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Linking soil erosion processes with arable weed seedbank dynamics to inform sustainable cropping

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Linking soil erosion processes with arable weed seedbank dynamics to inform sustainable cropping

By

Timothy D Lewis

University of Dundee

Submitted: March 2014

Declaration

I hereby declare that the following thesis is based on the results of investigations conducted by myself, and that this thesis is of my own composition. This thesis has not, in whole or part, been previously presented for a higher degree. Work other than my own is clearly indicated in the text by reference to the relevant researchers or publications. I would like to thank those who allowed me to refer to their unpublished observations and data, which are individually acknowledged where they occur

Signature ....

Date ....

I confirm that the conditions of the relevant Ordinance and Regulations have been fulfilled in relation to this thesis

Signature .... …… Prof. John S. Rowan

Date ....

Abstract

Accelerated soil erosion affects sustainable food production through the degradation of arable soils resulting in lower crop yields and compromising biodiversity. Over the past 50 years, the weed seedbank has been declining due to farming intensification, increased herbicide use and weed suppression through competitive autumn crop planting. However, there is less recognition of the potential of soil erosion affecting the weed seedbank. This thesis contributes to an improved understanding of the effect of geomorphological processes (soil erosion) on biological systems (weed seedbank) in arable ecosystems.

The first investigation assessed whether the management of farm machinery field tramlines would decrease soil erosion rates and effect the movement of weed seeds. Over three winter seasons, eroded material was collected by a network of Gerlach Troughs. The results showed that tramline management with a spiked harrow decreased soil and seed loss by 93.9% and 86.56% respectively, compared to regular tyre tramlines. Analysis of seed data to runoff and sediment load found seeds were transported along with sediment (r^2=0.62) rather than runoff (^{r2}=0.2) over the long term. In addition, tramline management significantly affected the number of seed species transported ($p<0.001$), which was found to relate to seed morphologies. Overall, tramlines cause 0.01% - 0.32% seed fluxes annually depending on management. These findings have implications for farmers to protect tramlines from erosion and displace seeds through management thereby, preventing the loss of biodiversity within the field.

The second investigation looked at the movement of weed seeds at the field scale by erosion through the use of a radionuclide (^{137}Cs) tracer. A single field was sampled for seedbank and soil cores taken for ^{137}Cs analysis in two sub field grids. The results indicated weak relationships between seedbank densities and erosion. The weak relationships in the grids (r^2 =0.13, p =0.029 in 2011 and r^2 =0.12, p = 0.036) were due to land management contributing to spatial variability within seedbank abundance and composition. Individual species showed mixed responses to erosion rates. The findings indicate farmers need to consider management strategies at field scale to effectively manage erosion and seedbanks because seedbank losses of between 2 – 2.5 % annually within the field which is linked to field scale sediment budgets.

The third investigation looked at specific environmental controls that would affect soil erosion and seedbanks. This was achieved by using a portable rainfall simulator on plots containing either seeds from the natural seedbank or spiked with seeds. The key control was the presence of crop/vegetation cover in affecting erosion rates ($p<0.001$) and seed movement ($p = 0.001$). The presence of crop cover resulted in low erosion rates but a greater loss of seeds compared to plots with no crop cover. This was linked to vegetation cover providing a protective environment for weeds to grow and produce additional seeds via seed rain. Ground cover prevents erosion but also highlighted seed movement was higher than on bare soil due to a greater availability. This means that surface wash is more important than rainfall in causing seed transport. For spiked plots, more seeds were displaced in short (3 minute) events compared with long (6 minute) events ($p = 0.04$). This shows protecting the soil and seedbank from rainfall detachment is crucial to preventing transport of sediment and seeds that could enter other transport pathways (e.g. tramlines, rills, gullies).

The fourth investigation looked into the processes and impacts of soil erosion on seedbanks at the catchment scale. This was done by establishing a monitoring station at the outlet of an arable catchment for one year to monitor discharge, suspended solids and seed flux. The results of monitoring in 2012 found seeds numbers were positively related to discharge (observed $r^2 = 0.62$, $p<0.001$; observed plus modelled $r^2=0.50$, $p <0.001$) and sediment load (observed $r^2 = 0.64$, $p<0.001$; observed plus modelled $r^2= 0.89$, $p<0.001$). Seed species had poor negative relationships with discharge (observed $r^2 = 0.03$, $p=0.357$; observed plus modelled $r^2=0.11$, $p = 0.017$) and sediment load (observed $r^2 <0.001$, $p=0.352$; observed plus modelled $r^2=0.14$, $p=0.004$). An initial estimate of losses from the catchment was around 0.008 – 0.027% of the weed seedbank. Interestingly, there appeared to be a trend in the abundance of seed collected relating to patterns of farming activity within the catchment. This finding has management implications as there is evidence, for the first time, of arable weed seeds being exported from the catchments, which could affect other agricultural land and ecosystems downstream.

The findings of these four investigations showed that the effect of soil erosion on the seedbank is connected at different spatial scales. Scope for future work is to improve the understanding of the role of seed morphologies, land management and field scale processes affecting the transportability of seeds by erosion processes.

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Involvement with Sustainable Arable LINK Project RD 2007-3386

In response to the need for better data on soil losses subject to different cultivation practices, specifically about tramline management techniques, a £1.2 million Sustainable Arable LINK project led by ADAS was established (Project RD 2007-3386). As part of the UK wide project, Balruddery Farm was used as one of four sites in the investigation into cost effective pollution reduction techniques from tramlines.

In this thesis, I collaborated with the project in order to conduct fieldwork over three winter seasons studying the movement of weed seeds down tramlines. The experimental design and results can be found in Chapter 2. Here, I outline the role and responsibilities I had with the overall project in the operation and maintenance of the field equipment and experiment. My main role was to be part of the team at the James Hutton Institute (led by Dr Blair McKenzie) to help with the installation and running of the experiment between 2010 and 2013. This involved being available to install equipment at the start of each winter season, visiting the farm to assess if sampling was necessary after precipitation events and collect samples for both the project and my own work.

For clarity, runoff and sediment data (excluding particle size analysis) were collected as part of the LINK project. I assisted in the collection of samples for analysis of phosphorus and nitrogen concentration, as well as measuring total suspended solids. In addition, I added value to the project through in addition of particle size analysis of sediments and the collection of weed seeds from samples. Data relating to the movement of seeds compliments the findings of the LINK project but were not part of the original project proposal.

Chapter 1: Introduction, Literature Review, Aims & Objectives

1.1 Introduction

Soil erosion is a natural process of landform and landscape evolution involving the detachment, transport and deposition of mineragenic and organic sediments. This process is naturally occurring but can be exacerbated by human activity, such as farming. Land cover change and intensification of farming are widely linked to accelerated soil erosion (Zhang *et al.*, 2007; Morvan *et al.*, 2008). The average annual rate of soil loss by erosion on arable land across Europe is estimated to lie within the range of ca. 3 – 40 t ha^{-1} yr^{-1}, which locally can exceed 100 t ha^{-1} yr^{-1} (Verheijen *et al.*, 2009). This raises concerns about on-site nutrient depletion, decreased soil aggregation and loss of productivity, and off-site impacts through sedimentation and eutrophication of downstream water bodies (Rowan *et al.*, 2012). Climate change is further expected to increase the extent and severity of soil erosion arising from more frequent extreme events (Cerdan *et al.*, 2010). Intensification of farming not only increases soil erosion, but is also associated with declines in the abundance and diversity of arable weeds and may generate increasingly homogeneous plant assemblages (Brazier, 2004; Baessler and Klotz, 2006; Hawes *et al.*, 2010; Gunton *et al.*, 2011).

Weeds provide valuable ecosystem services (e.g. nutrient cycling, pollination and pest regulation) within agro-ecosystems by maintaining a diverse flora that provides stable food and habitat resources for a range of detritivores, herbivores, pollinators, predators and parasitoids (Hawes *et al.*, 2003; Gibson *et al.*, 2006; Hyvönen and Huusela-Veistola, 2008; Evans *et al.*, 2011). This emerged weed flora is dependent on annual regeneration from the arable weed seedbank. Seedbank diversity is recognised as an important buffer against short-term disturbance events and provides a degree of redundancy facilitating adaption to long-term change (Venable and Brown, 1988; Loreau *et al.*, 2003; Fried *et al.*, 2009). However, there is a need for balance between managing a healthy arable ecosystem and maximising crop productivity. To achieve this, weeds need to be managed to achieve densities that are not competitive with the crop, whilst still occurring in sufficient abundance to maintain viable populations of species with high resource value to arable food webs (Albrecht and Auerswald, 2009).

The inter-relationship of soil erosion with vegetation is well documented as plants intercept direct rain splash, promote infiltration, enhance water retention and dissipate surface runoff (Jiao *et al.*, 2009; Zhongming *et al.*, 2010). However, there is a paucity of field studies exploring the linkages between soil erosion and seedbanks, particularly in arable contexts. Seedbanks are well described in terms of the biological (predation, pathogens and seed death) and agricultural (tillage, chemical treatments and cropping histories) controls on their diversity and abundance patterns (Buhler *et al.*, 1997; Albrecht and Auerswald, 2009), but the potential impact of erosion is rarely addressed. There have been some small-scale studies focusing on seed mobility in laboratory experiments (e.g. Cerdà and García-Fayos, 2002) whilst others that have assessed seed movement at the catchment scale (e.g. Goodson *et al.*, 2003; Gurnell *et al.*, 2006). However, the link between hillslope scale soil erosion and weed seedbank diversity and abundance within arable fields represents a major gap in our understanding of temperate agro-ecosystems.

This review assesses the potential significance of accelerated soil erosion as an under-recognised redistributive mechanism influencing the composition and abundance of weed seedbanks in arable agro-ecosystems. A brief review of erosion and field-scale sediment dynamics (entrainment, transport and deposition) is presented. This is followed by a synthesis of the key biological and agronomic factors influencing seed bank characteristics (e.g. field management, dispersal, seed rain and mortality). Finally, the likely consequences of the redistribution of weed seed assemblages by entrainment, transport and deposition processes associated with soil erosion at the field scale and beyond.

1.2 Literature Review

1.2.1 The extent and impact of soil erosion in arable ecosystems

Soil erosion, by water, wind, tillage or crop harvesting, is a three stage process involving detachment of soil particles (entrainment), transport of the detached material and finally deposition (Verheijen *et al.*, 2009). Water erosion is a balance between erosivity (determined by rainfall intensity and runoff shear stress) and erodibility (effective soil strength arising from texture, structure and the binding effects of plant roots) (Brazier, 2004). Water erosion occurs when raindrop impact dislodges material or when overland flow results from rainfall exceeding the infiltration rate by either ‘infiltration-excess’ or ‘saturation-excess’ mechanisms (Morgan, 2005). For temperate environments, intense rainfall (>10 mm hr^{-1}) for a single short duration event can be as erosive as lower intensity but longer duration events depending on antecedent water content and local soil conditions (such as aggregation) and vegetation cover (Bracken and Croke, 2007). In Europe, mean water erosion rates are between 0.1 and 5 t ha^{-1} yr^{-1} (Cerdan *et al.*, 2010).

Wind erosion of soil is also a widespread phenomenon in agro-ecosystem that can lead to removal and damage of top soils (Riksen *et al.*, 2003). Wind erosion also causes secondary disturbances by mobilisation of dust particles that damage vegetation and transport pathogens, leading to a decrease in vegetation cover, which creates a positive feedback and increases erosion susceptibility (Morgan, 2005). Wind erosion occurs mainly on vulnerable sandy or organic soils (Fullen, 2003; Banwart, 2011). However, Riksen *et al.* (2003) highlighted that wind erosion is not confined to these areas. Over three million hectares of lowlands in north-western Europe are prone to wind erosion due to poor management. Wind erosion rates across England and Wales are estimated at 0.1–2 t ha^{-1} yr^{-1} (Chappell and Thomas, 2002).

Tillage erosion, involving the systematic downslope displacement of soil by ploughs and associated tillage equipment, has long been recognised but only recently systematically evaluated. Arable land contributes over 70% of the total soil erosion in Europe with an average soil loss rate of 3.6 t ha^{-1} yr^{-1} (Cerdan *et al.*, 2010). The envelope of soil loss rates across European arable landscapes lie within the range of 0.1–10 t ha^{-1} yr^{-1} (Van Oost *et al.*, 2006; Verheijen *et al.*, 2009). Soil loss by crop harvesting, either by adhering to cultivation equipment or being co-extracted with the harvest, has also only relatively recently been acknowledged as a contributory ‘erosion’ mechanism, particularly for soil bound to root crops such as potatoes, beets and carrots. An indicative figure up to

2.5 t ha^{-1} yr^{-1} for soil loss associated with root and tuber crop harvesting was suggested by Quine *et al.* (2006), whilst Verheijen *et al.* (2009) report a wider range of between 1.3–19 t ha^{-1} yr^{-1} across mainland Europe.

The cost of soil erosion across the EU is estimated at £0.6 - 11 billion per year (Jones *et al.*, 2012). In the UK, the impact of accelerated soil erosion was valued up to £38 ha^{-1} yr^{-1} (Morgan, 2005; Verheijen *et al.*, 2009; Dobbie *et al.*, 2011). Importantly, these costs encompass on-site (productivity loss) and off-site environmental and socio-economic impacts, but hitherto such estimates have not accounted for value loss of ecosystem services provided by the weed seedbank or other soil biota. Dobbie *et al.* (2011) estimate erosion costs the economy of Scotland £60.5 million annually as a result of loss of organic matter from soils and related loss of ecosystem services but this is likely to be much smaller than the cost for agro-ecosystem loss of functionality.

Erosion processes span scales from the inter-particle scale, controlled by response to rain-splash, to the landscape scale where topography, hydrogeology and land management control hydrological pathways (Van Oost *et al.*, 2006). Challenges in reliably estimating erosion rates arise from short-term funding and difficulties in up-scaling from detailed plot-scale studies to the field and catchment scale (Boix-Fayos *et al.*, 2006). Thus a practical compromise is typically made between the physical scale over which measurements are made and their temporal resolution. For example, erosion field plots often produce high quality event-based data over a limited duration of an experimental programme. However, the complexity of routing and sediment delivery found over longer time (e.g. decadal) and large spatial (e.g. field and landscape) scales are not reflected with plot data (Boardman, 2006; Boix-Fayos *et al.*, 2006). Figure 1.1 illustrates the key elements of a sediment budget representing both erosion and sediment storage within arable landscapes.

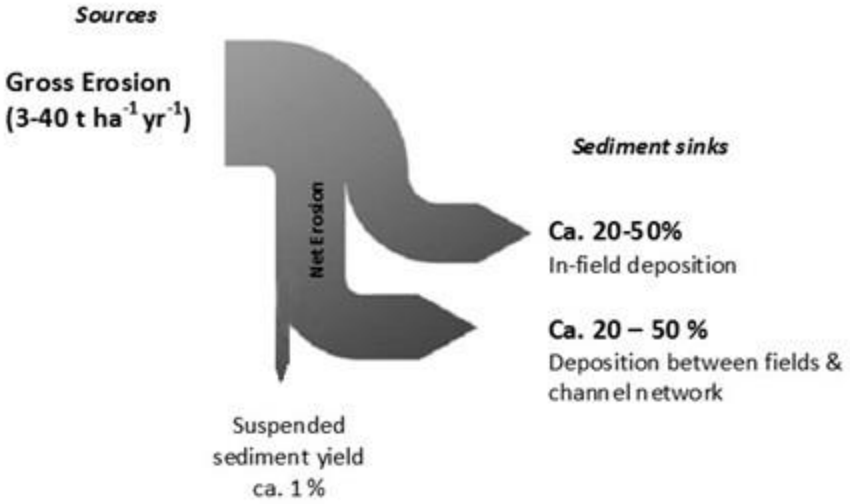

Figure 1.1 - Generalised field and headwater sediment budget within lowland arable landscape settings (data sources: Walling *et al.,* 2006; DEFRA, 2008; Verheijen *et al.*, 2009).

Quantifying sediment fluxes over larger scales may involve multiple assessment techniques ranging from measurement of rill dimensions, radiometric surveys, sediment fingerprinting and suspended-sediment yield determinations (*cf.* Walling *et al.,* 2006; Rowan *et al.,* 2012). An important distinction is made between ‘gross erosion’ which is the sum total of all eroded sediment mobilised and ‘net erosion’ which accounts for the proportion of the eroded sediment deposited within fields e.g. in hollows and foot slopes or vegetated buffer strips, ditches and field boundaries. The ratio of gross to net erosion equates to a ‘sediment delivery’ ratio and varies widely within the range between ca. 20–50% (Brazier, 2004; Walling *et al.*, 2006; DEFRA, 2008) dependent on climate, landscape setting, slope length and shape, soil texture, cultivation practices and slope-channel connectivity (Small *et al.*, 2003).

Erosion and downslope sediment delivery typically exhibit a high degree of size selectivity (Table 1.1). Unconfined sheet flow tends to be the most selective because the finest particles are most readily entrained, whilst the coarsest fraction tends to be preferentially deposited (Morgan, 2005). The size of particles can be expressed as water stable aggregates (effective particle size) or as ultimate particle size (after chemically and mechanically dispersing the water stable aggregates). Slattery and Burt (1995) showed that for rills and gullies the detachment of particles is by the collapse of channel side walls addition to basal scour. The material coming from the collapse does not require dispersion of aggregates and hence the effective particle size in the entrained material is larger than

Table 1.1 Characterisation of erosion processes to indicate the impacts on seedbank redistribution in arable ecosystems from Lewis *et al.* (2013).

Mode	Processes	Depth (m)	Description	Step-length (m yr^{-1})	Significance for seedbank redistribution within arable agro-ecosystems
Water Erosion	Splash	10^{-3}	Mechanical impact of precipitation on soil surface resulting in net down slope transport	10^{-2}	Within-field selective detachment and dispersal of small light seeds on soil surface.
	Interill	10^{-2}	Scour and down slope transport of soil by unconfined sheet flow and splash	10^{-1} - 10^{1}	Selective entrainment and transport of near surface seeds, especially those with small, light and simple morphologies without mucilage (feeds rill network).
	Rill	10^{-2}-10^{-1}	Rills are micro-channels formed by flow convergence to a threshold beyond which bed scour and channelized flow occurs	10^{-1} - 10^{2}	Soil and climate determine rill dimensions and densities. Bed scour and side-wall collapse means seeds lost to full profile depth and non-selective transport of seeds. Loss from field.
	Piping (tunnelling)	10^{-2} - 10^{0}	Subsurface erosion due to percolating water creating network of pipe-like conduits.	10^{-1} - 10^{2}	Seed loss patterns depend on depth where pipe gallery is active i.e. near-surface or several metres below ground.
	Gully	10^{-1}-10	Large linear channelised scour features typically with stepped long-profile	10^{0} - 10^{4}	Deep scour features can extend into the sub-soil resulting in complete loss of seedbank (no hydrodynamic sorting) from fields.
	Tramlines	10^{-2}-10^{-1}	Tracks within arable fields used by farm machinery to plant, manage and harvest crops	10^{-1} - 10^{2}	Tramlines typically compacted with decreased infiltration. Preferentially capture runoff so locus for rill/gully development.
Wind Erosion	Deflation & abrasion	10^{-2} - 10^{-1}	Combines abrasion (mechanical impact by wind-entrained debris) and deflation which is entrainment and transport of soil and seeds from the land surface	10^{0} - 10^{5}	Scour depth depends on soil conditions and wind climate; and seed transport depends on aerodynamic characteristics. Size selective in low intensity events and physical impacts may change viability of some seeds. Transport typically off-field.
Mass Movements	Creep, slides, slips and flows	10^{-1} - 10^{1}	Range of mechanisms represented from soil creep in surface layers to deep seated slides and rotational failures	10^{-1} - 10^{4}	Depth of active processes depends on geomorphology and landscape setting. Displacement and export of seed bank throughout the depth of the failure – loss into channel network.

Table 1.1: .cont.

Mode	Processes	Depth (m)	Description	Step-length (m yr^{-1})	Significance for seedbank redistribution within arable agro-ecosystems
Tillage Erosion	Ploughing and crop management	10^{-1} - 10^{0}	Conventional mouldboard tillage operations results in net local downslope soil displacement from the top of the field exposing subsoil at the crest while burying soil at the bottom.	10^{-1} - 10^{0}	Local topography and slope curvature important e.g. erosion greatest on upper slopes and ridges with displaced soil accumulating in swales and field base. Seed redistribution maybe size selective – effects include mechanical impact, displacement and seed burial. Processes are largely contained within-field.
	Harvesting	10^{-1} - 10^{0}	Soil loss associated with harvesting, especially root crops such as beets, potatoes & carrots	10^{2} - 10^{3}	Export of seeds from soil mass bound to root crops and farm vehicles translocated to off-field processing locations.

the ultimate particle size. Effective-grain size distributions are considerably greater than ultimate-grain size distributions because transported sediment mainly comprises of aggregates containing substantial amounts of clay and silt particles bound by organic matter and, potentially, seeds from the soil matrix. The specific mobility of seeds within the soil is likely to be similar to soil particles of the same size, but will also depend on the nature of local erosion processes, the depth distribution of seeds within the soil profile, and the seed's hydrodynamic properties (size, shape, mass and other surface characteristics such as mucilage and microsculpture) (*cf.* Benvenuti, 2007).

Recent years have witnessed much greater attention to the off-farm or downstream consequences of soil erosion from arable land in the form of sediment-associated nutrient losses. Much effort has been directed towards the control of diffuse pollution, and in particular the significant role played by runoff derived from farm machinery wheelings (tramlines). Deasy *et al.* (2009) found controlled trafficking and tramline disruption decreases soil and nutrient losses more effectively than traditional treatments such as residue incorporation, minimum tillage, contour cultivation and vegetation barriers. Silgram *et al.* (2010) showed that tramline disruption techniques reduced both soil and sediment-associated phosphorus loss by more than 86%. By comparison, little attention has been paid to assessing the rates and significance of seed mobilisation from the seedbank and the consequences, particularly in terms of systemic losses from perennial sources and accumulation within local deposition sites.

Conventional tillage practices are frequently associated with physico-chemical degradation of soil profiles. This is due to organic matter losses, compaction and decreased infiltration rates hence increasing soil profile susceptibility to erosion (Fullen, 2003; Brazier, 2004; Morgan, 2005). The style and intensity of erosion within any particular landscape setting will have different consequences in a direct sense through loss or gain in seedbank inventory but also indirectly in terms of the depth distribution and the quality of the resultant seedbed as a growth medium.

1.2.2 The weed seedbank of agro-ecosystems

The weed seedbank is a dynamic reserve of viable seeds on, or incorporated within, the soil (Brenchley, 1918; Brenchley and Warington, 1933; Roberts, 1964; Feast and Roberts, 1973; Csontos and Tamás, 2003). Seedbanks have been described as a botanical 'memory' because they preserve genotypes that maybe absent from the standing vegetation community (Harper, 1977; Davis *et al.*, 2005). The persistence of seeds in the seedbank make them far less sensitive than the emerged flora to immediate conditions of the field or weather and therefore confer some resilience to the arable weed community (Wilson and Lawson, 1992). The number and diversity of plants comprising the weed flora has declined over the past 50 years, along with other indicators of biodiversity: the main causes of this decline being farming intensification, the increased use of herbicide and the competitive suppression of weeds by autumn-sown crops (Robinson and Sutherland, 2002; Marshall *et al.*, 2003; Gibson *et al.*, 2006). The seedbank is therefore a valuable reference in studies of ecological impact and in the conservation and restoration of the commoner arable flora (Firbank, 1999; Firbank *et al.*, 2003; Heard *et al.*, 2003a; Heard *et al.*, 2003b; Perry *et al.*, 2003).

Within UK agro-ecosystems arable weed seed densities generally lay within a range between 10^3 - 10^6 seeds m^{-2}, most being concentrated in the top 15cm of the soil profile (Thompson *et al.*, 1997; Firbank, 1999; Squire *et al.*, 2003). High seed population densities ($> 10^5$ m^{-2}) and species richness (around 40 species per field) were recorded throughout the last century in ploughed land under poor weed control (Brenchley and Warington, 1933; Roberts and Feast, 1973; Squire *et al.*, 2000). Very low seedbank populations of around 10^2 m^{-2} and as low as 10 species in a field, were recorded whenever management suppressed weeds for many years, whether by mechanical cultivation (Brenchley, 1918) or the use of herbicides (Marshall and Arnold, 1994). Populations have remained capable of rapid dynamics, readily increasing if control is relaxed over several years, or declining by up to 50% a year if seed return is severely reduced or prevented (Brenchley and Warington, 1933; Roberts, 1962; Roberts and Feast, 1973; Wilson and Lawson, 1992).

Taxa can be separated according to the longevity of their viability within the seedbank (Bekker *et al.*, 2003), with a distinction typically made between transient species, i.e. seeds which remain viable only to the next opportunity to germinate, and persistent species i.e. seeds which enter secondary dormancy and remain viable in the soil for longer than one year (Hulme, 1998). The key biotic processes determining arable seedbank abundance and composition include augmentation through seed rain and immigration, and losses through dispersal, seed mortality, germination and emigration (Forcella, 2003). These processes are affected by the timing and intensity of crop management (Brenchley and Warington, 1933; Robinson and Sutherland, 2002; Hyvönen *et al.*, 2003; Andreasen and Skovgaard, 2009).

1.2.2.1 Seed Rain

Seed rain from parent plants is generally the primary input into the seedbank of arable fields (Jones *et al.*, 2003). Seed input varies depending on weed species fecundity, environmental conditions, surrounding vegetation, tillage and management intensity, rotation (particularly the frequency of winter cropping) and farming practice (Jones and Naylor, 1992; De Cauwer *et al.*, 2008; Hawes *et al.*, 2010). Thus seed inputs to the seedbank are susceptible to factors that affect the above-ground vegetation within cropped fields. The timing of disturbance events through the growing season (herbicide, cultivations, etc.) in relation to germination, flowering and seed-set is particularly important in determining the resulting species composition (Heard *et al.*, 2003a; Heard *et al.*, 2003b; Squire *et al.*, 2003).

Soil characteristics, such as concentrations of organic carbon and total nitrogen, play an indirect role on arable seedbanks through their effect on parent plant growth, thereby altering the reproductive potential of different species or plant functional types (Brenchley and Warington, 1933; Andreasen and Skovgaard, 2009; Hawes *et al.*, 2009). Field management can generate patchy distributions of emerged weeds across the field which will influence the input of new seed to the seedbank. For example, tramlines, headlands and wheelings create patches within the field where competition with the crop may be reduced allowing increased reproductive output and a potential change in species composition (Albrecht, 2003; Davis *et al.*, 2005; Bohan *et al.*, 2011). Soil erosion may also generate patches of low seed abundance in eroded regions of a field and greater seed abundance in depositional areas. Differential rates of seed rain in these patches may exacerbate the impact of erosion by increasing the rate of seed return to the soil in high density patches relative to areas where seeds are scarce.

1.2.2.2 Dispersal

Diplochory is the two stages of seed dispersal, comprising both detachment from the parent plant and subsequent translocation to the eventual site of germination (Chambers and MacMahon, 1994; Vander Wall and Longland, 2004; Cousens *et al.*, 2008). Detachment can involve multiple pathways ranging from immediate gravity fall from the parent plant (barochory) to distances of hundreds of kilometres for small and light (<0.0001 mg) wind dispersed seeds (Benvenuti, 2007). Larger and heavier seeds (> 4 mg) usually fall within 1-2 m of the parent plant but can be transported up to 100 m by wind (Smith and Kok, 1984; Benvenuti, 2007). From the soil surface, seeds may be further dispersed by a range of abiotic and biotic dispersal mechanisms (Cousens *et al.*, 2008). The suggestion that movement of soil (and the seeds therein) by water or wind erosion is a mechanism of dispersal that has been under-researched in relation to its potential biodiversity significance within and between arable fields.

1.2.2.3 Mortality

Predation is a major factor determining seed mortality rates, with reported annual loss rates ranging from 2 - 86%, varying with predator type and environmental conditions (Watson *et al.*, 2003; Westerman *et al.*, 2003; Navntoft *et al.*, 2009; Davis *et al.*, 2011; Westerman *et al.*, 2011). Seed mortality through oxidative damage (Bernal-Lugo and Leopold, 1998), disease and microbial activity (Chee-Sanford and Fu, 2010) has also shown to be locally significant. Finally, mortality due to the direct action of disturbance (e.g. field operations and erosion) on seeds also has the potential to alter the abundance, composition and structure of the remaining seedbank community by covering seed (effectively burial) with transported and deposited sediment (Roller *et al.*, 2003; Tørresen *et al.*, 2003).

1.2.2.4 Germination

Most seeds are lost from the seedbank through the process of germination (Grime *et al.*, 1981). Seed depth within the profile is a vital determinant of germination potential due to dormancy (Cousens *et al.*, 2008), which in turn is conditioned by the duration of burial (Grundy *et al.*, 2003a; Mennan and Zandstra, 2006). Furthermore, burial below the critical emergence depth will prevent germinating seedlings from reaching the surface (Thompson *et al.*, 1993; Grundy *et al.*, 2003a; Cousens *et al.*, 2008). The critical burial depth is a function of seed size, with larger seeds having greater energy reserves to emerge from deeper in the profile. Build-up of eroded soil in depositional regions of a field could therefore have a major impact on the germination potential of seeds in the seedbank and may alter the composition of the weed community by selectively preventing the germination of species with seeds smaller than the critical size for a given burial depth.

Seeds can be moved both up and down the soil profile depending on soil texture, tillage practice and the intensity of erosion and sedimentation (Benvenuti, 2007; Cousens *et al.*, 2008). Soil texture may influence seed movement: cohesion of soil particles (particularly in clay soils where cohesive forces are high) may either produce barriers to movement in stable soils, or increase movement by binding with seed in regions where soil is eroding (Benvenuti, 2007).

Tillage is a major factor affecting within-field seed distribution and abundance (Grundy *et al.*, 2003b; Tørresen *et al.*, 2003; Benvenuti, 2007). Preparing soil prior to sowing performs a number of functions: a) creating homogenous seed-bed that will encourage uniform crop germination, b) loosening the soil to enhance root penetration, c) exposing organic material to mineralisation and nutrient release, and d) controlling weeds, either by burying seeds to below the critical depth for emergence, or encouraging germination so that they can be controlled by a single pre-emergence herbicide application (Morgan, 2005; Lamour and Lotz, 2007). Annual ploughing of cereal fields can bury surface seed to below germination depth, but will bring seeds from previous years back up to the near-surface. Studies using beads show lateral movement can range between 0.26 and 1.58 m (Marshall and Brain, 1999) whilst vertical displacement can occur in the top 30 cm subject to tillage practice (Mohler *et al.*, 2006; Spokas *et al.*, 2007). This may have a significant impact on the population dynamics of annual or biannual weeds that rely on annual recruitment from the seedbank. Increased uptake of non-inversion tillage in Europe will alter these dynamics and could result in an increased weed burden as fewer seeds will be lost through burial. Surface tillage (e.g. harrows and rotary hoes) also promotes increased germination rates (10 – 80%) of selected species best adapted to rapid response of disturbance (Mohler, 1993; Moonen and Bàrberi, 2004). On the other hand, reduced tillage with lower frequency of disturbance events may prevent seed loss by germination (Albrecht and Auerswald, 2009).

1.2.3 The impact of soil erosion on arable seedbanks

The spatial relations of weed seedbank assemblages are an important element of biodiversity within agro-ecosystems (Benvenuti, 2007; Alignier and Petit, 2012). Assessing the significance of erosion and sedimentation to redistribute and restructure the seedbank is therefore an important but under-appreciated research challenge. Key to this is combining a better understanding of earth surface processes with specific biological and agronomic controls on seedbank dynamics – involving death, germination, weed control and replenishment through seed rain. Differential mobilities and mortalities depending on seed morphologies, sensitivity to damage during transport and viability following eventual deposition (which could be at depth) are all potentially important and will play out in different ways according to location, time and starting seedbank characteristics.

1.2.3.1 A first order assessment of the importance of soil erosion to seed transport

Field- and catchment-scale sediment budgets, as represented in Figure 1.1, provide a valuable analytical framework in assessing the spatial and temporal significance of erosion-controlled seedbank dispersal. Sediment budgets focus on sources, pathways and sinks of erosion and the timescales of delivery (Small *et al.*, 2003). Table 1.2 provides an estimate of potential seed losses from within different counties (administrative area) of the UK based on published soil erosion rates (Brazier, 2004). Table 1.2 also shows arable seedbank densities derived from 'Farm Scale Evaluations' of genetically modified herbicide tolerant crops data held at The James Hutton Institute in Scotland. Sampling methods have been previously described (Firbank *et al.*, 2003; Heard *et al.*, 2003a). Data at this scale are not available from other northern European countries, so the UK is used here for illustrative purposes. For each county with data available, average and maximum erosion rates and seedbank densities are given. These values are used to calculate rates of potential seed loss through soil erosion, based on the following assumptions: 1) seeds are concentrated in the top 15 cm of the soil profile and this is the 'active-layer' in relation to surficial erosion processes; 2) soil bulk density approximates to 1 t m^{-3}; 3) soil erosion processes are not selective for seeds with particular characteristics and so indiscriminately mobilise the seedbank in equal proportions to the bulk soil. Challenges to these assumptions and refinements to the calculations as presented require direct quantification which is currently unavailable.

Maximum erosion rates provide the worst case scenarios caused by agricultural practice at highly localised points (Brazier, 2004). For example, in Table 1.2, Kent has the highest average erosion rate but Nottinghamshire has the highest maximum rate. Nottinghamshire also has the lowest arable weed seedbank densities. Differences in erosion rates between counties are likely to reflect regional differences in hydro-climate, topography, soil types and land management practices (Department for Environment, 2008). Combining these datasets reveal substantial differences in potential seed flux between the average and maximum scenarios. Seedbank losses through germination, death and weed control have been estimated or quantified (Grime *et al.*, 1981; Watson *et al.*, 2003; Westerman *et al.*, 2003; Benvenuti, 2007; Navntoft *et al.*, 2009; Davis *et al.*, 2011; Westerman *et al.*, 2011). Additions to the seedbank have been quanitfied for seed rain (Jones *et al.*, 2003). The additions are exceeded by total losses since Gibson *et al.* (2006); Marshall *et al.* (2003) and Robinson and Sutherland (2002) noted the seedbank number and diversity are in decline. The losses due to movement by erosion are an additional to the other loss

Table 1.2 Observed soil erosion (Brazier, 2004) and seedbank values (Heard *et al.*, 2003a) providing seed loss estimates within UK counties.

UK County	**Erosion rates (t ha^{-1} yr^{-1})**		**Weed Seedbank**			**Seed Flux (seed ha^{-1}yr^{-1})**		**Annual Seed Export (% of original inventory)**	
	Average Scenario	*Maximum Scenario*	*Average seed density (seeds/m^2)*	*Maximum seed density (seeds/m^2)*	*Average Number of Species*	*Average Scenario*	*Maximum Scenario*	*Average Scenario*	*Maximum Scenario*
Cambridge	0.36	3.3	463	638	49	1111	10188	0.02	0.22
Cumbria	0.22	5.07	1422	2124	20	2085	48049	0.01	0.34
Dorset	1.29	31.08	551	768	53	4739	114168	0.09	2.07
Herefordshire	0.99	13.22	489	811	41	3227	43097	0.07	0.88
Kent	4.51	17.86	943	1459	42	28339	112223	0.30	1.19
Norfolk	0.92	10.705	505	547	87	3096	36030	0.06	0.71
Nottinghamshire	1.11	66.15	240	367	26	1773	105677	0.07	4.41
Shropshire	1.28	49.34	845	1076	61	7208	277856	0.09	3.29

mechanisms. Annual seed export rates represent only a small fraction of the original seed inventory (averaging approximately 0.1% across the case-study regions), however the long term (>10 years) impact may be significant, representing seed losses of up to 40%.

Although there is no quantified critical threshold for arable biodiversity, below which ecosystem functions may be compromised, this magnitude of loss from the arable seedbank over decadal timescales is likely to play-out through many within-field processes including nutrient cycling through soil, plant and invertebrate food webs (Marshall *et al.*, 2003). Using available seedbank data with published erosion rates, the contribution of erosion to the seedbank decline can be estimated. The potential significance of erosive redistribution can be made by combining average net erosion rates within the UK of ca. 7 t ha^{-1} yr^{-1} (*cf*. Brazier, 2004; Walling *et al.*, 2006; DEFRA, 2008) with average arable weed seed densities of ca. 2000 seeds m^{-2} within the plough layer (Heard *et al.*, 2003b) which results in an average annual loss rate of ca. 0.5% yr^{-1} of the total seedbank inventory. Thus erosion has the potential to alter seedbank abundance and compositions by an additional loss ca. 10% over a 20 year period, destabilising the seedbank. Furthermore, use of net erosion rates at the field-scale conceals transient and longer-term sediment storage within swales, foot slopes, boundary ditches, buffer strips and hedge-rows. The potential for within-field spatial restructuring of seedbank inventories is therefore potentially much greater than whole field averages, particularly in patches where erosion rates are high (e.g. > 10 kg m^{-2} yr^{-1}) and seed densities are low (e.g. <100 seeds m^{-2}).

Considerable scope exists to refine these preliminary estimates by quantifying the response of different weed seed species to different erosion processes. For example, splash-related dispersal and inter-rill transport have the potential to move small, light seeds on or near the soil surface at a very local scale (in the order of 1–10 cm). The impact of these transport processes is therefore species or phenotype specific, depending on seed characteristics (size, morphology, seed coat and mucilage) (García-Fayos *et al.*, 2010). Selectivity in terms entrainment and preferential deposition will contribute to a shift in seedbank composition favouring species with large, heavy seeds in eroded areas and those with small, light seeds accumulating in depositional areas. Whether these changes in species composition in different parts of the field have any impact on ecosystem service provision will depend on whether there are any correlations between seed morphology and other plant traits, such as germination requirements, competitiveness, shade tolerance, resource value to insect herbivores and timing of flowering and reproductive periods.

At a larger, but still within-field scale, surface runoff converges into rills and tramlines. There is increased connectivity with channel networks and seeds can be transported greater distances through the field (Bracken and Croke, 2007). In severe cases, rill and tramline erosion can penetrate the full plough-depth, resulting in potential full loss of the seedbank locally. The fate and viability of transported seed is likely to be species specific, with different species showing different responses to abrasion damage, burial and growth of viable seedlings within depositional regions ,where there is likely to be greater nutrient supply and increased competition (Davis *et al.*, 2008).

Movement of seeds from fields into a channel network can occur through sub-surface flows, gullies (deep scours extending into the sub-soil), mass movement of soil through creep, slides and flows, and on farm machinery at harvest. These larger scale processes depend on landscape setting, slope and soil types and, because they are non-selective for soil particle size, they also are likely to be non-selective for arable weed seeds of different sizes. Research is needed to quantify the relative importance of each of these processes to the dispersal distance and amount of seed moved within fields and beyond into the channel network.

Tillage erosion can selectively move seeds across fields, particularly from hill crests to the field base (Van Oost *et al.*, 2006; Cousens *et al.*, 2008). Depending on the field topography, eroded material may accumulate in low lying areas of fields, resulting in seed burial below germination depth. This could result in increased seed mortality or it could trigger dormancy until germination conditions are suitable. Using beads as proxies for seeds, Westerman *et al.* (2009) observed re-surfacing of beads after rain and wind removing topsoil. Therefore, depositional areas could have germination of re-surfaced seeds. Tillage can also change seed viability directly, increasing the germination potential for species requiring scarification and increasing the mortality rates of others. These factors are likely to have significant impacts on both the within-field distribution of seeds and the species composition of the seedbank community.

1.2.3.2 Timing of erosion events

Erosion events (through precipitation, wind, snow melt and tillage) are highly episodic and vary in intensity (Morgan, 2005). In temperate environments, seedbanks are characterised by seasonal patterns of seed rain, dispersal, germination and onset of dormancy. Erosion and seedbank composition are influenced by multiple factors including the amount of light and water available for germination and growth, soil conditions (chemistry and hydraulic conductivity), and the extent of vegetative cover. The susceptibility of the arable weed seedbank to impact from soil erosion is therefore influenced by the interplay of the number and size of runoff-generating storm-events with the local calendar of tillage and harvesting - inclusive of ploughing, seedbed preparation, and periods of bare ground prior to weed and crop emergence (Figure 1.2).

Periods of bare ground for spring and root crops in northern Europe occur from late autumn through to early spring, and tillage operations are usually carried out during autumn or spring prior to crop sowing. Without crop cover soil is exposed to splash, inter-rill (unconfined sheet flow) and rilling (channels formed by convergent flow). Seeds shed during this period are therefore concentrated on the soil surface and exposed to surficial erosional processes prior to incorporation into the seedbank (Westerman *et al.*, 2006). Weed species with a life-cycle characterised by late autumn seeding are therefore likely to be disproportionately affected by soil erosion compared to species that shed seed during periods of dense vegetative cover when soil disturbance is low.

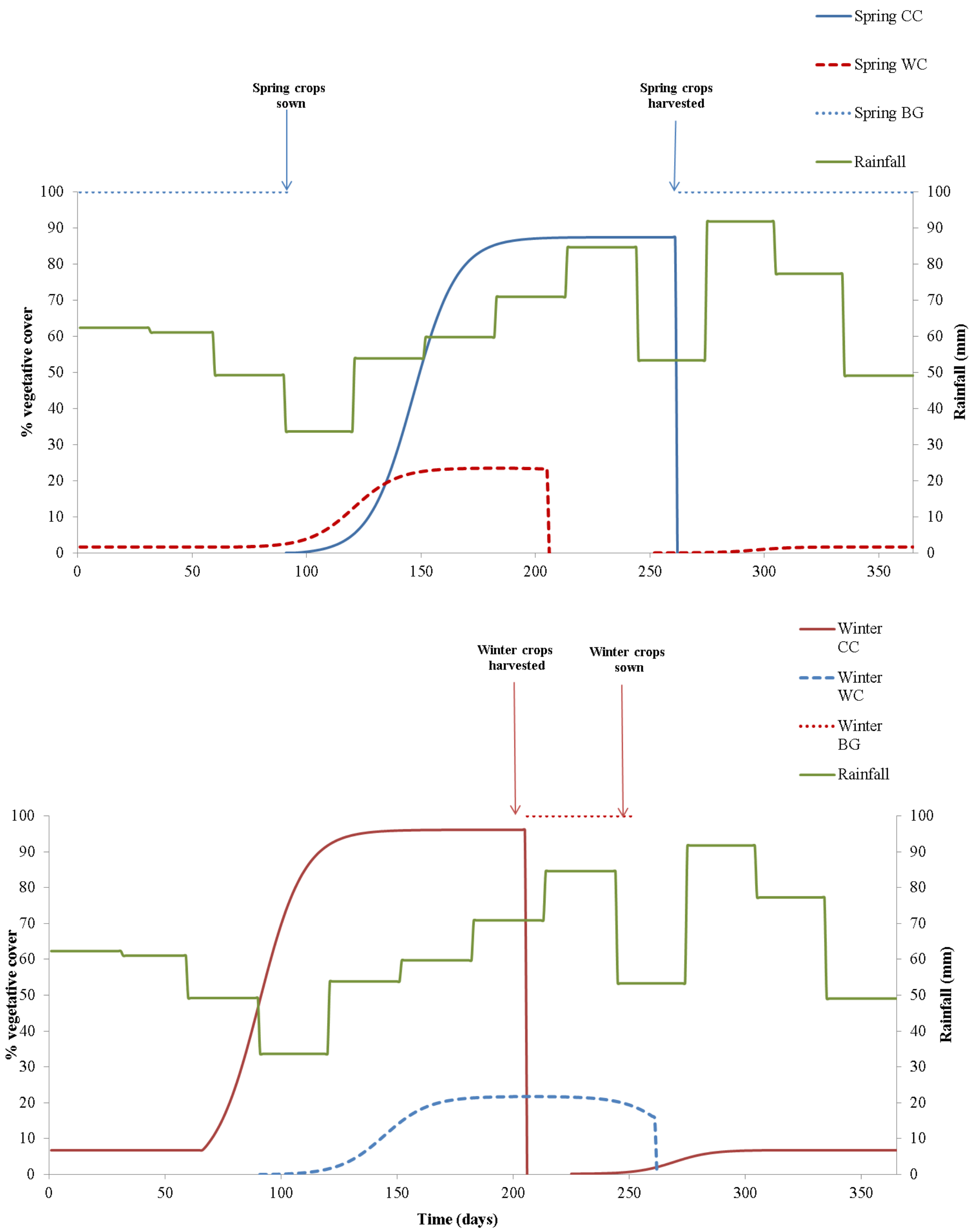

Figure 1.2: Data shown are generic crop and weed cover curves estimated from unpublished data gathered as part of the Farm-Scale Evaluations of genetically modified herbicide tolerant crops against 10 year average rainfall (Squire, 2012). CC: crop cover, WC: weed cover, BG: bare ground**.**

1.2.3.3 Morphology and hydrodynamic behaviour

Seed mass is commonly cited as an important determinant of dispersal distances (Smith and Kok, 1984; Benvenuti, 2007). Cerdà and García-Fayos (2002) demonstrated that below a threshold mass of 50 mg, seed size was the main factor affecting mobility, whereas above this threshold seed morphology becomes more important. The relationship between seed mass and size (average axial length) for a representative sample of commonly found arable weeds is shown in **Figure 1.3**. What is clear is that whilst seed size ranges over one order of magnitude (0.4 – 28 mm), seed mass (reflecting the shape and anatomy of the seeds) varies over three orders of magnitude (0.012 –50 mg) translating into a broad spectrum of hydrodynamic behaviours. Differential mobilities are therefore likely at the field-scale consistent with the selectivity of erosion and transport as demonstrated by Slattery and Burt (1995). Some species, especially those such as *Veronica sp* that have small, cup or boat shaped seeds, are particularly adapted to secondary dispersal by rain splash (diplochory) (Vander Wall and Longland, 2004; Benvenuti, 2007). The effect and importance of this process is yet to be determined for seed, however there is some evidence for seed movement by splash dispersal (Westerman *et al.*, 2009).

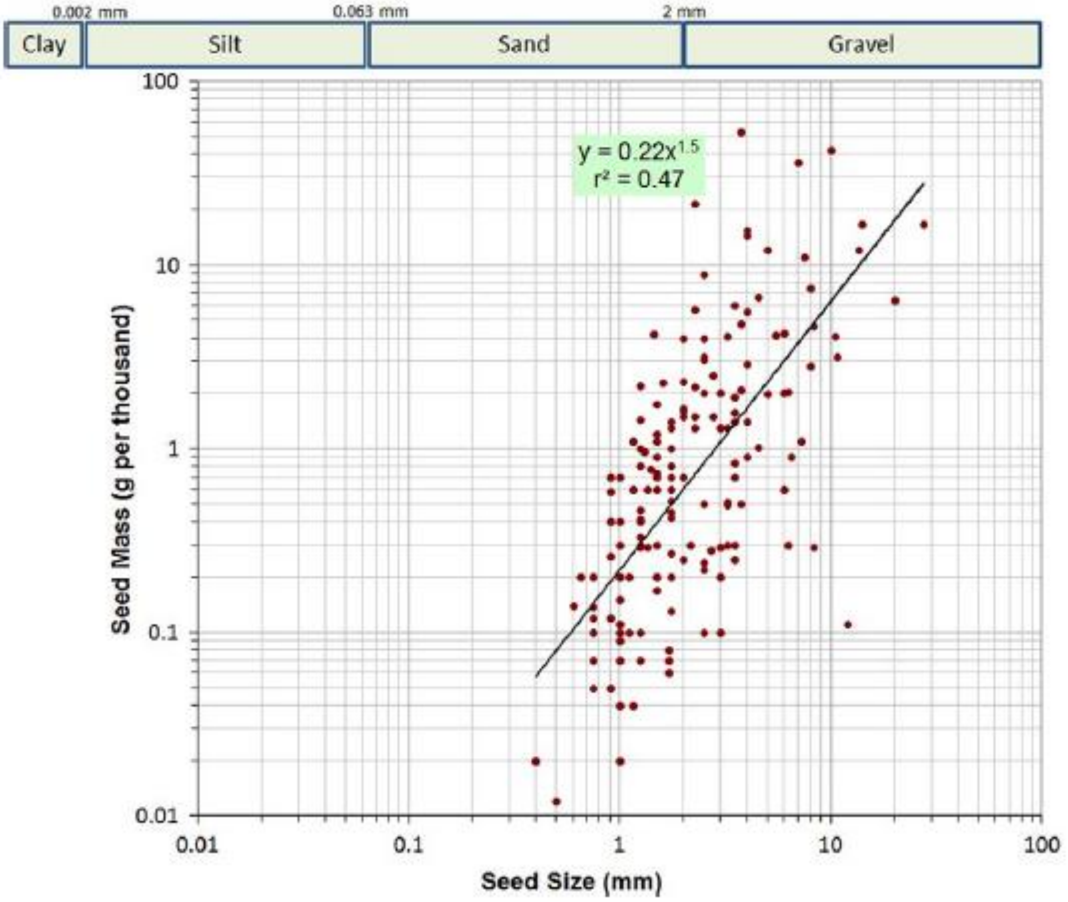

Figure 1.3 – Seed mass and size of UK arable seeds plotted in relation to Wentworth particle size classes. The sediment size scale is provided for an indication of the relative size of seeds. Source: Royal Botanical Gardens (2008); The James Hutton Institute (2011b).

