) using a nested full Factorial ANOVA. The objective of this analysis was to quantify any differences between individual treatment components (Non-SSD/SSD, St/Cp/No Mulch and L/H application rates) and any interaction effects between these treatment components. Individual testing of the effect of L and H application rates was not possible due to an insufficient number of controls. Where significant differences were observed post-hoc Fisher LSD analysis was undertaken. In all cases the reported means are in the original units and the significant differences were identified using the appropriately transformed data. Results for runoff volume and total soil loss were standardised against the Non-SSD Control (results shown as a percentage as compared with the control). This enabled differences in treatment hydrological response across all Sampling Periods to be observed, despite the variable rainfall characteristics of each Sampling Period.

4.1.3.3 Event driven hydrological response measurement

Event-driven hydrological response was determined using an automated system that linked a tipping bucket rain gauge via a DT80/2 data logger to pre-calibrated linear level sensors located in each of the runoff storage tanks. Data logging was rainfall event driven, so began automatically following the onset of rainfall. A GSM/GPRS modem attached to the data logger allowed GSM data pull to a webserver. The data logger was solar powered and maintained with an 80Ah professional gel cell battery linked to a 50W panel.

Logged data consisted of 30 min interval rainfall data, with more frequent, one minute interval data if ≥ 0.2 mm of rainfall fell. The 30 min interval data logging resumed 1.0 hr after rainfall ceased so that any ‘post-rainfall runoff could be captured. Rainfall event driven runoff monitoring allowed the hydrological response of the treatments to be assessed, under a range of rainfall intensities and runoff events.

4.1.3.4 Event-driven hydrological response analysis

Runoff hydrographs were used to measure treatment response to individual rainfall events that were not captured in the combined Sampling Period final tank volume. Treatment response parameters tested were cumulative runoff volume (l), runoff rate (l min^{-1}) and time of initiation and cessation (min).

In order to concentrate only on the events where significant rainfall fell, rainfall recorded within each Sampling Period was classified into separate rainfall events. These rainfall events were defined as ≥ 1.0 mm falling within a 10 minute period. A large rainfall event dataset was collected across the whole experimental programme (43 rainfall events, ranging from 3 to 98 minutes duration, recorded at one minute intervals). This is more than could be meaningfully analysed alongside the other parameters tested within this study. Therefore only the initial rainfall event (referred to as RE_1) of each Sampling Period was selected for analysis. The selection of RE_1 also meant that treatment response could be best observed prior to any pipes / troughs becoming blocked. RE_1 data was further reduced to two minute intervals starting from 1 minute post rainfall initiation, a frequency closer to that observed in other studies (Beighley et al., 2010; Faucette et al., 2004; Jasa and Dickey, 1991). This continued until rainfall cessation. Data was further analysed 1 minute and 10 minutes post cessation. If after 10 minutes runoff continued (≥ 1.0 l) and a new rainfall event had not begun then data was analysed at 5 minutes intervals until runoff had reached a steady state.

Within each of the five RE_1 data, statistical differences between treatment responses were tested using a one-way ANOVA within STATISTICA version 12. For all analyses undertaken, the assumptions of the ANOVA were checked (using residual analysis) with outliers identified and removed as appropriate. If required the data was transformed by calculating the log of each value. Data was analysed for statistical significance at $p \leq 0.2$. This level was selected as a large variation in plot response within treatment was expected. Where significant differences between treatment responses were observed post-hoc Fisher LSD analysis was undertaken.

4.1.4 Field site characterisation

4.1.4.1 Climate

The average annual rainfall recorded in Ross on Wye (SO601241) was 734 mm from 1981 to 2010 (Met Office, 2014). However, in 2012, 1370 mm was recorded at Cobrey Farms (SO614218), with the periods of heaviest rainfall starting from April and continuing through to December (Figure 4.6).

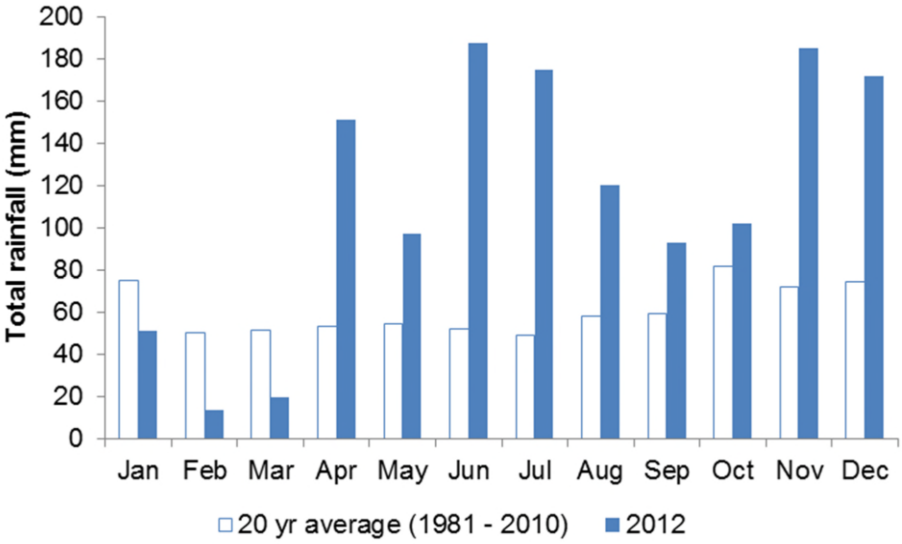


Figure 4.6. Rainfall data for Ross on Wye for 2012 as compared with the 20 year average. Data courtesy of Cobrey Farms and the Met Office.

In total approximately 562 mm of rainfall was recorded on-site during the Phase 1 field trial period (February to July 2012). Approximately 174 mm rainfall was received by treatments prior to sample collection due to a delay in final runoff collection setup. The rainfall characteristics of each Sampling Period varied and are presented in Table 4.5. Sampling Periods 1, 2, 3, 4 and 5 were associated with maximum rainfall intensities of 48, 72, 24, 48 and 96 mm hr-1, respectively. Total rainfall for all sampling periods collectively amounted to 388 mm, of which 76.6% was associated with Sampling Periods 4 and 5.

Table 4.5. A summary of rainfall characteristics associated with each Sampling Period.

Sampling Period	Collection period	Total rainfall (mm)	Total no. collection days	No. rain days‡	No rainfall events†	Mean rainfall intensity (mm hr^{-1})	Maximum rainfall intensity (mm hr^{-1})
1	1st-3rd May 2012	47.8	3	2	5	15	48
2	4th-14th May 2012	25.8	10	4	2	14	72
3	15th-28th May 2012	16.8	13	3	4	12	24
4	29th May-26th Jun 2012	149	28	16	16	13	48
5	27th Jun-17th Jul 2012	149	19	13	16	15	96

†Rainfall events defined as ≥1.0 mm rain over a 10 minute period. ‡Rain days defined as a ≥ 1.0 mm within one day.

4.1.4.2 Soil

The soil at the field site is classified as the Eardiston Soil Association (Whitfield, 1971). This typically consists of fine to very fine sandy loam soils and loam soils with < 20 % clay content (Whitfield, 1971). Historic organic matter levels taken from two local sites range from 4.1 % and 5.0 % at 0 – 35 cm depth and 2.7 – 2.9 % at 35 – 75 cm depth (Whitfield, 1971). Typical historic bulk density values were reported at 1.5 g cm^{-3}, with observations of earthworm channels and roots throughout the soil profile (Whitby, 1971).

To fully characterise the existing baseline soil properties, replicate samples were taken from the asparagus wheelings of each Non-SSD Control plot. A nine point randomly selected composite soil sample at 0 – 150 mm depth was taken from the length (40 m) of each Non-SSD Control plot post treatment application. Bulk density samples at 0 – 50 mm depth were from both Non-SSD Control plots and an asparagus ridge to characterise the degree of surface soil compaction.

Composite samples from each Non-SSD Control plot were air dried and ground to <2mm. They were analysed for particle size distribution (BS 7755-5.4, 2010) and organic matter content (BS EN 13039, 2000). These particular parameters were selected in order to understand the main structural components of the soil (Table 4.6). The data was checked for normal distribution, and analysed for statistical significance ($p= \leq 0.05$) using a Factorial ANOVA followed by Fisher LSD.

Table 4.6. Justification for the soil parameters selected for analysis.

Tested parameters	**Justification**
Particle size distribution	Particle size distribution will determine soil erodibility, and structure.
Organic matter content	The amount of organic matter can indicate soil stability and structure.

Soil particle size distribution results (Table 4.7) confirmed a sandy loam soil texture as stated by Whitby (1971). However, organic matter content has reduced to just one third of that originally reported in the upper soil profile. It is interesting to note that no earthworm activity and very few roots were observed during the soil sampling period. Whilst measured soil properties show little variation between field study control plots (Table 4.7) some significant differences do occur. Bulk density varies between the plots by up to 0.25 g cm^{-3}, soil organic matter by 0.1 % and sand content by up to 2.0%. However, these differences are considered negligible and would not result in differences in plot response. In conclusion, at the beginning of the trials, the plots were shown to have the same soil characteristics, so the subsequent field trials could be considered a fair test.

Table 4.7. Mean soil properties of field control plots. Within each parameter, values followed by a different letter indicate statistical difference at P ≤ 0.05.

Bulk density (g cm^{-3})	Soil organic matter† (%)	Sand (%)	Silt (%)	Clay (%)
1.80 b	1.4 b	68.0 a	16.8 a	15.2 a
1.76 b	1.4 ab	68.2 a	16.9 a	14.9 a
1.60 a	1.4 a	69.9 b	14.6 a	15.5 a
1.55 a	1.5 c	70.0 b	15.1 a	15.0 a

†Results based on loss on ignition analysis.

Slope gradient is an important factor in erosion, with slope length being equal, steeper slopes generate greater runoff velocity and can result in increased erosion. In this experiment the steepest field was selected for field trial setup. This served three purposes:

1. To simulate the worst case scenario for asparagus fields.
2. To ensure a more accurate measurement of plot runoff and soil loss, as with a steeper drop, collection pipes will more efficiently transport runoff reducing pipe blockages.
3. For ease of installation as a steeper drop makes it unnecessary to excavate a pit for the runoff collection tanks.

Typical slope angles currently adopted in new asparagus bed field layouts for erosion control rarely exceed 4 degrees, suggesting that even at these slopes erosion occurs (Simmons and Truckell, 2013).

Due to local slope variations of the site, each plot slope angle was measured. A hand-held clinometer was used for this measurement at the top of the plot and a point of equal height at the base of the plot. Results show that plots ranged from 5.2 – 6.0° (mean of 5.7 ± 0.3 STDEV). No significant difference in slope gradient was found between the plots following full factorial ANOVA (Table 4.8). These measured slope gradients in combination with the on-site soil texture are classified as at high risk of water erosion (Defra, 2005).

Table 4.8. Mean slope gradient measurements for each treatment type (no. 1, 3-10 n=3, no. 2 n=4). Within each parameter, values followed by a different letter indicate statistical difference at $p \leq 0.05$.

No.	Plot treatment code	Slope (degrees)	
1	Non-SSD Cp^L	5.2	a
2	Non-SSD Control	5.5	a
3	SSD St^H	6.0	a
4	SSD St^L	5.7	a
5	Non-SSD St^H	5.7	a
6	SSD Cp^H	6.0	a
7	Non-SSD Cp^H	6.0	a
8	Non-SSD St^L	5.7	a
9	SSD Cp^L	5.5	a
10	SSD No Mulch	5.5	a

A series of penetration resistance tests were carried out in the Non-SSD Control plots. This sought to establish whether the extent of compaction went deeper than the current practice 175 mm SSD. Three sets of tests were undertaken at the top, middle and bottom of each control plot using an Eijkelkamp Penetrologger with a 1.2 cm^2 30° internal angle cone operating to a maximum depth of 0.5 m. Prior to each measurement a 0 – 50 mm undisturbed soil bulk density sample was taken to ensure similar soil moisture conditions between measurements. The penetrometer was slowly inserted into the soil at a uniform rate and angle.

Results show compaction beyond the current cultivation depth of 175 mm. Penetration resistance readings ranged between 3 and 5 MPa up to a depth of 0.5 m (Figure 4.7).

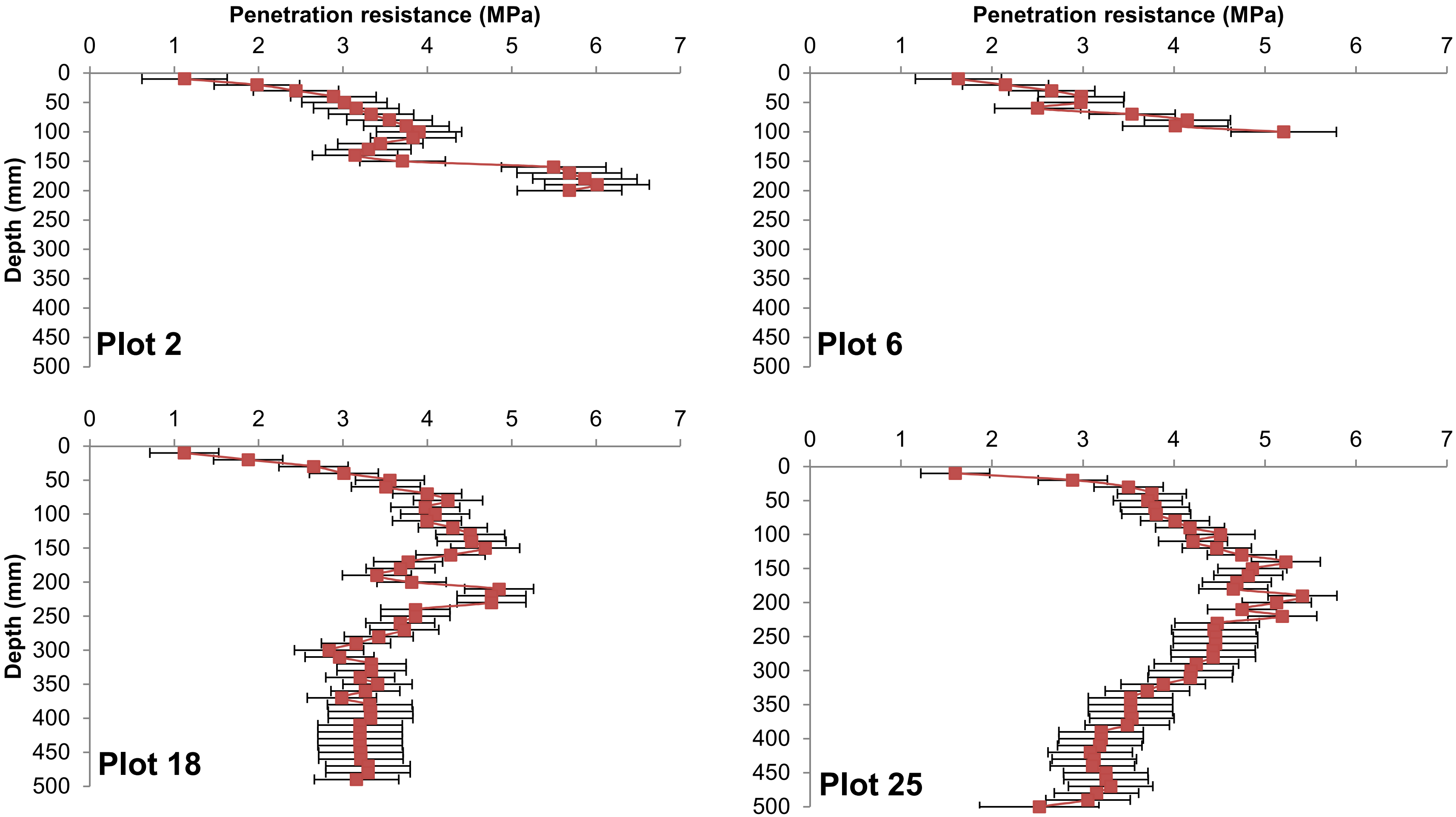


Figure 4.7. Mean soil penetration resistance readings taken from experimental control plots. Error bars show ± 1 SE.

This degree of penetration resistance indicates an extremely dense soil (>3.0 MPa), through which very few plant roots would be able to penetrate (Reijmerink, 1973). Where penetration to the full 0.5 m was achieved, a peak in soil resistance was observed between approximately 0.05 and 0.3 m. This suggests the presence of a plough pan. Below 0.3 m, penetrative resistance still remained at 3 MPa.

The original cause of compaction is most likely to be the legacy of potato cropping where cultivations can occur up to a depth of 0.6 m. This has the effect of removing soil structure and consequently makes the cultivated soil more susceptible to compaction. This problem is then exacerbated by repeating trafficking throughout the period of asparagus production on soils with little organic matter

4.2 Results

Treatment codes referred to in this section are defined in Table 4.1.

4.2.1 Runoff volume (l)

It was expected that the least runoff volume would be generated by the SSD treatments as compared with Non-SSD treatments due to increased porosity and increased infiltration. Furthermore, within the SSD plots it was expected that those with the high application rate mulch treatments would further reduce runoff volume by slowing runoff velocity as a result of increased surface roughness and surface depression storage, so allowing a longer time for infiltration.

4.2.1.1 Overall runoff volume

Runoff volumes totalled across the entire sample collection period partially met the treatment expectations outlined above. Some significant differences between treatment types were observed. These differences were a result of mulch alone and in interaction with SSD. Mulch expectations were not met as St and Cp treatments demonstrated mixed effects on runoff. St treatments increased runoff independent of SSD/Non-SSD and L/H application rates. Meanwhile Cp treatments reduced runoff volume independent of SSD/Non-SSD and L/H application rates. Only Non-SSD Cp^H, SSD Cp^L and SSD No Mulch resulted in significant reductions in runoff volume as compared to the Non-SSD Control by 43, 48 and 43 % respectively.

Table 4.9. Mean runoff volume (l) for each treatment across the entire Phase 1 sample collection period. Results followed by different letters are significantly different ($p \leq 0.05$) following one-way factorial ANOVA and post hoc Fisher LSD.

Treatment	Runoff volume (l)	
Non-SSD Cp^L	822	ab
Non-SSD Cp^H	636	a
Non-SSD Control	1118	bcd
Non-SSD St^L	1193	d
Non-SSD St^H	1147	cd
SSD Cp^L	581	a
SSD Cp^H	884	abc
SSD No Mulch	636	a
SSD St^L	1116	bcd
SSD St^H	1025	bcd

4.2.1.2 Individual Sampling Period runoff volume

SSD treatment expectations outlined above were not met in individual Sampling Periods. No significant differences were observed in runoff volume between SSD and Non-SSD treatments across all Sampling Periods (Table 4.10). However, mulch treatment expectations were met to some extent with significant differences observed in the first three Sampling Periods (Table 4.10). A significant difference was observed between the 2 way treatment interaction effect of tillage and mulch type in Sampling Period 2 (Table 4.10). However, no significant 3-way interaction effects were observed between SSD/Non-SSD, St/Cp/No Mulch and L/H application rate (Table 4.10).

Significant differences in mulch treatments were not consistent across St and Cp mulch types (Figure 4.8). Cp irrespective of tillage and application rate significantly reduced runoff volume by 32, 38 and 28 % as compared with St treatments in Sampling Periods 1, 2 and 3 respectively (Appendix A.3, Table_Apx A-3). Furthermore, no significant differences were observed between Cp and No Mulch treatments or St and No Mulch treatments, due to high variation between No Mulch replicates.

Table 4.10. Significance levels (p-values) of each treatment factor on runoff volume, derived from nested full factorial ANOVA

Dependent variable	Sampling Period	Factors Tillage (SSD/Non-SSD)	Mulch type (St/Cp)	Tillage and mulch type (2-way interaction)	Tillage, mulch type and rate (3-way interaction)
Runoff volume (l)	1	0.28	0.01*	0.48	0.93
	2	0.12	0.02*	0.04*	0.15
	3	0.50	0.01*	0.17	0.16
	4	0.38	0.20	0.54	0.20
	5	0.38	0.14	0.98	0.38

*A statistically significant result ($p \leq 0.05$)

A significant difference was observed in Sampling Period 2 treatment interaction effects between Non-SSD/SSD and Cp/St/No Mulch. Non-SSD/SSD Cp and Non-SSD No Mulch treatments significantly reduced runoff volume as compared with Non-SSD St treatments. Furthermore, Non-SSD Cp significantly reduced runoff volume as compared with SSD St and the Non-SSD No Mulch control. SSD No mulch also significantly reduced runoff volume as compared with the Non-SSD No mulch control.

The lack of statistical difference within the 3-way treatment interaction between tillage, mulch type and mulch rate for all treatments across all Sampling Periods is due to a similarity in results, with most tanks reaching their full capacity at the point of sampling. Furthermore, large variations in runoff volume existed between replicates. Despite no statistically significant differences in the 3 way treatment interaction, trends between results were evident with some treatments (Figure 4.8). Non-SSD Cp^H reduced runoff volume by 71 % in Sampling Period 2 as compared with the Non-SSD Control. In the same Sampling Period, SSD No Mulch resulted in runoff volume reductions of 69 % as compared with the Non-SSD Control. Non-SSD Cp^L reduced runoff volume by 52 % in Sampling Period 5 and SSD St^H by 45 % as compared to the Non-SSD Control.

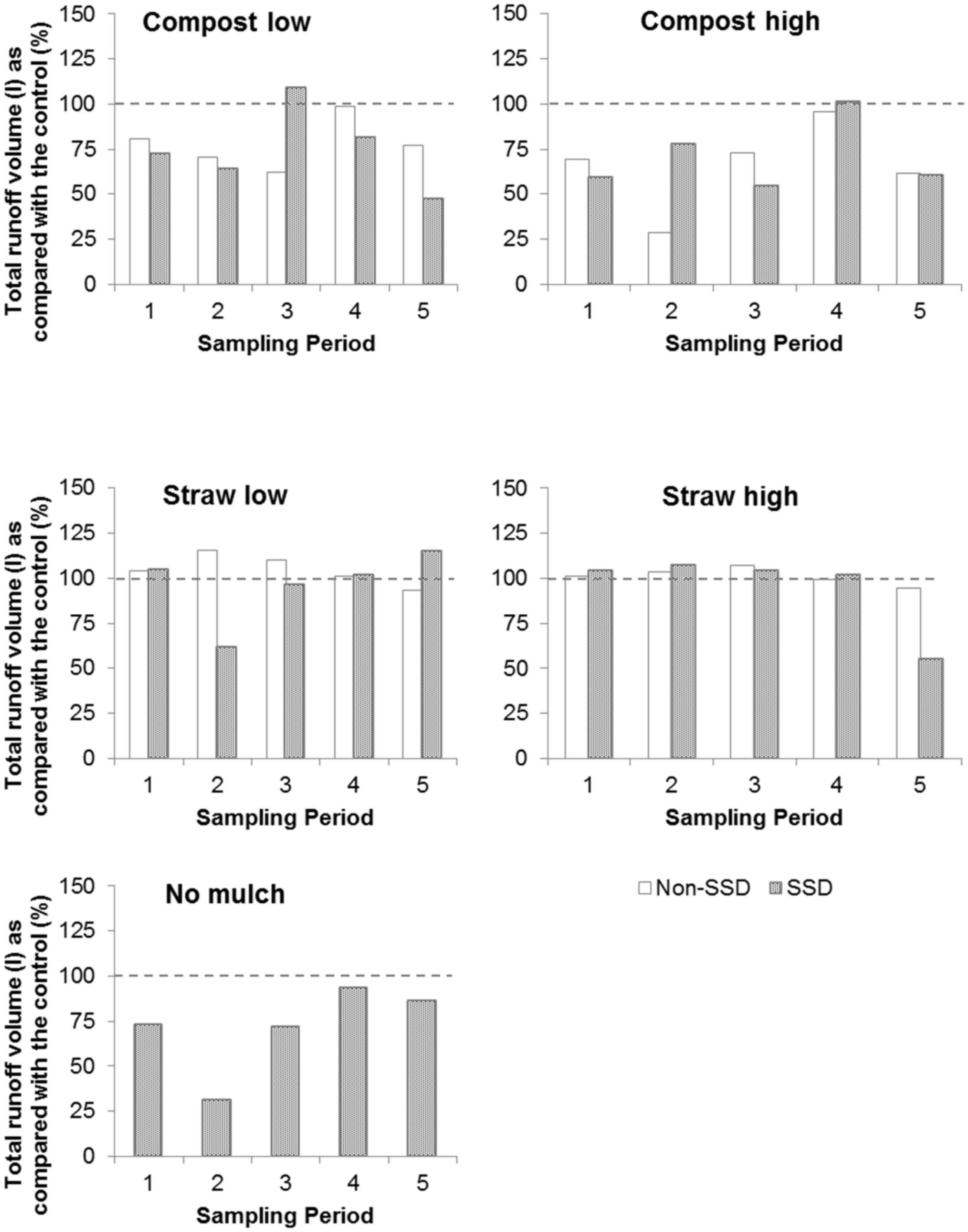


Figure 4.8. Relative runoff volume (l plot^{-1}) from each treatment compared with the Non-SSD Control (the dashed line). Filled circles denote a statistical difference from the Non-SSD Control. For statistical differences between treatments see Appendix A.3, Table_Apx A-3.

4.2.2 Event driven hydrological response of treatments

It was envisaged that a detailed analysis of the hydrological response of treatments (cumulative runoff volume, runoff rate, time to rainfall initiation and runoff cessation) to the RE_1 for each Sampling Period would have the potential to highlight differences in treatment response, allowing the interpretation of runoff volume results prior to the plot tanks reaching full capacity. The rainfall characteristics of the RE_1 for each Sampling Period differed (Table 4.11).

Table 4.11. RE_1 characteristics for each Sampling Period.

Sampling Period	RE_1 duration (mins)	Rainfall (mm)	Percentage of Sampling Period rainfall (%)	Mean Intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})	Frequency (years)*
1	4	1.4	3	21	36	< 2
2	14	5.4	63	27	72	2
3	8	1.0	17	15	24	< 2
4	18	1.6	3	12	12	< 2
5	13	9.0	12	45	72	10

*Frequency calculations based upon intensity and duration curves (Corney, 2011).

4.2.2.1 Cumulative volume (l)

Some significant differences in cumulative runoff volume between treatments were evident (Table 4.12). However, the treatment expectations outlined in Section 4.2.1 were not met by the event-based measurement of hydrological response; different treatments exhibited different cumulative volume responses.

Table 4.12. Significance levels (p-values) of the treatment effect on RE$_1$ cumulative runoff volume derived from one-way ANOVA.

Cumulative volume (l)	Sampling Period				
	1	**2**	**3**	**4**	**5**
0	0.03*	N/s	N/v	N/v	N/s
1	0.03*	N/s	N/v	N/v	N/s
3	0.01*	N/s	N/v	N/s	N/s
5	0.21	0.18*	N/s	N/s	*0.20**
7	-	0.50	0.05*	N/s	0.69
9	-	0.38	<0.01*	N/s	0.12*
11	-	0.33	-	*0.58*	0.15*
13	-	0.32	-	0.72	0.17*
14	0.32	-	-	-	-
15	-	0.35	-	0.64	-
17	-	-	-	0.46	-
18	-	-	*0.01**	-	-
19	0.29	-	-	0.38	-
23	-	-	-	-	0.16*
24	-	0.28	-	-	-
28	-	-	-	0.15*	-
33	-	-	-	0.11*	-

*A statistically significant result ($p \le 0.20$). N/v; No variance within results. N/s; Data is not suitable for ANOVA (assumptions not met).

Mulched treatments generated the most frequent significant reductions in RE$_1$ cumulative volume as compared to the Non-SSD Control. Non-SSD St^{H}, Non-SSD St^{L} and SSD St^{H} significantly reduced cumulative runoff in Sampling Periods 1-3, SSD Cp^{H} in Sampling Periods 2, 3 and 5 and SSD Cp^{L} in Sampling Periods 2, 3 and 4).

Furthermore, SSD St^L resulted in significant reductions in Sampling Periods 2 and 3, and Non-SSD Cp^L in Sampling Period 2.

In Sampling Period 1 (Figure 4.9) Non-SSD St^H, Non-SSD St^L and SSD St^H had significantly lower cumulative volumes as compared with the Non-SSD Control. Non-SSD St^H generated significantly lower cumulative runoff than all other treatments at 1 and 3 minutes post rainfall initiation with an 88 and 82 % reduction respectively as compared to the Non-SSD Control. In Sampling Period 2 (Figure 4.10) all mulch treatments generated significantly lower cumulative volumes at 5 minutes post rainfall initiation as compared to the Non-SSD Control. These reductions ranged from a 39 % (Non-SSD Cp^L) to 74 % (Non-SSD St^H) as compared with the Non-SSD Control. No statistical differences between the mulched treatments were observed. In Sampling Period 3 (Figure 4.11) both Non-SSD and SSD St treatments together with SSD Cp^H significantly reduced cumulative volume at 7 and 9 minutes post rainfall initiation as compared to the Non-SSD Control. These significant differences continued into the final cumulative volume 10 minutes post rainfall cessation. Both St^H treatments did not generate runoff throughout the event. SSD St^L only generated runoff at 18 minutes (10 minutes post RE_1 rainfall cessation) resulting in 88 % less runoff as compared with the Non-SSD Control. By Sampling Period 4 (Figure 4.12) fewer significant reductions in runoff between treatments were observed. SSD Cp^L generated no cumulative volume resulting in the only significant reduction as compared with the Non-SSD Control at just 28 and 33 minutes. This demonstrates a high degree of variability within the data with at least 1 out of three replicates not initially producing runoff. In Sampling Period 5 (Figure 4.13) SSD Cp^H significantly reduced cumulative volume by 67 % at 23 minutes (10 minutes post rainfall cessation) as compared to the Non-SSD Control, whilst Non-SSD St treatments, SSD St^L and SSD No mulch all generated significantly higher cumulative volumes as compared with the Non-SSD Control.

4.2.2.2 Runoff rate (l min^{-1})

Some significant differences in runoff rates between treatments were evident (Table 4.13Table 4.13. Significance levels (p-values) of the treatment effect on RE_1 runoff rates, derived from one-way ANOVA.Table 4.12). It was expected that runoff rate would be reduced by SSD and high mulched application rate treatments. This is because the frictional components imparted onto the runoff will reduce the velocity thus reducing the overall rate. However, this was not the case with a similar frequency of significant reductions in runoff rates from high and low mulch treatments (50:50). SSD treatments demonstrated a greater effect on runoff rate reduction as compared to Non-SSD treatments (60:40). Furthermore, high levels of mulch application dominated incidences of significantly greater runoff rate as compared to the Non-SSD Control 90:10. Non-SSD treatments also accounted for the majority of significant runoff rate increases (70:30). Mulched treatments again generated the most frequent significant reductions as compared to the Non-SSD Control. SSD Cp^H, SSD St^H and SSD St^L all significantly reduced runoff rate in 3 Sampling Periods. Furthermore, Non-SSD Cp^H, Non-SSD Cp^L, Non-SSD St^H, Non-SSD St^L and SSD Cp^L significantly reduced runoff rate in 2 Sampling Periods, and SSD No mulch in 1 Sampling Period.

Table 4.13. Significance levels (p-values) of the treatment effect on RE_1 runoff rates, derived from one-way ANOVA.

Runoff rate (l min^{-1})	**Sampling Period**				
	1	**2**	**3**	**4**	**5**
0	N/s	N/v	N/s	N/v	N/v
1	0.02*	N/s	N/v	N/v	N/v
3	0.33	N/v	N/v	N/s	_0.50_
5	0.11*	0.20	N/s	N/v	N/s
7	-	0.19*	_0.01*_	N/s	0.54
9	-	0.57	_<0.01*_	N/s	0.24
11	-	0.24	-	_0.54_	_0.01*_
13	-	0.53	-	0.66	_0.16*_
14	0.02*	-	-	-	-
15	-	0.97	-	0.28	-
17	-	-	-	_0.09*_	-
18	-	-	ns	-	-
19	0.02*	-	-	_0.09*_	-

Runoff rate (l $\min^{-1}$)	Sampling Period 1	 2	 3	 4	 5
23	-	-	-	-	*0.13**
24	-	0.74	-	-	-
28	-	-	-	0.01*	-
33	-	-	-	0.08*	-

*A statistically significant result ($p \leq 0.20$). N/v; No variance within results. N/s; Data is not suitable for ANOVA (assumptions not met).

In Sampling Period 1 (Figure 4.9), 5 minutes post rainfall initiation Non-SSD Cp^L, SSD Cp^H and SSD Cp^L significantly reduced runoff rate as compared to the Non-SSD Control by 93, 61 and 89 % respectively. At 14 and 19 minutes, SSD Cp^L and SSD No mulch significantly reduced runoff rate as compared to the Non-SSD Control with no runoff generated from either treatment. Furthermore, at 19 minutes SSD Cp^H and SSD St^L also generated no further runoff, whilst Non-SSD Cp^H and Non-SSD Cp^L reduced runoff by 99 and 54 % respectively as compared with the Non-SSD Control. All reductions in runoff rate had not preceded the observed reductions in cumulative volume.

In Sampling Period 2 (Figure 4.10), no significant reductions in runoff rate were observed. Meanwhile in Sampling Period 3 (Figure 4.11), Non-SSD St^H, SSD St^H and SSD St^L significantly reduced runoff rate with 0 l $\min^{-1}$ as compared with the Non-SSD Control at 7 and 9 minutes. This concurs with cumulative volume data that showed no runoff volume generation from Non-SSD and SSD St^H. Furthermore, Non-SSD St^L and SSD Cp^H significantly reduced runoff rate at 7 minutes by 87 and 75 % respectively and both by 73 % at 9 minutes. The occurrence of significantly reduced runoff rates at 7 and 9 minutes coincided simultaneously with significant reductions in cumulative volume. In Sampling Period 4 (Figure 4.12), Non-SSD Cp^L generated no runoff throughout. At 17, 19 and 28 minutes SSD St^H significantly reduced the rate of runoff by 69, 69 and 87 % respectively as compared with the Non-SSD Control. Furthermore, at 17 and 19 minutes SSD St^L significantly reduced the rate of runoff by 69 and 67 % respectively as compared with the Non-SSD Control. In Sampling Period 5 Non-SSD CpH significantly reduced the rate of runoff at 11 and 13 minutes by 100 and 99 %

respectively as compared with the Non-SSD Control. Furthermore, at 13 minutes SSD CpH and SSD StH significantly reduced the rate of runoff by 93 and 99 % respectively as compared with the Non-SSD Control.

4.2.2.3 Time to runoff initiation (min)

It was expected that SSD and high mulched treatments would increase the time to runoff initiation. This is because treatments could first allow rainfall to infiltrate rainfall and become stored on the surface before runoff was generated. Furthermore, surface roughness could reduce runoff velocity, increasing the time taken to travel downslope as compared with Non-SSD and No Mulch treatments. However, this was not the case as RE$_1$ runoff initiation was only significantly affected in Sampling Periods 1 and 3 (Table 4.14). In Sampling Period 1, Non-SSD St^{H} has a significant lag in time to runoff initiation as compared with the Non-SSD Control (3 minutes) and all other treatments. In Sampling Period 3, no runoff is initiated by any St treatments or SSD No mulch. Furthermore, SSD Cp^{L} and SSD Cp^{H} significantly increase time to runoff initiation as compared to the Non-SSD Control by approximately 2 and 1.5 minutes respectively. Runoff initiation takes longer in Sampling Period 4 across all treatments. This is due to a low rainfall intensity of RE$_1$, with peak rainfall not reached (0.4 mm in 2 minutes) until 9 minutes post rainfall initiation (Figure 4.12).

Table 4.14. Mean time to runoff initiation (minutes) of each treatment for RE$_1$ of each Sampling Period. Within each Sampling Period values followed by different letters denote statistical significance ($p \leq 0.2$) following one-way ANOVA.

		Sampling Period†									
No.	**Treatment**	**1**		**2**		**3**		**4**		**5**	
1	Non-SSD Cp^{L}	2.00	a	5.33	a	6.50	ab	13.50	a	7.50	a
7	Non-SSD Cp^{H}	1.00	b			5.67	a	10.00	a	7.00	a
2	Non-SSD Control	1.67	ab	5.00	a	5.75	a	12.33	a	8.00	a
8	Non-SSD St^{L}	1.67	ab	5.00	a			14.67	a	6.67	a
5	Non SSD St^{H}	4.33	c	5.67	a			13.67	a	7.67	a
9	SSD Cp^{L}	2.00	a	5.00	a	7.67	c			7.33	a

		Sampling Period[†]									
No.	**Treatment**	**1**		**2**		**3**		**4**		**5**	
6	SSD Cp^H	1.67	ab	5.33	a	7.00	bc	13.00	a	7.00	a
10	SSD No mulch	1.50	ab							7.00	a
4	SSD St^L	2.00	a	5.33	a			17.00	a	8.00	a
3	SSD St^H	1.00	b	5.33	a			17.50	a	7.67	a

[†] Blank cells indicate treatments that did not generate runoff.

Sampling Period 1

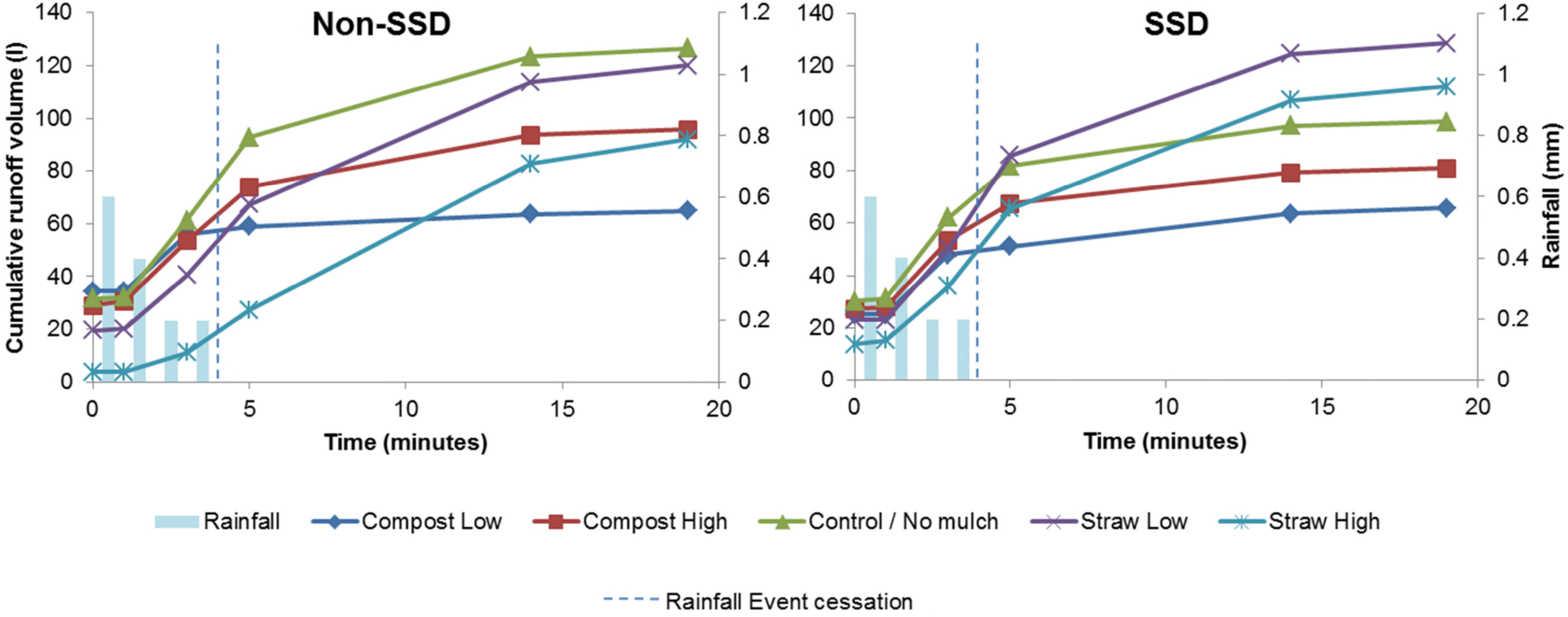


Figure 4.9. Runoff hydrographs for the first rainfall event of Sampling Period 1. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute, 10 minutes and 15 minutes post rainfall cessation. For significance levels see Table 1.1, for significant differences between treatments see Appendix A.4, Table_Apx_A-6.

Sampling Period 2

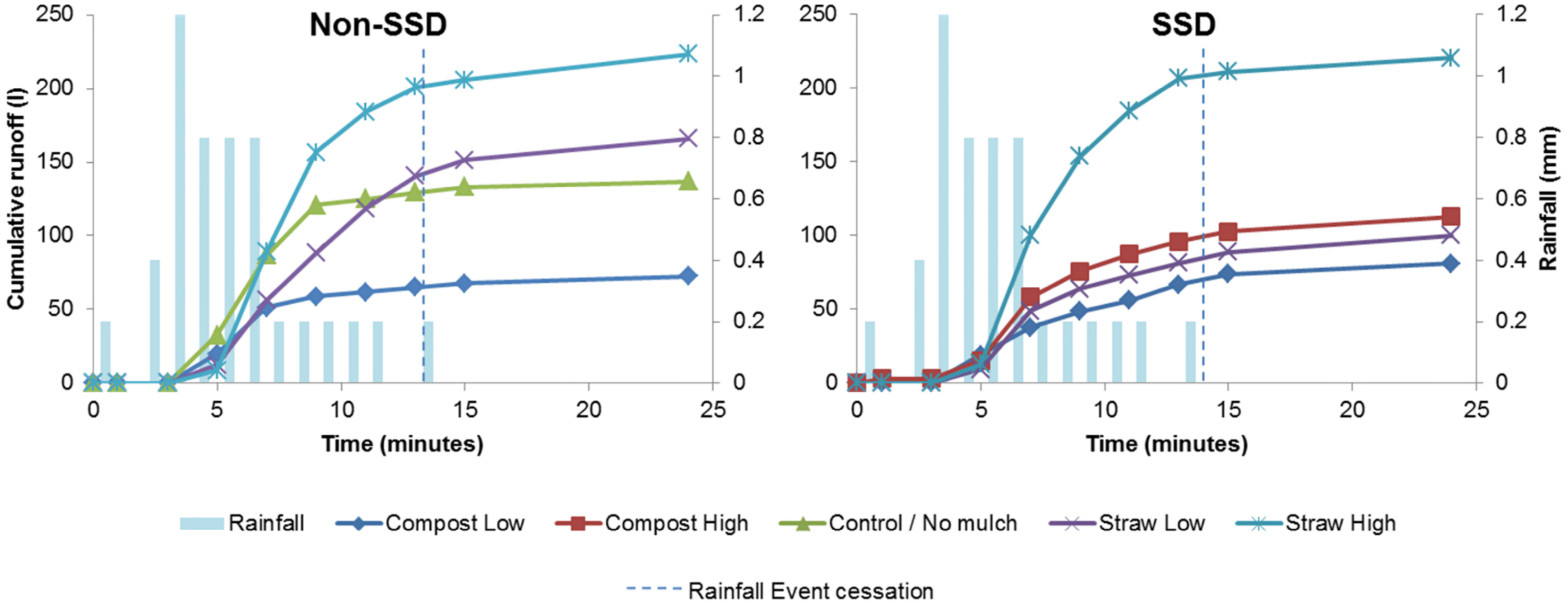


Figure 4.10. Runoff hydrographs for the first rainfall event of Sampling Period 2. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute and 10 minutes post rainfall cessation. N.B. Non-SSD Cp ^{H} and SSD No mulch are omitted due to insufficient sensor data. For significance levels see Table 1.1, for significant differences between treatments see Appendix A.4, Table_Apx A-7.

Sampling Period 3

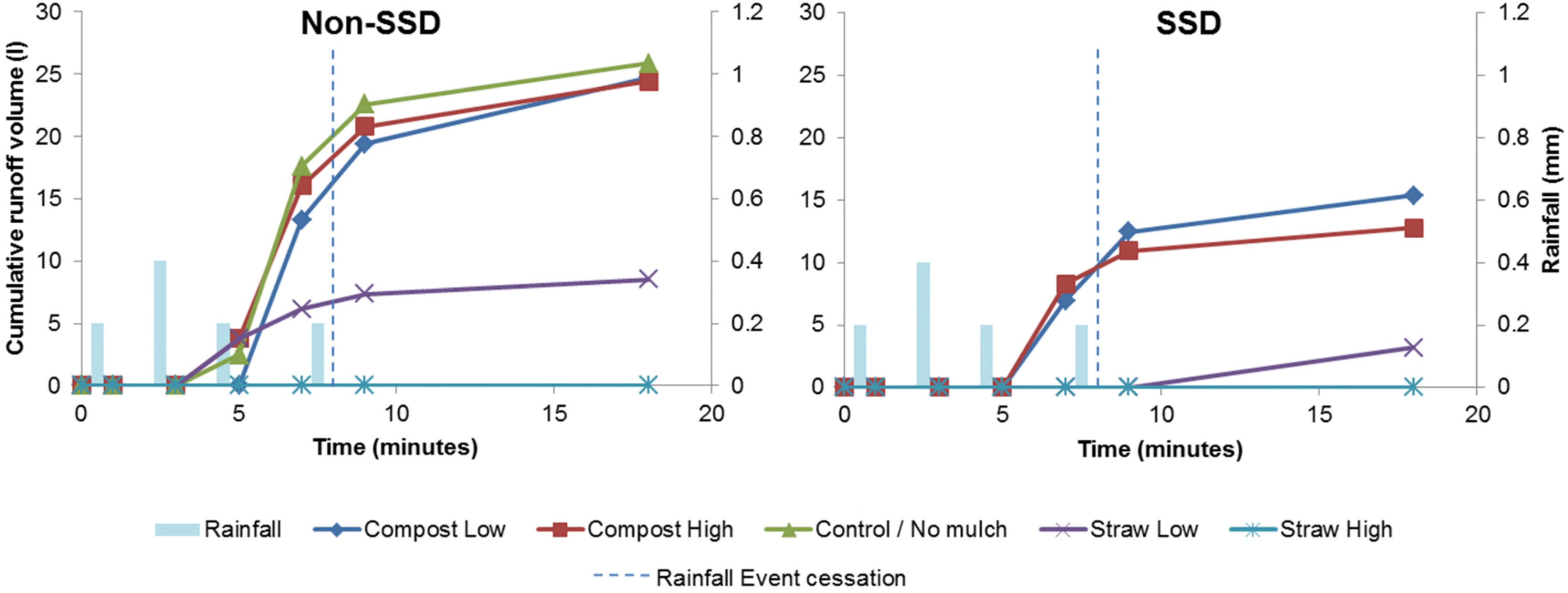


Figure 4.11. Runoff hydrographs for the first rainfall event of Sampling Period 3. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute and 10 minutes post rainfall cessation. N.B. SSD No mulch is omitted due to insufficient sensor data. For significance levels see Table 1.1, for significant differences between treatments see Appendix A.4, Table_Apx A-8.

Sampling Period 4

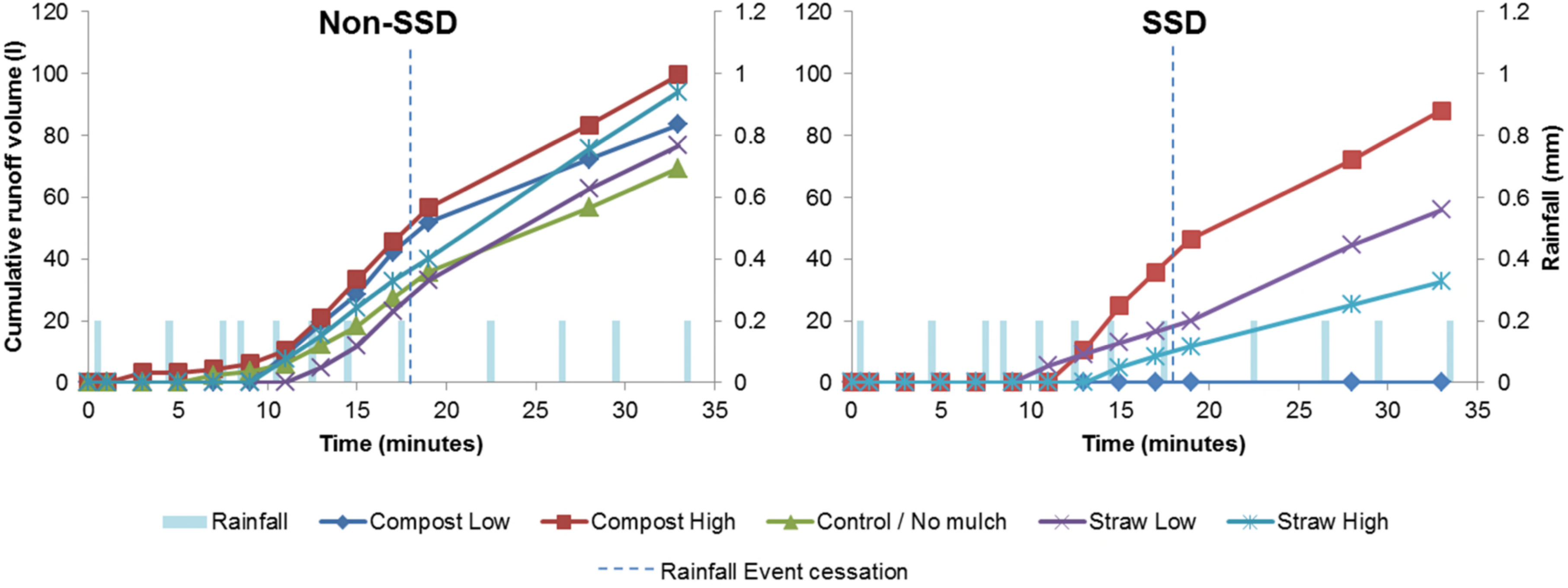


Figure 4.12. Runoff hydrographs for the first rainfall event of Sampling Period 4. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute, 10 minutes and 15 minutes post rainfall cessation. N.B. SSD No mulch is omitted due to insufficient sensor data. For significance levels see Table 1.1, for significant differences between treatments see Appendix A.4, Table_Apx_A-9.