Relationships between seed entrainment and seed size are further complicated by the presence of appendages (hairs, wings, awns) and secretion of mucilage upon hydration which increases the resistance to water-borne movement (García-Fayos *et al.*, 2010). Using *Capsella bursa-pastoris* (shepherd's purse) Deng *et al.* (2012) demonstrated that hydration resulted in a 6-fold increase in seed volume and a 2.5-fold increase in seed surface area. This mucilage release occurs within five seconds of wetting and its rapid expansion serves to increase the binding of seeds to the soil matrix. This binding also strengthens water stable aggregates further inhibiting detachment and lateral transport.

1.3 Aims and Objectives

From reviewing the literature on soil erosion and seedbanks, there is sufficient evidence of a tentative relationship between erosion and seedbanks relevant to arable environments in temperate northern Europe. This statement is underpinned by the following key findings from the literature review:

1. Quantitative data on erosion affecting seedbanks is limited to literature estimations and laboratory experiments (see section 1.2.3.1).
2. The selectivity of erosive processes may affect seeds differently due to seed morphologies (see Table 1.1, section 1.2.3. and section 1.2.3.1)
3. Environmental disturbances (physical and chemical) affects seeds but the effect of erosion as a physical disturbance mechanism is unknown (see sections 1.2.2.1, 1.2.2.3 and 1.2.2.4)
4. Scale of erosion processes is established but how the seedbank responds at this scale is not known (see Table 1.1 and section 1.2.3.1)
5. Storms events have both immediate and cumulative effects to erode soil and transport seeds (see Table 1.1 and section 1.2.3.2)

From the key findings, it can be hypothesised that the use of a field based approach would improve the understanding of the soil erosion processes on seedbanks. The aim of the thesis was to advance the understanding of soil erosion on weed seedbanks in an arable agricultural environment. Achieving this aim required the formulation of the following objectives:

1. To determine the nature (rates and timing) of seedbank transport by erosion and sediment transport processes and quantify the relative contribution from tramline sediment sources. This would provide an initial assessment of seed movement within a field.
2. To quantify the amount, composition, timing and frequency of seed movement at different spatial scales. This is important for understanding the effect of seed movement would have on agro-ecosystems.
3. To understand the extent to which the transportation processes are is linked to the sources, pathways and fate of sediments and the consequences for the seedbank and its ecological function.

1.4 Balruddery Field Site

Throughout this thesis the field experiments referred were conducted at the James Hutton Institute’s Balruddery Farm, Scotland (56°28'59.16"N; 3° 7'50.66"W). The site covers an area of 118 ha of arable land at an altitude of 70 – 160 m above sea level. According to Bell *et al.* (2009) the farm is located across Balrownie, Ruthven, Garvock and Buchanyhill series with a stone content of 5 - 25 %. The soil texture is sandy loam texture with a pH 5.8. Annual precipitation is 705 mm with a mean air temperature of 9°C monitored by a weather station on site. The site is divided into 17 fields of varying size between 2 and 11 ha bounded by dry stone dykes. The fields have an extensive sub terrain drainage network. The only open water course is located in the south eastern corner of the farm and is 550 m long before entering a final drain that’s 430m long. In addition, there is a wooded gorge (known locally as a den) to the east, as well as mature treelines, hedgerow and two watercourses running west to east across the site. Dron Burn is not within the farm catchment. Oilseed rape, potatoes, barley, wheat, beans and grass are grown on the farm. Figure 1.4 provides an overview of the eastern field of the farm where experimental work was conducted. In Chapters 2 – 4 the specific location is described.

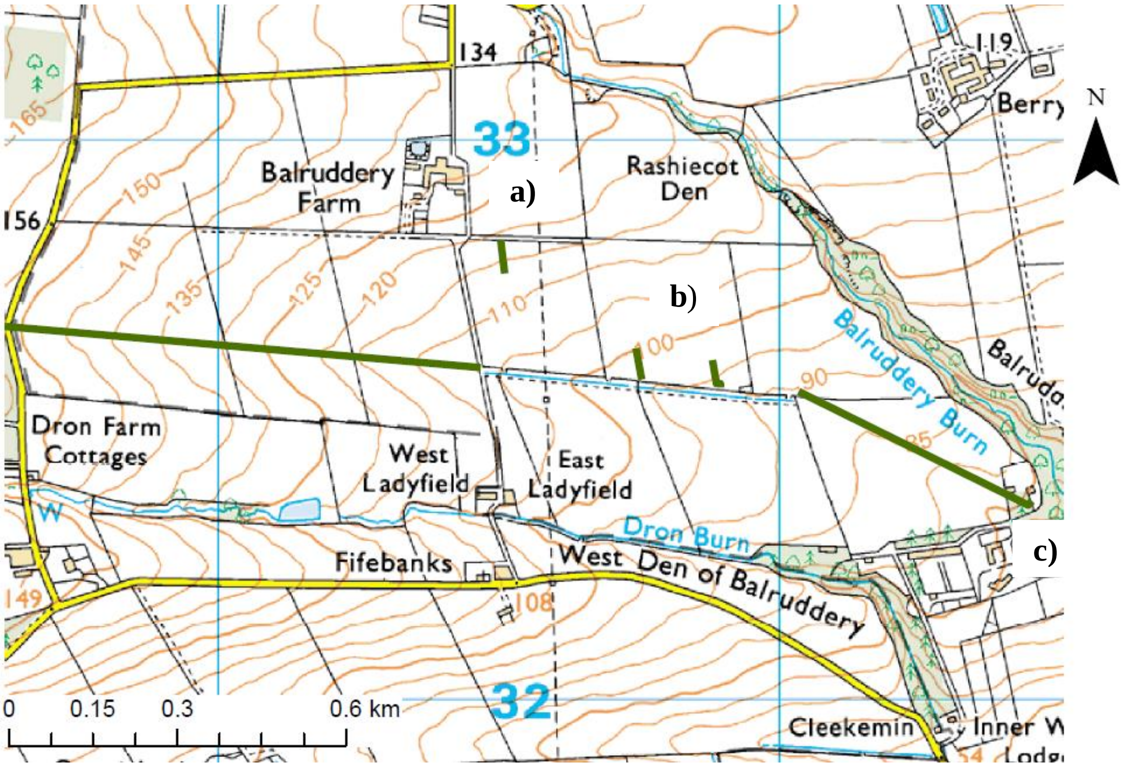

Figure 1.4 - Map of Balruddery farm with known drains in green. Labelled sites show location of tramline experiment (a), (b) radionuclide sediment budget field and (c) catchment monitoring station

1.5 Project Boundaries

Having established the aims and objectives of the thesis, there is a requirement to develop some project boundaries. This thesis primarily took a field based approach, which was supplemented by rainfall simulator experiments. A key aspect of the field-based approach was to tackle a range of spatial scales and accumulate data over three field seasons.

1.6 Thesis Structure

Scale of the environment (e.g. microbial to global) is important in quantifying the ecosystem biodiversity (Richie and Olff, 1999; Spokas *et al.*, 2007; Feld *et al.*, 2009). The connectivity between scales is important in maintaining biodiversity (Grashof-Bokdam and van Langevelde, 2005). The level of connectivity between different scales is defined by the boundaries between different habitats (e.g. soil crusts, crop edges, field boundaries, hedgerows, woodlands, rivers) which control how an organism interacts across boundaries. The weed seedbank shows a scale dependency which is reliant on the level of farm management (Hawes *et al.*, 2010). Moreover, the scale dependency of the seedbank at the field and region scale has implications for landscape complexity. Knowledge of finer scale processes enables better understanding of the landscape ecosystem (Gabriel *et al.*, 2005).

This thesis comprises of five chapters which are outlined as follows: Chapter 2 firstly identifies the processes of soil erosion and conservation tillage on the seedbank. It describes a three year experiment that monitored tramlines to understand the effect tramline management would have on the rates of soil erosion and seed movement. Chapter 3 describes an experiment that developed a sediment and seedbank budget at the field scale using radionuclides. Chapter 4 describes the use of a field rainfall simulator to understand the role of seed morphology on seed mobility. Chapter 5 describes an experiment that monitored an arable catchment to understand the loss of sediment and seeds over a year. Chapter 6 provides a synthesis of all results and discusses the findings of the research in terms of seedbank management for sustainable practice with recommendations for future research.

Chapter 2: Investigation of hill-slope scale tillage and tramline erosion effects on seed banks

2.1 Introduction

Runoff and associated transport of sediment, nitrogen and phosphorus have long been identified as significant polluting agents in UK water systems (DEFRA, 2002; Environment Agency, 2007; DEFRA, 2008). Phosphorus is a particular problem due to low solubility and ability to strongly bind to finer soil particles, which are preferentially entrained and transported from hill slopes (Tyler *et al.*, 2001). The on-going risk presented to downstream water quality has promoted the introduction of multiple agricultural policies by the European Union (Water Framework, Habitats and Freshwater Fish Directives) and UK Government. Example policies are the Environmental Stewardship scheme in England or agri-environment payments under the Strategic Rural Development Programme (SRDP) in Scotland. These government directives have promoted greater awareness and are preventing pollution from diffuse sources, especially from agro-ecosystems (Natural England, 2013).

Tramlines are defined as a pair of adjacent wheelings left bare by farm machinery within arable fields following agricultural operations (Silgram *et al.*, 2010). A tramline typically consists of two tracks each 30 - 35 cm wide with an inter-wheeling area of 165 – 170 cm depending on the axle width of the machinery. The length of tramlines varies depending on the field size. Research by Withers *et al*. (2006), Silgram *et al* (2007) and Silgram *et al* (2010) supports the theory that tramlines are the primary conduits for sediment and phosphorus loss at the field scale. Tramline management has been shown to mitigate sediment and phosphorus losses by as much as 86% (Silgram *et al.*, 2010).

Field management should be designed, not only for food production, but also to control soil loss and water body pollution, and to maintain the floristic biodiversity in arable farming systems. This management is guided by the Environmental Stewardship scheme which aims to conserve biodiversity, enhance landscape quality, safeguard historic environments, protect water quality and respond to climate change (Natural England 2013). The SRDP for 2014 – 2020 recommends agricultural environments should focus on improving land and water quality, protect key species and habitats, lower greenhouse gas emissions and increase carbon sequestration (Scottish Government, 2012).

Fundamental to achieving the goal of maintaining habitats for floristic biodiversity is managing the weed seedbank. Weeds have been considered a nuisance to farmers and research into weed control and biology has improved crop yields (Marshall *et al.* 2003). Since the signing of the Rio Convention on the Conservation of Biodiversity, arable habitats with a greater biodiversity may improve pest control showing biodiversity as having a functional component within the ecosystem (Estevez *et al.* 2000; Marshall *et al*. 2003). Weeds are important for providing functional biodiversity because of the ecosystem services providing nutrient cycling, giving resources for insect and pollinators; and accommodating natural enemies to crop pests (Marshall *et al.* 2003). The agro-ecosystems weed seedbank provides a persistent store of seeds offering some measure of resilience against agricultural activity (Wilson and Lawson, 1992). Whilst UK data suggests average weed densities ca. 2000 seeds m^{-2} (Heard *et al.*, 2003b) there has been a decline in both numbers and diversity of the seedbank in the past 50 years. This decline has been a result of farming intensification, increased herbicide use and weed suppression by competative winter sown species (Robinson and Sutherland, 2002; Bekker *et al.*, 2003; Gibson *et al.*, 2006).

Arable fields are dominated by crop species making the level of within field diversity relatively low, but the weed seedbank provides an important area for storage until seeds can germinate which is useful during winter when conditions are not favourable (Gulden and Shirtliffe, 2009). Changes to the seedbank affect other parts of the ecosystem and associated services, such as food webs and pollinators (Gibson *et al*., 2006, Evans *et al*., 2011). The importance and sensitivity of the seedbank in agro-ecosystems has ecological significance as the weed seedbank provides valuable ecosystem services (Marshal *et al.*, 2003). Furthermore, the field management practices (e.g. ploughing, herbicides and cropping sequence) that affect seedbank also affect soil erosion and sediment transfer (De Cauwer *et al.*, 2008; Andreasen and Skovgaard, 2009; Hawes *et al.*, 2010). At present, no one has attempted to quantify the ecological significance in the relationship between soil erosion and seedbanks, which are both affected by field management. However, previous studies suggest soil erosion has been an under-researched dispersal mechanism of the seedbank (Lewis *et al.*, 2013).

Evans (2010) identified a need for more field based studies of soil erosion to build erosion models that could be used in future sustainable land use policy development. In response to the need for better data on soil losses subject to different cultivation practices, specifically about tramline management techniques, a £1.2 million Sustainable Arable LINK project led by ADAS was established. The aim of this UK wide project was to understand the use of practical cost-effective techniques to reduce pollution from tramlines in combinable crops at both the field and catchment scale. This project involved four separate sites located in Shropshire (loamy sand), Herefordshire (silty clay loam) and Leicestershire (clay loam), as well as a Scottish site in Angus (sandy loam). A common experimental approach was applied at all sites to evaluate different tramline management techniques in terms of soil loss and nutrient (phosphorous (P) & nitrogen (N)) fluxes, with the results being used to model practicality and cost effectiveness of management strategies at the field and catchment scales. To enhance the significant infrastructural investment in this rigorously established hill-slope scale experiment, the opportunity was taken here to investigate seedbank mobility along tramlines as a result of soil erosion. This would provide important information on the impact of soil erosion on the biodiversity and ecological value of the field or catchment area.

The PhD investigation (for the Scottish site only) evaluated the influence of tramline management on seedbank mobility. This study was conducted in a single field at Balruddery Farm (location A in section 1.4) over three winter seasons. The objectives of this study were:

1. To establish, for the first time, the linkages between tramline erosion and delivery of arable weed seeds at the field scale.
2. To evaluate the effects of different tramline management practices on runoff generation, sediment delivery rates and seedbank mobility.
3. To characterise the extent of inter-annual variability over the three years of the tramline experiment, taking into account different climatic and tillage practices employed.
4. To determine the ecological significance in terms of a) physical soil loss soil in relation to concepts of tolerable soil loss b) rates of weed seed transport in numerical terms and in relation to the dynamic seedbank store and c) the ecological significance in terms of compositional changes to the seedbank (species abundance and composition).

5. To assess if seed morphology played a role in seed transport by runoff or sediment load, if tramline management influence particular seed morphology and determine the most transportable based on seed morphology.

2.2 Methodology

2.2.1 Specific Field Conditions

General farm conditions were described in Section 1.4. Steading field covers an area of 6.38 ha with a very pronounced convex slope and an average slope angle of 4.5 °. Soil texture varies from a sandy silt loam to sandy loam topsoil with poor drainage at the foot slope. The soil throughout the field, contained between 10 and 20 % of stones by volume consisting of subangular stones between 6 mm to 60 mm in diameter.

2.2.2 Experimental Design

The experimental design of this work was designed to determine the effects of tramline management on soil erosion as part of Sustainable Arable LINK project 3386 led by ADAS funded by the Scottish government, DEFRA and HGCA. The three monitoring periods ran from (1) October 2010 until March 2011, (2) October 2011 until April 2012, (3) October 2012 until March 2013. The following section describes the method for gathering erosion and seedbank data during all three monitoring periods.

2.2.2.1 Tramline Erosion Monitoring

Unbounded plots (3 m x 100 m) were established along the hill slope to capture and quantify eroded materials, surface runoff and nutrients. Tramlines were made by the same tractor (Massey Ferguson Demonstrator 7480) each year with a single pass upslope towing a sprayer with 3000 L of water. Figure 2.1 illustrates the tramline management techniques employed, whilst Figure 2.2 shows schematics of the resultant soil surfaces. Figure 2.3 shows tread patterns following the application by the tractor and sprayer. In 2010/11, tramline management techniques consisted of a tractor with i) regular tyres, ii) a set of low pressure tyres on all wheels including sprayer (Michelin Xeobib, Michelin 2013), iii) a spiked harrow behind the tractor to breakup the tramline surface wheels and iv) a roller pulled behind the tractor (Figure 2.1a-d). In 2011/12, the roller was substituted for a combination of low pressure tyres with the spiked harrow. In 2012/13, tramline management techniques consisted of i) regular tyres, ii) regular tyres with a spiked harrow to break up the tramlines, iii) regular tyres tramlines sown with crop (Figure 2.1e) and iv) low pressure tyres tramlines sown with crop. These tramline management techniques were applied in four replicates in a randomised block design (4 treatments x 4 replicates = 16 sampling sites). In addition, access tramlines were added after each second managed tramline to enable field maintenance. The field was sown with winter barley *Hordeum vulgare* cv. pearl each year. Sowing date for 2010/11 was 14th October 2010, 2011/12 was 20th September 2011 and 2012/13 was 22nd September 2012. Application and subsequent monitoring of tramlines for 2010/11 started on 22nd October 2010, 2011/12 started 11th October 2011 and 2012/13 started 8th October 2012.

Figure 2.1- Tramline management techniques showing the (a) regular tyre, (b) low pressure tyre, (c) spiked cultivator breaking up the tramline surface, (d) the roller creating a convex channel shape; and (e) typical tyres tramline sown with *Hordeum vulgare* during winter in 2012/13.

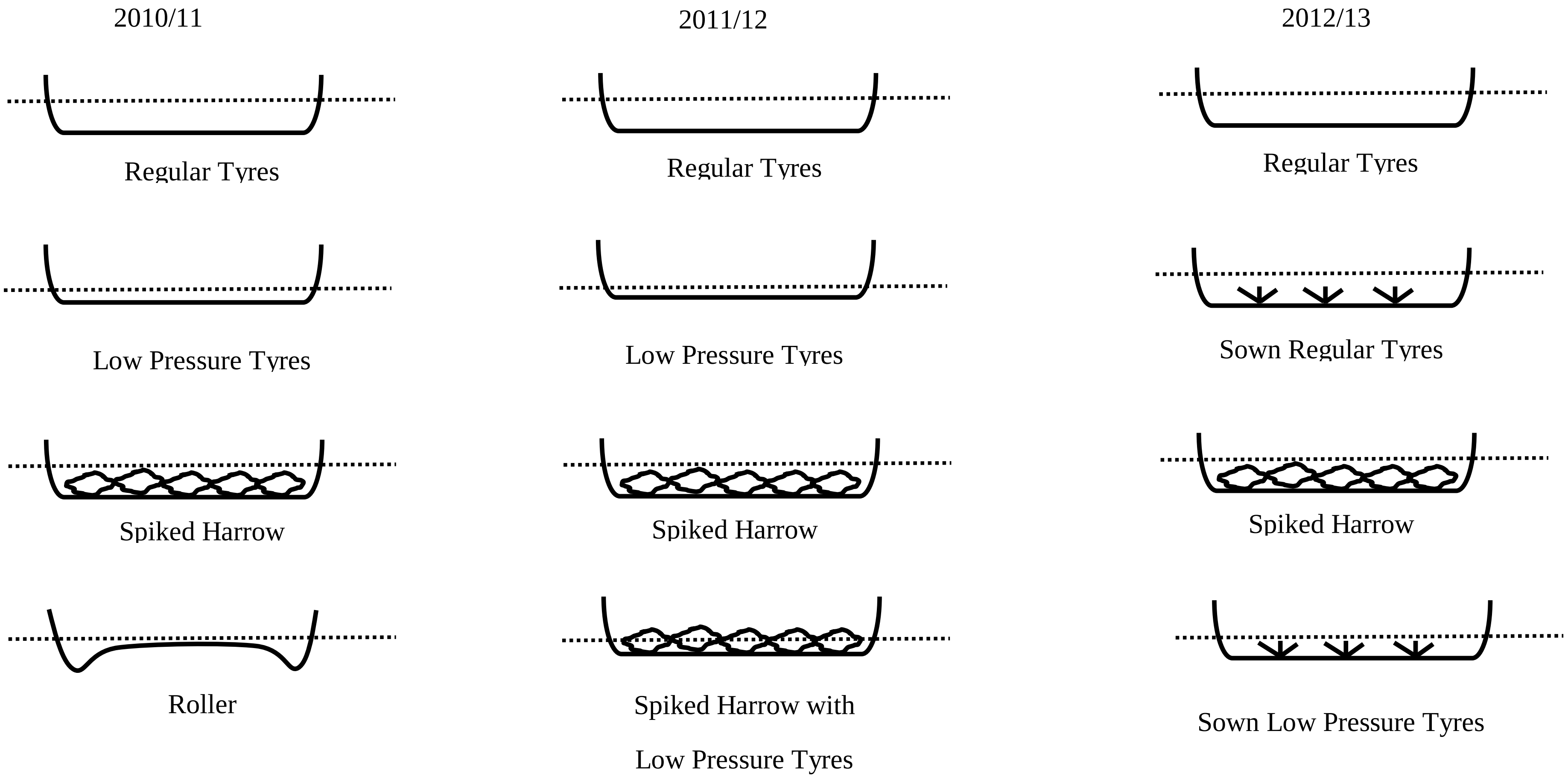

Figure 2.2 - Cross sectional schematic of each tramline management technique used for each year. The dotted line represents the soil surface without any tramline applications.

Regular Tyres Low Pressure Tyres

Spiked Harrow Roller

Figure 2.3 - Tread patterns for tramline management. The key differences are the depth of tread marks in the upper images and the disruption or the tramline in the lower. Spiked harrow with low pressure tyres image (not shown) was identical to spiked harrow with regular tyres image. Sown tramlines had same tread patterns as regular and low pressure tyres

During each monitoring period, runoff and sediment were collected using a series of Gerlach Troughs (Figure 2.4) for individual rainfall events. Each plot had a plastic gutter installed at a 60° angle across the tramline. The gutter was connected with plastic piping to a tipping bucket mechanism of known volume connected to a data logger enabling the measurement of runoff. The tipping bucket collected a representative sub-sample using a series of bungs as the plot size contributed large flows of runoff (Silgram *et al.*, 2010). For regular and low pressure tyres tramlines, 1/8th of the runoff was collected from the gutters. All other tramlines had half the runoff collected from the gutters. After some rainfall events, the number of bungs was altered to prevent tanks from overflowing. Sub-samples were stored in a tank underneath the tipping bucket. Tanks were sampled on an event by event basis. An event was defined as a period of precipitation sufficient to cause runoff. Trapped water in the tanks was agitated by a submersible petrol-powered water pump, prior to sampling sediment and seeds (see Section 2.2.2.2). As part of the larger project JHI colleagues took a 1 L sample for analysis of phosphorus and nitrogen concentration, as well as measuring total suspended solids. In 2012/13, a separate 2 L sample was taken for particle size analysis from each tank. Tanks were emptied and cleaned after each collection event.

Figure 2.4 - Runoff material from the tramlines (shown by white arrows) was collected in the Gerlach Trough (left and highlighted in right) and piped into the tipping bucket situated above the storage tank (right). Sub-samples were stored in the tank and excess material discharged down the waste pipe.

2.2.2.2 Seed Bank Sampling

Seeds entrained within the runoff and eroded soil were collected from the tanks to quantify seedbank densities and community composition. Tanks were emptied by pumping out the water and sediment. During the tank emptying, a 1 mm mesh was placed over the waste pipe to collect seeds and separate them from the sediment. In years 2 and 3, an additional 0.375 mm mesh was placed below the 1 mm mesh to improve trapping efficiency of seed samples. Each tank mesh containing the trapped seeds was placed into sealable labelled plastic bags for transfer to a glasshouse. Separate meshes were used for each tramline plot. These samples were used to calculate seed flux as shown in Section 2.2.3.

Following some concern during the first sampling season that the 1 mm mesh may be too large to trap all the seeds in the sample, a finer mesh was used in addition to the original mesh size during 2011/12 and 2012/13. In 2011/12, the 0.375 mm mesh captured 1.7 times more seeds compared to the 1 mm mesh (Figure 2.5). In 2012/13, the use of the 0.375 mm mesh caught 48 more seeds than the 1 mm. The 1 mm mesh capturing the most seeds in five events (events 5- 8 and 11), the 0.375 mm mesh capturing the most seeds in five events (events 1-4 and 10) and event 9 where the exact same amount was collected. These results showed that in 2010/11 without the 0.375 mm mesh, half of the number of seeds would had been lost. A similar result was found for seed species (Figure 2.6) where in both 2011/12 and 2012/13, the use of the 0.375 mm mesh did not significantly increase the number of species ($p = 0.423$ in 2011/12, $p = 0.195$ in 2012/13). For the remainder of this chapter, seed data in 2011/12 and 2012/13 refer to the combined result of using both sizes of the meshes to collect the seeds.

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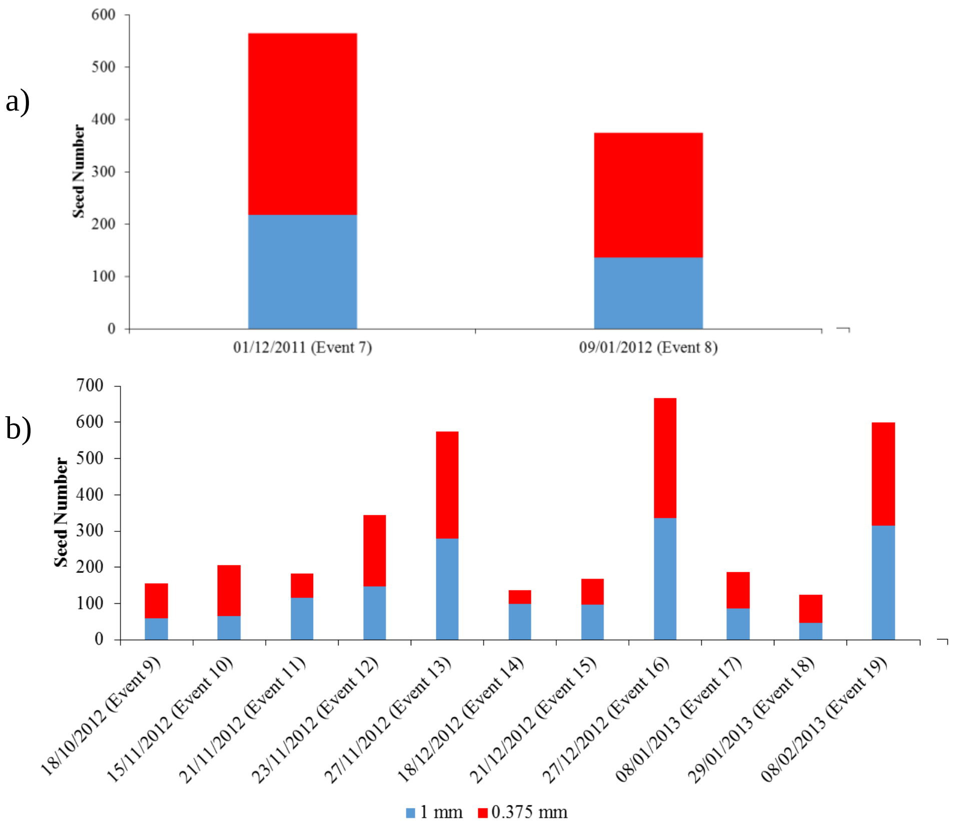


Figure 2.5- Seed numbers from 1 mm and 0.375 mm mesh in 2011/12 (a) and 2012/13 (b) for individual events. Use of the 0.375 mm increased the number of seeds retained, but was not a significant difference in the seed numbers (p = 0.341 in 2011/12, p = 0.941 in 2012/13).

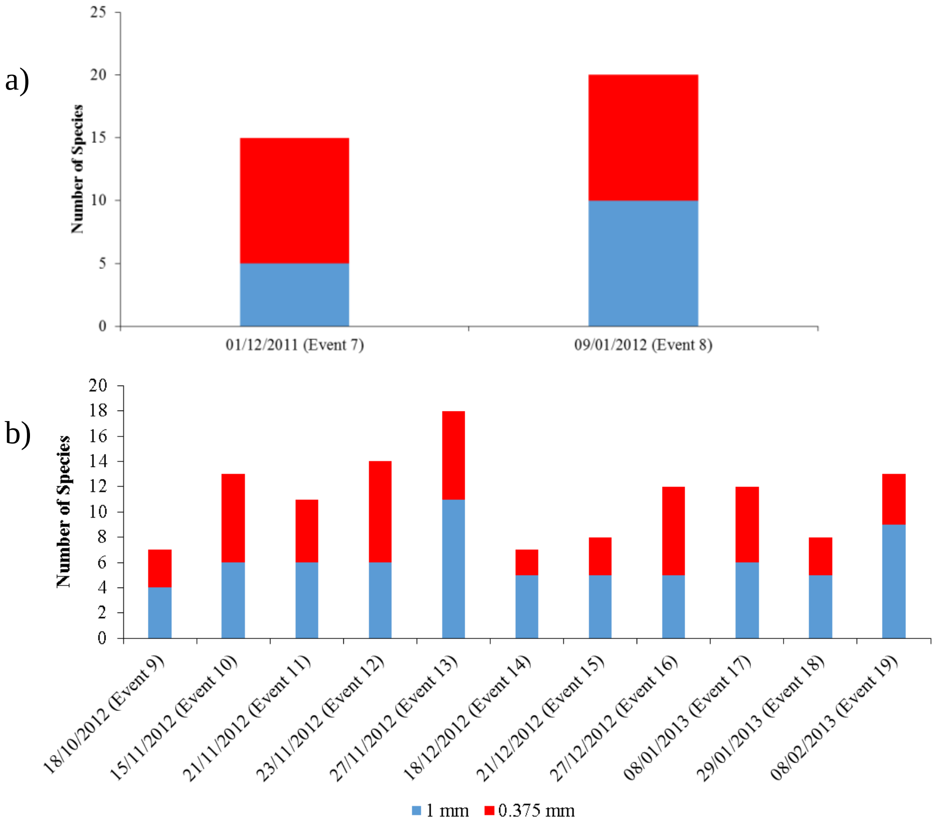


Figure 2.6 - Seed species numbers from 1 mm and 0.375 mm mesh in 2011/12 (a) and 2012/13 (b) for individual events. Use of the 0.375 mm did not significantly improve the number of species retained (p = 0.423 in 2011/12, p = 0.195 in 2012/13).

Samples were prepared for emergence assessments in accordance with standardised protocols used by The James Hutton Institute (2011a). Seed samples were placed in a glasshouse for species identification following emergence (Figure 2.7). The seed trays (15 x 21cm x 5cm) were filled with sterilised compost to provide a growing medium for the seedlings. Mesh samples were stretched over the seed tray and brushed by hand to detach the seeds and soil. Samples were then gently pressed with a wooden board to provide a solid substrate for germination. All samples were placed on shelves within the glasshouse with a lighting regime of 8 hours darkness and 16 hours light and kept moist with a sprinkler system. The glasshouse was regulated to produce natural light between 200 Wm^{-2} and 450 Wm^{-2}. When natural light fell below 200 Wm^{-2} artificial light was used and shades were used when light was greater than 450 Wm^{-2}. The glasshouse room temperature was maintained between 15 and 18°C. All seedlings samples were identified to species level as soon as possible after emergence. The seedlings were then counted and removed from the growing trays. Following 8 weeks in the glasshouse, samples in the trays were disturbed by hand and gently pressed into the substrate to encourage a second flush of germination. Samples were then left for a further two weeks and any new plants were counted and identified.

The field soil was sampled in January each year for seedbank characterisation at 20 m intervals along transects up-slope of the access tramlines. Forty eight samples were taken from eight transects that were 100 m long (6 sampling points x 8 tramlines = 48 samples). Starting from a sample point in-line with the tanks on the access tramlines, 20 x 20 x 15 cm pits were dug by hand in the area between the wheelings to minimise disturbance and compaction. Soil was mixed by hand in the pit and a 2 L sample was placed into a sealable labelled plastic bag (The James Hutton Institute, 2011b). Field soil samples were sieved through a 10 mm sieve to remove stones and roots. The sieved field soil samples were transferred to empty seed trays using the retained soil to provide a growth medium. Samples were then transferred to the glasshouse and maintained under the same conditions as the mesh samples. Samples were observed over the same germination time period as mesh samples. These samples provide data on seed density for each tramline, expressed as seeds m^{-2}, shown in section 2.2.3. All the seedlings were identified using the reference book by Ritchie and Ritchie (2003). Seed morphologies used in Section 2.3.6.4 were compiled from Royal Botanical Gardens (2008) and The James Hutton Institute (2011b). Selectivity as a result of differences in seed morphology between species was a possible effect of erosion on the weed seedbank and field functional diversity. Categories were selected with regards to size, weight, annual or perennial, surface texture, shape and appendages. Sub categories were used for seed size, weight and appendages based on the findings of Lewis *et al.* (2013). Big and small seeds were distinguished by an average length of greater or smaller than 2 mm respectively. Similarly, heavy and light seeds were distinguished by an average 1000 seed weight of greater or less than 1 g respectively. Appendages were classified by grouping seeds into two sub-categories of no appendages or those that have hairs, awes or mucilage.

Figure 2.7 - Eroded samples on compost (left) and field soil sample (right) being germinated in glasshouse facilities at The James Hutton Institute.

2.2.2.3 Particle Size Analysis

The 2 L suspended sediment samples were analysed for particle size using the Coulter LS13370 granulometer in the Geography Laboratory, University of Dundee. The governing principle of laser granulometer is diffraction of the light beam at a given angle to determine particle size (Zobeck, 2004). Two methods were applied to analyse these samples based on the "effective" (water stable) and "ultimate" (chemically dispersed) particle size method, developed by Slattery and Burt (1995). The use of both methods that are important to distinguish between water stable aggregates that are bound by organic matter and the mineral soil particles (Six *et al.*, 2004). The "effective" analysis samples were agitated by hand to re-suspend particles within the bottle. A pipette was used to transfer the sample into the laser granulometer until sufficient obscuration was achieved to analyse the sample.

Following particle size analysis the sample bottles were left to settle for 24 hours prior to the samples being treated to chemically disperse the mineral fraction. Samples were prepared by the following method stipulated by Rowan (1999). After 24 hours settlement period, the supernatant was decanted off. The residue in the bottle was transferred to a weighed evaporating dish, which was dried overnight at 40°C in a drying oven. Once dry, dishes were re-weighed to ascertain sediment weight. These dried samples were sieved through a 2mm sieve to remove any stones. 1 g of dried sediment from each sample was weighed into a beaker. The organic matter was removed from the dried sediment by the addition of 20 mL of hydrogen peroxide and 10 mL of distilled water and left to stand overnight. The beaker was warmed gently on a hotplate to 100°C to complete the reaction. The sample was transferred to a centrifuge bottle using a rubber ended rod with the addition of a small amount of water. The sample was centrifuged for 5 minutes at 2500 rpm to produce a clear supernatant. The supernatant was decanted and 10 mL of ethanol was added to the retained solid sample to aid drying. The sample was returned to the centrifuge for a further 10 minutes at 2500 rpm. A 0.4% solution of sodium hexametaphosphate was made by dissolving 3.35 g sodium hexametaphosphate, 0.65 g of sodium carbonate in 1 L of distilled water. After centrifugation, the ethanol was decanted and 30 mL of the sodium hexametaphosphate solution added. Finally, the sample was placed in an ultrasonic bath for 5 minutes, prior to being placed on a magnetic stirring plate. Samples were pipetted into the laser granulometer to reach obscuration for analysis.

2.2.3 Statistical Analysis

Analysis of Variance (ANOVA) was undertaken on the data collected from the tanks and soil samples to test for differences between treatments in the erosion and seedbank data sets. Tramline management techniques were considered as factors which affected runoff, sediment, rate of seed removal and seed species variables. Principle Co-ordinate Analysis (PCO) describes the differences between samples in the composition of the arable seedbank community. An ecological similarity Index (which takes into account zero values in the dataset) was used to calculate the degree of similarity between each pair of samples and these values were used to draw up a similarity matrix from which the principle component scores were calculated. Principle component scores for each sample were plotted to identify the degree of clustering on the first three axes of the PCO. Non-overlapping clusters of sample points indicate significant differences between groups of samples on the basis of species composition. Sample points were then re-examined to determine whether or not tramline treatment could explain the clustering of samples according to species composition. Regression analysis was used to identify any significant associations between PC scores and the abundance of individual species or weed seed functional groups. Chi square tests were used to determine if there were relationships between characteristics of seed morphologies that might explain why those seeds were transported. The Shannon-Weiner index was used to measure the diversity of weed seedbank (Margurran, 1988). The Shannon-Wiener index (H′) was calculated as:

$$H' = -\sum_{i=1}^{s} P_i(lnP_i) \tag{2.1}$$

Where

$$P_i = \frac{N_i}{N_{\ total}} \tag{2.2}$$

Where N_i is the number of individuals of species i, N_{total} is the total number of individuals in all the samples for a single ground management and s is the total number of seed species. H′ was used to characterise the weed community from each tramline management treatment to provide an evaluation of the effect of management on community diversity. Low values H′ indicate a few dominant species and/or low species richness, whilst high values of H′ indicate diverse communities with high species richness and/or low dominance. The relative influence of community dominance versus species number on the H value was calculated using the equitability index (E):

$$E = \frac{H'}{\ln(s)} \tag{2.3}$$

E is a value between 0 showing a community dominated by few species, and 1 representing a completely evenly distributed community. Here and throughout the results, differences stated were at the confidence level of 95% or higher.

Sediment load and seed flux, were calculated using values collected from tanks which were up scaled since the amount collected represented a sub-sample. Therefore, results from tanks were multiplied by the following factors: 1/8th collected = multiplied by 8, ¼ collected = multiplied by 4, ½ collected = multiplied by 2. This was not necessary for runoff as measurement was before sub-sampling by tipping bucket.

Sediment concentrations (kg L) and seed numbers were converted to sediment load (kg ha^{-1}) and seed flux (seeds m^{-2}). The conversion for sediment concentration to sediment load was calculated as:

$$SL = \left[\frac{(R\ \times SC)}{A}\right] \tag{2.4}$$

Where *SL* was sediment load in kg ha^{-1}, *R* was runoff in L, *SC* was sediment concentration in kg L and *A* was the area of the plot, which was 300 m^2. For clarity, the plot was 3 m wide (consisting of two wheelings and the inter-wheeling area) and 100 m length upslope from the Gerlach Trough. Within the plot, the tramlines occupied 70 m^2 (0.35 m tramline width x 100 m length x 2) which was 23% of the entire plot. For the purpose of this thesis, results are for the entire plot as exact determination from field or tramline was not possible.

For example, calculating sediment from Tank 1 in 2012/13 period for event 13 on 27th November 2012. The runoff for the event was 960 L with a sediment concentration of 198.24 kg L. Therefore the sediment load was:

$$\left[\frac{(959.63\ l\ \times 198.24\ kg\ L)}{300\ m^2}\right] = 634.12 \text{ kg ha}^{-1}$$

Seed number to seed flux was calculated as:

$$SF = \frac{S}{A} \tag{2.5}$$

Where *SF* was seed flux (seeds m^{-2}) and *S* was number of seeds. This conversion was calculated to represent seed density commonly used in seedbank research.

For example, calculating seed flux from Tank 1 in 2012/13 period for event 5 on 27th November 2012. Using the two meshes, a total of four seeds were identified (three on coarse mesh and one on fine mesh). Tank 1 had regular tyre tramline management meaning one hole was open thus the seed number was up scaled to 32 (8 x 4 seeds). Therefore using equation (2.5) the seed flux was:

$$\frac{32 \text{ seeds}}{300\ m^2} = 0.107 \text{ seeds } m^{-2}$$

Seed number to seed density for field soil samples was:

$$SD = S * \left(\frac{1}{(TA)}\right) \tag{2.6}$$

Where *SD* was seed density (seeds m^{-2}) and *TA* is seed tray area which is 0.0315 m^2 (0.21 m x 0.15 m). For example, calculating the seed density based on 16 seeds identified for the 20 m point on tramline 1 was:

$$16 \text{ seeds} * \left(\frac{1}{(0.0315 \text{ m}^2)}\right) = 508 \text{ seeds } m^{-2}$$

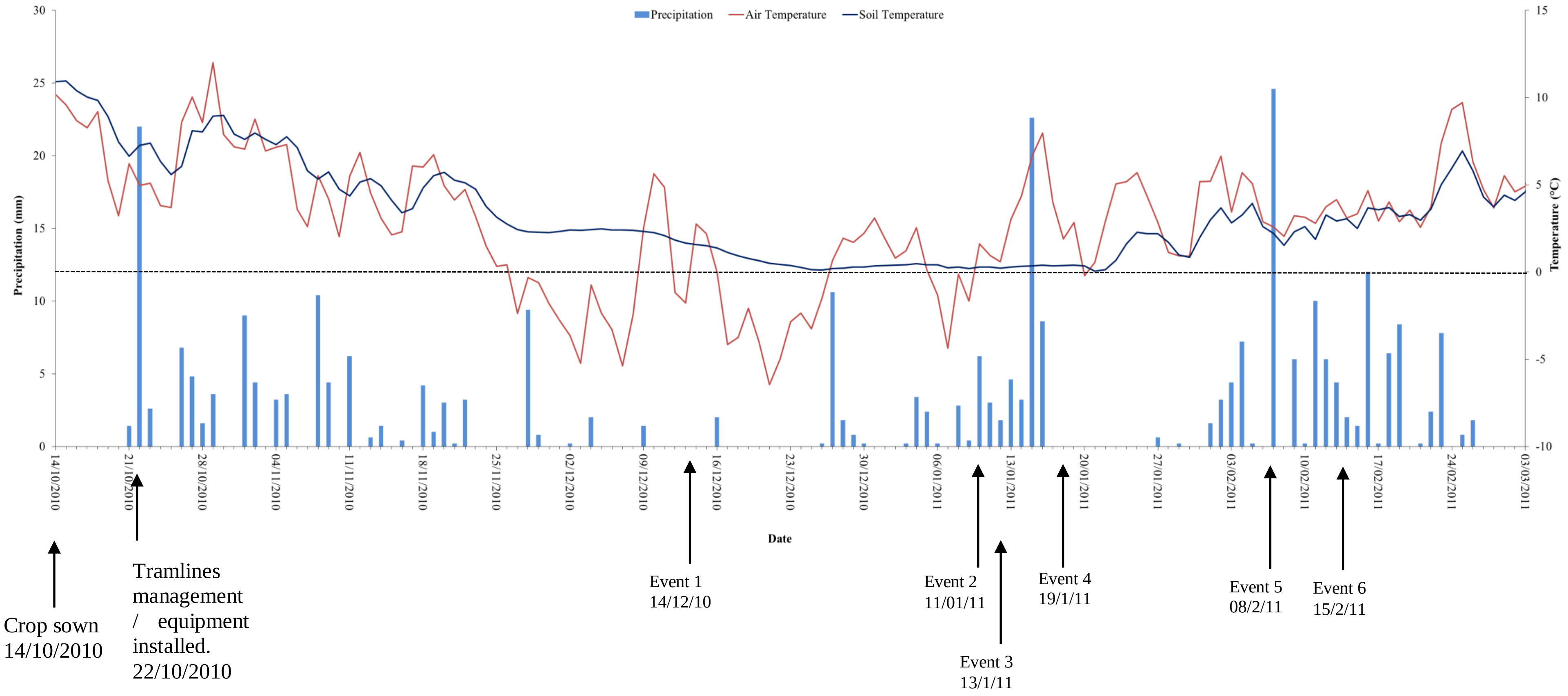
To give the average field seed density, the total seed density is divided by the number of sampling points (48). Statistical analysis was conducted using the software Genstat (version 13, 2010, VSN International).

2.3 Results

2.3.1 Meteorological data

Figure 2.8 shows the precipitation and temperature data between 14th October 2010 and 3rd March 2011 with the six event sampling dates. Hydrographs showing the duration of each event, precipitation and amount of water for each tramline management are shown in Appendix A. Figure 2.9 shows an example hydrograph.

The first four events were the result of snow melt, while events five and six were rainfall driven. Figure 2.10 shows a photograph of a tank during 2010/11 season emphasising the severity of the snow. The Gerlach Troughs were buried under the snow resulting in snowmelt events during thawing despite no additional precipitation. Events 2, 3 and 4 all occurred in a week as a result of increasing temperatures thawing the snow. Events 5 and 6 also occurred within one week of each other but differed in intensity and duration: event 5 lasted 14 hours with an average precipitation of 0.43 mm hr^{-1}; event 6 lasted 80 hours with an average precipitation of 0.07 mm hr^{-1}. There was a difference in runoff, sediment, seed removal and species numbers between the snow melt and rainfall driven events.



Crop sown
14/10/2010

Tramlines management / equipment installed.
22/10/2010

Event 1
14/12/10

Event 2
11/01/11

Event 3
13/1/11

Event 4
19/1/11

Event 5
08/2/11

Event 6
15/2/11

Figure 2.8 – Daily precipitation and temperature data for 2010/11 season with individual events highlighted. The first four events occur as a result of snowmelt whilst the last two are from rainfall. Dotted line represents freezing point of water.

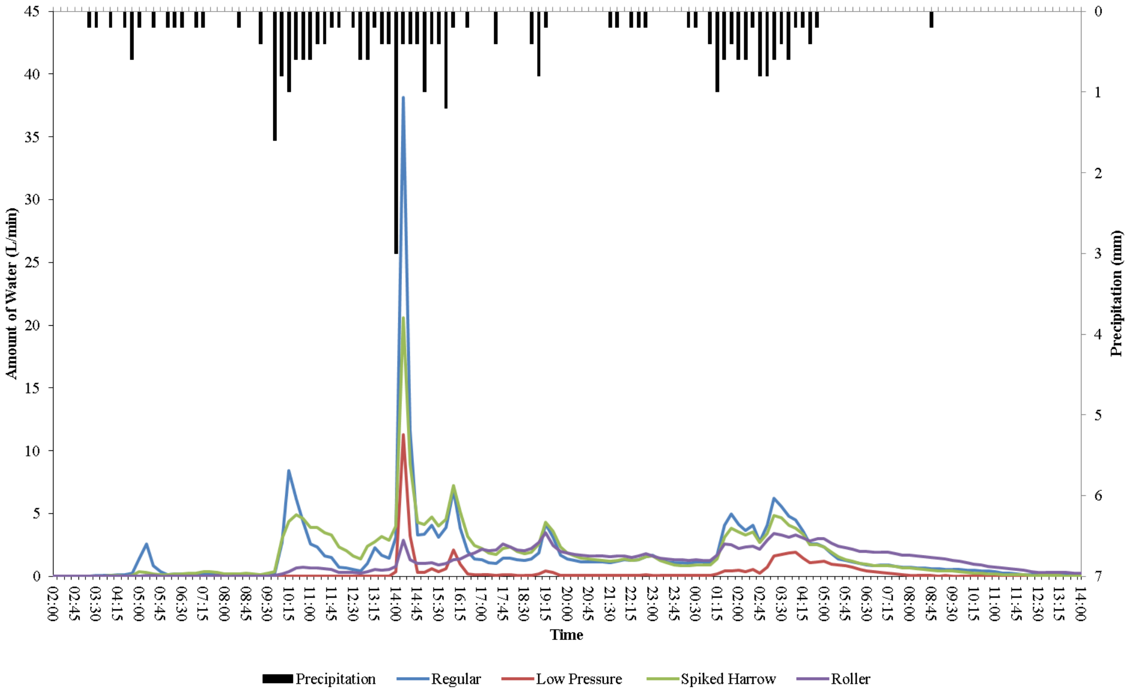
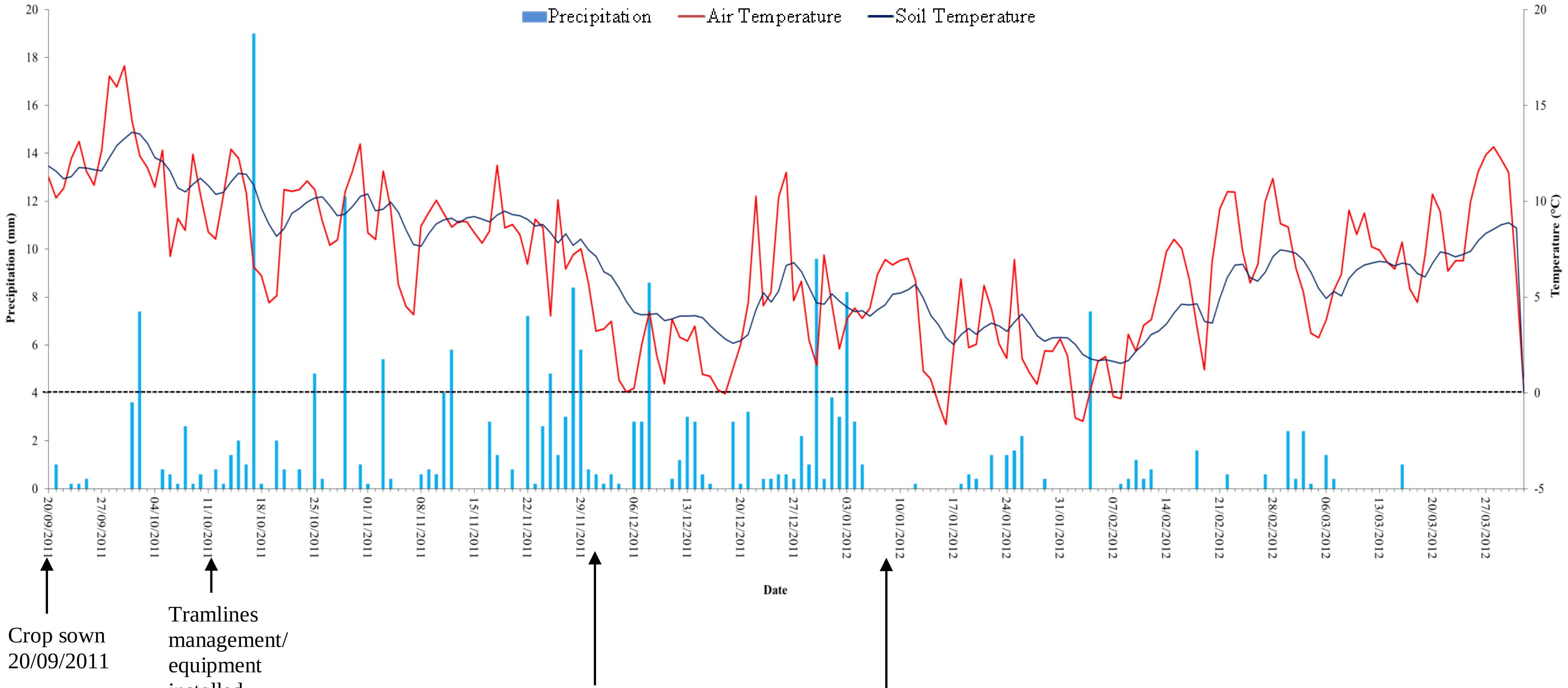


Figure 2.9 - Example hydrograph for event 4 running from 15th January at 02:00 until 16th January at 14:00

Figure 2.10 - Example of a tank on 10th December 2010 buried in snow. The Gerlach Trough is completely buried by snow prior to event 1 on 14th December 2010.

Figure 2.11 shows the precipitation and temperature data between 20th September 2011 and 31st March 2012 with the two event sampling dates. Hydrographs showing the duration of each event, precipitation and amount of water for each tramline management are depicted in Appendix A. An example is shown in Figure 2.12. The time series shows prior to the first event sampling on 1st December 2011 (event 7) there were 43 days when precipitation occurred. However, this rainfall did not become runoff due to low antecedent conditions when the tanks were only half full of runoff. The second event (event eight) was the result of three rainfall events over a total of 8 hours with an average rainfall of 0.05 mm. There was no snowfall during 2011/12.



Crop sown
20/09/2011

Tramlines
management/
equipment
installed.
11/10/2011

Event 7

01/12/2011

Event 8

09/01/2012

Figure 2.11 – Daily precipitation and temperature data for 2011/12 season with individual events highlighted. The two events were both rainfall events that had long durations in low antecedent conditions resulting in small runoff events. Dotted line represents freezing point of water.

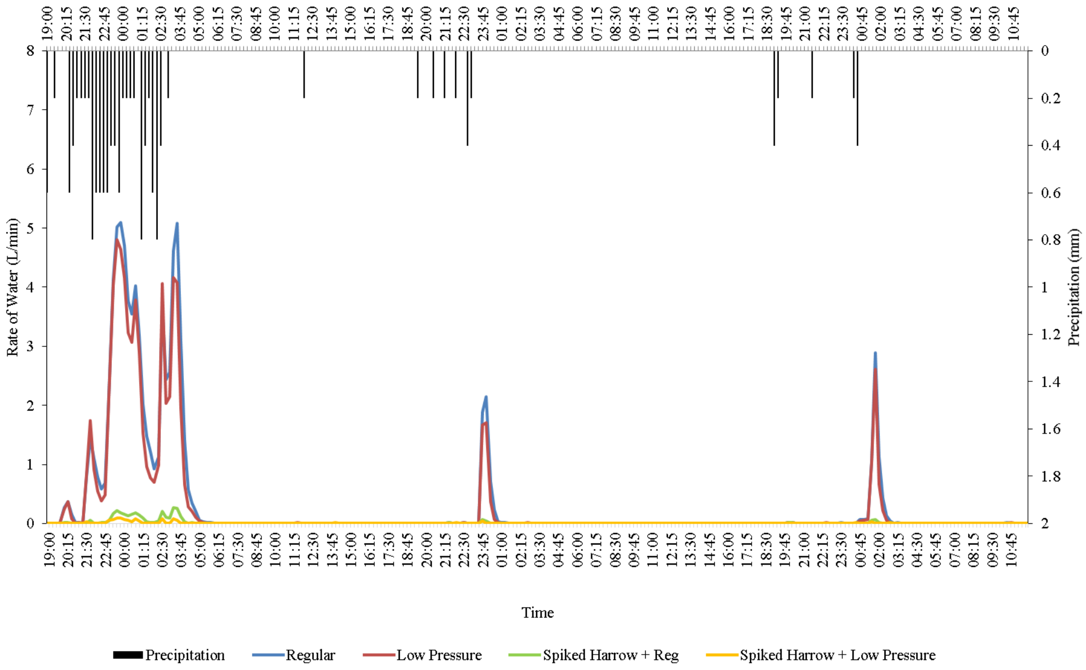


Figure 2.12 - Example hydrograph for Event 7 running from 28th November at 19:00 until 1st December at 11:45

Figure 2.13 shows the precipitation and temperature data between 21st September 2012 and 1st March 2013 with the eleven event sampling dates (events 9 – 19). An example hydrograph is shown in Figure 2.14. Precipitation and temperature data were not available after 21st December 2011. However, events six and ten were affected by both frozen ground and snow, which were determined by field observations. Similar to 2010/11, events 11 – 13 were all in a single week and all were intense. Event 11 produced 9.4 mm of runoff over 6.75 hours, event 12 produced 15 mm of runoff over 7 hours and event 13 produced 7.4 mm of runoff over 6.75 hours.

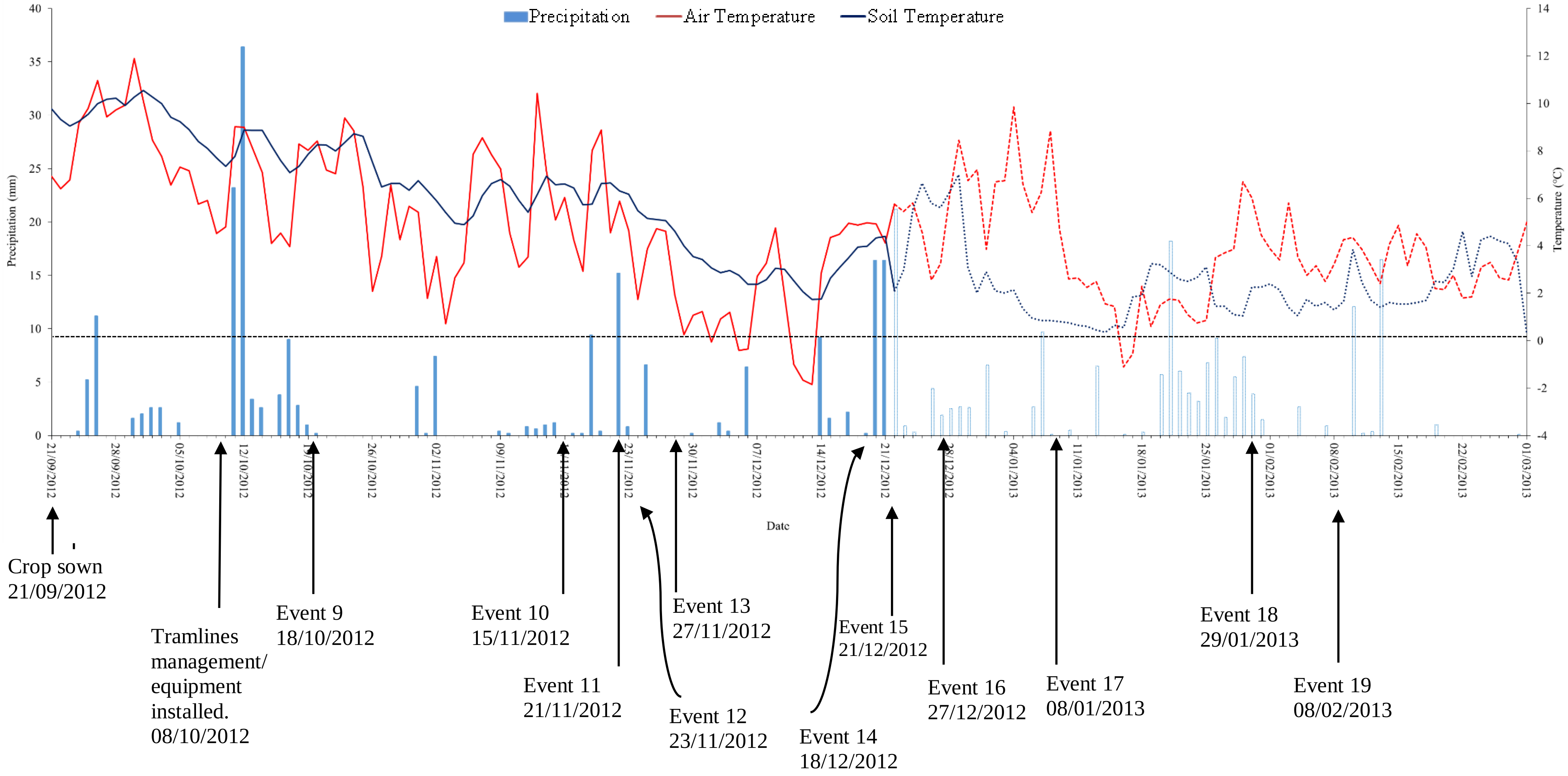


Figure 2.13 – Daily precipitation and temperature data for 2012/13 season with individual events highlighted. Events were frequent through November and December. Equipment failure on 22nd December means data from JHI weather station at Invergowerie (5 miles), shown by dotted lines, gives approximate conditions for precipitation and temperature. Horizontal black line shows the freezing point of water.

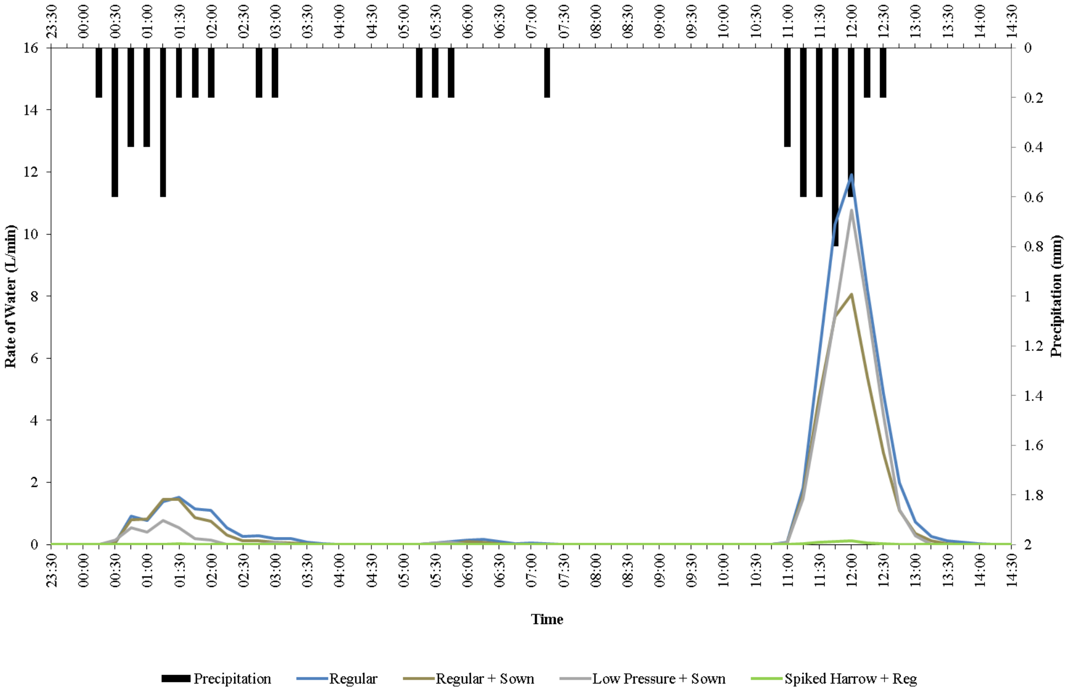


Figure 2.14 - Example hydrograph for Event 10 running from 1st November at 23:30 until 2nd November at 14:30

2.3.2 Treatment effects on runoff and sediment collection

As part of the bigger LINK project, the collection of runoff and sediment data were important in understanding how soil erosion from tramlines transports seeds. Significance values for differences between treatments are found in section 2.3.5.1 in Table 2.6 - Table 2.8 but are given in this section for reference.

2.3.2.1 Runoff

Figure 2.15 demonstrates the variability of runoff for each event in each year and the total over all three years. In 2010/11 (Figure 2.15a), data were unavailable for event 3 due to frozen tipping buckets and battery failures. Events 1 – 4 were the result of snow melt, although event 4 responded similarly to the rain driven events 5 and 6. In terms of runoff, events 1 and 2 shows the regular tyre resulted in less runoff compared to events 4 – 6. This is likely as a result of the different driving force between the two sets of events where events 1 – 3 were from snow fall whilst events 4-6 were from snow melting and rainfall. Overall, there was no significant in runoff difference between the tramlines (p = 0.076) likely due to the difference between snow melt and rainfall runoff events.

In 2011/12 (Figure 2.15b), regular tyres produced the greatest runoff. Unlike 2010/11, runoff decreased as a result of management from regular tyres, low pressure tyres, spiked harrow with regular tyres and spiked harrow with low pressure tyres. During 2011/12 season, the tramline management did have a significant difference on runoff ($p < 0.001$), however only having two events during a drier season than 2010/11 makes interpretation cautious.

In 2012/13 (Figure 2.15c), runoff was highly variable between events where the sown regular tyre tramlines produced more runoff in extreme events (Event 12 and 16). In comparison to other events, runoff was highest from the non-sown regular tyre managed tramlines. The frozen ground and snow in Events 14 and 18 respectively produced the least amount runoff. The tramline managements did not have a significant effect ($p = 0.079$) on runoff for 2012/13.

To gain a better understanding of the long term impact of tramline management on erosion between the regular tyres, low pressure tyres and spiked harrow the results were compared across three years (Figure 2.15d). Low pressure tyres were used only in conjunction with the sowing of the tramline in 2012/13. Regular tyres used across the three years had the greatest amount of runoff. The spiked harrow tramlines produced the least amount of runoff across all three years.

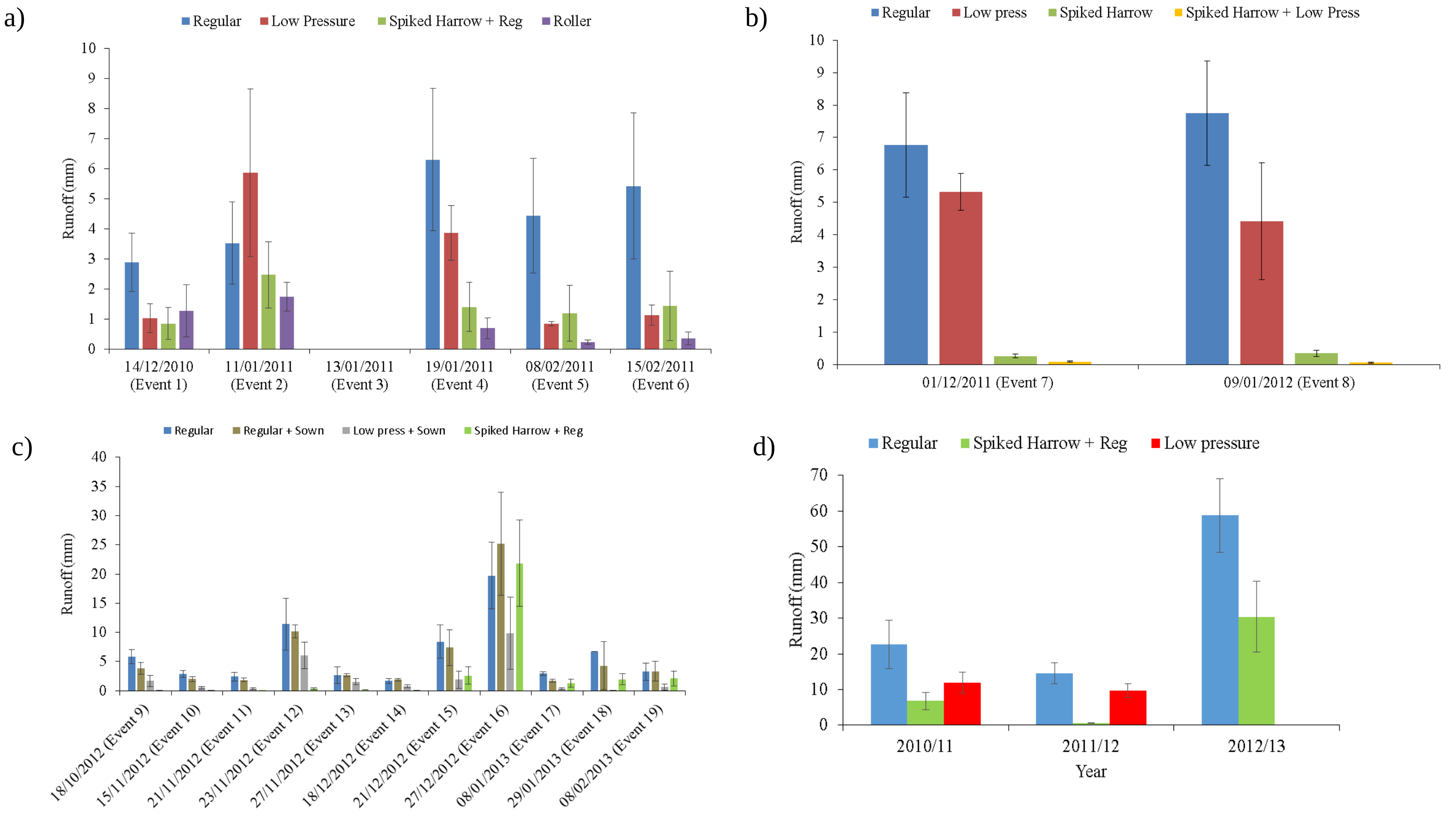


Figure 2.15 - Runoff results for (a) 2010/11, (b) 2011/12, (c) 2010/13 and (d) All three years showing individual events and tramline management with standard error. No data was available for event 3 in 2010/11.

2.3.2.2 Sediment

Figure 2.16 demonstrates the variability of sediment load for each event in each year and the total over all three years. Sediment data was unavailable for Event 3. The first four events in 2010/11 (Figure 2.16a) were caused by snow melt and show differences compared to the rainfall events. Noticeably, rainfall events produced more sediment than snow melt events suggesting the ground was frozen under the snow, preventing soil and seed detachment. In event 5, the spiked harrow tramlines produced slightly more sediment (52.36 kg ha^{-1}) than the low pressure tyres. This discrepancy was the only event in 2010/11 that showed these results and coincides with the first rainfall driven event, thus suggesting the spiked harrow managed tramlines were affected by the freezing conditions. Overall, sediment load was significantly affected by tramline management ($p = 0.005$).

In 2011/12 (Figure 2.16b), sediment load was greater over each event compared to 2010/11 although this was probably due to differences between the snow events and rainfall events in each season. Similar results compared to 2010/11 show regular tramlines produced the greatest amount of sediment. Tramline management decreased sediment load in order of management from regular tyres, low pressure tyres, spiked harrow with regular tyres and spiked harrow with low pressure tyres, with similar correlation to runoff. As with runoff for 2011/12, sediment load was significantly different between the tramline managements ($p < 0.001$).

In 2012/13 (Figure 2.16c), tramline management had a different effect on sediment load compared to previous years. Sown regular tyre tramlines produced more sediment than regular tyres in events 12, 16 and 19 compared to all other events when non-sown regular tyre tramlines produced a greater sediment load. Results from events 12, 16 and 19 showed less runoff in the sown regular tramline than the non-sown regular tramline. Events 14 and 18 were affected by frozen ground and snow and showed low amount of sediment load (<100 kg ha^{-1} for all tramlines). For the season, sediment load was different between the tramline management techniques ($p = 0.043$).

Across all three years, regular tyre tramlines produced the greatest sediment load (Figure 2.16d). Noticeably, in 2012/13 sediment load exceeded both 2010/11 and 2011/12 sediment loads combined, although these results could be due 11 events in 2012/13 compared to a total of 8 for the other two seasons. The use of low pressure tyres during the 2010/11 and 2011/12 seasons produced a lower sediment load compared to regular tyre tramlines, but higher than the spiked harrow tramlines. Spiked harrow tramlines produced the least sediment load across all three years.

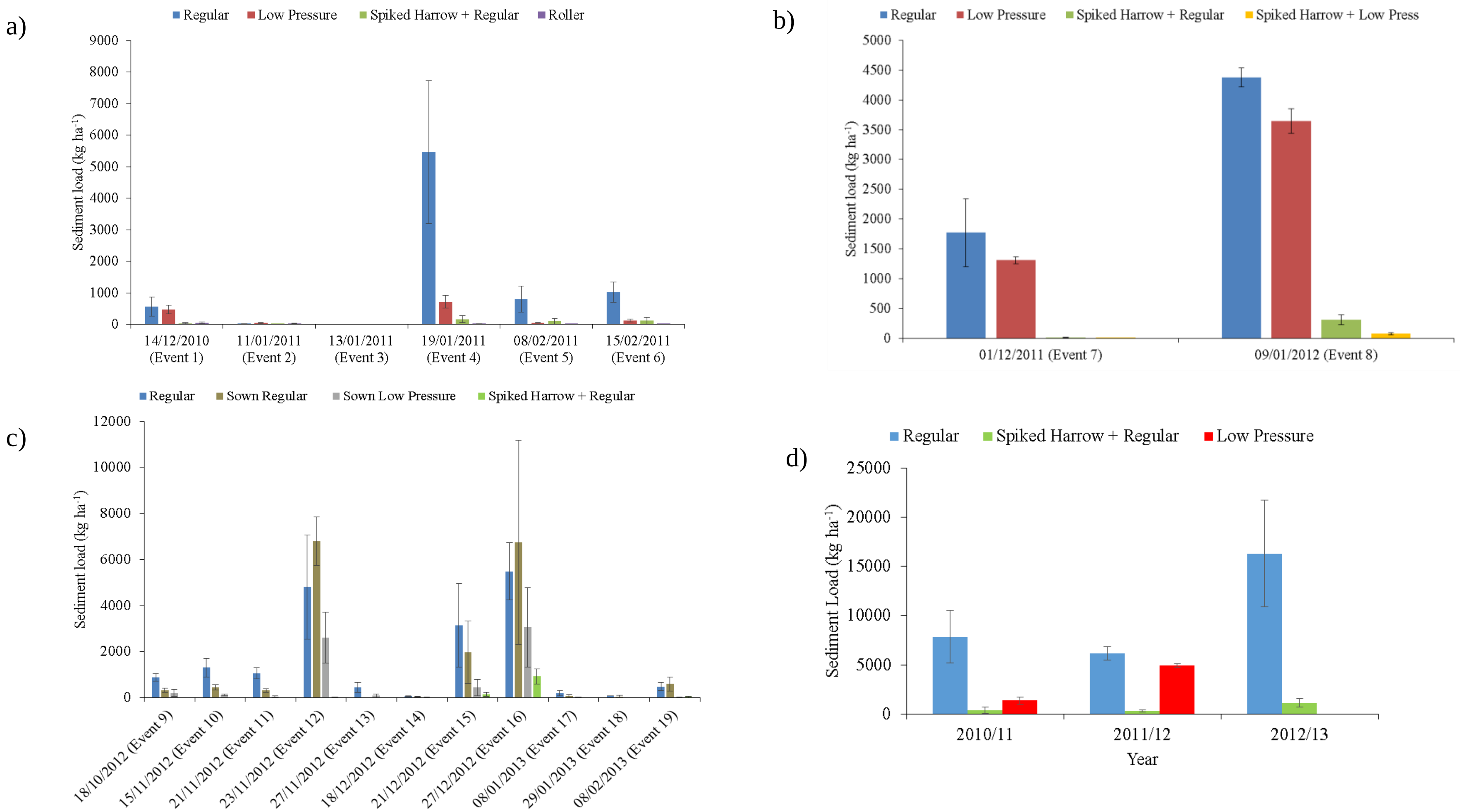


Figure 2.16 - Sediment results for (a) 2010/11, (b) 2011/12, (c) 2010/13 and (d) All three years for individual events and tramline management with standard error. No data was available for event 3 in 2010/11.

Particle size analysis of the eroded sediment samples (Figure 2.17 and Figure 2.18) showed the proportions of 63 – 2000 µm, 2 – 63 µm and < 2 µm were similar regardless of the type of tramline management ($p = 0.493$, 0.373 and 0.383 respectively). Particles sized 2 - 63 µm were frequently found in the highest concentration in the sample in all events. The chemically dispersed mineral fraction (CDMF) from ultimate analysis of samples indicated more < 2 µm and less 63 – 2000 µm sized particles than in the untreated sediment ($p<0.001$), illustrating that much of the eroded material was in the form of aggregates. Noticeably, there were three events which showed over 50% of the sample contained 63 – 2000µm particles, which was due to the whole sample being used to achieve the required obscuration in the laser granulometer for analysis. This means that sediment load was low due to frozen ground preventing fine particle detachment. Dispersed spiked harrow tramline samples were unusual as there were large amounts of sand in events 1 – 3 compared to other tramline managements. This analysis was used later in Section 2.3.6.4 to draw comparisons between particle sizes and seed sizes.

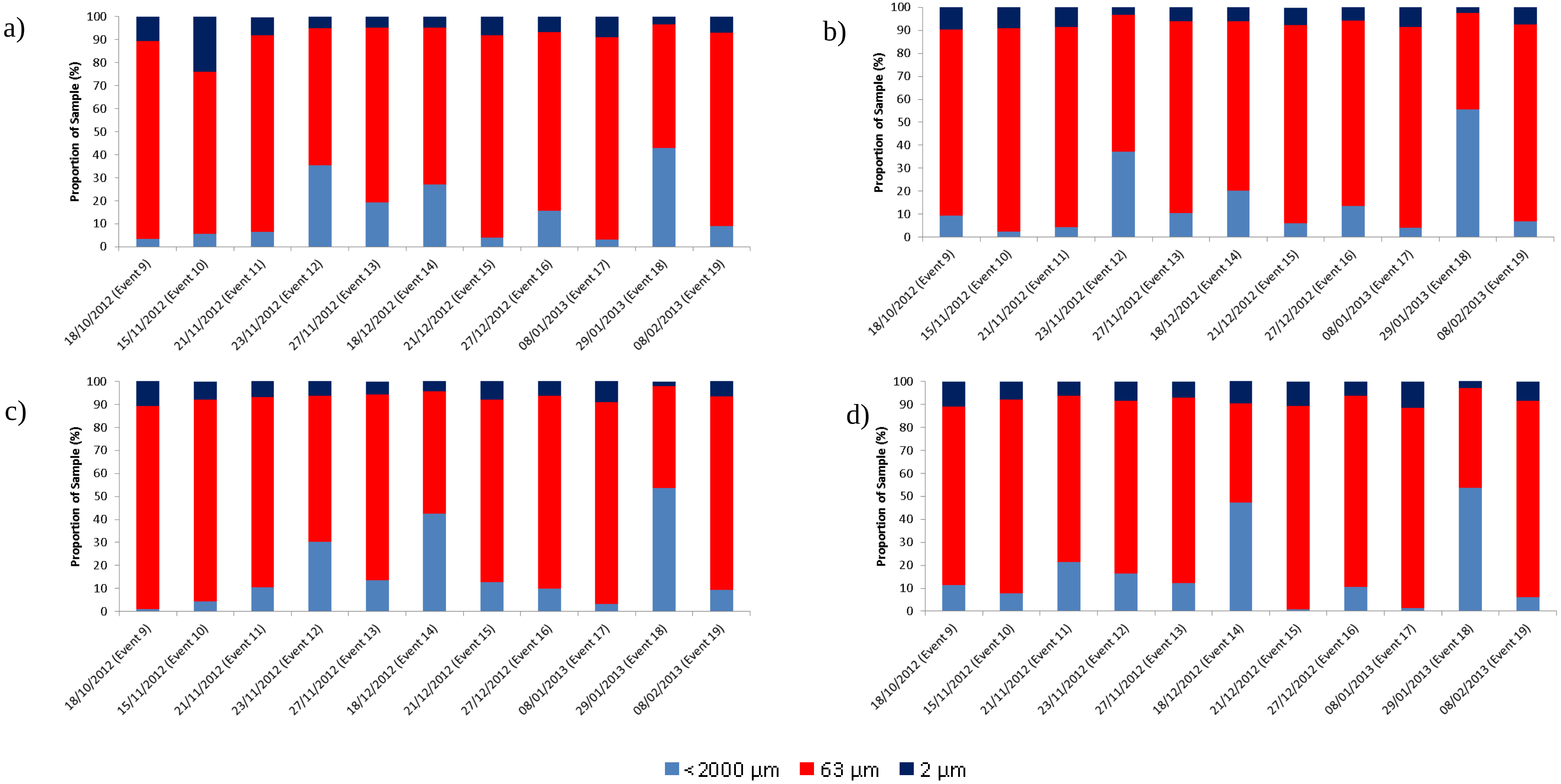


Figure 2.17- Proportions of <2000µm, 63 µm and >2 µm sized water stable (effective) aggregates from regular tyres (a), sown regular tyre (b), sown low pressure tyres (c) and spiked harrow (d) treated tramlines

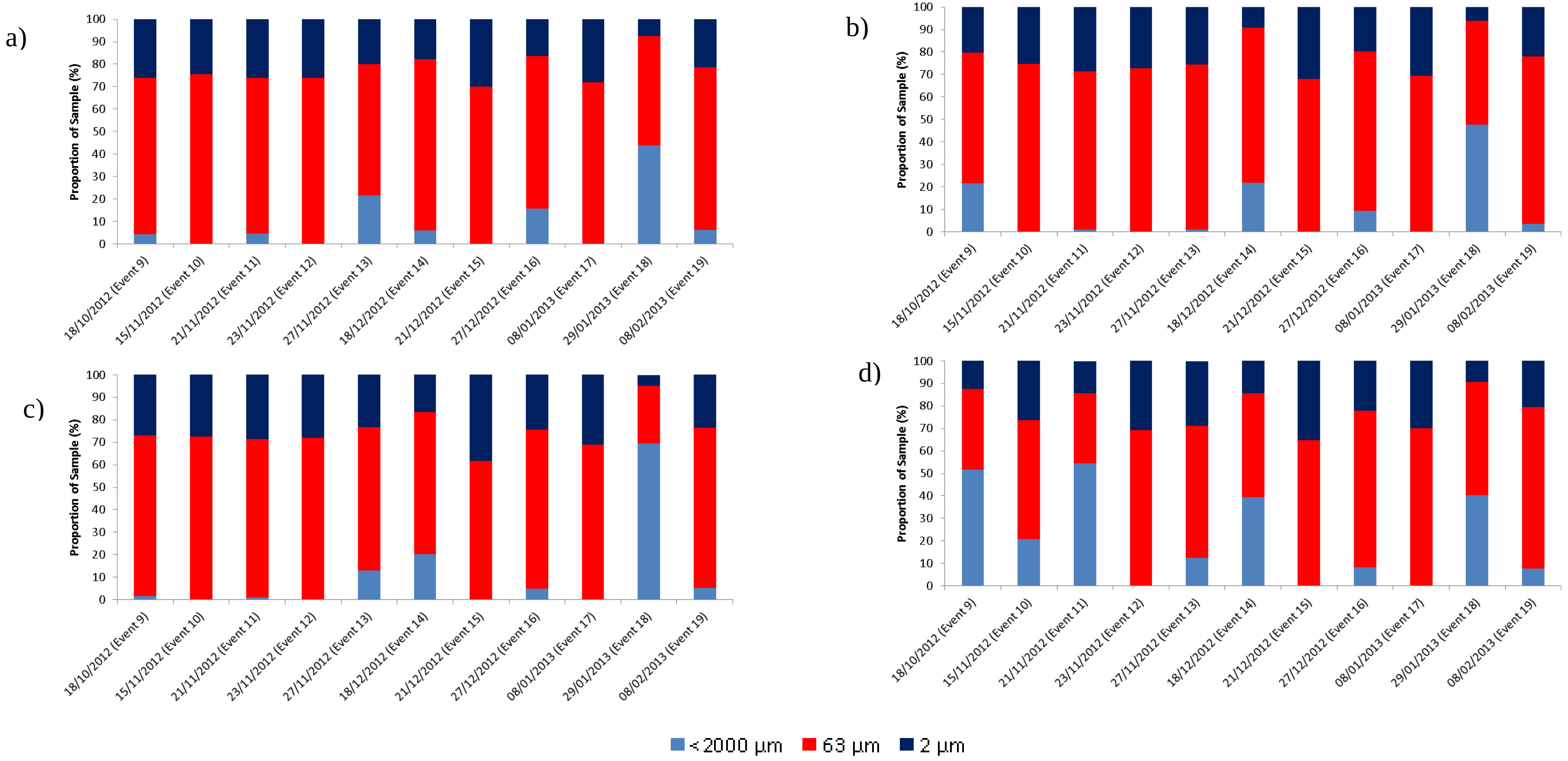


Figure 2.18- Proportions of <2000µm, 63 µm and >2 µm sized chemically dispersed (CDMF) (ultimate) particles from regular tyres (a), sown regular tyre (b), sown low pressure tyres (c) and spiked harrow (d) treated tramlines

Noticeably, events 6 and 10 (frozen ground and snow melt respectively) had a lower proportion of silt compared to other events however; the samples contained a higher proportion of 63 - 2000 µm. Table 2.1 and Table 2.2 present the median particle size (d_{50}) and mineral fractions for the field soil and the eroded material of all tramline managements. Management did not have a significant effect on the d_{50} or proportion of 63 - 2000 µm, 2 - 63 µm or < 2 µm sized particles. Comparisons between the eroded samples and the field soil samples show selectivity of the particle sizes. The water stable aggregates in Table 2.1 show the field soil comprised of almost equal proportions of 63 - 2000 µm and 2 - 63 µm sized aggregates however, the eroded soil samples have a greater proportion of silt compared to 63 - 2000 µm. Non-sown management techniques had a greater enrichment of clay than non-sown showing selectivity in response to vegetation. The ultimately dispersed field samples of soil contained more 2 - 63 µm and clay sized particles with less 63 - 2000 µm than the effective samples. The eroded soil samples contained greater amounts of 2 - 63 µm and < 2 µm with selective removal of aggregates compared to the field samples.

Table 2.1 - Mean effective d_{50} and mineral fractions of eroded soil samples (with *p* values) and field soil samples (excluded from analysis but presented for reference) over all events with standard error in 2012/13 showed tramline samples were mostly 2 - 63 µm (>70%) with some 63 - 2000 µm (14 – 18%) and little < 2 µm (<9%) sized particles.

Management Technique	**d_{50} (µm)**	**63 - 2000 µm (%)**	**2 - 63 µm (%)**	**< 2 µm (%)**
Mean				
Regular	11.89	14.86	76.73	8.38
Sown Regular	24.82	14.68	78.51	6.79
Sown Low Press	9.27	18.28	75.14	6.58
Spiked Harrow + Reg	17.85	17.95	73.48	8.59
Field Soil	63.64	48.76	47.47	3.77
p	*0.244*	*0.493*	*0.373*	*0.383*
Error				
Regular	2.92	2.24	2.47	1.45
Sown Regular	4.56	1.66	1.34	0.36
Sown Low press	7.35	2.56	2.56	0.33
Spiked Harrow + Reg	10.37	1.82	1.37	1.26
Field Soil	5.96	2.46	2.27	0.20

Table 2.2 - Mean ultimate d_{50} and mineral fractions for eroded samples (with *p* values) and field soil samples (excluded from analysis but presented for reference) for all events with standard error in 2012/13 showed tramline samples were mostly 2 - 63 µm (>=60%) with some < 2 µm (23 – 24%) but little 63 - 2000 µm (8 – 16%).

Management Technique	**d_{50} (µm)**	**63 - 2000 µm (%)**	**2 – 63 µm (%)**	**< 2 µm (%)**
Mean				
Regular	12.31	8.39	69.08	22.62
Sown Regular	11.63	7.67	68.70	23.69
Sown Low press	21.17	10.41	64.64	24.95
Spiked Harrow + Reg	23.58	16.86	59.87	23.28
Field Soil	20.56	26.70	58.11	15.18
p	*0.383*	*0.220*	*0.074*	*0.548*
Error				
Regular	3.01	1.47	0.91	0.63
Sown Regular	3.17	1.65	1.71	1.05
Sown Low press	7.25	3.67	3.33	0.56
Spiked Harrow + Reg	7.89	4.77	3.14	1.83
Field Soil	2.53	2.03	1.39	0.65

2.3.3 Seed assemblage of the field soil

To understand these findings in the wider context, UK and county average seedbank densities, given in Heard *et al.* (2003a), are presented with each year's seedbank densities from this field (Table 2.3). This data was chosen as seed export rates were given in Lewis *et al.* (2013) and provide a comparable number to tramline export rates in Section 2.3.4. Balruddery field had a very high seedbank density in 2010/11 but by 2011/12 decreased by 75.36% before recovering slightly but still 65.26% loss in 2012/13 compared to 2010/11. The number of species found for Balruddery Farm seedbank are lower than most of the other counties, except for Cumbria which 2010/11 seedbank figure exceeded. However, the comparison between Balruddery and the counties is not a fair comparison as the other counties contained multiple fields therefore a sampling effect is introduced to the number of species. The Shannon-Wiener index values (Table 2.4) is an index of diversity that integrates both species richness and rank-abundance. The diversity of the seedbank declined across the three years with the decrease in species richness over this period. Interestingly, the seedbank community evenness was hardly affected across time, indicated by the dominance of

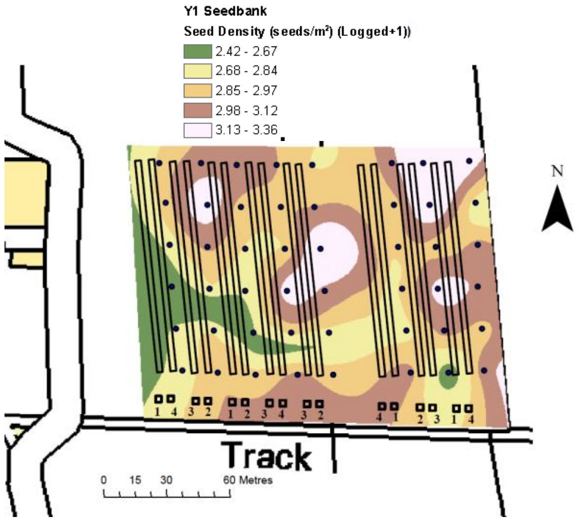
Poa annua and *Viola arvensis* (68% in 2010/11, 66% in 2011/12, and 74% in 2012/2013 of total) was relatively consistent across years. In addition to the seedbank abundance and composition changing, the spatial pattern changed across the three years (Figure 2.19). Evidently, the centre of the field appears to have higher seed densities compared to the edges of the field. However, in 2011/12 and 2012/13, the greatest seed densities were shown to be along the southern and eastern edges of the field.

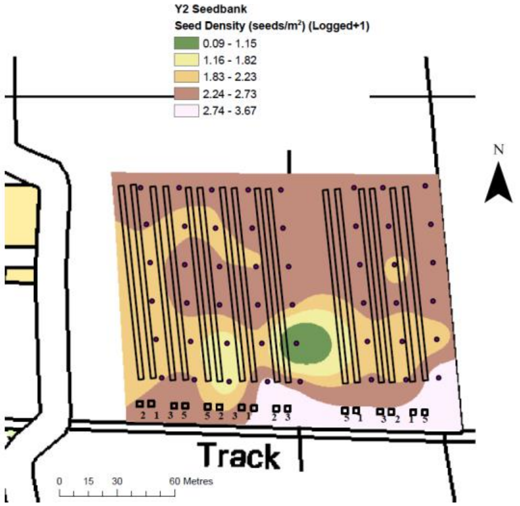
Table 2.3 - Seedbank densities and number of species for UK, county and Balruddery Farm (in bold) sorted by seed density.

Location	**Average Seed Density (seeds m^{-2})**	**Number of Species**
UK	2000	-
Cumbria	1422	20
Balruddery Farm – 2010/11	982	21
Kent	943	42
Shropshire	845	61
Dorset	551	53
Norfolk	505	87
Herefordshire	489	41
Cambridge	463	49
Balruddery Farm – 2012/13	351	14
Balruddery Farm – 2011/12	242	15
Nottinghamshire	240	26

Table 2.4 - Shannon-Wiener index values for field soil seedbank across all three years. Despite changes in seed numbers and diversity, the evenness of the community remained almost static across the three years.

	Year of Field Soil Sampling		
	2010/11	**2011/12**	**2012/2013**
Total Seeds	1485	377	608
Number of Species	21	15	14
Diversity (*H*)	1.76	1.639	1.56
Evenness (*E*)	0.58	0.61	0.59





<u>Key for Tank</u>

1. Regular Tyres, 2. Low Pressure Tyres, 3. Spiked Harrow, 4. Roller, 5. Spiked Harrow with Low Pressure Tyres, 6. Sown with Regular Tyres, 7. Sown with Low Pressure Tyres

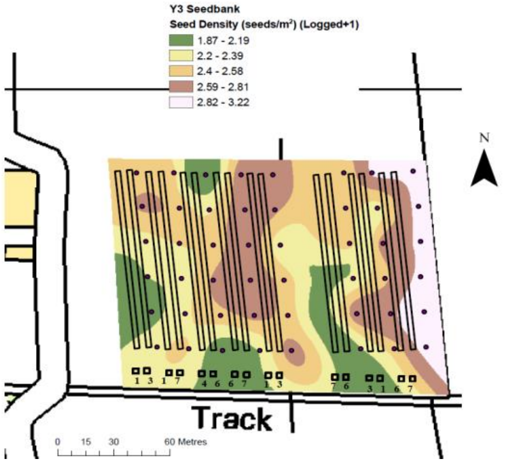


Figure 2.19 - Field seedbank density shown spatially for 2010/11 (Y1), 2011/2012 (Y2) and 2012/13 (Y3) with tramline management shown by numbered tanks at the south edge of the field.

2.3.4 Tramline effect on seed flux and species numbers

2.3.4.1 Seed Flux

Table 2.5 shows the species found in the soil seedbank (density) and transported seeds (flux) for all three seasons. In contrast to Table 2.3, the number of species in seed density and flux are not identical. Species present in arable soil but not in the tanks indicate that the seed was not transported along the tramline with eroded soil or runoff. Species present in the tanks but not in the soil samples could have been introduced to the seedbank through other dispersal mechanisms such as wind or fauna from outwith the field, or were present in the soil at densities too low to be detectable.

Figure 2.20 shows the variability in the number of eroded seeds during each event in each year and the total for all three years. In 2010/11 (Figure 2.20a), a total of 2830 seeds from 22 species were identified. Event 4 had the greatest seed number from all events in 2010/11, particularly from the use of regular tyre tramlines. This result coincides with the greatest runoff and sediment loads for 2010/11, suggesting large erosion events generates a large seed flux (see Section 2.3.5. for further analysis). Interestingly, the spiked harrow produced the second largest seed flux in event 4, which did not correlate to runoff and sediment load. Events 2 and 3 were found to have the least amount of seed flux and loss during 2010/11. Noticeably, the roller tramline management had the lowest loss of seed flux during 2010/11.

In 2011/12 (Figure 2.20b), a total of 938 seeds from 20 species were identified including 3 identified only to genera. *Carex sp., Geranium sp.* and *Trifolium sp* were seedlings not identified to species level as this would have required growing on to the maturity which was too time consuming. The seed flux during 2011/2012 was 66.86% lower than in 2010/11. Interestingly, tramline management had less impact on seed flux during event 6 compared to event 7, but this may be due to the limited data. Also, event 7 showed a similar pattern to 2010/11 in terms of management effects on seed flux and number of species.

In 2012/13 (Figure 2.20c), a total of 3736 seeds from 18 species and 1 genus were identified. No seeds were collected from spiked harrow tramlines in events 9 and 16. Events 14 and 18 which were affected by frozen ground and snow had less seed flux than all other events. No seedlings were germinated from regular tyre tramlines in event18, as only one tank had a sample from runoff following the event. Over the course of the season, there appeared to be diminishing effectiveness of tramline management on seed flux as seed flux increased over the season. These results may be a result of a jerky conveyor belt system where the seeds require multiple rainfall events to enable transportation into the tanks (Fryirs and Brierley, 2013).

Across all three years (Figure 2.20d), regular tyre tramlines had the greatest seed flux. In contrast to runoff and sediment, the greatest seed flux occurred during 2010/11 when 1.86 seeds m^{-2} were lost from regular tyres compared to the combined seed flux of 2011/12 and 2012/13. Spiked harrow tramlines across all years had the lowest seed flux over three years. The low pressure tyres used in 2010/11 and 2011/12 produced seed fluxes that were between the maxima seed fluxes of the regular tyre and minima seed fluxes of the spiked harrow tramlines.

Table 2.5 - List of species from soil seedbank density (density) and transported seeds (flux) for all three seasons.

Species	**2010/11**		**2011/12**		**2012/13**	
	Density	Flux	Density	Flux	Density	Flux
Aphanes arvensis		+				
Arabidopsis thaliana		+				
Bellis perennis	+	+				+
Brassica napus	+	+	+		+	+
Capsella bursa-pastoris	+	+	+	+	+	+
Carex sp.				+		+
Cerastium fontanum		+		+	+	+
Cirsium vulgare			+	+		+
Chenopodium rubrum				+		
Epilobium ciliatum	+	+	+	+	+	+
Fallopia convolvulus		+	+			+
Fumaria officinalis	+	+	+	+	+	
Geranium sp.			+			
Hordeum vulgare	+	+			+	+
Juncus bufonius		+		+		+
Lamium purpureum	+					
Matricaria recutita	+	+	+	+	+	+
Myosotis arvensis	+	+	+	+		
Persicaria maculosa	+					
Plantago lanceolata		+				
Poa annua	+	+	+	+	+	+
Polygonum aviculare	+	+		+	+	+
Senecio vulgaris	+	+	+		+	+
Solanum tuberosum	+					
Sonchus sp.				+		
Spergula arvensis		+				
Stellaria media	+	+	+		+	+
Taraxacum officinale	+			+		+
Trifolium sp.				+		+
Urtica dioica	+				+	
Urtica urens		+		+		+
Veronica arvensis	+	+	+	+	+	+
Veronica hederifolia	+		+	+		
Veronica persica	+	+		+		
Viola arvensis	+	+	+	+	+	+

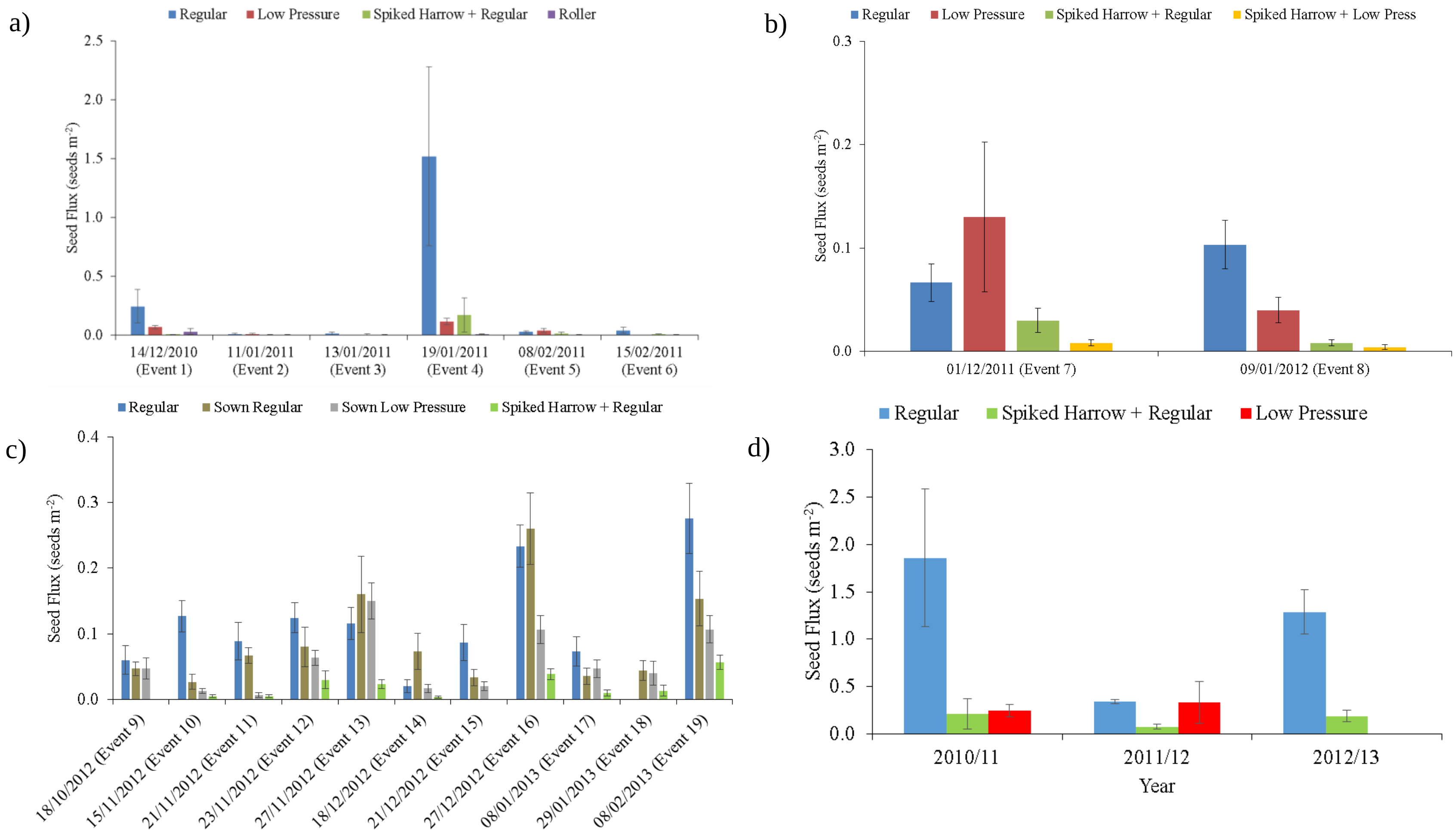


Figure 2.20 – Seed flux results for (a) 2010/11, (b) 2011/12, (c) 2010/13 and (d) All three years for individual events and tramline management with standard error.