Sampling Period 5

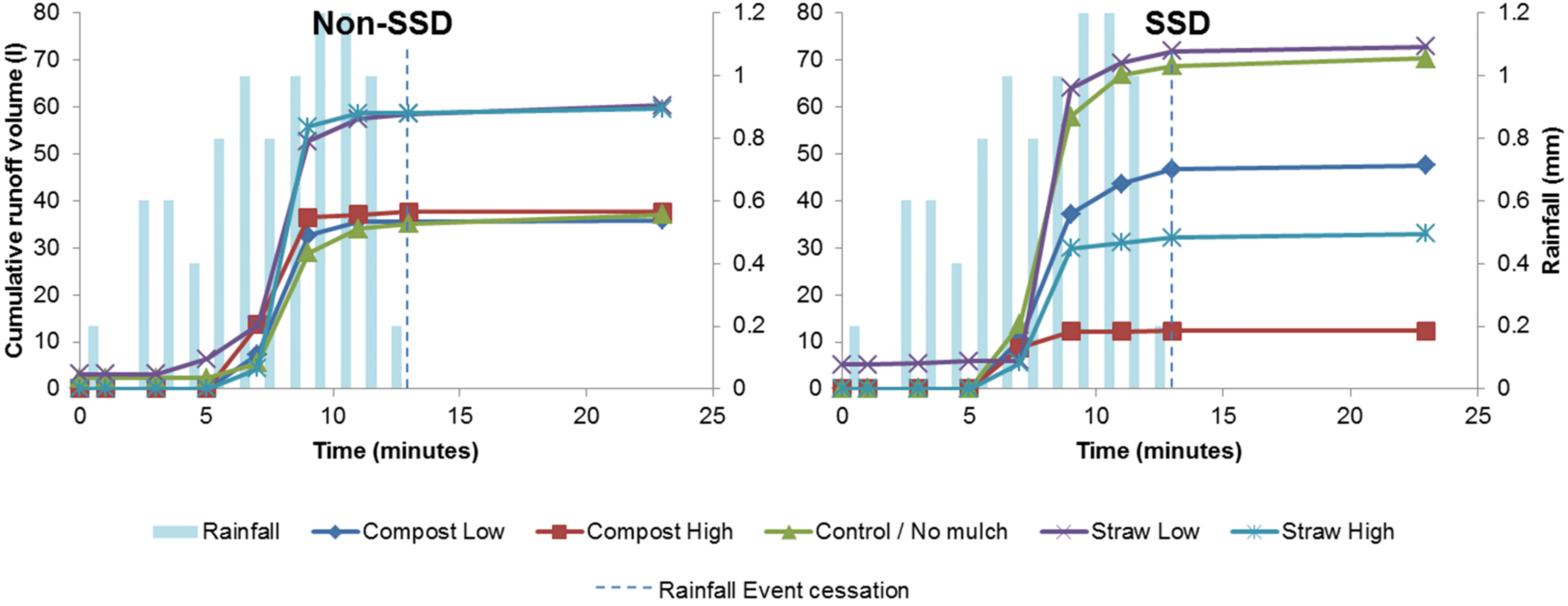


Figure 4.13. Runoff hydrographs for the first rainfall event of Sampling Period 5. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute and 10 minutes post rainfall cessation. For significance levels see Table 1.1, for significant differences between treatments see Appendix A.4, Table_Apx A-10.

4.2.3 Total soil loss (kg)

It was expected that SSD combined with St and Cp treatments at high mulch application rates would achieve the greatest reduction in TSL. This is because the increased infiltration associated with SSD will reduce the runoff volume capable of entraining and transporting sediment. Furthermore, the surface mulch will protect the soil surface from detachment and in combination with SSD will impart a frictional component to flow reducing runoff velocity resulting in fewer soil particles becoming entrained.

4.2.3.1 Overall TSL

TSL results for each treatment for the entire Phase 1 collection period were calculated (Table 4.15). These results met the expectations outline above with significant differences between SSD mulched and Non-SSD No Mulch treatments. Non-SSD Cp^H, Non-SSD St^L, Non-SSD St^H and SSD St^H significantly reduced soil loss as compared with the Non-SSD Control by 60, 57, 72 and 53 % respectively. SSD treatments generated relatively moderate soil loss as compared to equivalent Non-SSD treatments. Both Cp^L and No Mulch treatments (including the Control) resulted in the largest soil loss in excess of 100 kg plot^{-1}.

Table 4.15. Mean TSL (kg plot^{-1}) for each treatment across the entire Phase 1 sample collection period. Results followed by different letters are significantly different ($p \leq 0.05$) following one-way factorial ANOVA and post hoc Fisher LSD.

No.	Treatment code	Mean soil loss (kg plot^{-1})		Mean soil loss (t ha^{-1})
1	Non-SSD Cp^L	147	c	24.6
2	Non-SSD Cp^H	52.7	ab	8.79
3	Non-SSD Control	131	cd	21.8
4	Non-SSD St^L	56.7	ab	9.44
5	Non-SSD St^H	36.5	a	6.08
6	SSD Cp^L	148	c	24.7

No.	Treatment code	Mean soil loss (kg plot^{-1})		Mean soil loss (t ha^{-1})
7	SSD Cp^{H}	92.2	bcd	15.4
8	SSD No Mulch	124	cd	20.7
9	SSD St^{L}	72.5	abd	12.1
10	SSD St^{H}	61.8	ab	10.3

N.B. Results are reported in t ha^{-1} for ease of comparison with other studies.

4.2.3.2 Individual Sampling Period TSL

TSL results from individual Sampling Periods did not fully meet treatment expectations (Section 4.2.3). Non-SSD treatments were associated with greater TSL reductions as compared with the equivalent SSD treatments. These reductions were only significant in 1 out of 5 Sampling Periods. Significant differences between treatment factors were only observed in Sampling Periods 1, 2, 3 and 4, with significant 3-way interaction effects observed in Sampling Periods 1, 2 and 4 (Table 4.16). Sizeable differences between treatments were observed in Sampling Period 3; however, high variation between replicates meant that no significant differences were observed (Figure 4.14 and Appendix A.3, Table_Apx A-3).

Across Sampling Periods 1, 2 and 4, 6 treatments significantly reduced TSL as compared with the Non-SSD Control (Figure 4.14). Non-SSD St^{H} most frequently reduced TSL (Sampling Periods 1, 2 and 4). Furthermore, Non-SSD St^{L} and SSD St^{H} reduced TSL in Sampling Periods 1 and 2, and SSD St^{L} in Sampling Periods 1 and 4. Non-SSD Cp^{H} and SSD Cp^{H} both reduced TSL in Sampling Period 1.

Non-SSD St^{H} resulted in the greatest reduction in TSL as compared to the Non-SSD Control (Figure 4.14). TSL reductions associated with Non-SSD St^{H} were 76, 85 and 59 % for Sampling Periods 1, 2 and 4 respectively. This was followed by Non-SSD St^{L} with significant reductions in TSL of 41 and 64 % for Sampling Periods 1 and 2 respectively as compared with the Non-SSD Control. Non-SSD Cp^{H} significantly reduced TSL by 66 % as compared with the Non-SSD Control in Sampling Periods 1, but did not differ significantly from either Non-SSD St treatment (Figure 4.14).

Table 4.16. Significance levels (p-values) of each treatment factor on total soil loss, derived from nested full factorial ANOVA.

		Factors			
Dependent variable	**Sampling Period**	**Tillage (SSD/Non-SSD)**	**Mulch type (St/Cp)**	**Tillage and mulch type (2-way interaction)**	**Tillage, mulch type and rate (3-way interaction)**
Total soil loss (kg)	1	0.01*	<0.01*	0.90	0.01*
	2	<0.01*	<0.01*	0.48	0.04*
	3	0.02*	<0.01*	0.13	0.09
	4	0.26	<0.01*	0.96	0.03*
	5	0.79	0.06	0.90	0.11

*A statistically significant result ($p \leq 0.05$)

The equivalent SSD treatments also significantly reduced TSL as compared to the Non-SSD Control. SSD St^H significantly reduced TSL during Sampling Period 1 and 2 by 49 and 54 % respectively. In Sampling Period 1 and 4 SSD St^L resulted in the significant TSL reductions of 30 and 51 % respectively. SSD Cp^H only significantly reduced TSL as compared with the Non-SSD Control for Sampling Period 1 (33 %). However, this was not significantly different from SSD St^H and SSD St^L.

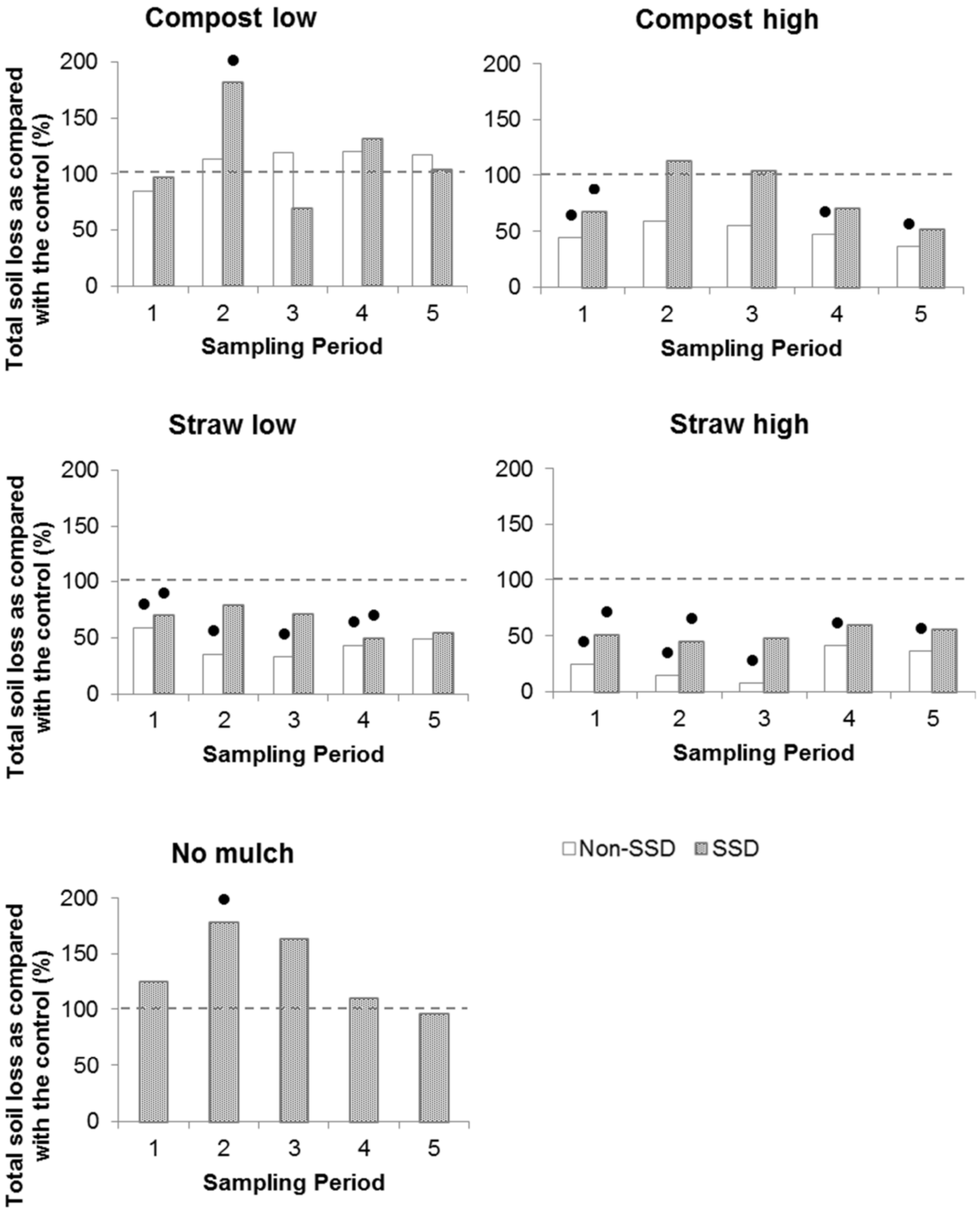


Figure 4.14. Relative mean TSL (kg plot^{-1}) from each treatment compared with the Non-SSD Control (the dashed line). Filled circles denote a statistical difference from the Non-SSD Control. For statistical differences between treatments see Appendix A.3, Table_Apx A-3.

4.2.4 Sediment concentration (g l^{-1})

As was the case for TSL, it was expected that the enhanced surface roughness imparted by treatments such as SSD St^H and Cp^H would result in the greatest reduction in suspended sediment in the runoff. This is because reduced runoff velocity and volume would result in less soil becoming entrained and transported by runoff. Furthermore, the mulch effect would minimise the supply of detached material as it forms a protective barrier between the soil surface and the rainfall and runoff. However, this was not the case with few significant differences observed between SSD treatments and the Non-SSD Control, although there was some evidence of a mulch effect in treatment response.

Only Sampling Periods 1 and 2 showed significant differences in treatment factors (Table 4.17). No significant differences were observed in Sampling Periods 3, 4 and 5 due to a high degree of variation between replicates for all treatments.

Table 4.17. Significance levels (p-values) of each treatment factor on sediment concentration in runoff, derived from nested full factorial ANOVA.

				Factors	
Dependent variable	**Sampling Period**	**Tillage (SSD/Non-SSD)**	**Mulch type (St/Cp)**	**Tillage and mulch type (2-way interaction)**	**Tillage, mulch type and rate (3-way interaction)**
Runoff sediment concentration (g l^{-1})	1	0.10	0.04*	0.24	0.77
	2	0.65	0.68	0.03*	0.96
	3	0.39	0.06	0.96	0.24
	4	0.19	0.63	0.12	0.71
	5	0.99	0.43	0.45	0.51

*A statistically significant result ($p \le 0.05$)

All treatments across all Sampling Periods exceed the suspended sediment concentration guideline value of 25 mg l^{-1} (0.025 g l^{-1}) set by the EU Directive 75/440/EEC for the quality of surface waters suitable for drinking water abstraction (Figure 4.16). Therefore, all events can be deemed to be polluting. Only one treatment is of the same order of magnitude as the 25 mg l^{-1} guideline; SSD No mulch in

Sampling Period 2. However, this result has a high degree of variation (± 5.3 g l^{-1} standard error).

In Sampling Period 1 no significant differences in sediment concentration were observed between any treatment and the Non-SSD Control. The high variability within the Non-SSD Control limited the occurrence of any statistical differences, despite SSD St^H producing a 43 % reduction in runoff sediment concentration (Figure 4.15). However, differences between St and Cp treatments were observed. St treatments resulted in a significant 38 % reduction in runoff sediment concentration as compared with No mulch treatments. This is evident within treatments for example; Non-SSD St^H runoff resulted in significantly less sediment concentration (66 %) as compared with Non-SSD Cp^H. Furthermore, Non-SSD St^L had a significantly lower sediment concentration (52 %) as compared with Non-SSD Cp^H. In Sampling Period 2 differences between 2-way treatment interactions were observed (Table 4.17). Non-SSD St^H differed significantly from the Non-SSD Control, generating 67 % less sediment concentration in runoff. Furthermore, there was a strong trend for SSD No Mulch to produce a 59 % reduction in mean runoff sediment concentration. However, this is not significant due to the high variability between replicates for both the Control and SSD No Mulch.

4.2.5 Total oxides of nitrogen (mg l^{-1})

It was expected that the greatest TON concentrations would be associated with Cp treatments. This is because the N contained within Cp will become slowly mineralised and released (WRAP, 2007). Furthermore, the addition of St can cause N to become immobilised by soil microbes (Christenson and Olesen, 1998). However, this was not found to be the case with significant differences only observed between mulch types in Sampling Period 1 (Table 4.18). Furthermore, significant differences were also observed between tillage in the same Sampling Period. Significant differences in the 3 way interaction between treatments was also observed, although only in Sampling Period 5.

Table 4.18. Significance levels (p-values) of each treatment factor on TON concentration in runoff, derived from nested full factorial ANOVA.

		Factors			
Dependent variable	**Sampling Period**	**Tillage (SSD/Non-SSD)**	**Mulch type (St/Cp)**	**Tillage and mulch type (2-way interaction)**	**Tillage, mulch type and rate (3-way interaction)**
TON concentration (mg l^{-1})	1	0.03*	<0.01*	0.51	0.10
	3	0.77	0.43	0.88	0.46
	5	0.24	0.60	0.83	0.03*

*A statistically significant result ($p \leq 0.05$)

In Sampling Period 1 (Figure 4.16), St significantly reduced TON in runoff by 50 % as compared to No Mulch treatments and 35 % as compared with Cp treatments. Non-SSD treatments also reduced TON in runoff in Sampling Period 1 by 18 % as compared with SSD treatments. In Sampling Period 5, SSD Cp^H is the only treatment that produces significantly less TON (57 %) as compared with the Non-SSD Control.

TON concentrations in Sampling Period 1 and 3 are below the standard 25 mg l^{-1} nitrate guideline set by the EU Directive 75/440/EEC (Figure 4.16). However, in Sampling Period 5, all treatments (including the control) exceeded this, producing concentrations of up to 5 times greater than the guideline. However, due to the type of TON analysis undertaken, the concentrations reported in Figure 4.16 included both nitrate and nitrite concentrations. Therefore, whilst runoff may still have exceeded the nitrates guideline, it is difficult to know the exact value.

4.2.6 Phosphorus (mg)

4.2.6.1 Orthophosphate-P (mg l^{-1})

It was expected that Cp treatments would result in increased orthophosphate-P concentrations, as a result of bringing additional P to the site. However, this was not the case, with few significant differences between treatments. Significant differences were only observed in Sampling Period 1 within individual tillage and mulch factors (Table 4.19).

Table 4.19. Significance levels (p-values) of each treatment factor on orthophosphate-P concentration in runoff, derived from nested full factorial ANOVA.

		Factors			
Dependent variable	**Sampling Period**	**Tillage (SSD/Non-SSD)**	**Mulch type (St/Cp)**	**Tillage and mulch type (2-way interaction)**	**Tillage, mulch type and rate (3-way interaction)**
Orthophosphate-P concentration (mg l^{-1})	1	0.04*	<0.01*	0.08	0.31
	3	0.25	0.13	0.65	0.37
	5	0.87	0.91	0.38	0.44

*A statistically significant result (p≤0.05)

Orthophosphate-P concentrations in treatment runoff all exceed the WFD annual mean range for soluble reactive P as prescribed for rivers of good ecological status for all alkalinity and elevation classifications (UKTAG, 2008). In Sampling Period 1, 90 % of treatments generated P concentrations that were 5 times greater than the upper P limit (0.12 mg l^{-1}). This increases to 100 % in Sampling Period 3 and drops to 40 % in Sampling Period 5.

In Sampling Period 1 (Figure 4.17), St treatments significantly reduced orthophosphate-P by 27 % as compared with No Mulch treatments and 22 % as compared with Cp treatments. Furthermore, Non-SSD treatments significantly reduced orthophosphate-P by 16 % as compared with SSD treatments. In Sampling Periods 3 and 5, replicate variability increased and consequently no significant differences between treatments were observed.

4.2.6.2 Sediment-bound P (mg kg^{-1})

It was expected that the lowest levels of sediment-bound P would be associated with SSD mulched treatments. This is because mulch will protect the soil from detachment and enhanced surface roughness and improved infiltration will reduce the likelihood of soil particle becoming entrained and transported in runoff. However, this was not the case with no significant differences between treatment factors (Table 4.20).

Table 4.20. Significance levels (p-values) of each treatment factor on sediment-bound P concentration in runoff, derived from nested full factorial ANOVA.

		Factors			
Dependent variable	**Sampling Period**	**Tillage (SSD/Non-SSD)**	**Mulch type (St/Cp)**	**Tillage and mulch type (2-way interaction)**	**Tillage, mulch type and rate (3-way interaction)**
Sediment bound P concentration (mg kg^{-1})	1	0.34	0.24	0.58	0.24
	3	0.52	0.04*	0.57	0.97
	5	Results do not meet the assumptions of ANOVA analysis			

*A statistically significant result ($p \leq 0.05$)

In Sampling Period 1 and 3 (Figure 4.18), no significant differences between treatments were evident. This is a result of similar concentrations between treatments. In Sampling Period 5, elevated results for SSD Cp^H meant that ANOVA could not be carried out as data was not normally distributed (Appendix A.3, Table_Apx A-4). Despite being considered a potential pollutant, no specific guideline value is available for sediment-bound P.

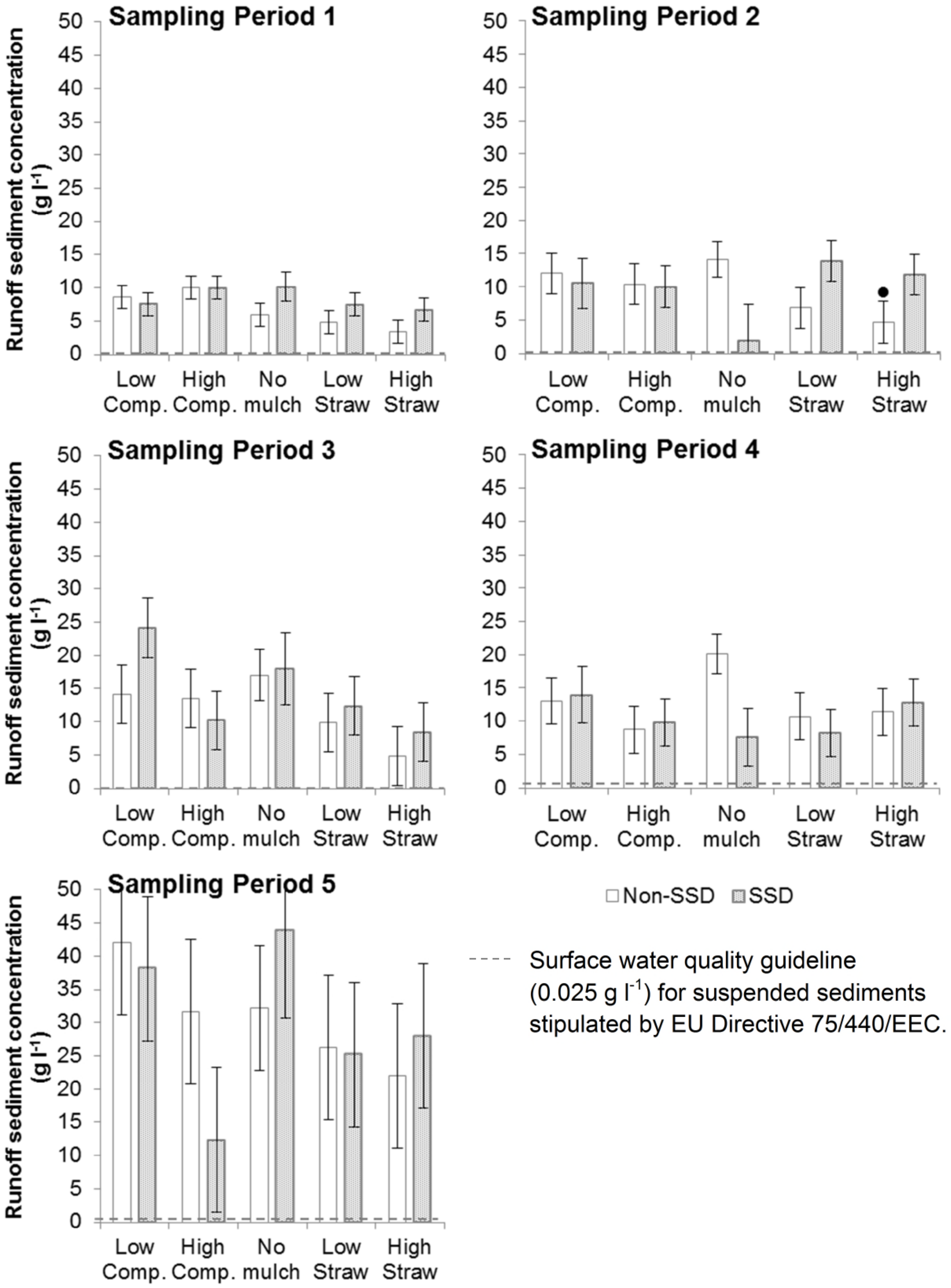


Figure 4.15. Mean sediment concentration in runoff (mg l^{-1}) across all Sampling Periods. Filled circles denote a statistical difference from the Non-SSD Control. Error bars show ± 1 SE. For statistical differences between treatments see Appendix A.3, Table_Apx A-3.

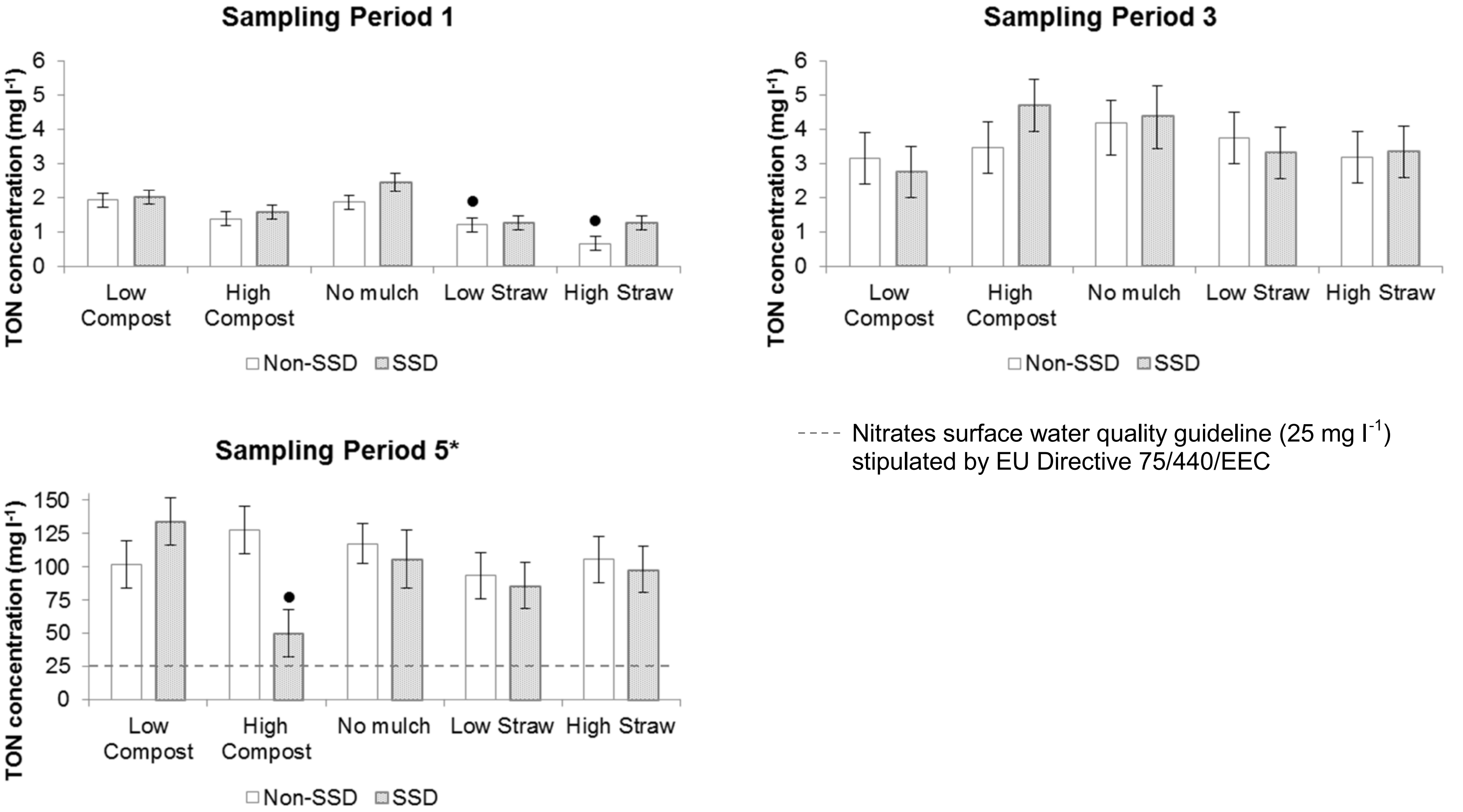
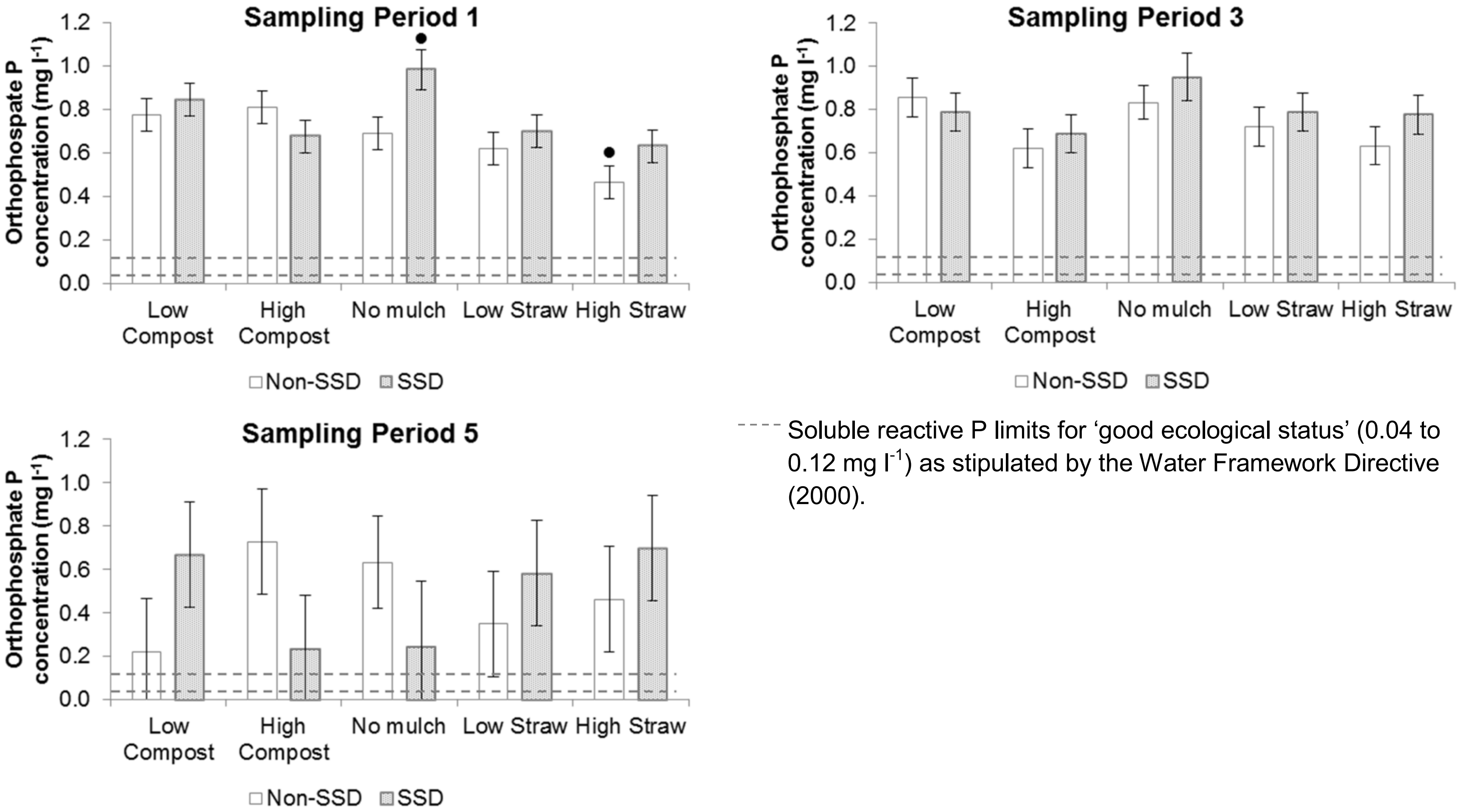


Figure 4.16. Mean concentration of TON in runoff (mg l^{-1}) for the three tested Sampling Periods. Filled circles denote a statistical difference from the Non-SSD Control. Error bars show ± 1 SE. For statistical differences between treatments see Appendix A.3, Table_Apx A-4. *Scales on the y axis vary.



---- Soluble reactive P limits for 'good ecological status' (0.04 to 0.12 mg l^{-1}) as stipulated by the Water Framework Directive (2000).

Figure 4.17. Mean concentration of Orthophosphate P in runoff (mg l^{-1}) for the three tested Sampling Periods. Filled circles denote a statistical difference from the Non-SSD Control. Error bars show ± 1 SE. For statistical differences between treatments see Appendix A.3, Table_Apx A-4.

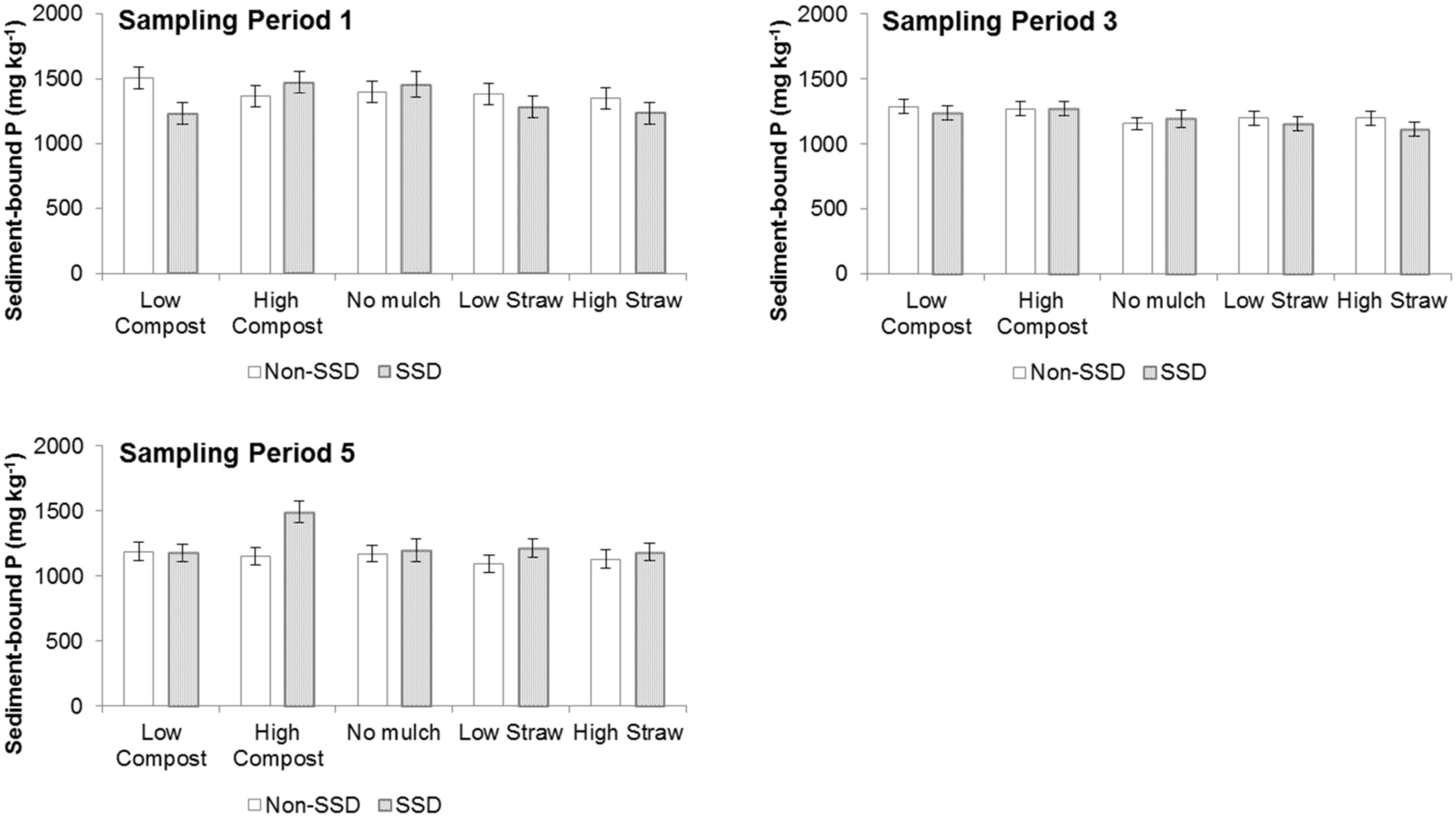


Figure 4.18. Mean concentration of sediment-bound P in runoff (mg kg^{-1}) for the three tested Sampling Periods. Filled circles denote a statistical difference from the Non-SSD Control. Error bars show ± 1 SE. For statistical differences between treatments see Appendix A.3, Table_Apx A-4.

4.3 Discussion

The effectiveness of individual treatments was ranked based on the treatment means for each key performance indicator; total runoff volume, total soil loss and sediment, TON, orthophosphate-P and sediment-bound P concentration in runoff. This was carried out across both individual Sampling Periods (Table 4.21) and overall for the entire Phase 1 sample collection period (Table 4.22 and Table 4.13) so that differences in performance and reliability could be clearly identified. Across each Sampling Period, the lowest means were assigned a rank of 1 and the highest means a rank of 10. The mean treatment rank was then calculated for each performance indicator across all Sampling Periods to indicate overall performance. These means were then tabulated for each treatment and a mean rank calculated across all performance indicators (Table 4.22).

Across all Sampling Periods, the most reductions were observed from Non-SSD St^H (TSL and sediment and orthophosphate-P concentration in runoff). Furthermore, Non-SSD Cp^H most reduced runoff volume, SSD St^L most reduced TON concentration in runoff and SSD St^H most reduced sediment-bound P concentration in runoff (Table 4.21). Overall, Non-SSD St^H ranked as the most effective treatment followed by Non-SSD St^L and SSD St^H, whilst SSD Mulch was the least effective treatment (Table 4.22).

Table 4.21. A ranked summary of the effectiveness of individual treatments on each performance indicator. Differences in rank are based on differences in mean values. Lower scores mean the 'best' treatment.

Variable	Treatment	Sampling Period					Mean
		1	2	3	4	5	
Total runoff volume	Non-SSD Cp^L	5	5	2	4	5	4.2
	Non-SSD Cp^H	2	1	4	3	4	2.8
	Non-SSD Control	6	7	6	6	9	6.8
	Non-SSD St^L	8	10	10	7	7	8.4
	Non-SSD St^H	7	8	8	5	8	7.2

Variable	Treatment	Sampling Period					Mean
		1	2	3	4	5	
	SSD Cp^L	3	4	9	1	1	3.6
	SSD Cp^H	1	6	1	8	3	3.8
	SSD No mulch	4	2	3	2	6	3.4
	SSD St^L	10	3	5	10	10	7.6
	SSD St^H	9	9	7	9	2	7.2
Total soil loss	Non-SSD Cp^L	7	8	9	9	10	8.6
	Non-SSD Cp^H	2	4	4	3	2	3
	Non-SSD Control	9	6	7	7	8	7.4
	Non-SSD St^L	4	2	2	2	3	2.6
	Non-SSD St^H	1	1	1	1	1	1
	SSD Cp^L	8	10	5	10	9	8.4
	SSD Cp^H	5	7	8	6	4	6
	SSD No mulch	10.0	9	10	8	7	8.8
	SSD St^L	6	5	6	4	5	5.2
	SSD St^H	3	3	3	5	6	4
Runoff sediment concentration	Non-SSD Cp^L	7	8	7	8	9	7.8
	Non-SSD Cp^H	9	5	6	3	6	5.8
	Non-SSD Control	3	10	8	10	7	7.6
	Non-SSD St^L	2	3	3	5	4	3.4
	Non-SSD St^H	1	2	1	6	2	2.4
	SSD Cp^L	6	6	10	9	8	7.8
	SSD Cp^H	8	4	4	4	1	4.2
	SSD No mulch	10	1	9	1	10	6.2

Variable	Treatment	Sampling Period					Mean
		1	2	3	4	5	
	SSD St^L	5	9	5	2	3	4.8
	SSD St^H	4	7	2	7	5	5
TON concentration	Non-SSD Cp^L	8	-	2	-	5	5
	Non-SSD Cp^H	5	-	6	-	9	6.7
	Non-SSD Control	7	-	8	-	8	7.7
	Non-SSD St^L	2	-	7	-	3	4
	Non-SSD St^H	1	-	3	-	6	3.3
	SSD Cp^L	9	-	1	-	10	6.7
	SSD Cp^H	6	-	10	-	1	5.7
	SSD No mulch	10	-	9	-	7	8.7
	SSD St^L	3.5	-	4	-	2	3.2
	SSD St^H	3.5	-	5	-	4	4.2
Orthophosphate P concentration	Non-SSD Cp^L	7	-	9	-	1	5.7
	Non-SSD Cp^H	8	-	1	-	10	6.3
	Non-SSD Control	5	-	8	-	7	6.7
	Non-SSD St^L	2	-	4	-	4	3.3
	Non-SSD St^H	1	-	2	-	5	2.7
	SSD Cp^L	9	-	6.5	-	8	7.8
	SSD Cp^H	4	-	3	-	2	3.0
	SSD No mulch	10	-	10	-	3	7.7
	SSD St^L	6	-	6.5	-	6	6.2
	SSD St^H	3	-	5	-	9	5.7
Sediment-	Non-SSD Cp^L	10	-	10	-	7	9.0

Variable	Treatment	Sampling Period					Mean
		1	2	3	4	5	
bound P concentration	Non-SSD Cp^H	5	-	8	-	3	5.3
	Non-SSD Control	7	-	3	-	4	4.7
	Non-SSD St^L	6	-	6	-	1	4.3
	Non-SSD St^H	4	-	5	-	2	3.7
	SSD Cp^L	1	-	7	-	5	4.3
	SSD Cp^H	9	-	9	-	10	9.3
	SSD No mulch	8	-	4	-	8	6.7
	SSD St^L	3	-	2	-	9	4.7
	SSD St^H	2	-	1	-	6	3.0

Table 4.22. Overall rank for each treatment performance indicator across all Sampling Periods based upon data presented in Table 4.21. Lower scores mean the 'best' treatment.

Treatment	Performance indicator						
	Runoff volume	TSL	Sediment concentration in runoff	TON concentration	Ortho-phosphate-P	Sediment -bound P	Mean rank
Non-SSD Cp^{L}	4.2	8.6	7.8	5.0	5.7	9.0	6.7
Non-SSD Cp^{H}	2.8	3.0	5.8	6.7	6.3	5.3	5.0
Non-SSD Control	6.8	7.4	7.6	7.7	6.7	4.7	6.8
Non-SSD St^{L}	8.4	2.6	3.4	4.0	3.3	4.3	4.3
Non-SSD St^{H}	7.2	1.0	2.4	3.3	2.7	3.7	3.4
SSD Cp^{L}	3.6	8.4	7.8	6.7	7.8	4.3	6.4
SSD Cp^{H}	3.8	6.0	4.2	5.7	3.0	9.3	5.3
SSD No mulch	3.4	8.8	6.2	8.7	7.7	6.7	6.9
SSD St^{L}	7.6	5.2	4.8	3.2	6.2	4.7	5.3
SSD St^{H}	7.2	4.0	5.0	4.2	5.7	3.0	4.8

4.3.1 Runoff volume

For Sampling Periods 1-5, Phase 1 results showed an uncertainty in the effectiveness of treatments to reduce total runoff volume. This uncertainty is due to partial failure of the field monitoring system used. During Phase 1, there was above average rainfall with 1370 mm recorded on-site as compared with the 30 year (1981 – 2010) average of 734 mm (Met Office, 2014). The continuous nature and above average volume of rainfall received over the Sampling Periods, in combination with long, steep-sloped plots meant high volumes of plot runoff were generated. This often resulted in collection tanks reaching capacity (approximately 250 l) and overtopping. Evidence of over-topping was observed at the point of sampling. As a consequence all tanks achieved maximum capacity during Sampling Periods 1-5, irrespective of treatment variations in runoff rate and event-based cumulative runoff volumes. However, within Sampling Periods significant differences in RE_1 driven runoff volumes and runoff rates were detectable by utilising the runoff hydrograph data generated by the linear level sensors.

Furthermore, the high degree of variability between replicates of the same treatment (unrelated to maximum tank volumes) are in large part a result of where blockages in the Gerlach troughs prevented the runoff reaching the collection tank. Whilst outliers generated by blocked pipes were removed, it was not possible to do so where blocked Gerlach troughs were observed, as they occurred too frequently. These blockages resulted in a high variation in treatment replicate response. Therefore even where maximum tank capacity was not reached, treatment response was not always indicative of true plot runoff volume.

Blockages demonstrate that erosion occurred in the plots. This is further supported by on-site recorded rainfall intensities of ≥ 12 mm hr^{-1} (mean) and up to a 96 mm hr^{-1} (maximum). Rainfall intensities as low as 1.5 mm hr^{-1} have been found to result in a 15 % occurrence of erosion in other UK erosion studies (Evans, 1990). Furthermore, rainfall intensities of 10 mm hr^{-1} are considered to result in erosion during moderate rainfall events and brief falls (Morgan, 1980, Fullen, 1992) and >15 mm hr^{-1} during very short rainfall periods (Fullen, 1992).

4.3.2 Event based hydrological response of treatments

In contrast to the measured runoff volume data, runoff hydrograph data for each Sampling Period RE_1 does show some significant differences in the hydrological response of each treatment. These suggest the efficacy and longevity of treatments in controlling runoff.

The Non-SSD Control was amongst the highest runoff producing treatments for three of the five Sampling Period RE_1's. This is to be expected as no improvement in soil porosity or surface roughness had been made and so infiltration was impeded by the pre-existing high level of compaction. St treatments (Non-SSD St^H, Non-SSD St^L and SSD St^H) significantly delayed runoff generation in RE_1 Sampling Period 1 and resulted in reduced cumulative volumes between Sampling Period 1 and 3. In Sampling Period 3 RE_1, both Non-SSD St^H and Non-SSD St^L did not generate any runoff. This was the smallest RE_1 with just 1 mm rainfall and a low mean intensity of 15 mm hr^{-1} peaking at just 24 mm hr^{-1}. This suggests that only higher intensity events result in runoff from these treatments, as confirmed by runoff generation in all other RE_1 Events.

SSD St^L did not generate significant reductions in runoff volume until Sampling Period 3. This delayed effectiveness as compared with SSD St^H could be a combination of the low mulch application rate and partial incorporation with SSD. This could have reduced the surface roughness and surface storage relative to SSD St^H, preventing the treatment from effectively reducing runoff. With time, the St could have become mobilised by the runoff (Berg, 1984) forming dams (Brown et al., 1998; Kwaad et al., 1998) that could have impeded the runoff providing surface storage and a greater opportunity for infiltration. In the case of SSD St^L, this process could have improved the effectiveness of the treatment over time resulting in significant reductions in Sampling Period 3 and 4. Overall, Non-SSD St^H proved most effective as a result of the increased surface roughness and surface applied St. Furthermore, there was no SSD effect to reduce over time thus effecting reliability.

In two of the RE_1 events all Cp treatments showed a greater reduction in runoff as compared with all St treatments. Similar results have been found in other studies (Beighley et al., 2010; Reinsch et al., 2007). This difference in mulch response suggests that Cp is more able to hold water (Persyn et al., 2004) than St. However, this was only observed in Cp^L treatments, whilst this effect would be expected to be more pronounced at high application rates (Beighley et al., 2010). This suggests that treatment effectiveness had been affected, which can be corroborated with field notes that list frequent blockages from the Cp plots. These blockages most likely result from the Cp fine particles moving downslope and blocking pipes, as was observed in the field following a large rainfall event prior to runoff collection.

4.3.3 Total soil loss

TSL results were standardised to give an equivalent t ha^{-1} soil loss (Table 4.15). This is an extrapolation of the soil loss measured over the 5 month experimental period of an extremely wet year, and assumes that TSL would be the same across a greater area, something that cannot currently be verified. However, this calculation allows an approximate comparison to be made with other studies. All values exceed the latest tolerable annual soil erosion rate for Europe estimated at 1.4 t ha^{-1} (Verheijen et al., 2009). These are indicative of a very erodible soil. The on-site sandy loam soil (Section 1.1.1.2) contains less than 16 % clay. Soils with less than 30 – 35 % clay have little cohesion (Evans, 1980). It is the clay fraction that can strengthen and stabilise soil aggregates (Davies et al., 2001) without which soils are more resistant to detachment by rainfall (Evans, 1980). On-site organic matter content is also low. With less than 2 %, this soil is classified as erodible (Fullen, 2000). Current onsite organic matter content is lower than that previously documented in local soils, and suggests that the soil has been degraded. The low clay and organic carbon content combined with a legacy of on-site compaction to depth will limit infiltration and create a very erodible soil. Furthermore, the continual disturbance of the soil surface by foot traffic during the harvest period might be providing a supply of detached material that could be readily transported by runoff. Despite being indicative of an extreme period, soil loss measured from the plots is unsustainable and needs to be further addressed.

The results indicate that both Non-SSD St^{H} and Non-SSD St^{L} were the most effective at reducing TSL across all Sampling Periods. However, of the two treatments Non-SSD St^{H} results in the greatest reduction in TSL across all Sampling Periods. This effectiveness suggests that the simple application of St at 6 t ha^{-1} can reduce TSL by between 59 to 92 % as compared with the Non-SSD Control.

The effectiveness of St^{H} may in large part be due to the greater degree of protection provided to the soil surface, intercepting rain and dissipating energy (Persyn et al., 2004; Morgan, 1979). However, whilst the 70 – 75 % cover prescribed by Morgan (2005) protects the soil surface from erosion relative to the other treatments, factors such as incorporation, foot-traffic, rainfall volume, slope (length and gradient) and soil characteristics affect its efficacy as erosion still occurs. In comparison to Cp, the uniform structure of St lends itself to creating mini dams thus reducing runoff velocity and reducing sediment entrainment (Döring et al., 2005; Brown et al., 1998). Similar soil loss reductions from the application of St have been observed in carrots (Holstrom et al., 2008) and potatoes (Döring et al., 2005), as well as in non-row crop settings (Rees et al., 2002; Shock et al., 1997; Tatham 1989; Brown and Kemper 1987; Berg 1984; Meyer et al., 1971). Edwards et al. (2000) only found a 49 % reduction in TSL with incorporated St. However, incorporation during potato ridging would have spread the straw over a larger area (both above and below ground) reducing the resulting surface coverage. In this Phase 1 study, focusing application of the St into the wheeling proved to be more successful overall.

TSL reductions between Non-SSD St^L and Non-SSD St^H were only significantly different in Sampling Period 1. This suggests that in this study post Sampling Period 1, both rates offered inadequate surface protection for erosion reduction. This could be a result of continuous reorganisation and incorporation of St by foot traffic in wet weather conditions during asparagus harvest reducing the initial increased effectiveness of Non-SSD St^H. However, the Non-SSD St^H treatments are not completely altered as the general trend showed that more TSL was produced from Non-SSD St^L, as found by other authors (Holstrom et al., 2008; Döring et al., 2005; Rees et al., 2002; Brown and Kemper, 1987 and Berg, 1984).

In the literature, Cp mulch blankets are expected to have the same effect on erosion as St (Persyn et al., 2004). However, this is not fully demonstrated in this study. Faucette et al. (2009) demonstrates no significant difference between compost blankets of 1.3, 2.5 and 5 cm depth as compared with single-net and double-net straw geotextile treatments. This difference in result can be explained by the nature of the Cp blankets used. Firstly, in this study Cp was hand applied directly onto the soil surface, whilst Faucette et al. (2009) applied compost onto polypropylene netting that was first laid onto the soil surface. This helped maintain the anchorage of the compost, preventing channeling and downslope movement (Beighley et al., 2010). Secondly, compost blanket thicknesses adopted by Faucette et al. (2009) were at least three times those used in this study, as application was not restricted by N content. Higher Cp application rates are known to provide better ground cover and rainfall interception more akin to the effects of St. Therefore, if more Cp was applied in this study, in combination with some form of anchorage, Cp treatments could have proved a more effective means of runoff and erosion control as compared to St.

Shallow soil disturbance interactions with mulch application were mainly associated with reductions in TSL in the early stages of Phase1 (Sampling Periods 1 and 2). TSL from SSD $Cp^{L,}$ actually exceeded the TSL of the Non-SSD Control in Sampling Period 2. This ties in with field observations that some Cp (both Cp^{L} and Cp^{H} treatments) had been washed off prior to Sampling Period 1. This meant that on SSD Cp^{L} little mulch was left protecting the SSD from the short and intense rainfall events of Sampling Period 2. This is supported by the fact that the TSL was no longer significantly different from SSD No Mulch. This goes against the findings of an initial proof of concept study (Niziolomski, 2011) in which mulch in combination with SSD resulted in a highly significant (>90 %) reduction in TSL throughout the trial. This may in part be attributable to differences in the rainfall characteristics and/or mulch types adopted between this and the present study. This study was conducted in an extremely wet year, receiving 557 mm more rainfall than the 2011 study. The present study was also conducted over an additional 105 days. Some studies have shown that soil disturbance is effective at only initially improving infiltration. Gomez et al., 1999 observed tilled soil infiltration rates to match that of non-tilled soils following 85 mm rainfall. Furthermore, Rao et al., 1998 observed similar runoff from tilled and un-tilled soils following approximately 150 mm rainfall. It could also be suggested that instead of a reduced effectiveness in SSD, the loosened soil on the plots was so overwhelmed by runoff that it carried with it, accumulating into a greater TSL. This matches observations from runoff rate data, as reduced rates do continue in high mulched treatments.

In the current study, St mulch was chopped to a length of < 40 mm, blown into the wheelings and loosely incorporated (in SSD plots), whilst the straw treatment in Niziolomski (2011) was uncut and surface applied. This could further account for differences in results with the previous study (Niziolomski 2011). In other studies, un-chopped straw been observed to stick to the sides of wheelings and become embedded when water was applied, making a more effective cover than when chopped (Berg, 1984). Whilst chopped straw has a tendency to lift up and float downslope (Berg, 1984), it has also been shown to better reduce sediment concentrations (Döring et al., 2005). Therefore the mobility of the cut straw contributes to the effectiveness in reducing sediment. Surface and incorporated mulch are documented as having mixed effects on erosion. Dango and Wakindiki (2009) demonstrate less erosion with surface applied straw (3 – 5 t ha^{-1}) as compared with incorporated straw to 0.2 m. This difference corresponds with a significant increase in aggregate stability between treatments. In contrast, Leys et al. (2010) showed no difference in erosion between incorporation at 0.05 m (0.1 to 1.5 t ha^{-1}) and surface applied (0.2 to 4.8 t ha^{-1}) straw treatments. Therefore it could be deduced that with St chopped and mostly incorporated in Phase 1 would make treatments less effective than Niziolomski (2011).

Treatment TSL results for Sampling Period 5 showed a high degree of variability. This variability is a result of two factors. Firstly, the length of time since the treatments have been installed meant that changes in treatment interactions (SSD, mulch and application rate) have occurred resulting in different treatment responses. This changes were a result of rainfall received compacting the surface and creating a surface crust, SSD slumping and foot traffic compaction from hand-harvest operations. Furthermore, in this time gradual pipe blockages across replicates may have occurred. Secondly, the rainfall characteristics leading up to Sampling Period 5 are the most intense of all the Sampling Periods. This puts a lot of pressure on already degrading treatments, thus resulting in a highly variable treatment responses.

4.3.4 Pollutant load

4.3.4.1 Sediment concentration

The extremely high levels of suspended sediment found for all treatments across all Sampling Periods confirms the frequency and magnitude of on-site erosion as already suggested by the TSL results.

Suspended sediment results demonstrated few significant differences between Sampling Periods. This is due to the high variability within and between treatments caused by the presence of pipe and trough blockages. These were most frequently observed in Sampling Periods 1, 3, 4 and 5. However, some significant differences were observed. Non-SSD St^{H} demonstrated initial significant reductions in sediment concentration, despite increasing runoff. This suggests that the friction component imparted to surface runoff by the St reduced flow velocity and hence transport capacity allowing sediment to drop out of suspension. Sediment transported as bed load and via saltation will be reduced as a result of reduced runoff velocity. Furthermore, at high rates of application (6 t ha^{-1}) the St sufficiently protects the soil surface, preventing rain splash soil detachment. Furthermore, the surface cover is protecting the surface from sediment displacement by foot traffic as observed by Monti and Mackintosh (1979) with leaf litter on frequently trafficked forest footpaths. The fact that SSD St^H does not also show reductions in suspended sediment suggests that either the surface cover is not as effective due to incorporation, or that the loose soil resulting from the SSD or subsequent foot trafficking is contributing to the higher suspended sediment.

The results indicate that the efficacy of Non-SSD St^H in reducing sediment concentration is lost by Sampling Period 3. This period also coincides with the highest number of trough and pipe blockages. By Sampling Period 5 there is a great inconsistency within treatments resulting in a high variability of data and thus no observed significant differences in sediment concentration between treatments. This could be a result of the high volume and intensity of rainfall received by Sampling Period 5. This rainfall could have inundated each treatment degrading the SSD effect, and force mulch to move exposing areas of bare soil. Furthermore, the intensity of the rainfall could result in surface compaction. Any differences in replicates could become more pronounced with the development of the asparagus as cloches were removed and asparagus fern allowed to develop. This makes the effectiveness more dependent upon the bed conditions (e.g. the presence of surface crusting, deformations and surface compaction resulting from pickers).

4.3.4.2 Total oxides of Nitrogen

Both Non-SSD St treatments were the only treatments to significantly reduce TON as compared to the Non-SSD Control in Sampling Period 1. This suggests that No Mulch treatments were contributing TON to the runoff. This could result from soil N mobilisation as runoff is entraining both suspended and soluble soil components. TSL and TON results appear to be linked as mulched treatments reduce both. However, the increase in TON observed is not of a significant level to result in pollution as defined by EC guidelines / limits. In these results, no first flush of TON is evident as it is in other studies (Simmons and Alexander, 2011). However, in this study one large rainfall event had already occurred prior to data collection that could have been the first flush.

The elevated TON concentrations observed in Sampling Period 5 coincides 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 minute duration, 36 mm hr^{-1} maximum intensity, 19.8 mm hr^{-1} mean intensity). Results suggest that this rainfall event washed away a large amount of the applied fertiliser, not allowing time for it to dissolve and infiltrate into the compacted soil profile. SSD Cp^H is effective under these conditions at reducing runoff TON, although due to the analysis used it is unclear exactly how this relates to the nitrate guidelines (EU Directive 75/440/EEC). However, this could be related to a reduced runoff observed suggesting pipe blockage. SSD infiltration could be inferred but this is not observed in the Non-SSD No mulch or SSD St treatments.

4.3.4.3 Orthophosphate P

All treatments resulted in orthophosphate-P concentrations in excess of the WFD ecological status criteria for soluble reactive P. However, treatments did not consistently or significantly affect the concentration of orthophosphate-P in runoff. This suggests that other environmental factors are responsible for P concentrations in runoff; i.e. the soil. A critical P soil index of 3 (26 – 45 mg l^{-1}) is assigned to vegetable farming systems (Defra, 2010). However, on-farm soil sampling conducted by SOYL in January 2014 showed the average P soil concentration for the field-trial field to equal 56 mg l^{-1} (P index 4, following Olsen’s P analysis). Above the critical P index, crops do not utilise the increased P and therefore it remains and accumulates in the soil (Johnston and Dawson, 2005). A soil considered to be P enriched (P index ≥ 3) has an increased risk of P loss into surface water (Johnston and Dawson, 2005). Consequently when soil erosion takes place, the detached soil has a greater P concentration (both sediment bound and soluble forms) and thus poses a significant pollution risk to receiving water bodies.

For the duration of the field trials, just two treatments gave a significant difference in orthophosphate-P as compared with the Non-SSD Control. Knowing the high P soil index, higher values associated with the increase from SSD No Mulch are to be expected. SSD increases the exposure of P-enriched soil particles to runoff, thus resulting in a higher concentration of P being solubilised by the runoff. In other studies, this increase did not occur often (Smith et al., 2007; Quincke et al., 2007). Soil mixing is even advised as a means of reducing P in upper surface layers, by exposing deeper soil layers with lower P. However, these studies have been conducted on long-term, no-till plots that have good soil structure, where low P sub-soils can desorb the high P top soil (Sharpley, 2003). By comparison, the soils at Cobrey Farm, which have been continuously tilled to depth, are homogenous and compacted and thus are likely to have little variation in P through the soil profile. Instead the low P surface runoff desorbs the readily soluble soil P.

The second significant difference is an initial reduction in orthophosphate-P with Non-SSD St^H. This too is to be expected as the soil is being protected by a good surface coverage of St. Any particles detached from 50 % of each bed either side of the treated wheeling, will be dropped from suspension due to the reduced flow velocity resulting from the St imparted surface roughness.

4.3.4.4 Sediment-bound P

No significant differences from the Control were observed across all treatments and Sampling Periods. This is to be expected as the sediment-bound P concentration only originates from the soil, with no mulch treatments able to affect this. The one significant difference observed between SSD Cp^H and SSD St^H represents a very small reduction (13 %, 162 mg kg^{-1}) by SSD St^H in sediment-bound P. This could be a result of P contained within the Cp but this would generate a significant difference from the SSD No mulch as well. It is very difficult to assess the potential threat to the environment of the concentrations observed, as the release of the P is dependent of many environmental conditions (Haygarth et al., 1999). However, the combination of high runoff volumes, high total soil loss and high soil P index equates to a very large stock of P that could threaten receiving water bodies being mobilised.

4.4 Conclusion

This Phase 1 experimental programme has assessed the resulting runoff and associated nutrient and sediment loads from Non-SSD and SSD replicated treatments in combination with No mulch, St (6 t ha^{-1} and 3 t ha^{-1}) and Cp (15 t ha^{-1} and 7 t ha^{-1}). Overall, results show mulch alone can significantly reduce runoff volume and associated nutrient and sediment loads allowing sub-hypothesis b to be accepted. The most significant and consistent improvements in runoff volume and associated nutrient and sediment loads was achieved by Non-SSD St^H. The nature of Cp does not allow for effective erosion control under the tested conditions and application rates (7 and 15 t ha^{-1}). To improve Cp effectiveness at these rates, a biodegradable geotextile could be laid beneath or on top of the compost to improve anchorage. In fields not subject to NVZ nitrogen application restrictions, Cp could be used to better effect with a higher application rate (>15 t ha^{-1}).

SSD was not found to significantly reduce runoff and associated nutrient and sediment loads and therefore sub-hypothesis a. cannot be accepted. Significant reductions were evident from SSD treatments in combination with St^H and Cp^H. However, these only occurred with TSL, therefore sub-hypothesis c. can also not be accepted. This reduction effect in TSL did not match the consistency of that observed in Non-SSD St^H through all Sampling Periods, with SSD St^H reduction evident only up to Sampling Period 2.

The results show that soil erosion can be dramatically reduced in asparagus production. However, over five months, total soil loss remained in excess of annual tolerable erosion (1.4 t ha^{-1}), as well as sediment concentration exceeding environmental guidelines. This suggests that if used in isolation under the tested field conditions other supporting mitigation measures will be needed to bring soil loss to a sustainable level. To support the findings of this study further studies are required.

5 SOIL BIN EXPERIMENTAL WORK

5.1 Methodology

In order to test the research hypothesis (Chapter 3) the following methodology was developed.

To date, the effectiveness of the currently adopted SSD practice had not been critically evaluated, in terms of compaction alleviation and soil erosion control. Phase 1 field trials demonstrated that SSD does not have a significant impact on runoff and erosion control. However, different tine configurations may generate different effects. Therefore, under controlled laboratory conditions the effect on soil conditions pertinent to compaction alleviation and erosion control of the currently adopted winged tine were compared against a range of commercially available and innovative tillage alternatives. From this experiment, the resulting ‘optimum’ tine configurations would be selected and evaluated in the Phase 2 field trial runoff and soil loss plots (Chapter 6).

5.1.1 Tine configuration selection

5.1.1.1 Implement geometry and arrangement

Following a detailed literature review (Chapter 2), four tine geometries and arrangements were identified and compared against the currently adopted winged tine (Table 5.1, Figure 5.1 and Figure 5.2).

Table 5.1 Types of tine to be tested in the soil bin.

No.	Tine type	Code	Geometry	Configuration
1	Winged tine°	WT	Rake angle; 45 degrees, wing inclination 30 degrees.	Single tine, in-line
2	Narrow tine	NT	Rake angle; 45 degrees	Single tine, in-line
3	Modified para-plough	MPP	Tine and rake angle; 45 degrees	Two tines, in parallel.
4	Winged tine with shallow leading narrow tines	WSLT	Rake angle; 45 degrees, wing inclination 30 degrees.	Two leading shallow tines spaced 220 mm apart, 350 mm ahead of the main tine.
5	Narrow tine with shallow leading narrow tines	NSLT	Rake angle; 45 degrees	Two leading shallow tines spaced 220 mm apart, 350 mm ahead of the main tine.

°Currently adopted on-site. Original designs and configurations are included in Appendix B.1.

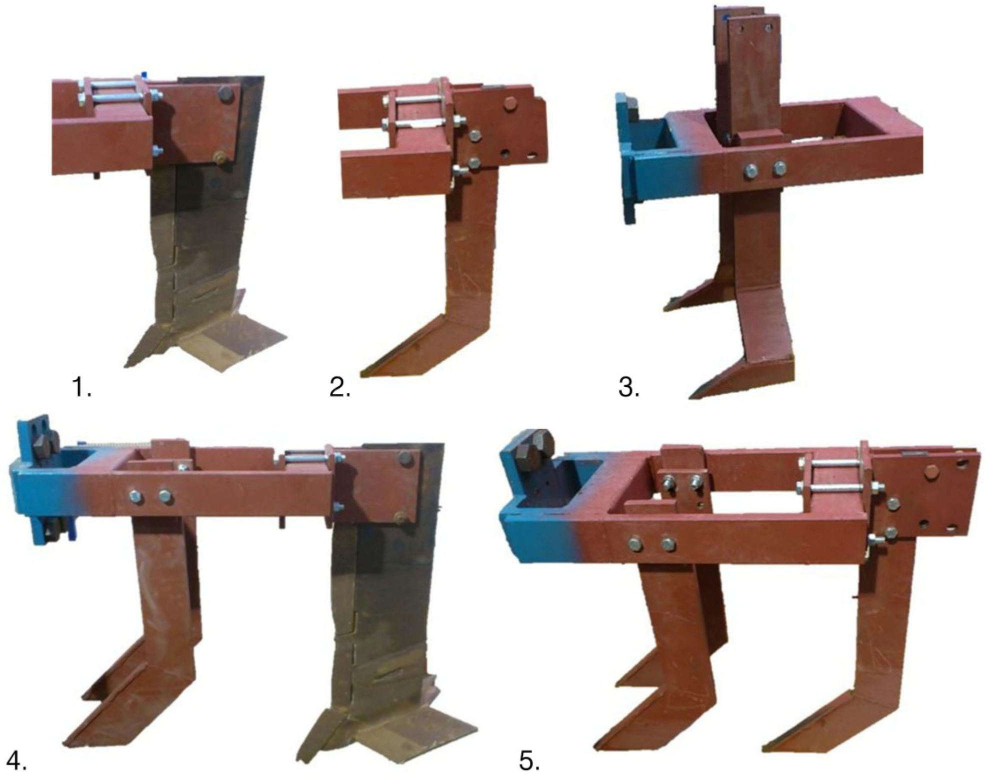


Figure 5.1. Tine configurations to be tested (not to scale); winged tine (WT; 1), narrow tine (NT; 2), modified para-plough (MPP; 3), winged tine with shallow

leading tines (WSLT; 4) and narrow tine with shallow leading tines (NSLT; 5). See Appendix B.1 for detailed tine designs and measurements.

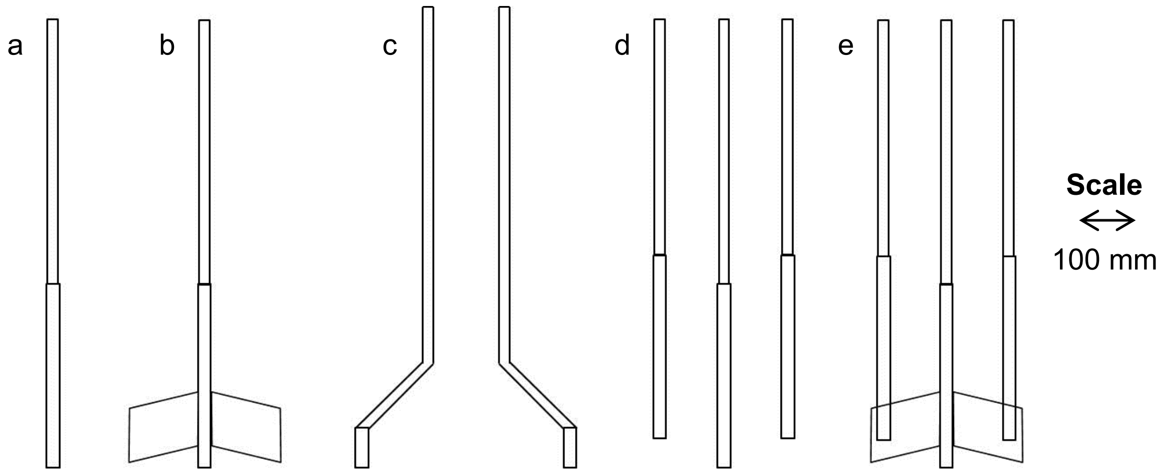


Figure 5.2. Plan view of the tine configurations; NT (a), WT (b), MPP (c), NSLT (d) and WSLT (e). See Appendix B.1 for specific tine geometry and configuration designs.

Tine selection criteria for this experiment was based on the need for a large area of below ground soil disturbance within the asparagus wheelings (i.e. compaction alleviation). NT was selected as a simple non-winged tine for comparison with the currently used WT. The inclusion of shallow leading tines for both WT and NT was to increase the area of soil disturbance with little or no increase in draught force required (Spoor and Godwin, 1978). Spacing between the shallow leading tines was based upon the width of the asparagus wheeling, to ensure that disturbance was confined to the wheeled areas. The MPP was selected as an innovative option based upon a previously tested tramline drainer (Tatham, 1989). The MPP loosens either side of the wheeling, rather than breaking through the heavily compacted centre as the other tines are designed to do. This should allow water to infiltrate into the less compacted soil associated with the asparagus bed (Figure 5.3). This however might translate to increased draught as compared with the other tines, as the two tines work separately through the soil.

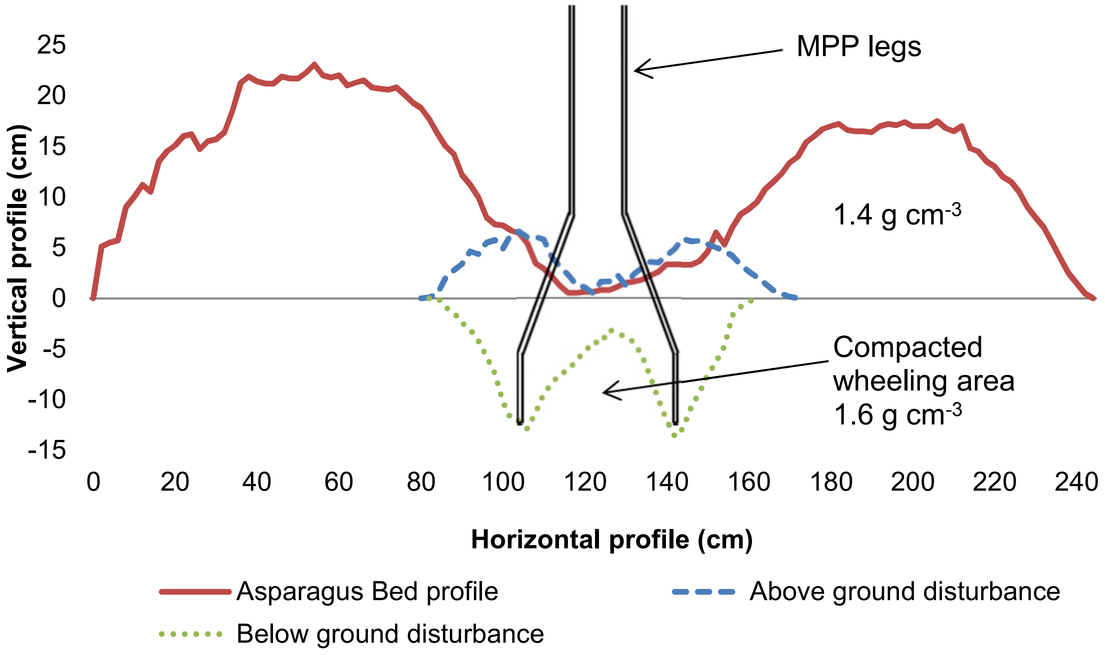


Figure 5.3. Soil disturbance using the MPP relative to the area of compaction. Bulk density values are true to in-field measurements.

5.1.1.2 Implement Depths

Each tine was tested at three different depths. These were; the current on-site working depth of 175 mm, the optimum depth for effective soil loosing operations as recommended by Spoor (2006) (i.e. 300 mm) and an intermediate depth of 250 mm.

The depths of the shallow leading tines were calculated with the effective depth formulae proposed by Spoor and Godwin (1978) (Equation 2). The resulting shallow leading tine depths are presented in Table 5.2.

SLD = 2 / 3 x WD

(Equation 2)

Where SLD = Shallow leading tine depth; WD = Working depth.

Table 5.2 Calculated depths for shallow leading tines (based on Spoor and Godwin, 1978).

Main tine depth (mm)	Shallow leading tine depth (mm)
175	120
250	170
300	230

N.B. Calculated shallow tine depths have been rounded up for practical application.

5.1.2 Experimental setup

A controlled laboratory-based study was designed and implemented in the Cranfield Soil Dynamics Facility, specifically in the soil bin which measures 20 x 1.7 x 0.7 m. The bin was filled with a sandy loam soil (64% sand, 18% clay and 18% silt), comparable to that found in the field (Table 4.7, Phase 1 field trials). The soil profile was built up in 50 mm layers to the prescribed bulk density (Section 1.1.3.2), using a 700 kg roller and the application of small amounts of water to allow the desired soil compression.

5.1.2.1 Soil Bin Calibration

Prior to starting the experiment, the force measuring Extended Octagonal Ring Transducer (EORT) was calibrated. The EORT is made up of a series of strain gauges that simultaneously monitor the vertical force and draught (kN) associated with pulling an implement through the soil, as a function of tine geometry and configuration (Godwin, 1975).

For calibration, a series of known forces were applied to the EORT in several directions (Table 5.3) and the resulting voltage (v) recorded. From this data it was possible to calculate a voltage to kN conversion that could be used in the data logging programme (Data Acquisition System, DASY, laboratory Version 8.00.04) to convert EORT voltage readings into kN force.

Table 5.3 Means of calibration for the various forces.

Force	Method of calibration
Draught	Instron 8500 digital control load frame.
Vertical	Manual

Draught force calibration was carried out using an Instron 8500 digital control. Force was applied in 5 kN intervals starting from 0 kN up to 80 kN, and the resulting EORT output voltage recorded.

Vertical force calibration was carried out manually with the EORT fixed in situ on the soil bin processor. Using a weight holder, kilogram weights were suspended from the EORT. Weights were added in 10 kg intervals starting from 0 kg and going up to 100 kg. The resulting voltage output was recorded.

Both EORT calibrations were carried out in triplicate, using increasing and decreasing loadings to account for any hysteresis within the EORT. This data was inputted into Excel and graphed to ascertain the voltage and kN correlation (Appendix B.2, Figure_Apx B-8). The resulting formula from the linear trend line was input to the relevant channel (draught/vertical) of the DASY logging programme. This was then checked by repeating the vertical calibration and comparing the resulting kN reading with that calculated during calibration.

5.1.2.2 Soil Bin Preparation

To recreate a bulk density in the soil bin similar to that observed in the field (1.67 g cm^{-3} ± 0.12), a number of test soil bin preparations were undertaken, each with a different number of roller passes (ranging from 10 to 30). With each preparation triplicate bulk density samples were taken at three points across the centre of the bin. Following several test preparations it was evident that 1.6 g cm^{-3} (±0.01) was the most consistently achievable bulk density (Appendix B.2, Table_Apx B-1). Considering this, 13 roller passes were selected for experimental preparation. This was the most time and energy efficient option whilst still achieving the desired bulk density.

To check the continuity of these test conditions, single bulk density measurements were made at three randomly selected points along the length of the soil bin following each soil bin preparation (Appendix B.2, Table_Apx B-2). Once prepared, the processor, with instrumented mounting points, was fitted with the tines ready to be tested.

5.1.2.3 Experimental Design

Soil bin availability constraints meant that the experiment had to be conducted in two stages; firstly the 175 mm depth was tested, followed later by 250 mm and 300 mm depths. The experiment was not of an entirely randomised design due to the health and safety considerations of repeatedly mounting and dismounting the tines from the bracket. However, randomisation did occur in other ways. In the 175 mm depth testing the order in which the tines were tested was randomised. This was also true for the 250 mm and 300 mm depths. Furthermore, randomisation was also facilitated with the selection of the individual depth sequences for each tine.

With each soil bin preparation two separate tine runs were tested each measuring approximately 8 m in length. All tines were operated at a constant speed of 2.1 km h^{-1}. This allowed good control of the experiment, particularly when ensuring consistent run lengths.

5.1.3 Data collection and analysis

Tine performance was based on the following six indicators; draught force, specific draught, above and below ground disturbance, in-line and parallel surface roughness.

Table 5.4. Performance indicators and their relationship to the sub-hypothesis.

Sub-hypothesis component	Performance indicator
Implement dynamics	Draught force
	Specific draught
Degree and extent of soil disturbance	Above ground / surface disturbance (D_{AG})
	Below ground disturbance (D_{BG})
	Surface roughness; perpendicular (SR_P) and in-line (SR_I) relative to tine run.

5.1.3.1 Draught and Vertical Force

Draught is frequently measured in tillage experiments (Arvidsson and Hillerström, 2010). It is an important consideration for fuel and tractor power requirements (Arvidsson and Hillerström, 2010). Vertical force data, although not a performance indicator in this experiment, was also collected to understand the engagement of the tine in the soil i.e. whether it was remaining in position, pushing up or pulling down. This would indicate whether ballast or depth control wheels would be required when used in a non-controlled field setting. For both draught and vertical force measurement a separate mean of peaks was taken from the graphed outputs of each run generated by the DASY software.

5.1.3.2 Specific draught

Specific draught, also known as specific resistance, is a commonly used value to demonstrate the efficiency of the draught force in disturbing soil. Once D_{BG} had been measured (Section 5.1.3.3) the specific draught was calculated for each tine run using Equation (Equation 3). Tine configurations that most efficiently use draught force have a low specific draught.

Specific draught (kN m^{-2}) = D / D_{BG}

(Equation 3)

Where D = mean draught (kN), D_{BG} = Cross sectional area of disturbed soil below ground (m^2).

Given that the focus of this study is compaction alleviation, a new specific draught measurement has been developed (Equation 3). This incorporates the degree of soil disturbance both above and below ground.

$SD_D = D / D_{AG} + D_{BG}$

(Equation 4)

Where SD_D (kN m^{-2}) = specific draught for complete soil disturbance; D = mean draught (kN); D_{AG} = Cross sectional area of above ground /

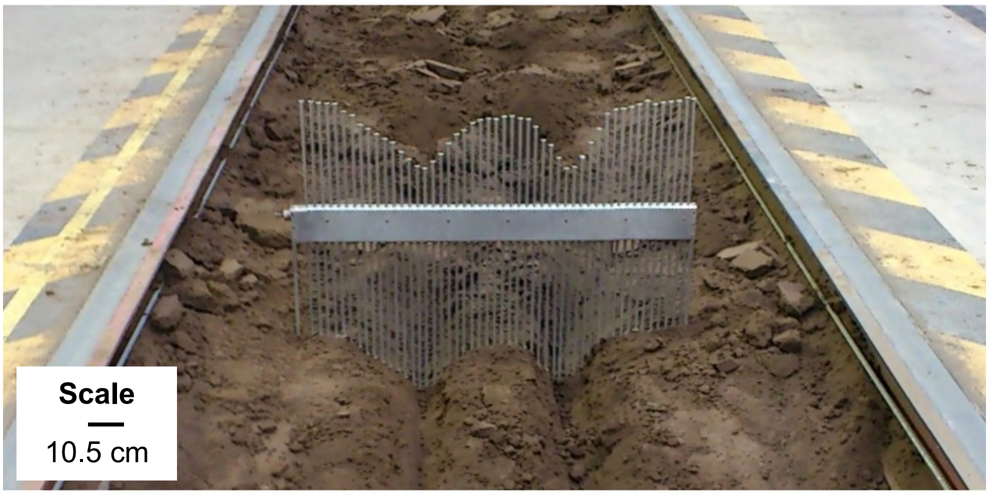
surface soil disturbance (m^2); D_{BG} = Cross sectional area of below ground soil disturbance (m^2).

5.1.3.3 Soil disturbance

Soil disturbance measurement quantifies the area of compaction that is alleviated. Measurements of D_{AG} and D_{BG} were carried out using a profile metre. This comprised of 50 adjustable pins, 72 cm long and set at 2 cm intervals covering a 105 cm length with a clamping section in the middle (Figure 2.5). One fixed pin existed on either end of the metre.

Above ground (D_{AG}) and below ground (D_{BG}) soil disturbance measurements were taken at three random points along each tine run. For the above ground soil disturbance, the profile metre was placed carefully onto the disturbed area with the outer prongs resting on the adjacent original (undisturbed) soil surface. The adjustable prongs were carefully lowered to take the shape of the surface soil disturbance. Once the pins were fixed, the profile metre was placed onto brown paper, and the shape was traced. The differences in height between each prong and the adjacent undisturbed soil surface (captured by the two outer pins) was measured, and subsequently entered into Excel. The three resulting graphs for each replicate were aligned with one another and the mean cross sectional area calculated.

The loosened soil was then carefully excavated by hand until the entire D_{BG} area was exposed. The excavation depth was checked using metre sticks to ensure that it had reached the depth of cultivation. The profile metre was placed across the top of the excavation and the prongs carefully released to take the shape of the area excavated (Figure 5.4). The shape was then transferred, measured and graphed in the same way as for the D_{AG}.



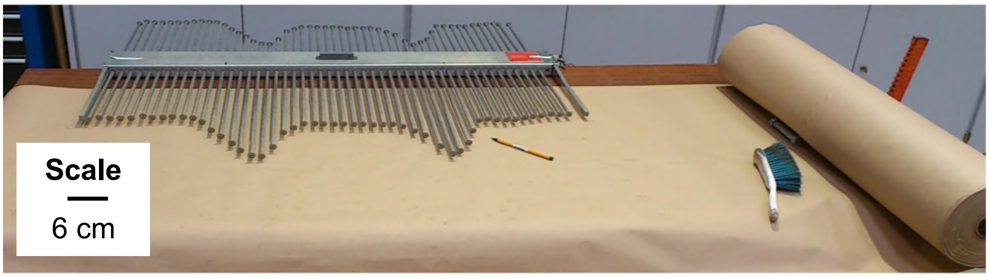


Figure 5.4. Profile measurement of D_{BG}.

Using these measurements the new bulk density of the soil following SSD was calculated. This first required the calculation of the mass of the soil moved by the tine (Equation 5). To do this the bulk density (between 0 – 5 cm depth) of the soil prior to cultivation was multiplied by the cross sectional volume of D_{BG} (cm^3). This mass was then applied to (Equation 6) and divided by the total volume of the soil post-SSD; the sum of D_{BG} and D_{AG} (cm^3).

Mass = Density x Volume

(Equation 5)

Mass (g) = Initial bulk density (g cm^{-3}) x D_{BG} (cm^3)

Density = Mass / Volume

(Equation 6)

Density (g cm^{-3}) = Calculated mass of soil (g) / D_{BG} + D_{AG} (cm^3)

5.1.3.4 Surface roughness

Whilst the D_{AG} profile provided the cross sectional area of disturbance and an indication of the shape at 2 cm intervals, it was unable to provide a specific measure of surface roughness. The chain method (Saleh, 1993) compares favourably to the profile metre measure but provides a more detailed surface roughness measurement (depending on the size of chain links used), and allows the calculation of a surface roughness index.

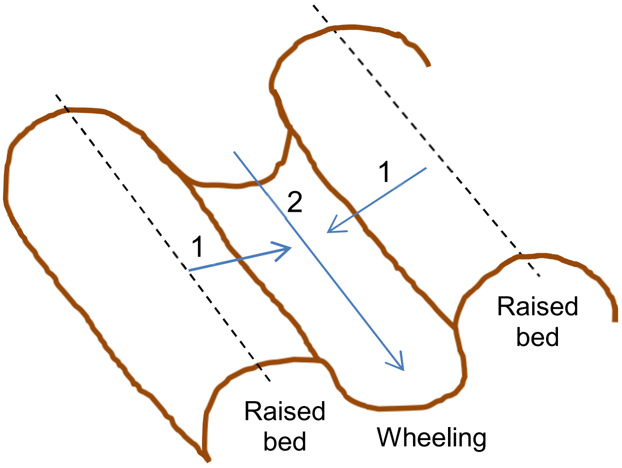


Figure 5.5. The two water runoff pathways from an asparagus raised bed system demonstrating the need for two different SR measures. 1. Runoff flows from the top of the raised beds (dashed line) into the wheeling (relevant to SR_P). 2. Runoff flows downslope in the wheeling (relevant to SR_I).

Surface roughness was assessed both perpendicular to (SR_P) and in-line with (SR_I) the direction of the tines. This reflects the two runoff pathways identified in the field (Figure 5.5). For SR_P a chain with 3 mm links, that was 1 m (at 175 mm depth testing) or 1.5 m (250 and 300 mm depths) in length was carefully placed across the disturbed surface at the same points at which the profile metre measurements had been taken (Figure 5.6). The horizontal distance covered by the chain was measured, recorded and divided by the original chain length. This was then subtracted from 1, to provide an index of roughness, with 0 equating to a completely smooth surface (Equation 7). This was repeated for SR_I using the 1 m length of chain placed along the central line of the disturbance at three separate points (Figure 5.6).

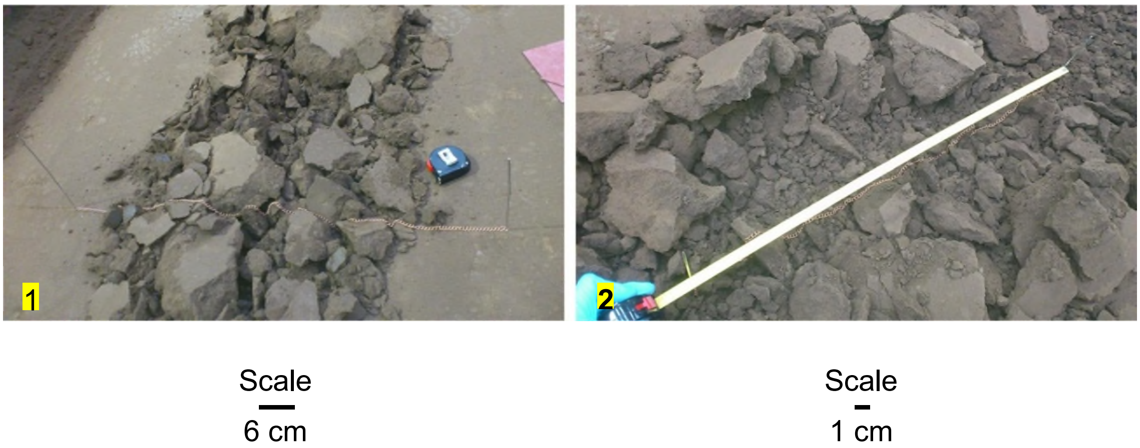


Figure 5.6 Measurement of surface roughness by the chain method, both perpendicular to (SR_P; (1) and in-line with (SR_I; (2) the tine direction.

$$SR = 1 - (L_1 / L_2)$$

(Equation 7)

Where SR = surface roughness, L_1 = length of chain when laid on the surface (m), L_2 = original length of chain (m)

5.1.3.5 Statistical analysis

For all analysis the data was checked for normal distribution using residual analysis. Outliers were identified and removed as appropriate. Data was then analysed for statistical significance ($p \leq 0.05$) using full factorial ANOVA. Where statistical differences were observed this was followed by post-hoc Fisher LSD.

5.1.3.6 Potential root damage

As each tine interacts with the soil it has the potential to damage asparagus roots. This damage can stress the plant making it susceptible to disease (Nigh, 1990) and could facilitate *fusarium* infection (Lim Group, 2013). Furthermore, this can reduce asparagus yields and the life span of the crop.

This risk can be considered by looking at both the area of the tine leading edge and D_{BG}. To estimate the potential root damage, the leading edge surface area of each tine configuration was calculated (Figure 5.7). This takes into account the potential for roots to be cut or damaged by the tine leading edge as it passes through the soil. The size of the D_{BG} area was also taken into consideration as larger areas have the potential to disturb and damage more roots.

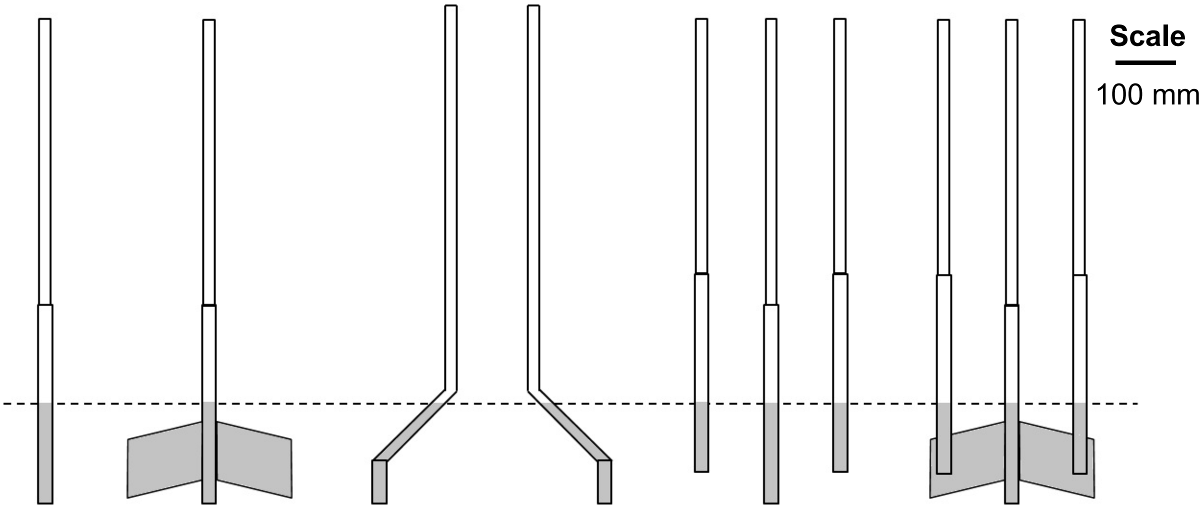


Figure 5.7. Plan view of the leading edge area of each tine (shaded) at 175 mm depth (the dashed line).

5.2 Results

5.2.1 Soil disturbance

Of the five tine configurations tested, the currently adopted WT did not generate the highest level of D_{BG} at any of the depths tested (Figure 5.8).

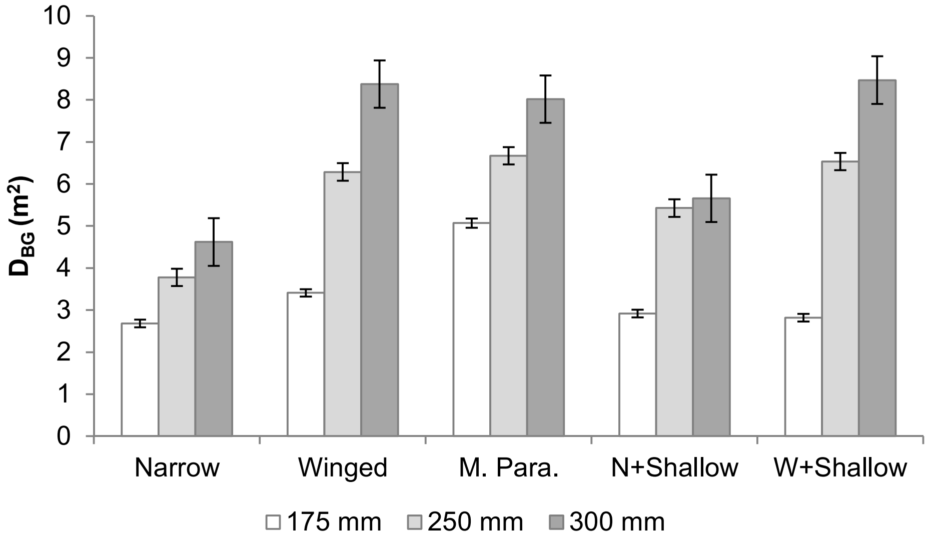


Figure 5.8. The mean area of D_{BG} (m^2) generated by each tine configuration at each tested depth. Error bars indicate ±1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

It was expected that the greatest area of D_{BG} would be generated by the MPP, WT and shallow leading tine configurations. This is because the MPP generates two distinct area of disturbance. The increased width of the WT would create a greater breadth of disturbance than NT. Similarly this would be expected to occur with the addition of shallow leading tines. However, this was the case with MPP, WT and WSLT often generating the large areas of D_{BG} across all depths.

The MPP created significantly more D_{BG} (5.1 m^2 at 175 mm; Figure 5.8) than any other tine configuration. This was almost 1.5 times the area disturbed by the WT. The WT generated the second highest D_{BG} of 3.4 m^2, whilst the remaining tines did not differ significantly from each other. At 250 and 300 mm there was no significant difference between the WT (6.3 and 8.4 m^2), MPP (6.7 and 8.0 m^2) and WSLT (6.5 and 8.5 m^2). However, these differed significantly from the NT and NSLT. The NT generated the least D_{BG} of 3.8 m^2 at 250 mm. At 300 mm both the NT and NSLT generated the least D_{BG} at 4.6 and 5.7 m^2 respectively.

It was also expected that the tines generating the greatest area of D_{BG} (MPP, WT and WSLT) would also generate the greatest D_{AG}. This is because a greater volume of soil is being disturbed, increasing the volume of the soil. This was found to be the case as the MPP generated a significantly greater area of D_{AG} (3.1 m^2) at 175 mm depth as compared with all other tine configurations (Figure 5.9). At 250 mm and 300 mm the MPP, WT and WSLT created significantly higher D_{AG} than the NT and NSLT.

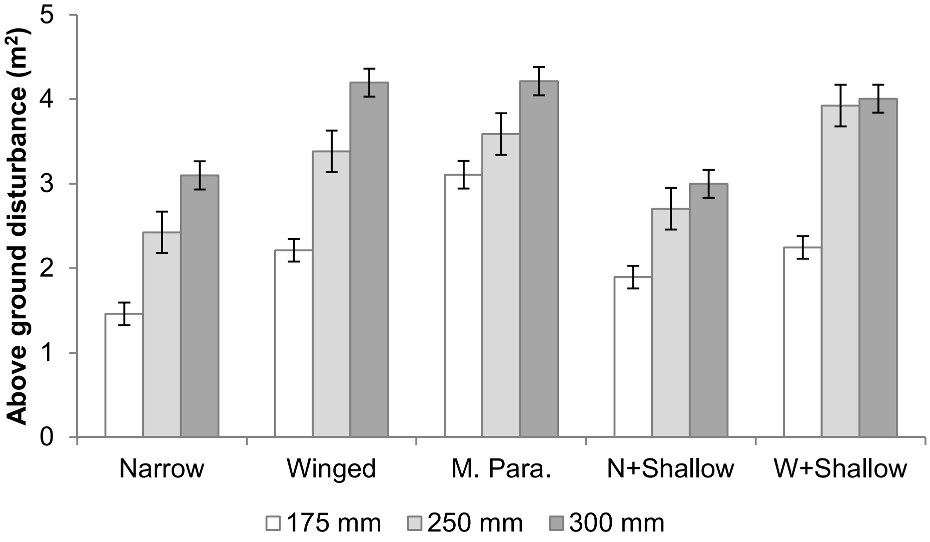


Figure 5.9. The mean area of D_{AG} (m^2) generated by each tine configuration at each tested depth. Error bars indicate ±1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

When the D_{BG} profiles were graphed it was possible to see the extent of the cross sectional area of the tine disturbance and the different profile shapes generated (Figure 5.10). There was little difference in profile shape between NT and NSLT and WT and WSLT. However, one notable difference between WT/WSLT, NT/NSLT and MPP profiles was observed. Typically in MPP, NT and NSLT profiles disturbance radiates at a uniform angle right up to the soil surface. However, in both WT and WSLT the angle is less uniform with a notch present (Figure 5.10). This notch becomes more defined with depth and could mean that the soil at depth is being compacted and not loosened; the tine is operating below the critical depth.

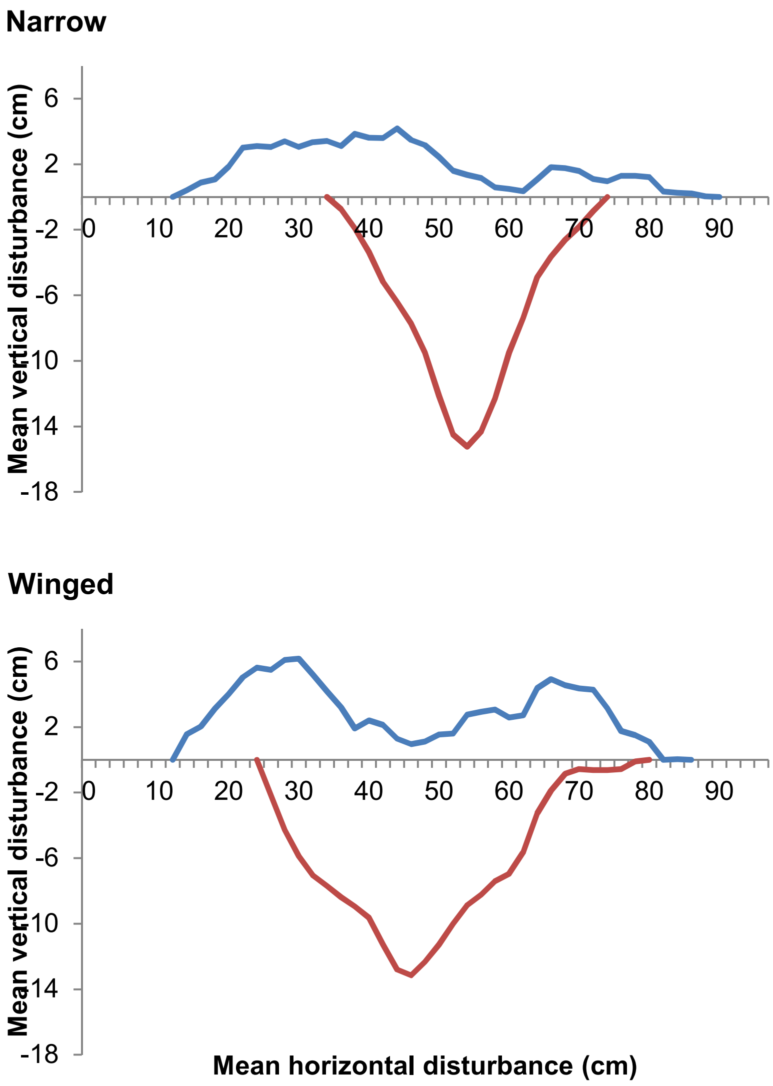


Figure 5.10. Soil disturbance profiles for the NT and WT at 175 mm. See Appendix B.3, Figure_Apx B-9 to B-11 for profiles of tines at all depths.