2.3.4.2 Seed Species

Figure 2.21 shows the variability of the total number of species for each event in each year and the total amount of species over all three years. In 2010/11 (Figure 2.21a), the snow melt (events 1-4) and rain (events 5-6) events showed different responses in the number of species being transported. Except for event 3, regular tyre tramlines had the greatest number of species transported. In comparison, the spiked harrow and roller tramline managements for events 5 and 6 respectively had the highest amount of species loss (although lower than in events 1 – 4). These results indicate differences at the species level, in response to event type as well as tramline management. Furthermore, the low pressure tyre tramlines transported fewer species than regular tyres, except in event 5, where the same number of species was transported. Comparing this finding with seed flux (Figure 2.20a) indicates lower seed flux resulted in fewer species. These results lead to the hypothesis that seed morphologies have a role to play in the transport of seeds, which is further explored in 2.3.6.

In 2011/12 (Figure 2.21b), the total number of species per tramline management was higher than in 2010/11, despite lower seed fluxes. Event 7 had the greatest number of species lost from regular tramlines. However, the highest seed flux was from low pressure tyre tramlines. Comparing the two spiked harrow tramlines with regular and low pressure tyre tramlines shows a similar pattern which occurred during event 7. The spiked harrow with regular tyre tramlines produced the lowest total number of species but a higher seed flux than the spiked harrow low pressure tyre tramlines. This result may be due to the difference in seed assemblage (Figure 2.19b), thus showing the seedbank was smaller in the centre of the field, affecting the seed flux and number of species collected. Event 8 showed an identical pattern in seed species as in seed flux with decreasing numbers in order of management from regular tyre to low pressure tyre, spiked harrow with regular tyre and spiked harrow with low pressure tyre tramlines.

In 2012/13 (Figure 2.21c), the total number of species in any event from any tramline management was generally lower than in the previous two seasons. Sown regular tyre tramlines were found to have a greater number of species transported in five events (events 9, 11, 13, 14 and 18) compared to the non-sown regular tyre tramlines. However, events 13, 14 and 18 had a higher seed flux from sown regular tramlines than non-sown tramlines. Furthermore, events 14 and 18 were affected by frozen ground and snow which resulted in low amount of seed flux due to a low amounts of material being transported in the runoff.

Across all three years (Figure 2.21d), regular tyre tramlines had the greatest total number of transported species. Similarly the seed flux results showed, the spiked harrow had a greater effect at preventing transportation of seed species over the three years. In contrast to seed flux, the low pressure tyres had the lowest number of species transported in 2010/11, despite having the second highest seed flux. In 2011/12 low pressure tyres had the second greatest loss of species as well as decreased seed flux.

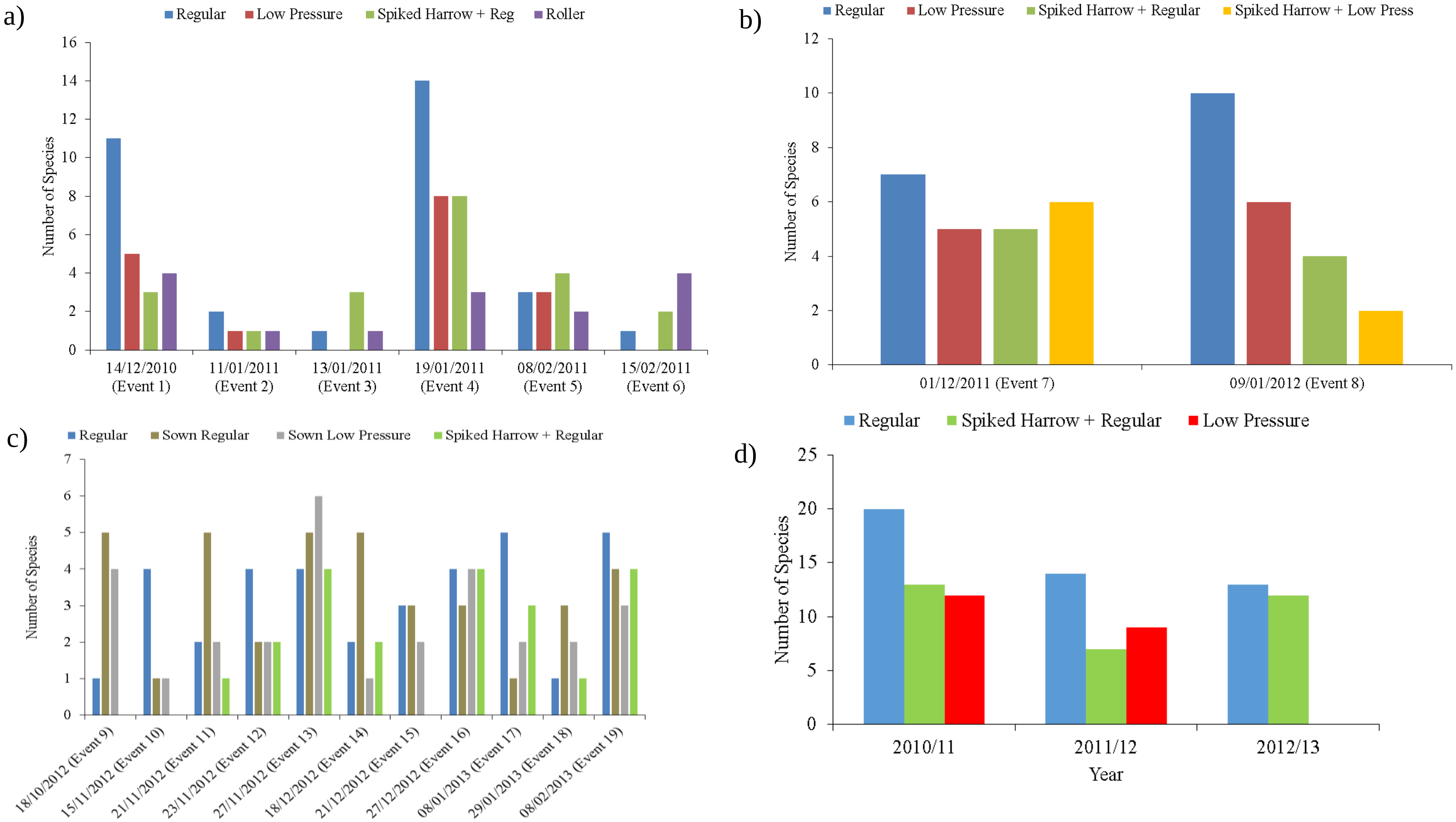


Figure 2.21 – Total number of seed species results for (a) 2010/11, (b) 2011/12, (c) 2010/13 and (d) All three years for individual events and tramline management with standard error.

2.3.5 Association between soil erosion and the arable seedbank

2.3.5.1 Effects of tramline management on runoff, sediment, seed flux and species numbers

Before direct links can be established between runoff, sediment, seed flux and species number, the effect of tramline management should be considered. Table 2.6 - Table 2.9 show the effects of tramline management on mean runoff, sediment load, seed flux and total species numbers for each individual season and the effect across the three seasons of repeated tramline managements.

In 2010/11 (Table 2.6) sediment load ($p = 0.005$), seed flux ($p = 0.016$) and seed species ($p = 0.007$) were found to be significantly affected by tramline management. Runoff was not significantly affected, which was probably due to two thirds of the events being the result of snow melt. The thawing process would have been slower but longer than rain driven events resulting in less erosive runoff on the tramlines. Noticeably, the regular tyre tramline had the greatest losses across all categories. The spiked harrow tramlines had a relatively high range for seed flux most probably caused by event 4 having a greater seed flux than other events. As a mean proportion of the field seedbank, regular tramlines had transported 0.19%, low pressure tyres had 0.03 %, and spiked harrow had 0.02% and roller 0.01% of the seedbank for 2010/11.

In 2011/12 (Table 2.7) runoff ($p<0.001$), sediment load ($p<0.001$) and seed species ($p = 0.006$) were significantly lowered by tramline management. Regular tyre tramlines had the greatest runoff and sediment load, followed by low pressure tyre, spiked harrow with regular tyre and spiked harrow with low pressure tyre tramlines. However, seed flux was not significantly affected by tramline management ($p = 0.144$). This was probably due to the lower amount of seeds (938 seeds) being transported across the field. Similarly in 2010/11, the spiked harrow had a large error associated with seed flux caused by a single tank having nearly a third of the total number of transported seeds. As a mean proportion of the field seedbank, regular tyre tramlines had transported 0.14%, low pressure tyres had 0.03%, spiked harrow with regular tyres had 0.14%, and spiked harrow with low pressure tyres 0.01% of the seedbank for 2011/12.

Table 2.6- Tramline management decreased mean seasonal losses (with standard error) and total number of species losses for the six events in 2010/11.

Tramline Management	**Runoff (mm)**	**Sediment Load (kg ha^{-1})**	**Seed Flux (seeds m^{-2})**	**Seed Species Number**
		Mean		
Regular tyres	22.6	7856	1.86	20
Low pressure Tyres	12	1380	0.25	12
Spiked Harrow	6.8	402	0.21	13
Roller	8	89	0.06	8
p	0.076	0.005	0.016	0.007
		Error		
Regular tyres	6.8	2689	0.73	-
Low pressure Tyres	2.9	380	0.06	-
Spiked Harrow	2.4	308	0.16	-
Roller	3	47	0.02	-

Table 2.7 - Tramline management decreased mean seasonal losses (with standard error) and total number of species losses for the two events in 2011/12.

Tramline Management	**Runoff (mm)**	**Sediment Load (kg ha^{-1})**	**Seed Flux (seeds m^{-2})**	**Seed Species Number**
		Mean		
Regular tyres	14.5	6150	0.34	13
Low pressure Tyres	9.7	4952	0.08	9
Spiked Harrow	2.4	317	0.34	7
Spiked Harrow + Low Pressure Tyres	0.1	79	0.03	6
p	<0.001	<0.001	0.144	0.006
		Error		
Regular tyres	2.9	695	0.02	-
Low pressure Tyres	2	161	0.02	-
Spiked Harrow	0.2	84	0.23	-
Spiked Harrow + Low Pressure Tyres	0	18	0.01	-

In 2012/13 (Table 2.8) sediment load (p = 0.043) and seed flux (p = 0.005) were significantly affected by tramline management. Regular tyres had the greatest seed flux and number of seed species transported however, the sown equivalent had a greater loss runoff and sediment. The difference between the sown and non-sown regular tyre tramlines were not significant for runoff, sediment, seed flux or number of species (p = 0.839, 0.854, 0.743 and 0.399 respectively). As a mean proportion of the field seedbank, regular tramlines had transported 0.32%, sown regular tyre tramlines had 0.26 %, sown low pressure tyres had 0.15%, and spiked harrow with regular tyres 0.04% of the seedbank for 2012/13.

Table 2.8- Tramline management decreased mean seasonal losses (with standard error) and total number of species losses for the 11 events of 2012/13. The exception was sown regluar tramlines where runoff and sediment load were greater than regular tyres.

Tramline Management	**Runoff (mm)**	**Sediment Load (kg ha^{-1})**	**Seed Flux (seeds m^{-2})**	**Seed Species Number**
			Mean	
Regular	58.8	16293	1.29	13
Sown + Regular	62.8	17318	1.03	11
Sown + Low Pressure	22.9	6453	0.61	11
Spiked Harrow + Reg	30.4	1131	1.29	12
p	0.079	0.043	0.005	0.612
			Error	
Regular	10.3	5422	0.23	
Regular + Sown	15.9	5556	0.20	
Low press + Sown	9.9	2479	0.18	
Spiked Harrow + Reg	10	443	0.06	

Table 2.9 shows the runoff, sediment load, seed flux and number of species transported by tramlines for repeated management techniques. For Years 1 – 2 runoff ($p<0.001$), sediment load ($p = 0.002$), seed flux ($p = 0.041$) and number of species (<0.001) were affected by tramline management. Regular tyres had the greatest values, followed by the spiked harrow and the low pressure tyres had the least. Years 1 – 3 runoff ($p = 0.034$), sediment load ($p<0.001$), seed flux ($p = 0.003$) and number of species (<0.001) were affected by tramline management. The spiked harrow tramlines had lowered runoff by 60%, sediment load by 94%, seed flux by 87% and species number by 22%.

Table 2.9 – Mean runoff, sediment load, seed flux with standard error and total number of seed species for all 3 winter years and all available treatments. Seed flux was found to be unaffected by tramline treatment across any time period compared to runoff, sediment load and number of seed species which were significantly affected by treatment.

Treatment	**Years 1 - 2**				**Years 1-3**			
	Runoff (mm)	**Sediment Load (kg ha^{-1})**	**Seed Flux (seeds m-^{2})**	**Seed Species**	**Runoff (mm)**	**Sediment Load (kg ha^{-1})**	**Seed Flux (seeds m^{-2})**	**Seed Species**
Mean								
Regular tyres	18.6	7003	1.10	21	32	10099	1.16	23
Low Pressure tyres	3.7	359	0.14	16	-	-	-	-
Spiked Harrow + Reg	10.9	3166	0.29	16	12.6	616	0.16	18
p	<0.001	0.002	0.041	<0.001	0.034	<0.001	0.003	<0.001
Error								
Regular tyres	3.7	1325	0.44	-	7	2271	0.30	-
Low Pressure tyres	1.7	149	0.08	-	-	-	-	-
Spiked Harrow+ Reg	1.6	702	0.11	-	5	198	0.19	-

2.3.5.2 Runoff association with seed flux and species

Figure 2.22 and Figure 2.23 show the relationships between runoff and seed flux for each individual season, and across multiple seasons, respectively. Regression analysis on 2010/11 data (Figure 2.22a) showed a moderate relationship between runoff and seed flux ($r^2 = 0.6$, $p = 0.002$). This different relationship compared to the other two years was probably due to the snow melt events in 2010/11 producing runoff which did not transport as many seeds. Regression analysis on 2011/12 data (Figure 2.22b) found a positive weak linear relationship ($r^2 = 0.39$, $p = 0.006$). There was a distinct difference between both tramlines managed by tyre type and those managed with a spiked harrow. The fact there was no snow or frozen ground affecting these results, the difference was probably due to disruption of the soil surface which impeded runoff. The 2012/13 data (Figure 2.22c), showed there was a very weak positive correlation between runoff and seed flux ($r^2=0.16$, 0.067). The high runoff and lower seed flux of the sown regular tyre tramlines probably affected the relationship as in the previous seasons, there was higher runoff which gave a higher seed flux.

Regression analysis for multiple seasons (Figure 2.23) showed positive correlations of runoff with seed flux. The combined 2010/11 and 2011/12 data (Figure 2.23a) which had regular tyre, low pressure tyre and spiked harrow tramlines found a strong positive relationship ($r^2=0.53$, $p<0.001$) between runoff and sediment flux. Results for regular tyres and the spiked harrow with regular tyres across all three seasons (Figure 2.23b), showed a weaker positive relationship ($r^2=0.2$, $p = 0.017$) between runoff and seed flux.

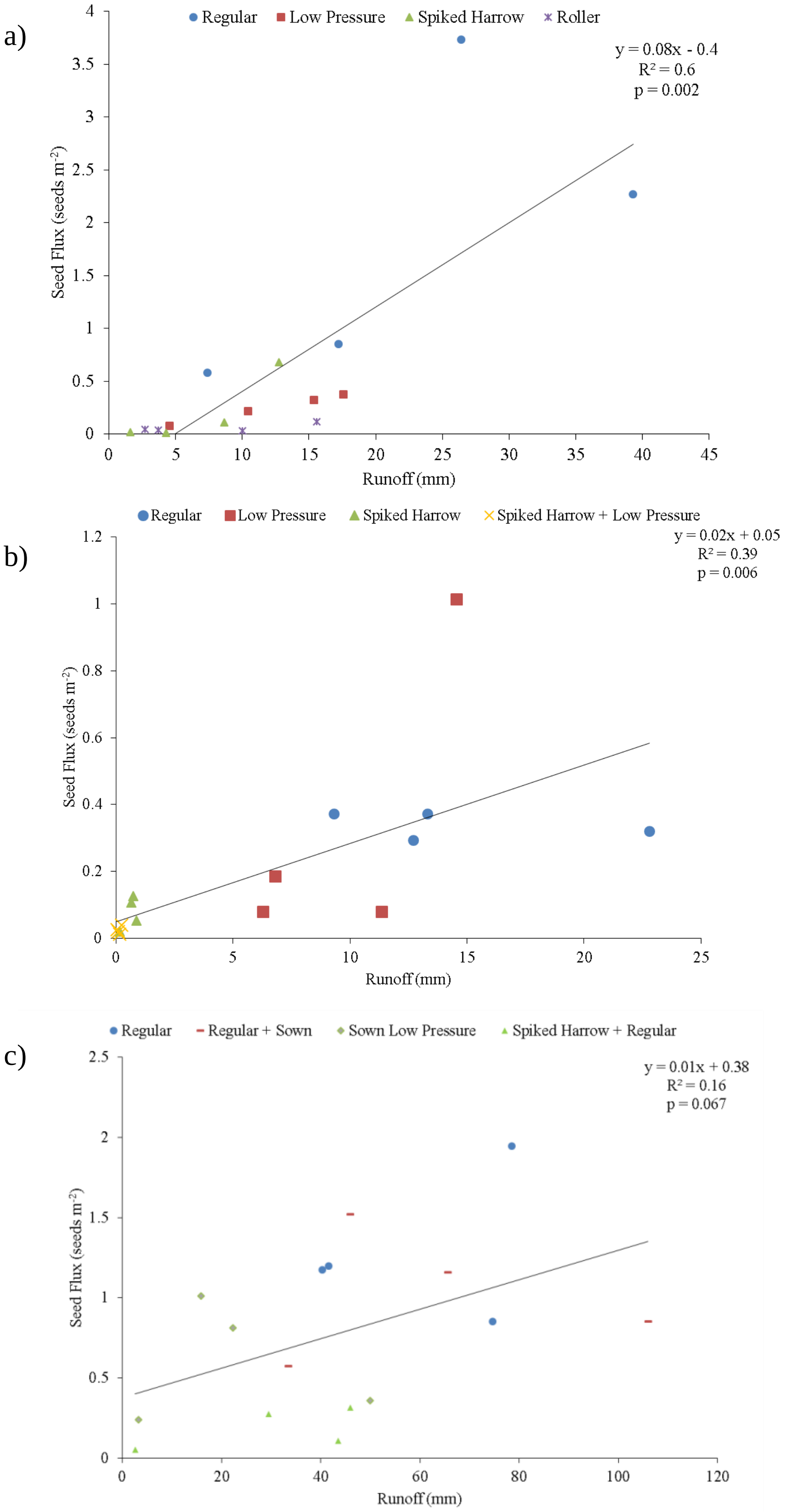


Figure 2.22 - Regression analysis of seed flux against runoff for all events in (a) 2010/11, (b) 2011/12 and (c) 2012/13 classified by management tyre. There was an exponential relationship (p = 0.002) in 2010/11 with positive correlations in 2011/12 (p= 0.006) and 2012/13 (p = 0.067).

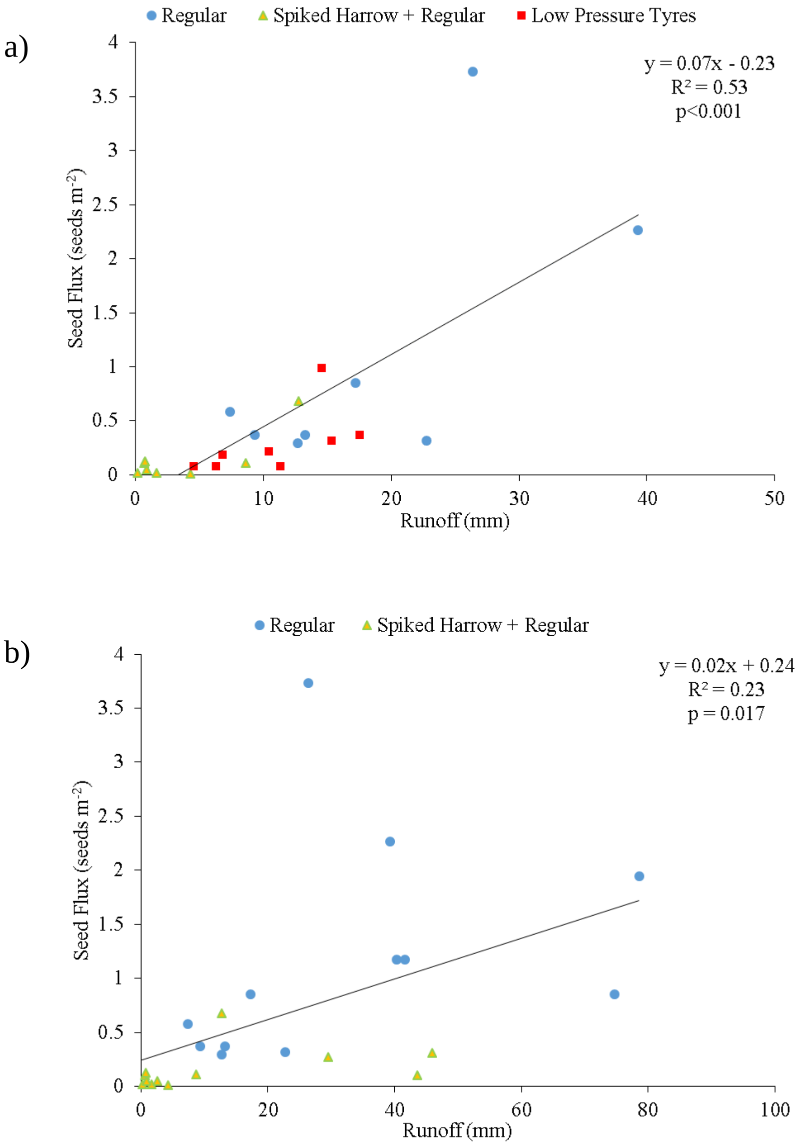


Figure 2.23 - Regression analysis of seed flux against runoff for (a) 2010/11 + 2011/12 and (b) 2010/11, 2011/12 and 2012/13 for repeated treatments. Runoff was positively correlated to seed flux for (a) where p<0.001, and (b) where p= 0.017.

Regression analysis of seed species data with runoff for 2010/11 (Figure 2.24a) found a strong positive relationship (r^2=0.76). In 2011/12 (Figure 2.24b) the same positive relationship was found but was considerably weaker than 2010/11 (r^2=0.36), although this lower figure might be due to the low number of events. Importantly, the relationship in 2012/13 (Figure 2.24c) was almost non-existent showing that despite differences in runoff, the number of seed species did not change.

Results of the regression analysis for the repeated treatments during the first two seasons (Figure 2.25a) showed a strong positive relationship (r^2 = 0.64). However, two of the regular tyre values which had the largest number of species with runoff were distinctly different. This was probably due to the snowmelt in 2010/11 which caused a small but very diverse seed flux to be transported by runoff. Analysis of the two repeated treatments over three years shows (Figure 2.25b) found a positive relationship which was weaker than the two year relationship. This result was caused by a half of the spiked harrow samples having less than 10 mm of runoff, but ranged between 2 and 6 different seed species.

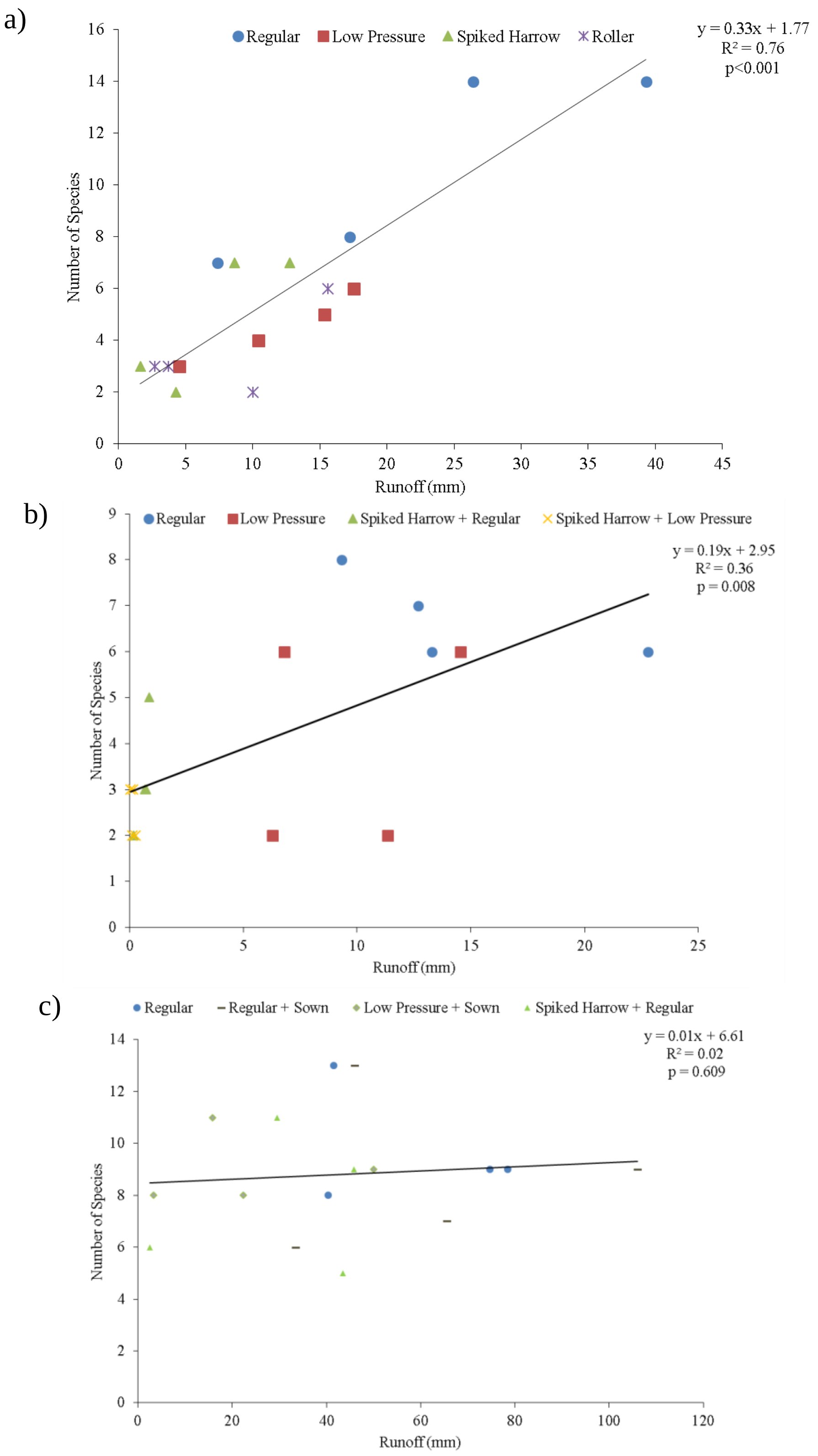


Figure 2.24 - Regression analysis of seed species against runoff for all events in (a) 2010/11, (b) 2011/12 and (c) 2012/13 classified by n ere were positive correlations across all the seasons, although these be er time (p<0.001, p =0.008 and p =0.609).

y = 0.28x + 2.53
R^2 = 0.64
p < 0.001

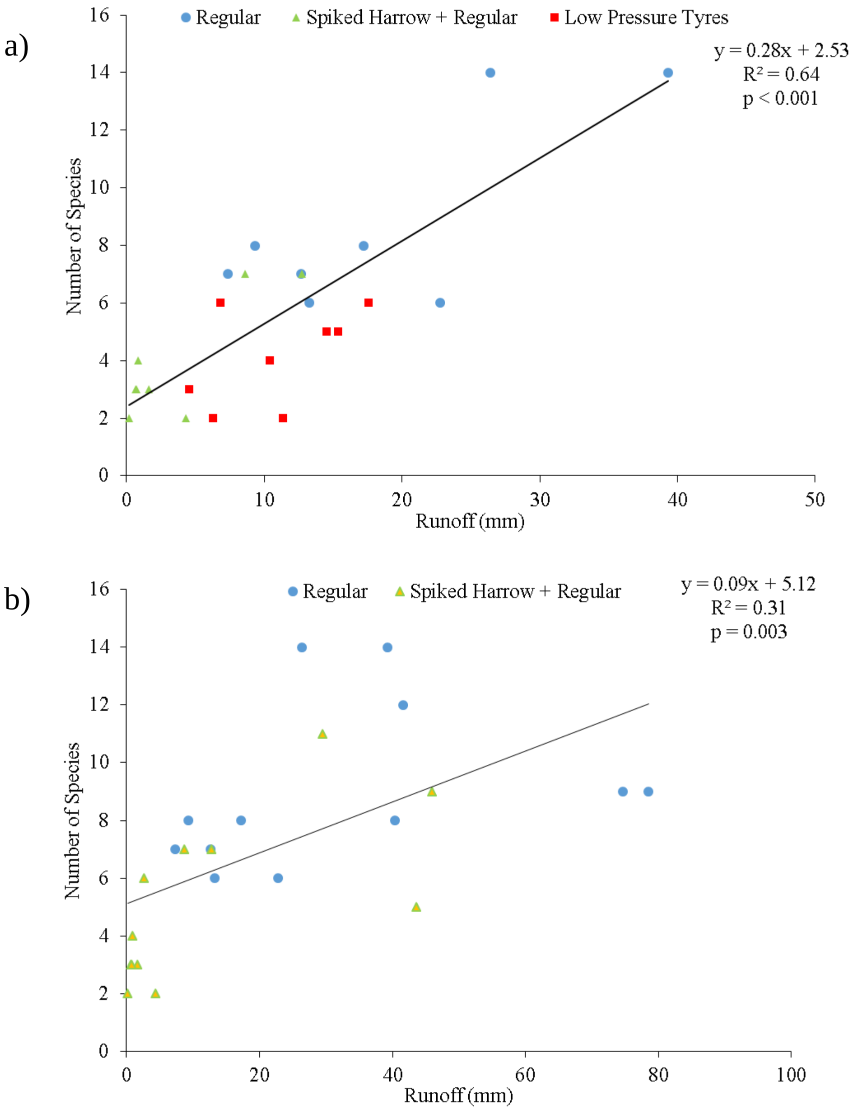


Figure 2.25 - Regression analysis of seed species against runoff for (a) 2010/11 + 2011/12 and (b) 2010/11, 2011/12 and 2012/13 for repeated treatments. Runoff was positively correlated to seed species for (a) where $p<0.001$, and (b) where $p= 0.003$.

2.3.5.3 Sediment association with seed flux and species number

Figure 2.26 and Figure 2.27 shows the relationships between sediment load and seed flux for each individual year and for multiple years using repeated management techniques.

In 2010/11 (Figure 2.26a) the relationship was found to have a very strong positive correlation (r^2= 0.96). However, this strong relationship contains two extreme values for the regular tyre tramlines, which could not be discounted because the samples were part of the largest event recorded. Therefore, they have a strong effect on the final relationship, but still are valid. In 2011/12 (Figure 2.26b) the relationship was still positive but weaker than the previous year (r^2=0.30). One of the low pressure tyre tramlines showed an unusually high seed flux (5 times more than other low pressure tyre tramlines), which may have influenced the analysis. In 2012/13 (Figure 2.26c) sediment had a positive relationship with seed flux (r^2=0.43). The previous two years, also showed two samples affecting the analysis. These two samples are from a sown and non-sown tyre regular tramline, which had over 30,000 kg/ha of sediment. Although this value appeared to be extremely high, given the size and frequency of events during this season, these two samples cannot be discounted. Also, these are high figures as a result of channelised flow down tramlines, which occupy 7.5% of the field, meaning the values were unlikely to be replicated across the field.

Regression analysis for repeated treatments in the first two seasons (Figure 2.27a) found a strong positive relationship (r^2=0.62) between sediment load and seed flux. The two extreme regular tyre tramlines have affected this relationship similar to the extreme values in 2010/11. However, these two value demonstrate the result of extreme events against other smaller events, emphasising the scale of erosion affecting sediment and seed flux. The regular tyre and spiked harrow managed tramlines across three years showed a positive relationship (r^2= 0.47) between sediment and seedbank. The extreme value of over 30,000 kg/ha sediment load for a regular tyre tramline had a strong effect on the analysis which could not be disproved.

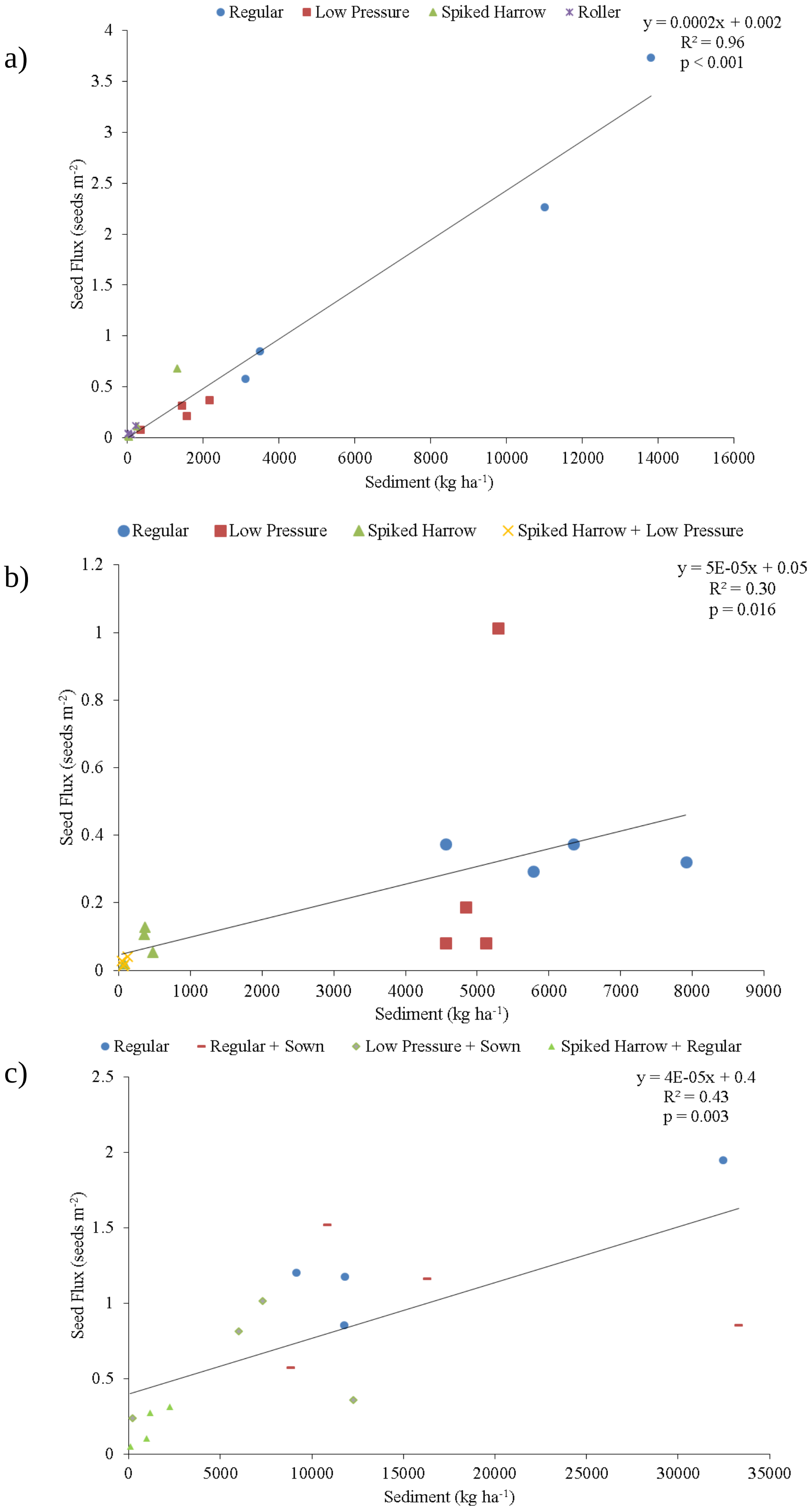


Figure 2.26 - Regression analysis of seed flux against sediment load for all events in (a) 2010/11, (b) 2011/12 and (c) 2012/13 classified by management. There was a positive linear relationship for all three years (where (a) p<0.001, (b) p = 0.016 and (c) p =0.003).

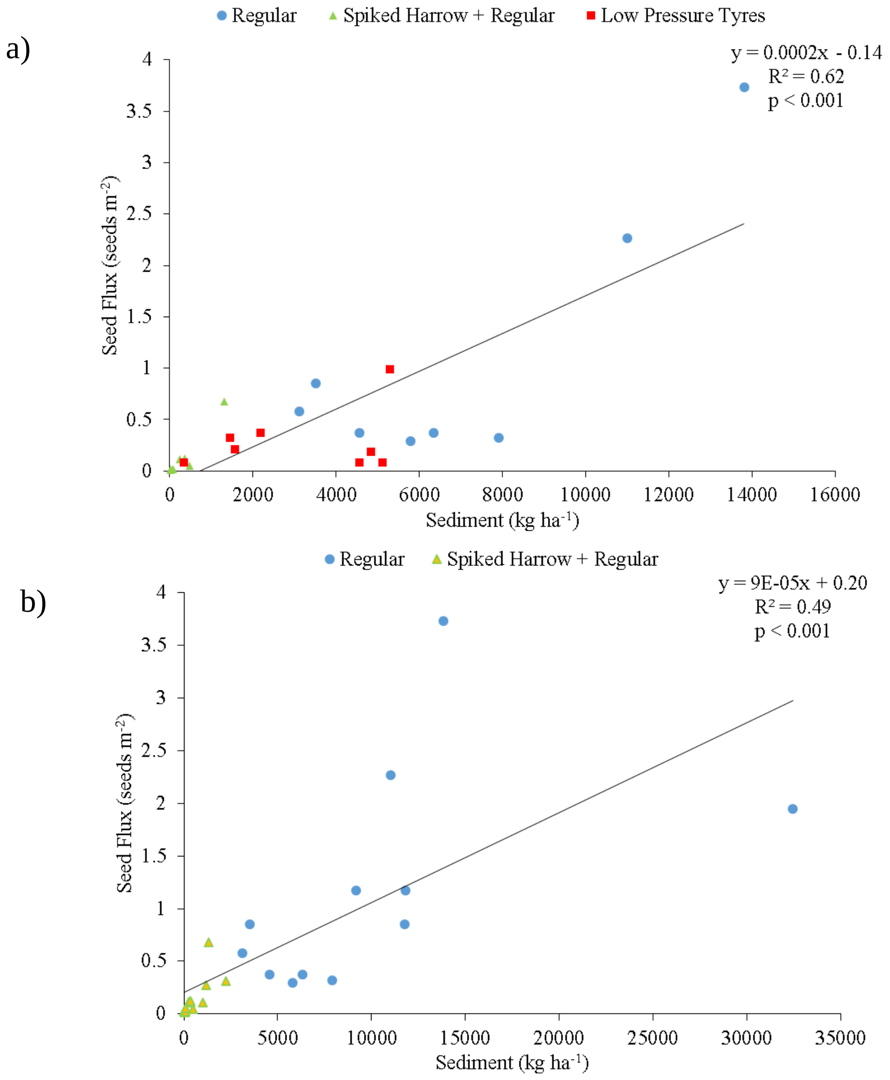


Figure 2.27 - Regression analysis of seed flux against sediment load for (a) 2010/11 + 2011/12 and (b) 2010/11, 2011/12 and 2012/13 for repeated treatments. Sediment load was positively correlated to seed flux for (a) and (b) $p<0.001$

Figure 2.28 and Figure 2.29 show the results of regression analysis for sediment load and seed species for each season and repeated tramline managements across all seasons. In 2010/11 (Figure 2.28a) sediment load was found to have a strong positive relationship with the number of species (r^2=0.83, $p<0.001$). This strong relationship was mirrored the strong correlation with seed loss, so a greater seed loss in 2010/11 resulted in a greater loss of seed species. In 2011/12 (Figure 2.28b) sediment load was positively correlated with number of seed species. Noticeably, there were three times more species in two of the low pressure tyre tramline samples compared to the other two tyres. The relationship was unlikely to be affected by the split between two regular tyre and two low pressure tyre management techniques but the number of species was not sufficient to determine the implications of tramline management. In 2012/13 (Figure 2.28c) the sediment load showed no correlation with number of species (r^2=0.02, p =0.625), which was not due to extreme sediment values.

Across the first two seasons (Figure 2.29a), sediment load correlated with the number of species (r^2=0.55, $p<0.001$). The spiked harrow showed the least number of species transported followed by the low pressure tyre tramlines whilst the regular tyre tramlines had the greatest loss. Across all three seasons (Figure 2.29b), the regular tyres and spiked harrow tramlines showed some positive correlation with seed species (r^2 = 0.28, p = 0.007). Importantly, there was a division between regular and spiked harrow managed tramlines around 3500 kg/ha sediment load. This division showed the spiked harrow might have had less sediment load, but still had a high number of species transported, similar to regular tyres tramlines.

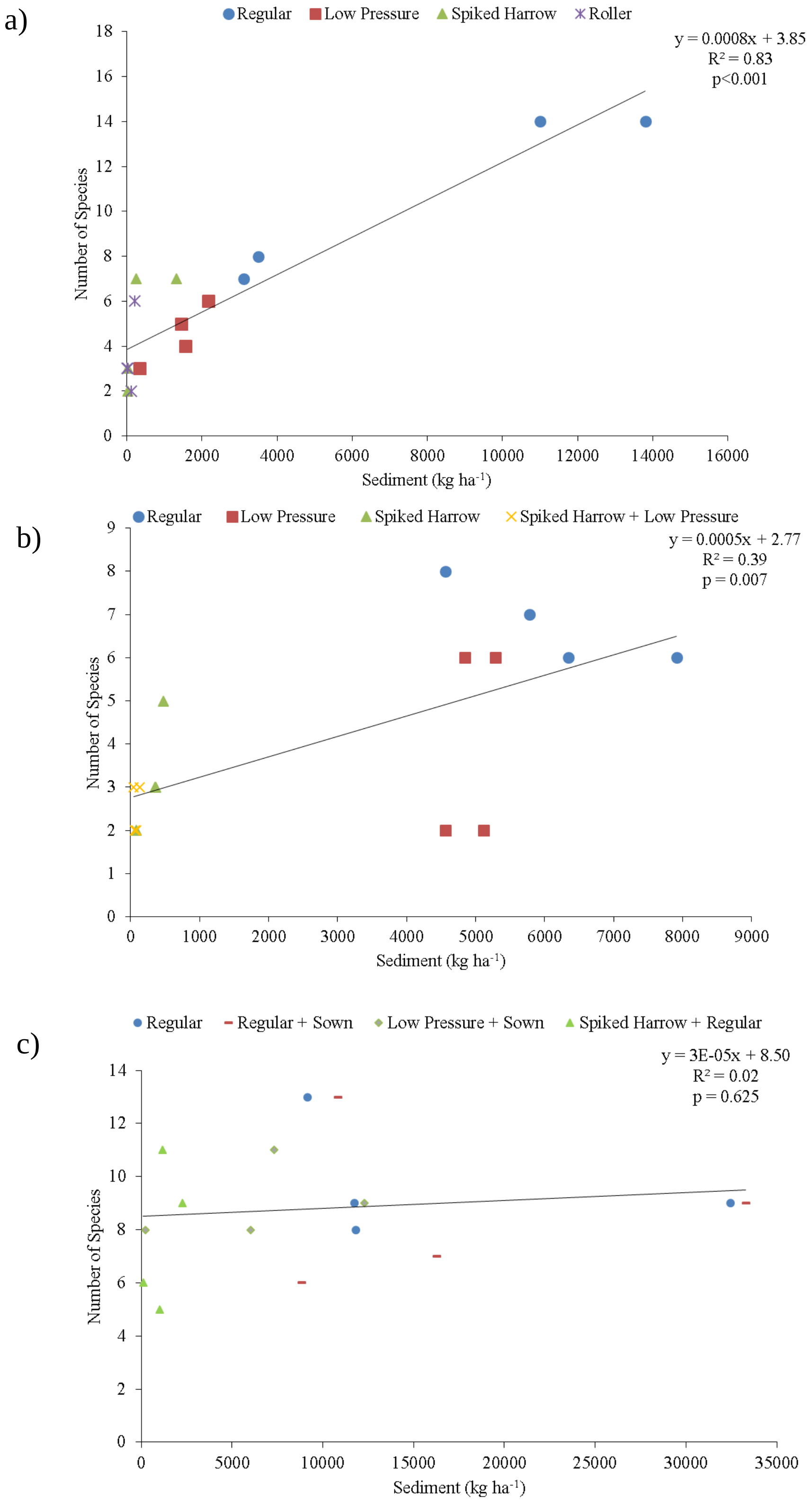


Figure 2.28- Regression analysis of seed species against sediment load for all events in (a) 2010/11, (b) 2011/12 and (c) 2012/13 classified by management. There was a positive linear relationship for (a) $p<0.001$ and (b) $p = 0.007$ but no relationship for (c) $p = 0.625$.

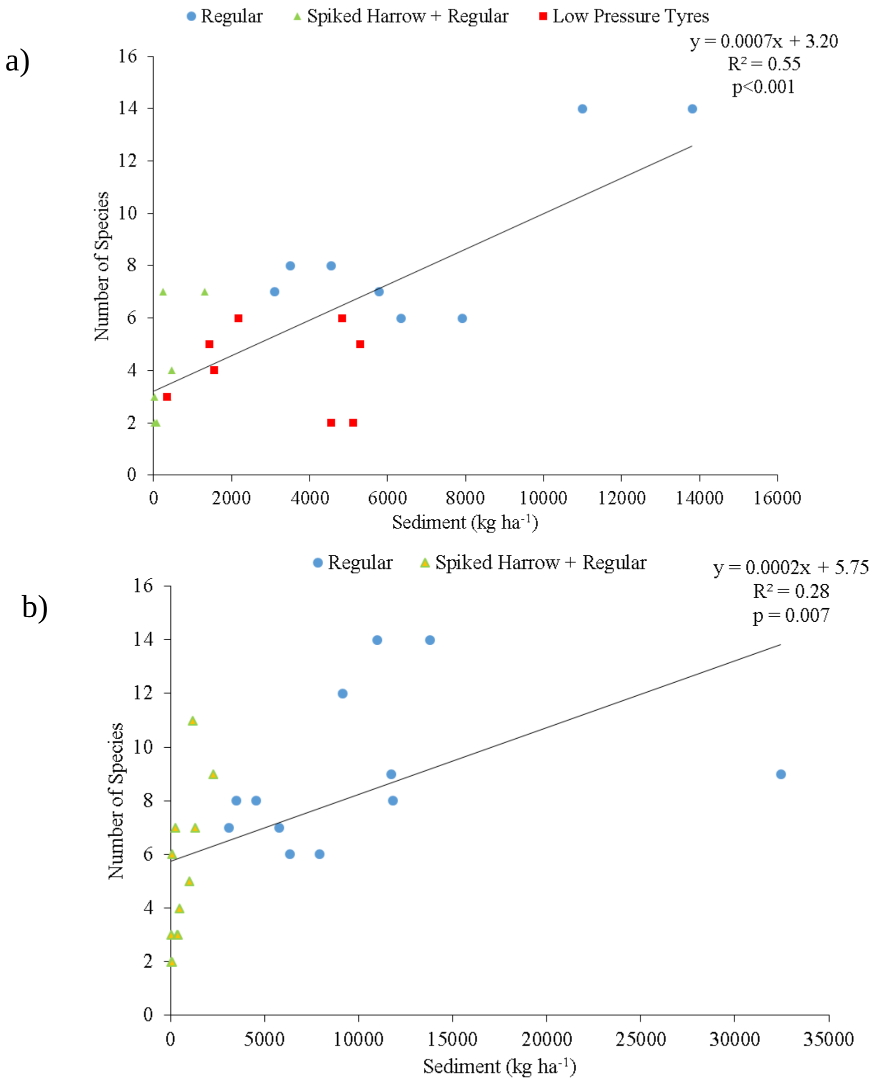


Figure 2.29 - Regression analysis of seed species against sediment load for (a) 2010/11 + 2011/12 and (b) 2010/11, 2011/12 and 2012/13 for repeated treatments. Sediment load was positively correlated to seed species for (a) $p<0.001$ and (b) $p = 0.007$.

2.3.6 Seed species diversity, assemblage composition – treatment effects and individual species responses

2.3.6.1 Seedbank Community Index Values

The Shannon-Wiener index values (Table 2.10) showed differences in the seedbank community's diversity and evenness. The low values of H and E both for regular tyre and spiked harrow management compared to the low pressure tyres and roller management corresponded with the amount of seed flux. Seed flux was known to be related to erosion (Figure 2.22 and Figure 2.26), and the selective removal of specific seed species by erosion was governed by tramline management (Table 2.6 - Table 2.8). Comparison of the field soil samples with the eroded samples showed the difference in the seedbank abundance and number of seed species (Table 2.11). Regular tyre and spiked harrow managed tramlines produced greater proportions of *Viola arvensis* compared to field soil samples. *Poa annua* was found in lower numbers when using the regular tyre and spiked harrow management compared to the field soil seedbank, but roller treated tramlines had a greater proportion than the field soil. Therefore, a process of selectivity of *Poa annua* and *Viola arvensis* was found between managed tramlines.

Table 2.10 - Shannon-Wiener index values for each tramline management technique for 2010/11.Regular pressure tyres and the spiked harrow had the greatest impact upon diversity and evenness by having the lowest diversity and evenness.

	Tramline Management Technique				
	Regular Tyres	**Low Pressure Tyres**	**Spiked Harrow**	**Roller**	**Field**
Total Seeds	2230	296	248	72	1485
Number of Species	20	12	13	8	21
Diversity (*H*)	1.36	2.14	1.40	1.77	1.76
Evenness (*E*)	0.45	0.86	0.54	0.85	0.58

Table 2.11 - Proportions (% of entire seed count) of *Viola arvensis* and *Poa annua* within samples in field soil samples (baseline) and tramline management (eroded soil) for 2010/11. Regular tyres and spiked harrow had proportionally more *Viola arvensis* compared to the field soil samples. The roller management produced proportionally more *Poa Annua* than the field soil samples.

	Baseline	**Eroded**			
Species		**Tramline Management**			
	Field Soil (%)	**Regular Tyres (%)**	**Low Pressure Tyres (%)**	**Spiked Harrow (%)**	**Roller (%)**
Viola arvensis	37.64	68.90	27.03	62.18	14.29
Poa annua	30.64	10.37	21.62	14.29	42.86

Table 2.12 showed the results of the Shannon Wiener index values for 2011/12. Low pressure tyre tramlines had the least *H* and *E* values indicating this treatment caused some selectivity of seeds based on species. Noticeably, the combination of spiked harrow and low pressure tyres resulted in *H* values being between the individual treatments, but the *E* value was nearly the same as regular tyres. Regular tyres had the greatest loss of diversity, despite losing the same number of seeds as spiked harrow with regular tyre tramlines. These findings for regular tyres coupled with the highest mean runoff and sediment load indicated seeds were not being selectively removed from the soil. Table 2.13 summarised the proportions of seeds found in field soil and in each treatment during the season. *Viola arvensis* was only higher in the low pressure tyre tramlines than the field soil. *Poa annua* was found to be double that of the field soil in spiked harrow tramlines. Finally, *Epiliobium ciliatum* was poorly represented in the field soil however, *Epiliobium ciliatum* was found to have a greater proportion in all tramlines.

Table 2.12 - Shannon-Wiener index values for each tramline management technique for 2011/12. Regular tyre tramlines had the greatest diversity, species richness and evenness in the eroded seed samples.

	Tramline Management Technique			
	Regular Tyres	**Low Pressure Tyres**	**Spiked Harrow**	**Spiked Harrow + Low Pressure Tyres**
Total Seeds	408	92	408	30
Number of Species	14	7	9	6
Diversity (*H*)	2.11	1.07	1.44	1.41
Evenness (*E*)	0.8	0.55	0.66	0.79

Table 2.13 - Proportions (% of entire seed count in sample) of the most dominant species (*Epiliobium ciliatum*, *Poa annua* and *Viola arvensis*) within samples for field soil samples and tramline treatments for 2011/12. All tramlines lost more *Epiliobium ciliatum* proportionally than present in field soil. Spiked harrow tramlines had the greatest loss of *Poa annua* compared to field soil. Low pressure tyres had the greatest loss of *Viola arvensis* compared to field soil.

	Baseline	**Eroded**			
Species		**Tramline Management**			
	Field Soil (%)	**Regular Tyres (%)**	**Low Pressure Tyres (%)**	**Spiked Harrow (%)**	**Spiked Harrow + Low Pressure Tyres (%)**
Epiliobium ciliatum	1.59	28.57	59.18	10.20	2.04
Poa annua	27.11	22.41	8.62	55.17	13.79
Viola arvensis	35.31	31.82	36.36	22.73	9.09

Table 2.14 showed the results of the Shannon-Wiener index values for 2012/13. Sown and non-sown regular tyre treatments had almost identical *E* values, despite the non-sown treatment producing more seeds and greater diversity. The sown low pressure tyre tramlines had the greatest *H* and *E* values, since there was a similar number of species compared to other treatments, but the number of seeds was lower. Table 2.15 summarised the proportion of seeds found in field soil samples and each tramline management. Both *Poa annua* and *Viola arvensis* had a larger proportion in the field soil compared to the tramlines showing these species were less prone to erosion. The exception was the spiked harrow where more *Poa annua* was found as a proportion of seeds than in the field soil. *Epiliobium ciliatum* was poorly represented in field soil, yet was found to be the third most eroded species across all treatments.

Table 2.14- Shannon-Wiener index values for each tramline management technique for 2012/13. Sown low pressure tyres had the lowest seed loss and number of species yet had the highest diversity and evenness within the seed community.

	Tramline Management Technique			
	Regular Tyres	**Sown Regular Tyres**	**Sown Low Pressure Tyres**	**Spiked Harrow**
Total Seeds	1552	1232	728	234
Number of Species	15	15	16	16
Diversity (*H*)	2.01	1.94	2.16	2.07
Evenness (*E*)	0.74	0.72	0.78	0.75

Table 2.15 - Proportions (% of entire seed count in sample) of *Epiliobium ciliatum, Poa Annua* and *Viola Arvensis* within samples for in situ samples and tramline treatments during 2012/13. All tramlines lost more *Epiliobium ciliatum* proportionally than present in field soil. Spiked harrow tramlines had the greatest loss of *Poa annua* compared to field soil. Sown regular tramlines had the greatest loss of *Viola arvensis* compared to field soil.

	Baseline	**Eroded**			
Species		**Tramline Management**			
	Field Soil (%)	**Regular Tyres (%)**	**Sown Regular Tyres (%)**	**Sown Low Pressure Tyres (%)**	**Spiked Harrow (%)**
Epiliobium ciliatum	0.67	21.51	19.87	14.74	9.18
Poa annua	35.34	30.81	26.92	23.16	36.73
Viola arvensis	39.36	27.33	35.26	27.37	25.51

2.3.6.2 Seedbank Assemblage Composition

Further investigation of the seedbank data using PCO highlights differences between the tramline managements (Figure 2.30). Axis 1 contained 24.02%, 23.38%, 21.33% of the variation in 2010/11, 2011/12 and 2012/13 respectively. Axis 2 contained 11.61 %, 12.33%, 13.55% of the variation in 2010/11, 2011/12 and 2012/13 respectively. In all years, tramline management does not cause account for the variations in either axis. The majority of points in all years have positive axis 1 values showing a common trait between the years. Investigation of the original transported seed data found that Axis 1 to be representing total seed abundance. In 2010/11 and 2011/12, negative axis 1 values represent high seed abundance whilst in 2012/13 the opposite occurs.

To determine the controls on Axis 2, regression analysis was necessary to identify species with a relationship with PCO values prior to investigation of the dataset (Table 2.16). For 2010/2011, the four species that had significant relationships were all positive, which were found to influence the community the most. For example, the only sample that contained all four species was the regular tyre tramline sample in the upper left corner. For 2011/12, *Capsella bursa-pastoris, Myosotosis arvensis, Viola* *arvensis* had negative relationships with PCO2 whilst *Poa Annua*, *Taraxacum officinale and Veronica arvensis* had positive relationships. Investigating the original data found that these species were driving the clustering in Figure 2.30b because there was less than 2 seeds of all species except for *Poa annua* in the 7 samples identified in the cluster. For 2012/13, the clustering of point is due to the four species identified in Table 2.16. Cluster A had less than 16 seeds of any of the four species, Cluster B had both *Brassica napus* and *Fallopia convolvulus* but no *Polygonum aviculare* and *Urtica urens* and Cluster C had a large amount (median = 32 seeds), no *Fallopia convolvulus* but some (8 – 16 seeds per sample) of *Polygonum aviculare* and *Urtica urens*.

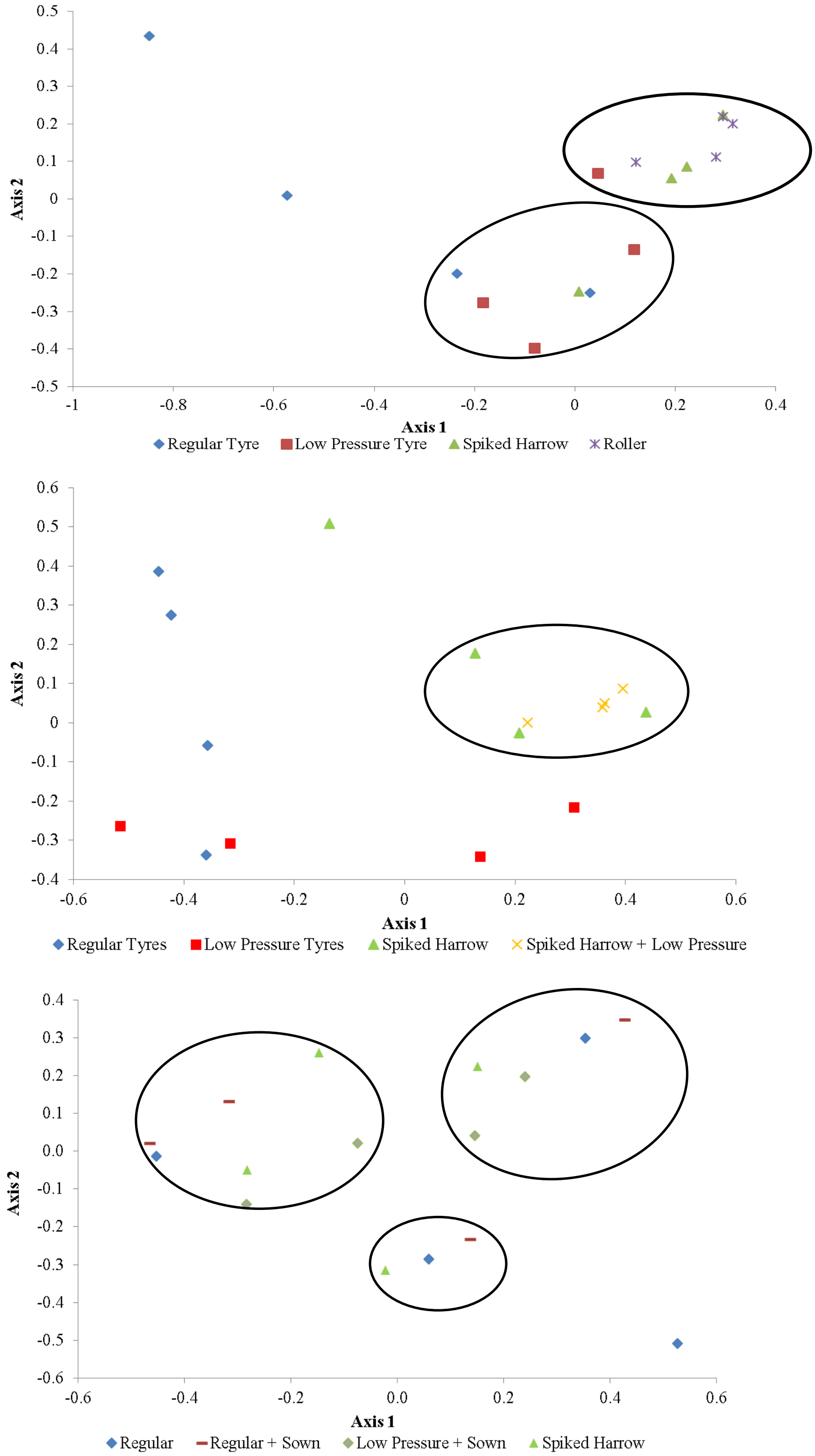


Figure 2.30 - PCO results showing the variability of eroded seedbank by treatment in (a) 2010/11, (b) 2011/12 and (c) 2012/13. Individual clusters of samples highlighted to show differences in the seed communities.

Table 2.16 - Regression analysis of PCO values and seed abundance in all years (-) or ( ) prior to r value shows direction of response. N/A = No r was calculated. *, **, *** are p values of <0.05, <0.01, <0.001 respectively.

Species	**2010/11**				**2011/12**				**2012/13**			
	PCO 1		PCO 2		PCO 1		PCO 2		PCO 1		PCO 2	
	r	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**
Aphanes arvensis	-0.02	-	N/A	-								
Arabidopsis thaliana	N/A	-	N/A	-								
Bellis perennis	**-0.44**	**	**0.21**	*					N/A		0.11	
Brassica napus	-0.08	-	N/A	-					**0.3**	*	**-0.33**	*
Capsella bursa-pastoris	**-0.37**	**	N/A	-	-0.28		**-0.27**	*	0.16		N/A	
Carex sp.					N/A		N/A		-0.09		N/A	
Cerastium fontanum	-0.16	-	N/A	-	N/A		-0.04		0.03		N/A	
Chenopodium rubrum					-0.05		0.1					
Cirsium vulgare					N/A		-0.04		-0.09		N/A	
Epilobium ciliatum	-0.08	-	-0.16	-	**-0.23**	*	-0.01		**0.66**	***	N/A	
Fallopia convolvulus	-0.16	-	N/A	-					N/A		**-0.61**	***
Fumaria officinalis	**-0.36**	**	N/A	-	-0.12		N/A					
Hordeum vulgare	**-0.7**	***	0.08	-					N/A		-0.03	
Juncas bufonius	N/A	-	N/A	-	N/A		N/A		0.03		0.17	
Matricaria recutita	-0.09	-	-0.09	-	N/A		N/A		**0.21**	*	N/A	
Myosotosis arvensis	N/A	-	-0.17	-	**-0.21**	*	**-0.25**	*				
Plantago lanceolata	**-0.62**	***	0.03	-								
Poa Annua	**-0.83**	***	N/A	-	**-0.59**	***	**0.21**	*	**0.83**	***	N/A	
Polygonum aviculare	**-0.44**	**	**0.21**	*	-0.01		N/A		0.18		**0.28**	*
Senecio vulgaris	**-0.39**	**	**0.26**	*					**0.27**	*	N/A	
Sonchus sp.					-0.13		N/A					
Spergula arvensis	N/A	-	-0.04	-								
Stellaria media	-0.09	-	**0.2**	*					**0.55**	***	-0.03	
Taraxacum officinale					N/A		**0.23**	*	0.15		0.17	
Trifolium sp.					-0.09		-0.01		0.03		0.04	
Urtica urens	N/A	-	N/A	-	-0.01		N/A		0.06		**0.44**	**
Veronica arvensis	**-0.45**	**	N/A	-	-0.16		**0.24**	*				
Veronica hederifolia					-0.04		0.02					
Veronica persica	**-0.68**	***	0.18	-	-0.03		0.02					
Viola arvensis	**-0.8**	***	0.06	-	**-0.23**	*	**-0.43**	**	**0.64**	***	N/A	

2.3.6.3 Seedbank species responses to erosion

Tramline management did not therefore affect the composition of the seedbank community, but had a major impact on the total number of seeds transported. Therefore, selective removal of species from the field seedbank is caused by other processes. Runoff and sediment transport might be causing the selective removal of seeds similar to different sized soil particles. Table 2.17 shows the results of regression analysis for runoff and sediment load against species that showed a significant relationship with PCO scores. Although all relationships were positively correlated with runoff and sediment load, there are noticeable differences between species and years. Crucially, sediment load had 17 significant relationships whilst runoff had 11 significant relationships showing selective transport of seeds is a result of seeds being transported in eroded sediment than washed from the soil via runoff. Grouping the individual species into runoff and sediment load relationships shows common traits between the species. First, *Hordeum vulgare, Plantago lanceolata, Poa Annua, Veronica arvensis, Veronica persica, Viola arvensis* were affected by runoff and sediment load (Table 2.17). Second, species that were affected by runoff had round seed shapes whilst for sediment load 81% of the species had round seed shapes opposed to flat. Third, the majority of seeds in runoff (63%) and sediment load (73%) were shown to have average 1000 seed weights of less than 1 g. These preliminary findings would indicate seed morphology to be playing a role in the selective removal of seeds.

Table 2.17 - Regression analysis of runoff and sediment load against seed abundance in all years for species identified as significant in Table 2.16. All relationships are positive. N/A = No r was calculated. *, **, *** are *p* values of <0.05, <0.01, <0.001 respectively.

Species	**2010/11**				**2011/12**				**2012/13**			
	Runoff (mm)		Sediment Load (kg/ha)		Runoff (mm)		Sediment Load (kg/ha)		Runoff (mm)		Sediment Load (kg/ha)	
	r	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**	**r**	**Sig**
Bellis perennis	0.08	-	0.52	***								
Brassica napus									0.24	*	0.47	**
Capsella bursa-pastoris	0.08	-	0.31	*	0.09	-	0.17	-				
Epilobium ciliatum					0.15	-	0.07	-	N/A	-	0.09	-
Fallopia convolvulus									0.12	-	0.21	*
Fumaria officinalis	0.09	-	0.15	-								
Hordeum vulgare	0.64	***	0.9	***								
Matricaria recutita									0.01	-	0.02	-
Myosotosis arvensis					0.2	*	0.17	-				
Plantago lanceolata	0.56	***	0.74	***								
Poa Annua	0.69	***	0.95	***	0.28	*	0.14	-	0.15	-	0.41	**
Polygonum aviculare	0.08	-	0.52	***					N/A	-	N/A	-
Senecio vulgaris	0.18	-	0.52	**					N/A	-	N/A	-
Stellaria media	0.03	-	0.11	-					0.2	-	0.47	**
Taraxacum officinale					N/A	-	N/A	-				
Urtica urens									N/A	-	N/A	-
Veronica arvensis	0.75	***	0.58	***	0.31	*	0.19	*				
Veronica persica	0.38	**	0.84	***								
Viola arvensis	0.51	**	0.93	***	0.34	***	0.53	***	0.14	-	0.25	*

2.3.6.4 Seed morphology and association with runoff and sediment

All the results indicate selectivity of erosion processes for individual seed species above and beyond total seed abundance. Individual seed species had a diverse range of seed morphologies. Categorising species by seed morphology may provide an explanation for the selectivity of runoff and sediment erosion. Seed categories were based upon the size, an average 1000 seed weight, shape, surface, presence of appendages, and whether the seeds were annual or perennial. Table 2.18 provides a summary of the findings of the regression analysis for each seed morphology variable against runoff and sediment load for each season. Appendix B contains the graphs associated with Table 2.18. Seed size and weight were found to have a stronger relationship with sediment load compared to runoff, except for seeds <2mm and <1g seeds in 2011/12. Both annual and perennial species were associated more strongly with sediment load than with runoff, with the exception of the 2011/12 season when the opposite was true. This could be due to the number of events in 2011/12 being smaller than during the other seasons. Seed surfaces had the same response over time to runoff and sediment as the annual and perennial seeds. Round seeds had a stronger correlation with erosion (sediment load) compared to flat seeds. Interestingly, seeds without an appendage (hairs, awes or mucilage) were more prone to being transported by erosion compared to those seeds with appendages. This would be consistent with Deng *et al.* 2012 who showed that mucilage from *Capsella bursa-pastoris* can increase seed volume by 6 times and surface area by 2.5 times, allowing binding to soil particles. Importantly, 2010/11 did not conform to this hypothesis, although this may be due to the nature of snowmelt events, which produced less sediment or seeds within the runoff. Therefore, seeds without appendages were found to be strongly associated with sediment load rather than runoff.

Table 2.18 - Regression analysis of seed morphology variables against runoff and sediment load for 2010/11, 2011/12 and 2012/13.

	Runoff						**Sediment Load**					
	2010/11		**2011/12**		**2012/13**		**2010/11**		**2011/12**		**2012/13**	
	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p
Size (>2mm)	0.55	<0.001	0.34	0.011	0.19	0.053	0.92	<0.001	0.23	0.034	0.47	0.002
Size (<2mm)	0.57	<0.001	0.30	0.017	0.11	0.111	0.96	<0.001	0.24	0.032	0.32	0.011
Weight (>1g)	0.27	0.024	0.12	0.10	0.24	0.031	0.6	<0.001	0.22	0.038	0.49	0.002
Weight (<1g)	0.58	<0.001	0.36	0.009	0.11	0.111	0.96	<0.001	0.27	0.024	0.35	0.010
Annual	0.56	<0.001	0.71	<0.001	0.24	0.033	0.95	<0.001	0.68	<0.001	0.51	0.001
Perennial	0.50	<0.001	0.15	0.077	0.00	0.838	0.64	<0.001	0.08	0.152	0.02	0.266
Surface (Rough)	0.61	<0.001	0.24	0.031	0.06	0.192	0.92	<0.001	0.14	0.086	0.3	0.016
Surface (Smooth)	0.56	<0.001	0.6	<0.001	0.29	0.018	0.92	<0.001	0.74	<0.001	0.52	0.001
Shape (Flat)	0.4	0.005	0.19	0.053	0.011	0.699	0.45	0.003	0.12	0.107	0.07	0.171
Shape (Round)	0.56	<0.001	0.69	<0.001	0.22	0.037	0.95	<0.001	0.65	<0.001	0.49	0.001
Without Appendages	0.54	<0.001	0.48	0.002	0.27	0.023	0.95	<0.001	0.64	<0.001	0.49	0.002
Appendages	0.68	<0.001	0.28	0.021	0.07	0.166	0.97	<0.001	0.17	0.62	0.34	0.011

Classifying seeds as either small (<2 mm) or large (> 2 mm) allowed comparisons to be made with the soil particle size analysis. Eighteen seed species were identified in soil samples included nine large seed species and eight small seed species (*Carex sp.*). Figure 2.31 shows the percentage of small seeds for each tramline management technique and field soil samples. Comparison of the tramlines to the field soil revealed the spiked harrow was the only treatment to have a lower median proportion small seeds compared the field seedbank. This result is important because it showed selectivity in seed transport whereas the soil particles were removed by a different selectivity.

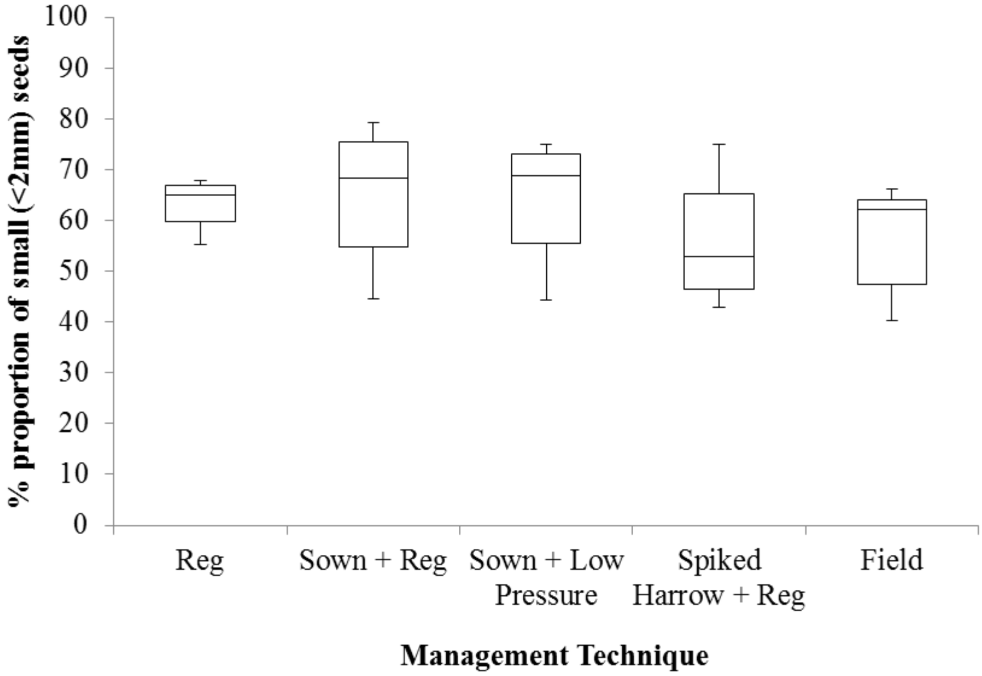


Figure 2.31 - Box and Whisker plot for the proportion of seeds classified as small (< 2 mm) found in eroded samples and field soil for 2012/13. Large seeds (>2mm) are the remaining proportion not shown. Proportion of seed size was not affected by tramline management

Although particle size data was not available during 2010/11 and 2011/12, using the seed morphology categories from Table 2.18 allowed comparisons to be made between tramlines for each year to determine whether tramline management had a significant effect on the seeds transported. Table 2.19 showed the significance of tramline management on individual seed morphologies. Tramline management affected the size of seeds transported with smaller seeds (< 2mm) being affected more than large seeds (>2mm) with the exception of 2011/12. Therefore, tramline management was more important in preventing small seeds being transported by preventing loss of runoff, but more importantly sediment. Tramline management was found to affect light seeds (<1g) in 2010/11 and 2012/13. The explanation for the effect on heavy seeds in 2010/11 being more significantly affected was due to snow melt, which encouraged greater amounts of runoff, particularly in regular tyre tramlines. Annual species were significantly affected by tramline management in all seasons, whilst perennial species were only significantly affected by tramline management in 2010/11. This result occurred in the same seasons when runoff and sediment load were correlated to annual and perennial species, showing a direct link between tramline management, which affected runoff and sediment load influencing annual and perennial species. Smooth surfaced seeds appeared to be affected more than rough surfaced seeds by tramline management. This effect could be linked to the presence of appendages, which had the same pattern of results over the three seasons, allowing seeds to bind to the soil and be transported with sediment, rather than runoff. Round seeds appear to be more influenced by tramline management than round or flat seeds. These results were probably due to runoff and sediment exerting a greater influence over round compared to flat seeds, which resulted in tramline management significantly affecting the number of round seeds being transported. Importantly, these results show seeds from specific seed species were being selectively eroded in tramlines and may be managed in the same way as the soil in tramlines

Table 2.19 – Result of ANOVA testing to determine significance of tramline management on different seed morphologies over all three seasons.

	2010/11	**2011/12**	**2012/13**
Seed Morphology	***p***	***p***	***p***
Size (>2mm)	0.01	0.066	0.065
Size (<2mm)	0.019	0.178	0.001
Weight (>1g)	0.002	0.201	0.339
Weight (<1g)	0.022	0.191	0.003
Annual	0.018	<0.001	0.006
Perennial	0.027	0.419	0.063
Surface (Rough)	0.029	0.418	0.013
Surface (Smooth)	0.015	<0.001	0.008
Shape (Flat)	0.007	0.372	0.035
Shape (Round)	0.019	<0.001	0.007
Without Appendages	0.015	<0.001	0.006
Appendages	0.027	0.368	0.015

The results in this section have shown that erosion is selective based on characteristics of the seed morphology although exactly which seeds are prone to this selectivity is unclear. Further analysis using Chi-square tests for seed size and weight; and seed shape and presence of appendages identified the types of seeds prone to erosion. Table 2.20 - Table 2.22 show the results for the Chi-square results for transported seeds from all three seasons. Seed size and mass were found to have a significant relationship across all three seasons (p<0.001). In all three years, the small light seeds (<2mm + 1g) were the most abundant in the transported seed community showing these were most selected by erosion processes. Also, the transported community for all three years showed the same proportion of losses in terms of categories. After the small light seeds, big light (>2 mm + <1 g) seeds were the second most transported followed by big heavy (>2 mm + >1 g) seeds. No small heavy seeds were transported (<2 mm + >1g).

Table 2.20 – Results of Chi-square testing for seed size and mass categories for transported seeds in all three seasons.

	2010/11	**2011/12**	**2012/13**
<2 mm + < 1g	2158	646	2152
<2 mm + >1g	0	0	0
>2 mm + <1 g	422	226	1022
>2 mm + >1 g	250	40	540
p	<0.001	<0.001	<0.001

Seed shape and the presence of appendages (Table 2.21) were found to have a significant relationship across all three years (p<0.001). Round seeds with no appendages were the most transported in 2010/11 and 2012/13. In 2011/12, flat seeds with appendages were the most transported. This difference between seasons is likely due to 39% of the total seed community was dominated by *Epiliobium ciliatum*. In all three seasons, round seeds with appendages were 2nd most transported seeds and flat seeds without appendages least. Overall, this shows round sees are more selectively transported than flat seeds regardless of appendages.

Table 2.21 – Results of Chi-square testing for seed shape and presence of appendages categories for transported seeds in all three seasons.

	2010/11	**2011/12**	**2012/13**
Round + Appendages	620	280	1372
Round + No Appendages	2058	210	1650
Flat + Appendages	134	406	656
Flat + No Appendages	18	16	36
p	<0.001	<0.001	<0.001

Seed shape and mass (Table 2.22) were found to have a significant relationship in all three years (p<0.001). Round and <1 g seeds were most transported in all three years making up 87.7% in 2010/11, 49.3% in 2011/12 and 66.8% in 2012/13 of the total seed transport. In 2010/11 more round and >1 g seeds were transported than flat and <1 g seeds, which contrasts the behaviour found in the subsequent years. This possibly was caused by the snow melt event triggering runoff that had sufficient energy to detach and transport heavier seeds. No flat and >1g seeds were found to be present in the transport community for any year.

Table 2.22 – Results of Chi-square testing for seed shape and mass categories for transported seeds in all three seasons.

	2010/11	**2011/12**	**2012/13**
Round + <1 g	2428	450	2482
Round + >1 g	250	40	540
Flat + <1 g	152	422	692
Flat + >1 g	0	0	0
p	<0.001	<0.001	<0.001

2.4 Discussion

2.4.1 Tramline management and soil erosion

Tramlines have been acknowledged by Cuttle *et al.* (2007) as a major contributor to diffuse pollution and farmers are advised not to perform farming operations during the winter months. However, most farmers need to apply pesticides in the autumn for winter crops (Cuttle *et al.*, 2007). Delaying agricultural activities, and thus tramline establishment, creates additional risk to crop yields as there will be increased weeds and pests due to lack of herbicide spraying. Furthermore, controlled trafficking may exacerbate surface runoff from increased tractor tyre compaction thus requiring improved tramline management to minimise the impacts (Withers *et al.*, 2006; Silgram *et al.*, 2010).

The evidence from this study confirmed that the use of tramline management had a significant effect on the transport of water and sediment, during individual storm events, seasons and over consecutive winter seasons. The use of regular tractor tyres (representing current practice) was found to consistently generate the most soil loss across all temporal scales. The use of low pressure tyres decreased runoff by 80% and sediment by 95% and the spiked harrow decreased runoff by 60.5% and sediment by 93.9% over the whole three year period. The key difference between treatments is the surface compaction of the soil and the pathway created by tyre tread in the tramline after each applied management technique. Although compaction was not monitored in this study, increased soil compaction is strongly associated with lower infiltration rates and thus increased runoff (Batey, 2009). The spiked harrow tramlines performed poorer than the low pressure tyres, which was probably due to the initial compaction of the soil by the tractor and the following loosening of the soil surface. The soil loosening would have resulted in the soil surface being disrupted, thus improving surface infiltration and soil structure, but below this layer, drainage would be impeded because of soil compaction (Chamen *et al.*, 2003). An important consideration is the proportion of the field that tramlines occupy. In this study, tramline plots (300 m^2) occupied 0.48 ha of the 6.38 ha field (7.5%), although under normal farming practice this would be only 0.12 ha (1.9%) because fewer tramlines would be needed for access. Furthermore, tramlines occupied 23% of the plot with the remainder being the inter-wheeling area that was cropped. These facts are important to consider because generating >1 t ha^{-1} yr^{-1} of sediment in a small fraction of the field could be an indicator of greater losses at the field scale. Although not possible in this study, transport pathways into the tramline plots could originate laterally or further upslope indicating field scale processes using tramlines in a similar manner to rills and gullies.

Some tramline managements were unique to each season, such as the roller (designed to make a convex tramline) which was used in 2010/11 and was effective at decreasing soil loss but did not generate the lowest runoff. Relatively high runoff rates were probably a result of water being channelled down the sides of the tramline to discourage channelised flow. In 2011/12, the spiked harrow treatment was combined with the low pressure tyres to produce the lowest runoff, as well as the lowest amount of sediment. These results were expected, because less compaction affected the soil structure as well as limiting the soil surface disruption and thus improving infiltration (Chamen *et al.*, 2003; Batey, 2009). In 2012/13, both regular and low pressure tyres were used on sown tramlines. Interestingly, the sown tramlines had limited effect compared to non-sown tramlines. It was predicted that the presence of crop cover should prevent erosion by providing a buffer from initial precipitation impacting the surface, thus preventing soil detachment, as well as improving infiltration rates and increasing surface roughness against runoff (Dabney *et al.*, 2001; Deasy *et al.*, 2009). However, the lack of difference between the sown and non-sown tramlines in this research may be due to the difference in compaction from the tyres and the initial responses to erosion which occurred before crop establishment.

2.4.2 Tramline management and seedbank

Tramline soil erosion adversely affected the number and species of seeds transported from the seedbank. The total seed loss ($p<0.001$) and number of species ($p=0.007$) strongly correlated with sediment load rather than runoff (p=0.003 for seed number and p<0.001 for species number), regardless of treatment over the three years of research. These factors were important since hydrochory (water dispersal) is seen as one of the common seed dispersal mechanisms (Benvenuti, 2007). However, this research demonstrated that seeds are being removed in sediment, indicating that soil erosion also has a major role in seed dispersal.

Comparing the total seed and species loss to different tramline managements revealed that seed flux was significantly affected by management in 2010/11 (p=0.016) and 2012/13 (p = 0.005), but not in 2011/12 (p=0.144). An explanation of this fact may be due to rapid recovery of the seedbank between seasons over the three years of the project, as well as environmental conditions such as light, temperature and water availability (Brenchley and Warington, 1933; Roberts, 1962; Roberts and Feast, 1973; Wilson and Lawson, 1992). Seed species were affected by treatment in years 2010/11 (p=0.007) and 2011/12 (p=0.006), but not in 2012/13 (p=0.612). However, there was a signifcant difference (p<0.001) in the number of seed species over the three year research period. Importantly, comparing the seed flux to the seed density in the field showed that tramlines lost between 0.01% and 0.32% of the seedbank per year. This was signficant because these values are for a single field which are the same magnitude as estimates by Lewis *et al.* (2013) for UK counties. Although, total seed transport was dictated by sediment load, it appeared that species specific differences in seed morphology had an important role in seed transport similar to those observered by García-Fayos *et al.* (2010).

In addition to the above factors, particle size analysis in 2012/13 showed that three quarters of the plots had the same proportions of seed sizes to soil particles. The spiked harrow treatment caused larger sized (>2 mm) seeds to be transported compared to smaller sized seeds (<2 mm) whereas all the other treatments caused the opposite effect which would indicate a selective removal of specific seeds based upon seed size. Furthermore, classifcation of seed species by seed morphologies found sepcifc characteristics to be associated with runoff and sediment, as well as being affected by tramline management. Figure 2.32 illustrates this point with a selecion of seed species which were eroded in the tramlines.

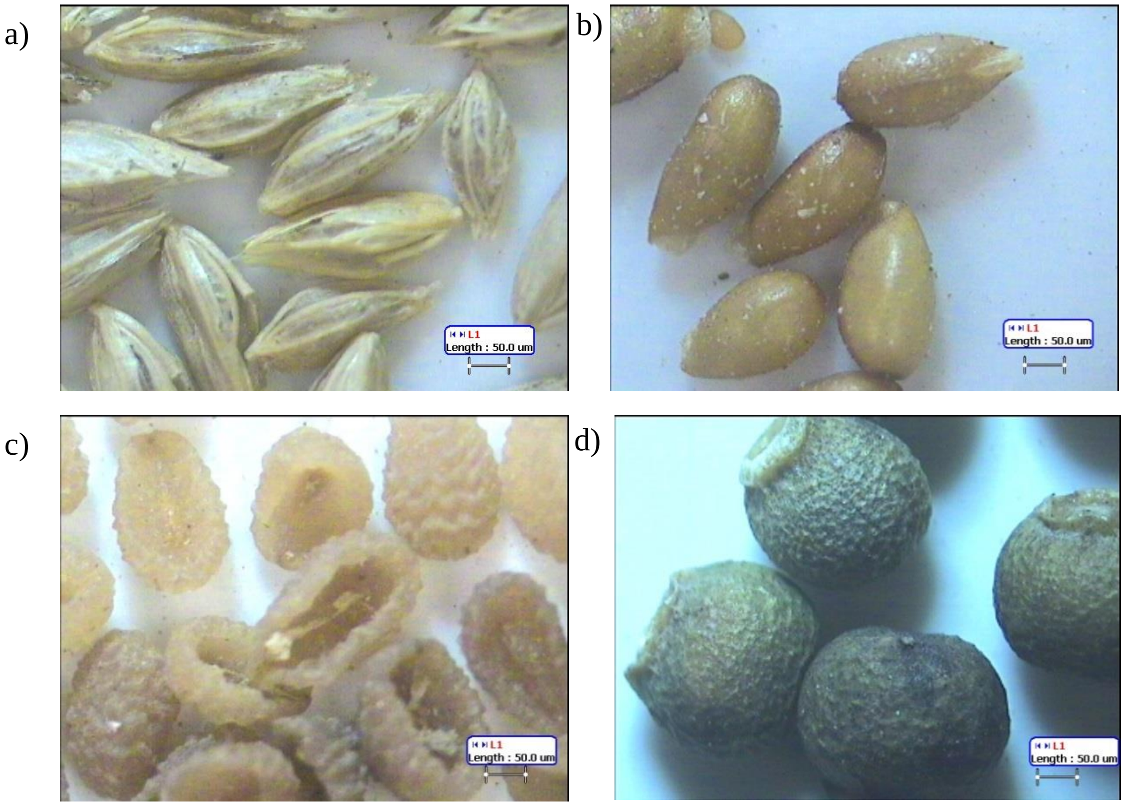


Figure 2.32 - Examples of eroded seeds from tramlines across all years. a) *Poa annua*, b) *Viola arvensis*, c) *Veronica persica* and d) *Fumaria officinalis*

Seed morphology plays a vital role in seed transport by soil erosion. The primary control on a seed’s transportability was seed mass. According to Cerdà and García-Fayos, (2002) a seed mass of 50 mg was the threshold between seed mass and seed shape as the key control on seed transportability. Seeds weighing less than 50 mg were affected by weight, whilst seeds above 50 mg had the shape as the controlling factor. On the other hand, the chi square test showed that light (<1g), round seeds without appendages were the most susceptible to transport by tramline erosion. This is an important step towards understanding the movement of weed seeds in temperate arable ecosystems but further work is required to detail transport distances. As Figure 2.32 above demonstrates, the seeds from the seedbank in this study were different in shape, thus affecting seeds’ transportability by erosion. Results in Table 2.18 showed the different seed shapes were likely to be one of the key controlling factors in seed transportability coupled with seed mass. The rounder the seed in conjunction with other seed morphology factors increases suspectiblity to transport by erosion (García-Fayos *et al.*, 2010). However, Benvenuti (2007) showed that cup shaped seeds were more affected by rainsplash because this seed shape ensured optimal transport and dispersal. Seed physical and chemical defences may also affect their erosivity (Davis *et al.*, 2008). Specifically, the use of appendages and mucliage can cause a decrease in seed transport by erosion. Appendages such as wings, hairs and awns are likely to affect seed transportability by changing surface roughness and seed morphology (García-Fayos *et al.*, 2010). Hydration of mucliage may substanially lower seed transportability by binding the seeds to surrounding soil, thus increasing the seed volume and surface area of the seed (Deng *et al.*, 2012). In this study seeds without appendages or mucliage showed strong associations with sediment load and thus increasing the role of transport by erosion. Therefore, seeds with appendages or mucliage were less prone to transportation and remained furthermore resitent to transport. Further work will be required to understand the effect that seed morphology has on seed transportability within temperate arable ecosystems to determine thresholds for transport.

The data gathered here on numbers of seed and species eroded down tramlines may be an underestimate of the actual number eroded, due to two compounding issues within the experiment. Firstly, calculations assumed that erosion was occuring from the entire field plot to be collected in the trough. Indications from a previous laboratory experiment showed seed travel distances of only between 0.3 and 26 cm for each single rainfall events lasting up to 1 hour (Han *et al.*, 2011). These figures assumed a lack of obstruction to the transport pathway.However, in an arable field there were obstructions caused by stones, litter and tramline treatment. Similiarly, seeds may have been lost from the soil by adhesion or ingestion by fauna (Benvenuti, 2007). Transport of seeds downslope were more likely to be the result of a jerky conveyor belt, where multiple steps were needed to reach the final end of the seed delivery system (Newson, 1997). Secondly, seeds identified from the samples did not represent the total of transported seeds. The lower amount of identifiable seed samples was due to either seed mortality from erosion or the seeds being dormant over winter and not germinating due to imperfect weather conditions (e.g. wrong temperature, light exposure or water availability) (Baskin and Baskin, 2006). Microscopic identification may have revealed a greater number of identifiable seeds but would not have determined viability. Thirdly, the use of meshes did affect seed retention which led to an underestimation of seed numbers trapped. Seed may also have been lost where large amounts of sediment were present due to overflow. To improve the sampling procedure the use of multiple and/or larger pieces of mesh would lessen the chance of clogging and subsequent loss of seeds.

2.5 Conclusions

This chapter aimed to quantify the rate and significance of seedbank restructuring caused by tramline soil erosion. The approach was to identify whether tramline management would affect erosion and seedbank flux, as well as quantify the amount of erosion and seed flux using a series of Gerlach Troughs over three winter seasons. The germination and identification of viable seed samples allowed comparisons between runoff and sediment loads for each treatment. Comparing the runoff plus sediment data to the seed data found sediment load was a stronger influence on seed flux and species transport than runoff. However, management of the tramlines did significantly affect the amount of seeds being transported but, more importantly, the composition of seedbank being eroded. In 2010/11, tramline management lowered seed transport by up to 93% with the number of species lost lowered by up to 58% compared to regular tyre tramlines. In 2011/12, tramline management effectively lowered seed flux by up to 71%, plus a decrease in the number of seed species by 54% compared to regular tyre tramlines. In 2012/13, management caused a decrease of up to 45% in seed flux and 15% in seed species compared to regular tyre tramlines. These figures showed that tramlines caused mobilisation of seedbank biodiversity with changes in community compositions downslope favouring annual species over perennials. Furthermore, small smooth round seeds were most frequently found in depositional areas at the end of tramlines. The implication being a concentration of selected species seedbank in the foot slope, which maybe different to the rest of the field. In essence, soil erosion restricts agro-ecosystems by displacing seeds which grow into weeds and provide fundamental ecosystem services within the field.

Management of tramlines has been shown to have a significant effect on the rate of erosion. Tramlines with regular tyres led to the greatest runoff and sediment transport. In 2010/11, management decreased runoff by up to 70% and sediment load by up to 98%. In 2011/12, runoff was decreased by up to 99% and sediment load by up to 95%. In 2012/13, sown regular tyre tramlines caused a slight increase in runoff of 7% and sediment load 9%, although the amounts were not significant. Other treatments in 2012/13 caused a decrease of up to 61% for runoff and 71% for sediment load. These findings support the need to manage tramlines effectively to prevent the occurrence of soil erosion.

Chapter 3: Assessment of the field scale interactions of soil erosion and seedbanks using caesium 137

3.1 Introduction

Seedbanks are spatially and temporally dynamic systems which evolve through the germination of viable seeds and growth of weeds (Hawes *et al.*, 2003; Gibbons *et al.*, 2006; Csontos, 2007; Hyvönen and Huusela-Veistola, 2008). Similarly, soil erosion is variable spatially and temporally (refer to Section 1.2.1). The dynamics and linkages of both seedbanks and soil erosion in the field scale, present a knowledge gap which may be important to inform ecological trends. Therefore, the question may be asked whether the patterns of erosion and deposition at the field scale explain the spatial variation in seedbank abundance and composition.

Caesium-137 (^{137}Cs) is an artificial radionuclide that entered the atmosphere primarily during the 1950s and 1960s as a result of nuclear weapons testing (Zapata *et al.* 2003). Figure 3.1 shows the input of ^{137}Cs in France and UK up until 2000. The explosion of a nuclear reactor in Chernobyl in 1986 introduced further fallout of ^{137}Cs into European soils, which affected the utility of ^{137}Cs as a tracer because Chernobyl had a very high degree of spatial variability as compared to bomb-test fallout that was deposited over several years and relates to longer-term precipitation patterns (Walling and Quine, 1991). In the UK, Chernobyl fallout was low with 160 km^2 receiving >40 kBq m^{-2} with inventories in Wales, North West and eastern England; and south west and north east Scotland showing >25% or more ^{137}Cs from Chernobyl (Walling and Quine, 1991, Golosov, 2002). More recently, the Fukushima accident on 11th March 2011 led to deposition of <0.1 kBq m^{-2} over the course of four weeks after the accident (Evangeliou *et al.* 2013).

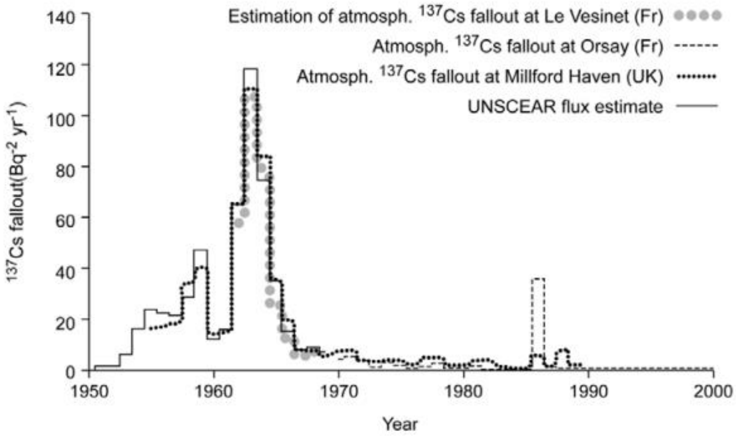


Figure 3.1 - Annual atmospheric fallout of ^{137}Cs, in Bq m^{-2}at Orsay, Paris (UNSCEAR) and Le Vesinet, France; and Milford Haven, UK from 1957 to 1991. *Source*: Le Roux and Marshall (2011).

The subsequent redistribution of ^{137}Cs occurs when soil particles are redistributed by erosion because ^{137}Cs anion is highly particle reactive and sorbs onto the surface - particularly of clays and other ligands in the soil (Quine and Walling, 1991). Measuring ^{137}Cs is an established method to estimate the amount and rate of soil erosion on a field scale over the medium term (30+ years) (Morgan, 2005, Parsons and Foster 2011). Loss or gain of ^{137}Cs fallout allows the calculation of radionuclide inventories (Bq m^{-2}) which allows the estimation of soil loss to be made since the period of global dispersion and fallout. The methodology of estimated soil loss makes several assumptions described by Walling and Quine (1992) including (1) fallout was uniform spatially and locally, (2) fallout was rapidly and irreversibly bound to soil particles, (3) re-distribution of fallout was caused by soil particle movement; and (4) estimated erosion rates may be calculated from ^{137}Cs inventories.

Following these assumptions, ^{137}Cs inventories within the soil may be established to determine a spatial pattern of the ^{137}Cs. For an arable system, the depth of ^{137}Cs was uniformly distributed within soil profiles, due to soil mixing by ploughing (Walling and Quine, 1992; Morgan, 2005). Therefore, changes caused by soil erosion would be evident in the spatial pattern of ^{137}Cs inventories as eroding sites would have lower ^{137}Cs inventories and deposition sites would have higher ^{137}Cs inventories relative to a reference value (Walling and Quine, 1992; Morgan, 2005). Calculation of erosion rates from ^{137}Cs inventories requires the use of a conversion model, (described in Section 3.2.2), that compares field samples to a reference site value (Walling *et al.*, 2002a).

The purpose of this study was to evaluate the extent to which medium to long term patterns of erosion and sedimentation at the field scale are reflected in arable weed seed patterns. The underlying fundamental issue is how the medium to long term patterns of erosion contrast with the short term seedbank dynamics. Field data suggests seedbank populations are related to slope gradient (Hawes, 2011). In addition, preliminary field observations indicate soil erosion was present at the site with gullies and spillage flows from tracks (e.g. between field connectivity) interacting with slope and land management practice. The objectives of this study were:

- To use the ^{137}Cs technique to quantify and map soil erosion at the field scale at Balruddery Farm.
- To quantify and map seedbank data within the same field.
- To determine the relationship between seedbanks and soil erosion within the field scale.

3.2 Methodology

3.2.1 Specific Field Conditions

A general field description was given in Section 1.4. Middle East field, which measured 6.85 ha, was used for this study (shown in Figure 3.2). First impressions suggest it to be topographically simple with a concave slope ranging from 1^0 to 5^0, but it also features important micro topography affecting flow generation and runoff patterns. Field elevation ranges from 112 m in the north west to 90 m above mean sea level in the south east. Generally, the soil within the field was a brown earth (Balrownie Series) with poor drainage. Soil texture changed within the slope from sandy loam on the upper slope to a sandy silt loam in the foot slope. There was a stone content of up to 35% within the field.