5.2.1.1 Change in bulk density

It was expected that multiple tines would result in the greatest reduction in bulk density. This is because the soil becomes increasingly disturbed by each tine resulting in a greater porosity.

However, this was not the case with few significant differences in bulk density reduction at each cultivation depth (Table 5.5). All tines reduced bulk density by one third or more of the original bulk density. At 175 mm the reduction in bulk density was greater with the WSLT as compared with the MPP, NSLT and NT. However, the initial bulk density for both WT and WSLT at 175 mm was significantly greater than all other treatments. Furthermore, at 300 mm NT generated a significantly higher reduction in bulk density as compared with NSLT, WT and WLST.

Table 5.5. Mean soil bulk density (g cm^{-3}) both prior to SSD (measured) and post SSD (calculated). Within each variable and working depth, different letters following results denote statistical differences ($p \leq 0.05$).

Working depth (mm)	Tine	Initial bulk density (g cm^{-3})		Estimated post SSD bulk density (g cm^{-3})		Reduction in bulk density (g cm^{-3})		Percentage reduction in bulk density (%)
175	MPP	1.50	a	0.93	a	0.57	a	38
	NSLT	1.50	a	0.91	a	0.59	a	39
	NT	1.53	a	0.99	a	0.54	a	35
	WSLT	1.60	b	0.89	a	0.71	b	44
	WT	1.60	b	0.97	a	0.63	ab	39

Working depth (mm)	Tine	Initial bulk density ($g\ cm^{-3}$)		Estimated post SSD bulk density ($g\ cm^{-3}$)		Reduction in bulk density ($g\ cm^{-3}$)		Percentage reduction in bulk density (%)
250	MPP	1.57	a	1.02	a	0.54	a	35
	NSLT	1.53	a	1.02	a	0.51	a	33
	NT	1.53	a	0.93	a	0.60	a	39
	WT	1.57	a	1.02	a	0.55	a	35
	WLST	1.53	a	0.96	a	0.58	a	38
300	MPP	1.57	a	1.02	a	0.55	ab	35
	NSLT	1.53	a	1.00	a	0.53	a	35
	NT	1.53	a	0.91	a	0.62	b	40
	WT	1.57	a	1.04	a	0.52	a	33
	WLST	1.50	a	1.02	a	0.48	a	32

5.2.2 Surface roughness

It was expected that the simplest tine arrangements would generate the greatest surface roughness. This is because with minimum soil contact it will break the soil into larger peds generating a coarser, rougher surface than soil that has been worked more by multiple and bent-leg tines. However, this was not the case with no significant difference in SR_P between all tine configurations at 175 and 250 mm (Figure 5.11). Furthermore, at 300 mm the WSLT generated significantly greater SR_P (0.34) than the WT, NT and MPP.

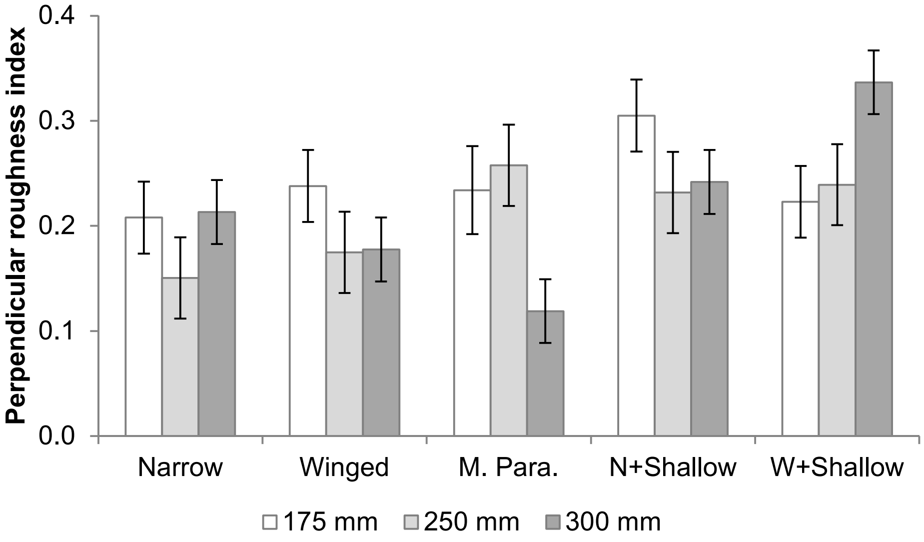


Figure 5.11. The mean SR_P resulting from each tine configuration at each tested depth. Error bars indicate ±1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3. NB. An index of zero equates to a perfectly smooth surface.

SR_I showed more significant differences than SR_P (Figure 5.12). These results are more akin to those expected. At 175 mm the NT generated a significantly higher SR_I (0.45) than all other tines. At 250 mm the NT continued to create greater SR_I (0.44) as compared with WT, WSLT and MPP. Furthermore, at 300 mm no significant difference occurred between the WSLT (0.40), NSLT (0.38) and NT (0.37) (Figure 1.10). However, these were associated with significantly higher levels of SR_I as compared with the WT and MPP.

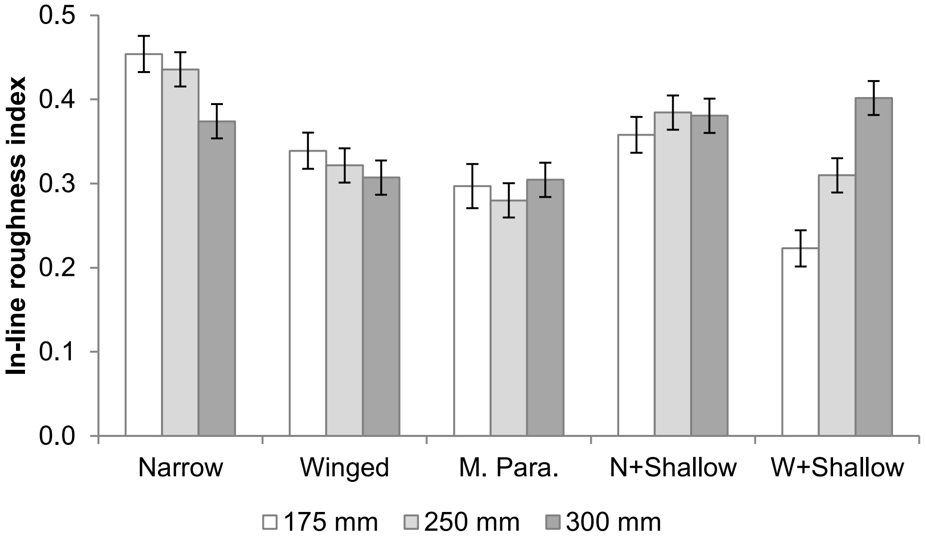


Figure 5.12. The mean SR_I resulting from each tine configuration at each tested depth. Error bars indicate ±1 SE. NB. An index of zero equates to a perfectly smooth surface. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

5.2.3 Root damage

It was expected that tines with the greatest leading edge surface area would be tines made up of the greatest components (wings and additional legs) such as the WT, WSLT, NSLT and MPP. This is because the WT wings have a large angled surface area. Furthermore, the presence of multiple tines such as the WSLT and NSLT and the MPP also increases the leading edge surface area. However, this was the case with WSLT having the greatest area (Table 5.6) followed by the WT. This was 9 times greater than the NT, and 3.5 times that of the MPP. Furthermore the addition of shallow leading tines increased the potential root cutting area. The NT followed by the MPP and NSLT had the smallest leading edge surface area.

Table 5.6. The leading edge area for each tine geometry and configuration. Calculations are included in Appendix B.3.1.

Tine type	Tine leading edge surface area (m^2)			
	Foot	Wing	Leg	Total area
NT	0.004	N/A	N/A	0.004
WT	0.004	0.032	N/A	0.036
MPP	0.004	N/A	0.006	0.01
NSLT	0.01	N/A	N/A	0.01
WSLT	0.01	0.032	N/A	0.042

N/A not applicable

5.2.4 Draught force

It was expected that the tines with the greatest components, such as wings and multiple legs would exert the greatest draught force to move through the soil. This is because of the increased frictional resistance that comes with an increased surface area in contact with the soil. This was found to be the case with WT and WSLT exerting the most force and NT the least. At 175 mm both the WSLT and WT exerted significantly more draught force as compared with the other tines with values of 2.75 and 2.55 kN respectively (Figure 1.11). The NT exerted the least draught force at 1.31 kN (Figure 5.13). At 250 mm draught forces increased for all tine configurations, by between 8 and 11 times that of the 175 mm depth values. The WSLT exerted significantly more force (25.7 kN) than all other tine configurations. The NT and NSLT exerted the least draught of 14.3 and 14.7 kN respectively. At 300 mm draught force increased again for all tine configurations. Unexpectedly, the MPP required the highest draught force of 37.0 kN, whilst the NT and NSLT required the lowest (22.3 and 19.7 kN).

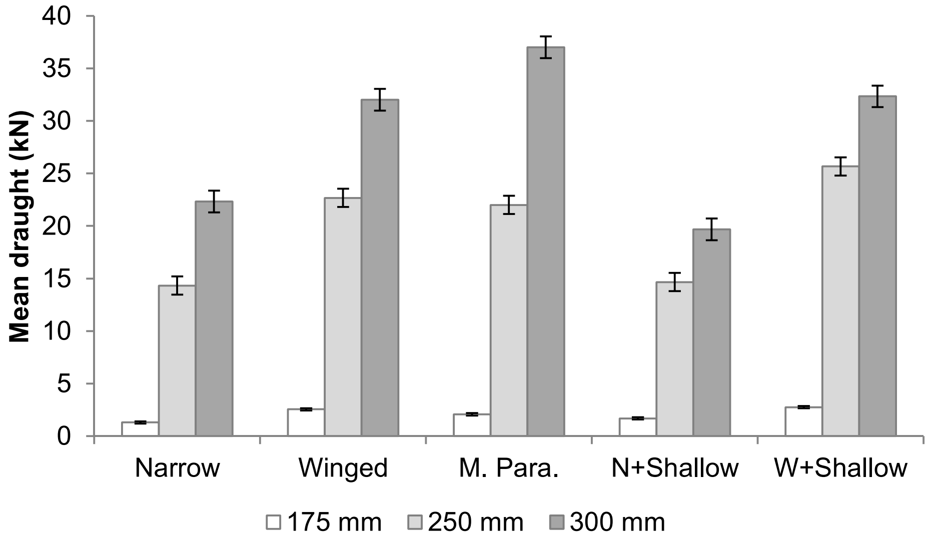


Figure 5.13. The mean draught force exerted by each tine configuration at each tested depth. Error bars indicate ±1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

5.2.5 Specific draught

It was expected that the lowest specific draught would be created by the MPP and NT and NSLT. This is because the MPP created the greatest area of disturbance, whist the NT exerted the least draught force and the addition of shallow leading tines generates increased disturbance for little additional draught force. However, this was the case with the MPP, NT and NSLT demonstrating significant reductions in SD, although not consistently with depth. At 175 mm the MPP had significantly lower specific draught (0.41 kN m^{-2}) as compared with WT, WSLT and NSLT. However, it was not significantly different from the NT (0.49 kN m^{-2}). The WSLT (0.98 kN m^{-2}) had significantly higher specific draught than all other tines. Both narrow tine configurations had significantly less specific draught than the winged tine configurations (Figure 1.12). At 250 mm values for all treatments increased by between 4 and 8 times that recorded at 175 mm. NSLT had the least specific draught (2.7 kN m^{-2}) as compared with NT, WT and WSLT. However, it was not significantly different from the MPP of 3.3 kN m^{-2}. At 300mm no significant difference in specific draught was observed between the different tine configurations.

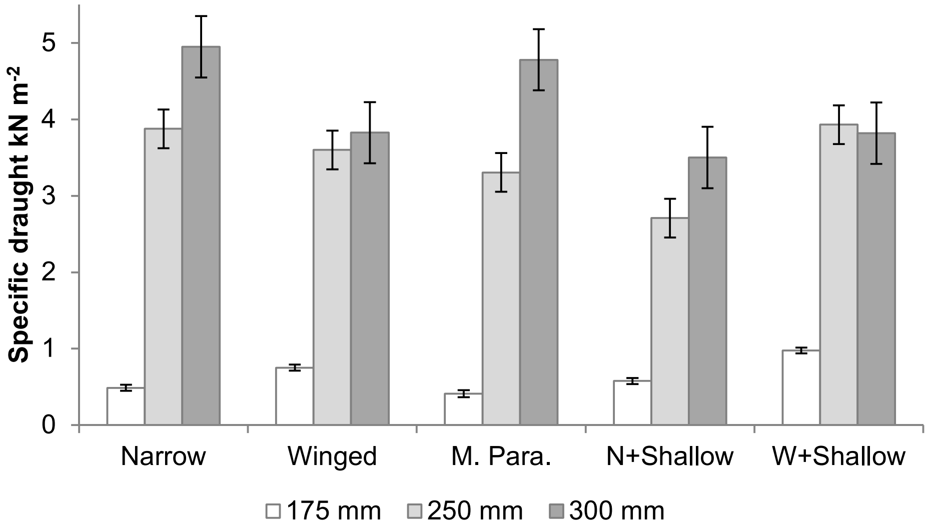


Figure 5.14. Mean SD (kN m^{-2}) required by each tine configuration at each tested depth. Error bars indicate ± 1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

Considering SD_D, where the specific draught includes both D_{AG} and D_{BG}, significant differences were only observed at 175 mm. At this depth the MPP (0.25 kN m^{-2}), NT (0.32 kN m^{-2}) and NSLT (0.35 kN m^{-2}) were the most efficient, generating the most D_{AG} and D_{BG} for the least draught when compared with the other tines. In comparison to SD, SD_E generates lower values for each treatment. This is to be expected as draught force is considered over a greater area with the inclusion of D_{AG}. This also has the effect of reducing statistical variation between results, especially between the narrow tine configurations.

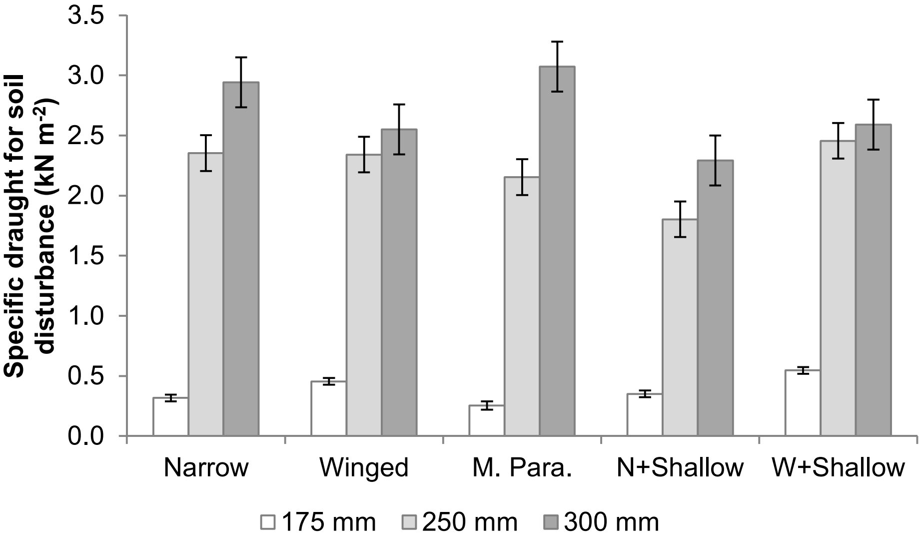


Figure 5.15. Specific draught for soil disturbance (SD_D) (kN m^{-2}) required by each tine configuration. Error bars indicate ±1 SE. For statistical differences between tine configurations see Appendix B.3, Table_Apx B-3.

5.2.6 Tine suitability for Shallow Soil Disturbance (SSD)

In order to summarise the overall effectiveness of each tine type on soil disturbance several performance indicators were identified from the tested parameters (Table 5.7). For each performance indicator each tine was graded against the currently adopted WT and ranked using the Pugh ranking matrix (Burge, 2009). A worked example is given in Table 5.8. Where tine results showed a positive statistical difference ($p \leq 0.05$) as compared with the WT (Table 5.7) a '+' was assigned. Negative statistical differences were assigned a '-', and where no significant difference was observed an 'S'. Within each tine, the number of '+' and '-' classes were totalled and the '-' total subtracted from the '+' total. This final value (with 3 in this case being the best, Table 5.8) was ranked from the most effective (1) to the least effective (max. 5). Once ranked, the top 3 tines at 175 mm (field cultivation depth) were selected for testing in the Phase 2 field trials. This restriction was a result of field trial equipment availability.

Table 5.7. Performance criteria for Pugh ranking matrix, the desired effect on soil properties and the positive result sought.

Performance indicator	Desired effect of soil properties	Optimum positive result
SD_D	Greatest disturbance for minimum force exertion.	Low
D_{BG}	Good compaction alleviation, reducing bulk density and increased infiltration potential.	High
D_{AG}	Good mass of soil above ground creating surface roughness.	High
SR_P	A rough surface perpendicular to the line of cultivation.	High
SR_I	A rough surface along the line of cultivation.	High
Change in bulk density	A reduction in bulk density, increasing pore space.	Low

Table 5.8. A worked example of the Pugh ranking matrix as applied to the 175 mm results.

Criteria	Soil bin results					Pugh matrix ranking				
	WT	**WSLT**	**NT**	**NSLT**	**MPP**	**WT**	**WSLT**	**NT**	**NSLT**	**MPP**
SR_P	0.24 ^{a}	0.22 ^{a}	0.21 ^{a}	0.31 ^{a}	0.23 ^{a}	S	S	S	S	S
SR_I	0.34 ^{a}	0.22 ^{b}	0.45 ^{c}	0.36 ^{a}	0.30 ^{ab}	S	-	+	S	S
SD_E	0.45 ^{b}	0.55 ^{c}	0.32 ^{a}	0.35 ^{a}	0.25 ^{a}	S	-	+	+	+
D_{BG}	3.41 ^{b}	2.82 ^{a}	2.68 ^{a}	2.92 ^{a}	5.07 ^{c}	S	-	-	-	+
D_{AG}	2.21 ^{a}	2.25 ^{a}	1.46 ^{b}	1.9 ^{a}	3.11 ^{c}	S	S	-	S	+
BD reduction	0.63 ^{ab}	0.71 ^{b}	0.54 ^{a}	0.59 ^{a}	0.57 ^{a}	S	S	S	S	S

Total +	0	0	2	1	3
Total -	0	3	2	1	0
Total score	0	-3	0	0	3
Rank	2	5	2	2	1

Pugh ranking matrix results (Table 5.9) showed that the MPP was the optimal tine configuration for soil disturbance at 175 mm (Table 5.9), the current depth of cultivation. The WSLT was the least optimal. Three tines ranked jointly; the WT, NSLT and NT. Of these three, only two tines could be selected in addition to the MPP for the Phase 2 field trials. These were the currently adopted WT (against which the others could be compared) and the NSLT, this generated a better '-' and '+' scoring than the NT.

At 250 mm depth the NSLT configuration was ranked the most optimal tine and the NT the least optimal (Table 5.9). At 300 mm depth the WSLT ranks the highest, whilst the NT and NSLT are jointly assigned the lowest rank (Table 5.9).

Table 5.9. Pugh ranked tine configurations for each cultivation depth. Full calculations are available in Appendix B.3.1, Table_Apx B-4.

Tine configuration	Cultivation depth (mm)		
	175	250	300
MPP	1	2	2
NSLT	2	1	5
WT	2	2	2
NT	2	5	2
WSLT	5	2	1

5.3 Discussion

5.3.1 Soil disturbance

From the results it is clear that the currently adopted WT is out-performed by other tine configurations in terms of D_{AG}, D_{BG} and SR_I at the current on-site cultivation depth of 175 mm. Application of the WT at a greater depth however would achieve improved disturbance (D_{AG} and D_{BG}) making it one of the significantly highest tines (with MPP and WSLT) at 250 and 300 mm depth.

5.3.1.1 Below ground soil disturbance

At 175 mm, the MPP created a larger area of D_{BG} than the currently adopted WT. The success of the MPP at 175 mm can be attributed to the spatial configuration of the tines in this treatment, with two tines running parallel, creating two separate entry points into the soil profile which disturbs two distinct areas.

Winged tines typically increase the lateral extent of D_{BG} by forcing the soil mass to flow over the wings (Spoor, 2006). This should result in 1.5 times more D_{BG} than non-winged tines (Spoor and Godwin, 1978). However, results show that the WT achieved just 21 % additional D_{BG} at 175 mm when compared with the NT. At 250 and 300 mm, the WT created over 1.5 times more D_{BG} as compared with the NT. This suggests that with increased depth the wings are disturbing soil more effectively, as the closer the wings are to the soil surface, the less soil lift will occur. This effect was observed from photographs taken during testing where the top of the wing plates were visible as it passed through the soil at 175 mm depth.

The presence of a distinct notch in the WT below-ground cross section profile as compared with the NT suggests that the tine is operating below the critical working depth (Figure 5.10). This means that the soil is no longer being loosened at depth, as a result of confining forces preventing the upward movement of the soil. Instead it is forced forward and sideways resulting in compaction (Spoor and Godwin, 1978). If this is true in the field, then the current loosening operation is generating as much D_{BG} as it should be. Furthermore, it is generating an impermeable base to the disturbance and so would restrict infiltration exacerbating the compaction further at depth. This will have serious consequences in terms of reducing water infiltration down the soil profile as well as possible hindrance to root development. However, owing to the different soil properties affecting critical depth; soil compressibility, moisture content and bulk density in the field (Spoor, 2006), it cannot necessarily be assumed that this is also taking place in the field.

5.3.1.2 Above ground soil disturbance

As the D_{BG} increases, so too does $D_{AG.}$ This is to be expected as the area loosened increases (D_{BG}) the volume of soil expands and moves upwards, thus generating a larger area of D_{AG}. The D_{AG} measurement represents the new pore space created by SSD. This increased pore space will result in a reduction in bulk density. This is demonstrated by calculated reductions in bulk density from all SSD types. Furthermore, the D_{AG} increases surface roughness and depression storage on the soil surface.

Differences in estimated bulk density reductions can largely be accounted for by a significantly greater initial bulk density (WSLT and WT at 175 mm). However, at 300 mm this is not the case. The NT results in a significantly greater bulk density with an initial bulk density not significantly different from the other tines. This could be attributed to the type of soil disturbance undertaken by the NT (fracture at a 45 degree angle), generating greater pore spaces or larger pores than the other SSD types that result in greater soil rearrangement.

5.3.1.3 Surface roughness

Winged tines typically result in a greater rearrangement of the soil than non-winged tines as the tine point first fractures the soil, after which it is lifted over the wings (Spoor and Godwin, 1978). Therefore, it would be expected that the winged tine treatments would generate the greatest surface roughness. However, this study shows that the greatest SR_P was achieved by the action of both NSLT and WSLT. Furthermore, the greatest SR_I was achieved using the NT.

It was observed that the resulting surface roughness from the WT comprised of much finer soil clods than from the NT. The soil fracture and partial lift undertaken by the NT left large clods of compacted soil on the surface, generating a rougher surface. The reduced roughness measured from the WT can be attributed to the combined effect of soil rearrangement by the wings. The more the soil was fractured, the looser the soil became and without any inherent structure, the soil broke down into very small soil clods. This resulted in a relatively smooth surface.

However, whilst large surface clods are here viewed as beneficial to erosion control it is not considered so in the field. Spoor and Godwin (1978) observed that the limited soil rearrangement by narrow tines could be more likely to fall back into place and re-compact than greater rearranged soil –such as that achieved with winged tines- thus reducing the longevity of effect of the initial loosening. Despite this it could be argued that smaller clods (as produced by winged tine configurations) would be more readily broken down under rainfall, compaction and soil surface sealing (insert ref). However, when combined with a surface cover, clod break down by rainfall and sealing could be reduced and the longevity of disturbance and the associated improved infiltration could be increased.

5.3.1.4 Root damage

The type and degree of D_{BG} will have an effect on the tine's potential to damage asparagus roots. A smaller cross sectional area of D_{BG} would reduce the risk of root damage as a smaller potential root-holding soil mass is disturbed. Therefore, the NT configurations would most minimise root damage at 175 mm whilst the WT and MPP could potentially result in the most root damage. However, the shape of the D_{BG} would also have an effect. For example, a narrow but deep area of D_{BG} may have the same area as a wide but shallow D_{BG} but if the roots are more concentrated at depth then the narrow but deep D_{BG} could result in higher root damage potential. In this study the only real difference in shape is that of the MPP that targets a different area of the wheeling to the other tine configurations. This area may be of a lower root density and thus result in less root damage.

The type of soil disturbance could also affect the likelihood of root damage. The rearrangement associated with the winged tine could result in more root damage due to a greater soil movement; lifting and lowering both from the tine foot and over the wings. A non-winged tine just lifts and lowers the soil mass over the tine foot, potentially resulting in less root breakage.

The WSLT and WT have the greatest leading edge area thus increasing the likelihood of cutting roots that lie in its path than the other tines. The WT vertical arrangement (the bulk of mass being situated at the base of the tine) also means that this potential cutting area is concentrated at depth where roots are perceived as most likely to be (Figure 5.2). Whilst the MPP with a much smaller tine surface area than the WT and WSLT and less mass at depth has a reduced potential root impact. The addition of shallow leading tines might also reduce root damage despite having a greater potential cutting area, as the roots may not be present at the shallower depth to which they cultivate.

5.3.2 Forces

5.3.2.1 Draught force

The high draught forces observed for the WT at 175 and 250 mm are to be expected. This configuration has a greater leading edge area than other configurations creating a larger frictional component as it is pulled through the soil (Figure 5.7).

5.3.2.2 Specific draught

The MPP had one of the lowest SD results across two sampling depths (175 and 250 mm), something that was not observed with any other tine. This was a result of the MPP exerting a large amount of draught force whilst also generating the greatest D_{BG}. NT was not significantly different from the MPP at 175 mm. This is despite generating the least D_{BG}, as it also exerted significantly lower draught force as compared with any other tine. This is helped by the small leading edge area of the tine minimising the frictional resistance as it passes through the soil. The success of the NSLT at 250 mm suggests that the shallow leading tines are working more effectively at this depth generating sufficiently greater D_{BG} in combination with the NT. Both winged tine configurations have the highest SD at 175 mm, which reflects the increased frictional resistance as well as the observed incomplete engagement of the wings with the soil. SD then decreases with depth for both winged tine configurations, as the wings become fully engaged.

SD_D shows higher values as compared to SD results. This is to be expected as these values consider draught force over a larger area of disturbed soil; i.e. both D_{AG} and D_{BG}. Statistical differences between tine configurations do not change much with the inclusion of D_{AG} in SD_D. This is because D_{AG} and D_{BG} increase at the same rate.

5.3.3 Tine suitability for SSD

At 175 mm the MPP ranks as the most effective tine configuration for soil disturbance. This is a result of the significantly higher D_{AG} and D_{BG} generated and the SD. The high degree of D_{AG} and D_{BG} is to be expected as two tines run in parallel through the soil creating two separate disturbance areas. The effect of two tines working in combination also results in an increased draught efficiency.

If compaction at depth is to be addressed, the Pugh matrix ranking suggests that the NSLT would be most effective at 250 mm, and the WSLT at 300 mm. This highlights the benefits of adding shallow leading tines. The role of the shallow leading tine is to initially disturb soil in the path of the main tine, thus reducing the confining forces (Spoor, 2006). This enables the main tine to disturb the soil using less draught and so increases the area of D_{BG}.

5.3.4 Soil disturbance and erosion control

The soil property changes observed in this study are not just pertinent to compaction alleviation but will also have an effect on runoff and erosion processes. Soil disturbance reduces compaction by increasing soil porosity. This increased soil porosity will increase infiltration (Davies et al., 2001) and reduce runoff (Gomez et al., 1999, Meek et al., 1992 and Jasa and Dickey, 1991). Furthermore, increased soil porosity means a greater below ground water storage capacity also resulting in reduced runoff volumes. A reduction in runoff (rate and volume) will reduce the capacity of the runoff to entrain and transport detached soil particles, thus reducing erosion (Morgan, 2005). The resulting D_{AG} increases the volume of soil (by reducing bulk density) resulting in a roughened area of soil above ground. This has the potential to impart a frictional component to runoff, reducing velocity and the capacity of runoff to entrain soil particles (Burwell et al., 1966). Furthermore a roughened surface can increase surface depression storage (Idowu et al., 2002). Therefore the tine configurations that significantly increase the extent and degree of soil disturbance should also reduce runoff and soil erosion.

5.4 Conclusion

Shallow soil disturbance results in a change in soil properties; it reduces bulk density, increases porosity and increases surface roughness. This study has assessed the resulting changes in soil properties from different tine configurations under controlled conditions at three different depths. Tine configurations including geometry, arrangement and depth have shown to significantly change the degree and extent of soil disturbance as well as tine dynamics in the case of all parameters tested. Therefore the tested hypothesis can be accepted. Furthermore, results show that the currently adopted winged tine compares unfavourably to the other tine configurations at the current cultivation depth (175 mm). Furthermore, the design of the currently adopted winged tine is compromising its soil disturbance potential.

The observed changes in soil properties will lead to a different soil system response to rainfall, affecting runoff and erosion control. Based on the results of this study, on-site erosion control potential could be improved by using the modified para-plough at the current depth of cultivation. Where root damage is not a concern, such as in recently planted asparagus fields with limited root development, or for non-asparagus row crops, erosion control could be further improved by increasing the depth of cultivation. In this case, the NSLT (at 250 mm) and the WSLT (at 300 mm) would be the most effective for compaction alleviation and thus erosion control.

Whilst this study has tested tine configurations under controlled conditions, both the soil type and the bulk density used were similar to that observed in the field. Therefore, whilst some conditions such as soil moisture content and whether the winged tine is operating below the critical depth may differ in the field, the comparative performance of each tine should not. However, it is important to check whether the differences observed under these conditions do have an effect on soil physical conditions and thus erosion control in the field under natural rainfall conditions. Therefore, field testing should be undertaken to relate these results to in-field effectiveness of tillage configurations on runoff and erosion.

The changes in soil properties observed in the soil bin relate to conditions obtained immediately following soil disturbance. In a field setting these conditions can degrade rapidly with time through rainfall impact and trafficking. In order to maintain the longevity of the initial soil disturbance effect mulch can be added. This can protect the shallow soil disturbance from rainfall degradation and help keep it open for longer.

6 PHASE 2 FIELD TRIALS

6.1 Methodology

In order to test the research hypotheses (Chapter 3) the following methodology was developed.

The Phase 2 experimental programme took place between 2nd May to 26th November 2013 at Cobrey Farms, Coughton, Ross on Wye. A different field was used for Phase 2 (SO612219) to that used for Phase 1. This was so that residue effects of Cp and St applied in Phase 1 were avoided. The ‘new’ field had been under asparagus production for 10 years. Replicated field runoff plots were setup in which the three shallow soil disturbance practices selected from the Soil Bin experimental work and mulch treatment combinations were tested (Section 6.1.1). The runoff sampling and analysis methods used were identical to those reported for the Phase 1 field trials (Chapter 4).

6.1.1 Treatment selection

6.1.1.1 Shallow soil disturbance

SSD selection was based upon the top three ranked tines from the Soil bin experiment results (Chapter 5). The treatments tested in Phase 2 are detailed in Table 6.1.

6.1.1.2 Surface mulch

In this experiment only wheat straw mulch was applied at a single application rate (6 t ha^{-1}). Wheat straw was firstly selected based upon its consistency as a mulch product as compared to the variable nature of PAS 100 compost due to the complex nature of the feedstock. Secondly, it has generated good and consistent results in both the Phase 1 Field trials and the initial proof of concept trials (Niziolomski, 2011). Unlike Phase 1, straw used in Phase 2 was un-chopped for ease of setup.

Table 6.1. Summary of Phase 2 experimental treatments and their associated reference codes.

Treatment number	Shallow soil disturbance[†]	Tine type[‡]	Mulch type*	Treatment code
1	SSD	MPP	No mulch	MPP No mulch
2	SSD	MPP	St	MPP St
3	Non-SSD	N/a	No mulch	Non-SSD Control
4	Non-SSD	N/a	St	Non-SSD St
5	SSD	WT	No mulch	WT No mulch
6	SSD	WT	St	WT St
7	SSD	NSLT	No mulch	NSLT No mulch
8	SSD	NSLT	St	NSLT St

[†]Non-SSD = Without shallow soil disturbance; SSD = With shallow soil disturbance. [‡]MPP = Modified para-plough; WT = Winged tine; NSLT = Narrow tine with two shallow leading tines. *St = Straw. N/a = Non applied

6.1.2 Experimental setup

Figure 6.1. Overview of Phase 2 experimental setup.

6.1.2.1 Runoff plots

Runoff plots were setup similar to that described in the Phase 1 Field Trials methodology, but with the following modifications:

- Water tanks were situated below the soil surface in a ditch at the end of the treatment area (Figure 6.1). This was to ensure a sufficient drop for effective runoff and detached soil capture, and to minimise pipe blockages.
- Treatment plots were 10 m shorter than in Phase 1 (30 m in length), thus reducing the runoff catchment area. This was a precaution to reduce the risk of tanks filling to their maximum capacities following multiple rainfall events thus masking the differences in runoff volume between treatments.
- Plots were of shallower slope gradients than Phase 1. This was again a precaution to reduce the risk of tanks filling to their maximum capacities following multiple rainfall events thus masking the differences runoff volume between treatments. This meant that plots were situated mid-slope for uniform gradients and so were bounded by a purpose made ditch at the top of the plot to prevent runoff entering the plots from upslope areas.

6.1.2.2 Experimental design

The experimental design was randomised and included an untreated control (Non-SSD Control). Each treatment was repeated in triplicate. A pseudo control was also included (Non-SSD St) for a complete statistical design. Shallow soil disturbance was first randomly assigned, followed by the presence/absence of mulch (Table 6.2).

Table 6.2. Phase 2 experimental design.

Plot #	Treatment code	Plot #	Treatment code
1	MPP No mulch	13	WT No mulch
2	Non-SSD Control	14	WT No mulch
3	WT St	15	MPP St
4	MPP St	16	Non-SSD St
5	NSLT St	17	MPP No mulch
6	MPP St	18	Non-SSD St
7	Non-SSD Control	19	Non-SSD St
8	NSLT St	20	NSLT No mulch
9	NSLT No mulch	21	Non-SSD Control
10	MPP No mulch	22	WT No mulch
11	NSLT St	23	NSLT No mulch
12	WT St	24	WT St

Non-SSD = Without shallow soil disturbance, MPP = Modified para-plough, WT = Winged tine, NSLT = Narrow with shallow leading, St = Straw

As with Phase 1, typical farming operations of cloche removal, harvesting and spraying continued both around and within the experimental plot area for the duration of the experiment. In order to facilitate spraying operations, two wheelings were left bare in the middle of the experimental layout.

6.1.2.3 Treatment application

Treatments were only applied to the asparagus wheelings. Shallow soil disturbance was undertaken first, to a depth of approximately 175 mm (standard on-site practice). Each treatment was applied on a wheeling-by-wheeling basis on an offset tractor mounted bracket (Figure 6.2 and Appendix C.1). Straw was first weighed out and then applied by hand to the designated plots.

Figure 6.2. Shallow soil disturbance application using an offset mounted bracket.

6.1.3 Data collection and analysis

The runoff sampling and analysis methods used were identical to those reported for the Phase 1 field trials. Statistical analysis did differ as the Phase 2 experimental design involved just two levels of treatment; SSD and mulch, this lent itself to a two-way full factorial ANOVA.

Event driven hydrological response measurement was also identical to that of the Phase 1 Field Trials. However, the analysis of this data did differ for RE_1 definition. In Phase 2, the RE_1 was defined as the first rainfall event to generate runoff from > 50 % of plots. This was intended to minimise the observed variation between replicates.

6.1.4 Field site characterisation

6.1.4.1 Climate

As discussed in Chapter 4 the average rainfall for Ross on Wye (SO601241) is 734 mm yr^{-1} (Met Office, 2014). During 2013, 771 mm was recorded on-site (SO614218). For the duration of the Phase 2 field trial monthly rainfall was generally below the 20 year average (Figure 6.3). The high rainfall experienced in October did not influence results as samples were not collected over that period. Five sampling periods took place in total (Table 6.3). However, Sampling Period 4 was omitted as only 2 out of 8 treatments generated runoff (Non-SSD Control and MPP No Mulch).

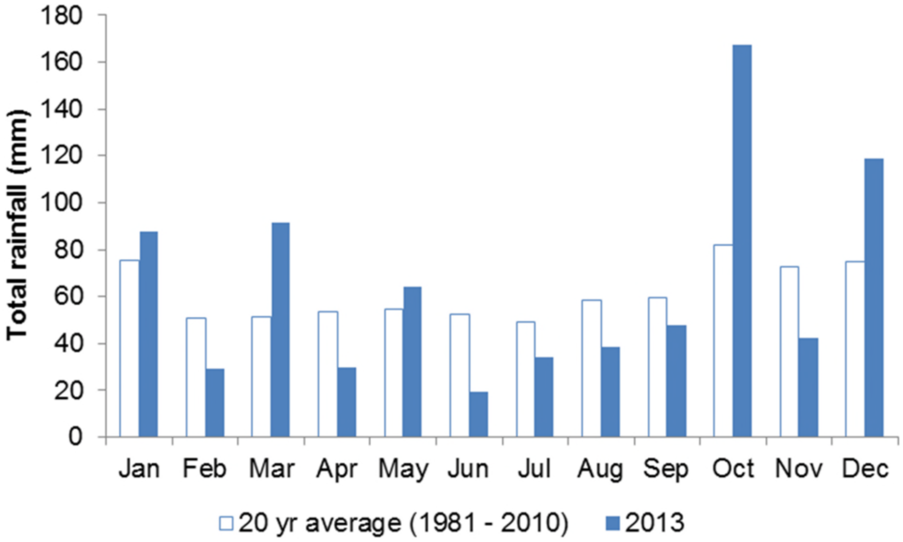


Figure 6.3. Rainfall data for Ross on Wye for 2013 as compared with the 20 year average. Data courtesy of Cobrey Farms (2014) and the Met Office (2014).

Total rainfall across the Phase 2 collection period (1st May to 26th November 2013) amounted to 428 mm. Approximately 65 mm of rainfall was received by treatments prior to sample collection due to a delay in weather station installation. In addition, a break in sampling occurred between Sampling Period 4 and 5, due to other work commitments, over which 240 mm rainfall was recorded on-site. The rainfall characteristics of each Sampling Period varied and are presented in Table 6.3. Sampling Periods 2, 3 and 5 were associated with maximum rainfall intensities of 588, 792 and 792 mm hr^{-1} (based on a 1 minute logging interval). The occurrence of storm based rainfall allowed a more event-based runoff and erosion monitoring programme than in Phase 1.

Table 6.3. A summary of the rainfall characteristics associated with each Sampling Period.

Sampling Period	Collection period	Total no. days	Total rainfall (mm)	No. rain days†	No. rainfall events‡	Maximum rainfall intensity (mm hr^{-1})*	Mean rainfall intensity (mm hr^{-1})*
1	30th May - 6th Jun	8	3.6	2	3	N/a	N/a
2	7th Jun - 24th July	48	16.2	1	1	588	54
3	25th Jul - 6th Aug	13	46.6	7	11	792	124
5	6th Nov - 26th Nov	21	28.8	5	5	792	97

†Rain days defined as ≥ 1.0 mm received. ‡Rainfall Events defined as ≥ 1.0 mm rain over a 10 minute period. *Based on a 1 minute logging interval. N/a; High resolution data not available due to logging error.

6.1.4.2 Soil

The documented soil properties identified for the Phase 1 field trials are also applicable to Phase 2. Baseline characterisation of soil properties was undertaken as per the Phase 1 methodology described in Chapter 4.

Table 6.4. Mean soil properties of Phase 2 Non-SSD Control plots. Within each parameter, values followed by a different letter indicate statistical difference at p ≤ 0.05.

Bulk density (g cm^{-3})		Soil organic matter (%)		Sand (%)		Silt (%)		Clay (%)	
1.58	a	1.0	a	80.6	a	12.7	a	6.70	a
1.59	a	1.0	a	78.7	a	13.9	a	7.36	a

Bulk density ($g\ cm^{-3}$)		Soil organic matter (%)		Sand (%)		Silt (%)		Clay (%)	
1.70	a	1.1	b	76.0	b	15.7	a	8.26	b

Few significant differences in soil properties were observed between control plots (Table 6.4). Significant differences observed in organic matter (0.1 %) and sand and clay content (2 %) are not large enough to result in a difference in treatment response. No significant difference between treatment plot slopes was observed (Table 6.5).

Table 6.5. Mean slope gradient for each treatment type. Values followed by a different letter indicate statistical difference at p ≤ 0.05.

No.	Treatment code	Slope (degrees)	
1	MPP No Mulch	3.2	a
2	MPP_St	3.0	a
3	Non-SSD Control	2.8	a
4	Non-SSD St	2.8	a
5	WT No mulch	3.0	a
6	WT St	3.0	a
7	NSLT No mulch	3.0	a
8	NSLT St	3.0	a

6.2 Results

Treatment codes referred to in this section are summarised in Table 6.1. Full factorial ANOVA showed no significant interaction effects between SSD type and mulch for any variables across all Sampling Periods. Despite this, distinct differences were evident between treatments for some variables. In order to quantify these differences one-way ANOVA was carried out in which some significant differences were evident between individual treatments. For example, in Sampling Period 1 the sediment concentration in runoff was orders of magnitude greater from MPP No mulch plots than Non-SSD St, NSLT St, MPP St, and WT St (Table 6.6), with different data populations. This difference was not captured by full-factorial analysis as it was not a result of a significant 2-way interaction between SSD and mulch (p-value = 0.44). However, following one-way ANOVA a significant difference (p-value = <0.01) was observed between individual treatment types MPP No mulch as compared with Non-SSD St, NSLT St, MPP St, and WT St (Table 6.7).

Table 6.6. Sampling Period 1 results for sediment concentration (g l-1) in runoff from each plot

Sampling Period	Plot No.	Treatment	Addition	Rep	Sediment concentration (g l^{-1})
1	1	MPP	No mulch	1	1.25
1	10	MPP	No mulch	2	No data
1	17	MPP	No mulch	3	1.04
1	2	Non-SSD	No mulch	1	0.69
1	7	Non-SSD	No mulch	2	0.68
1	21	Non-SSD	No mulch	3	0.83
1	9	NSLT	No mulch	1	1.12
1	20	NSLT	No mulch	2	0.67
1	23	NSLT	No mulch	3	0.55
1	13	WT	No mulch	1	0.97
1	14	WT	No mulch	2	0.41
1	22	WT	No mulch	3	0.59
1	4	MPP	St	1	0.38
1	6	MPP	St	2	0.64
1	15	MPP	St	3	0.45

Sampling Period	Plot No.	Treatment	Addition	Rep	Sediment concentration (g l^{-1})
1	16	Non-SSD	St	1	0.18
1	18	Non-SSD	St	2	0.17
1	19	Non-SSD	St	3	0.36
1	5	NSLT	St	1	0.27
1	8	NSLT	St	2	0.47
1	11	NSLT	St	3	0.58
1	3	WT	St	1	0.42
1	12	WT	St	2	0.31
1	24	WT	St	3	0.28

Table 6.7. Significant differences in mean sediment concentration in runoff (g l^{-1}) for Sampling Period 1 following full factorial two-way and one-way ANOVA. Within each ANOVA type, values followed by different letters denote statistical significance ($p \leq 0.05$).

	Mean sediment concentration (g l^{-1})	
Treatment	Full factorial two-way ANOVA	Full factorial one-way ANOVA
MPP No Mulch	1.14 a	1.14 d
MPP St	0.49 a	0.49 abc
Non-SSD No Mulch	0.73 a	0.73 bc
Non-SSD St	0.24 a	0.24 a
WT No Mulch	0.66 a	0.66 bc
WT St	0.34 a	0.34 a

	Mean sediment concentration (g l^{-1})	
Treatment	Full factorial two-way ANOVA	Full factorial one-way ANOVA
NSLT No Mulch	0.78 a	0.78 c
NSLT St	0.44 a	0.44 ab

6.2.1 Runoff volume (l)

It was expected that plots with SSD and St would result in reduced runoff as compared with Non-SSD No Mulch plots. This is because with SSD the soil porosity has been increased; increasing infiltration and thus generating a greater water storage area below the soil surface (Davies et al., 2001). Meanwhile, St imparts a surface roughness that slows runoff allowing more time for infiltration (Foster et al., 1982a). Furthermore, St provides surface depression storage as well as holding runoff back behind mini dams that are formed with mulch movement (Brown et al., 1998).

6.2.1.1 Overall runoff volume

Runoff volumes totalled across the entire sample collection period did not meet the expectations outlined above. No significant differences were observed in runoff volume between SSD or mulch alone, SSD and mulch interactions or individual treatments.

6.2.1.2 Individual Sampling Period runoff volume

Individual Sampling Period results also did not meet the treatment expectations outlined above, with no significant differences observed between mulch and SSD both separately and in combination (Table 6.8, Figure 6.4). This is a result of a large variation in runoff volumes between replicates for most treatments.

Table 6.8. Significance levels (p-values) of each treatment factor on runoff volume, derived from full factorial and one-way ANOVA.

		Full factorial ANOVA factors			One-way ANOVA
Dependent variable	**Sampling Period**	**SSD type (MPP, Non-SSD, WT, NSLT)**	**Mulch (St/No Mulch)**	**SSD and mulch (two-way interaction)**	**Individual treatment type**
Runoff volume (l)	1	0.78	0.68	0.91	0.91
	2	0.38	0.17	0.32	0.30
	3	0.93	0.92	0.19	0.55
	5	0.13	0.65	0.30	0.20

N.B. Results of full factorial ANOVA presented are across all treatment types. *Denotes a statistically significant result ($p \leq 0.05$).

6.2.2 Event driven hydrological response

It was envisaged that a detailed analysis of the hydrological response of treatments (cumulative runoff volume, runoff rate and time to rainfall initiation) to the RE_1 for each Sampling Period would have the potential to highlight differences in treatment response to rainfall that are not apparent in total runoff volume results presented above. The rainfall characteristics of each Sampling Period RE_1 are presented in Table 6.9.

It was expected that SSD and St treatments would be associated with different hydrological responses to other treatments. This is because SSD would result in greater initial infiltration and St reduce runoff velocity. However, this was not the case with few significant differences between treatment hydrological responses. This is due to a large variability within treatment replicates due to different runoff response times, as well as homogenous values between plots that made data often not suitable for ANOVA. Only Sampling Periods with significant differences will be discussed here.

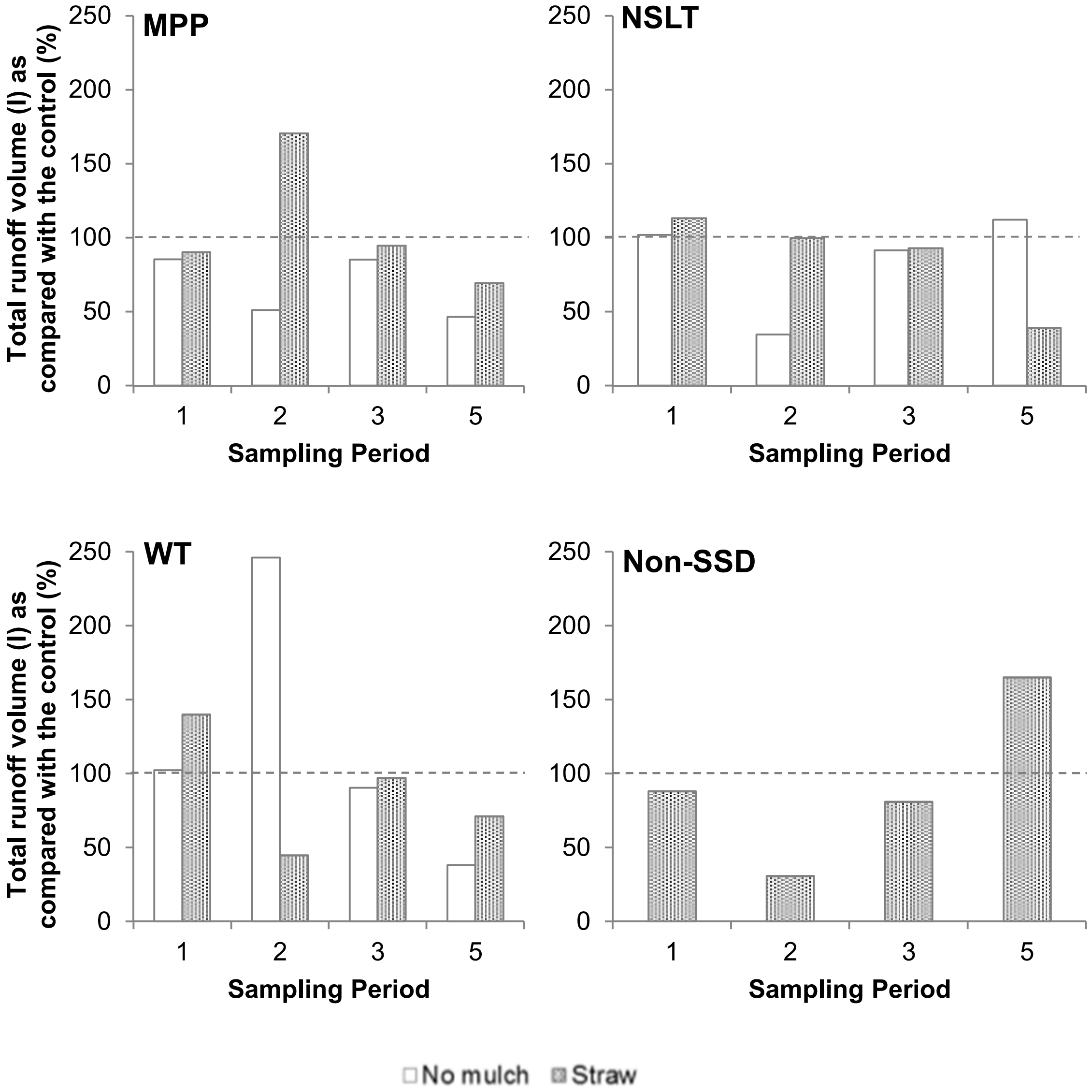


Figure 6.4. Relative runoff volume (l $plot^{-1}$) from each treatment as compared with the Non-SSD Control (the dashed line). For statistical differences between treatments see Appendix C.3, Table_Apx C-2.