The field had been under arable cultivation for at least 11 years, but had a longer unknown history of use since at least the 1850s. Crops sown in the past 11 years included winter wheat, winter rapeseed, spring barley and beans. The tillage practice was assumed to have been conventional for the past decade. The tillage pattern during the past decade had been up and down the slope.

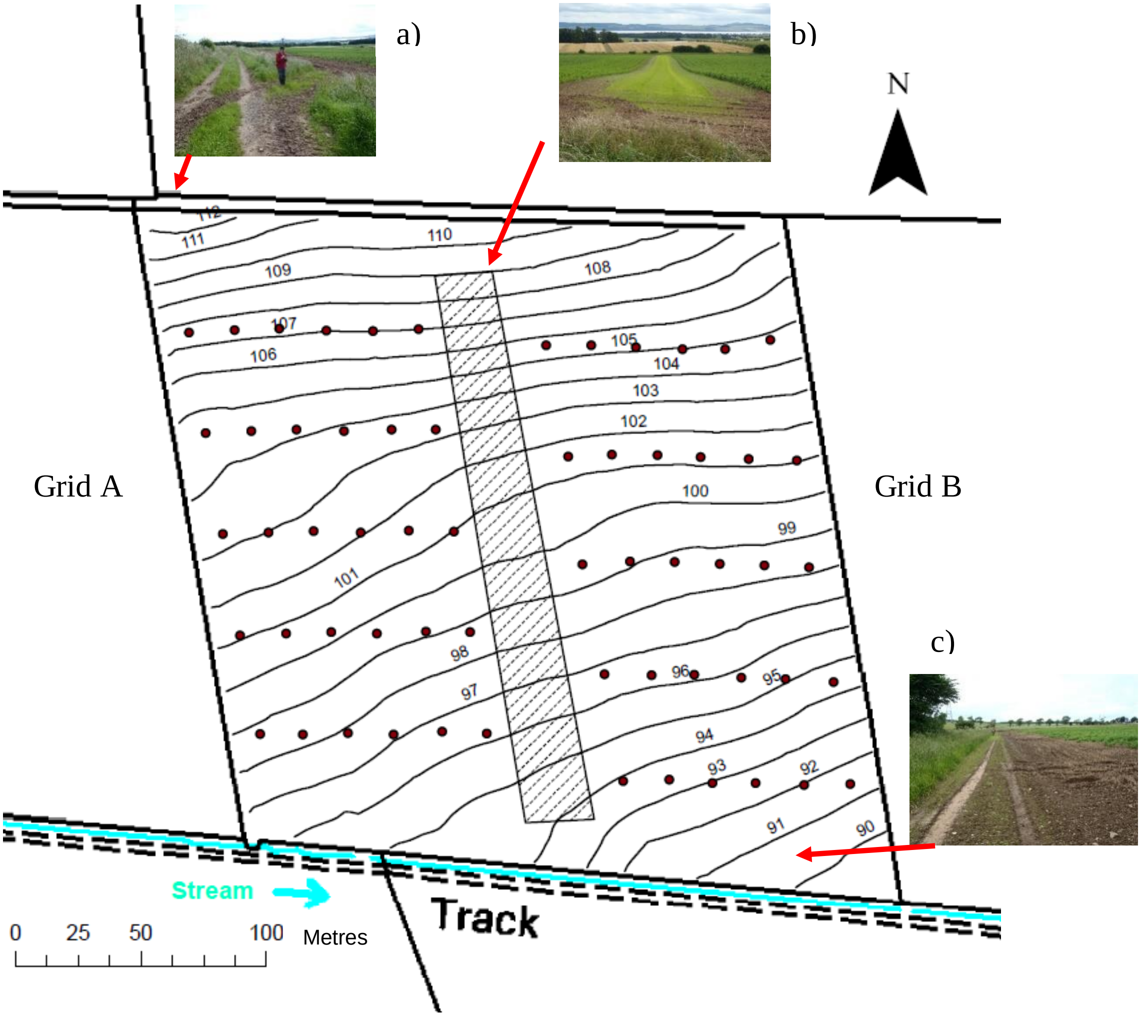


Figure 3.2- Field plan of the two sampling grids (A and B) showing30 sample points in each grid with 1 m contour line with main access looking east (a), beetle bank (hashed area) looking south (b) and the headland at the foot of the field looking west.

3.2.2 Soil Sampling and ^{137}Cs measurements

In May 2011, 60 undisturbed cores (diameter 6 cm) were taken from the field to a depth of 0.5 m in two grids of 30 cores using a percussion auger rig. The grids covered two tillage practices.

1) Grid A used a conventional tillage that covered 3.4 ha of the west portion of the field. The treatment consisted of cultivation to a depth of 20 cm in August 2010 prior to the sowing of spring barley at 180 kg ha^{-1} in April 2011. Fertiliser (with a 30% N concentration) was applied twice, first a rate of 380 kg ha^{-1}during the seed sowing and a second treatment in May of 60% concentration K_2O at a rate of 160 kg ha^{-1}. Pest control was applied in May to control weeds and fungi using a spray of 120 L ha^{-1}.

2) Grid B used a minimum tillage that occupied 3.4 ha of the east portion of the field. Tillage depth was 10 cm with rye grass was planted in August 2010 and treated with herbicide in March 2011. In March, municipal waste compost was applied at 34.9 t ha^{-1}and incorporated to a depth of 10 cm. In May 2011, after crop sowing, white clover (*Trifolium repens*) was sown at 7 kg ha^{-1}. A beetle bank (hashed area) in the middle of the field isolated the sides from each other.

Sample cores from grids A and B were bulked and stored in a labelled sealable bag for transport. In addition, reference cores were taken in a pasture field, which was undisturbed by tillage, in the centre of the farm (56°28'58.52"N, 3° 7'52.49"W). Nine reference cores were collected within a 1 m^2 quadrat in an identical manner to the field samples. The purpose of the reference cores was to provide a baseline ^{137}Cs inventory to determine if erosion or deposition occurred within the Middle East field. The determination and use of ^{137}Cs reference values are explained below with a worked example in Section 3.2.4.1.

Core samples required the following preparation prior to ^{137}Cs measurement. Each core was weighed prior to being oven dried at 105°C for 24 hours to remove all water. After drying, samples were re-weighed before being passed through a 2 mm sieve to remove stones, gravel and roots. Sieved soil was retained in sealable bags until ^{137}Cs measurements were conducted. Particles of >2mm were weighed in order to correct for soil bulk density since ^{137}Cs does not bind to rock particles. The following correction for soil bulk density, outlined by Pennock and Appleby (2003), was achieved by first determining the bulk volume of rock fragments:

$$Brv = \frac{Mr}{Bg} \tag{3.1}$$

Where *Brv* was the bulk volume of rock in g cm^{-3}, *Mr* was the mass of the >2 mm particles in grams and *Bg* was the bulk density of >2 mm rock fragments taken to be 2.65 g cm^{-3}. Next the bulk volume of the soil without >2 mm rock fragments was calculated:

$$Bsv = V - Brv \tag{3.2}$$

Where *Bsv* was the bulk volume of the soil in g cm^{-3} and *V* was volume of the sample which was 1414 cm^3. Finally, bulk density of the soil was calculated as follows:

$$BDs = \frac{Ms}{Brv} \tag{3.3}$$

Where *BDs* was the bulk density of the soil in g cm^3 and *Ms* was mass of soil in grams. For use in ^{137}Cs conversion model, *BDs* is multiplied by 1000 to give *BDs* in kg m^3.

Gamma spectrometry was used to measure ^{137}Cs by determining decay energy of ^{137}Cs. Each gamma emitting radionuclide produces one or more signatures at known points along a gamma radiation energy spectra indicating the energy of emissions from different radionuclides within the sample. Measuring ^{137}Cs radioactivity was determined using a single high resolution, low-background gamma spectrometer (EG&G Ortec model no. GEM-FX7025-S) containing an ultra-pure germanium crystal housed in the Environmental Diagnostics Laboratory in the School of the Environment at the University of Dundee. Figure 3.3 illustrates the gamma spectrometer used alongside a schematic of the instrument with a further technical description by Wallbrink *et al.* (2002).

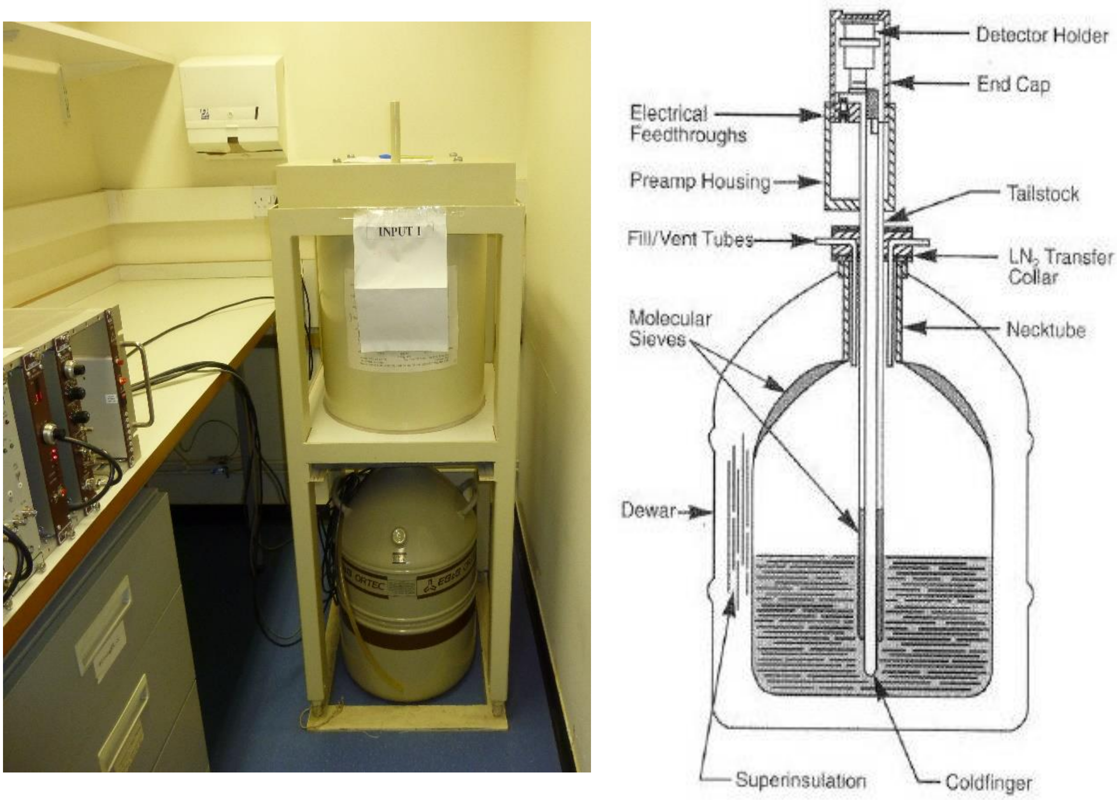


Figure 3.3 – The gamma spectrometer used for ^{137}Cs inventory counts in the Environmental Diagnostics Laboratory at the University of Dundee (left). The detector is housed within a 1.5 t aged lead shielding protecting the detector from ambient background gamma radiation. A simplified annotated diagram of the gamma spectrometer (right), modified from Wallbrink *et al.* (2002), shows the detector without the shielding.

The germanium crystal was located in the detector holder and is connected to the Dewar underneath, which was filled with liquid nitrogen. The Dewar maintained an optimum and stable operation temperature of the crystal at -198°C. This temperature was necessary as electrons from the ^{137}Cs generate heat from interaction with the crystal as well as the high voltage subjected to the crystal (Wallbrink *et al.*, 2002). In order to convert the emitted signatures into inventories, several electronic components are needed in conjunction with the gamma spectrometer. The electronics allow identification of the different radionuclide present by calibration of the energy and efficiencies of the radionuclides. Figure 3.4 shows the nuclear instrumentation module (NIM Bin) electronic components for the gamma spectrometer system, which can be seen on the bench in Figure 3.3.

A core sample was placed within the detector and a signal was generated in the 1st stage of the preamplifier (an interface between the detector and the rest of the electronic components). The NIM Bin contained the high voltage supply, amplifier and analogues to digital converter (ADC). The high voltage supply unit provided between ±5 and 800 keV to generate charge collection within the germanium crystal with ^{137}Cs measured best at 661keV. The amplifier shaped the signal into an analogue signal which was converted to a digital signal in the ADC. The mixer or router provided capacity for additional detectors to be used simultaneously. Finally, the multi-channel analyser (MCA) was part of the computer which stored the counts from the detector based on the energy output (Wallbrink *et al.*, 2002).

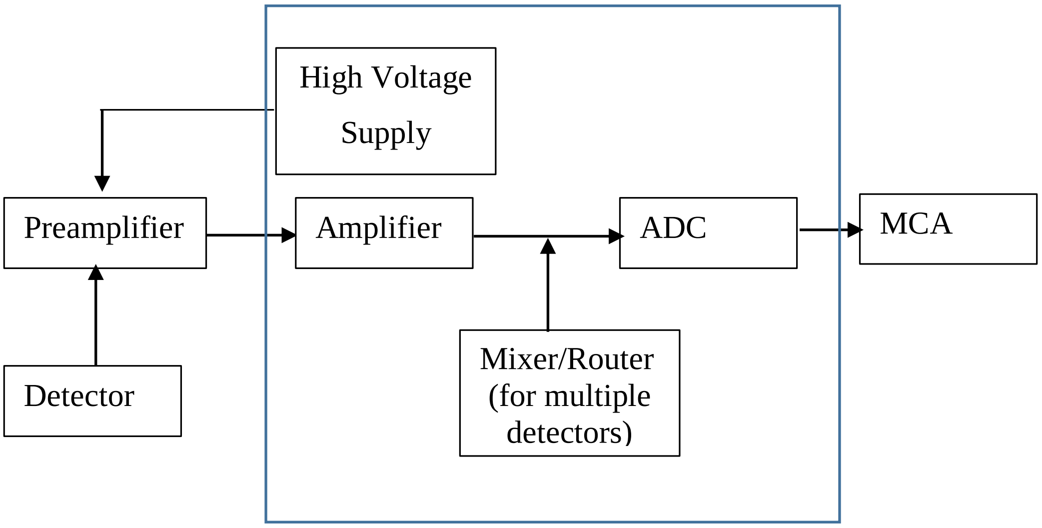


Figure 3.4 - Schematic of electronic components for the gamma spectrometer system to convert radionuclide signatures into inventories. The blue box represents the components within the nuclear instrumentation module. Adapted from Wallbrink *et al.* (2002).

A cylindrical screw cap container was filled with 900 g of sieved material from a single core. The lid was tightly sealed and the container was placed on top of the geranium crystal housing (Figure 3.5) before sealing the gamma spectrometer. Two gamma spectrometers were used, therefore two samples were analysed at the same time. Since duration and container dimensions affected measurements, samples remained in the gamma spectrometer for 24 hours enabling sufficient detection of ^{137}Cs (Wallbrink *et al.*, 2002). To validate the results, additional runs were performed. Firstly, a random sample was chosen for grid A and B samples and left on the gamma spectrometer for 72 hours. Every 24 hours the ^{137}Cs count was recorded. Secondly, validation involved taking three random samples from grid A and B samples and running each of them for 24 hours. The same method was used for the reference cores to obtain an average value for the reference site.

Figure 3.5 - Inside of gamma spectrometer where samples are placed on top of the Germanium crystal housing in the centre of anti-coincidence and aged lead shielding.

Once all 60 samples had been counted, the counts were converted to a radioactivity area (Bq m^{-2}) for the individual point using the following equation:

$$A = \frac{C}{(T.M.de.br)} \tag{3.4}$$

Where A = activity concentration of^{137}Cs (Bq kg^{-1}), C = count of ^{137}Cs signature derived from the region of interest given by the MCA, T = time of sample in gamma spectrometer (seconds), M = the mass of the sub-sample from the core, de = the detector efficiency and br = the emission probability of ^{137}Cs (0.85).

Uncertainty with the precision of the measurements can be calculated as:

$$Me = 1.96\left(\frac{\sqrt{C}}{C}\right) \times 100 \qquad (3.5)$$

Where Me is the percentage error at 95% confidence level (Owens *et al.* 1996). Before modelling erosion rates A requires conversion into ^{137}Cs inventory:

$$\mathrm{Cs}_i = A.\left(\frac{Mt}{S}\right) \qquad (3.6)$$

Where C_{si} = the inventory per unit area (Bq m^{-2}), Mt = the total mass of the core and S = the surface area of the core (0.0028 m^2).

To calculate erosion rates from the radioactive areas as t ha^{-1}yr^{-1}, the mass-balance-model was used (also termed Power model) developed by de Jong *et al.* (1983). This model was selected because there was knowledge about rainfall and tillage regimes but no evidence of tillage translocation (Walling *et al.* 2007). This model was applied to samples considered to be eroding (where $C_{si}<C_{sr}$):

$$E_{Cs} = \frac{\rho_T \mathrm{D_T}}{n}\left[1 - \left(\frac{\mathrm{Cs}_i}{\mathrm{Cs_r}}\right)^{\frac{1}{\mathrm{Y}}}\right] \qquad (3.7)$$

Where E_{cs} = the estimated soil loss rate (kg m^{-2} yr^{-1}); ρ_T = soil bulk density (kg m^{-3}); D_T = tillage depth which was 0.2 m for both grids because the sustainable practice had begun in 2010 and would not be representative of the decadal history of the field; n = the particle size correction factor; Y = the time period since ^{137}Cs maximum input in 1963 (48 yrs); and C_{si} = the ^{137}Cs inventory at the sampling point (Bq m^{-2}); and C_{sr} is the reference ^{137}Cs level (Bq m^{-2}). The particle size correction factor (n) was calculated as described by He and Walling (1996):

$$n = \left(\frac{P_m}{P_d}\right)^{v} \qquad (3.8)$$

Where P_m = the specific surface area for eroded sediment, P_d = the specific surface area for the field soil and v = a constant of 0.65.

The model compensated for tillage mixing of the basal soil into the till layer therefore it was deemed suitable to use for the data. However, this model does not work in cases where soil accumulation prevents mixing of the basal soil into the tillage layer. Therefore, the proportional model, also proposed by Walling and Quine (1990) is suitable for deposition areas (where $C_{si}>C_{sr}$):

$$E_{Cs} = \frac{\rho_T D_T (Cs_i - Cs_r)}{nYCs_r} \qquad (3.9)$$

3.2.3 Seedbank Sampling and Measurement

The coring pattern was selected to match and directly map the seedbank sampling programme conducted by The James Hutton Institute as part of the core dataset collection for the Centre for Sustainable Cropping (CSC). These samples were collected in the same manner as Steading field soil samples (Section 2.2.2.2). Identification of seeds was conducted using the same germination method outlined in Section 2.2.2.2. *Capsella bursa-pastoris, Epilobium sp., Myosotis arvensis, Poa annua, Veronica arvensis, Veronica persica* and *Viola arvensis* were selected for investigation since these species were identified from the tramline experiment (Chapter 2), where they were shown to be related to tramline erosion. Furthermore, these species were present in sufficiently large numbers to allow for detection and identification of the different species.

3.2.4 Visualisation and Statistical Analysis

The aim of this research was to determine the extent of the relationship on a field scale between seedbanks and soil erosion therefore, visualisation using GIS was desirable. Data was plotted using ArcGIS suite 10.1 with a topo-to-raster function across the entire field. The data was analysed for both erosion values and seed data. In addition, a digital elevation model (DEM) was generated with a resolution of 1 mm from a dGPS (Leica GPS system 1200) survey collected separately in July 2012, exaggerated by a z factor of 10 and contours applied to identify in-field topography.

Statistical analysis was determined using Genstat version 13 (VSN International, U.K.). Analysis of Variance (ANOVA) was used to test for significant differences in erosion and seedbank variables using conventional and sustainable sides as controlling factors. The use of a generalised linear regression models determined relationships between erosion and seedbank.

3.2.4.1 Example calculation of ^{137}Cs Inventory

The sample from a single point (Grid A 1.1) was an example of calculating ^{137}Cs inventories and erosion rates. Grid A 1.1 had a 0.9 kg (M) subsample removed from the

1.4 kg dry stone free soil mass of the core. This sample was placed on the detector (input) to give the following counts:

Live count time in seconds (T) = 86096

Count (C) = 1584 ±121

Uncertainty measurement error as % is

$$Me = 1.96\left(\frac{\sqrt{C}}{C}\right) \times 100 \qquad (3.5)$$

$$1.96\left(\frac{\sqrt{1584}}{1584}\right) \times 100 = 5\%$$

Conversion of counts in Bq kg^{-1}:

$$A = \frac{C}{(T.M.de.br)} \qquad (3.4)$$

Where A = activity concentration of ^{137}Cs (Bq kg^{-1}), C = count of ^{137}Cs signature derived from the region of interest given by the MCA, T = time of sample in gamma spectrometer (seconds), M = the mass of the sub-sample from the core, de = the detector efficiency (0.0064), which was calibrated from a National Physical Laboratory gamma standard; and br = the emission probability of ^{137}Cs (0.85).

Therefore:

$$A = \frac{1584}{(86096 * 0.9 * 0.0064 * 0.85)}$$

A = 3.76 Bq kg^{-1} ± 5%

Conversion of Bq kg^{-1} to Bq m^{-2}:

$$\mathrm{Cs}_i = A.\left(\frac{Mt}{S}\right) \qquad (3.6)$$

Where C_{si} = the inventory per unit area (Bq m^{-2}), Mt = the total mass of the core and S is the area of the top of the corer (0.0028 m^2).

To calculate the inventory:

$$\mathrm{Cs}_i = 3.76 * \left(\frac{1.4}{0.0028}\right)$$

$$\mathrm{Cs}_i = 1862 \text{ Bq m}^{-2} \pm 5\%$$

3.2.4.2 Example of converting ^{137}Cs to Erosion Rate using Power Model

The ^{137}Cs inventory for Grid A 1.1 was lower than that of the reference site (2092 Bq m^{-2}) therefore the site was considered to be eroding and the power model was applied:

$$E_{Cs} = \frac{\rho_T \mathrm{D_T}}{n}\left[1 - \left(\frac{\mathrm{Cs}_i}{\mathrm{Cs_r}}\right)^{\frac{1}{\mathrm{Y}}}\right] \quad (3.7)$$

Where E_{cs} = the estimated soil loss rate (kg m^{-2} yr^{-1}); ρ_T = soil bulk density (kg m^{-3}); D_T is tillage depth (0.2m); *n* = the particle size correction factor; Y = the time period since ^{137}Cs maximum input in 1963 (48 yr); C_{si} = the ^{137}Cs inventory at the sampling point (Bq m^{-2}); and C_{sr} = the reference ^{137}Cs level (Bq m^{-2}). Particle size correction factor (*n*) was calculated as described by He and Walling (1996):

$$n = \left(\frac{P_m}{P_d}\right)^v \quad (3.8)$$

Where P_m = the specific surface area for eroded sediment, P_d = the specific surface area for the field soil and *v* = a constant of 0.65.

To calculate *n* for Grid A 1.1

$$n = \left(\frac{6825}{14486}\right)^{0.65}$$

$$n = 0.613$$

To calculate erosion rate (E_{cs}) in kg m^{-2} yr^{-1}:

$$E_{Cs} = \frac{1151.194 * 0.2}{0.613}\left[1 - \left(\frac{1086.02}{2092.64}\right)^{\frac{1}{48}}\right]$$

$$E_{cs} = 0.912 \text{ kg m}^{-2} \text{ yr}^{-1}$$

To convert into t $ha^{-1}yr^{-1}$ use the following conversions:

1 tonne = 1000 kg

1 ha = 10000 m^2

Therefore:

E_{cs} (t ha^{-1}) = E_{cs} (kg m^{-2}) x 1000 x 10000

Simplified to:

E_{cs} (t ha^{-1}) = E_{cs} (kg m^{-2}) x 10

Thus

E_{cs} (t ha^{-1}) = 9.12 t $ha^{-1}yr^{-1}$

3.3 Results

3.3.1 ^{137}Cs measurements

Table 3.1 shows the ^{137}Cs inventories found in the field were comparable to other UK studies. Appendix C contains information on bulk density and stone content of the field soil. The concentration of ^{137}Cs inventories across the field provided an evaluation of the spatial distribution of erosion (Figure 3.6). The 60 measurements of ^{137}Cs inventories showed there was no difference between Grid A (average = 1514 ± 55 Bq m^{-2}) and Grid B (average = 1562 ± 50 Bq m^{-2}) tillage ($p = 0.527$). The ^{137}Cs inventories for the Grid A side ranged between 914.5 and 2474 Bq m^{-2}with the Grid B side ranging 998.9 and 2163 Bq m^{-2}. Appendix D contains the information on the nine reference cores. The average of the nine cores was 2092 Bq m^{-2}, which was considered the reference value. Comparison with the reference value shows that three cores were classed as deposition points with one point in the Grid A side and two in the Grid B side.

Table 3.1 – ^{137}Cs inventories from studies within the UK with average rainfall between 1981 and 2010 from Met Office (2013). Balruddery Field is at the top of the list in bold.

Study	**Location**	**^{137}Cs Inventory (kBq m^{-2})**	**Rainfall (mm)**	**Erosion Rates (t ha^{-1} yr^{-1})**
This Study	**Balruddery Farm, Angus**	**0.92 – 2.47**	**705**	**23.9 - 30.6**
Tyler *et al.* (2001)	Littleour, Perthshire	1.44 – 3.24	819.5	-
Walling *et al.* (2002b)	Preston Wynne, Herefordshire and Smisby, Derbyshire	1.98 – 2.78	644 -703	0.33 – 7.44
Walling *et al.* (2003)	Crediton, Devon	1.61 – 2.93	784.9	6.2 – 10.4
DEFRA (2008)	Tamworth, Staffordshire	1.37 – 2.58	712.4	-
DEFRA (2008)	England and Wales	1.60 – 3.54	1128.28	7.7

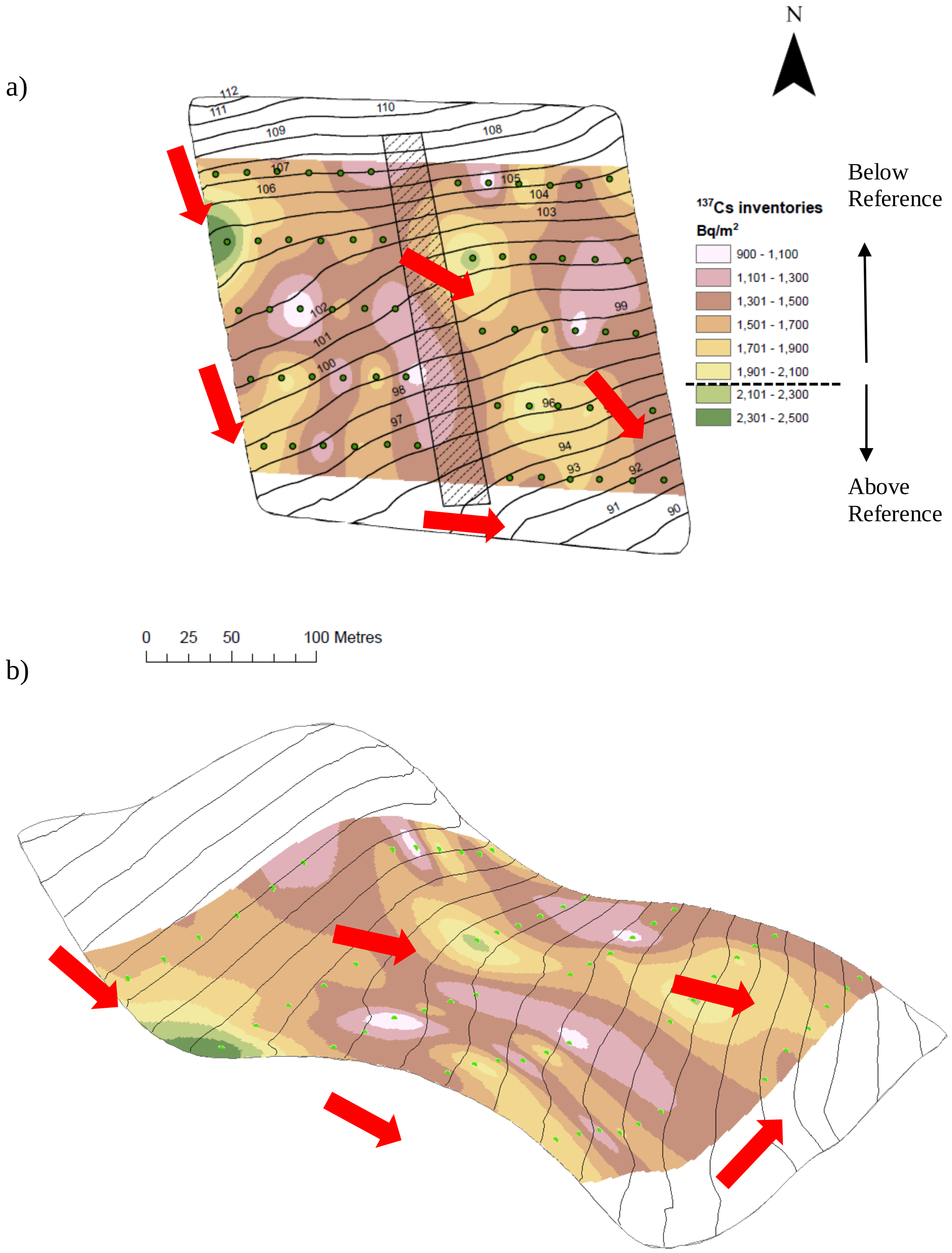


Figure 3.6 - ^{137}Cs inventories showing (a) plan view and (b) exaggerated DEM from south western corner for both Grid A and Grid B with 1 m contours and beetle bank (hashed area). Arrows indicate direction of observed surface water flow. Anything below 2100 Bq m^{-2} was considered to be an erosion area whilst above was considered depositional.

Erosion rate estimates derived from the ^{137}Cs inventories show the spatial patterns and variability across the field (Figure 3.7). The ^{137}Cs inventories and soil erosion maps show a near identical pattern. The values of ^{137}Cs inventories higher than the reference value show deposition. No significant differences were found between Grid A (mean = 30.6 t ha^{-1} yr^{-1}) and Grid B (mean = 23.9 t ha^{-1} yr^{-1}) in erosion rates ($p = 0.093$). The difference in erosion rates between the grids was much greater than the ^{137}Cs inventories probably due to difference in bulk density in the models. Overall, the difference between Grid A and Grid B is likely in the difference in slope shape and angle. Groves *et al*. 1996 states that steeper slopes generate greater overland flow and thus cause more erosion and movement of ^{137}Cs. This is consistent with the results here as Grid A had a steeper slope than Grid B. The greatest deposition rate was 16.5 t ha^{-1} yr^{-1}and located in a depression within the slope in Grid A. This point also corresponded with the flow of water into the field. Furthermore, the deposition in Grid B corresponded with observed water flow along the furrow in Grid A. The greatest erosion rates were found to be in Grid A with over 65 t ha $^{-1}$ yr^{-1}. The central erosion hotspot was located on top of a ridge (Figure 3.7b) south of the depositional furrow. The combination of the highest erosion and deposition points were on Grid A indicating an erosion source within the field which was depositing on the north into the furrow. This pattern is indicative of tillage erosion (cf. Govers *et al.,* 1996; Quine *et al.*, 1999). With an average of 27.25 t ha^{-1} yr^{-1} for both grids, the rate of erosion for the field is much higher than those found elsewhere in the UK (Section 1.2.3.1), which long term maybe consistent with field sediment wedges.

Even though there was no statistical difference, Grid B showed erosion rates were generally less than Grid A which were most likely due to a gentler gradient. There was a greater rate of erosion down the eastern side of the field which may be due to periodic spillage of water from upslope fields which is connected and controlled by walls, ditches and track breaches. This erosion may be caused by the access point in the north east of the field, allowing water to enter the field, but at a different rate to the north west access as the north west access was less used by farm machinery. The increased erosion rate towards the south eastern corner of the field indicated it was caused by water erosion as opposed to tillage because the direction of soil movement followed the contours of the field and not vertically on the slope. However, the models show erosion occurred along the southern edge of the field, which was unexpected due to a change in gradient (see Figure 3.2c for example) and was thought to be a zone of deposition. Given the relative steepness of the slopes in the field the loss of soil at these rates is not sustainable.

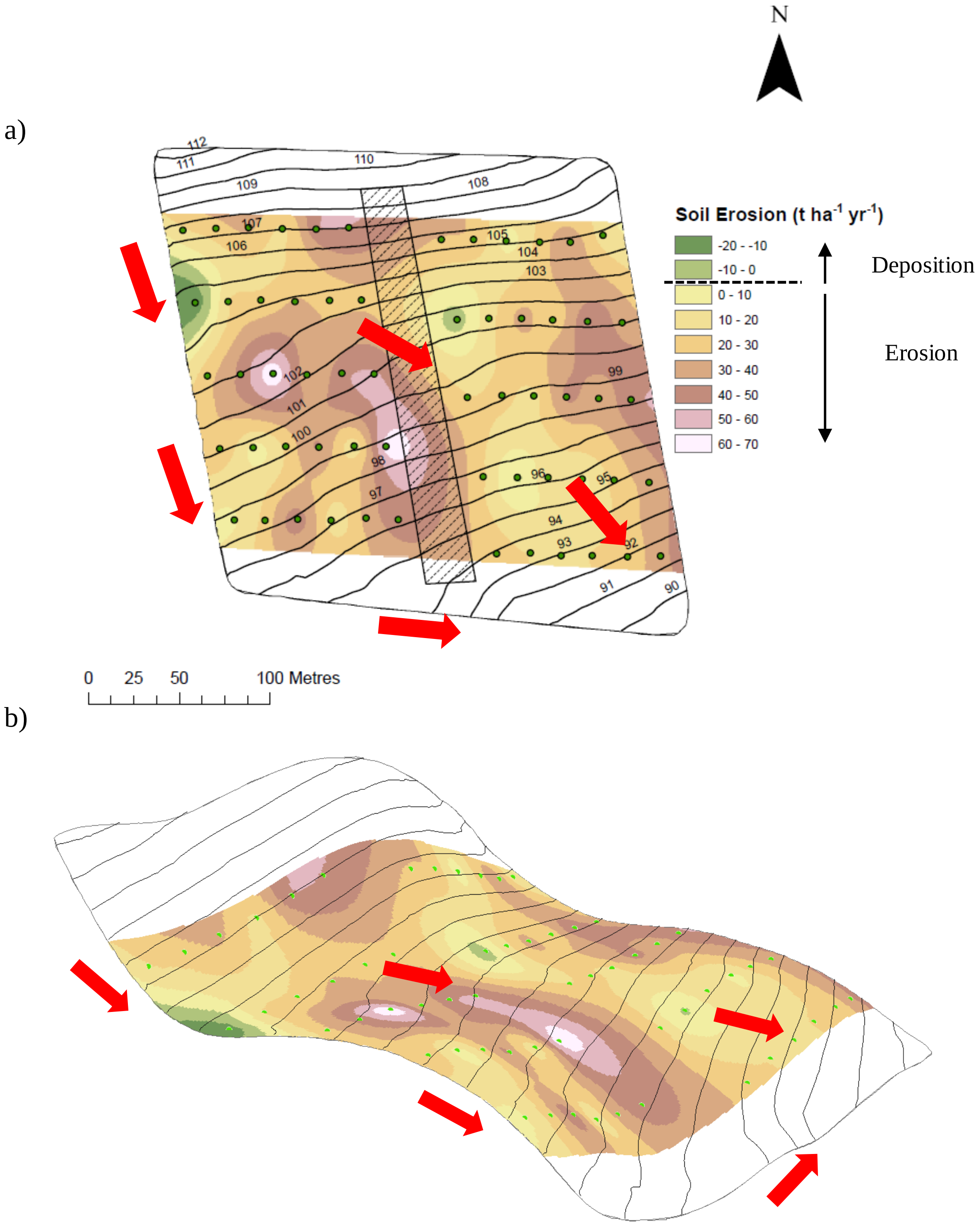


Figure 3.7 – Soil erosion rates estimates derived from ^{137}Cs shown (a) plan view and (b) exaggerated DEM from south western corner showing both Grid A and B plots with 1 m contours and beetle bank (hashed area). Arrows indicate direction of observed surface water flow. Anything above was 0 t ha^{-1} yr^{-1} was considered to be an erosion area, whilst figures below were considered depositional

3.3.2 Seedbank Abundance and Composition

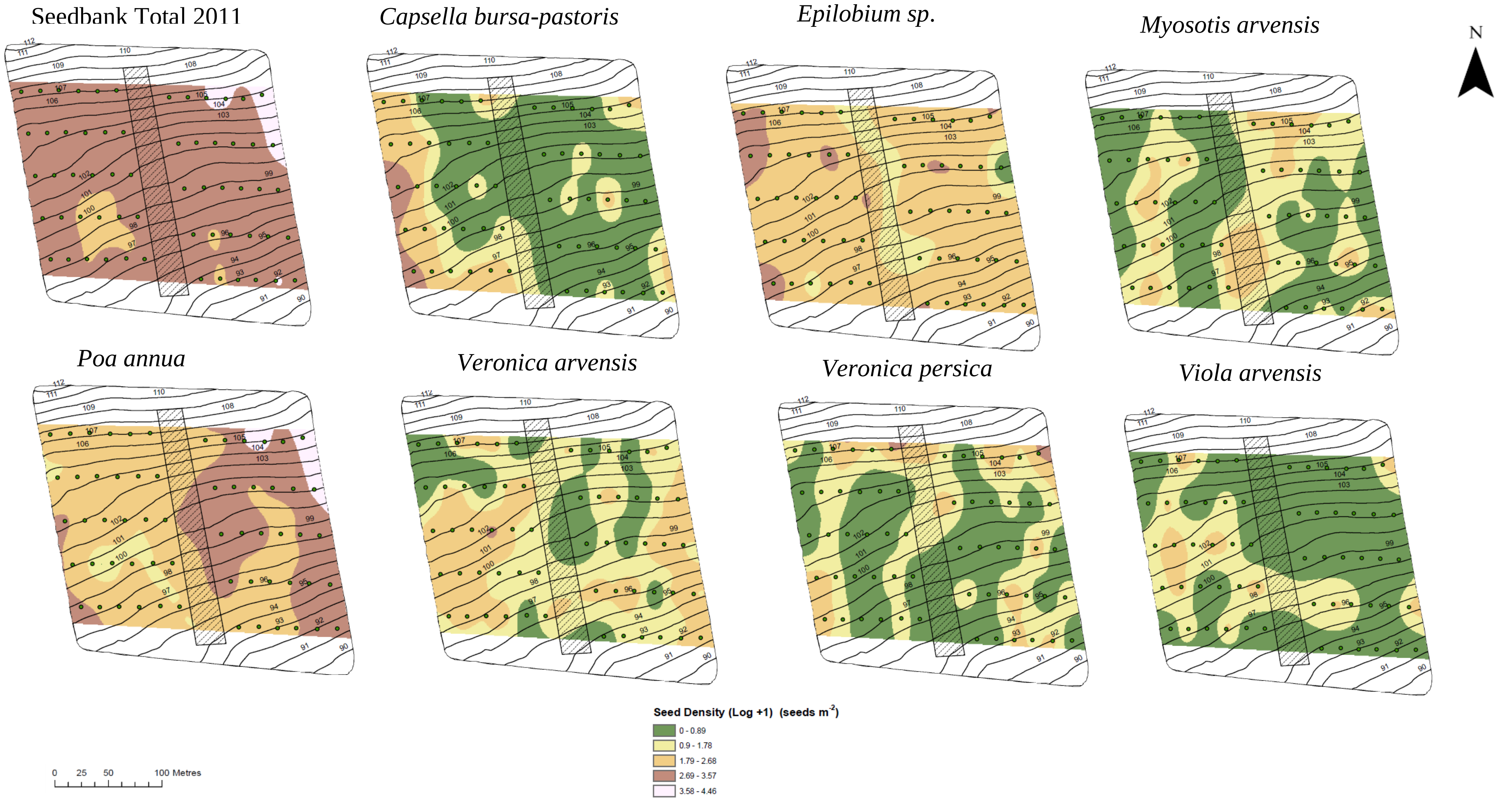
Table 3.2 shows the results of ANOVA testing for each side in each year. A total of 2965 seeds from the 60 measuring points were identified in 2011 and 1667 seed were identified in 2012. In 2011, there was a significant difference between Grid A and B given the total seeds numbers were 879 and 2086 seeds respectively. In 2012, there was no significant difference between Grid A and B, as the seedbank totals were similar at 795 and 872 respectively.

Table 3.2 - Significance testing of Grid A and B seed abundances (using a log + 1 transformation) for 2011 and 2012 covering selected seed species and total seedbank.

Parameter	**2011**	**2012**
	p	***p***
Seedbank Total	**0.002**	0.866
Capsella bursa pastoris	**<0.001**	0.772
Epilobium sp.	0.703	**0.002**
Myosotis arvensis	0.158	0.322
Poa annua	**<0.001**	0.814
Veronica arvensis	0.217	**0.005**
Veronica persica	0.559	0.251
Viola arvensis	**0.003**	**0.028**

Figure 3.8 and Figure 3.9 show the distributions of the seedbank across the field for both 2011 and 2012.

Table 3.3 and Table 3.4 show the proportions of each category for the total seedbank and individual species. In 2011, the highest overall seedbank abundance was located in the north east corner of the field. Noticeably, *Epilobium sp*, *Poa annua* and *Veronica arvensis* shared the same pattern with the highest abundance of seeds. *Myosotis arvensis* and *Viola arvensis* had the lowest seed abundance with little spatial distribution. In 2012, the seedbank showed the highest numbers towards the field boundaries with hot spots in the middle of Grid A and the top of Grid B. The lowest numbers of seeds were located in the middle of the field. *Poa annua* had the greatest abundance and distribution of seeds followed by *Epilobium sp.* Similar to the previous year, *Myosotis arvensis* and *Viola arvensis* showed the least abundance and distribution.

 Seedbank Total 2011

Capsella bursa-pastoris

Epilobium sp.

Myosotis arvensis

Poa annua

Veronica arvensis

Veronica persica

Viola arvensis

Figure 3.8 – Log$_{10}$ + 1 transformed seedbank density for total seedbank and individual species found in 2011 shown on Grid A and Grid B sampling grid with 1 m contour lines.

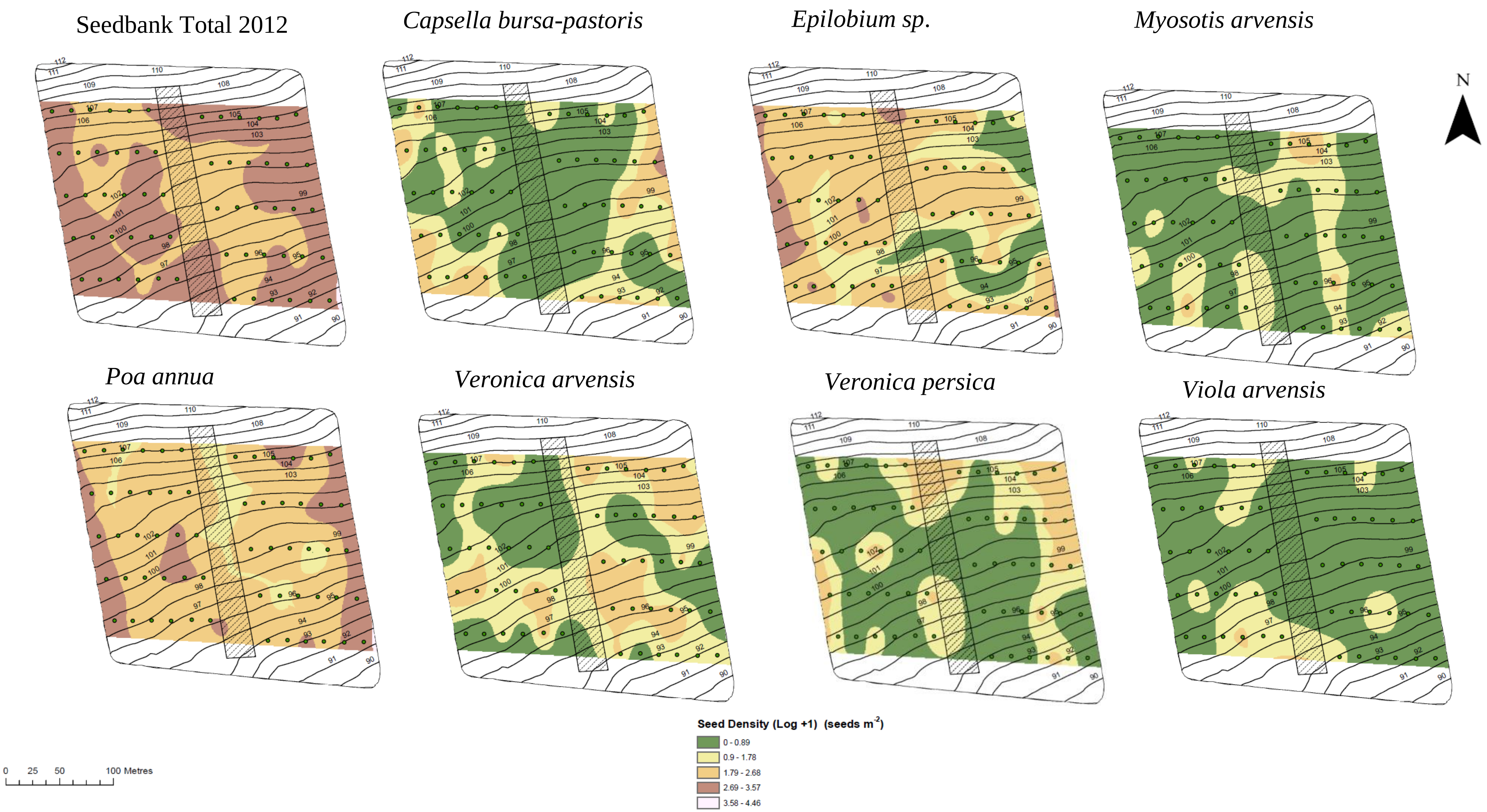


Figure 3.9 - Log$_{10}$ + 1 transformed seedbank density for total seedbank and individual species found in 2012 shown on Grid A and Grid B sampling grid with 1 m contour lines.

Table 3.3 - Proportions (%) of Log$_{10}$ + 1 transformed seed densities shown in Figure 3.8 for seedbank and selected species in 2011.

Species	**Very Low (0 - 0.89)**	**Low (0.9 - 1.78)**	**Medium (1.79 – 2.68)**	**High (2.69 – 3.57)**	**Very High (3.58- 4.46)**
Capsella bursa-pastoris	55.81	23.14	16.8	4.25	-
Epilobium sp.	0.55	11.73	79.93	7.79	-
Myosotis arvensis	46.33	35.7	16.6	1.37	-
Poa annua	-	3.57	57.57	33.04	5.82
Veronica arvensis	28.2	43.99	27.67	0.14	-
Veronica persica	43.92	32.75	18.36	4.97	-
Viola arvensis	70.58	24.89	4.53	-	-
Seedbank Total	-	0.69	13.35	72.77	13.88

Table 3.4 - Proportions (%) of Log$_{10}$ + 1 transformed seed densities shown in Figure 3.9 for seedbank and selected species in 2012.

Species	**Very Low (0 - 0.89)**	**Low (0.9 - 1.78)**	**Medium (1.79 – 2.68)**	**High (2.69 – 3.57)**	**Very High (3.58- 4.46)**
Capsella bursa-pastoris	56.53	26.88	15.69	0.9	-
Epilobium sp.	10.13	20.39	63.81	5.67	-
Myosotis arvensis	70.2	25.56	4.24	-	-
Poa annua	-	11.99	64.33	23.39	0.29
Veronica arvensis	38.88	37.04	24.08	-	-
Veronica persica	53.59	29.4	17.01	-	-
Viola arvensis	73.17	24.29	2.54	-	-
Seedbank Total	-	-	43.82	55.68	0.5

Further analysis using the combined two year dataset revealed differences within the seedbank over time and field side (Table 3.5). The seedbank was different between the two years (p <0.001), between the two grids regardless of year (p = 0.018). Comparing Grid A and Grid B seedbanks between each other in both years, there was a significant difference in the abundance (p = 0.032). This spatial and temporal difference in the overall seedbank shows the seedbank to be a dynamic system. Furthermore, individual species show mixed responses to time and field side. All seeds were annual species except for *Epilobium sp*. which was perennial. However, *Myosotis arvensis*, *Veronica persica* and *Viola arvensis* were the only species which did not to differ with time. Field side was shown to have a significant effect for most species except *Myosotis arvensis* and *Veronica arvensis*. The combined effect of time and field side only affected the seedbank total for, *Capsella bursa pastoris, Epilobium sp.*, *Myosotis arvensis* and *Poa annua*.

Table 3.5 - Significance testing to determine if time, field management or the combined effect changed seed density (Log_{10} + 1 transformed) for total seedbank and selected species. Significant results are in bold.

Parameter	**Year**	**Field Side**	**Year x Field Side**
	p.	***p.***	***p.***
Seedbank Density Total	**<0.001**	**0.018**	**0.032**
Capsella bursa pastoris	**<0.001**	**0.002**	**0.001**
Epilobium sp.	**0.018**	**0.006**	**0.035**
Myosotis arvensis	0.278	0.144	**0.016**
Poa annua	**<0.001**	**0.003**	**0.045**
Veronica arvensis	**<0.001**	0.942	0.178
Veronica persica	0.234	**0.021**	**0.096**
Viola arvensis	0.20	**<0.001**	0.441

3.3.3 Comparison of ^{137}Cs measurements and Seedbank Abundance

Correlations between the ^{137}Cs measurements and the seedbank revealed no relationships during 2011 and 2012. Investigation of the individual species found no relationship between the erosion rate and individual species. However, investigation between the Grid A and B field sides separately revealed some relationships (Table 3.6). The most striking observation was field side caused a different response for each parameter. In 2011, Grid A showed a significant weak negative relationship between erosion and seedbank density. In 2012, Grid B side showed a significant stronger positive relationship between erosion and the overall seedbank (Figure 3.10). Interestingly, 2011 and 2012 both grids showed differences to erosion patters. The relationship in Grid A changed as the spatial pattern of the seedbank changed but this would only explain part of the difference between years (Wiles and Schweizer 2002). The other main factor would be the climate as prior to 2011 the climate was cold and wet which then became warmer and drier in 2012, that would have affected seed rain, dispersal and seed mobility within the grid (Jones and Naylor, 1992; Cousens *et al.*, 2008; De Cauwer *et al.*, 2008). Although not tested, Grid B is likely to be different due to the treatment applied taking effect in the 2nd year altering above ground weed vegetation and soil characteristics from the different tillage depths (Jones and Naylor, 1992; De Cauwer *et al.*, 2008).

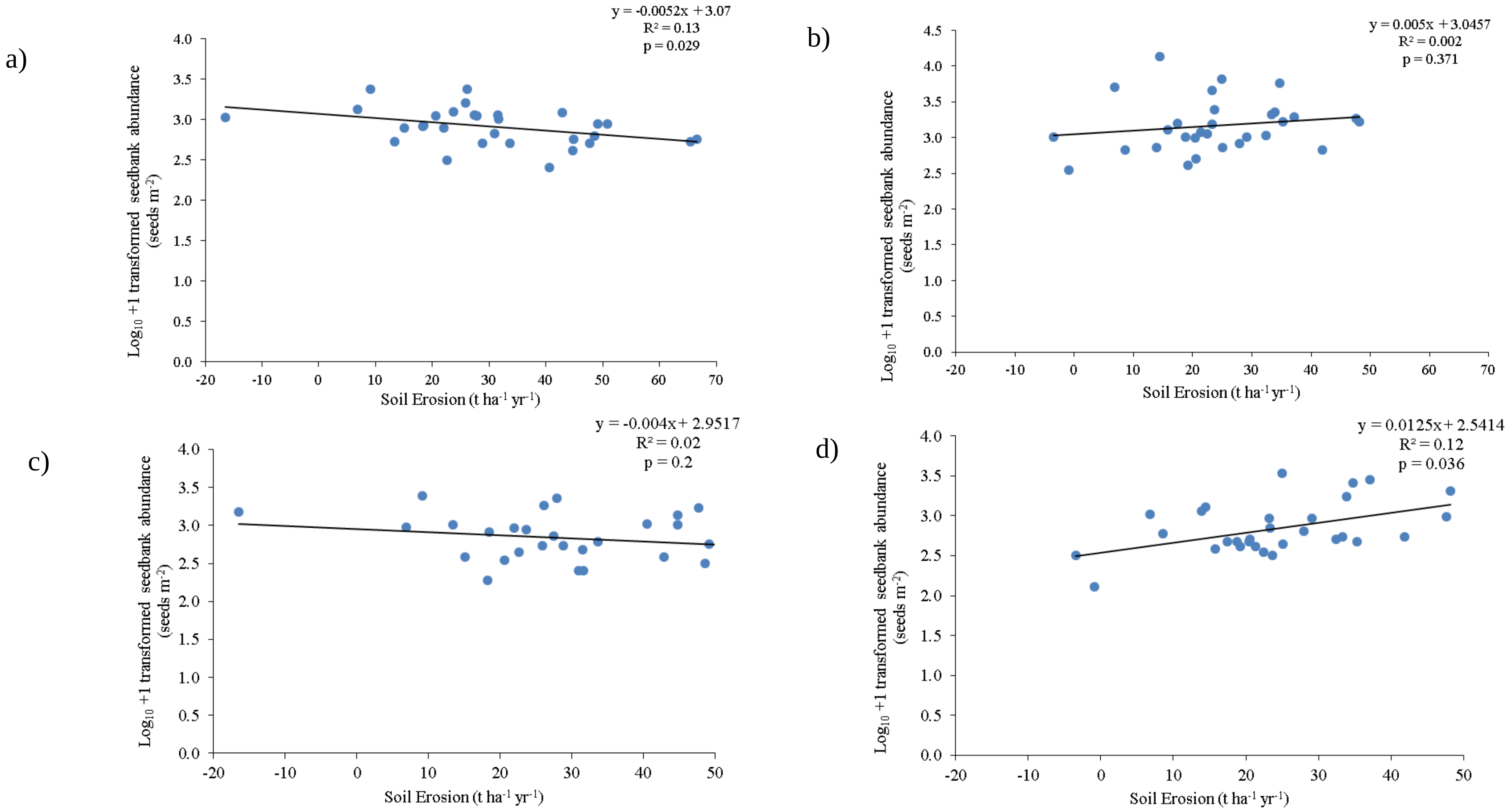


Figure 3.10 - Relationship between soil erosion rates derived from ^{137}Cs inventories and Log_{10} + 1 transformed seedbank densities for (a) Grid A in 2011, (b) Grid B in 2011, (c) Grid A in 2012 and (d) Grid B in 2012

Table 3.6 - Regression analysis of erosion rates with seedbank densities and selected species abundance in 2011 and 2012. r^2 is coefficient of determination and p is the significance of the relationship, which are highlighted in bold

Parameter	**Grid A**		**Grid B**	
	$\mathbf{r^2}$	***p***	$\mathbf{r^2}$	***p***
Log Seedbank Density 2011	**0.13**	**0.029**	N/A	0.371
Log Seedbank Density 2012	0.02	0.2	**0.12**	**0.036**
Capsella bursa pastoris 2011	0.06	0.110	0.04	0.153
Capsella bursa pastoris 2012	**0.15**	**0.019**	**0.13**	**0.029**
Epilobium sp. 2011	**0.35**	**<0.001**	N/A	0.816
Epilobium sp. 2012	0.02	0.206	N/A	0.665
Myosotis arvensis 2011	N/A	0.151	0.01	0.203
Myosotis arvensis 2012	0.06	0.078	0.03	0.196
Poa annua 2011	N/A	0.250	N/A	0.506
Poa annua 2012	N/A	0.398	0.1	0.056
Veronica arvensis 2011	N/A	0.533	0.06	0.110
Veronica arvensis 2012	N/A	0.483	0.04	0.167
Veronica persica 2011	N/A	0.456	0.04	0.158
Veronica persica 2012	**0.11**	**0.043**	0.05	0.134
Viola arvensis 2011	N/A	0.948	0.02	0.203
Viola arvensis 2012	N/A	0.814	N/A	0.467

N/A = No r^2 was calculated.

A key difference between the ^{137}Cs derived erosion and seedbanks may be the ^{137}Cs inventory only showing the medium term pattern (50 years) and the seed data over the two years of this research programme. The dynamic nature of the seedbank response to tillage and environmental changes means that the seedbank can vary between year to year as seed rain, dispersal and germination all occur in an annual cycle (Lewis *et al.*, 2013). On the other hand, ^{137}Cs redistribution has been occurring since the 1960s resulting in a longer term pattern of soil movement (Walling and Quine 1991). Therefore, these comparisons may be premature without a longer term seedbank pattern for analysis

Variability in the seedbank might be driven spatially by seedbank composition and abundance affecting community structures. Examination of individual species found *Epilobium sp.* in 2011, as well as *Capsella bursa-pastoris* and *Veronica arvensis* in 2012 had significant relationships with erosion (Figure 3.11). *Epilobium* genus had a complex negative relationship with erosion as the species was not identifiable, but it was most likely *Epilobium ciliatum* as this species was in high abundance in the adjacent Steading field. The positive and negative relationship of *Capsella bursa pastoris* in 2012 show there was a difference in Grid A and B. However, the key difference was in the deposition sides where Grid A showed a density of 350 seeds m^{-2} compared to 0 seeds m^{-2} in Grid B. *Veronica persica* showed a positive relationship in Grid A in 2011, but given the high number of core points with no seeds, this relationship might not be a true representation of the species relationship with erosion.

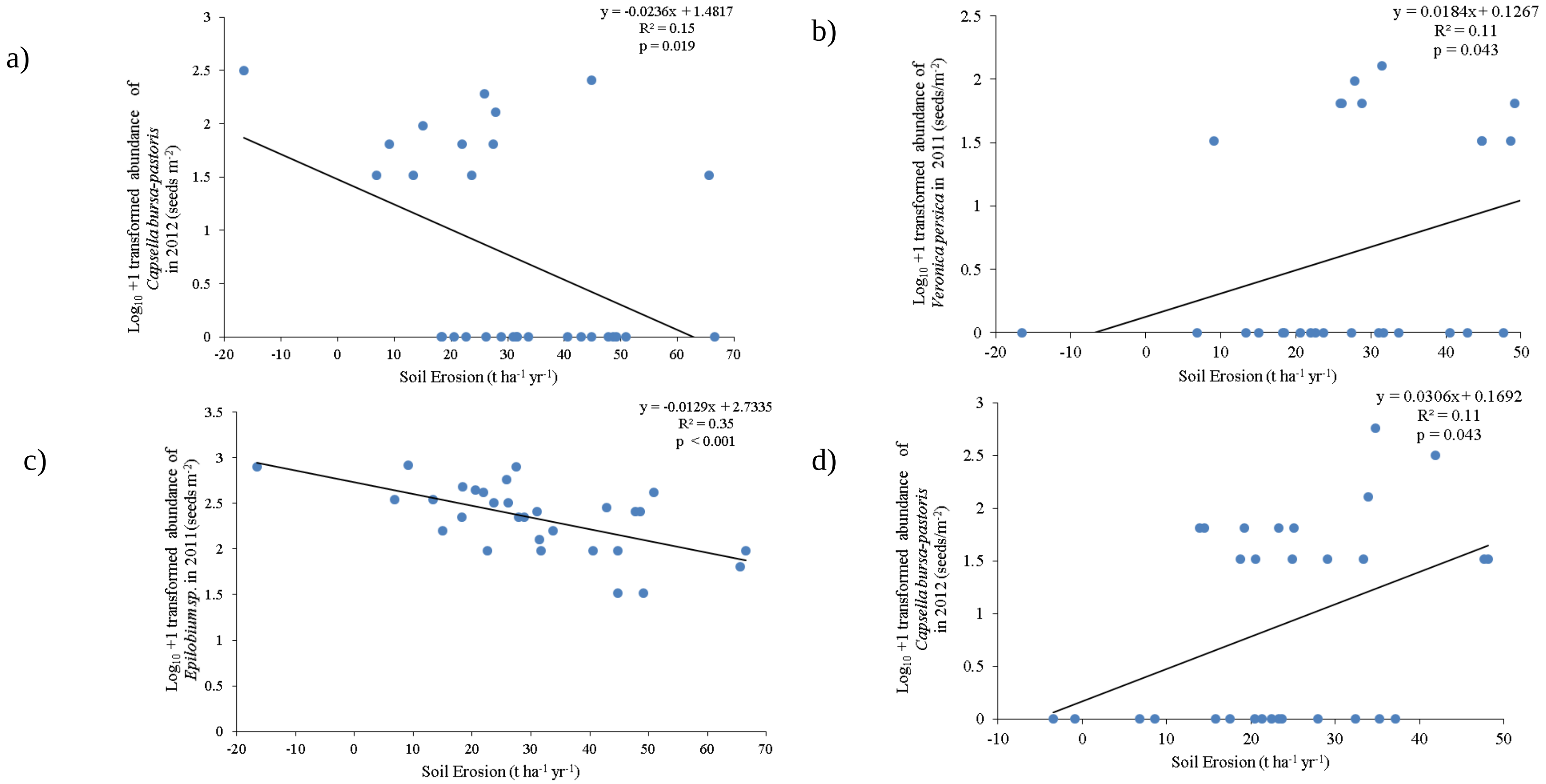


Figure 3.11 - Relationships between erosion rates and individual seed species (except *Epilobium sp.*) seed densities (a) *Capsella bursa pastoris* in 2012 in Grid A, (b) *Epilobium sp*. in 2011 in Grid A, (c) *Veronica persica* in 2011 in Grid A; and (d) *Capsella bursa pastoris* in 2012 Grid B. Negative erosion values indicate deposition.

3.4 Discussion

3.4.1 ^{137}Cs measurements

The measurement of ^{137}Cs at Balruddery Farm allowed for successful calculation of ^{137}Cs inventories and modelling of erosion rates for two field scale sampling grids. The findings of this study are consistent with the near 3000 papers that cite the ^{137}Cs technique as a method for gaining information on soil erosion rates (Ritchie and Ritchie, 2003).

Overall, the results showed 95% of the sampled field was considered to be eroding. In addition, there was no significant difference between Grid A and B in both ^{137}Cs inventories and erosion rate. This is important because the ^{137}Cs technique assumes that fallout was uniform spatially and locally (assumption 1), and fallout was rapidly and irreversibly bound to soil particles (assumption 2) (Walling and Quine 1992). Parsons and Foster (2011) challenge the validity of these assumptions with contradictory evidence. Rainfall may provide bias as rain fronts have the greatest rainfall on the leading edge which may lead to local variations in reference values (Parsons and Foster, 2011). In the case of this study, the two grids are contained in a single 6.85 ha field that is affected by frontal rain. However, rainfall occurs simultaosly at the farm due to the small area covered therefore local variations in ^{137}Cs are unlikely to occur due to rainfall. Vegetation can further compicate both assumption 1 and 2 through the interception and adsorption of ^{137}Cs prevetning the binding to soil particles (Parsons and Foster 2011). In this study, ^{137}Cs input to the soil may have varied with crop rotation and time of year, since arable systems do not have uniform vegetation canopies covering the soil. Further evidence of vegetation having a role in the ^{137}Cs inventories was found in the reference values taken from a grassland site. Comparision of the reference site cores to those of the field showed that 78% of the reference cores had >2000 Bq m^{-2} compared to just 5% in the field. The difference was caused by reference site being a grassland with year round protective cover meaning the site was non-eroding (Pennock and Appleby, 2003).

The ^{137}Cs inventories and modelled erosion rates displayed patterns of sptial variability that were consistent with topographical differences although this was not quantifiable due to the number of samples taken being too low for geo-statistical analysis or interpolation (Webster and Lark, 2013). However, qualitative assessment of the ^{137}Cs inventories and erosion maps allowed some topographical relationships to be observed. Evidence of hydrological and tillage movement can be identified from field observations and the mapped data. Grid A had highest erosion and deposition rates of the two grids. The results showed these to be located within a ridge and furrow system within the grid. Figure 3.12 shows that hydrological connectivity of the farm with previous waterpathways from the field above (Steading field in Chapter 2) entering into the field below and transporting material down the edge of the field. This would be consistent with assumption 3 that ^{137}Cs re-distribution is caused by soil particle movement, which in this case is predominatenly hydrological (Walling and Quine, 1992). Grid B showed similar rates of erosion to Grid A but were in areas less topgrpahical pronouced. In addition, the pattern does not conform to the hillslope profile with higher rates being found below lower rates upslope. This could be indicative of tillage erosion because of the similar rates of loss to the water driven erosion in Grid A (Van Oost *et al.,* 2006). The Power model does not account for tillage erosion but if additional data were available on relaxation depths, slope profiles, diffusion, and then a differential model could have been applied (e.g. mass balance model II or III) to sepearate water and tillage erosion (Walling *et al.,* 2002a).

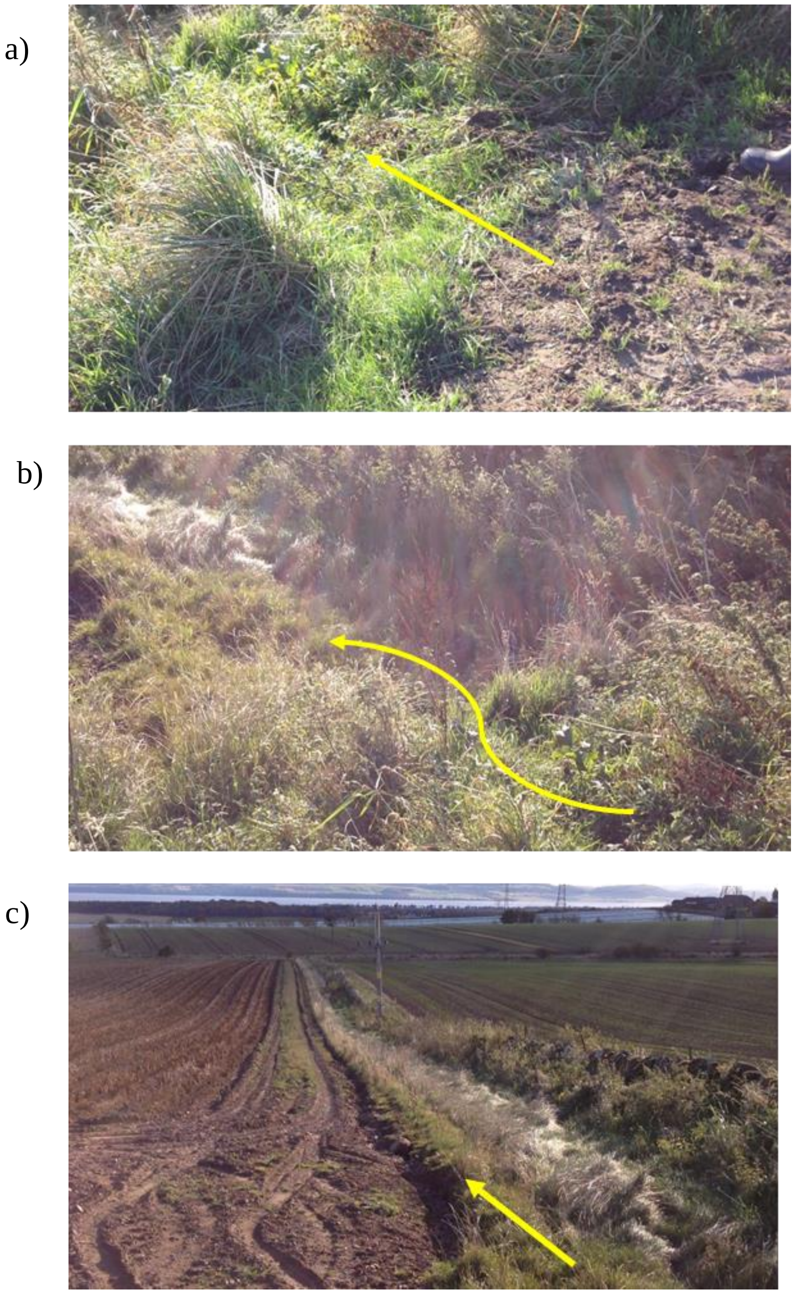


Figure 3.12 - Hydrological connectivity of fields via tracks found by vegetation displacement (a) passing through the field margins (b) and entering the field forming a gully that causes erosion and ^{137}Cs movement downslope (c).

Assumption 4 is that estimated erosion rates may be calculated from ^{137}Cs inventories, which have been shown to be successful in this study, but the inventories do not directly measure soil erosion (Parsons and Foster 2011). Therefore, errors in the sampling and collection of data need to be minimised to produce high quality data for use in the conversion models. The sampling protocols used in this study were set to generate quality data. First, the sampling grid was designed to allow comparison of 6 x 18m wide cultivar strips up and down each field. This grid design ignored headlands because these areas were used for farm machinery to access the field and for turning. Such disturbance may confound comparisons with the rest of the field. However, the foot slope headland did show characteristics of deposition (Figure 3.13) in 2012, which was not evident in 2011. Second, the stony soil of the field made sampling difficult and potentially underestimating the ^{137}Cs inventories. If the corer hit a stone, a new core was taken to obtain a complete core length. However, if there were stones (<2 mm) within the core these were removed later during sample preparation (as outlined by Pennock and Appleby (2003), which could have lead up to a third of loss in ^{137}Cs inventories (McFarlane *et al.*, 1992). Third, the use of gamma spectrometry can introduce errors due to the length of time of exposure and sample mass affected by the ^{137}Cs counts (Walling *et al.*, 2002a) resulting in a random decay measurements. This was not a problem because all radioactive measurements have random decays which were minimised by good sample geometry and lab practice. Finally, the gamma spectrometry method was limited by the need for energy and calibration calculations which resulted in potential differences in the ^{137}Cs inventory.

Figure 3.13 - Bottom of the field looking east where deposition occured in the headland in 2012. The sampling grid ends at the vegetation on the left side and the field margin is on the right. Yellow line shows the southern extent of sampling Grid A and B.

3.4.2 *Erosion and seedbank dynamics at the field scale*

The total seedbank abundance varied between 2011 and 2012, with the number of seeds found in 2012 was about half of that in 2011. This difference in seed abundance may be attributed to changes in crop rotation affecting seed input as well as seed dormancy (Jones and Naylor, 1992; De Cauwer *et al.*, 2008). Grid A and B seedbank changed in nature over the two year period of sampling. During 2011 there was a significant difference between both sides which did not occur in 2012. Various studies have shown seedbank densities are decreased by tillage frequency, intensity and herbicide usage (Grundy *et al.*, 2003a; Grundy *et al.*, 2003b; Tørresen *et al.*, 2003; Albrecht, 2005; Benvenuti, 2007; Hawes *et al.*, 2010). However, individual seed species appeared to respond differently from the overall seedbank. For example, *Capsella bursa-pastoris* showed the highest densities (up to 1270 seeds m^{-2}) in Grid A in 2011 whilst Grid B showed a seed density of less than 225 seeds m^{-2}. In 2012, the distribution of seeds in Grid A had changed with two hot spots in the north west and the south of the sampling grid. However, the seed density had decreased from 1270 seeds m^{-2} to 317 seeds m^{-2} indicating changes between years. In Grid B seed density at the highest sample point increased from 225 seeds m^{-2} to 571 seeds m^{-2} although the highest density in 2012 was found 40 m upslope of 2011 density. The difference in the two grids indicates seed density was adversely affected, but the composition and distribution of the seedbank were not affected individually. However, the overall picture masks a range of responses that are species specific relating to seed morphologies. Using *Capsella bursa-pastoris* as an example, the seed is characterised as a small (<2 mm), light (<1 g), and flat seed that excretes mucilage. In Chapter 2, small light seeds were the most prone to erosion transport whilst flat seeds with appendages were less likely to be selectively transported. However, seeds were more prone to be moved with sediment rather than in runoff. Evidence from Chapter 2 showed seeds are predominately transported in sediment, therefore *Capsella bursa-pastoris*’s morphology (small, light and with appendages) and spatial distribution changes between years are likely to be caused by tillage erosion rather than water. This could be because sediment was moved by farming activities resulting in *Capsella bursa-pastoris* seeds being shown upslope.

Seedbank sampling was done as part of the Centre of Sustainable Cropping’s long term investigation into quantifying the reservior of within-field biodiversity and providing an assessment of the gradual change in system response to more sustainable practice over time. In this study, there was a difference in the seedbank of the two sampling grids which was shown to be attributed to soil erosion but the overall responses mask sutile differences in the individual seed species. Erosion was found to have significantly affected the *Epilobium sp.* in 2011 in Grid A. *Epilobium sp.* seeds were only identified to genus although it was probably *Epilobium ciliatum* as the seeds were found in adjacent fields (see Chapter 2). The negative trend showed an increase in erosion rate lead to a decrease in seed numbers. A hypothesis to explain this would be by the erosion process physically removing the seeds prior to germination thus preventing weeds growing and producing more seeds. Previous evidence from the tramlines work in Chapter 2 showed *Epilobium ciliatum* was transported within sediment, rather than runoff. In areas of deposition, the seeds were able to germinate into weeds and produce seeds due to lack of disturbance from erosion (Howe and Smallwood, 1982). The erosion process might have reciprocal interactions within the seedbank as a disturbance mechanism depending on the seeds species (Hughes, 2012). However, *Capsella bursa-pastoris* in 2012 was significantly affected by erosion in both grids but in different ways. In Grid A the relationship was negative whilst in Grid B the relationship was positive showing that erosion was not the single contributing factor to abundances. Further work is required to how the timing of flowering and seed morphologies would affect selective transport of the seeds.

The evidence from this study shows that erosion is partly affecting the distribution of the seedbank and individual species at the field scale. The significance of this process is highlighted when combing the seed densities and erosion data. For Grid A, average erosion rates were 30.63 t ha^{-1} yr^{-1} with an average bulk density of 1240.8 kg m^{-3} resulted in a field soil loss of 2.47%. For Grid B, average erosion rates were 23.91 t ha^{-1} yr^{-1} with an average bulk density of 1196.93 kg m^{-3} resulting in a field soil loss 2%. Thus, a seed export rate for 2011 and 2012 for both grids can be calculated using average seed densities. For 2011, Grid A had an average seed density of 930.16 seeds m^{-2} and Grid B 1812.8 seeds m^{-2} resulting in a loss of 22.96 and 36.21 seeds m^{-2} respectively. For 2012, Grid A had an average seed density of 841.16 seeds m^{-2} and Grid B 922.75 seeds m^{-2} resulting in a loss of 20.76 and 18.43 seeds m^{-2} respectively.

Compared with UK estimates compiled by Lewis *et al*. (2013), the soil loss is four to five times higher with seedbank losses two to four times higher. Therefore, erosion has the potential to alter seedbank abundances and composition by 20 – 25% in 10 years, which would lead to substantial shifts in biodiversity and community compositions. However, the presence of tillage erosion may offset some of the downslope movement by water erosion through soil (and seedbank) translocation upslope from seed rich depositional areas at the foot slope (Van Oost *et al.*, 2006; Cousens *et al.*, 2008; Westerman *et al.*, 2009; Lewis *et al.*, 2013). These preliminary findings are based on a medium term (20 – 50 year) ^{137}Cs dataset comapred to a short term seedbank data set. To resolve the disparity between the two temporal scales, a long term continous monitoiring of the seedbank is necessary to match that of the ^{137}Cs to remove superimposed variables (e.g. management practice) and sucessfully determine the significance of the erosion seedbank relationship at the field scale (Müller *et al.* 2010). Nevertheless, this case study has provided a first order assessment of the effect of erosion on the seedbank at a field scale.

3.5 Conclusions

This chapter aimed to provide a first order assessment of the extent of the relationship between soil erosion and seedbanks at the field scale. The research approach was to combine the measurement of soil erosion by using ^{137}Cs and seedbank abundance from germination of weeds from soil samples. The analysis of 60 soil cores split into two field sized grids produced an erosion map, which revealed a large depositional swath within a topographical low point in the field. Furthermore, the ridges and furrows topography meant that both water and tillage erosion processes were present although differentiating and quantifying both process was not possible. Grids showed no significant difference between them in erosion rates although seedbank density and individual species did differ.

The main finding of this study was that seedbanks showed a differential response to erosion overall and for individual species. Weak relationships ($p < 0.05$) between erosion and overall seedbank and species found in both grids and years could be due to the differential responses exhibited. It is hypothesised these responses were due to a combination of different erosion processes (water and tillage) and species specific conditions (seed morphologies and flowering times). Importantly, the significance of the findings were that seedbank transport by erosion was two to four times greater than first estimates for the UK. This means the effect on arable ecosystem biodiversity would be more rapid and severe than previously thought but the movement would be mostly within field. Future work would involve the investigation of species specific differences in selectivity by erosion transport. Furthermore, additional sampling would improve the seedbank dataset minimising short term variability and provide a longer term comparison to erosion rates.

Chapter 4: Exploration of Seed Mobility and Entrainment by Erosion Using a Rainfall Simulator

4.1 Introduction

Chapter 1 described and discussed how accelerated erosive processes cause physical and chemical environmental disturbances to agricultural soils. Seed morphology and soil conditions influence the fate of seeds in the soil (Chambers *et al.*, 1991). The shape and size of the seeds control dispersal, as well as survivability against physical, chemical and biological influences (De Cauwer *et al.*, 2008; De Cauwer *et al.*, 2011). Physical soil conditions, such as bulk density and soil structure, are modified by tillage, which affect seed input, germination, dormancy and mortality (Jones and Naylor, 1992; De Cauwer *et al.*, 2008). However, the specific interactions between seed morphology and soil physics, which control seed movement by erosion processes are not well known.

Some understanding of how soil erosion processes affect seeds has come from rainfall simulators used under controlled conditions (García-Fayos and Cerda, 1997; Cerdà and García-Fayos, 2002; García-Fayos *et al.*, 2010; Han *et al.*, 2011), but these studies have focussed on seed species from loess and “badlands”. Han *et al.* (2011) found that seed loss positively correlated with sediment yield and runoff, whilst negatively correlated with slope length. The main advantage of rainfall simulators is the amount of control provided to investigate erosion processes (e.g. splash and runoff) (Iserloh *et al.*, 2012). However, rainfall simulators are unable to replicate exact field conditions due to physical design limitations (e.g. fall height being insufficient to achieve raindrop terminal velocity) and performance issues (e.g. nozzle clogging) (Brombacher and Eppink, 1991; Iserloh *et al.*, 2012).

The substantial literature regarding seed shape and size characterisation was reviewed previously (Chambers *et al.*, 1991; Moles *et al.*, 2005; Moles *et al.*, 2007). There was limited research on seed morphology relating to the removal of seed by water erosion; but if seeds were greater than 50 mg, seed size was the main factor in determining transportability, further regulated by shape, appendages and mucilage. (García-Fayos and Cerda, 1997; Cerdà and García-Fayos, 2002; García-Fayos *et al.*, 2010). Whilst these studies provide an initial assessment in laboratory conditions, there was no research into temperate species based on field conditions. The lack of data means different field conditions affecting seeds are poorly understood and provides challenges and opportunities for further investigation into seed mobility, transfer and ongoing viability following redistribution.

Chapter 2 showed that seeds are moved in tramline plots although the seed's starting location was indeterminable between the crop and tramline. Also, Chapter 2 showed that tramline management had affected erosion processes that have selectively been transporting seeds indirectly by controlling runoff and sediment loads. This selectivity appeared to be driven by the differences in seed morphologies between individual species. Flatter, lighter seeds are adapted for buoyancy and can be transported in runoff whilst cup shaped seeds are designed for rain splash dispersal (Nakanishi, 2002; Benvenuti, 2007). However, the environmental controls (e.g. slope angle, vegetation cover, event intensity and duration) for detachment of soil particles are well understood compared to those for seeds. Understanding the source of the seed means appropriate management techniques may be used to prevent seed transport within the field and beyond. Therefore, to better understand the transport of seeds by soil erosion, the susceptibility of seeds to detachment erosion processes requires further exploration. The use of a rainfall simulator will allow the study of specific environmental controls on both detachment of soil and seeds.

The aim of this study was to determine specific environmental controls on seed mobility. The objectives of this study were:

(i) To evaluate the effects of combinations for slope, ground management and event duration, using a field rainfall simulator, within a temperate agro-ecosystem setting on soil erosion and seedbank mobility.

(ii) To determine if there was selectivity by erosion processes on the seedbank.

4.2 Methodology

4.2.1 Specific Field Conditions

This experiment was conducted in Steading Field as outlined in Section 2.2.1.

4.2.2 Experimental Design

Although the site was the same as the one used in the tramlines experiment in Chapter 2 (Steading field), the design for this experiment was scaled down to meet the requirements of the rainfall simulator. The experimental design was split into i) field sampling strategy ii) data processing and analysis.

4.2.2.1 Field Sampling Strategy

4.2.2.1.1 Non -spiked Plots

Unbounded plots (3 x 100 m) within the hill slope of the field were established in October 2011 in order to capture and quantify eroded material, surface runoff and nutrients as part of the tramline experiment (Section 2.2.2.1). Figure 4.1 illustrates the experimental layout used in the field strategy. Eight of the 16 plots with tramline managements of regular and low pressure tyre were used. In addition, plots were established 1 m into the crop for simulations on a vegetated soil surface. Within an individual tramline plot and adjacent cropped area, two sub plots were established on a 2° and 6° slope. Following rainfall simulations lasting three minutes, eroded samples were collected prior to a second three minute simulation on the same plot (referred to as six minute simulation). Four replicates were established of all combinations of management, slope angle and duration, since the original design of the tramline experiment used four replicates of the tramlines.

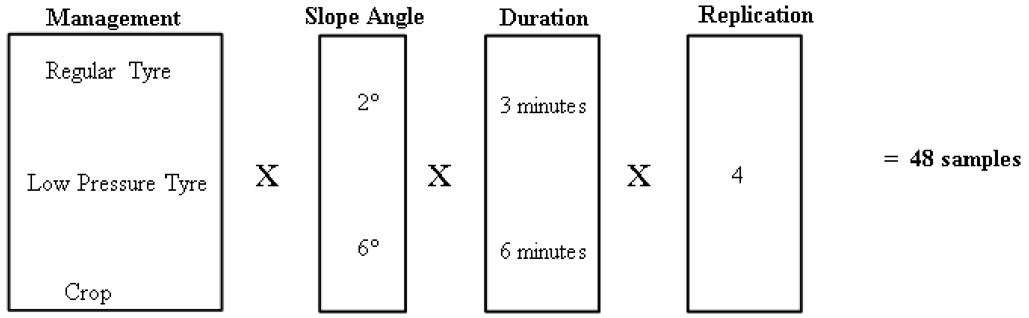


Figure 4.1 - Illustration of the combination of rainfall simulation parameters of the 48 samples. Three ground managements, two slope angles and two durations were used with four replicates of each combination.

A first phase of rainfall simulation runs was conducted in May 2012, after tramline monitoring for Chapter 2 had ceased, using a portable rainfall simulator (Figure 4.2) developed by Kamphorst (1987). The equipment is commercially available in the UK, supplied by Van Walt Limited, Model 09.06.

The simulator consists of four main parts shown in Figure 4.2:

(a) The 49 capillary sprinkler fed by a cylindrical reservior with a capactiy of 2.3 L.
(b) An adjustable support frame for the sprinkler with two small spirit levels.
(c) Ground frame (0.35 m x 0.32 m) for the support frame to stand on, secured with four nails, provided a plot size of 0.0625 m^2 (0.25 m x 0.25 m)
(d) Gutter for channeling and collecting runoff and eroded material into a 1 L beaker.

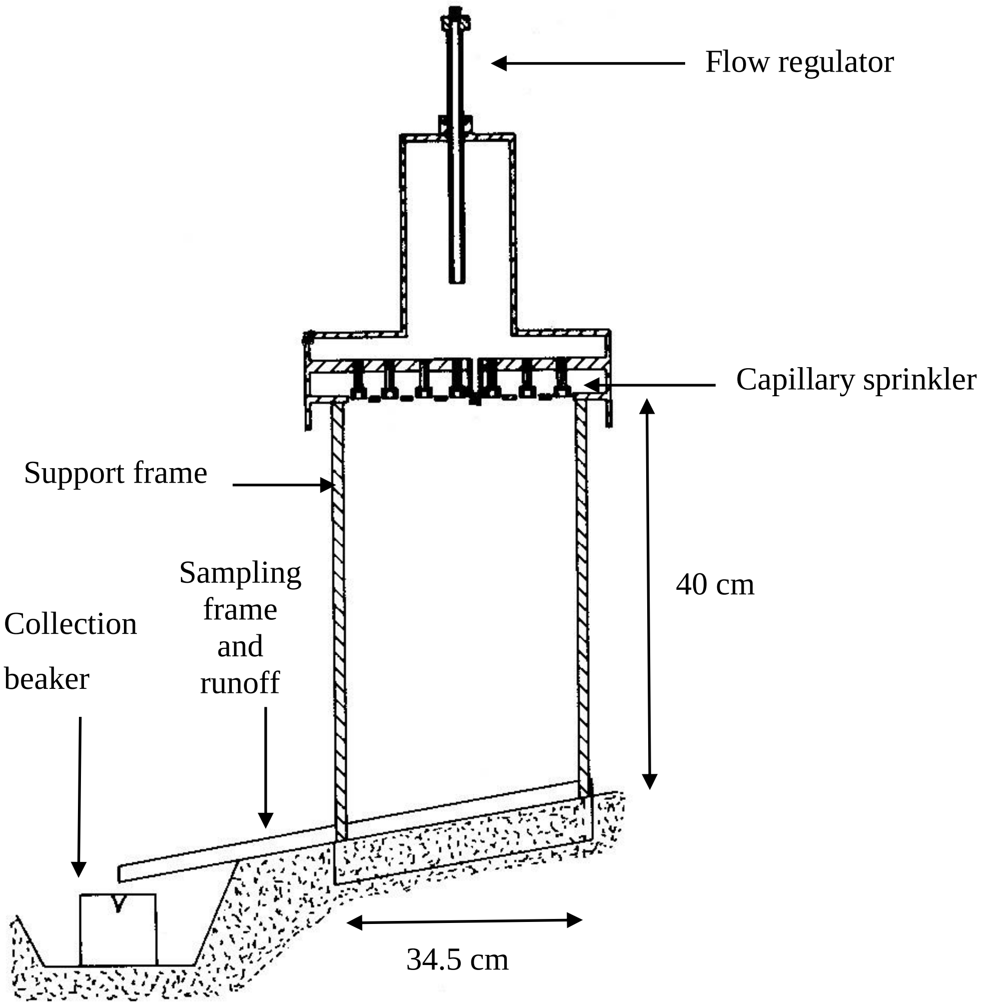


Figure 4.2 - Schematic of the Kamphorst rainfall simulator adapted from Kamphorst (1987) showing fall length of plot and the fall height of raindrop (Iserloh *et al.*, 2013).

The capacity of the rainfall simulator tank limited simulations to three minutes before refilling. Artificial rainfall fell at a rate of 375 mL min^{-1} equating to an intensity of 6 mm min^{-1} to compensate for the lack of height for raindrops to reach terminal velocity (the equilibrium reached between drag and gravity). Figure 4.3 demonstrates the use of the rainfall simulator. The simulator ran twice for three minutes on each sub-plot to simulate a three and six minute event. Additionally, a separate vegetated sub-plot was established one metre adjacent to the tramline within the barley crop. The crop was trimmed to a height of 30 cm prior to the rain simulation to allow the installation of the simulator. Vegetated plots were replicated four times at 2° and 6° slope across the entire field with both three minute and six minute events. Runoff and sediment were collected from all plots taken at three minutes and six minutes intervals, which were recorded and stored separately. Runoff volume was measured *in situ* using a measuring cylinder and the sample retained for particle size analysis, sediment yield and seeds identification (Section 4.2.2.2). After each simulation, the individual plots were excavated a depth of 5 cm to establish the remaining surface seedbank to compare with eroded samples.

Figure 4.3 - Kamphorst (1987) rainfall simulator being used in the field. On a tramline (a) the rainfall simulator demonstrates rain splash and runoff. The difficulties of use in tall vegetation are demonstrated in (b).

4.2.2.1.2 Spiked Plots

In November 2012, a second phase of runoff trials were conducted using unbounded plots that were re-established for the tramline experiment in Chapter 2, focussing on regular tyre ground management in the same manner as described in Section 1.2.2.1.1. Four plots were spiked with radish (*Raphanus sativus*) seeds coated in bright green Iprodione and Thiram dye. Coloured radish seeds allowed for ease of seed recovery, as they were larger (average size 3 mm in length) and bright green compared to the weed seeds. In addition, any seeds not eroded would not affect the weed seedbank. Spiking the plots was necessary to overcome the low densities of the natural seedbank. This field experiment was designed to understand the effect of event duration on soil characteristics and seed mobility, while ground management and slope were fixed by the use of regular tyres on a 6° field slope. Sixty seeds were randomly distributed onto each plot prior to simulation. This represented a seed density of 960 seeds m^{-2} that was found to comparable to the field seedbank sampled in Chapter 2. Simulations and sample collection were identical to those described previously.

4.2.2.2 Sample Analysis

4.2.2.2.1 Seed Data

Samples from both the spiked and non-spiked experiments were transferred to the laboratory and processed as outlined in Figure 4.4. In the spiked plot samples, the seeds were counted and recorded at step seed (c) (Figure 4.4). Non spiked plots required seeds to be removed from the mesh by washing in a sequence of water baths. The first bath contained 200 mL of water and was used to remove the majority of material collected on the mesh. The mesh was then transferred to another water bath with 100 mL of water and any residual material was rinsed off. The contents of the two baths were combined in a beaker and agitated by a magnetic stirrer to prevent settling (Figure 4.4 step seed (d)). Each sample was vacuum filtered (Figure 4.4 step seed (e)) to remove water and accumulate sediment, along with the seeds on a single 47 mm diameter filter paper (Whatman Grade 934-AH)**.** Filter papers were weighed prior to use for each sample, in order to determine the dry mass of material on the filter after germination was complete. Filter papers were transferred to labelled Petri dishes for seed germination (Figure 4.4 step seed (f)). The 14 day germination was conducted in a forced air incubator set at 22°C in darkness (Figure 4.4 step seed (g)). The dishes were watered twice a week with distilled water to keep the filter papers damp. To minimise light exposure (except during watering), all dishes were wrapped in aluminium foil. Once the seeds had started to germinate, they were transferred to plant pots in the glasshouse for identification. After 14 days, samples were treated with gibberellic acid (2 mg L^{-1}) to break any seed dormancy. This process was performed twice over the next seven days. Field soil samples were prepared and germinated in glasshouses for eight weeks as described in Section 2.2.2.2.

4.2.2.2.2 Sediment Data

Sediment data were determined from the runoff samples and seed filters (Figure 4.4 step seed (h)). The pre-weighed evaporating dishes were dried at 40°C overnight (Figure 4.4 step sediment (c)) and the mass of eroded sediment determined from the difference in weight of the dishes (Figure 4.4 step sediment (d)). In addition, the weight of sediment from seed germination filter papers was added to the amount in the dishes, to give the total sediment loss. Particle size analysis using the Coulter LS13370 granulometer was performed on each sample as described in Section 2.2.2.1 (Figure 4.4 step sediment (e)). Three and six minute samples from vegetated plots were combined to provide sufficient material for optimal resolution in the instrument (Merkus, 2009).

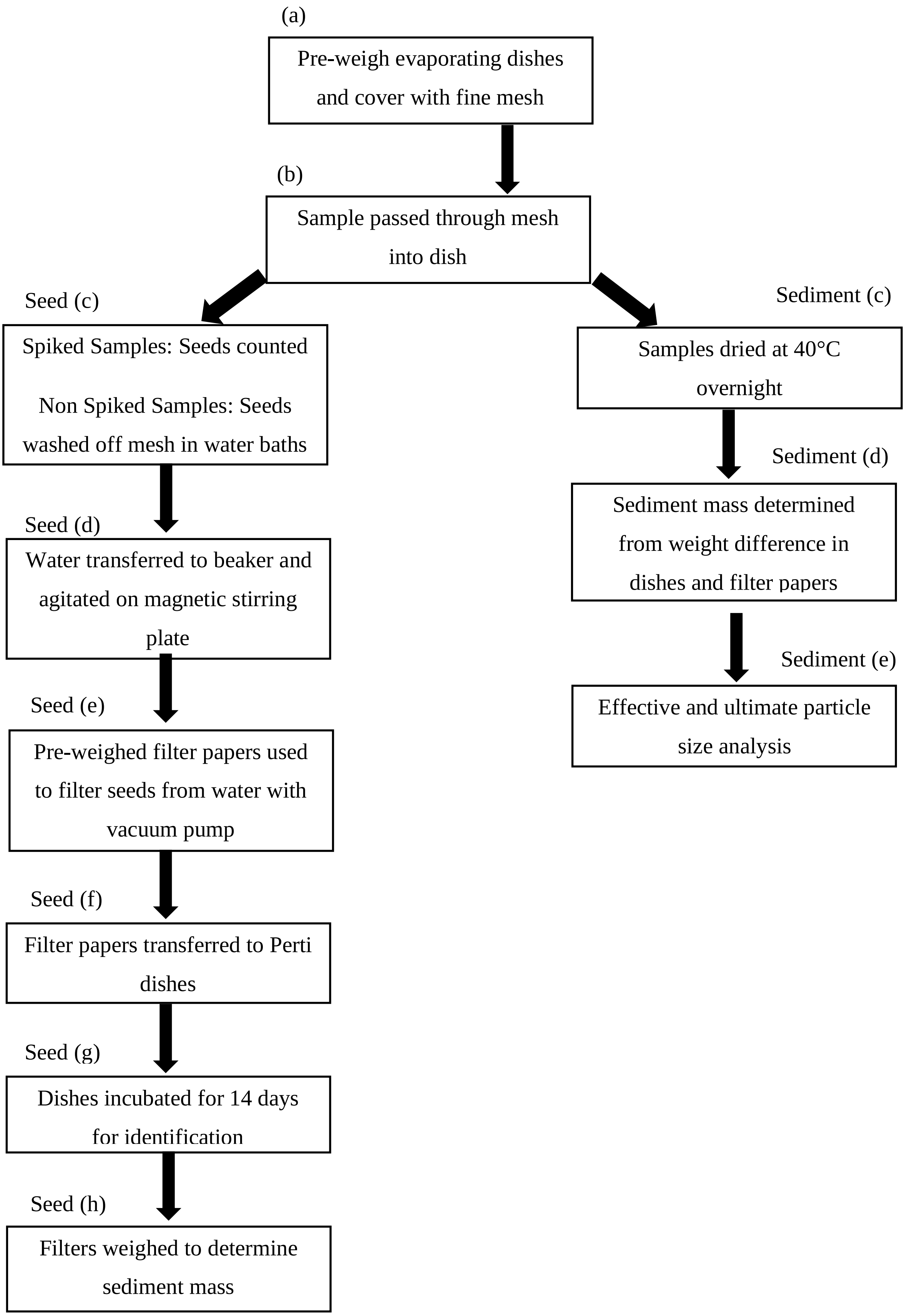


Figure 4.4 - Flow diagram of the rainfall simulation sample processing. The left side describes the seed identification process and the right side described to sediment processing.

4.2.3 Statistical Analysis

Statistical analysis of the data was undertaken using Genstat (version 13, 2010, VSN International) for ANOVA and Shannon Weiner index values as described in Section 2.2.3. Seed flux was calculated as:

$$SF = S * \left(\frac{1}{PA}\right) \tag{4.1}$$

Where *SF* is seed flux (seeds m^{-2}), *S* is number of seeds and *PA* is the plot area of the rainfall simulator which was 0.0625 m^2. For example, one simulation that lasted for three minutes on a crop covered 6° slope yielded 6 seeds, which as a seed flux was:

$$6 * \left(\frac{1}{0.0625}\right) = 96 \text{ seeds m}^{-2}$$

4.3 Results

4.3.1 Non-Spiked Plots

4.3.1.1 Event Totals

Analysis of the simulation samples revealed ground management was the most significant parameter (Figure 4.5). Crop covered surfaces had significantly less runoff and sediment (both $p<0.001$) compared to the tramlines. Slope angle had no effect on the amount of runoff ($p = 0.844$) and sediment ($p = 0.362$) likely due to the short (0.25 m) slope length. A total of 43 seeds from five weed species were collected in the seed flux from the eroded sample. Of these seeds, nine were from tramline plots and 34 from crop covered plots.

Seed flux for eroded samples was found to be greatest from crop covered plots ($p = 0.001$). Slope did not affect seed flux in eroded soil samples ($p = 0.597$) in this set of results. The *in situ* samples contained 223 seeds from 13 different species. Investigation of the *in situ* seedbank, that remained after simulations, showed the seedbank to be relatively homogenous in size regardless of ground cover ($p = 0.806$) , slope angle ($p = 0.847$) or combination of both ($p = 0.730$). This figure was substantial as the *in situ* bank was similar in size following erosion yet crop covered plots had significantly more losses. The number of species found in eroded soil samples did not differ with ground cover ($p = 0.667$), slope ($p = 0.116$) or the combination of both ($p = 0.316$). Similarly, the field soil showed little difference between ground cover ($p = 0.269$), slope ($p = 0.887$) or the combination of both ($p = 0.981$). These results showed the seedbank was relatively stable in both size and diversity following erosion indicating erosion had little impact on the overall seedbank.