Table 6.9. RE_1 characteristics for each Phase 2 Sampling Period.

Sampling Period	RE_1 duration (mins)	Rainfall (mm)	Percentage of Sampling Period rainfall (%)	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})	Frequency* (years)
1	Data unavailable due to logging error.					

2	19	15.2	94	54	588	20
3	3	8.2	18	82	432	5
4	10	14.4	50	123	432	> 30

*Frequency calculations based upon intensity (mean) and duration curves (Corney, 2011).

Table 6.10. Significance levels of the treatment effect on RE_1 cumulative runoff volume and runoff rate derived from one-way ANOVA.

Time from RE_1 initiation (min)	**Cumulative volume (l)**				**Runoff rate (l min^{-1})**			
	Sampling Period				**Sampling Period**			
	1	**2**	**3**	**5**	**1**	**2**	**3**	**5**
0		N/v	N/v	N/v		N/v	N/v	N/v
1		N/v	0.75	0.38		N/s	*0.32*	0.38
3		N/s	0.71	0.38		N/s	N/s	N/s
5		*0.16**	0.68	0.37		*0.22*	N/s	N/s
7		*0.07**	0.68	0.39		*0.24*	N/v	N/s
9		0.30	0.69	0.39		N/s	N/s	*0.94*
11		0.30	0.69	0.39		N/s	N/s	*0.39*
12		-	-	0.40		-	-	N/s
13		0.30	0.69	-		N/s	N/s	-
15		0.27	-	-		N/s	-	-
17		0.27	-	-		*0.98*	-	-
19		0.29	-	-		N/s	-	-
21		0.30	-	0.40		N/s	-	*0.01**
22		-	0.68	-		-	N/s	-
30		0.30	-	-		N/s	-	-

N/v; No variance within results. N/s; Data is not suitable for ANOVA (assumptions not met).* Denotes significant differences ($p \geq 0.2$). N.B. Values in italics are derived from the log of mean values.

6.2.2.1 Cumulative volume (l)

Significant differences between treatments were only observed in Sampling Period 2 (Table 6.10). All treatments in Sampling Period 2 demonstrated a slow initial runoff response despite high intensity rainfall at 1 minute (Figure 6.5). MPP No Mulch and WT No mulch showed a significant delay in time to runoff initiation by 8 and 9.5 minutes as compared with the Non-SSD Control (Appendix C.4, Table_Apx C-8). At 5 minutes post rainfall initiation, WT No mulch, MPP No mulch and Non-SSD St had still not generated any runoff, making them significantly different from WT St, MPP St, NSLT St and NSLT No Mulch treatments. At 7 minutes post rainfall initiation, only WT No Mulch had not generated runoff, this meant a significant reduction in cumulative runoff of 100 % as compared with the Non-SSD Control. Furthermore, MPP No mulch and Non-SSD St also generated significantly less cumulative runoff volume at 7 minutes as compared with the Non-SSD Control by 83 and 74 % respectively.

6.2.2.2 Runoff rate (l min^{-1})

Significant differences between treatments were only observed in Sampling Period 5 (Table 6.10). At 21 minutes (10 minutes post rainfall cessation), NSLT No mulch, MPP St and WT St generated significantly higher runoff rates as compared with all other treatments, as runoff from the other treatments had ceased.

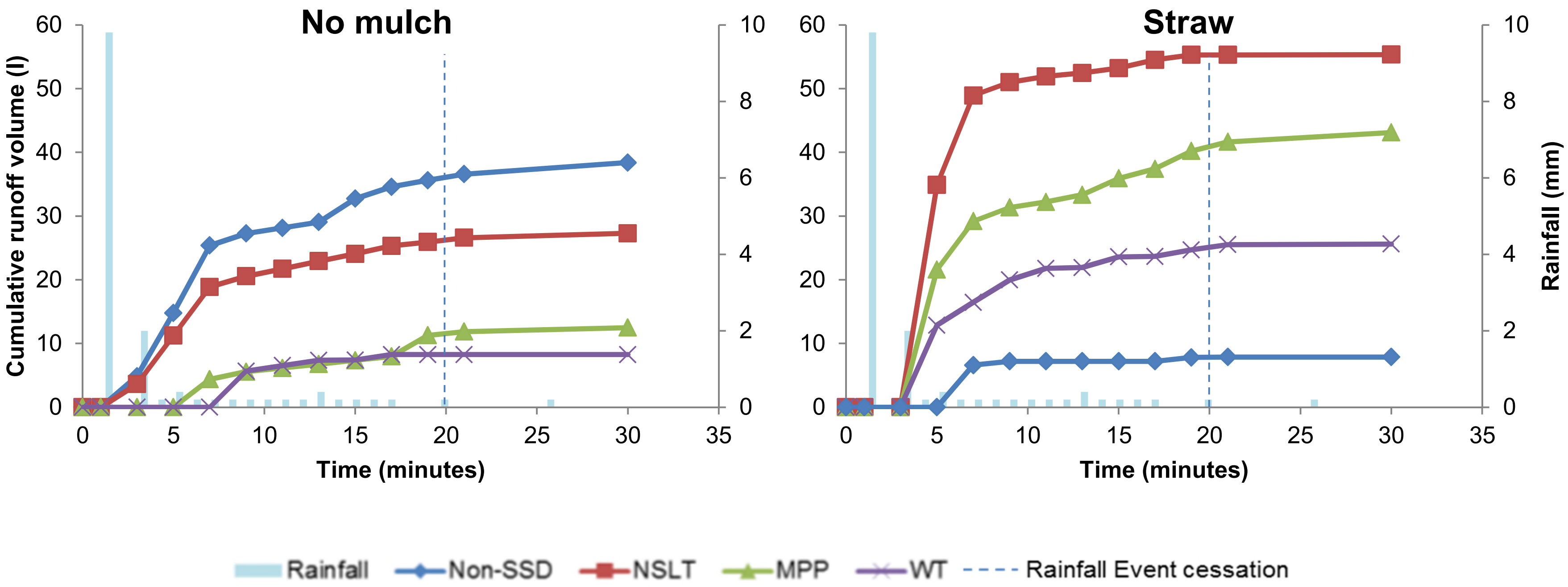


Figure 6.5. Runoff hydrographs for RE$_1$ of Sampling Period 2. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute and 10 minutes post rainfall event cessation. For significant differences between treatments see Appendix C.4, Table_Apx C-9.

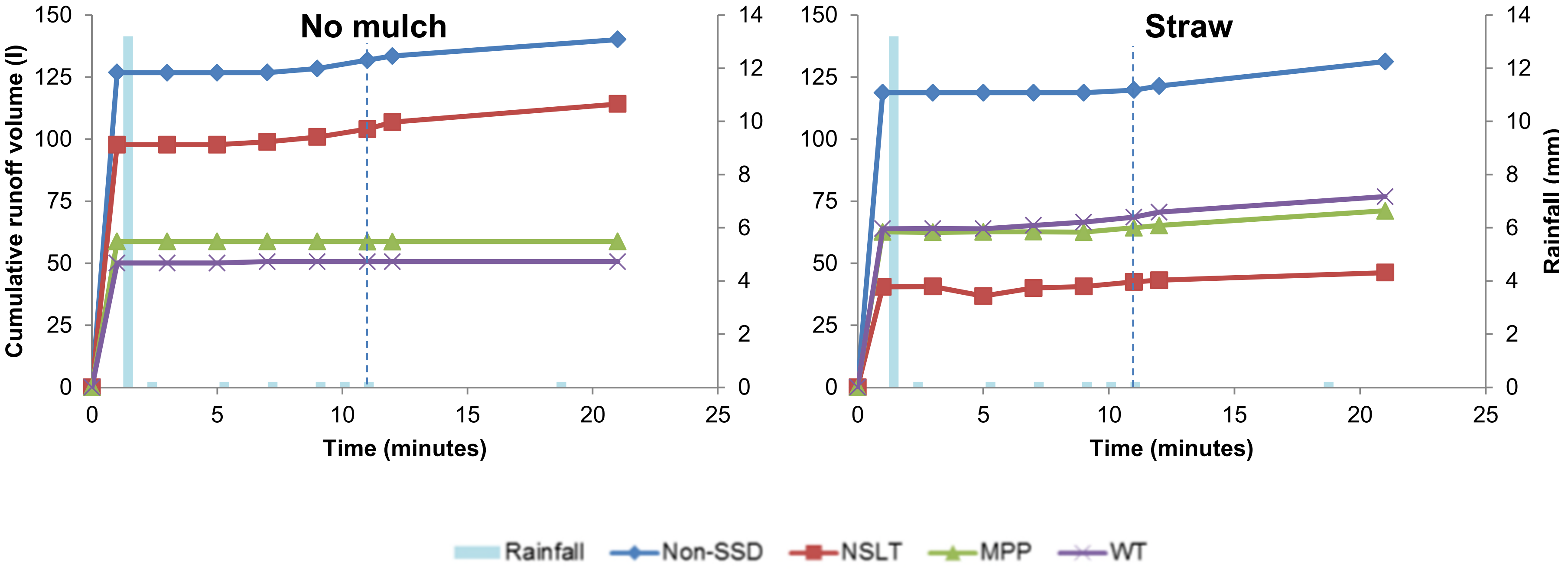


Figure 6.6. Runoff hydrographs for RE$_1$ of Sampling Period 5. Cumulative runoff volume is shown at set intervals during the rainfall event as well as 1 minute and 10 minutes post rainfall event cessation. For significant differences between treatments see Appendix C.4, Table_Apx C-11.

6.2.3 Total soil loss (kg)

It was expected that the least total soil loss (TSL) would result from St treatments. This is because the soil surface is protected from detachment by rain splash (Morgan, 2005). Furthermore, it would impart a roughness to the flow resulting in a reduced flow velocity causing any soil particles entrained in the runoff to drop out. It was also expected that SSD (MPP, WT and NSLT) would reduce TSL by increasing infiltration thus reducing the transport capacity of the runoff.

6.2.3.1 Overall TSL

Soil loss results totalled across all five Sampling Periods partially met the treatment expectations outlined above with significant differences in TSL between individual treatments (Table 6.11). This was not a result of a significant interaction between mulch and SSD type, but a significant mulch effect. On average St resulted in a total reduction in TSL of 81 % as compared to No mulch treatments. This resulted in significant reductions between MPP St, WT St, Non-SSD St and NSLT St treatments of 87, 82, 77 and 76 % respectively as compared with the Non-SSD Control.

Table 6.11. Mean TSL (kg plot^{-1} and t ha^{-1}) for each treatment across the entire Phase 2 sample collection period. Values followed by different letters denote statistical significance ($p \leq 0.05$) following one-way ANOVA.

No.	Treatment	TSL (kg plot^{-1})		TSL (t ha^{-1})
1	MPP No mulch	4.09	b	0.91
2	MPP St	0.45	a	0.10
3	Non-SSD Control	3.54	b	0.79
4	Non-SSD St	0.83	a	0.18
5	WT No mulch	2.99	b	0.66
6	WT St	0.64	a	0.14

No.	Treatment	TSL (kg plot^{-1})		TSL (t ha^{-1})
7	NSLT No mulch	3.58	b	0.80
8	NSLT St	0.85	a	0.19

N.B. Results are reported in t ha^{-1} for ease of comparison with other studies.

6.2.3.2 Individual Sampling Period TSL

Significant differences in TSL were only observed between St/No Mulch treatments and individual treatments (Table 6.12). Treatment expectations outline in Section 6.2.3 were partially met with significant TSL reductions observed for St treatments. With regards to an SSD effect this was only observed in Sampling Period 5 (Table 6.12), with reductions in TSL associated with SSD treatments as compared with Non-SSD treatments. Whilst no significant two-way interaction was observed between SSD and mulch, significant differences were observed between individual treatment types following one-way ANOVA (Table 6.12).

In Sampling Periods 1, 2 and 3 (Figure 6.7), St significantly reduced TSL by 54, 88 and 79 % respectively across WT, MPP, NSLT and Non-SSD treatments as compared to the No Mulch treatments (Appendix C.3, Table_Apx C-6). This was reflected in differences between treatments in Sampling Period 3 (Figure 6.7) where all St treatments significantly reduced TSL as compared to the Non-SSD Control. The most significant difference was observed from MPP St with an 84 % reduction in TSL as compared to the Non-SSD Control. Non-SSD St generated the least significant reduction (69 %) as compared to the Non-SSD Control, but did not differ significantly from WT St or NSLT St treatments. All SSD No Mulch treatments were observed to increase TSL as compared to the Non-SSD Control (Figure 6.7). However, this difference was not significant. In Sampling Period 5 MPP and WT treatments significantly reduced TSL both by 65 % as compared to Non-SSD treatments (Appendix C.3, Table_Apx C-4). NSLT treatments also resulted in significant reductions in TSL of 45 % as compared with Non-SSD treatments.

Table 6.12. Significance levels of each treatment factor on TSL, derived from full factorial and one-way ANOVA.

		Full factorial ANOVA factors			One-way ANOVA
Dependent variable	**Sampling Period**	**SSD type (MPP, Non-SSD, WT, NSLT)**	**Mulch (St/No Mulch)**	**SSD and mulch (two way interaction)**	**Individual treatment type**
Total soil loss (kg)	Total	0.38	<0.01*	0.42	<0.01*
	1	0.90	<0.01*	0.92	0.18
	2	0.63	<0.01*	0.55	0.05
	3	0.69	<0.01*	0.08	<0.01*
	5	0.03*	0.07	0.41	0.05

Results of full factorial ANOVA presented are across all treatment types. *Denotes a statistically significant result ($p \leq 0.05$).

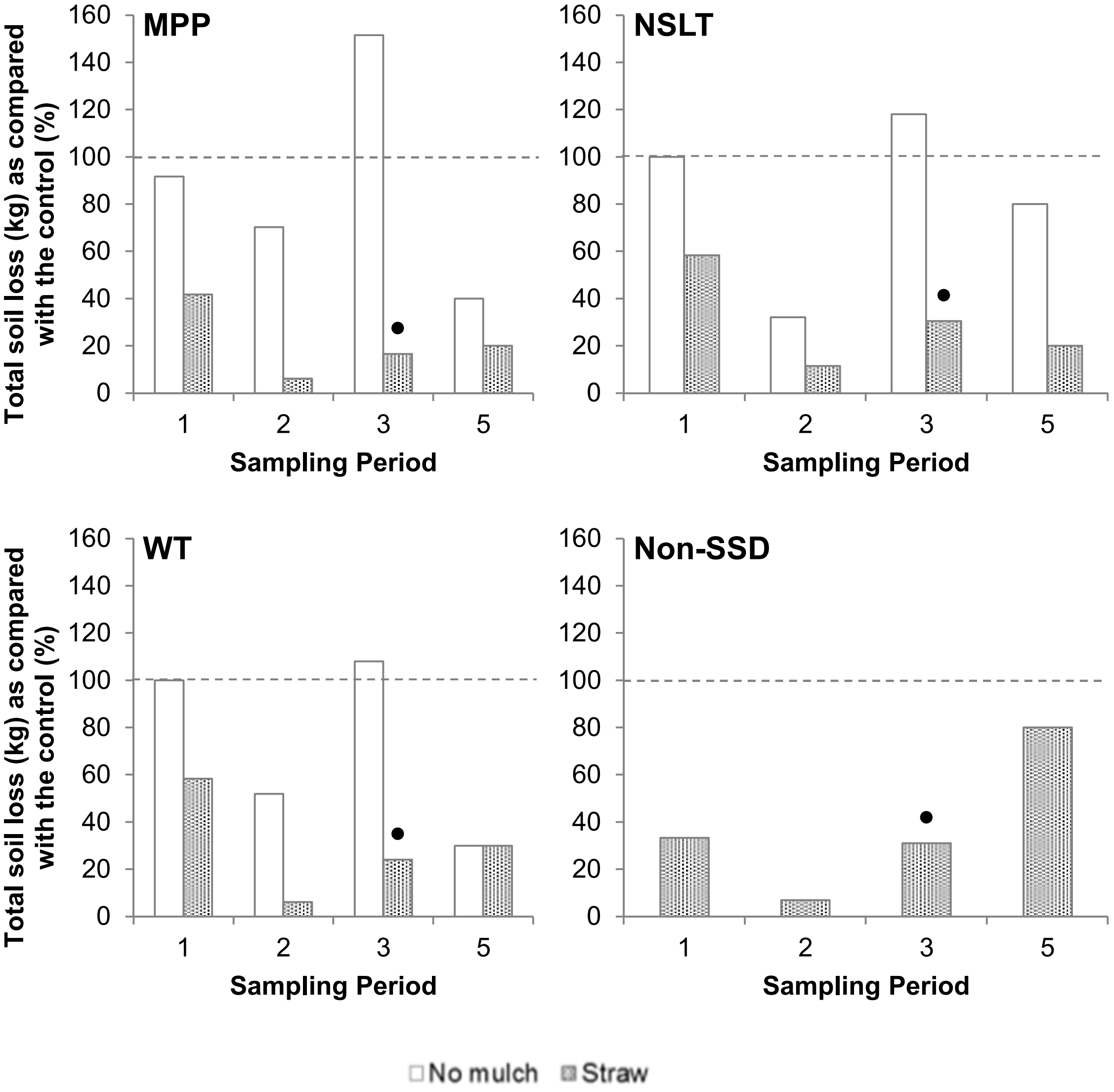


Figure 6.7. Relative TSL (kg plot^{-1}) from each treatment compared with the Non-SSD Control (the dashed line). Filled circles denote a statistical difference from the Non-SSD Control. For statistical differences between treatments see Appendix C.3, Table_Apx C-2.

6.2.4 Sediment concentration (g l^{-1})

Significant differences in runoff sediment concentration were observed between mulch and SSD factors as well as between individual treatment types (Table 6.13). Treatment expectations were the same as with TSL, with the least sediment concentration in runoff expected from St plots. This is because initial soil detachment will have been prevented by surface protection afforded by straw and runoff velocity reduced by surface roughness allowing soil particles to be deposited. This was found to be the case with St treatments resulting in a significant reduction in sediment concentration in the first three Sampling Periods.

Table 6.13. Significance levels of each treatment factor on sediment concentration in runoff, derived from full factorial and one-way ANOVA.

		Full factorial ANOVA factors			**One-way ANOVA**
Dependent variable	**Sampling Period**	**SSD type (MPP, Non-SSD, WT, NSLT)**	**Mulch (St/No Mulch)**	**SSD and mulch (two-way interaction)**	**Individual treatment type**
Runoff sediment concentration (g l^{-1})	1	0.04*	<0.01*	0.44	<0.01*
	2	0.53	<0.01*	0.56	0.02*
	3	0.37	<0.01*	0.39	<0.01*
	5	0.26	0.34	0.25	0.59

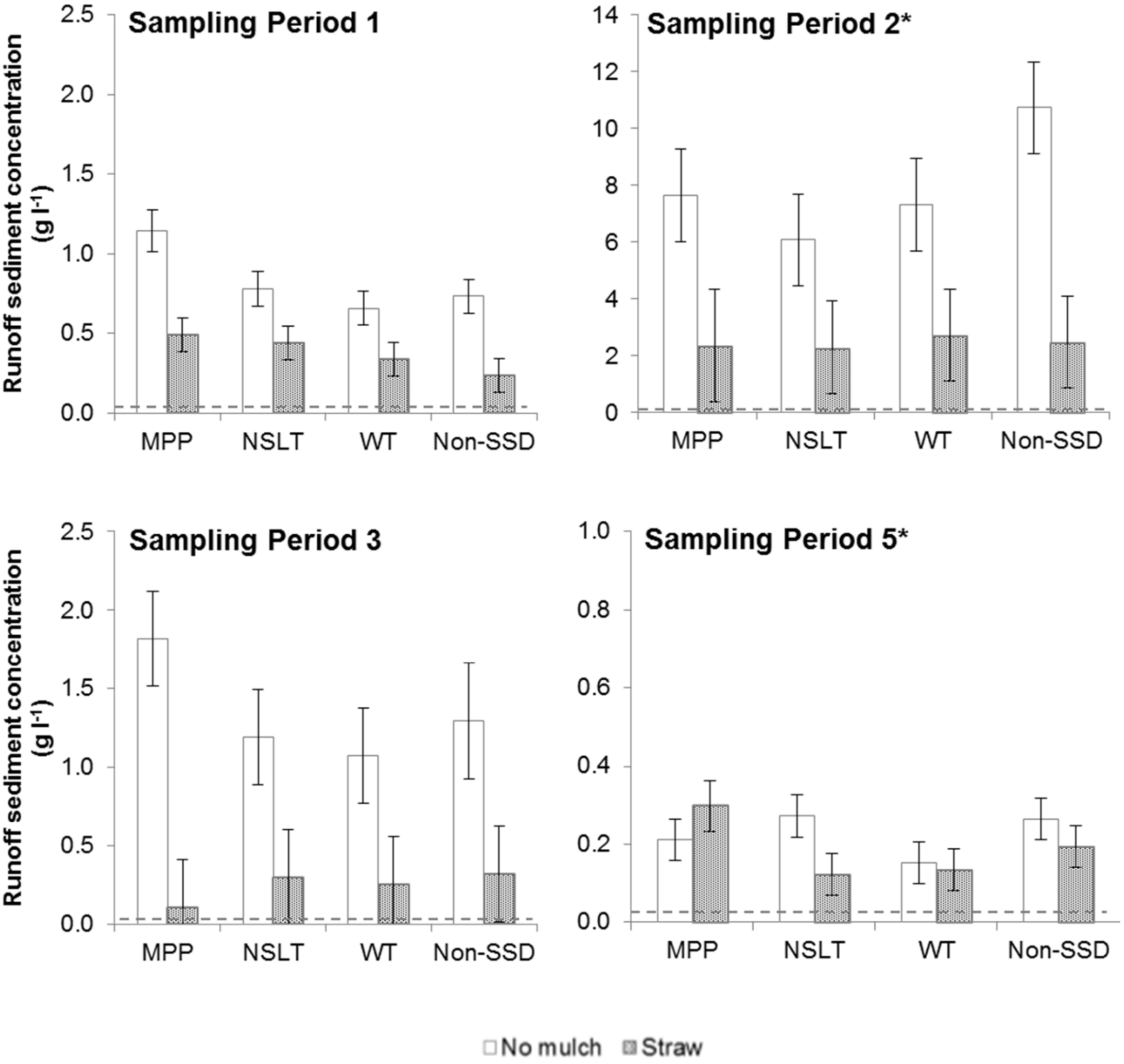
Results of full factorial ANOVA presented are across all treatment types.
*denotes a statistically significant result ($p \leq 0.05$).

Furthermore, it was expected that SSD would also reduce sediment concentration. This is because it too imparts a roughness to the flow reducing velocity in addition to increasing infiltration resulting in a reduction in runoff and thus its capacity to entrain and transport detached soil particles. However, this was not the case with no significant differences observed between SSD and Non-SSD treatments.

It was also expected that the combined effect of SSD and mulch on runoff and soil loss would result in significant reductions in runoff sediment concentrations. This was found to be the case, although not as a result of significant interactions between the two treatment factors. Significant reductions were observed in sediment concentration following one-way ANOVA from most SSD St treatments over 3 out of 4 Sampling Periods.

St treatments significantly reduced sediment concentration in runoff across Sampling Periods 1, 2 and 3. These reductions were of 55, 88 and 76 % respectively as compared with the Non-SSD Control (Appendix C.3, Table_Apx C-6). This trend was also evident in differences between individual treatment types. In Sampling Period 1, only Non-SSD St and WT St significantly reduced runoff sediment concentration as compared with the Non-SSD Control by 67 and 54 % respectively. This significant difference was not observed with MPP St and NSLT St as a result of a greater variation between replicates. In Sampling Period 2 and 3, all St treatments significantly reduced sediment concentration. These reductions were 78 and 84 % (MPP St), 77 and 75 % (Non-SSD St), 75 and 77 % (WT St) and 79 and 78 % (NSLT St) as compared with the Non-SSD Control.

In Sampling Period 1, MPP treatments with and without St generated a significant 68 % increase in sediment concentration as compared with Non-SSD treatments (Appendix C.3, Table_Apx C-4). MPP treatments also generated significantly more runoff sediment concentration (64 %) as compared with WT treatments. This difference was also reflected between individual treatments, with significantly increased sediment concentration with MPP No Mulch in Sampling Period 1 as compared with all other treatments. This was an increase of 56 % as compared with the Non-SSD Control.



---- Surface water quality guideline (0.025 g l^{-1}) for suspended sediments stipulated by EU Directive 75/440/EEC.

Figure 6.8. Mean sediment concentration (g l^{-1}) in runoff across all Sampling Periods. For statistical differences between treatments see Appendix C.3, Table_Apx C-2. *Scales on the y axis vary.

6.2.5 Total oxides of nitrogen (mg l^{-1})

Significant differences in TON were observed between SSD treatments and mulch treatments as well as between individual treatment types (Table 6.14). However, no two-way treatment interactions were observed. It was expected that the least TON would result from SSD plots. This is because SSD plots have a greater water storage area that can reduce runoff and thus the concentration of TON. This was found to be the case with SSD treatments resulting in some TON reductions. Furthermore, reductions were expected as a result of surface depression storage created in St treatments as well as N immobilisation by microbes associated with St decomposition (Christenson and Olesen, 1998). However, this was not the case with a variable effect observed from St treatments. It was also expected that the combined effect of SSD and mulch would reduce TON. However, only in Sampling Period 1 was this observed and not as a result of significant interaction effects.

Table 6.14. Significance levels of each treatment factor on TON in runoff, derived from full factorial and one-way ANOVA.

		Full factorial ANOVA factors			One-way ANOVA
Dependent variable	**Sampling Period**	**SSD type (MPP, Non-SSD, WT, NSLT)**	**Mulch (St/No Mulch)**	**SSD and mulch (two-way interaction)**	**Individual treatment type**
TON concentration (mg l^{-1})	1	0.18	<0.01*	0.75	<0.01*
	3	0.03*	0.02*	0.18	0.01*
	5	<0.01*	0.69	0.06	0.01*

Results of full factorial ANOVA presented are across all treatment types.
*denotes a statistically significant result ($p \leq 0.05$).

In Sampling Period 3 all SSD treatments significantly reduced TON as compared with the Non-SSD Control (Figure 6.9). MPP, NSLT and WT treatments irrespective of mulch all reduced TON by 73, 67 and 28 % respectively (Appendix C.3, Table_Apx C-

5). This was reflected in differences between individual treatments with MPP No mulch and WT No Mulch resulting in significant reductions of 73 and 52 % as compared with the Non-SSD Control (Figure 6.9). In Sampling Period 5, only NSLT and WT treatments independent of mulch resulted in reduced TON of 42 and 40 % respectively as compared with the Non-SSD Control (Appendix C.3, Table_Apx C-5). This too was reflected in differences between individual treatments with a 43 and 52 % reduction from WT St and NSLT St treatments respectively as compared with the Non-SSD Control (Figure 6.9).

St treatments independent of SSD first reduced TON in runoff by 73 % as compared with No Mulch treatments in Sampling Period 1 (Appendix C.3, Table_Apx C-7). This was reflected in differences between treatments with a reduction in TON from MPP St (60 %), Non-SSD St (87 %), WT St (68 %) and NSLT St (67 %) as compared with the Non-SSD Control (Figure 6.9). However, in Sampling Period 3, St treatments resulted in an 173 % increase in TON as compared with No mulch treatments. This trend continued into Sampling Period 5 with a non-significant increase of 5 % TON as compared to the No Mulch treatments.

6.2.6 Phosphorus (mg)

6.2.6.1 Orthophosphate-P (mg l^{-1})

Significant differences were observed in orthophosphate-P between mulch treatments, and between individual treatments (Table 6.15, Figure 6.10). It was expected that the greatest reduction in orthophosphate-P would be created by St treatments. This is because the St protects the soil surface and so any P present is less at risk of becoming solubilised by the runoff. However, this was not the case with a mixed effect of St on orthophosphate-P evident. Furthermore, it was expected that Non-SSD treatments would reduce orthophosphate-P as soil P reserves are not exposed to runoff. However, this was not found to be the case as no significant differences were observed between Non-SSD and SSD treatments. It was further expected that in combination Non-SSD and St treatments would reduce orthophosphate-P. However, this was only observed in Sampling Period 1 as a difference between individual treatment type and not an interaction effect (Figure 6.10).

Table 6.15. Significance levels of each treatment factor on orthophosphate-P in runoff, derived from full factorial and one-way ANOVA.

Dependent variable	Sampling Period	Full factorial ANOVA factors			One-way ANOVA
		SSD type (MPP, Non-SSD, WT, NSLT)	Mulch (St/No Mulch)	SSD and mulch (two-way interaction)	Individual treatment type
Orthophosphate-P concentration (mg l^{-1})	1	0.09	0.01*	0.36	0.03*
	3	0.33	0.06	0.93	0.36
	5	0.78	0.05*	0.78	0.46

Results of full factorial ANOVA presented are across all treatment types.
*denotes a statistically significant result ($p \leq 0.05$).

For Sampling Periods 1 and 3, significant differences in orthophosphate-P concentration in runoff were observed between St and No Mulch treatments independent of SSD. St significantly reduced orthophosphate-P by 40 % in Sampling Period 1 as compared with the No Mulch treatments independent of SSD (Appendix C.3, Table_Apx C-7). This was reflected in differences between individual treatments with Non-SSD St generating significantly less (61 %) orthophosphate-P as compared with the Non-SSD Control (Figure 6.10). However, by Sampling Period 3 orthophosphate-P levels from St treatments had increased by 67 %, as compared with Sampling Period 1, although the concentration was not significantly different (37 %) from No Mulch treatments (Appendix C.3, Table_Apx C-7). This trend continued into Sampling Period 5 with a significant 31 % increase in orthophosphate-P as compared with No Mulch treatments. Over the three Sampling Periods tested, 96 % of treatments exceeded the stipulated concentration levels for ‘good ecological status’ under the EU WFD (2000).

6.2.6.2 Sediment-bound P (mg kg^{-1})

As with orthophosphate-P, significant differences were observed in sediment-bound P between mulch treatments independent of SSD, and between individual treatment types (Table 6.16). It was expected that the greatest reduction in sediment-bound P would be achieved by mulched treatments. This is because mulch protects the soil from detachment thus reducing the runoff sediment concentration and associated P. However, this was not the case with St treatments showing a variable effect on sediment-bound P.

Furthermore, it was expected that sediment-bound P would be reduced by SSD treatments. This is because SSD increases infiltration reducing the velocity and volume of runoff. This reduces the entrainment and transport of any detached soil particles thus reducing concentration in runoff and associated P. However, this was not the case as no significant differences were observed between SSD and Non-SSD treatments (Table 6.16, Figure 6.11).

Table 6.16. Significance levels of each treatment factor on sediment-bound P in runoff, derived from full factorial and one-way ANOVA.

		Full factorial ANOVA factors			**One-way ANOVA**
Dependent variable	**Sampling Period**	**SSD type (MPP, Non-SSD, WT, NSLT)**	**Mulch (St/No Mulch)**	**SSD and mulch (two-way interaction)**	**Individual treatment type**
Sediment-bound total P concentration (mg kg^{-1})	1	0.11	<0.01*	0.46	0.01*
	3	0.37	0.03*	0.32	0.15
	5	0.58	0.46	0.46	0.70

Results of full factorial ANOVA presented are across all treatment types.
*denotes a statistically significant result (p ≤ 0.05).

St significantly reduced sediment-bound P by 30 % in Sampling Period 1 as compared with No mulch treatments (Appendix C.3, Table_Apx C-7). This was reflected in differences between individual treatments in Sampling Period 1 with a significant reduction in sediment-bound P from MPP St and Non-SSD St treatments by 35 and 45

% respectively as compared with the Non-SSD Control (Figure 6.11). However, in Sampling Period 3 St resulted in a significant 10 % increase in sediment-bound P.

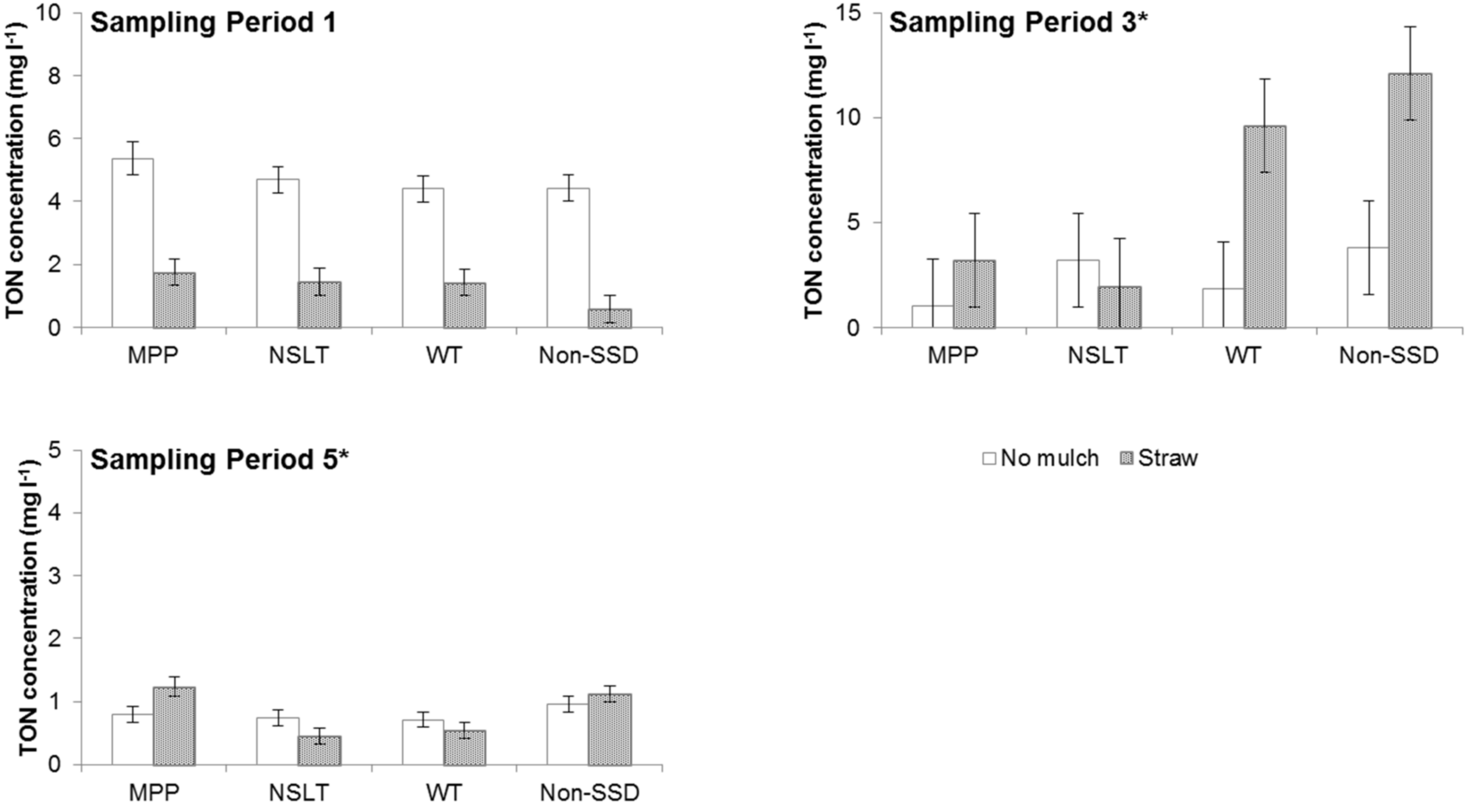


Figure 6.9. Mean concentration of TON (mg l^{-1}) in runoff for the three tested Sampling Periods. Error bars show ± 1 SE. For statisitical differences between treatments see Appendix C.3, Table_Apx C-3. *Scales on the y axis vary.

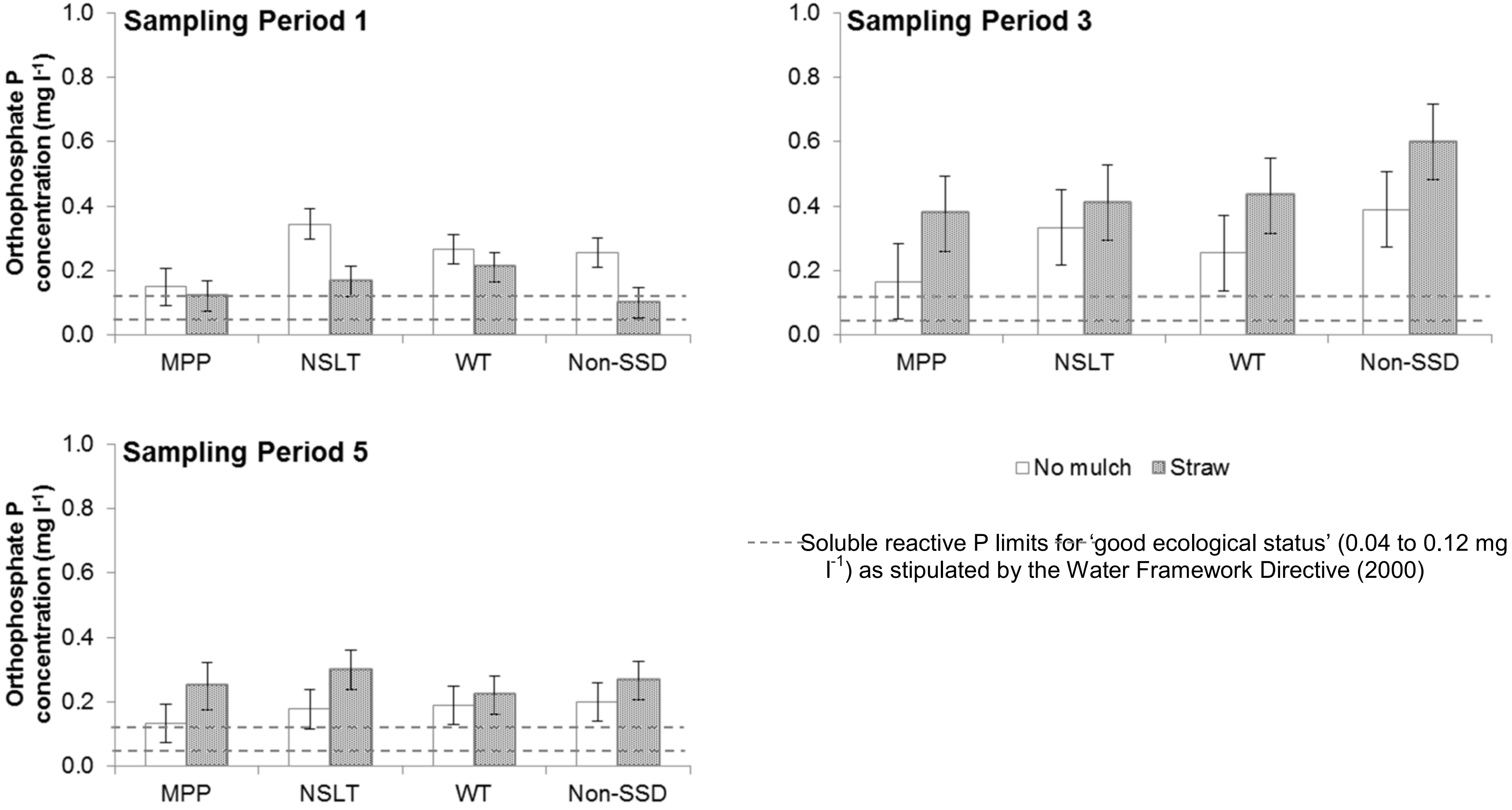


Figure 6.10. Mean concentration of Orthophosphate P (mg l^{-1}) in runoff for the three tested Sampling Periods. Error bars show ± 1 SE. For statisitical differences between treatments see Appendix C.3, Table_Apx C-3.

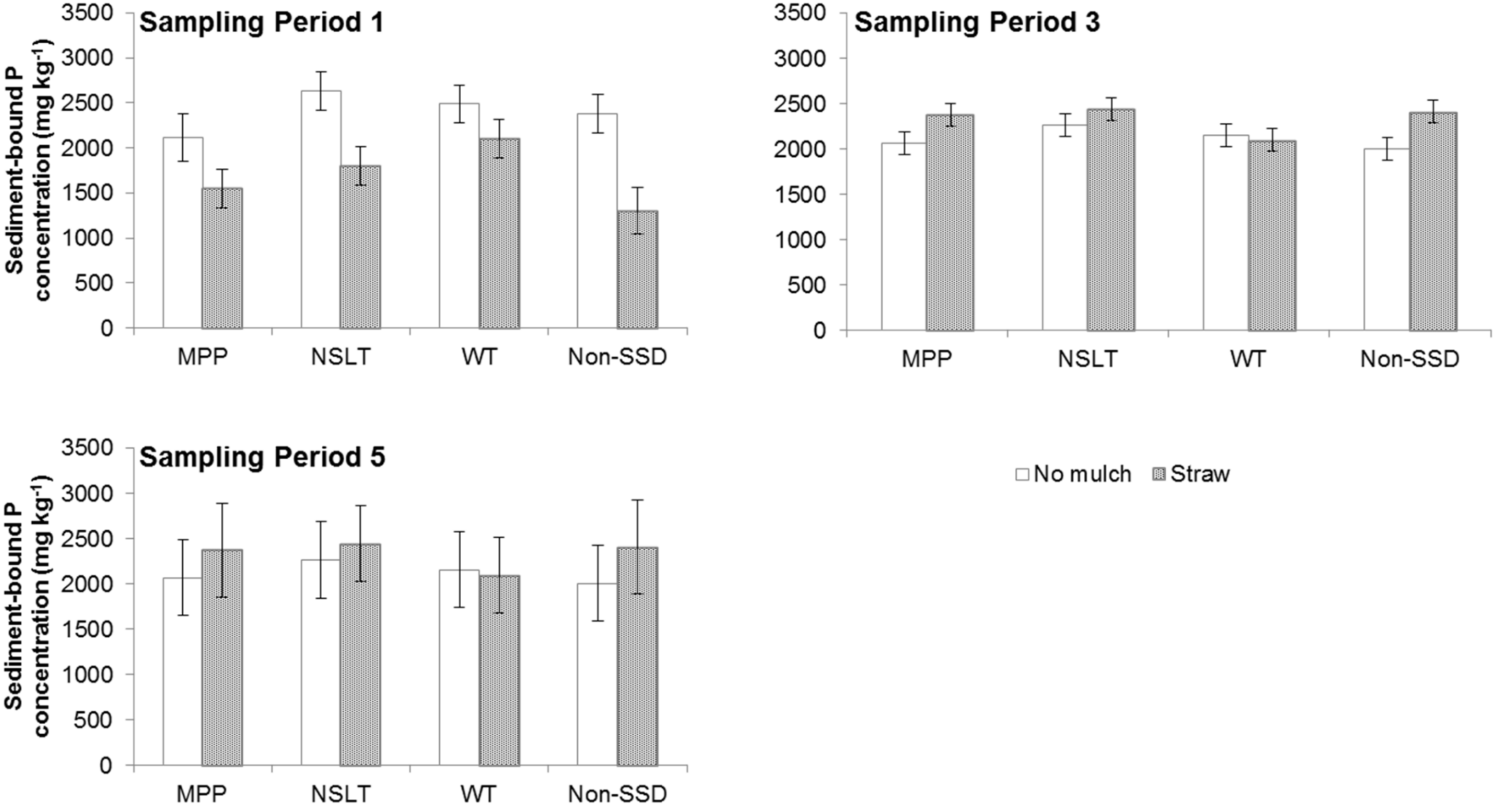


Figure 6.11. Mean concentration of sediment-bound P (mg kg^{-1}) in runoff for the three tested Sampling Periods. Error bars show ± 1 SE. For statisitical differences between treatments see Appendix C.3, Table_Apx C-3.

6.3 Discussion

The effectiveness of individual treatments was ranked based on the treatment means for each performance indicator; total runoff volume, total soil loss and sediment, TON, orthophosphate-P and sediment-bound P concentration in runoff. This was carried out across both each Sampling Period (Table 6.17) and overall for the entire Phase 2 sample collection period (Table 6.18) so that differences in performance and reliability could be clearly identified. Across each Sampling Period, the lowest means were assigned a rank of 1 and the highest means a rank of 10. The mean treatment rank was then calculated for each performance indicator across all Sampling Periods to indicate overall performance (Table 6.17). These means were then tabulated for each treatment and a mean rank calculated across all performance indicators (Table 6.18).

Across all Sampling Periods, the most reductions were observed from MPP No Mulch, MPP St and NSLT St treatments. MPP No Mulch most reduced runoff volume and orthophosphate-P concentration, MPP St most reduced TSL and sediment-bound P and NSLT St most reduced sediment and TON concentration (Table 6.17). Overall, NSLT St ranked as the most effective treatment followed by MPP St and WT St, whilst Non-SSD No Mulch was the least effective treatment (Table 6.18).

Table 6.17. A ranked summary of the effectiveness of individual treatments on each performance indicator. Differences in rank are based on differences in mean values. Lower scores mean the 'best' treatment.

Performance Indicator	Treatment code	Sampling Period				Mean
		1	2	3	5	
Total runoff volume	MPP No mulch	1	4	2	3	2.5
	Non-SSD Control	4	6	8	6	6.0
	WT No mulch	6	8	3	1	4.5
	NSLT No mulch	5	2	4	7	4.5
	MPP St	3	7	6	4	5.0
	Non-SSD St	2	1	1	8	3.0

Performance Indicator	Treatment code	Sampling Period				Mean
		1	2	3	5	
	WT St	8	3	7	5	5.8
	NSLT St	7	5	5	2	4.8
Total soil loss	MPP No mulch	5	7	8	5	6.3
	Non-SSD Control	8	8	5	8	7.3
	WT No mulch	6	6	6	4	5.5
	NSLT No mulch	7	5	7	6	6.3
	MPP St	2	2	1	2	1.8
	Non-SSD St	1	3	4	7	3.8
	WT St	3	1	2	3	2.3
	NSLT St	4	4	3	1	3.0
Runoff sediment concentration	MPP No mulch	8	7	7	5	6.8
	Non-SSD Control	6	8	8	6	7.0
	WT No mulch	5	6	5	3	4.8
	NSLT No mulch	7	5	6	7	6.3
	MPP St	4	2	1	8	3.8
	Non-SSD St	1	3	4	4	3.0
	WT St	2	4	3	2	2.8
	NSLT St	3	1	2	1	1.8
TON concentration	MPP No mulch	8		1	5	4.7
	Non-SSD Control	6		6	6	6.0
	WT No mulch	5		2	3	3.3
	NSLT No mulch	7		4	4	5.0
	MPP St	4		5	8	5.7

Performance Indicator	Treatment code	Sampling Period				Mean
		1	**2**	**3**	**5**	
	Non-SSD St	1		8	7	5.3
	WT St	2		7	2	3.7
	NSLT St	3		3	1	2.3
Orthophosphate-P concentration	MPP No mulch	3		1	1	1.7
	Non-SSD Control	6		5	4	5.0
	WT No mulch	7		2	3	4.0
	NSLT No mulch	8		3	2	4.3
	MPP St	2		4	6	4.0
	Non-SSD St	1		8	7	5.3
	WT St	5		7	5	5.7
	NSLT St	4		6	8	6.0
Sediment-bound P concentration	MPP No mulch	5		2	7	4.7
	Non-SSD Control	6		1	5	4.0
	WT No mulch	7		4	4	5.0
	NSLT No mulch	8		5	6	6.3
	MPP St	2		6	1	3.0
	Non-SSD St	1		7	8	5.3
	WT St	4		3	3	3.3
	NSLT St	3		8	2	4.3

Table 6.18. Overall rank for each treatment performance indicator across all Sampling Periods based upon data presented in Table 6.17. Lower scores mean the 'best' treatment.

Treatment	Performance indicator						
	Runoff volume	TSL	Sediment concentration	TON concentration	Orthophosphate-P	Sediment-bound P	Mean
MPP No mulch	3	6	7	5	2	5	4.4
Non-SSD Control	6	7	7	6	5	4	5.9
WT No mulch	5	6	5	3	4	5	4.5
NSLT No mulch	5	6	6	5	4	6	5.4
MPP St	5	2	4	6	4	3	3.9
Non-SSD St	3	4	3	5	5	5	4.3
WT St	6	2.25	3	4	6	3	3.9
NSLT St	5	3	2	2	6	4	3.7

6.3.1 Runoff volume

No significant differences were found between treatment effect (SSD type, mulch type or interactions between the two) and individual treatment type (one-way ANOVA) on runoff volume. This was a result of highly variable hydrological responses between treatment replicates. Results suggest that infiltration was variable with some treatments associated with 50 % (non-significant) reductions in runoff volume as compared with the Non-SSD Control (Figure 6.4).

The non-significant differences observed from SSD and Non-SSD treatments alike could have resulted from plots becoming inundated by the high intensity rainfall events observed, with rain falling at a greater rate than infiltration. This could have limited any SSD effect and result in equal runoff volumes from all treatments. Furthermore the kinetic energy of the high intensity rainfall could have accelerated the temporal degradation of the SSD effectiveness (Rao et al., 1998). However, some reductions in runoff volume from MPP, WT and NSLT treatments as compared with Non-SSD treatments occurred in Sampling Period 5 suggesting that the SSD effect has not been entirely degraded. This is not supported by field observations (Appendix C.5, Figure_Apx C-2).

The lack of effectiveness observed in runoff volume reduction from St treatments goes against findings of the proof of concept field trials (Niziolomski, 2011). Furthermore, it contradicts the findings of many other studies (Gholami et al., 2012, Brown and Kemper, 1987, Silgram et al., 2010, Jiang et al., 2011 and Jordán et al., 2010) in which percentage reductions of runoff from St were observed. However, this could be a result of the continual rearrangement of St into the wheelings by the foot-traffic of hand-harvesters (between late April and late June) in wet weather conditions, particularly over Sampling Period 2 where 54 mm of rainfall was received over the final month of harvest. This would have degraded St treatments, reducing the effectiveness of mulch in slowing and reducing runoff. Previous studies, with the exception of Niziolomski (2011), were not subject to foot-traffic, with plots completely isolated during testing. Furthermore, Niziolomski (2011) only captured the final month of harvest in which little rainfall was received and so less rearrangement during this period may have occurred. One further possibility is that in Phase 2 the rainfall volume was so high that the occurrence of sheet runoff masked the effect of surface applied mulch making all treatments equal (Cattan et al., 2006).

6.3.2 Event-driven hydrological response

Few significant differences were observed in the event-driven hydrological response of treatments based on one-way ANOVA results. This is due to the high degree of within treatment variation in plot responses. Furthermore, the homogenous nature of the data shortly after rainfall initiation suggests that other, untested variables are affecting treatment response. Several factors are known to be uniform across all treatments. These include the rainfall received, plot catchment area and the plot slope gradients. Furthermore, soil property tests carried out on the randomly distributed control plots showed similar characteristics in organic matter, particle size distribution and bulk density. This suggests that the differences could be attributed to the effect of foot-traffic in wet weather conditions as discussed in Section 6.3.1.

Some significant differences in runoff rate were observed for a limited period of time. WT and MPP No mulch and Non-SSD St significantly delayed runoff during Sampling Period 2 RE_1. When tested in the Soil Bin, both WT and MPP generated the largest area of below ground disturbance significantly exceeding that of the NSLT tine (Chapter 5). This could account for the delay in runoff as water first infiltrates and becomes stored below ground. The stored water is unable to infiltrate further as a result of the compaction to depth. Therefore once the below ground storage has reached capacity runoff is initiated from the plots (Rao et al., 1998; Blough et al., 1990).

The delay observed from Non-SSD St can be attributed to the effect of St as discussed in Chapter 4. Similar delays in runoff from wheat straw have been observed by Jordán et al. (2010) and from rice straw mulch by Gholami et al. (2012) and Rao et al. (1998). The effectiveness of St without SSD on runoff rate in this instance could relate to the smooth soil surface beneath (Non-SSD) allowing a freer movement than when it is placed on top of a rougher SSD soil surface. In this case St can move and rearrange with the runoff and re-align to form mini dams for surface water storage. Similar results were observed by Tatham (1989), where surface mulch alone had a greater reduction in runoff volume as compared with MPP with straw. Contrary to this, Foster et al. (1982a) observed a similar straw movement across tilled and untilled soils. However, the untilled component of the trial was not replicated and although not measured the roto-tiller used does not generate much above ground disturbance that could affect straw movement. Rao et al. (1998) conducted a triplicated trial and showed no difference between tilled and untilled plots using a duck foot tine (comparable to the WT) at 100 and 200 mm depths.

In Sampling Period 5 an increased runoff rate is evident post rainfall cessation from NSLT No mulch, MPP St and WT St. This acceleration suggests that runoff is being slowed by the effect of surface roughness and improved infiltration.

6.3.3 Total soil loss

The key treatment factor found to most consistently reduce total soil loss was the addition of St irrespective of SSD treatment. This meant a significant reduction in TSL over the combined Sampling Periods from all St treatments as compared with the Non-SSD Control. MPP St was associated with the greatest reduction of 87 %. Straw effectiveness irrespective of SSD type was also observed in Sampling Period 1, 2 and 3. This highlights the importance of detachment in the erosion process (Evans, 1980) as St protects the vulnerable soil from detachment by rainfall. This protective cover negates the potential for loosened soil from SSD becoming entrained and transported downslope. The effectiveness of St alone corroborates the findings of many other studies that have shown similar significant reductions in TSL with similar St application rates (Brown and Kemper, 1987; 3 and 4.5 t ha^{-1}, Brown et al., 1998; 7.8 t ha^{-1}, Döring et al., 2005; 5 t ha^{-1}, Rees et al., 2002; 4.5 and 9 t ha^{-1}). Other studies have found similar reductions using lower St application rates (Berg, 1984; 0.6, 1.2 and 2.2 t ha^{-1}; Holstrom et al., 2008; 2.25 and 3.5 t ha^{-1}; Griffin and Honeycott, 2009; 1.5 t ha^{-1}).

The lack of a consistent effect of SSD on TSL in the presence of St can also be corroborated in the literature. Tatham (1989) investigated a very similar implement to the MPP used in this study with a lower St application rate (2.5 t ha^{-1}) and found that soil loss was most significantly reduced by St treatments, followed by MPP St treatments and then by MPP No Mulch treatments. In this current study, although MPP did not significantly reduce TSL at the individual Sampling Periods, the MPP St treatment did result in the most significant reduction in overall TSL as compared with the Non-SSD Control. It is also of note that there was no significant difference between Non-SSD St and MPP St in overall TSL values. Significant increases in TSL have also been observed once mulch had been removed from SSD treatments (McGregor et al., 1990; Rao et al., 1998; Holstrom et al., 2008). This could be accounted for by the short-lived effect of SSD on infiltration as shown in mean time to runoff initiation in Sampling

Period 2 discussed in Section 6.3.2, and also observed by Rao et al. (1998) and Cattan et al. (2006).

6.3.4 Pollutant load

6.3.4.1 Sediment concentration in runoff

As expected, the sediment concentration in runoff was as significantly reduced by St as TSL. This is because TSL was partially derived from sediment concentration results. Further to this, a significant effect on sediment concentration was also observed with SSD. In Sampling Period 1, MPP treatments (St and No mulch) increased sediment concentration by 68 % as compared with Non-SSD treatments and 64 % as compared with WT treatments (Appendix C.3, Table_Apx C-4). In the Soil Bin, the MPP generated a significantly greater area of above and below ground disturbance as compared with the WT. Surface roughness is known to degrade with successive rainfall events (Idowu et al., 2002). By the end of Sampling Period 1 (30th May – 6th June) almost 70 mm of rainfall had been received on-site. These results suggest that MPP surface roughness had been degraded through the process of entrainment and transport of the loosened soil. Given that MPP had previously shown a greater area of disturbance the loosened soil may have already been eroded from WT plots whilst in MPP plots more remained, thus generating the 64 % difference. Results also suggest that multiple legged tines increased the risk of runoff sediment concentration initially with no significant difference between MPP and NSLT irrespective of mulch.

6.3.4.2 Total oxides of nitrogen

The addition of St was observed to both positively and negatively affect TON concentration in runoff. When St is applied the protection provided to the soil surface reduces the TON concentration in runoff. This is supported by Non-SSD St generating the greatest reduction in TON. However, post Sampling Period 1 the opposite effect was observed. The increase in TON concentration observed between Sampling Period 1 and 3 can be attributed to the routine on-site application of N fertiliser (69.16 kg) undertaken on the 26th June, half way through Sampling Period 2. With the addition of fertiliser, the St treatments generated significantly higher TON concentrations in runoff. This effect was not observed in the Phase 1 field trials post fertiliser application. However, in Phase 1 St was partially incorporated whilst in Phase 2 it was not. This could mean that the St in Phase 2 was associated with more of a blanket effect not allowing applied fertiliser to dissolve and infiltrate into the soil. Instead it was dissolved in the runoff as it flowed over the mulch surface. Phase 2 also had greater rainfall intensities than Phase 1, therefore St TON concentrations could also have been attributed to rainfall falling at such an intensity that runoff could not percolate through the St instead it flowed over the St as sheet flow (Cattan et al., 2006) solubilising the applied N with it. Faucette et al., (2007) observed a similar increase in Total N when applying straw blanket mulch combined with N fertiliser.

Whilst St increased the TON concentration in runoff following fertiliser application, SSD treatments reduced it. A reduction in TON concentrations with tillage has been observed previously by Silgram et al. (2010) on tramlines and in olive orchards by Francia et al. (2006). However, in the absence of reliable infiltration data in this current study the reduction could relate to a greater area of above ground loosened soil that has become re-organised by foot traffic. This could increase the surface area over which the runoff passes giving more time for applied TON to dissolve and become stored on the soil surface in surface depressions (Burwell et al., 1966).

6.3.4.3 Orthophosphate-P

Only the addition of St was observed to reduce orthophosphate-P in runoff. Straw has been observed in many studies to have the effect of reducing nutrient concentrations in runoff as a result of surface protection (Silgram et al., 2010; Rees et al., 2002). Similar to TON, orthophosphate-P results increased from Sampling Period 3, with St generating the greatest increase and most significantly in Sampling Period 5. However, no on-site application of P was recorded. Whilst this is not typically found in literature, Rees et al. (2002) observed a one-off increase in Total P from straw applied for the fourth consecutive year at a high rate of 9 t ha^{-1}. This was deemed to be the result of the accumulated residual fertiliser contained in the straw. Although St in this current study had not been applied for such an extended period of time, results suggest that St is the source of the P. The effect of intense rainfall at high depths and durations in Sampling Period 3 and 5 combined with foot-traffic could have caused St to have moved to such an extent that a great area of soil was exposed resulting in sediment-bound P reserves becoming solubilised.

6.3.4.4 Sediment-bound P

Straw was again the only treatment resulting in a positive effect on sediment-bound P. This is a result of the protection effect previously described preventing sediment from becoming detached. This effect was particularly significant in Sampling Period 1 when treatments were relatively fresh and in-tact. However, in Sampling Period 3 sediment-bound P increased by 10 % across all St treatments as compared with No Mulch treatments. This suggests that a greater area of bare soil was exposed and subject to detachment by rainfall resulting in higher rates of detachment and provision of material available for transport.

6.4 Conclusion

The following sub-hypotheses were tested in Phase 2.

a. Tine configuration (geometry and arrangement) can significantly affect runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no soil disturbance.
b. Tine configuration (geometry and arrangement) in combination with mulch can significantly affect runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no soil disturbance and no mulch.

The tested sub-hypotheses can be rejected as in general, SSD (irrespective of tine configuration, with and without St) was ineffective at reducing key performance indicators (runoff volume, rate, total soil loss, sediment concentration, TON, orthophosphate-P and sediment-bound P). However, both MPP and WT without mulch improved runoff initiation and TON concentration for one Sampling Period.

Soil erosion across the Phase 2 sample collection period can be dramatically reduced with the surface application of St to wheelings at 6 t ha^{-1}. Of these treatments MPP St resulted in the greatest reduction. NSLT St was the most reliable treatment to improve key performance indicators. Out of four total Sampling Periods, St mulch improved runoff cumulative volume and rate once, total soil loss once, sediment concentration three times, TON twice and orthophosphate-P and sediment-bound P once. Despite the effectiveness of St treatments, sediment concentration was not reduced to such a level that could be potentially harmful to receiving water bodies.

7 SYNTHESIS, ECONOMIC APPRAISAL AND CONCLUSION

7.1 Synthesis

This research has sought to address soil erosion management in asparagus production systems. This on-site problem arises as a result of historical potato production resulting in compaction to a depth of 0.5 m. This has been further exacerbated by asparagus production practices in which large areas of erodible soil are exposed to rainfall for 65 % of the year, including over winter. Beds are also covered with plastic cloches for up to 5 months of the year concentrating rainfall runoff into the wheelings. The wheelings are heavily foot-trafficked by hand-harvesters for two months of the year in all weather conditions generating surface compaction and smearing. Wheelings are further subject to compaction from field operations of bed formation, cloche installation and removal and fern chopping. The problems of runoff generation and associated soil erosion have been addressed in three experimental programmes that set out to test several sub-hypotheses. Phase 1 and Phase 2 field trials were undertaken in a dynamic farm environment with treatments subject to the normal operations associated with an asparagus production system.

7.1.1 Phase 1 field trials

Phase 1 tested sub-hypotheses a, b and c using replicated field trials treated with Non-SSD and SSD in combination with mulch (Cp/chopped St) applied at high and low rates and partially incorporated when combined with SSD. Results showed that Non-SSD St^H resulted in the most significant and consistent improvements in runoff volume and associated nutrient and sediment loads, allowing sub-hypothesis b (that the application of mulch materials can significantly reduce runoff volume, and associated nutrient and sediment loads compared with control plots with no mulch application) to be accepted. The nature of Cp did not allow for effective erosion control under the tested conditions and application rates. SSD was not found to significantly reduce runoff and associated nutrient and sediment loads and therefore sub-hypothesis a (that shallow soil disturbance alone can significantly reduce runoff volume and associated nutrient and sediment loads in an asparagus production system, compared with control plots with no shallow soil disturbance) was rejected. Significant reductions were evident from SSD treatments in combination with St^H and Cp^H however only in TSL therefore sub-hypothesis c (that the application of mulch materials in combination with shallow soil disturbance can significantly reduce runoff volume, and associated nutrient and sediment loads, compared with control plots with no mulch application and no shallow soil disturbance) was also rejected. This reduction effect in TSL did not match the consistency of that observed in Non-SSD St^H through all Sampling Periods, with SSD St^H reductions only evident up to Sampling Period 2.

Overall, the results showed that soil erosion can be dramatically reduced in asparagus production. However, over five months, total soil loss remained in excess of annual tolerable erosion (1.4 t ha^{-1}), as well as sediment concentration exceeding environmental guidelines. This suggests that if used alone under field conditions other supporting mitigation measures will be needed to bring soil loss to a sustainable level.

7.1.2 Soil Bin experimental programme

In the Soil Bin, soil disturbance properties of the currently adopted SSD were tested against other tines. Shallow soil disturbance was observed to result in a change in soil properties with all tine configurations. However, significant differences in the degree and extent of soil disturbance and draught force and specific draught tine were observed between the currently adopted tine (WT) and other tested tine configurations. Therefore the tested sub-hypothesis d (that tine configuration - geometry, arrangement and depth of operation - can significantly change the degree and extent of soil disturbance and affect implement dynamics as compared with the currently adopted tine) was accepted. Furthermore, results showed that the currently adopted WT compares unfavourably to the MPP at the current cultivation depth (175 mm). Therefore the design of the currently adopted winged tine is compromising its soil disturbance potential.

The observed changes in soil properties will lead to a different soil system response to rainfall, affecting runoff and erosion control. Based on the results of this study, on-site erosion control potential could be improved by using the MPP at the current depth of cultivation. Where root damage is not a concern, such as in recently planted asparagus fields with limited root development, or for non-asparagus row crops, erosion control could be further improved by increasing the depth of cultivation. In this case, the NSLT (at 250 mm) and the WSLT (at 300 mm) would be the most effective for compaction alleviation and thus erosion control.

7.1.3 Phase 2 field trials

Phase 2 tested sub-hypotheses e (that tine configuration -geometry and arrangement- can significantly affect runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no soil disturbance) and f (that tine configuration -geometry and arrangement- in combination with mulch can significantly affect runoff volume, and associated nutrient and sediment loads in an asparagus production system, as compared with control plots with no soil disturbance and no mulch). These were tested using replicated field trials treated with surface applied St (0 and 6 t ha^{-1}) in combination with three tine configurations (MPP, NSLT, WT) identified as effective for soil disturbance in the Soil Bin experimental work as well as a Non-SSD control.

Tine configurations demonstrated very few significant effects as compared with the Non-SSD Control on performance indicators (runoff volume, total soil loss, sediment concentration, TON, orthophosphate-P and sediment-bound P) across all Sampling Periods. This meant that sub-hypothesis e. was rejected. SSD in combination with mulch showed limited significant effects on TON concentration and no significant interaction effects between treatments. This meant that sub-hypothesis f. was also rejected. St mulch applied at 6 t ha^{-1} irrespective of SSD showed the most significant reductions in runoff volume, total soil loss, sediment concentration, TON, orthophosphate-P and sediment-bound P.

In this study no treatments produced sufficient total soil loss to exceed the tolerable soil erosion limit within the trial period. However, measured sediment concentration still exceeded guideline values.

7.1.4 Phase 1 and 2 field trial interrelations

Both field trials demonstrate that St applied in isolation can control runoff and erosion from asparagus fields. However, in Phase 1 total sol loss still remains higher than the tolerable soil erosion rate. This was most likely a result of larger plot sizes, greater slope gradients and extreme rainfall conditions (exceeding the 30 year average). Furthermore, both field trials generate sediment concentrations that exceed guideline values that could result in river level sediment concentrations breaching the annual requirements under the Water Framework Directive. Values associated with soil loss and sediment concentration are greater in Phase 1 as compared with Phase 2. This is most likely the result of lower runoff volumes between both trials, with Phase 2 generating 3 times less runoff volume than Phase 1. These differences could be a result of different rainfall characteristics (Table 7.1) with Phase 1 treatments subject to long periods of relatively low intensity rainfall, and Phase 2 treatments subject to short periods of high intensity rainfall. Furthermore Phase 2 used shorter and shallower slopes that would have reduced runoff volume and runoff velocity, affecting detached soil entrainment and transport.

Table 7.1. Sampling Period rainfall characteristics of each field trial phase.

	Sampling Period rainfall characteristics			
Field trial phase	**Mean rainfall event duration (mins)**	**Range of rainfall depths (mm)**	**Range of mean rainfall intensity (mm hr^{-1})**	**Range of maximum rainfall intensity (mm hr^{-1})**
Phase 1	21	25.8 - 149	12 – 15	24 - 96
Phase 2	10	3.6 - 48	54 - 124	588 - 792

N.B. Intensity calculations based on a 1 minute data logger readings.

In Phase 1 a difference in effect between SSD St and Non-SSD St treatments was evident that was not observed in Phase 2. This could be a result of differences in treatment application. In Phase 1 St was chopped and surface applied prior to SSD. With SSD, the St became partially incorporated. Therefore, SSD mulched plots were testing the effects of both SSD and the partial incorporation of St. However, in Phase 2 St was surface applied post SSD making any differences observed accountable to just the effect of SSD alone. In which case it would suggest that surface applied St at 6 t ha^{-1} negates the effect of SSD. Furthermore, St applied to the surface is an effective runoff and erosion control measure across different rainfall conditions.

7.1.5 Soil Bin and Phase 2 field trial interrelations

The differences observed in soil disturbance in the Soil Bin between the MPP, WT and NSLT did not manifest into significant differences in soil system response to rainfall in the Phase 2 field trials. However, this does not necessarily mean that no differences exist between tines, particularly as no difference was observed between Non-SSD and SSD treatments both with and without mulch. This suggests that compaction alleviation is not a necessary part of runoff and erosion control in this study. However, early on, differences in runoff associated with the MPP were initially observed. This (in combination with the Phase 1 effectiveness of SSD as compared with Non-SSD with incorporated St) suggests that to be effective, mulch is needed to keep the SSD open but not to completely cover it.

7.2 Economic appraisal

Phase 1 and Phase 2 trials have tested the effectiveness of soil management practices in controlling runoff and soil erosion (Chapters 4 and 6). However, the financial cost of these practices is yet to be determined in the present study. Using available agricultural contract work costing resources (NAAC, 2014; AgriContractor.com), the financial implications of adopting these practices have been calculated. Furthermore, some of the potential costs of not implementing these practices have also been calculated.

7.2.1 Soil management costing

The cost of applying soil management has two components; the materials cost and the cost of treatment application. These costs were estimated on a hectare basis in line with other research (Newell Price et al., 2011; Rickson et al., 2010) to standardise the results so they are applicable to any field/farm size.

From the initial calculated mulch application rates (Appendix A.1); the true rate of straw and compost mulch required per hectare of asparagus field was first calculated by ascertaining the maximum area of wheelings within 1 hectare (Table 7.2). This area was subsequently multiplied by the mulch application rate (t m^2) to give a total rate of mulch required per hectare. Finally this value was multiplied by the material cost (£ t^{-1}) of the mulch used to give a total mulch cost (£ ha^{-1}) (Table 7.3). This cost does not take into account transport costs so unless the mulch is available very locally the total value is most likely to be an underestimate.

Table 7.2. Calculation of the maximum wheeling area within 1 ha.

1. Number of asparagus beds in 100 m[†]

= 100m / 1.5 m[‡]

= approximately 66 beds

2. Maximum run length of wheeling area.

= 0.4 m^2[*] x 100 m

= 40 m^2

3. Maximum potential wheeling area.

= 40 m^2 x 66

= 2640 m^2

[†]Assuming a square field of 100 m × 100 m. [‡]Raised bed spacing. [*]Approximate wheeling width.

Table 7.3. Calculation of mulch costs.

Mulch type and application rate[†]	**Mulch cost (£ t^{-1})**[‡]	**Total mulch cost (£ ha^{-1})**
Straw		
3 t ha^{-1} (0.8 t ha^{-1})	31.81	25.45
6 t ha^{-1} (1.6 t ha^{-1})	31.81	50.90
Compost		
7 t ha^{-1} (1.8 t ha^{-1})	6.00	10.80
15 t ha^{-1} (4.0 t ha^{-1})	6.00	24

[†]Application rates shown in brackets indicate the total rate per ha when applied only to the wheelings. [‡]Wheat straw price (big square baled) sourced from Farmers Weekly (2014) based on British Straw and Hay Merchants' Association prices for week ending 26/10/14 averaged for all UK areas. Price for PAS 100 Quality Compost, 20 – 40 grade sourced from Quality Garden Supplies Ltd (2014).

With regard to the costs of applying the mulch, NAAC (2014) costs farmyard manure (FYM) spreading at £36 hr^{-1}. This includes labour, machinery costs and fuel (based on red diesel prices of 70 ppl). This was deemed to be the most similar operation to St and Cp spreading in the absence of a cost for a straw blower similar to that used in Phase

1, or a suitable machine for spreading Cp into the wheelings. However, the area included in the cost was not stated. This had to be approximated using other resources (Table 7.4). Using an online agricultural contractor rates estimator (AgriContractor.com), FYM spreading was calculated for a 30 acre area (acres were the only available unit). The resulting value was divided by the NAAC (2014) cost rate (£36 hr^{-1}) to ascertain the duration (hours) taken for the practice to be carried out. This value was divided by 30 to ascertain the length of time required for a single acre, and then converted for a single hectare. Finally, the original NAAC contractor rate (£ 36 hr^{-1}) was divided by the time required to apply materials for one hectare, resulting in an estimated cost of £ 12.37 ha^{-1}.

Table 7.4. Calculations of the application cost associated with spreading mulch.

FYM spreading tractor and side discharge contracting rate.[1]	£ 36.00 hr^{-1}
Agricultural contract estimate for 30 acres of FYM spreading tractor and rear discharge.[2]	£ 1282.50
Time required to complete the contract estimate (calculated using the known £ 36 hr rate).	35.62 hr
Time required for one acre.	1.18 hr
Time required for one hectare.	2.91 hr
Approximate cost per hectare.	£ 12.37 ha

[1] NAAC Contracting Charges 2013/14 (2014) based on red diesel pricing at 70 ppl.
[2] AgriContractor.com (2014) based on FYM spreading tractor rear discharge.

For the calculation of the Phase 1 SSD treatment, a standard cost was sourced from NAAC Contracting Charges 2013/2014, as all treatments used the same tine configuration. The closest operation was taken to be “ploughing light soil”, which was listed at £ 23 acre (£ 56.81 ha^{-1}). This cost includes labour, machinery and fuel (based on red diesel prices of 70 p l^{-1}).

For the calculation of the Phase 2 SSD treatments, the draught force of the respective tine configurations measured in the Soil Bin at Cranfield University were used to estimate the fuel requirement. Fuel requirement was first calculated using (Equation 8). Several assumptions were used in the calculation; a slip value ratio of 0.1, transmission loss of 0.8 and a thermal input factor of 3 (personal communication with K. Blackburn, 2014). The resulting fuel requirement (Table 7.5) was then multiplied by the time taken (seconds) to cultivate the maximum asparagus inter-bed wheeling length contained within 1 ha (Table 7.6). This value was multiplied by a red diesel cost of 70 p l^{-1} as used in NAAC (2014) to give a total fuel cost (£ ha^{-1}). A labour cost was added to the total fuel cost based upon the time taken to cultivate 1 hectare (3.2 hrs, Table 7.6) at a rate of £ 8 hr^{-1} (personal communication with H. Chinn, 2014). This final value does not take into account machinery costs for the tractor, as these costs excluding fuel could not be found. Furthermore the machinery costs for the tine configuration were also excluded, and therefore the total costs estimated can be considered to be an underestimate of the true cost. It is important to note that the fuel cost used in this calculation is based upon the test conditions of the Soil Bin; i.e. cultivation of a ‘light’ soil operating at 175 mm depth at a speed of 0.58 m s^{-1} (2.1 km hr^{-1}), soil moisture content of 8 %, and bulk density of approximately 1.6 g cm^{-3}. The total costs of soil management implementation for each treatment are presented in Table 7.9 and Table 7.10.

Fuel requirement (l s^{-1}) = (((F x S / 1 – s) / Tr) x Th) / Se **(Equation 8)**

Where F = draught force (N), S = speed (m s^{-1}), s = slip ratio, Tr = transmission loss percentage, Th = Thermal input power factor, SE = specific energy of diesel (J l^{-1}). Source: Personal communication with K. Blackburn, 2014).

Table 7.5. Calculated fuel requirement for Phase 2 tine configurations. For full calculations see Appendix D.1.

Tine configuration	Fuel requirement (l s^{-1})
MPP	1.38 $\times10^{-4}$
NSLT	1.12 $\times10^{-4}$

Tine configuration	Fuel requirement (l s^{-1})
WT	1.69 x10^{-4}

Table 7.6. Calculation of the time taken to cultivate the wheelings contained within 1 hectare.

1. Number of asparagus beds in 100 m[†]

= 100 m / 1.5 m[‡]

= approximately 66

2. Total length of wheelings

= 66 x 100 m

= 6600 m

3. Time taken to cultivate

= 6600 m / 0.58 m[*]

= 11379 seconds (3.2 hours)

[†] Assuming a square field of 100 m × 100 m. [‡] Raised bed spacing. [+] Approximate wheeling width. *Length of wheeling cultivated per second, based on the tine speeds used in the Soil Bin.

7.2.2 Soil erosion costing

Graves et al. (2011) estimated the total cost of soil erosion in England and Wales. The costs relate to the consequences of soil erosion in terms of the loss of soil ecosystem services listed in Table 7.7. Using this approach, it was possible to approximate a cost of each tonne of soil eroded (Table 7.8), based upon the reported annual soil erosion in England and Wales of 2.9 Mt (Graves et al., 2011). The potential cost per tonne of lost soil due to erosion (£ 60.37) was then applied to the measured soil loss (t) of each Phase 1 and 2 treatments to give a total estimated cost of soil loss per treatment (Table 7.9 and Table 7.10). The difference between the soil loss cost and the Non-SSD Control for each treatment was calculated and the cost of soil management subtracted. This gave a total cost saving for each treatment (Table 7.9 and Table 7.10). Finally a unit cost for each treatment was calculated by dividing the cost of soil management by the difference in soil loss as compared with the Non-SSD Control. This provided a standardised value (£ t^{-1}) for the cost of soil management per unit of soil conserved that could be used to select the most cost effective treatment (Table 7.9 and Table 7.10).

Table 7.7. Soil ecosystem services and associated erosion impacts and costs, adapted from Graves et al. (2011).

Ecosystem service group	Service type	Erosion impacts
Provisioning†	Crop productivity	Loss of soil depth.
	Soil nutrient stock	Nutrient loss (N, P, K).
	Soil carbon stock	Carbon loss.
Regulating‡	Clean drinking water	Higher concentration of nutrients in incoming water.
	Flood prevention	Increased sediment in rivers, reservoirs and urban drainage systems.
	Clean air (greenhouse gas emissions)	Soil carbon lost to the atmosphere.
Cultural‡	Leisure and tourism	Increased N and P in rivers and lakes reducing fish populations.
	Aesthetically pleasing landscapes	Eutrophication of water bodies results in large algal blooms.

†On-site costs of erosion ‡Off-site costs of erosion

Table 7.8. Calculated cost of soil loss (£ t^{-1}) in England and Wales, based on data presented in Graves et al. (2011).

Total soil loss (t yr^{-1})	Total cost of soil loss (£ yr^{-1})	Cost of soil loss (£ t^{-1})
2.9 million	176.3 million	60.37

7.2.3 Economic appraisal findings

Cost savings afforded by implementation of soil management measures were only evident in Phase 1 (Table 7.9). In Phase 2, soil losses were negligible and as such the costs of soil management measures exceeded the cost benefit of reducing soil loss (Table 7.10). In Phase 1, the application of Non-SSD St^H under the climatic and soil conditions observed during the Phase 1 research period would have yielded the greatest saving of approximately £ 885.75 ha^{-1}. This treatment was also ranked as the overall most effective in reducing key performance indicators (e.g. runoff and soil loss) across all Sampling Periods. Graves et al. (2011) estimated that on-site cost savings are equal to 23 % of the total costs saved. Therefore the on-site cost saving that would directly benefit the grower would be approximately £204 ha^{-1}. Savings of > £500 ha^{-1} were also calculated from Non-SSD Cp^H (£ 749.04 ha^{-1}), Non-SSD St^L (£ 708.35 ha^{-1}), and SSD St^H (£ 574.18 ha^{-1}). However, Non-SSD Cp^L and SSD Cp^L yielded no savings.

Even so, Non-SSD St^H is not the most cost effective with regards to the standardised unit cost. Instead it has the third lowest standardised unit cost of £4.02 t^{-1} after Non-SSD Cp^H at £2.80 t^{-1} and Non-SSD St^L at £3.06 t^{-1} (Table 7.9). However, in the absence of an available commercial machine to apply compost into wheelings, this cost difference could change.

It is accepted that there are a number of assumptions made during this financial analysis of the treatments. In the cost of soil loss calculations, it is assumed that every tonne of eroded soil has the same on-site and off-site effect. However, this is not the case as the magnitude of effect depends upon the bio-physical environment in which the soil is eroded (Rickson et al., 2010). For example, runoff and erosion that does not occur in close proximity to a river or water body will not result in their subsequent pollution and therefore are not associated with the off-site costs of water pollution and remediation.

The potential costs of uncontrolled soil erosion for growers in terms of soil resource lost could be an underestimation. Additional financial penalties could be incurred as a result of prosecution for polluting local water supplies under the EU Water Framework Directive. These penalties could be as much as £ 50,000 (UKELA, 2014). However the likelihood of prosecution is low due to the difficulty (not least limited staff resource available) in finding evidence to support diffuse pollution related incidents (Maltby and Walker, 2011; Howarth, 2011). It is possible that this may change as the environmental authorities strive to meet the surface water quality standards imposed by the Water Framework Directive better. The requirement for the UK to meet water quality standards could however also benefit growers through the increased availability of financial incentives for sustainable soil management that is seen to limit pollution of waterbodies by sediment (Maltby and Walker 2011). This would incentivise growers to adopt soil conservation treatments.

Other costs (of erosion) and benefits (of soil management practices) exist that have not been costed in this section due to their relative unknown value. These include the potential cost of hindrance to farm operations by erosion and management practices, loss of agricultural production and maintenance of field practices, as well as on-site benefits to soil and crop health (Rickson et al., 2010). As the treatments used in the present study have been applied in an existing asparagus production system, it is known that none of the treatments hinder farm operations or result in a loss of land for production. Furthermore, maintenance was not required over the experimental period (February to July 2012 and May to November 2013), although treatment consistency was observed to decrease with time. With regard to on-site benefits, treatments without SSD will have the added benefit to crops of not cutting roots when implemented, resulting in reduced incidence of disease and asparagus decline. Furthermore, the addition of St or Cp mulch will increase the organic matter content of the soil over time that will result in increased soil health (including resistance to erosion) as well as reduced nutrient input costs.

Table 7.9. Calculated costs (soil management and soil loss) and savings for each Phase 1 treatment. Treatments are ordered according to maximum cost saving.

Phase 1 treatment	Materials cost (£ ha^{-1})	Treatment application (£ ha^{-1})	Total cost of soil management (£ ha^{-1})	Mean soil loss (t ha^{-1})	Cost of measured soil loss (£)	Total cost saving (£)[†]	Unit cost of soil management (£ t^{-1})[‡]
Non-SSD St^{H}	50.90	12.37	63.27	6.08	367.05	885.75	4.02
Non-SSD Cp^{H}	24.00	12.37	36.37	8.79	530.65	749.04	2.80
Non-SSD St^{L}	25.45	12.37	37.82	9.44	569.89	708.35	3.06
SSD St^{H}	50.90	69.18	120.08	10.3	621.81	574.18	10.44
SSD St^{L}	25.45	69.18	94.63	12.1	730.48	490.96	9.76
SSD Cp^{H}	24.00	69.18	93.18	15.4	929.70	293.19	14.56
SSD No mulch	0.00	56.81	56.81	20.7	1249.66	9.60	51.65
Non-SSD Control	0.00	0.00	0.00	21.8	1316.07	0.00	0.00
Non-SSD Cp^{L}	11.40	12.37	23.77	24.6	1485.10	-192.81	-8.49
SSD Cp^{L}	11.40	69.18	80.58	24.7	1491.14	-255.65	-27.79

[†] The difference between the costs of measured soil loss as compared with the Non-SSD Control minus the cost of soil management.

[‡] The cost of soil management divided by the difference in mean soil loss as compared with the Non-SSD Control. N.B. Negative values indicate a saving loss.

Table 7.10. Calculated costs (soil management and soil loss) and savings for each Phase 2 treatment.

Phase 2 treatment	Materials cost (£ ha^{-1})	Treatment application (£ ha^{-1})	Total cost of soil management (£ ha^{-1})	Mean soil loss (t ha^{-1})	Cost of measured soil loss (£)	Total cost saving (£)[†]	Unit cost of soil management (£ t^{-1})[‡]
MPP No mulch	0.00	26.70	26.70	0.91	54.94	-33.94	-222.50
MPP St	50.90	39.07	89.97	0.1	6.04	-48.31	130.39
Non-SSD Control	0.00	0.00	0.00	0.79	47.69	0.00	0.00
Non-SSD St	50.90	12.37	63.27	0.18	10.87	-26.44	103.72
WT No mulch	0.00	26.95	26.95	0.66	39.84	-19.10	207.30
WT St	50.90	39.32	90.22	0.14	8.45	-50.98	138.80
NSLT No mulch	0.00	26.49	26.49	0.8	48.30	-27.09	-2648.84
NSLT St	50.90	38.86	89.76	0.19	11.47	-53.54	149.60

[†] The difference between the costs of measured soil loss as compared with the Non-SSD Control minus the cost of soil management. [‡] The cost of soil management divided by the difference in mean soil loss as compared with the Non-SSD Control. N.B. Negative values indicate a saving loss.

7.3 Conclusions

- This research demonstrates for the first time that asparagus production can result in levels of unsustainable soil loss that will contribute to the degradation of the existing soil resource.
- In both Phase 1 and Phase 2 field trials, a straw mulch, applied at 6 t ha^{-1}, significantly delayed time to runoff initiation in the first runoff producing rainfall events in 25 % of Sampling Periods and reduced cumulative runoff volume and runoff rate in the first runoff producing rainfall events in 50 % and 13 % of Sampling Periods respectively. It also significantly and consistently reduced total soil loss both overall and within 50 % of Sampling Periods, in addition to reducing sediment concentration, TON, orthophosphate-P and sediment-bound P as compared with the Non-Shallow soil disturbance (SSD) Control.
- A straw mulch applied at 3 t ha^{-1} significantly reduced cumulative runoff volume and runoff rate in the first runoff producing rainfall events in 38 % and 13 % of Sampling Periods respectively and total soil loss both overall and within 38 % of Sampling Periods. It also significantly reduced TON in one Sampling Period as compared with the Non-SSD Control.
- A compost mulch applied at 15 t ha^{-1} significantly reduced runoff rate in the first runoff producing rainfall events in 25 % of Sampling Periods and reduced total soil loss (both overall and within 25 % of Sampling Periods) as compared with the Non-SSD Control.
- In general, under the field trial conditions namely the continuation of normal harvesting and agronomic operations, SSD alone (irrespective of tine configuration) is ineffective at improving runoff initiation, cumulative volume, rate, soil loss, sediment concentration, TON, orthophosphate-P and sediment-bound P as compared with the Non-SSD Control.
- Shallow soil disturbance undertaken using a winged tine in isolation significantly delayed time to runoff initiation and reduced cumulative volume and runoff rate for the first runoff producing rainfall event of one Phase 2 Sampling Period. It also significantly reduced orthophosphate-P and TON for one Sampling Period as compared with the Non-SSD Control.
- Shallow soil disturbance in combination with the straw mulch (applied at 3 t ha^{-1} and 6 t ha^{-1}) significantly reduced cumulative runoff volume and runoff rate in the

first runoff producing rainfall events in 38 % (volume and rate for St at 6 t ha^{-1}) and 25 % and 38 % (St at 3 t ha^{-1}) of Sampling Periods.

- Shallow soil disturbance in combination with the straw mulch applied at 6 t ha^{-1} significantly reduced overall total soil loss as compared with the Non-SSD Control; however this reduction was not as great as with St alone at 6 t ha^{-1}.
- Shallow soil disturbance in combination with the compost mulch (applied at 7 t ha^{-1} and 15 t ha^{-1}) significantly delayed rainfall initiation for one Sampling Period's first runoff producing rainfall event and cumulative runoff volume and runoff rate in 38 % of Sampling Periods first runoff producing rainfall events as compared with the Non-SSD Control.
- Shallow soil disturbance in combination with the compost mulch applied at 15 t ha^{-1} significantly reduced total soil loss for one Sampling Period as compared with the Non-SSD Control.
- The modified para-plough generated the greatest degree and extent of soil disturbance for the least draught, followed by the narrow tine with shallow leading tines.
- During Phase 2, SSD undertaken using the modified para-plough significantly delayed time to runoff initiation in the initial rainfall event of one Sampling Period and reduced TON for only one Sampling Period as compared with the Non-SSD Control.
- The implementation of the most effective treatments only resulted in cost savings when high soil loss occurred.
- The application of straw at 6 t ha^{-1} under the rainfall and site conditions associated with the Phase 1 field trials would result in the greatest cost saving of £885 ha^{-1}.
- This research highlights the variation in effectiveness and reliability of in-field mitigation measures with 'extreme' rainfall events which are likely to become more frequent.

8 WIDER IMPLICATIONS AND FURTHER WORK

8.1 Wider implications

This research provides data on the effectiveness of in-field shallow soil disturbance and mulch application in asparagus. With the subsequent adoption of the treatments in the tested fields as well as further development (Section 8.2), asparagus can potentially be grown without excessive environmental impact specifically with regard to water pollution. Although the erosion and runoff measured was from two single asparagus fields, the similarity of asparagus production systems in the UK (e.g. suitable soil types) makes these erosion and runoff management options potentially applicable to other UK asparagus fields. The application of this work contributes towards ensuring the sustainable growth of the UK asparagus industry, and the reduction of our dependence on imported produce. Furthermore, it can help sustain our agricultural land for future agricultural production and food security.

This data provides scientific evidence of soil erosion rates and control practices that can be used to inform policy. It contributes knowledge of the effect of asparagus production on erosion and runoff that was previously unknown. Furthermore, it provides data on erosion and runoff under different rainfall extremes that are set to become more common place in our future climate. This will help fill in some of the knowledge gaps in the effectiveness of in-field mitigation measures on reducing soil erosion to a more ‘acceptable’ level as identified by Defra (2014a). This will help plan for and address the proposed 50 % reduction in erosion as part of the Rio+20 aspiration of land degradation neutral world by 2030.

This research can also be applied in the context of the Water Framework Directive (2000). Surface waters and ground waters need to meet a ‘good ecological status’ by 2027, with interim targets set for 2015 and 2021. This status includes limits for soluble P and nitrates. The data provided in this study can inform UK policy makers of what can be used in-field to achieve reductions in P and N runoff from agriculture that currently contribute to high levels found in receiving surface waters that fail to meet the standards of ‘good ecological status’.

There is a knowledge gap within the British horticultural industry for soil management research for the control of soil degradation (Rickson and Deeks, 2013). This research can address that gap with practical erosion control measures for asparagus.

Furthermore, it provides research on interaction effects between two soil management practices (shallow soil disturbance and mulch) that few horticultural studies currently cover (Rickson and Deeks, 2013).

This research could also be applied to other horticultural crops and production systems that share similar soil and water management problems. Graves et al. (2011) states that horticulture in silt and sand is highly likely to suffer soil loss via erosion. In UK soils, horticulture includes brassicas, lettuce, parsnip, leeks, potatoes and carrots (Figure 8.1). These crops, as well as sugar beet, bulbs and soft fruit have been identified as vulnerable to erosion (Defra, 2005; Environment Agency, 2007; Graves et al., 2011). In addition, since undertaking this project, several recommendations for SSD and mulching suitability in other cropping systems have been made. These are; perennial field grown herbs (personal communication with R Simmons, November, 2014), European white asparagus (personal communication with L. Aldenhoff, October, 2013) and maize (personal communication with J. Chinn, November, 2014).

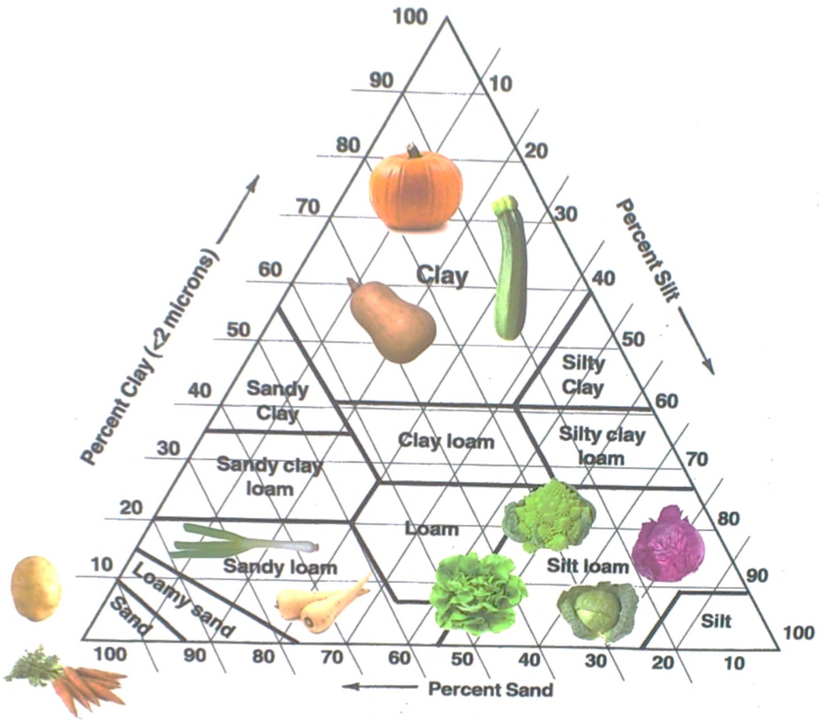


Figure 8.1. Suitability of different soil types to vegetable production. Source: Sarrouy and Lillywhite (2013).

8.2 Further work

In order to be able to apply this work most effectively to the broader asparagus industry and beyond, further work is required. In particular trials could be conducted in fields of different slope gradients and lengths and geographic locations where there are some variations in soil type as well as different rainfall conditions. Furthermore, soils that have been under asparagus for different periods of time and with different soil legacies could be tested. It would also be interesting to isolate the effects of foot traffic on treatment effectiveness that would make treatments more applicable to newly established asparagus fields (pre hand-harvest) as well as for other (not hand-harvested) horticultural systems. This could also be carried out to establish treatment longevity. In order to ascertain winder applicability, field work could also be carried out across different horticultural production systems identified above (Section 8.1) as these are potentially highly vulnerable to erosion. Finally, on fields most vulnerable to erosion (such as used in Phase 1) treatments could be tested in conjunction with other erosion measures (such as grass waterways) to see how final soil loss results compare to tolerable and sustainable levels.

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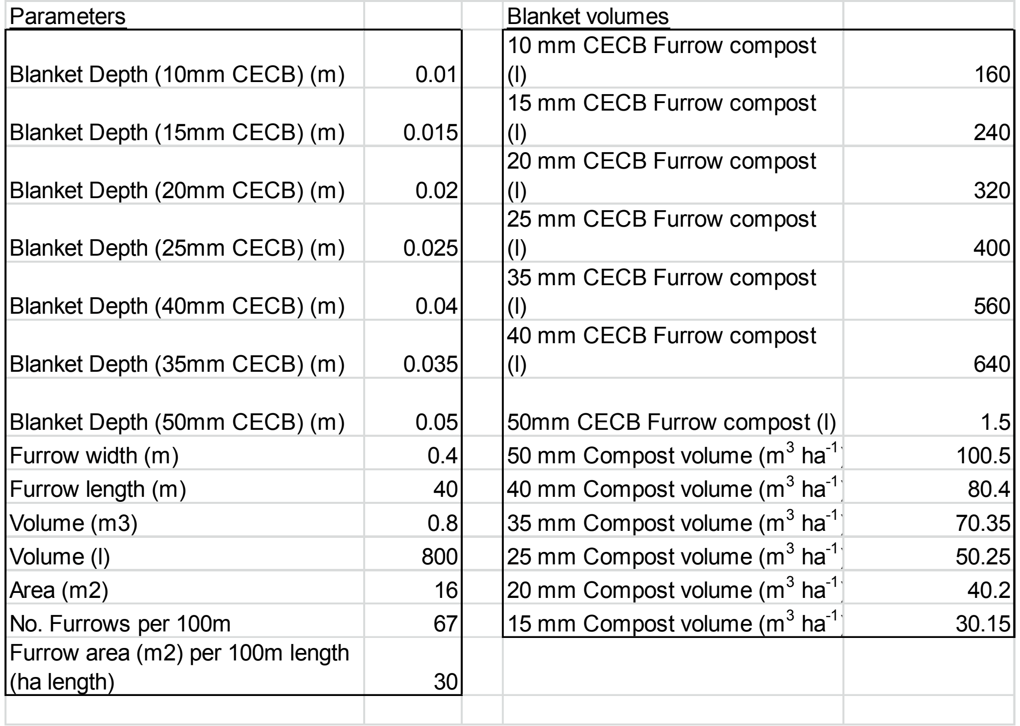
APPENDICES

Appendix A Phase 1 Field Trials

A.1 Treatment application rate calculations



Parameters		Blanket volumes	
Blanket Depth (10mm CECB) (m)	0.01	10 mm CECB Furrow compost (l)	160
Blanket Depth (15mm CECB) (m)	0.015	15 mm CECB Furrow compost (l)	240
Blanket Depth (20mm CECB) (m)	0.02	20 mm CECB Furrow compost (l)	320
Blanket Depth (25mm CECB) (m)	0.025	25 mm CECB Furrow compost (l)	400
Blanket Depth (40mm CECB) (m)	0.04	35 mm CECB Furrow compost (l)	560
Blanket Depth (35mm CECB) (m)	0.035	40 mm CECB Furrow compost (l)	640
Blanket Depth (50mm CECB) (m)	0.05	50mm CECB Furrow compost (l)	1.5
Furrow width (m)	0.4	50 mm Compost volume (m^3 ha^{-1}	100.5
Furrow length (m)	40	40 mm Compost volume (m^3 ha^{-1}	80.4
Volume (m3)	0.8	35 mm Compost volume (m^3 ha^{-1}	70.35
Volume (l)	800	25 mm Compost volume (m^3 ha^{-1}	50.25
Area (m2)	16	20 mm Compost volume (m^3 ha^{-1}	40.2
No. Furrows per 100m	67	15 mm Compost volume (m^3 ha^{-1}	30.15
Furrow area (m2) per 100m length (ha length)	30		

Figure_Apx A-1. Values used for compost application rate calculations.

	Initial compost analytical results					
	N mg l^{-1}	**BD mg m^{-3}**				
	3738.00	0.25				
	3425.00	0.22				
	2285.00	0.16				
	3149.33	**0.21**				
Nitrogen content						
	50 mm CECB	**40 mm CECB**	**35 mm CECB**	**20 mm CECB**	**15 mm CECB**	
Total N applied to plot (mg)	2519467	2015573	1763627	1007787	755840	
Total N applied to plot (g)	2519	2016	1764	1008	756	
Total Napplied to plot (kg) = $16m^2$	2.52	2.02	1.76	1.01	0.76	
Total N (kg) applied per m^2	0.16	0.13	0.11	0.06	0.05	
Total N (kg) applied per ha (assuming 67 furrows per 100m)	317	253	**222**	127	**95.0**	<250 kg ha (NVZ)
	Selected blanket depth based on N results (m)	**Volume per plot (m^3)**	**Mass (t $plot^{-1}$)**	**Mass (kg $plot^{-1}$)**	**Mass (t ha^{-1})**	
	0.035	0.56	0.12	118	**14.9**	
	0.015	0.24	0.05	50.7	**6.37**	
	Applied compost analytical results					
	N mg l^{-1}	**BD mg m^{-3}**				
	5669	0.31				
	5717	0.31				
	5306	0.31				
	5564	**0.31**				
Nitrogen content						
	50mm CECB	**40mm CECB**	**35mm CECB**	**20mm CECB**	**15mm CECB**	**10mm CECB**
Total N applied to plot (mg)	4451200	3560960	3115840	1780480	1335360	890240
Total N applied to plot (g)	4451	3561	3116	1780	1335	890
Total Napplied to plot (kg) = $16m^2$	4.45	3.56	3.12	1.78	1.34	0.89
Total N (kg) applied per m^2	0.28	0.22	0.19	0.11	0.08	0.06
Total N (kg) applied per ha (assuming 67 furrows per 100m)	559	447	**391**	224	**168**	112
	Selected blanket depth based on N results (m)	**Volume per plot (m^3)**	**Mass (t $plot^{-1}$)**	**Mass (kg $plot^{-1}$)**	**Mass (t ha^{-1})**	
	0.035	0.56	0.1736	173.6	**21.81**	
	0.015	0.24	0.0744	74.4	**9.35**	

Figure_Apx A-2. Compost applicate rate calculations.

Table_Apx A-1. Straw application rate calculations.

	Phase 1 High rate based on Morgan (1995)†	**Phase 1 high application rate based on Niziolomski (2011)‡**	**Phase 1 low application rate based on Niziolomski (2011)‡**	**Phase 2 application rate**
Rate (t ha^{-1})	5	6.3	3.1	6.3
Conversion to m2 (t m^{-2})	0.0005	0.00063	0.00031	0.00063
Conversion to kg (kg m^{-2})	0.5	0.63	0.31	0.63
Phase 1 plot size (m^2)	16	16	16	-
Phase 2 plot size (m^2)	-	-	-	12
Applied to wheeling (kg $plot^{-1}$)	8	10.08	4.96	7.56

†Sourced from Morgan, R. P. C. (1995), *Soil erosion and conservation*, 2nd Edition, Longman Group Limited, UK. ‡modified from 6.7 to 6.3 to bring down to 10.

A.2 Sampling Period characteristics

Table_Apx A-2. Rainfall characteristics for each Phase 1 Sampling Period.

Sampling Period 1

Rainfall event no.	Date	Start time	Duration (hh:mm)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	01/05/2012	02:15	00:03	1.40	2.9%	21.0	36.0
2	01/05/2012	03:47	01:06	16.6	35%	20.8	48.0
3	01/05/2012	05:25	00:20	3.20	6.7%	14.8	24.0
4	01/05/2012	06:13	00:10	1.00	2.1%	12.0	12.0
5	03/05/2012	08:01	00:21	2.00	4.2%	12.0	12.0

Sampling Period 2

Rainfall event no.	Date	Start time	Duration (hh:mm)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	07/05/2012	15:49	00:13	5.40	63%	27.0	72.0
2	09/05/2012	13:11	00:25	3.20	37%	12.8	24.0

Sampling Period 3

Rainfall event no.	Date	Start time	Duration (hh:mm)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	15/05/2012	15:35	00:07	1.00	17%	15.0	24.0
2	15/05/2012	16:50	00:19	2.60	45%	13.0	24.0
3	18/05/2012	18:24	00:13	1.20	21%	12.0	12.0
4	19/05/2012	00:38	00:09	1.00	17%	12.0	12.0

Sampling Period 4

Rainfall event no.	Date	Start time	Duration (hh:mm)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	02/06/2012	22:34	00:17	1.60	3.3%	12.0	12.0
2	02/06/2012	23:07	00:52	9.40	20%	14.1	24.0
3	03/06/2012	18:43	00:19	1.80	3.8%	12.0	12.0

4	07/06/2012	15:15	00:10	1.20	2.5%	12.0	12.0
5	07/06/2012	16:02	00:18	2.60	5.4%	14.2	24.0
6	11/06/2012	17:50	00:12	1.60	3.3%	13.7	24.0
7	14/06/2012	22:18	00:41	4.80	10%	12.5	24.0
8	14/06/2012	23:09	00:41	4.20	8.8%	12.0	12.0
9	15/06/2012	12:40	00:06	1.00	2.1%	12.0	12.0
10	16/06/2012	12:18	00:21	2.20	4.6%	12.0	12.0
11	16/06/2012	12:51	00:08	1.00	2.1%	12.0	12.0
12	16/06/2012	13:03	00:31	7.60	16%	20.7	48.0
13	21/06/2012	01:52	00:43	4.60	10%	12.0	12.0
14	21/06/2012	02:43	00:11	1.20	2.5%	12.0	12.0
15	21/06/2012	03:02	00:17	1.60	3.3%	12.0	12.0
16	21/06/2012	15:03	00:17	1.60	3.3%	12.0	12.0

<u>Sampling Period 5</u>

Rainfall event no.	Date	Start time	Duration (hh:mm)	Total rainfall	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	28/06/2012	09:48	00:12	9.00	11.7%	45.0	72.0
2	30/06/2012	01:24	00:21	2.00	2.61%	12.0	12.0
3	30/06/2012	02:05	00:17	1.60	2.09%	12.0	12.0
4	06/07/2012	05:33	01:38	35.6	46.5%	24.6	96.0
5	06/07/2012	08:03	00:31	5.20	6.79%	13.0	24.0
6	07/07/2012	22:11	00:10	1.00	1.31%	12.0	12.0
7	07/07/2012	22:38	00:17	1.60	2.09%	12.0	12.0
8	08/07/2012	18:28	00:14	1.40	1.83%	12.0	12.0
9	11/07/2012	09:45	00:11	1.40	1.83%	14.0	24.0
10	11/07/2012	16:38	00:28	3.80	4.96%	17.5	36.0
11	13/07/2012	19:46	00:22	6.60	8.62%	19.8	36.0
12	13/07/2012	23:44	00:21	2.60	3.39%	12.0	12.0
13	14/07/2012	00:31	00:10	1.00	1.31%	12.0	12.0
14	14/07/2012	01:58	00:13	1.20	1.57%	12.0	12.0
15	14/07/2012	15:59	00:11	1.60	2.09%	12.0	12.0
16	14/07/2012	18:44	00:09	1.00	1.31%	15.0	24.0

A.3 Runoff analysis means

Table_Apx A-3. Mean values for runoff sample variables tested on all Sampling Periods. Within each Sampling Period, results followed by different letters are significantly different (p = ≤0.05) following factorial nested ANOVA and post-hoc Fisher LSD.

Treatment code	Total runoff volume (l)									
	1		2		3		4		5	
Non-SSD Cp^{L}	209	a	164	a	153	a	262	a	96.0	a
Non-SSD Cp^{H}	180	a	67.2	a	178	a	254	a	76.6	a
Non-SSD Control	259	a	233	a	245	a	265	a	125	a
Non-SSD St^{L}	270	a	269	a	269	a	268	a	116	a
Non-SSD St^{H}	263	a	241	a	262	a	263	a	118	a
SSD Cp^{L}	189	a	150	a	268	a	217	a	59.2	a
SSD Cp^{H}	154	a	182	a	134	a	269	a	75.6	a
SSD No mulch	190	a	73.2	a	177	a	249	a	108	a
SSD St^{L}	273	a	145	a	236	a	270	a	143	a
SSD St^{H}	271	a	249	a	255	a	270	a	68.9	a

Treatment code	Total soil loss (kg)									
	1		2		3*		4		5**	
Non-SSD Cp^{L}	14.9	bde	21.4	ce	20.6	a	40.1	de	46.8	a
Non-SSD Cp^{H}	7.75	ac	11.2	abd	9.57	a	15.6	ab	14.4	a
Non-SSD Control	17.7	ef	18.9	cd	17.4	a	33.5	cde	39.8	a
Non-SSD St^{L}	10.5	ab	6.74	ab	5.69	a	14.4	a	19.4	a
Non-SSD St^{H}	4.28	c	2.77	a	1.36	a	13.8	a	14.2	a
SSD Cp^{L}	17.0	def	34.2	f	11.9	a	44.0	e	41.1	a
SSD Cp^{H}	11.9	ab	21.4	ce	18.1	a	23.8	abcd	20.6	a
SSD No mulch	22.1	f	33.8	ef	28.4	a	36.9	bcde	38.5	a
SSD St^{L}	12.3	abd	14.8	bcd	12.3	a	16.4	ab	21.5	a
SSD St^{H}	8.96	ac	8.62	ab	8.32	a	20.23	abc	22.39	a

Treatment code	Runoff sediment concentration (g l^{-1})									
	1		2		3		4		5	
Non-SSD Cp^{L}	8.58	abc	12.0	ab	14.1	a	13.0	a	42.0	a
Non-SSD Cp^{H}	10.1	a	10.4	ab	13.5	a	8.72	a	31.7	a
Non-SSD Control	5.92	abc	14.1	a	17.0	a	20.1	a	32.2	a
Non-SSD St^{L}	4.80	bc	6.81	ab	9.87	a	10.7	a	26.2	a

Non-SSD St^H	3.43	b	4.65	b	4.87	a	11.4	a	22.0	a
SSD Cp^L	7.51	abc	10.5	ab	24.1	a	14.0	a	38.1	a
SSD Cp^H	10.0	a	10.0	ab	10.2	a	9.78	a	12.3	a
SSD No mulch	10.2	ac	1.92	ab	18.0	a	7.57	a	43.9	a
SSD St^L	7.50	abc	13.8	a	12.3	a	8.26	a	25.2	a
SSD St^H	6.68	abc	11.9	ab	8.40	a	12.8	a	28.0	a

Table_Apx A-4. Mean values for runoff nutrient analysis. Within each Sampling Period, results followed by different letters are significantly different ($p = \leq 0.05$) following factorial nested ANOVA and post-hoc Fisher LSD.

No.	Treatment code	TON concentration (mg l^{-1}) 1	3	5
1	Non-SSD Cp^{L}	1.92 def	3.17 a	102 ab
2	Non-SSD Cp^{H}	1.39 abd	3.47 a	128 a
3	Non-SSD Control	1.87 bdef	4.18 a	117 a
4	Non-SSD St^{L}	1.21 ac	3.74 a	93.4 ab
5	Non-SSD St^{H}	0.67 c	3.18 a	105 a
6	SSD Cp^{L}	2.01 ef	2.74 a	134 a
7	SSD Cp^{H}	1.57 abde	4.70 a	50.0 b
8	SSD No mulch	2.45 f	4.37 a	106 ab
9	SSD St^{L}	1.26 abc	3.30 a	85.9 ab
10	SSD St^{H}	1.26 abc	3.34 a	98.1 ab

No.	Treatment code	Runoff phosphorus concentration (mg l^{-1}) 1	3	5
1	Non-SSD Cp^{L}	0.78 abd	0.86 a	0.22 a
2	Non-SSD Cp^{H}	0.81 abd	0.62 a	0.73 a
3	Non-SSD Control	0.69 ab	0.83 a	0.63 a
4	Non-SSD St^{L}	0.62 ac	0.72 a	0.35 a
5	Non-SSD St^{H}	0.47 c	0.63 a	0.46 a
6	SSD Cp^{L}	0.84 bd	0.79 a	0.67 a
7	SSD Cp^{H}	0.68 abc	0.69 a	0.24 a
8	SSD No mulch	0.98 d	0.95 a	0.25 a
9	SSD St^{L}	0.70 ab	0.79 a	0.58 a
10	SSD St^{H}	0.63 abc	0.78 a	0.70 a

No.	Treatment code	Sediment-bound phosphorus concentration(mg kg^{-1}) 1	3	5
1	Non-SSD Cp^{L}	1510 a	1288 a	1189 a
2	Non-SSD Cp^{H}	1367 a	1273 a	1152 a
3	Non-SSD Control	1406 a	1159 ab	1171 a
4	Non-SSD St^{L}	1385 a	1201 ab	1093 a
5	Non-SSD St^{H}	1354 a	1199 ab	1130 a
6	SSD Cp^{L}	1233 a	1238 ab	1178 a
7	SSD Cp^{H}	1476 a	1274 a	4792
8	SSD No mulch	1459 a	1195 ab	1198 a
9	SSD St^{L}	1286 a	1153 ab	1214 a
10	SSD St^{H}	1237 a	1112 b	1185 a

*Significant differences derived from Log n of mean values.

**Significant differences derived from Log 2n of mean values.

A.4 Event-driven hydrological response means

Table_Apx A-5. Mean time to runoff initiation (minutes) of each treatment for the RE_1 of each Sampling Period. Within each Sampling Period, values followed by different letters denote statistical significance ($p \leq 0.2$) following one-way ANOVA.

Treatment	Sampling Period									
	1		2		3		4		5	
Non-SSD Control	1.67	ab	5.00	a	5.75	a	12.3	a	8.00	a
Non-SSD Cp^H	1.00	b			5.67	a	10.0	a	7.00	a
Non-SSD Cp^L	2.00	a	5.33	a	6.50	ab	13.5	a	7.50	a
Non-SSD St^H	4.33	c	5.67	a			13.7	a	7.67	a
Non-SSD St^L	1.67	ab	5.00	a			14.7	a	6.67	a
SSD Cp^H	1.67	ab	5.33	a	7.00	bc	13.0	a	7.00	a
SSD Cp^L	2.00	a	5.00	a	7.67	c			7.33	a
SSD No Mulch	1.50	ab							7.00	a
SSD St^H	1.00	b	5.33	a			17.5	a	7.67	a
SSD St^L	2.00	a	5.33	a			17.0	a	8.00	a

N.B. Blank cells exist where no runoff was initiated from 2 or more treatment replicates.

Table_Apx A-6. Mean values for runoff cumulative volume and rates for RE_1 Sampling Period 1. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

No.	Treatment	Time from RE_1 initiation (mins)											
		0		1		3		5		14		19	
Cumulative volume (l)													
2	Non-SSD Control	31.6	bc	32.2	bc	61.3	a	92.8	a	123	a	127	a

No.	Treatment	Time from RE_1 initiation (mins)											
		0		1		3		5		14		19	
7	Non-SSD Cp^H	28.9	abc	30.6	abc	53.5	ab	73.8	a	93.7	a	95.7	a
1	Non-SSD Cp^L	34.5	c	34.5	c	55.9	a	59.0	a	63.5	a	64.9	a
5	Non-SSD St^H	3.73	e	3.74	e	11.1	d	27.3	a	82.7	a	92.0	a
8	Non-SSD St^L	19.5	ad	20.1	ad	40.4	bc	67.3	a	114	a	120	a
6	SSD Cp^H	27.3	abc	28.0	abc	53.5	ab	67.3	a	79.1	a	80.8	a
9	SSD Cp^L	25.1	abc	25.2	abcd	48.0	abc	51.2	a	63.6	a	65.7	a
10	SSD No Mulch	30.3	abc	31.3	abc	62.1	a	81.7	a	97.2	a	98.6	a
3	SSD St^H	13.7	de	15.3	d	35.8	c	65.5	a	107	a	112	a
4	SSD St^L	22.9	abd	23.0	abd	50.3	ab	85.8	a	125	a	129	a
Runoff rate (l min-1)													
2	Non-SSD Control	0.55	‡	0.57	abc	20.70	a	13.37	ab	1.22	ac	1.17	c
7	Non-SSD Cp^H	0.06	‡	1.68	de	14.95	a	9.03	abde	0.72	ab	0.01	ad
1	Non-SSD Cp^L	0.08	‡	0.00	a	10.78	a	0.88	c	0.62	ab	0.54	bd
5	Non-SSD St^H	0.00	‡	0.01	ab	5.60	a	10.25	abe	3.15	d	1.24	bc
8	Non-SSD St^L	1.15	‡	0.61	abc	14.19	a	13.70	ab	2.18	cd	0.92	bc
6	SSD Cp^H	0.56	‡	0.66	bc	18.40	a	5.17	cde	0.56	ab	0.00	a
9	SSD Cp^L	0.00	‡	0.11	ab	13.42	a	1.48	cd	0.00	b	0.00	a
10	SSD No Mulch	0.00	‡	0.96	cd	22.80	a	7.53	acde	0.00	b	0.00	a
3	SSD St^H	0.00	‡	1.68	e	15.67	a	13.16	ab	1.31	ac	0.86	bc
4	SSD St^L	0.11	‡	0.08	ab	17.84	a	16.85	b	1.34	ac	0.00	a

†No data variance ‡Data not suitable for ANOVA.

Table_Apx A-7. Mean values for runoff cumulative volume and rates for RE_1 Sampling Period 2. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

No.	Treatment	Time from RE_1 initiation (mins)																			
		0		1		3		5		7		9		11		13		15		24	
Cumulative runoff (l)																					
2	Non-SSD Control	0.00	‡	0.00	‡	0.00	‡	32.6	b	86.8	a	121	a	125	a	129	a	133	a	137	a
7	Non-SSD Cp^H																				
1	Non-SSD Cp^L	0.00	‡	0.00	‡	0.00	‡	19.9	a	51.1	a	58.7	a	61.5	a	64.9	a	67.6	a	72.4	a
5	Non-SSD St^H	0.00	‡	0.00	‡	0.00	‡	8.55	a	89.1	a	156	a	184	a	201	a	206	a	224	a
8	Non-SSD St^L	0.00	‡	0.00	‡	0.00	‡	12.5	a	56.1	a	88.2	a	118	a	141	a	151	a	166	a
6	SSD Cp^H	3.07	‡	3.09	‡	3.07	‡	15.3	a	58.3	a	76.0	a	87.4	a	96.1	a	103	a	113	a
9	SSD Cp^L	0.00	‡	0.00	‡	0.00	‡	19.2	a	37.8	a	48.8	a	55.9	a	66.8	a	74.1	a	81.0	a
10	SSD No Mulch																				
3	SSD St^H	0.00	‡	0.00	‡	0.00	‡	12.7	a	100	a	154	a	185	a	207	a	211	a	220	a
4	SSD St^L	0.00	‡	0.00	‡	0.00	‡	9.41	a	49.0	a	63.7	a	73.3	a	81.4	a	88.8	a	100	a
Runoff rate (l min^{-1})																					
2	Non-SSD Control	0.00	†	0.00	†	0.00	†	32.6	a	22.7	ab	10.9	a	1.81	a	2.24	a	1.23	a	0.00	a
7	Non-SSD Cp^H	0.00	†		†		†														
1	Non-SSD Cp^L	0.00	†	0.00	†	0.00	†	19.9	a	7.48	a	2.98	a	1.66	a	1.68	a	1.09	a	1.00	a
5	Non-SSD St^H	0.00	†	0.00	†	0.00	†	8.55	a	51.2	c	20.2	a	11.9	a	5.44	a	2.35	a	1.14	a
8	Non-SSD St^L	0.00	†	0.00	†	0.00	†	12.5	a	21.3	ab	16.7	a	13.6	a	9.22	a	3.38	a	1.05	a
6	SSD Cp^H	0.00	†	0.02	†	0.00	†	12.3	a	16.6	ab	6.37	a	5.36	a	4.10	a	2.94	a	0.00	a
9	SSD Cp^L	0.00	†	0.00	†	0.00	†	19.2	a	7.17	a	3.51	a	3.61	a	4.55	a	2.71	a	0.79	a
10	SSD No Mulch	0.00	†		†		†														
3	SSD St^H	0.00	†	0.00	†	0.00	†	12.7	a	38.3	bc	21.5	a	14.2	a	8.54	a	1.71	a	0.42	a

No.	Treatment	Time from RE$_1$ initiation (mins)																			
		0		1		3		5		7		9		11		13		15		24	
4	SSD St^{L}	0.00	†	0.00	†	0.00	†	9.41	a	16.0	a	5.91	a	4.32	a	4.09	a	3.46	a	1.01	a

†No data variance ‡Data not suitable for ANOVA. N.B. Blank cells exist where errors in sensor measurement occurred for 2 or more treatment replicates.

Table_Apx A-8. Mean values for runoff cumulative volume and rates for RE$_1$ Sampling Period 3. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

No.	Treatment	Time from RE$_1$ initiation (mins)													
		0		1		3		5		7		9		18	
Cumulative runoff (l)															
2	Non-SSD Control	0.00	†	0.00	†	0.00	†	2.47	‡	17.6	d	22.6	b	25.9	c
7	Non-SSD Cp^{H}	0.00	†	0.00	†	0.00	†	3.76	‡	16.1	cd	20.8	b	24.4	c
1	Non-SSD Cp^{L}	0.00	†	0.00	†	0.00	†	0.00	‡	13.3	bcd	19.4	bc	24.7	bc
5	Non-SSD St^{H}	0.00	†	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	0.00	a
8	Non-SSD St^{L}	0.00	†	0.00	†	0.00	†	3.78	‡	6.14	ab	7.36	ac	8.54	ab
6	SSD Cp^{H}	0.00	†	0.00	†	0.00	†	0.00	‡	8.29	abc	10.9	c	12.8	b
9	SSD Cp^{L}	0.00	†	0.00	†	0.00	†	0.00	‡	6.93	ab	12.5	b	15.4	c
10	SSD No Mulch														
3	SSD St^{H}	0.00	†	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	0.00	a
4	SSD St^{L}	0.00	†	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	3.21	ab
Runoff rate (l min-1)															
2	Non-SSD Control	0.00	‡	0.00	†	0.00	†	2.47	‡	4.85	b	2.25	bc	0.00	‡

No.	Treatment	Time from RE$_1$ initiation (mins)													
		0		1		3		5		7		9		18	
7	Non-SSD Cp^H	0.00	‡	0.00	†	0.00	†	3.76	‡	3.56	b	1.83	bc	0.00	‡
1	Non-SSD Cp^L	0.00	‡	0.00	†	0.00	†	0.00	‡	6.30	bc	2.07	be	0.00	‡
5	Non-SSD St^H	0.00	‡	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	0.00	‡
8	Non-SSD St^L	0.00	‡	0.00	†	0.00	†	3.78	‡	0.63	ad	0.61	ad	0.00	‡
6	SSD Cp^H	0.03	‡	0.00	†	0.00	†	0.00	‡	1.20	cd	0.61	de	0.01	‡
9	SSD Cp^L	0.00	‡	0.00	†	0.00	†	0.00	‡	6.93	bc	4.40	c	0.00	‡
10	SSD No Mulch														
3	SSD St^H	0.00	‡	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	0.00	‡
4	SSD St^L	0.00	‡	0.00	†	0.00	†	0.00	‡	0.00	a	0.00	a	0.00	‡

†No data variance ‡Data not suitable for ANOVA. N.B. Blank cells exist where errors in sensor measurement occurred for 2 or more treatment replicates.

Table_Apx A-9. Mean values for runoff cumulative volume and rates for RE$_1$ Sampling Period 4. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

Time from RE$_1$ initiation (mins)	Treatments																			
	Non-SSD Control		Non-SSD CpH		Non-SSD CpL		Non-SSD StH		Non-SSD StL		SSD CpH		SSD CpL		SSD No Mulch		SSD StH		SSD StL	
Cumulative runoff (l)																				
0	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†			0.00	†	0.00	†
1	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†	0.00	†			0.00	†	0.00	†
3	0.00	‡	3.19	‡	0.00	‡	0.00	‡	0.00	‡	0.00	‡	0.00	‡			0.00	‡	0.00	‡

Time from RE$_1$ initiation (mins)	Treatments									
	Non-SSD Control	Non-SSD CpH	Non-SSD CpL	Non-SSD StH	Non-SSD StL	SSD CpH	SSD CpL	SSD No Mulch	SSD StH	SSD StL
5	0.00 ‡	3.20 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
7	2.40 ‡	4.33 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
9	3.68 ‡	6.11 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
11	5.96 a	10.4 a	8.91 a	7.64 a	0.00 a	0.00 a	0.00 a		0.00 a	5.51 a
13	12.2 a	21.1 a	19.4 a	15.4 a	4.93 a	10.7 a	0.00 a		0.00 a	9.16 a
15	18.4 a	33.4 a	28.6 a	24.2 a	11.8 a	24.8 a	0.00 a		4.88 a	13.0 a
17	27.2 a	45.6 a	42.1 a	32.9 a	23.0 a	35.8 a	0.00 a		8.47 a	16.6 a
19	35.7 a	56.6 a	51.7 a	40.0 a	33.1 a	46.5 a	0.00 a		11.7 a	20.0 a
28	56.6 abc	83.4 b	72.2 ab	75.6 ab	62.8 ab	72.1 ab	0.00 d		25.0 cd	44.6 ac
33	69.4 ab	99.6 b	83.6 ab	94.2 ab	76.7 ab	88.0 ab	0.00 c		32.7 cd	55.9 ad
Runoff rate (l min^{-1})										
0	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †		0.00 †	0.00 †
1	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †		0.00 †	0.00 †
3	0.00 ‡	3.19 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
5	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †	0.00 †		0.00 †	0.00 †
7	2.40 ‡	0.57 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
9	0.85 ‡	1.19 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 ‡		0.00 ‡	0.00 ‡
11	1.37 a	2.45 a	8.91 a	4.35 a	0.00 a	0.00 a	0.00 a		0.00 a	1.73 a
13	4.40 a	4.35 a	4.34 a	3.67 a	1.71 a	5.56 a	0.00 a		0.00 a	1.85 a
15	2.93 a	8.36 a	3.79 a	4.54 a	5.06 a	5.54 a	0.00 a		1.70 a	1.96 a
17	5.84 a	5.65 a	3.96 a	4.12 ac	6.96 a	5.77 a	0.00 b		1.82 bc	1.53 bc
19	4.42 a	5.32 a	3.83 a	3.41 ac	5.15 a	4.81 a	0.00 b		1.38 bc	1.44 bc
28	1.73 a	2.61 bcd	1.81 ab	3.00 d	2.87 cd	1.73 ab	0.00 e		0.22 e	2.03 abc
33	2.45 ab	2.87 ac	1.78 ab	3.64 c	3.05 ac	2.86 ac	0.00 d		1.59 b	2.20 ab

†No data variance ‡Data not suitable for ANOVA. N.B. Blank cells exist where errors in sensor measurement occurred for 2 or more treatment replicates.

Table_Apx A-10. Mean values for runoff cumulative volume and rates for RE_1 Sampling Period 5. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

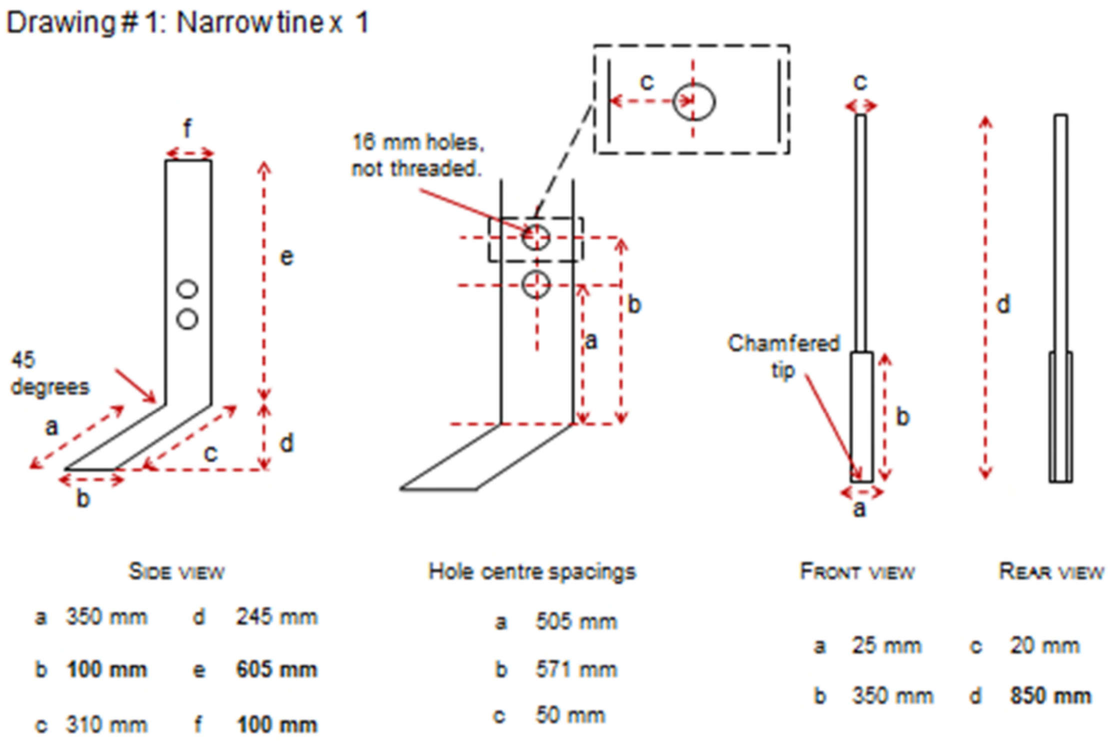
No.	Treatment	Time from RE_1 initiation (mins)																	
		0		1		3		5		7		9		11		13		23	
Cumulative runoff (l)																			
2	Non-SSD Control	2.30	a	2.30	a	2.32	a	2.30	ab	5.59	a	28.9	bc	34.1	ad	35.2	abd	37.1	ab
7	Non-SSD Cp^H	0.00	a	0.00	a	0.00	a	0.00	a	13.7	a	36.5	ab	37.1	ab	37.6	ab	37.7	abd
1	Non-SSD Cp^L	0.00	a	0.00	a	0.00	a	0.00	a	7.34	a	32.6	abc	35.6	abd	35.6	abd	35.9	abd
5	Non-SSD St^H	0.00	a	0.00	a	0.00	a	0.00	a	4.39	a	55.8	ad	58.7	bc	58.7	ac	59.6	ac
8	Non-SSD St^L	3.09	a	3.08	a	3.13	a	6.42	c	13.6	a	52.7	ad	57.5	bc	58.6	ac	60.3	ac
6	SSD Cp^H	0.00	a	0.00	a	0.00	a	0.00	a	8.75	a	12.3	c	12.3	d	12.3	d	12.3	d
9	SSD Cp^L	0.00	a	0.00	a	0.00	a	0.00	a	10.5	a	37.1	ab	43.7	abc	46.7	abc	47.6	abc
10	SSD No Mulch	0.00	a	0.00	a	0.00	a	0.00	a	13.8	a	58.0	ad	67.0	c	68.8	c	70.3	c
3	SSD St^H	0.00	a	0.00	a	0.00	a	0.00	a	5.53	a	29.9	bc	31.1	ad	32.2	bd	33.0	bd
4	SSD St^L	5.18	a	5.18	a	5.42	a	5.92	bc	6.00	a	64.0	d	69.4	c	71.9	c	72.8	c
Runoff rate (l min^{-1})																			
2	Non-SSD Control	0.00	†	0.00	†	0.02	a	0.00	‡	3.28	a	13.8	a	1.66	a	0.63	bc	0.00	a
7	Non-SSD Cp^H	0.00	†	0.00	†	0.00	a	0.00	‡	13.7	a	4.03	a	0.00	b	0.01	a	0.00	ab
1	Non-SSD Cp^L	0.00	†	0.00	†	0.00	a	0.00	‡	7.34	a	7.14	a	1.09	cd	0.02	abd	0.00	a
5	Non-SSD St^H	0.00	†	0.00	†	0.00	a	0.00	‡	4.39	a	16.6	a	2.02	a	0.01	ad	0.03	b
8	Non-SSD St^L	0.00	†	0.00	†	0.03	a	3.28	‡	6.99	a	19.2	a	1.73	a	0.56	bc	0.53	c

No.	Treatment	Time from RE_1 initiation (mins)								
		0	1	3	5	7	9	11	13	23
6	SSD Cp^H	0.00 †	0.00 †	0.00 a	0.00 ‡	8.75 a	0.59 a	0.01 bc	0.05 a	0.00 ab
9	SSD Cp^L	0.00 †	0.00 †	0.00 a	0.00 ‡	10.5 a	7.30 a	2.83 ad	1.35 bc	0.00 ab
10	SSD No Mulch			0.00 a	0.00 ‡	13.8 a	14.8 a	3.06 a	0.82 bcd	0.00 a
3	SSD St^H	0.00 †	0.00 †	0.00 a	0.00 ‡	5.53 a	6.50 a	0.11 bc	0.00 a	0.00 ab
4	SSD St^L	0.00 †	0.00 †	0.23 a	0.31 ‡	0.00 a	24.2 a	1.28 ad	1.32 c	0.01 ab

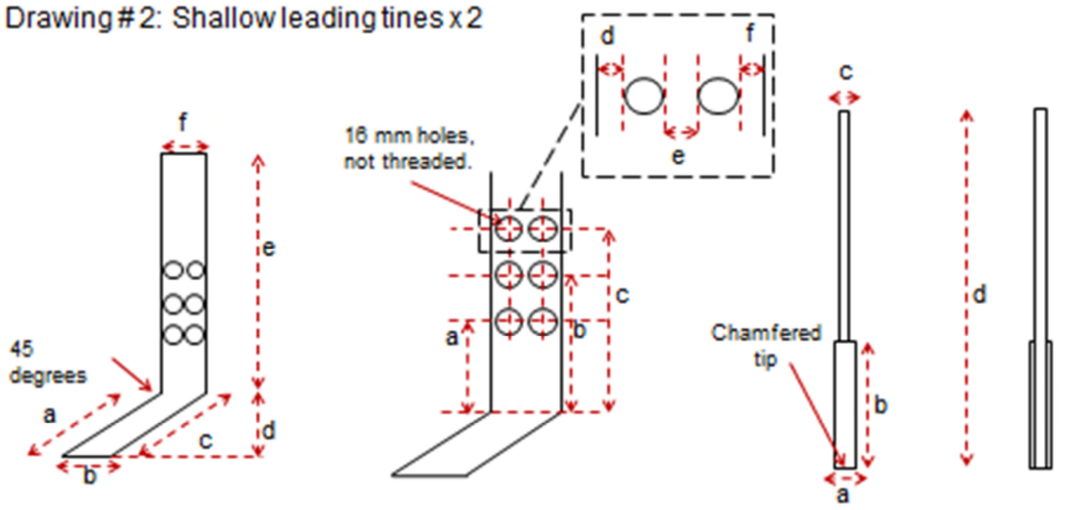
†No data variance ‡Data not suitable for ANOVA. N.B. Blank cells exist where errors in sensor measurement occurred for 2 or more treatment replicates.

Appendix B Soil Bin Experimental Work

B.1 Tine geometry and configuration designs



Figure_Apx B-1. Narrow tine design.



SIDE VIEW

a	350 mm	d	245 mm
b	**100 mm**	e	470 mm
c	310 mm	f	**120 mm**

Hole centre spacings

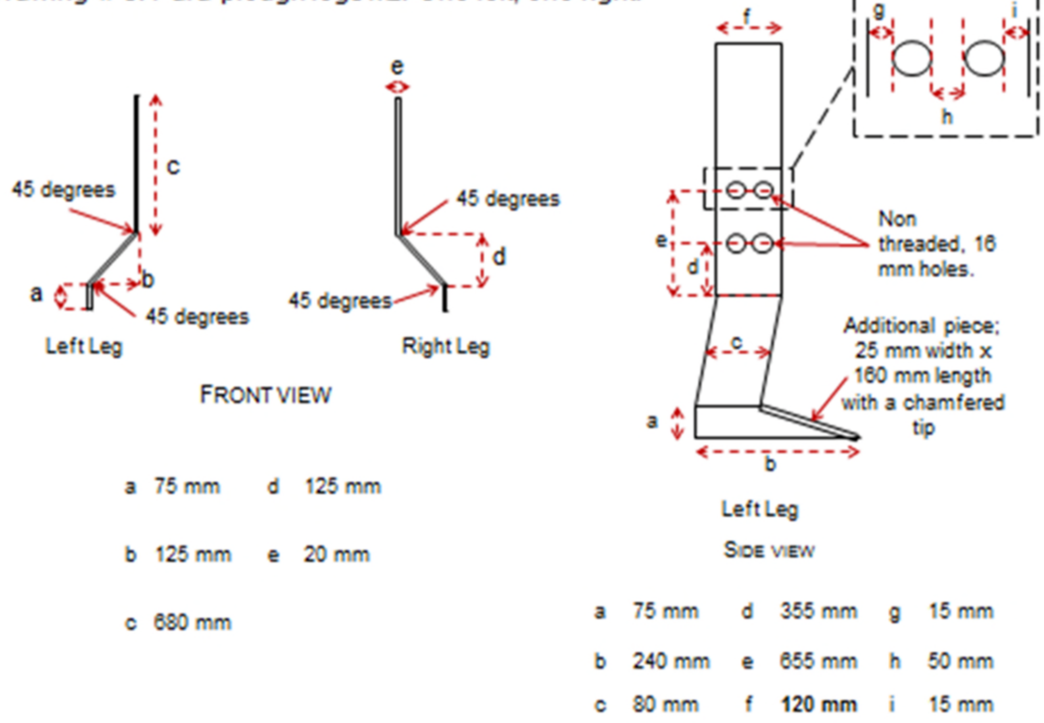
a	385 mm	d	15 mm
b	425 mm	e	50 mm
c	450 mm	f	15 mm

FRONT VIEW REAR VIEW

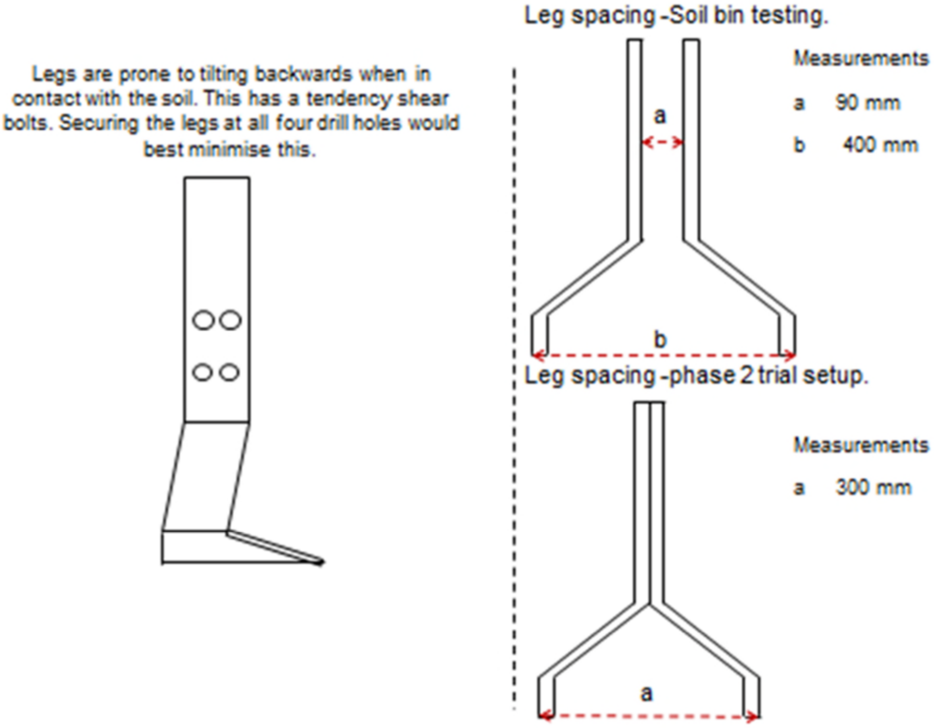
a	25 mm	c	20 mm
b	350 mm	d	715 mm

Figure_Apx B-2. Shallow leading tines design.

Drawing # 3: Para-plough legs x 2. One left, one right.

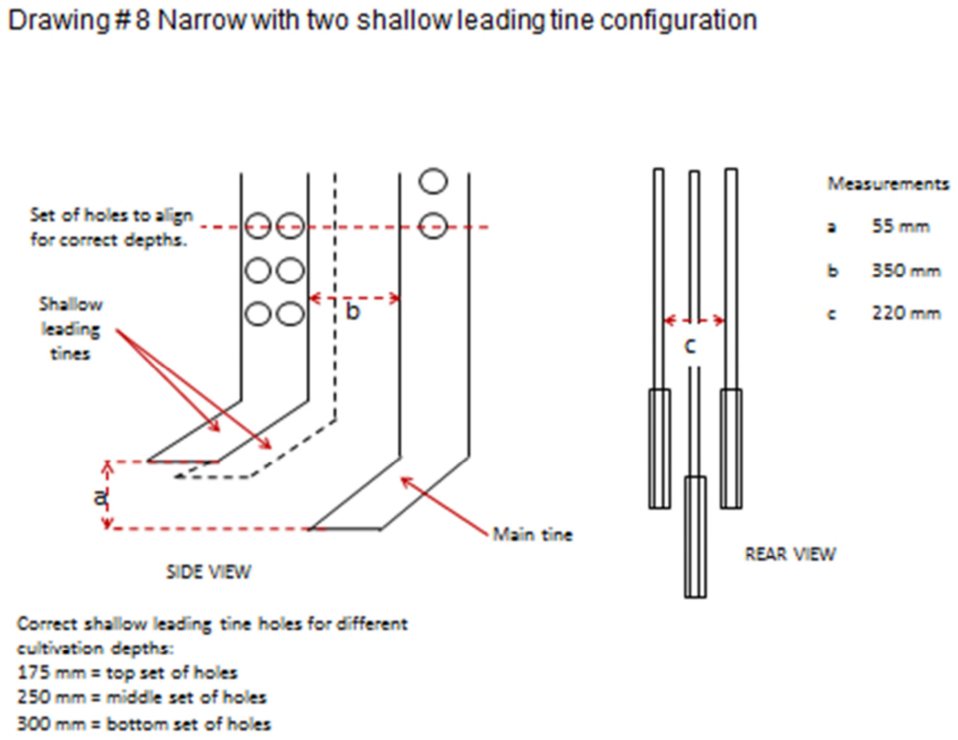


Drawing # 7 Modified para-plough configuration

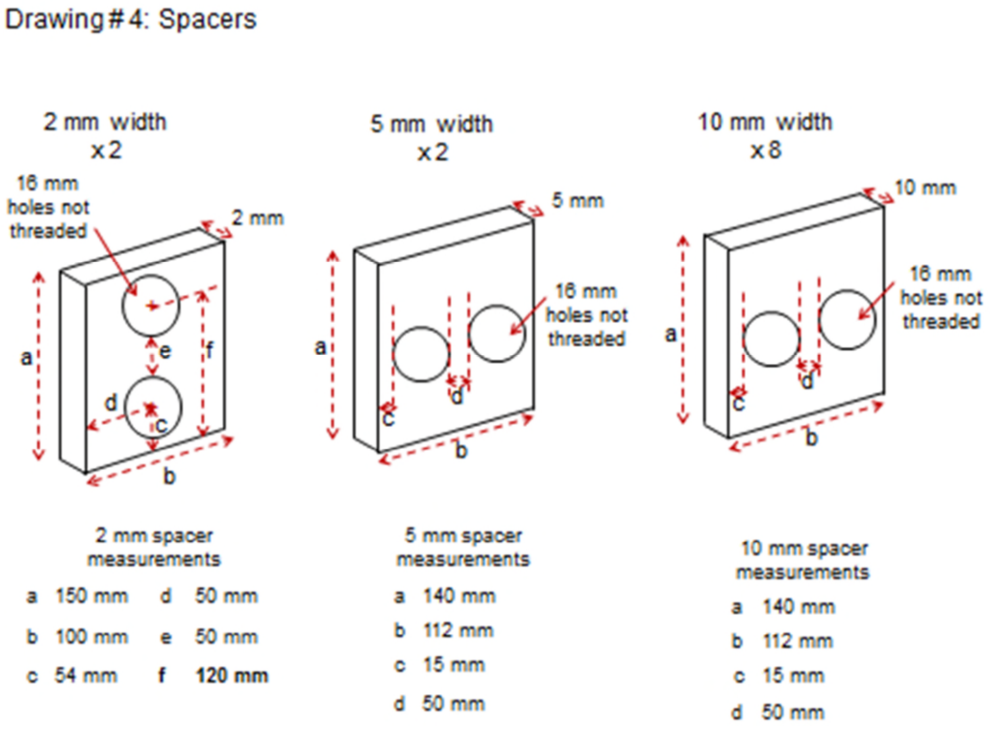


Legs are prone to tilting backwards when in contact with the soil. This has a tendency shear bolts. Securing the legs at all four drill holes would best minimise this.

Figure_Apx B-3. Modified para-plough designs and configuration.

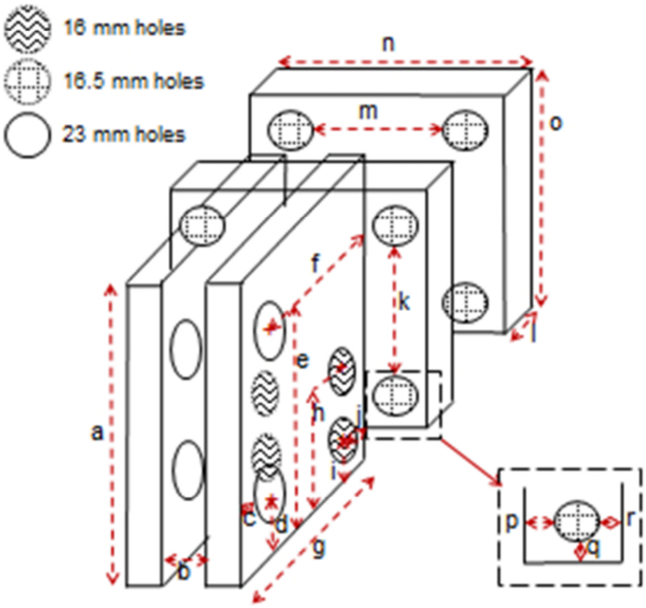


Figure_Apx B-4. Narrow with shallow leading tines configuration design.



Figure_Apx B-5. Design for spacers for use between the bracket and tine legs.

Drawing # 5: Bracket for rear mounting of narrow and winged tine x 1

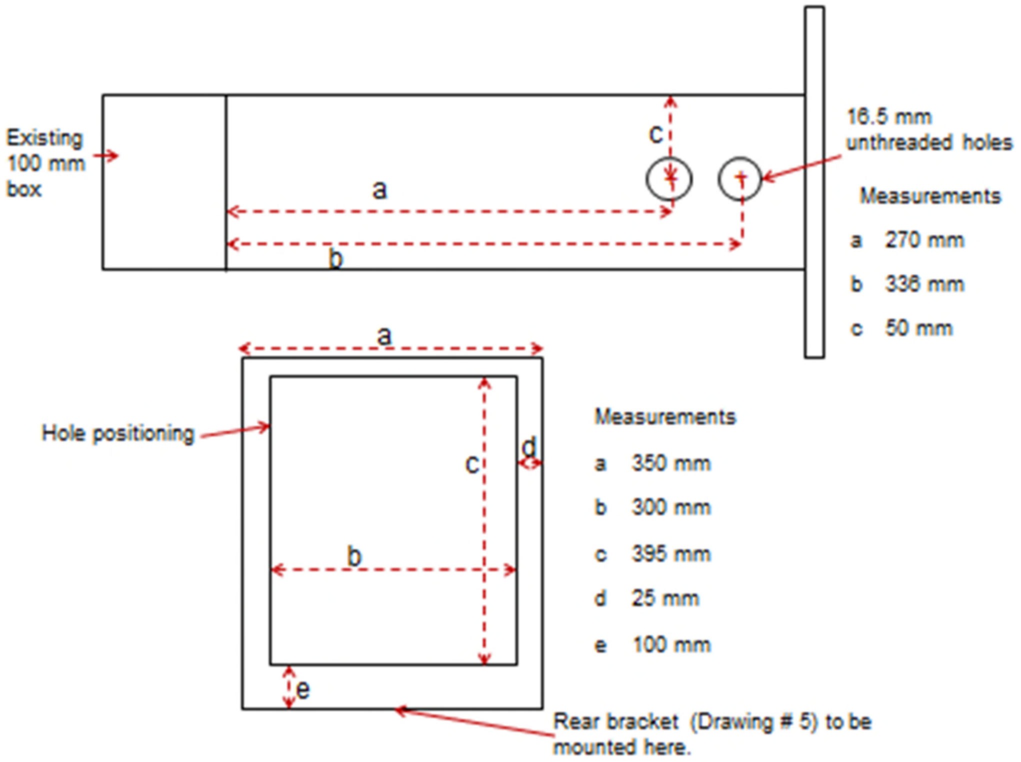


Front 2 plates.		Rear 2 plates.	
a	197 mm	k	102 mm
b	26 mm*	l	15 mm
c	10 mm	m	106 mm
d	27 mm	n	169 mm
e	170 mm	o	165 mm
f	175 mm	p	25 mm
g	208 mm	q	15 mm
h	90 mm	r	15 mm
i	24 mm		
j	50 mm		

*Needs to be a sliding fit for a 25 mm wide piece.

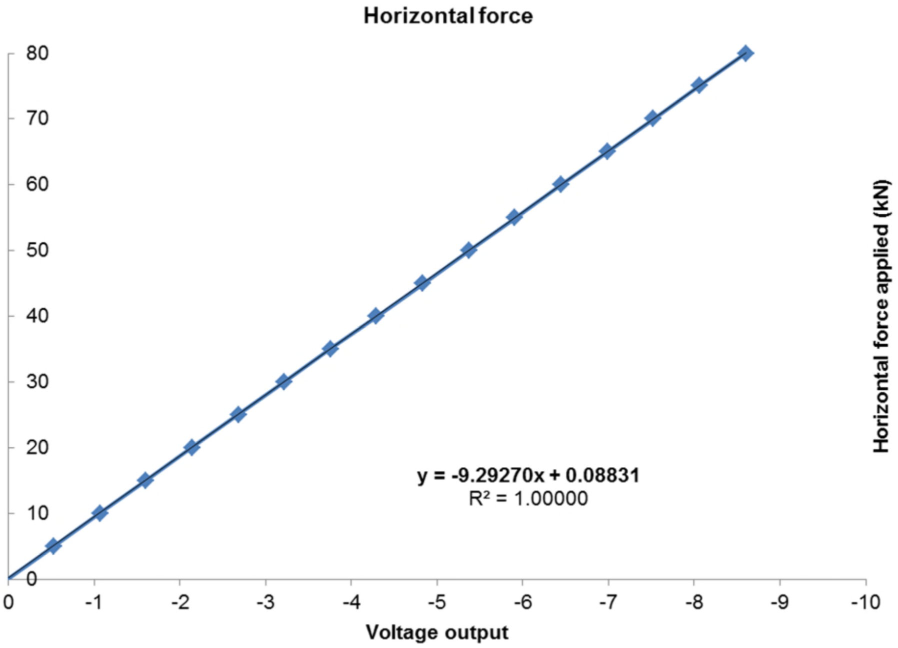
Bolts needed:
4 x 16 mm width by 150 mm length.

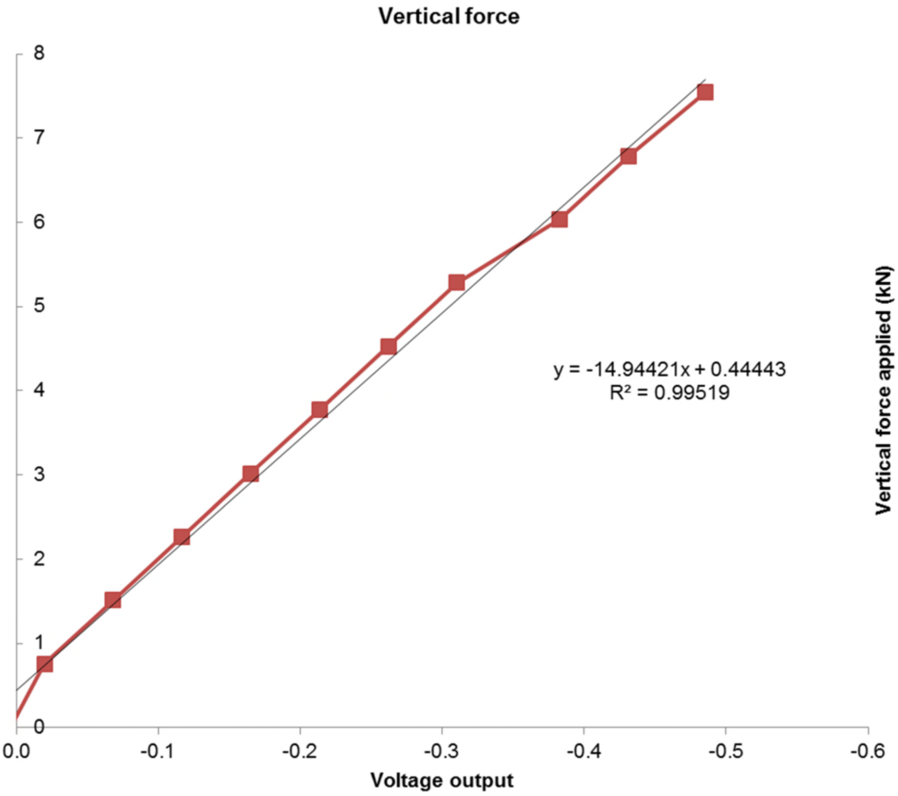
Figure_Apx B-6. Rear mounting bracket design.



Figure_Apx B-7. Modification design for existing bracket.

B.2 Soil Bin calibration





Figure_Apx B-8. Calibration curves for the draught and vertical channels of the EORT.

Table_Apx B-1. Mean bulk densities of soil bin preparation tests with varying numbers of rolls. Results followed by different letters denote a statistical difference following ANOVA analysis and post-hoc Fisher LSD.

Bin fit no.	No. rolls	Bulk density (gcm^{-3})		Moisture content (%)	
1	10	1.55	a	7.01	a
1	14	1.56	a	7.27	ab
2	16	1.56	a	7.05	a
2	20	1.59	a	7.84	bcd
3	26	1.60	a	7.32	ab
3	30	1.57	a	7.06	a
4	10	1.57	a	7.85	bcd
4	16	1.55	a	8.10	cd
5	14	1.59	a	8.32	d
5	20	1.59	a	7.58	abc

Table_Apx B-2. Mean bulk densities of soil bin preparations for stage 1 (175 mm) and stage 2 (250 and 300 mm) testing. Results followed by different letters denote a statistical difference following ANOVA analysis and post-hoc Fisher LSD.

Experimental stage	Bin fit no.	Bulk density (gcm^{-3})		Moisture content (%)	
1	1	1.59	a	8.34	b
1	2	1.56	a	7.70	ac
1	3	1.54	a	8.09	ab
1	4	1.58	a	8.09	ab
1	5	1.58	a	8.08	ab
1	6	1.54	a	7.90	abc
1	7	1.54	a	7.53	ac
1	8	1.51	a	6.93	d
1	9	1.51	a	7.32	cd
2	1	1.46	a	7.32	a
2	2	1.56	bcd	8.36	b

Experimental stage	Bin fit no.	Bulk density (gcm^{-3})		Moisture content (%)	
2	3	1.53	bc	8.36	b
2	4	1.53	bc	8.14	b
2	5	1.56	bcd	8.44	bc
2	6	1.57	cd	8.52	bc
2	7	1.53	bc	8.36	b
2	8	1.52	bc	8.72	bc
2	9	1.56	bcd	8.61	bc
2	10	1.56	bcd	8.40	b
2	11	1.54	bc	8.35	b
2	12	1.55	bcd	8.11	b
2	13	1.52	abc	8.26	b
2	14	1.55	bc	8.47	bc
2	15	1.56	bcd	8.49	bc
2	16	1.51	ab	9.04	c
2	17	1.61	d	9.69	d

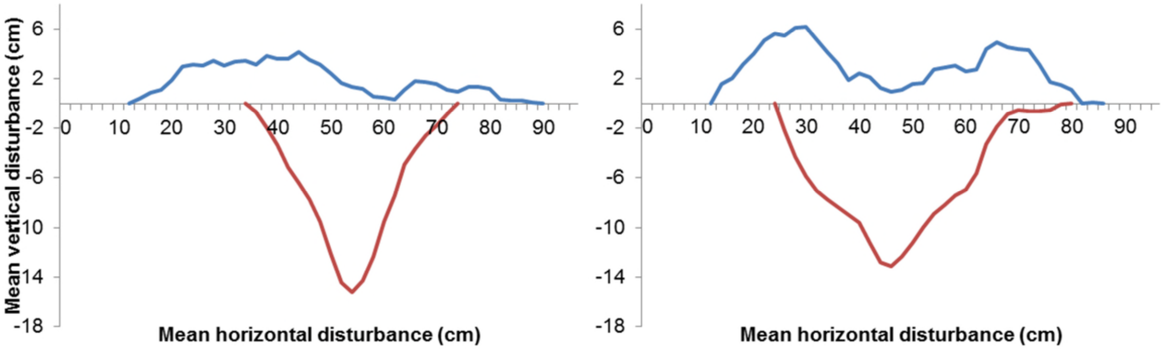
B.3 Soil Bin results

Table_Apx B-3. Mean results for each tine configuration at all three tested depths. Within each cultivation depth, different letters following results for each variable denote statistical differences (p =<0.05).

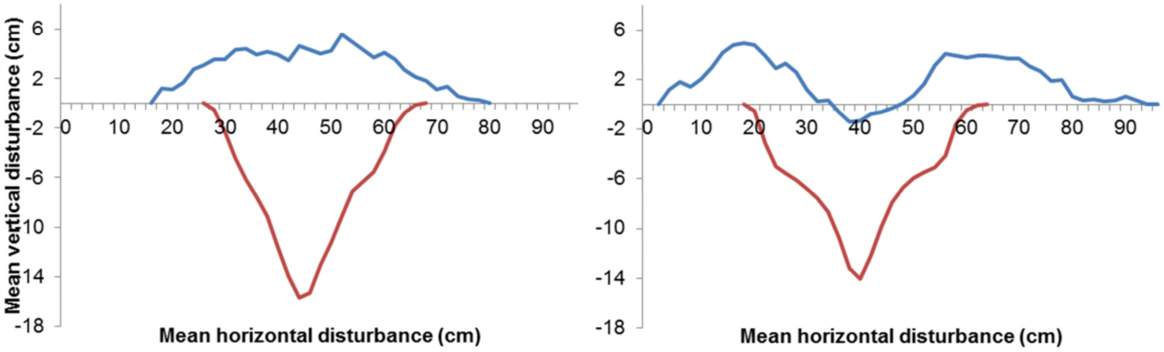
	Tine	**D_{BG} (m^2)**	**SR_P**	**SR_I**	**D_{AG} (m^2)**	**Draught force (kN)**	**Vertical force (kN)**	**SD (kN m^{-2})**	**SD_E (kN m^{-2})**
175 mm									
1	NT	2.68 ^{a}	0.21 ^{a}	0.45 ^{c}	1.46 ^{b}	1.31 ^{b}	0.32 ^{c}	0.49 ^{ab}	0.32 ^{a}
2	WT	3.41 ^{b}	0.24 ^{a}	0.34 ^{a}	2.21 ^{a}	2.55 ^{a}	-0.09 ^{ab}	0.75 ^{c}	0.45 ^{b}
3	MPP	5.07 ^{c}	0.23 ^{a}	0.30 ^{ab}	3.11 ^{c}	2.08 ^{d}	0.81 ^{d}	0.41 ^{a}	0.25 ^{a}
4	NSLT	2.92 ^{a}	0.31 ^{a}	0.36 ^{a}	1.90 ^{a}	1.68 ^{c}	0.17 ^{bc}	0.58 ^{b}	0.35 ^{a}
5	WSLT	2.82 ^{a}	0.22 ^{a}	0.22 ^{b}	2.25 ^{a}	2.75 ^{a}	-0.37 ^{a}	0.98 ^{d}	0.55 ^{c}
250 mm									
1	NT	3.78 ^{b}	0.15 ^{a}	0.44 ^{c}	2.42 ^{b}	14.3 ^{a}	-6.67 ^{ab}	3.9 ^{a}	2.35 ^{a}
2	WT	6.28 ^{a}	0.17 ^{a}	0.32 ^{ab}	3.38 ^{ac}	22.7 ^{b}	-0.33 ^{d}	3.6 ^{a}	2.34 ^{a}
3	MPP	6.67 ^{a}	0.26 ^{a}	0.28 ^{a}	3.59 ^{a}	22.0 ^{b}	-9.33 ^{a}	3.3 ^{ab}	2.15 ^{a}
4	NSLT	5.43 ^{c}	0.23 ^{a}	0.38 ^{bc}	2.71 ^{bc}	14.7 ^{a}	-4.00 ^{bc}	2.7 ^{b}	1.80 ^{a}
5	WSLT	6.53 ^{a}	0.24 ^{a}	0.31 ^{a}	3.93 ^{a}	25.7 ^{c}	-2.33 ^{cd}	3.9 ^{a}	2.46 ^{a}
300 mm									
1	NT	4.62 ^{b}	0.21 ^{ab}	0.37 ^{a}	3.10 ^{b}	22.3 ^{a}	-9.00 ^{b}	5.0 ^{a}	2.94 ^{a}

	Tine	D_{BG} (m^2)	SR_P	SR_I	D_{AG} (m^2)	Draught force (kN)	Vertical force (kN)	SD (kN m^{-2})	SD_E (kN m^{-2})
2	WT	8.38 ^{a}	0.18 ^{ab}	0.31 ^{b}	4.20 ^{a}	32.0 ^{b}	-1.67 ^{e}	3.8 ^{a}	2.55 ^{a}
3	MPP	8.02 ^{a}	0.12 ^{a}	0.30 ^{b}	4.21 ^{a}	37.0 ^{c}	-14.3 ^{a}	4.8 ^{a}	3.07 ^{a}
4	NSLT	5.66 ^{b}	0.24 ^{bc}	0.38 ^{a}	3.00 ^{b}	19.7 ^{a}	-6.00 ^{c}	3.5 ^{a}	2.29 ^{a}
5	WSLT	8.47 ^{a}	0.34 ^{c}	0.40 ^{a}	4.01 ^{a}	32.3 ^{b}	-4.00 ^{d}	3.8 ^{a}	2.59 ^{a}

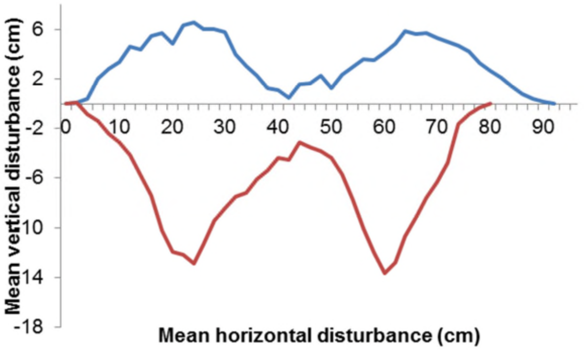
Narrow Winged



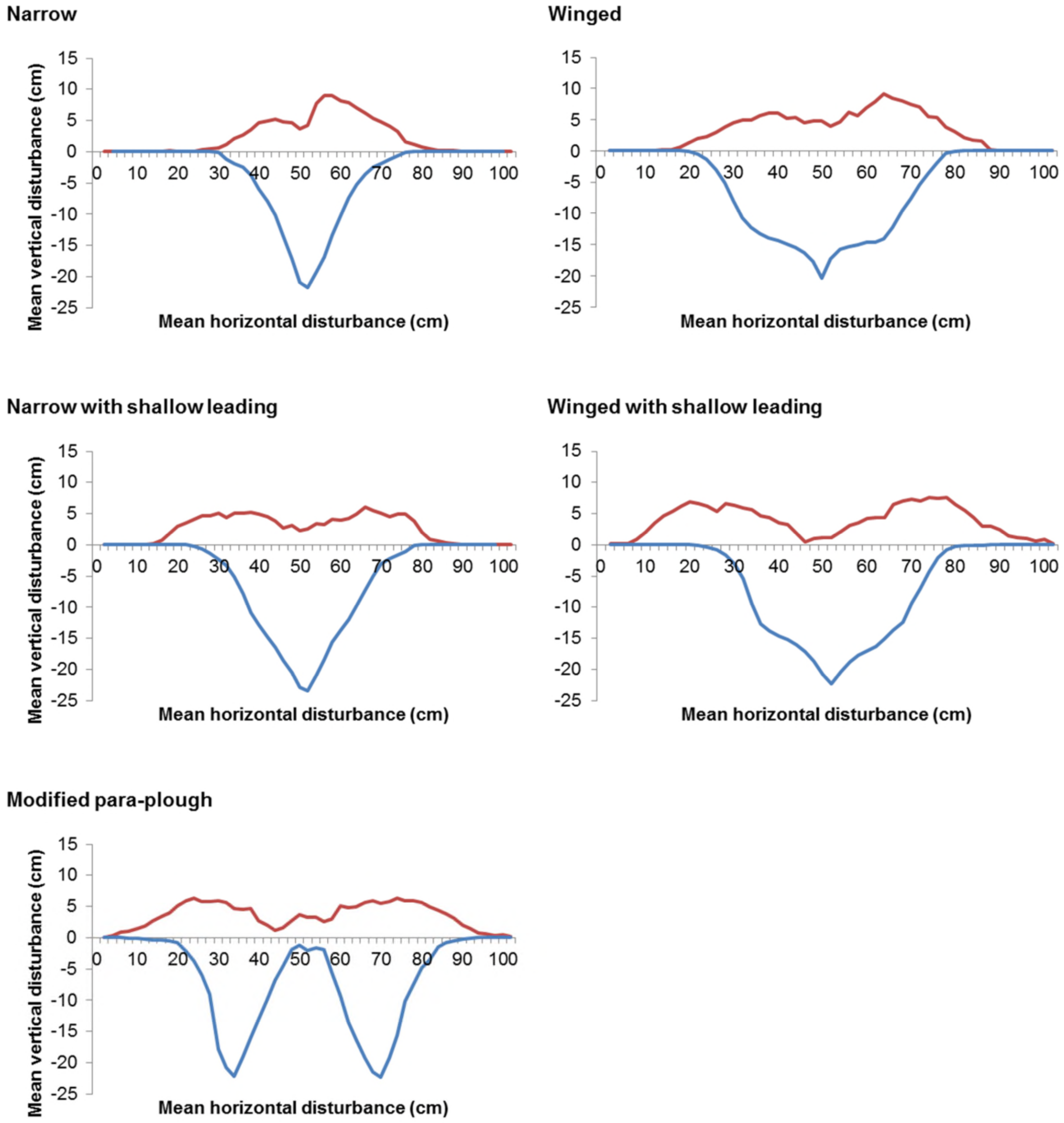
Narrow with shallow leading Winged with shallow leading



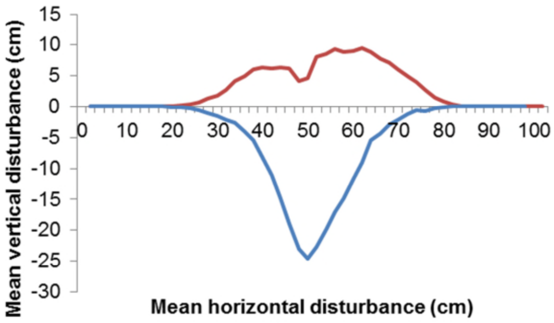
Modified para-plough

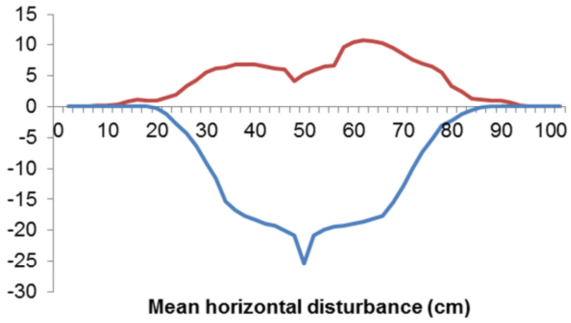


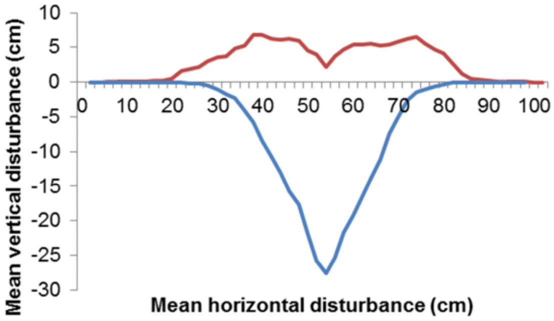
Figure_Apx B-9. Above and below ground disturbance of each tine configuration at 175 mm, derived from the mean profile measurements of three runs of each experimental tine.

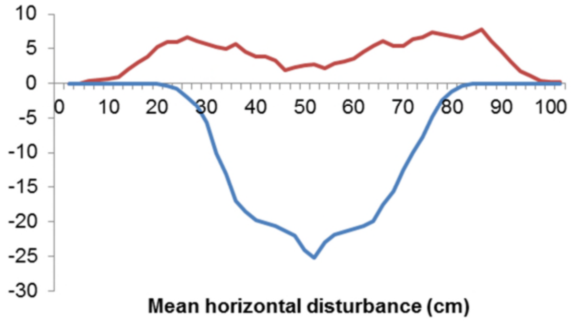


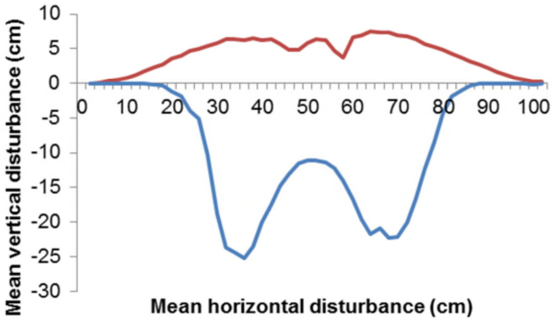
Figure_Apx B-10. Above and below ground disturbance of each tine configuration at 250 mm, derived from the mean profile measurements of three runs of each experimental tine.


Narrow


Winged


Narrow with shallow leading


Winged with shallow leading


Modified para-plough

Figure_Apx B-11. Above and below ground disturbance of each tine configuration at 300 mm, derived from the mean profile measurements of three runs of each experimental tine.

Figure_Apx B-12. Above ground disturbance at 300 mm resulting from the narrow tine (top image) and the winged tine (bottom image).

B.3.1 Tine cutting face calculation for 175 mm depth cultivation

Narrow tine

Components interacting with the soil at 175 mm: tine foot.

Dimensions

Foot: 175 (h), 25 (w)

= 4375 mm^2 (0.004 m^2)

Winged tine

Components interacting with the soil at 175 mm: tine foot and wings (x 2).

Dimensions

Wings: 100 (lift height), 160 (w)

Foot: 175 (h), 25 (w)

= 20375 mm^2 (0.02 m^2)

Modified para-plough

Components interacting with the soil at 175 mm: tine foot (x 2) and bent leg (x 2).

Dimensions

Foot: 75 (h), 25 (w) (x2)

Bent leg: 141 (l) 20 (w) (x2)

= 4965 mm^2 (x2)

= 9390 mm^2 (0.009 m^2)

Narrow with shallow leading tines

Components interacting with the soil at 175 mm: main tine foot, shallow tine foot (x 2).

Dimensions

Shallow leading foot: 120 (h), 25 (w)

=3000 mm^2 (x2)

=6000 mm^2 + 4375 mm^2 (from narrow tine calculation)

= 10375 mm^2 (0.01 m^2)

Winged with shallow leading tines

Components interacting with the soil at 175 mm: main tine foot, wings (x 2) and shallow tine foot (x 2).

Dimensions

Shallow leading foot: 120 (h), 25 (w)

=3000 mm^2 (x2)

=6000 mm^2 + 36375 mm^2 (from winged tine calculation)

= 42375 mm^2 (0.042 m^2)

Table_Apx B-4. Results of the Pugh ranking matrix for all cultivation depths.

Performance criteria	175 mm depth					250 mm depth					300 mm depth				
	WT	**WSLT**	**NT**	**NSLT**	**MPP**	**WT**	**WSLT**	**NT**	**NSLT**	**MPP**	**WT**	**WSLT**	**NT**	**NSLT**	**MPP**
SR_P	S	S	S	S	S	S	S	S	S	S	S	+	S	S	S
SR_I	S	-	+	S	S	S	S	+	S	S	S	+	+	+	S
SDD	S	-	+	+	+	S	S	S	S	S	S	S	S	S	S
D_{BG}	S	-	-	-	+	S	S	-	+	S	S	S	-	-	S
D_{AG}	S	S	-	S	+	S	S	-	S	S	S	S	-	-	S
BD reduction	S	S	S	S	S	S	S	S	S	S	S	S	+	S	S
Total +	0	0	2	1	3	0	0	1	1	0	0	2	2	1	0
Total -	0	3	2	1	0	0	0	2	0	0	0	0	2	2	0
Total score	0	-3	0	0	3	0	0	-1	1	0	0	2	0	-1	0
Rank	2	5	2	2	1	2	2	5	1	2	2	1	2	5	2

Appendix C Phase 2 Field Trials

C.1 Experimental setup

The attached CD contains short films showing the application of SSD in treatment wheelings using the MPP, NSLT and WT tine configurations.

C.2 Sampling Period characteristics

Table_Apx C-1. Rainfall characteristics for each Phase 2 Sampling Period.

Sampling Period 1

Rainfall event no.	Date	Start time	Duration (mins)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
Data not known.							

Sampling Period 2

Rainfall event no.	Date	Start time	Duration (mins)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	23/07/2013	04:02:00	00:19	15.2	93.80	54	588

Sampling Period 3

Rainfall event no.	Date	Start time	Duration (mins)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	27/07/2013	20:01:00	00:01	13.2	28.3	792	792
2	28/07/2013	19:17:00	00:11	8.2	17.6	82	432
3	29/07/2013	12:21:00	00:03	2.0	4.3	60	108
4	02/08/2013	20:08:00	00:04	3.6	7.7	43	132
5	02/08/2013	21:38:00	00:04	0.8	1.7	24	36
6	02/08/2013	22:05:00	00:09	1.0	2.1	12	12
7	04/08/2013	12:06:00	00:05	5.2	11.2	78	276
8	05/08/2013	08:57:00	00:00	3.6	7.7	216	216
9	05/08/2013	09:23:00	00:31	5.8	12.4	16	36
10	05/08/2013	14:35:00	00:02	1.0	2.1	30	48
11	05/08/2013	15:00:00	01:05	11.0	23.6	15	36

Sampling Period 4

Rainfall event no.	Date	Start time	Duration (mins)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	16/08/2013	09:14:00	00:05:00	6.6	19.4%	132	372
2	24/08/2013	00:17:00	00:00:00	7.2	21.2%	432	432
3	09/09/2013	01:01:00	00:04:00	10.2	30.0%	306	600
4	09/09/2013	03:17:00	00:00:00	2.6	7.6%	156	156

5	09/09/2013	06:07:00	00:06:00	1.0	2.9%	30	48
6	09/09/2013	08:57:00	00:13:00	1.2	3.5%	12	12

Sampling Period 5

Rainfall event no.	Date	Start time	Duration (mins)	Total rainfall (mm)	% Total rainfall	Mean intensity (mm hr^{-1})	Peak intensity (mm hr^{-1})
1	06/11/2013	14:16:00	00:01:00	3.8	13.2	114	204
2	08/11/2013	12:31:00	00:09:00	4	13.9	120	228
3	14/11/2013	00:12:00	00:10:00	14.4	50	123	792
4	17/11/2013	08:12:00	00:00:00	1.2	4.2	72	72
5	20/11/2013	11:18:00	00:08:00	3.6	12.5	54	180

C.3 Runoff analysis means

Table_Apx C-2. Mean values for runoff sample variables from each treatment type. Within each Sampling Period, results followed by different letters are significantly different (p ≤ 0.05) following one-way ANOVA and post-hoc Fisher LSD.

No.	Treatment code	Total runoff volume (l)							
		1		2		3		5	
1	MPP No mulch	64.0	a	13.1	a	227	a	65.0	a
2	MPP St	67.7	a	43.8	a	252	a	96.9	a
3	Non-SSD Control	75.1	a	25.7	a	267	a	140	a
4	Non-SSD St	66.1	a	7.88	a	216	a	231	a
5	WT No mulch	76.7	a	63.2	a	241	a	53.2	a
6	WT St	105	a	11.5	a	259	a	99.4	a
7	NSLT No mulch	76.5	a	8.87	a	244	a	157	a
8	NSLT St	84.9	a	25.6	a	248	a	54.4	a

No.	Treatment code	Total soil loss (kg)							
		1		2		3		5	
1	MPP No mulch	0.11	a	0.92	a	3.03	a	0.04	a
2	MPP St	0.05	a	0.08	a	0.33	c	0.02	a
3	Non-SSD Control	0.12	a	1.31	a	2.00	a	0.10	a
4	Non-SSD St	0.04	a	0.09	a	0.62	b	0.08	a
5	WT No mulch	0.12	a	0.68	a	2.16	a	0.03	a
6	WT St	0.07	a	0.08	a	0.48	bc	0.03	a
7	NSLT No mulch	0.12	a	0.42	a	2.36	a	0.08	a
8	NSLT St	0.07	a	0.15	a	0.61	b	0.02	a

No.	Treatment code	Runoff sediment concentration (g l^{-1})							
		1		2		3		5	
1	MPP No mulch	1.14	d	7.64	cd	5.33	b	0.21	a
2	MPP St	0.49	abc	2.35	abc	0.89	a	0.30	a
3	Non-SSD Control	0.73	bc	10.7	d	5.69	b	0.26	a
4	Non-SSD St	0.24	a	2.47	ab	1.41	a	0.19	a
5	WT No mulch	0.66	bc	7.31	bcd	4.45	b	0.15	a
6	WT St	0.34	a	2.71	ab	1.29	a	0.13	a
7	NSLT No mulch	0.78	c	6.08	abcd	4.81	b	0.27	a
8	NSLT St	0.44	ab	2.29	a	1.23	a	0.12	a

Table_Apx C-3. Mean values for runoff nutrient analyses from each treatment type. Within each Sampling Period, results followed by different letters are significantly different ($p \leq 0.05$) following one-way ANOVA and post-hoc Fisher LSD.

No.	Treatment code	TON concentration (mg l^{-1})					
		1		3		5	
1	MPP No mulch	5.37	b	1.04	a	0.80	abc
2	MPP St	1.76	a	3.20	ab	1.23	d
3	Non-SSD Control	4.43	b	3.80	bc	0.96	bcd
4	Non-SSD St	0.58	a	12.1	c	1.12	cd
5	WT No mulch	4.40	b	1.83	a	0.71	ab
6	WT St	1.42	a	9.62	bc	0.54	a
7	NSLT No mulch	4.69	b	3.19	ab	0.74	ab
8	NSLT St	1.46	a	1.99	ab	0.46	a

No.	Treatment code	Orthophosphate P concentration (mg l^{-1})					
		1		3		5	
1	MPP No mulch	0.15	abc	0.17	a	0.13	a
2	MPP St	0.12	ab	0.38	a	0.25	a
3	Non-SSD Control	0.26	bcd	0.39	a	0.20	a
4	Non-SSD St	0.10	a	0.60	a	0.27	a
5	WT No mulch	0.27	cd	0.26	a	0.19	a
6	WT St	0.21	abcd	0.43	a	0.22	a
7	NSLT No mulch	0.34	d	0.33	a	0.18	a
8	NSLT St	0.17	abc	0.41	a	0.30	a

No.	Treatment code	Sediment-bound P concentration (mg kg^{-1})					
		1		3		5	
1	MPP No mulch	2112	abc	2067	a	2886	a
2	MPP St	1544	bd	2370	a	1872	a
3	Non-SSD Control	2379	ac	2004	a	2763	a
4	Non-SSD St	1304	d	2407	a	3288	a
5	WT No mulch	2485	a	2154	a	2629	a
6	WT St	2106	abc	2095	a	2486	a
7	NSLT No mulch	2630	a	2259	a	2791	a
8	NSLT St	1803	bcd	2441	a	2455	a

Table_Apx C-4. Mean values for runoff sample variables for different SSD types. Within each Sampling Period, results followed by different letters are significantly different ($p \leq 0.05$) following full factorial ANOVA and post-hoc Fisher LSD.

No.	SSD type	Total runoff volume (l)							
		1		2		3		5	
1	MPP	82.8	a	28.4	a	239	a	80.9	a
2	Non-SSD	70.6	a	16.8	a	241	a	186	a
3	WT	90.8	a	17.2	a	250	a	76.3	a
4	NSLT	80.7	a	39.9	a	246	a	106	a

No.	SSD type	Total soil loss (kg)							
		1		2		3		5	
1	MPP	0.08	a	0.50	a	1.68	a	0.03	a
2	Non-SSD	0.08	a	0.70	a	1.31	a	0.09	b
3	WT	0.09	a	0.38	a	1.32	a	0.03	a
4	NSLT	0.09	a	0.29	a	1.48	a	0.05	a

No.	SSD type	Runoff sediment concentration (g l^{-1})							
		1		2		3		5	
1	MPP	0.82	b	4.99	a	3.11	a	0.26	a
2	Non-SSD	0.49	a	6.60	a	3.55	a	0.23	a
3	WT	0.50	a	5.01	a	2.87	a	0.14	a
4	NSLT	0.61	ab	4.18	a	3.02	a	0.20	a

Table_Apx C-5. Mean values for runoff nutrient analyses from each SSD type. Within each Sampling Period, results followed by different letters are significantly different ($p \leq 0.05$) following full factorial ANOVA and post-hoc Fisher LSD.

No.	SSD type	TON concentration (mg l^{-1})					
		1		3		5	
1	MPP	3.56	a	2.12	a	1.02	b
2	Non-SSD	2.51	a	7.96	b	1.04	b
3	WT	2.91	a	5.73	a	0.63	a
4	NSLT	3.07	a	2.59	a	0.60	a

No.	SSD type	Orthophosphate P concentration (mg l^{-1})					
		1		3		5	
1	MPP	0.14	a	0.27	a	0.19	a
2	Non-SSD	0.18	a	0.49	a	0.23	a
3	WT	0.24	a	0.34	a	0.21	a
4	NSLT	0.26	a	0.37	a	0.24	a

No.	SSD type	Sediment-bound P concentration (mg kg^{-1})					
		1		3		5	
1	MPP	1828	a	2219	a	2379	a
2	Non-SSD	1841	a	2205	a	3025	a
3	WT	2296	a	2124	a	2558	a
4	NSLT	2217	a	2350	a	2623	a

Table_Apx C-6. Mean values for runoff sample variables for different mulch types. Within each Sampling Period, results followed by different letters are significantly different ($p \leq 0.05$) following full factorial ANOVA and post-hoc Fisher LSD.

No.	Mulch type	Total runoff volume (l)							
		1		2		3		5	
1	No mulch	73.1	a	18.0	a	245	a	104	a
2	Straw	89.4	a	33.2	a	244	a	120	a

No.	Mulch type	Total soil loss (kg)							
		1		2		3		5	
1	No mulch	0.12	b	0.83	b	2.39	b	0.06	a
2	Straw	0.05	a	0.10	a	0.51	a	0.04	a

No.	Mulch type	Runoff sediment concentration (g l^{-1})							
		1		2		3		5	
1	No mulch	0.83	b	7.94	b	5.07	b	0.23	a
2	Straw	0.38	a	2.45	a	1.20	a	0.19	a

Table_Apx C-7. Mean values for runoff nutrient analyses from each SSD type. Within each Sampling Period, results followed by different letters are significantly different ($p \leq 0.05$) following full factorial ANOVA and post-hoc Fisher LSD.

No.	Mulch type	TON concentration (mg l^{-1}) 1		3		5	
1	No mulch	4.72	b	2.47	a	0.80	a
2	Straw	1.30	a	6.73	b	0.84	a

No.	Mulch type	Orthophosphate P concentration (mg l^{-1}) 1		3		5	
1	No mulch	0.25	b	0.29	a	0.18	a
2	Straw	0.15	a	0.46	a	0.26	b

No.	Mulch type	Sediment-bound P concentration (mg kg^{-1}) 1		3		5	
1	No mulch	2402	b	2121	a	2767	a
2	Straw	1689	a	2328	b	2525	a

C.4 Event driven hydrological response means

Table_Apx C-8. Mean time to runoff initiation (minutes) of each treatment for the RE_1 of each Sampling Period. Within each Sampling Period values followed by different letters denote statistical significance ($p \leq 0.2$) following one-way ANOVA.

	Treatment	Sampling Period 1*	2		3		5	
1	Non-SSD Control		4.00	a	1.00	a	1.67	a
2	Non-SSD St		6.00	ab	1.00	a	1.33	a
3	NSLT No mulch		4.33	a	1.00	a	1.00	a
4	NSLT St		5.00	a	1.00	a	1.00	a
5	MPP No Mulch		12.0	bc	1.00	a	1.00	a
6	MPP St		4.50	a	1.00	a	1.00	a

	Treatment	Sampling Period			
		1*	2	3	5
7	WT No mulch		13.5 c		1.00 a
8	WT St		4.50 a	1.00 a	1.00 a

*Data not available due to logging error. N.B. Blank cells exist where no runoff was initiated.

Table_Apx C-9. Mean values for runoff cumulative volume and rates for RE$_1$ Sampling Period 2. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

		Time from RE$_1$ initiation (minutes)											
No.	**Treatment**	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**30**
Cumulative volume (l)													
1	Non-SSD Control	0.00 †	4.85 ‡	14.8 ab	25.4 a	27.3 a	28.1 a	29.1 a	32.7 a	34.6 a	35.6 a	36.6 a	38.4 a
2	Non-SSD St	0.00 †	0.00 ‡	0.00 b	6.60 bc	7.20 a	7.20 a	7.20 a	7.20 a	7.21 a	7.81 a	7.87 a	7.87 a
3	NSLT No mulch	0.00 †	3.63 ‡	11.2 a	18.9 a	20.5 a	21.7 a	22.9 a	24.1 a	25.3 a	25.9 a	26.6 a	27.3 a
4	NSLT St	0.00 †	0.00 ‡	34.9 a	48.9 a	51.0 a	51.9 a	52.5 a	53.2 a	54.5 a	55.3 a	55.3 a	55.3 a
5	MPP No Mulch	0.00 †	0.00 ‡	0.00 b	4.38 bc	5.56 a	6.15 a	6.75 a	7.35 a	7.96 a	11.3 a	11.9 a	12.5 a
6	MPP St	0.00 †	0.00 ‡	21.6 a	29.2 ac	31.3 a	32.2 a	33.3 a	35.9 a	37.4 a	40.2 a	41.6 a	43.1 a
7	WT No mulch	0.00 †	0.00 ‡	0.00 b	0.00 b	5.66 a	6.52 a	7.37 a	7.40 a	8.25 a	8.25 a	8.25 a	8.25 a
8	WT St	0.00 †	0.00 ‡	12.9 a	16.5 a	20.0 a	21.8 a	21.9 a	23.6 a	23.7 a	24.7 a	25.5 a	25.6 a
Runoff rate (l min^{-1})													
1	Non-SSD Control	0.00 ‡	4.85 ‡	7.41 a	1.88 a	0.87 ‡	0.04 ‡	0.06 ‡	0.91 ‡	0.94 a	0.95 ‡	0.12 ‡	0.02 ‡
2	Non-SSD St	0.00 ‡	0.00 ‡	0.00 a	1.19 a	0.56 ‡	0.00 ‡	0.00 ‡	0.00 ‡	0.00 a	0.56 ‡	0.05 ‡	0.00 ‡
3	NSLT No mulch	3.98 ‡	3.63 ‡	4.70 a	1.31 a	1.12 ‡	1.16 ‡	0.65 ‡	0.62 ‡	0.63 a	0.08 ‡	0.11 ‡	3.06 ‡
4	NSLT St	0.00 ‡	0.00 ‡	15.31 a	6.90 a	0.59 ‡	0.23 ‡	0.54 ‡	0.78 ‡	0.75 a	0.55 ‡	0.00 ‡	0.01 ‡
5	MPP No Mulch	0.00 ‡	0.00 ‡	0.00 a	0.57 a	0.56 ‡	0.56 ‡	0.56 ‡	0.56 ‡	0.56 a	0.05 ‡	0.00 ‡	0.00 ‡

		Time from RE_1 initiation (minutes)											
No.	**Treatment**	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**19**	**21**	**30**
6	MPP St	0.00 ‡	0.00 ‡	10.56 a	2.09 a	0.81 ‡	0.05 ‡	0.05 ‡	1.13 ‡	0.59 a	1.44 ‡	1.05 ‡	0.00 ‡
7	WT No mulch	0.00 ‡	0.00 ‡	0.00 a	0.00 a	0.86 ‡	0.03 ‡	0.01 ‡	0.01 ‡	0.85 a	0.00 ‡	0.00 ‡	0.00 ‡
8	WT St	0.00 ‡	0.00 ‡	7.32 a	1.85 a	1.76 ‡	0.85 ‡	0.09 ‡	0.00 ‡	0.07 a	0.08 ‡	0.84 ‡	0.00 ‡

†No data variance ‡Data not suitable for ANOVA.

Table_Apx C-10. Mean values for runoff cumulative volume and rates for RE_1 Sampling Period 3. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

		Time from RE_1 initiation (minutes)							
No.	**Treatment**	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**22**
Cumulative volume (l)									
1	Non-SSD Control	68.3 a	72.2 a	73.9 a	73.8 a	73.5 a	73.4 a	73.2 a	73.8 a
2	Non-SSD St	42.1 a	42.1 a	42.1 a	42.1 a	42.1 a	42.1 a	42.1 a	42.1 a
3	NSLT No mulch	41.0 a	41.0 a	41.0 a	41.0 a	41.0 a	41.0 a	41.0 a	41.0 a
4	NSLT St	38.8 a	38.8 a	38.8 a	38.8 a	38.8 a	38.8 a	38.8 a	38.8 a
5	MPP No Mulch	33.3 a	33.3 a	33.3 a	33.3 a	33.3 a	33.3 a	33.3 a	33.3 a
6	MPP St	52.8 a	52.8 a	52.8 a	52.8 a	52.8 a	52.8 a	52.8 a	52.8 a
7	WT No mulch	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a

		Time from RE$_1$ initiation (minutes)															
No.	**Treatment**	**1**		**3**		**5**		**7**		**9**		**11**		**13**		**22**	
8	WT St	21.4	a	21.4	a	21.4	a	21.4	a	21.5	a	21.4	a	21.4	a	21.4	a
Runoff rate (l min^{-1})																	
1	Non-SSD Control	68.28	a	0.59	‡	1.41	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.03	‡
2	Non-SSD St	42.07	a	0.00	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.00	‡
3	NSLT No mulch	40.95	a	0.01	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.00	‡
4	NSLT St	38.81	a	0.01	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.01	‡
5	MPP No Mulch	33.31	a	0.01	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.00	‡
6	MPP St	59.47	a	0.00	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.00	‡
7	WT No mulch	0.00	a	0.00	‡	0.00	‡	0.00	†	0.00	‡	0.00	‡	0.00	‡	0.00	‡
8	WT St	21.39	a	0.00	‡	0.00	‡	0.00	†	0.02	‡	0.00	‡	0.00	‡	0.00	‡

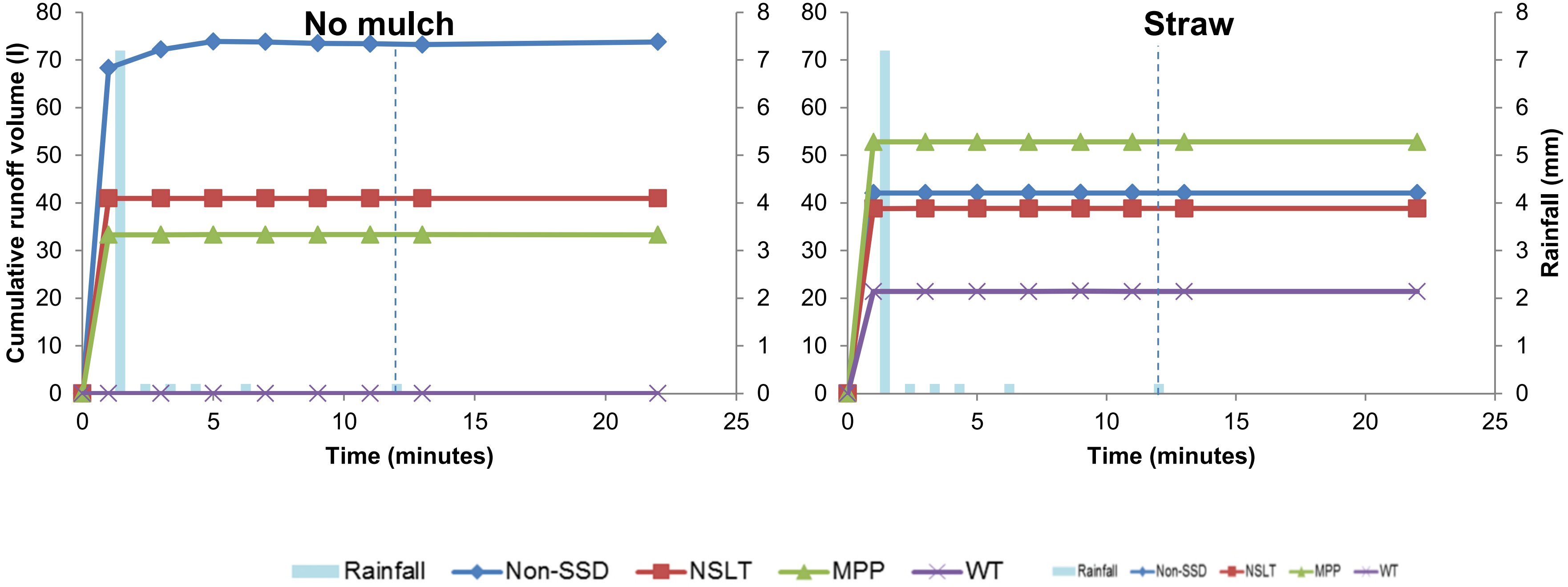
†No data variance ‡Data not suitable for ANOVA.

Table_Apx C-11. Mean values for runoff cumulative volume and rates for RE$_1$ Sampling Period 5. Within each variable and time interval, results followed by different letters are significantly different ($p \leq 0.20$) following one-way ANOVA and post-hoc Fisher LSD.

		Time from RE$_1$ initiation (minutes)							
No.	**Treatment**	**1**	**3**	**5**	**7**	**9**	**11**	**12**	**21**
Cumulative volume (l)									

		Time from RE_1 initiation (minutes)															
No.	**Treatment**	**1**		**3**		**5**		**7**		**9**		**11**		**12**		**21**	
1	Non-SSD Control	127	a	127	a	127	a	127	a	128	a	132	a	133	a	140	a
2	Non-SSD St	119	a	119	a	119	a	119	a	119	a	120	a	121	a	131	a
3	NSLT No mulch	97.8	a	97.8	a	97.7	a	98.9	a	101	a	104	a	107	a	114	a
4	NSLT St	40.4	a	40.6	a	36.8	a	40.0	a	40.6	a	42.5	a	43.1	a	46.2	a
5	MPP No Mulch	58.7	a	58.7	a	58.7	a	58.7	a	58.7	a	58.7	a	58.7	a	58.7	a
6	MPP St	62.6	a	62.5	a	62.6	a	62.6	a	62.5	a	64.3	a	65.2	a	71.1	a
7	WT No mulch	50.1	a	50.1	a	50.1	a	50.6	a	50.6	a	50.6	a	50.6	a	50.6	a
8	WT St	63.9	a	63.9	a	63.9	a	65.2	a	66.6	a	68.6	a	70.6	a	76.9	a
Runoff rate (l min^{-1})																	
1	Non-SSD Control	127	a	0.01	‡	0.00	‡	0.09	‡	1.42	a	1.68	a	1.70	‡	0.00	a
2	Non-SSD St	119	a	0.01	‡	0.00	‡	0.00	‡	0.01	a	1.06	a	1.63	‡	0.00	a
3	NSLT No mulch	97.8	a	0.00	‡	0.00	‡	1.13	‡	0.42	a	1.99	a	2.83	‡	1.34	b
4	NSLT St	40.4	a	0.00	‡	0.00	‡	0.00	‡	0.07	a	1.15	a	0.64	‡	0.00	a
5	MPP No Mulch	58.7	a	0.01	‡	0.00	‡	0.02	‡	0.01	a	0.00	a	0.00	‡	0.00	a
6	MPP St	62.6	a	0.01	‡	0.19	‡	0.23	‡	0.07	a	0.93	a	0.94	‡	0.85	b
7	WT No mulch	50.1	a	0.00	‡	0.00	‡	0.56	‡	0.00	a	0.00	a	0.00	‡	0.00	a
8	WT St	63.9	a	0.01	‡	0.00	‡	0.62	‡	0.63	a	1.31	a	2.01	‡	0.84	b

†No data variance ‡Data not suitable for ANOVA.



Figure_Apx C-1. Runoff hydrographs for RE$_1$ of Sampling Period 3. Cumulative runoff volume is shown at set intervals during the Rainfall Event as well as 1 minute and 10 minutes post Rainfall Event cessation.

C.5 Treatment observations

Figure_Apx C-2. Shallow soil disturbance degradation over the duration of Phase 2 field trials. Plots from left to right show soil disturbance undertaken by WT, NSLT and MPP. The top photograph was taken on the 30th April 2013 and the bottom three photos on the 24th July 2013.

Appendix D Economic Appraisal

D.1 Phase 2 tine configuration fuel requirement calculations

The following calculations are based on formula sourced from personal communication with K. Blackburn (2014).

1. Draught power calculation

Draught Power = Force x Speed

Tine configuration	Draught force (N)	Speed (m s^{-1})	Draught power (Watts)
MPP	2080	0.58	1206.4
NSLT	1680	0.58	974.4
WT	2550	0.58	1479.0

2. Engine mechanical output calculation

= (Draught Power / 1 – Slip) / Transmission loss

Tine configuration	Draught power (Watts)	Slip ratio†	Transmission loss ratio†	Mechanical power (Watts)
MPP	1206.4	0.1	0.8	1676
NSLT	974.4	0.1	0.8	1353
WT	1479.0	0.1	0.8	2054

†Assumptions based on personal communication with K. Blackburn, 2014.

3. Thermal input power calculation

= Mechanical Power / Thermal input

Tine configuration	Mechanical power (Watts)	Thermal input factor†	Power (energy) released (Watts)
MPP	1676	3	5027

Tine configuration	Mechanical power (Watts)	Thermal input factor[†]	Power (energy) released (Watts)
NSLT	1353	3	4060
WT	2054	3	6163

[†] Based on personal communication with K. Blackburn (2014).

4. Fuel required to generate power

= Power released / Specific energy of diesel

Tine configuration	Power (energy) released (Watts)	Specific energy of diesel ($J\ l^{-1}$) [†]	Fuel required ($l\ s^{-1}$)
MPP	5027	38.6×10^{-6}	1.38×10^{-4}
NSLT	4060	38.6×10^{-6}	1.12×10^{-4}
WT	6163	38.6×10^{-6}	1.69×10^{-4}

[†] Based on a low heating value sourced from the Engineering Tool Box available at: http://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html.