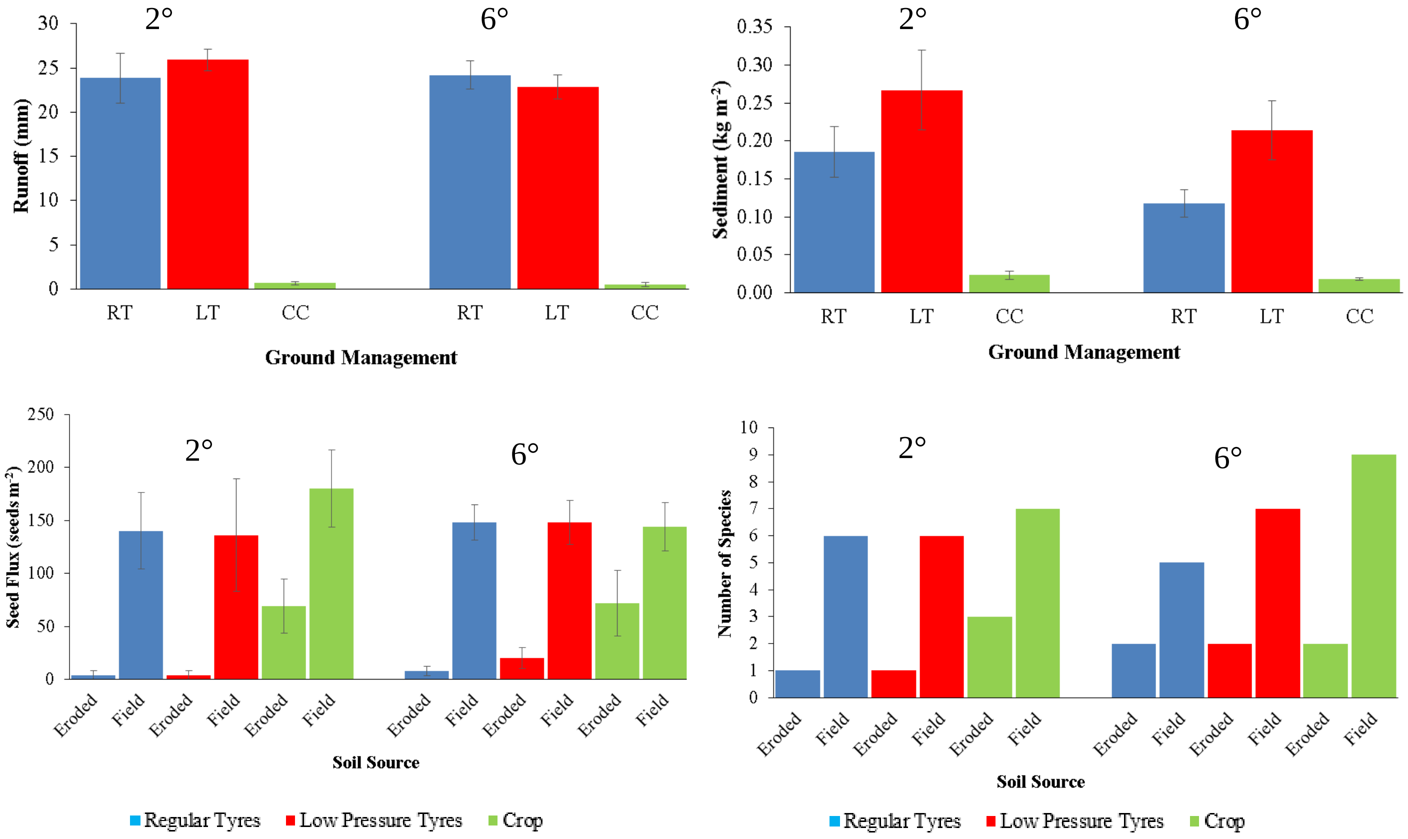


Figure 4.5 - Mean with standard errors for runoff (a) and sediment (b) for rainfall simulations for each ground management grouped by slope angle. Seed fluxes (c) and number of species (d) are shown from eroded samples and field soil after simulations for each ground management grouped by slope angle Seed numbers are species absolute values. RT = Regular Tyre, LT = Low Pressure Tyre and CC = Crop Covered.

The Shannon-Wiener index allowed further analysis of the community composition of the eroded soil samples and field soil samples (Table 4.1) with a species list for each category (Table 4.2). Field soil samples from vegetated areas contained ten individual species, whilst soil under regular tyres and low pressure tyres contained seven and six individual species respectively. Comparison to the seedbank sampled in Chapter 2 found the number of species was lower for crop covered (8 species) and regular tyre (6 species) simulator plots but the same for low pressure tyre plots (6 species). This shows the seedbank composition increasing between the seedbank sampling and rainfall simulations.

Comparing the field soil species to the species from the eroded soil samples, vegetated plots lost three species compared to regular and low pressure tyres which both lost two species. The evenness of the eroded community, whilst having high values for the both tyres, was a misleading figure since there was only one seed per species. However, the field soil samples showed a greater distinction between ground managements. The evenness order was the low pressure tyres (average = 0.82), vegetated (average = 0.75) and regular tyres (average = 0.69). The difference between the regular tyres and the other two ground managements was due to the dominance of *Poa annua* (>20 seeds) in the seedbank coupled with low species number resulting in the lowest diversity values (average = 1.15). Diversity values for low pressure tyre (average = 1.52) and vegetated (average = 1.54) plot residual samples were affected by the same dominance of *Poa annua*, but they contained more species resulting in a greater diversity value than regular tyres. Diversity values for eroded samples in both tyre ground managements differed because the abundance of seeds in the regular tyres was half of the low pressure tyres, but contained a great number of species. Eroded soil samples from vegetated areas had a slightly higher diversity value due to the dominance of *Poa annua* of the three species.

Comparing the residual community plot to the *in situ* seedbank community shows that there is only a significant difference in the community diversity (p = 0.04) whilst seed abundance, number of species and community evenness do not differ (p = 0.49, 0.15 and 0.26 respectively). This difference in diversity shows that seedbank diversity was higher in the plots than the field seedbank showing changes over time since the field seedbank was sampled in January.

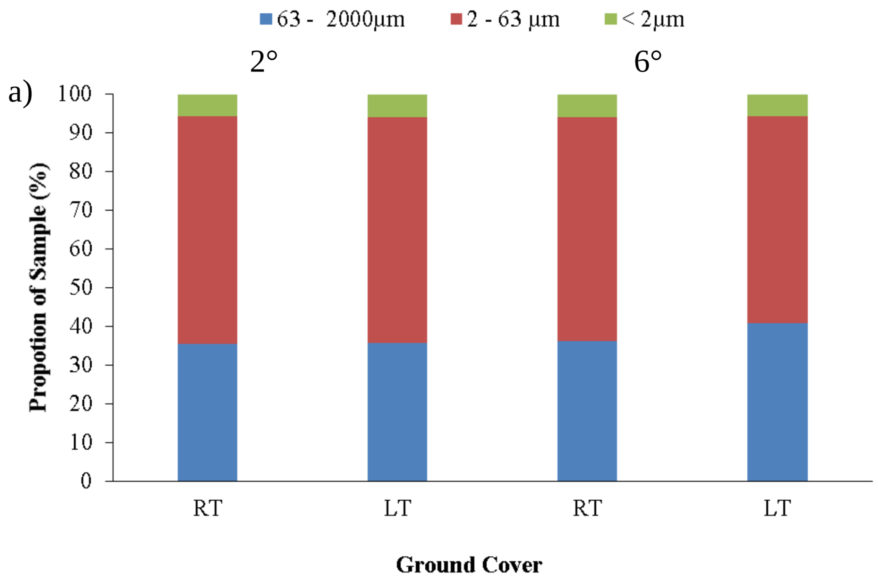
Table 4.1- Shannon-Wiener index values based on number of species to obtain evenness (*E*) and diversity (*H*). Values range from 0 (dominated) to 1 (even) whilst H values show community structure where high H values indicate low dominance and low H values indicate dominance by a few species. R = Regular Tyres, L = Low Pressure Tyres and C = Crop Covered

	Eroded						**Plot Remainder**						***In Situ* Seedbank based on samples collected for Chapter 2**					
	R2	**L2**	**C2**	**R6**	**L6**	**C6**	**R2**	**L2**	**C2**	**R6**	**L6**	**C6**	**R2**	**L2**	**C2**	**R6**	**L6**	**C6**
Number of Seeds	1	1	16	2	5	18	35	34	45	37	37	36	45	21	18	39	39	41
Number of Species	1	1	3	2	2	2	6	6	7	5	7	9	6	4	6	4	6	7
Evenness (*E*)	-	-	0.64	0	0.97	0.92	0.59	0.81	0.77	0.78	0.82	0.73	0.47	0.64	0.82	0.75	0.7	0.69
Diversity (*H*)	0	0	0.7	0	0.67	0.64	1.05	1.45	1.49	1.25	1.59	1.59	0.84	0.89	1.48	1.04	1.26	1.34

Table 4.2 - Seed abundance for individual species from rainfall simulation eroded samples, the residual plot and field seedbank from Chapter 2. R = Regular Tyres, L = Low Pressure Tyres and C = Crop Covered

	Eroded						**Plot Residual**						**In Situ Seedbank based on samples collected for Chapter 2**					
	R2	**L2**	**V2**	**R6**	**L6**	**V6**	**R2**	**L2**	**V2**	**R6**	**L6**	**V6**	**R2**	**L2**	**V2**	**R6**	**L6**	**V6**
Brassica napus	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
Capsella bursa-pastoris	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cerastium fontanum	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-
Epilobium ciliatum	-	-	-	-	3	-	3	6	-	8	9	3	1	-	1	1	-	1
Fallopia convolvulus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3
Fumaria Officinalis	-	-	-	-	-	-	-	-	-	-	-	1	1	-	1	-	-	-
Matricaria recutita	-	-	-	-	-	-	-	-	-	-	-		1	1	1	-	1	1
Myosotosis arvensis	-	-	-	-	-	-	-	-	2	-	-	1	-	-	-	-	-	-
Poa annua	-	1	12	-	2	12	24	16	18	20	16	13	35	15	8	20	14	18
Rumex obtusifolius	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Senecio vulgaris	-	-	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-	-
Stellaria media	-	-	-	-	-	-	1	-	-	-	1	1	-	-	-	-	-	-
Veronica arvensis	-	-	-	1	-	-	5	6	10	4	4	7	4	2	3	4	2	2
Veronica hederifolia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
Veronica persica	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
Viola arvensis	1	-	3	1	-	6	1	2	11	4	3	7	3	3	4	14	18	15
Total	1	1	16	2	5	18	35	34	45	37	37	36	45	21	18	39	39	41

Particle size analysis of the eroded sediment (Figure 4.6, Table 4.3) showed that there was no significant difference between both ground cover or slope for the water dispersed mineral fraction (WDMF) ($p = 0.99$ and $p = 1$ respectively) and chemically dispersed mineral fraction (CDMF) sample ($p = 1$ and $p = 0.983$ respectively). The change in 63 - 2000 µm size particles decreased by 24 – 30 %, 2 - 63 µm size particles increased by 11 – 16% and < 2 µm size particles increased between 13 – 14 %. This shows that the WDMF were aggregated particles bound by organic matter than were being transported. For the CDMF samples, ground cover was shown to have a significant effect on all three sizes of particles. Neither the slope angle nor the combined effect of ground cover and slope angle showed any differences. Furthermore along with runoff, sediment, seed flux and species the difference between the two tramline managements and the crop covered plots was significantly noticeable (63 - 2000 µm, $p = 0.006$; 2 - 63 µm, $p = 0.011$; < 2 µm $p = 0.001$). Crop covered plots had less 63 - 2000 µm than tramlines, indicating the tramlines contained larger particles which were probably a result of greater amounts of runoff carrying more sediment. However, the result was unlikely to have been due to a greater runoff velocity because previous results from the slope showed no effects on runoff. Therefore, these results might indicate rain splash erosion was driven by the movement of particles under the simulation.



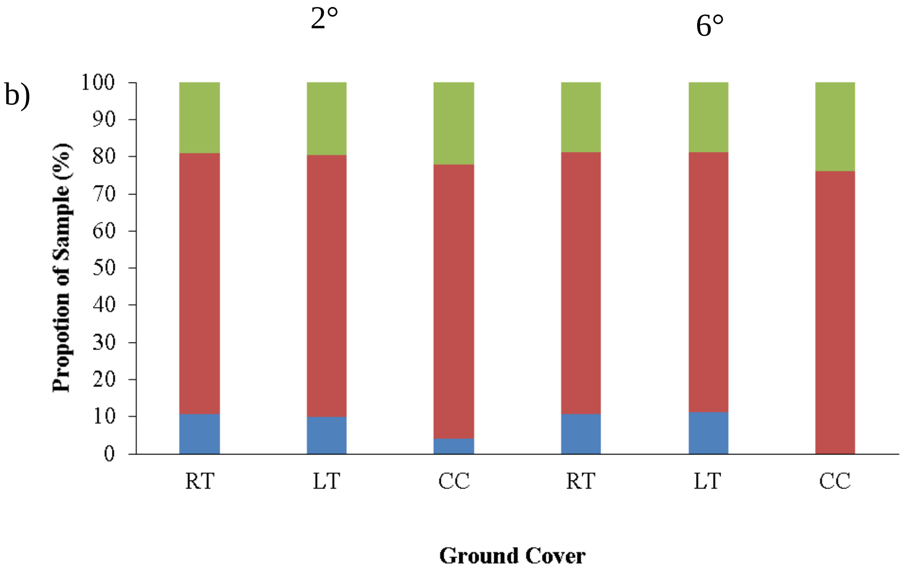


Figure 4.6 – Particle size distributions from WDMF (a) and CDMF (b) eroded samples for each ground management grouped by slope angle. RT = Regular Tyre, LT = Low Pressure Tyre and CC = Crop Covered. Proportions of 63 – 2000 µm to be higher than in CDMF indicating aggregates bound by organic matter were present in the eroded samples. No CC samples were processed for WDMF due to individual samples containing insufficient sediment for analysis by the laser granulometer.

Table 4.3 - *p* values for WDMF and CDMF eroded samples for 63 - 2000 µm, 2 - 63 µm and <2µm.

Variables	**63 - 2000 µm (WDMF)**	**2 - 63 µm (WDMF)**	**< 2µm (WDMF)**	**63 – 2000 µm (CDMF)**	**2 - 63 µm (CDMF)**	**< 2µm (CDMF)**
Ground Cover	0.368	0.326	0.811	0.006	0.011	0.001
Slope	0.256	0.206	0.877	0.743	0.693	0.912
Both	0.418	0.426	0.520	0.639	0.758	0.838

4.3.1.2 Individual Events

Exclusion of the vegetated ground management comparisons between tyre types, allowed the comparison of slope angle and event duration for tramlines (Figure 4.7). Tyre type only significantly affected sediment load (p=0.046). Low pressure tyres doubled loss of seed compared to regular tyres, although these results were not significant (p =0.344), however, there was no difference in the number of seed species. Slope angle did not have a significant effect on runoff (p = 0.384), sediment (p = 0.105), seed flux (p = 0.121) or number of seed species. However, 6° slopes did have almost four times as many seeds (three different species types) compared to 2° slopes which had fewer seeds (two different species types). Comparisons between event duration showed six minute events produced significantly greater runoff (p<0.001), sediment load (p=0.004), seed flux (p = 0.034) and seed species (p = 0.034) compared to three minute events. However, half of the plots had no seeds transported (three of the three minute events and one six minute event), which could affect the significance of the seed findings.

The 32 simulations resulted in the identification of nine seeds from four different seed species. These seeds consisted of four *Epilobium ciliatum*, three *Poa annua*, one *Viola arvensis* and one *Veronica arvensis*. Noticeably, the greatest number of seeds and species occurred in plots which had 6° slope, low pressure tyres and six minute events. However, it was impossible to perform statistical analysis because of the low number of seeds collected in the trials.

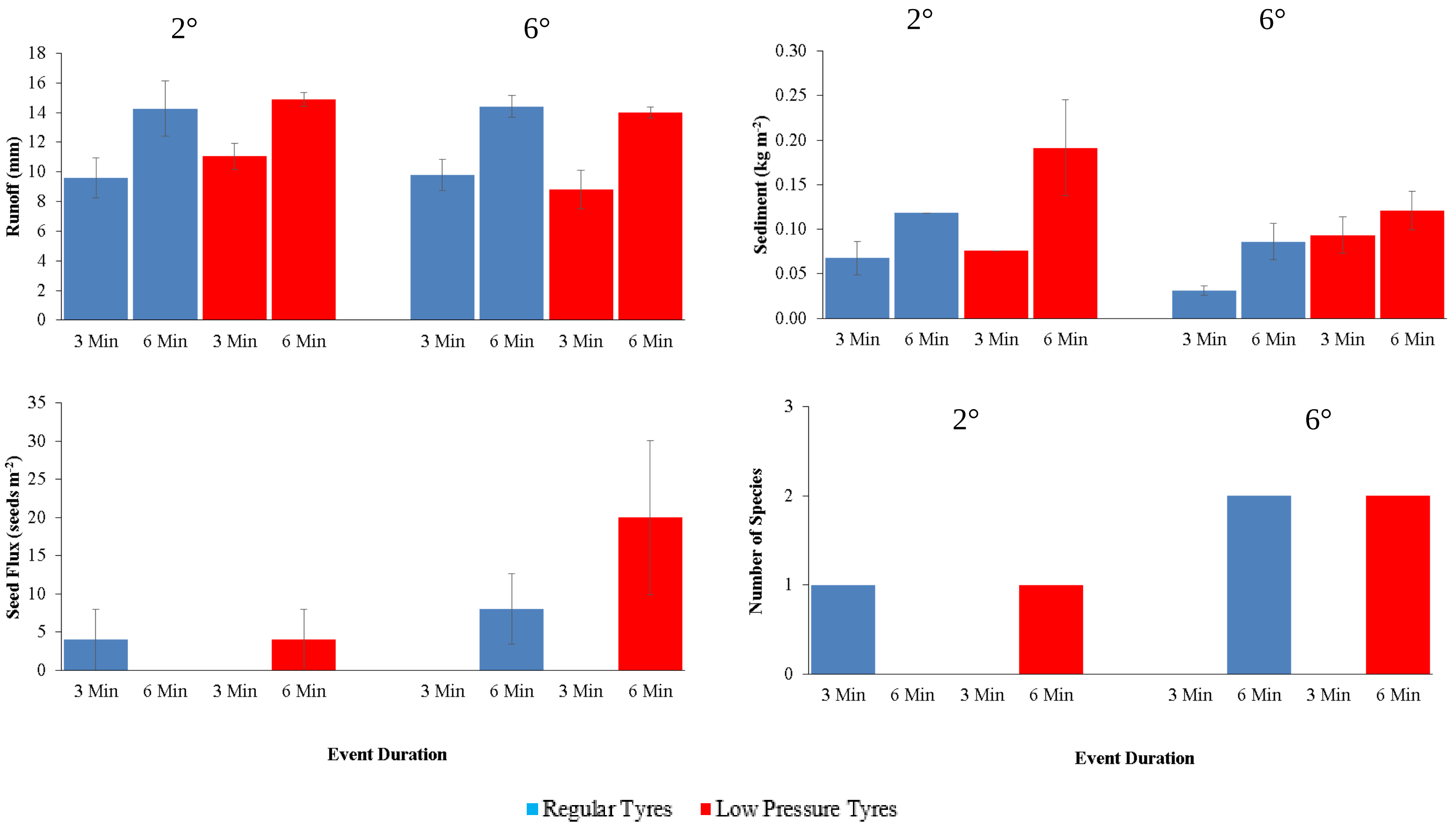


Figure 4.7 - Mean with standard errors for runoff (a) and sediment (b) for rainfall simulations for event durations for each ground management grouped by slope angle. Seed fluxes (c) and number of species (d) are shown from eroded samples for event durations for each ground management grouped by slope angle. Seed species numbers are absolute values.

Figure 4.8 shows the particle size analysis for both tramlines to draw comparisons between tramline type, slope angle and event duration. The key difference between the WDMF and CDMF particle size was the change from 30 – 40% particles between 63 and 2000 µm in the WDMF to approximately 10% over all events. As aggregates bonded by organic matter were destroyed, the proportion of 2 – 63 µm and <2 µm both increased by 10 % individually. Overall, the change in 63 - 2000 µm size particles was a decrease of 19 – 37 %, 2 - 63 µm size particles showed an increase of 7 – 16% and < 2 µm size particles depicted an increase of between 12 – 15 %. These changes show that substantial amounts of < 2 µm were bound within aggregates. This is important as seeds could have been transported within the aggregate rather than suspended within the eroded material.

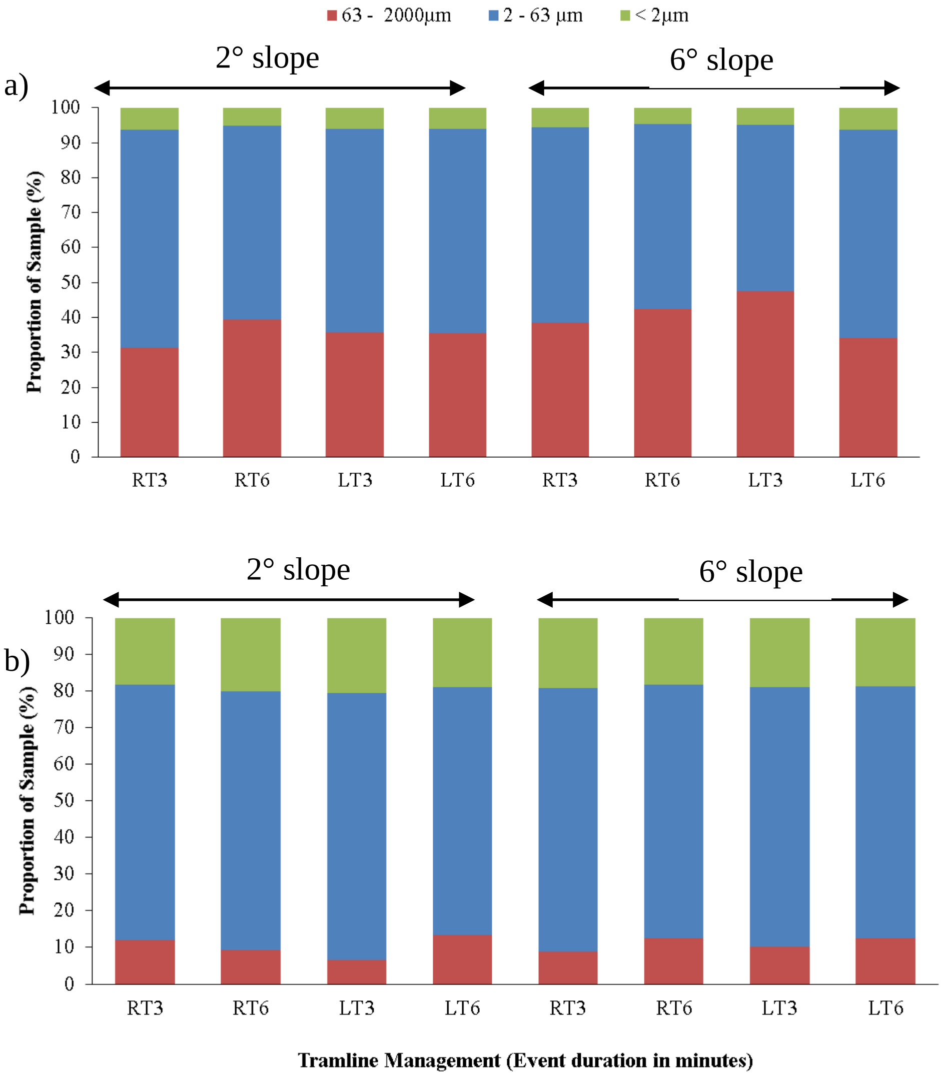


Figure 4.8 - Particle size distributions from WDMF (a) and CDMF (b) eroded samples for each tramline type with event duration grouped by slope angle. No crop covered samples were processed for WMDF due insufficient sediment in the individual samples.

Table 4.4 showed that there was no significant differences for any fraction size as a result of tramline type, slope angle or event duration. However, analysis of the combined effect of tramline management and event duration showed a difference for all WDMF sizes (63 - 2000 µm p = 0.024, 2 – 63 µm p = 0.028 and <2 µm p = 0.033). Samples from six minute regular tyres and three minute low pressure tyres had more 63 - 2000 µm particles compared to the three minute regular tyres and six minute low pressure tyres. Conversely, samples from three minute regular tyres and six minute low pressure tyres had more 2 – 63 µm and <2 µm particles compared to six minute regular tyres and three minute low pressure tyres.

Table 4.4 - *p* values for WDMF and CDMF eroded samples for 63 - 2000 µm, 2 - 63 µm and <2µm for ground cover, slope, event duration and the combined effect.

Variables	**63 - 2000 µm (WDMF)**	**2 - 63 µm (WDMF)**	**< 2µm (WDMF)**	**63 – 2000 µm (CDMF)**	**2 - 63 µm (CDMF)**	**< 2µm (CDMF)**
Ground Cover	0.914	0.795	0.424	0.982	0.911	0.805
Slope	0.067	0.063	0.226	0.852	0.991	0.606
Duration	0.903	0.831	0.682	0.469	0.329	0.835
All	0.391	0.417	0.374	0.424	0.428	0.456

4.3.2 Spiked Plots

Plots spiked with *Raphanus sativus* were affected by the duration of the rainfall simulation (Figure 4.9). Three minute simulations produced a mean of 4 seeds (64 seeds m^{-2}) compared to 1 seed during the six minute simulations which produced a significant difference (p = 0.04) between the two. The loss of 7% of the spiked seeds in a single three minute event is important because the cumulative effect of similar events over a single year might be have a significant impact on the seedbank. Other significant results observed were the 63 - 2000 µm (p = 0.042) and 2 – 63 µm (p = 0.023) sized water stable aggregates. The mean mass of 63 - 2000 µm found in three minutes events (7.4%) was higher compared to the six minute events (2%). The opposite was true for 2 – 63 µm aggregates where the higher amount was produced in six minute (89.3%) events compared to three minute events (84.2%).

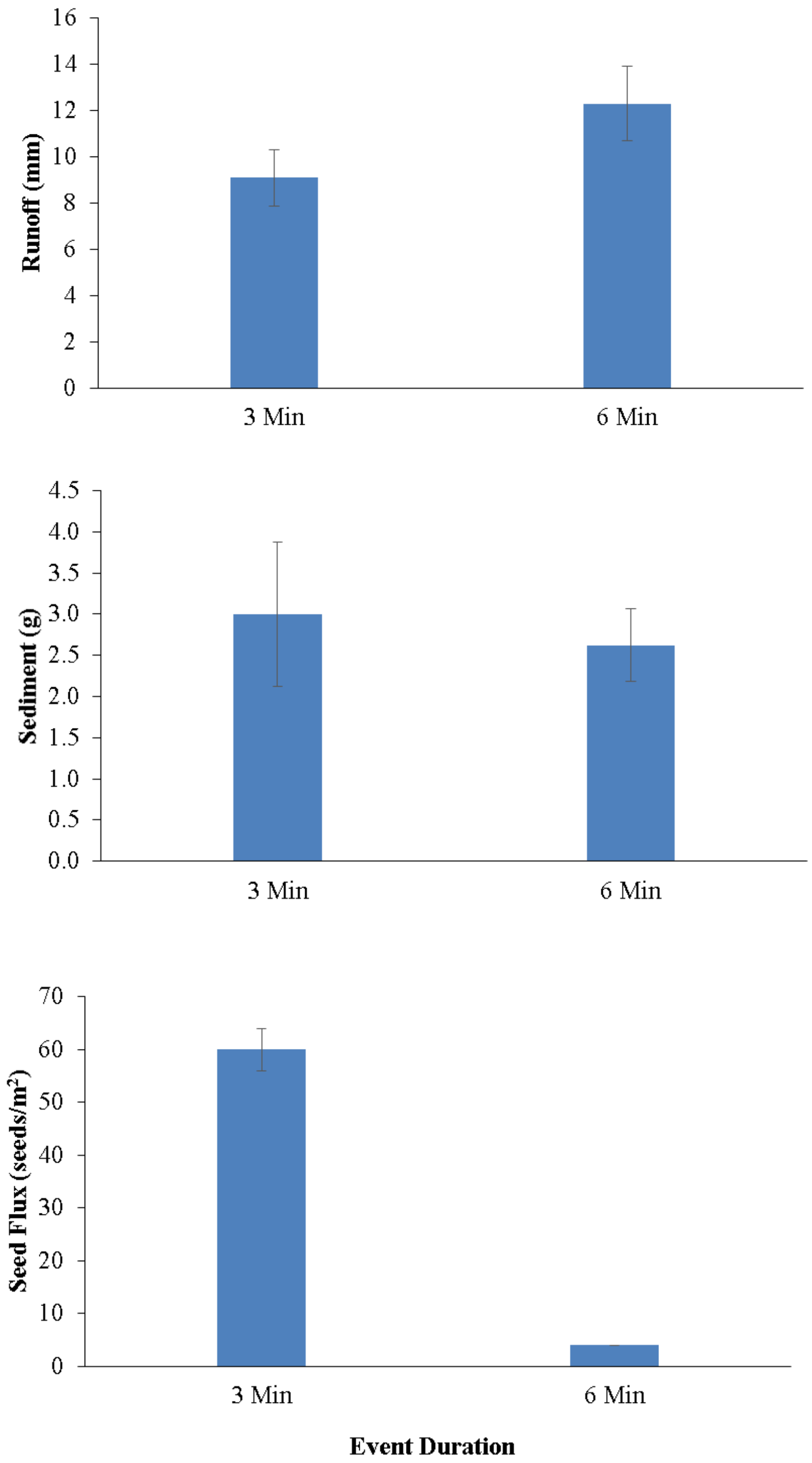


Figure 4.9 - Mean with standard errors (±1SE) for runoff (a) and sediment (b) and seed fluxes (c) for three and six minute event durations (four event replicates) for spiked plots. Only *Raphanus sativus* were used hence no species data are presented.

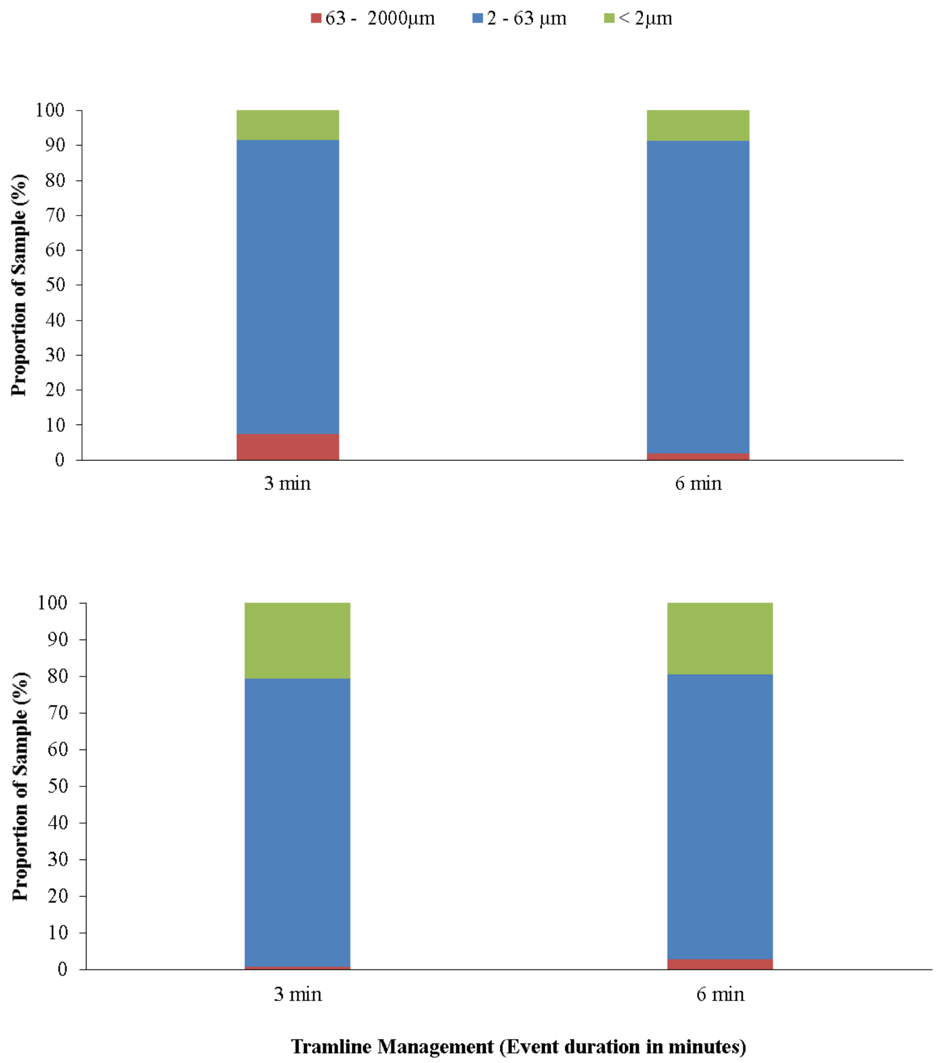


Figure 4.10 - Particle size distributions from WDMF (a) and CDMF (b) eroded samples for each event duration for spiked plots in November.

4.3.3 *Non Spiked vs. Spiked Plots*

Direct comparison of seed data was not appropriate given the spiked plots are a homogenous and exaggerated representation of the natural community. However, eroded sediment was comparable on the 6° slopes on using regular tyres. Table 4.5 and Table 4.6 shows the results of significance testing between event durations (grouped by time of year) and the time of year (grouped by event durations). The only significant result was runoff (p=0.005) compared to simulations times. Importantly, seed flux did not differ significantly despite having shown five times more seed loss in three minutes than six minutes, shown by five of the eight samples having no seeds. Of the three samples with seeds, two were from non-spiked plots and one from spiked plots although with 1 seed in each sample any interpretation would be speculative but possibly further work would show difference between spiked and non-spiked plots. On the other hand, WDMF particle of 2 - 63 µm and < 2 µm size; and CDMF 2 - 63 µm size particles were significantly different between months of the year ($p<0.001$ for both WDMF and $p = 0.025$ for CDMF). This shows that conditions changed between May and November in soil texture likely due to the length of time the tramline had been present for in the field. Runoff and sediment were not significantly different between months.

Table 4.5 - Means with standard error (±1 SE) for runoff, sediment, particle size and seed flux for spiked and non-spiked events grouped by duration. Runoff in the six minute events was significantly greater than in three minute events. For particle size results, WDMF and CDMF mean effective and ultimate method respectively.

Event Duration	**Runoff (mm)**		**Sediment (g)**		**% of 63 - 2000 µm (WDMF)**		**% of 2 - 63 µm (WDMF)**		**% of < 2µm (WDMF)**		**% of 63 – 2000 µm (CDMF)**		**% of 2 - 63 µm (CDMF)**		**% of < 2µm (CDMF)**		**Seed Flux (seeds m^{-2})**
	Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Total**
3 minutes	9.45	0.76	2.48	0.48	8.89	1.46	61.26	8.75	32.18	9.02	4.83	2.29	75.35	1.71	19.83	0.72	240
6 minutes	13.35	0.91	4.00	0.82	8.24	3.98	65.8	9.06	30.84	8.56	7.69	4.39	73.53	3.15	25.35	6.84	48
p	0.005		0.129		0.947		0.91		0.717		0.572		0.618		0.435		0.137

Table 4.6 - Means with standard error (±1 SE) for runoff, sediment and particle size for spiked and non-spiked events grouped by month. Effective sand, silt and clay, and ultimate silt differed between May and November. For particle size results, WDMF and CDMF mean effective and ultimate method respectively.

Month	**Runoff (mm)**		**Sediment (g)**		**% of 63 - 2000 µm (WDMF)**		**% of 2 - 63 µm (WDMF)**		**% of < 2µm (WDMF)**		**% of 63 – 2000 µm (CDMF)**		**% of 2 - 63 µm (CDMF)**		**% of < 2µm (CDMF)**	
	Mean	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**	**Mean**	**SE**
May	12.10	1.05	3.67	0.89	12.42	3.42	40.43	2.36	54.51	2.17	10.65	4.38	70.68	2.98	25.23	6.88
November	10.7	1.11	2.81	0.46	4.7	1.42	86.7	1.24	8.6	0.35	1.86	0.59	78.20	0.37	19.95	0.41
p	0.376		0.406		0.056		<0.001		<0.001		0.067		0.025		0.456	

4.4 Discussion

4.4.1 Non – Spiked Plots

Assessment of the rainfall simulations and parameters to determine the amount of erosion and seed mobility under rainfall simulations demonstrated that vegetated ground management decreased the movement of water and sediment but led to increased seed loss. Protecting the soil surface with either vegetation (Hill, 1973; Slattery and Burt, 1997; Morgan, 2005), mulches or crop stubble (Shannon and Weaver, 1949; Wild, 1993) decreases erosion rates. The experiments in this chapter demonstrated crop-covered ground produced lower runoff and sediment yield compared with the regular and low pressure tyre ground management.

Despite the low runoff and sediment yields, the crop-covered sites still produced the greatest seed losses when subjected to designed storms. The differences in seed numbers could be explained by ground management because the seedbank structure depends upon the presence of soil canopy, which is only present in vegetated plots within the field (Ryan *et al.*, 2010). Conversely, Chapter 2 showed seedbank density was lower (242 seeds m^{-2}) in the 2011/12 season than in 2010/11 (982 seeds m^{-2}) meaning less available seed for transport. Furthermore, the tramlines had been established seven months prior to rainfall simulations were conducted, which meant that the seedbank would have been depleted by erosion during the winter period with some recovery during the spring (Lewis *et al*. 2013). The different responses between tramlines and crop-covered ground are important when considering a set of tramlines consists of two wheelings and a cropped inter wheeling area (Figure 4.11). The results of rainfall simulations support the hypothesis that seed transport is greatest from crop covered surfaces and not individual tramlines. However, the transport from crop covered surfaces might be important in delivering seeds across hill slopes into tramlines, which subsequently transport the seeds downslope. Further work is required to determine if this process is occurring.

Figure 4.11- Example of a tramline showing the two wheelings from the tractor with a crop covered area between the pair of wheelings.

Although soil texture difference may affect seedbank abundance and diversity, no differences were found between texture (particle size) and ground managements, except when factoring in the effect of the slope. Similarly, the compaction of the soil in the tramlines decreases seedbank number and diversity, through the restriction of pore space leading to less infiltration and increased runoff transporting soil nutrients (Brombacher and Eppink, 1991). However, crop cover resulted in greater seed availability compared to regular and low pressure tyre management, due to the lack of tillage and disturbance which would trigger germination (Conn, 2006).

Seed species in the field seedbank did not differ significantly with ground management processes. However, a community response was observed between eroded samples and *in situ* samples for the two most dominate species in low pressure tyres (*Poa annua* and *Epilobium ciliatum*) and under vegetation (*Poa annua* and *Viola arvensis*). Regular tyre plots evidenced an absence of *Poa annua* in eroded samples, despite being the most dominant seed species type. However, the other dominant species *Epilobium ciliatum, Veronica arvensis* and *Viola arvensis* were found in eroded soils. These results again point to selective entrainment and transport according to seed morphology which allowed seeds to resist transportation (Han *et al.*, 2011). Analysis of seed morphology was not feasible in this chapter because the transported seeds were too low in quantity and diversity to enable a clear result.

Evaluation of erosion data from different tyre types showed event duration was a significant factor in the erosion of soil and seeds. Runoff, sediment, seed abundance and seed species were greater after six minute events compared to three minute events. These event data were consistent with Castro *et al.* (2006) who found over time, erosion produced greater sediment yields. Simulations from plots with the steepest slope and longest events produced the greatest number and diversity of seeds. This finding could explain the low numbers of eroded seeds captured in samples because the large amounts of erosion are required to cause substantial losses to the seedbank community. Seed morphology may play a role in the resistance of seeds to erosion. The findings of this experiment conflict with those of García-Fayos and Cerdà (1997), who found lower slope angles (2°) had erosion rates 40 times lower and seed loss rates six times higher than steep (22-55°) slopes. However, the range of slopes in tramline field was 0 - 6° meaning further work is needed for steeper slopes to add to the current findings. This conflict of findings may be the result of different soil types and seed species between this experiment and García-Fayos and Cerdà (1997) results. Further work to understand the effect of soil texture and seedbank composition will be necessary to improve the understanding of erosion processes on the seedbank.

The particle size of eroded sediment within the tyre ground managements proved to be different between the ground managements and event duration times. These findings were only true for the WDMF samples. Regular tyres produced more 63 - 2000 µm sized aggregates over time, compared to low pressure tyres, but low pressure tyres produced more 2 – 63 µm and < 2 µm over time. This difference was probably due to the rill formation within the tramline causing a difference in the selective transport of 2 – 63 µm and < 2 µm in the low pressure tyres and sand in the regular tyres (Slattery and Burt, 1997). The quantity of water-stable 2 – 63 µm -sized aggregates were affected by slope, which demonstrates that slope steepness was an important component with regards to erosion of specific particle sizes (Morgan, 2005).

4.4.2 Spiked Plots

The spiked plots were designed to have a seedbank which was comparable to the field seedbank sampled in Chapter 2 thus producing a noticeable effect in the number of seeds lost from the plot in the simulated storm. Despite the limited number of conducted simulations, the number of seeds in three minute events was four times greater compared to six minute events. However, runoff was greater in six minutes than three minutes events, indicating rain splash was more important in the transport of seeds compared to runoff in short small scale events (Nakanishi, 2002; Benvenuti, 2007). Another explanation could be differences in entrainment of the spiked seeds. Up to 10% of the seeds were transported in 3 minute events whilst only 1.6% were for six minute events. This difference might have been caused by the three minute event driving seeds into the soil surface and preventing transport in the six minute event. This is possible as seeds would normally bury into the soil seedbank awaiting germination. Differences in the sand and silt aggregates conflict with the previous discussion concerning ground management affecting particle size. However, the timing of the spiked simulations led to the conflict in data because soil relaxation had allowed the soil to “recover” from the previous tramline disturbance compared to May plots.

4.4.3 Non Spiked vs. Spiked Plots

Comparison of erosion data revealed the duration and timing of simulations affected runoff and aggregate size respectively. The pattern was identical in both tyre ground managements in the non-spiked plots, which was explained in Section 4.4.1. The timing of the non-spiked and spiked plots was important in relation to grain size, due to the length of time since the soil had been disturbed. Tillage of the tramlines breaks up the compacted structure and loosens the soil (Morgan, 2005). The loose structure and lack of rill formation for the spiked plots caused the differences in runoff, sediment and particle size compared to the established structure rill formation of the non-spiked plots (Slattery and Burt, 1997; Al-Ghazal, 2002).

4.4.4 Rainfall Simulator Design

The rainfall simulator designed by Kamphorst (1987) was portable and simple but had some constraints, which may have influenced simulations. Crop height may have interfered with the precision of the simulator, as the fall height of simulated rainfall was 40 cm, leading to blockages of the sprinkler system (Fiener *et al.*, 2011; Iserloh *et al.*, 2013). The installation of the frame disturbed the soil surface especially on the rim where infiltration may be higher and thus leading to leakage (Brombacher and Eppink, 1991). One of the key design features is the rainfall simulator delivers rainfall at an exaggerated intensity of 360 mm hr^{-1} to compensate for drop not reaching terminal velocity in fall height of 40 cm. Based on rainfall events for Chapter 2, rainfall intensity at Balruddery farm in the range of 0.98 – 2.4 mm hr^{-1}, which is 0.67% the intensity of the rainfall simulator making the two rainfall type completely different. However, the kinetic energy of rainfall from the simulator (50.32 J m^{-2} mm^{-1}) is higher than kinetic energy values for England and Wales where rainfall similar to Balruddery Farm (708 mm yr^{-1}) the daily kinetic energy can be 8.92 - 25 J m^{-2} mm^{-1} (Davison *et al*. 2005; Iserloh *et al.* 2013). This would mean the findings from the rainfall simulation are 2 – 5 times greater than a daily kinetic energy for rainfall in a temperate arable field meaning the results might be over-estimating the effect of a single rainfall event. The main experimental problem was the installation of the ground frame, since achieving a sealed border was difficult on rough surfaces, due to tyre tread patterns, leading to uncontainable flows (Fiener *et al.*, 2011). A limitation of the rainfall simulator was observed during the field experiments that the soil on the plot required saturation to generate erosion (Kamphorst, 1987). However, soil saturation led to slaking and instability in the soil surface, which affected the simulation by only showing the effects on saturated ground. Furthermore, the three minutes on crop covered plot samples all had less than 50 mL of runoff indicated a different level of water input needed to achieve saturation. Therefore, it may be assumed crop covered six minute samples were similar to three minute tramline plots when saturation was achieved.

4.5 Conclusions

The work described in this chapter has sought to assess the environmental controls on seed mobility using a field rainfall simulation. The experiment was conducted in two parts where the natural seedbank (non-spiked) was eroded under different ground managements, slopes and durations plus when seeds were applied (spiked) to plots under a regular tyres on a 6° slope for three and six minute events. The first objective was to quantify the amount of erosion and seed mobility under different combinations of slope, treatments and event durations.

For non-spiked plots, the results demonstrated the natural seedbank seed numbers and diversity within the tramlines was low. However, ground treatment did have significant effects on the amount of runoff, sediment and number of seeds produced following rainfall simulations, since crop cover mitigated erosion, as well as increasing the availability of seeds. Tramlines lost under 10% of the seedbank, compared to crop covered plots which resulted in losses of between 25 and 33%. Comparison of these losses showed the tramlines lost most seed following six minute events whilst crop covered plots lost most seeds following the three minute events. Moreover, the seedbank under vegetation was the most diverse which was reflected in the field soil and eroded samples. These findings show that both initial and cumulative storm events have an element of selectivity in transporting seeds, likely by seed morphology, although the size of the dataset means further work is needed to reinforce this hypothesis. Importantly, the findings quantify seed movement at a bound plot scale for a single and cumulative storm event to give a better understanding of amount, timing and composition of seed movement (Aim 2 in Section 1.3).

Removing crop covered plots from the analysis allowed for significant comparisons to be made between duration of plot exposure and simulation variables. Longer exposure to simulated rainfall, resulted in a greater amount of runoff and sediment generation, but effective grain sizes differed with time and tyre management. For the spiked plots, three minute duration events mobilised most seeds and 63 - 2000 µm particles, but six minute duration events produced more 2 - 63 µm particles. Event duration had no effect on runoff and sediment from the spiked plots because of soil relaxation between May and November. The second objective was to determine whether there was selectivity during the erosion processes. In the non-spiked plots, there were indications of selectivity within both erosion and seedbank data. Differences in the sizes of eroded mineral fractions and seed numbers indicated selectivity. These differences were probably due to differences in rill formation, which was not measured in this experiment. In the spiked plots, selectivity was important as tillage of the field one month prior to the spiked plot simulations, resulted in loose soil structure which had not produced sufficient rill formation. It was recognised that the rainfall simulator had some limitations in plot preparation, which may have affected the collection of eroded material. Undertaking a laboratory based experiment, using species found within the field, might yield further information regarding seed mobility, particularly in association with seed morphology, which was difficult to interpret from this experiment, due to low seed numbers.

Chapter 5: Soil Erosion and Seedbank Mobility within an Arable Catchment

5.1 Introduction

Fluvial processes at the catchment scale have been extensively studied to trace water and sediment pathways as well as developing land management tools (Foster *et al.*, 1996; Russell *et al.*, 2001; Wallbrink *et al.*, 2002; Walling *et al.*, 2006; Walling and Collins, 2008a; Walling *et al.*, 2008b; Collins *et al.*, 2012). Identification and quantification of sediment supply, storage and eventual delivery gives insight into sediment dynamics (Parsons, 2012). Catchment sediment yield is quantified through empirical approaches or field based assessment. Empirical approaches are often used in global scale applications such as carbon budgeting using data such as basin area, relief, lithology, climate and anthropogenic factors (Syvitski and Milliman, 2007). Field based assessments rely on the measurement of erosion rates using direct observations (Hancock and Evans 2010); tracing techniques (Walling *et al.*, 2002b) and suspended sediment determination at the catchment outlet (Singer and Dunne, 2001). Such observations have allowed the development of catchment sediment budget frameworks (in Section 1.2). These frameworks are useful for determining the fate of sediment from a catchment but rarely do such studies incorporate any biological fluxes beyond dissolved organic carbon (Dawson *et al.*, 2008).

Hydrochory (the dispersal of seeds by water) is one of several processes important in the study of seed dispersal across the field scale and their translocation to field boundaries and drainage ditches (Benvenuti, 2007). Fluvial hill slope processes transport seeds to waterways which in turn influences downstream riparian vegetation communities inundating flood plain ecosystems (Goodson *et al.*, 2003; Gurnell *et al.*, 2006; Gurnell *et al.*, 2008). Knowing the sources, rates and composition of sediment containing seeds is a key first stage in assessing downstream consequences (Gurnell *et al.*, 2008). To date, previous research has been focused on riparian species however, the fate of weed species from arable fields remains uncertain.

The aim of this chapter was to quantify weed seed fluxes on a catchment scale over the course of a single calendar year. A series of objectives were developed to achieve the aim:

1. To establish a hydrometric monitoring station at the outlet of an arable catchment.
2. To monitor discharge, sediment and seed fluxes from the instrumented catchment.
3. To assess the relative importance of arable versus non-arable seeds entering the stream network.
4. To establish process relationships between discharge, sediment and seed flux at the catchment scale.

5.2 Methodology

5.2.1 Specific Site Details

Balruddery Farm was chosen as the arable catchment area for this experiment. General site conditions are described in Section 1.4. Balruddery catchment covered an area of 1.23 km^2 (Figure 5.1). Drainage begins upstream of the north western lochan, which appears to behave as a seepage lane with no well-defined surface flow or outflow drainage (a) to the south, an unmapped lake (b) was found to be between underground drainage from the western edge of the catchment towards the western edge of Balruddery Farm. Additionally, open surface drains along the side of the road (c) drains into the farm through underground drains. Also, the roads provided a transport conduit for runoff in the farm (d). Inside the farm, there was evidence of long term soil erosion as there was a step between the upper and lower fields (e). To the east of the farm house, there was evidence of a track providing conduits for runoff into the field (f) and into the open stream (g). The consequences of runoff into the field resulted in erosion down the field edge, which was also used for farm machinery access (h). Emerging at a culvert outside the farm (56°28'40.61"N, 3° 6'53.88"W) water entered a stilling pond (1.7 m x 5.2 m) above an artificial weir (Figure 5.2). The environment around the stilling pond consisted of deciduous woodland.

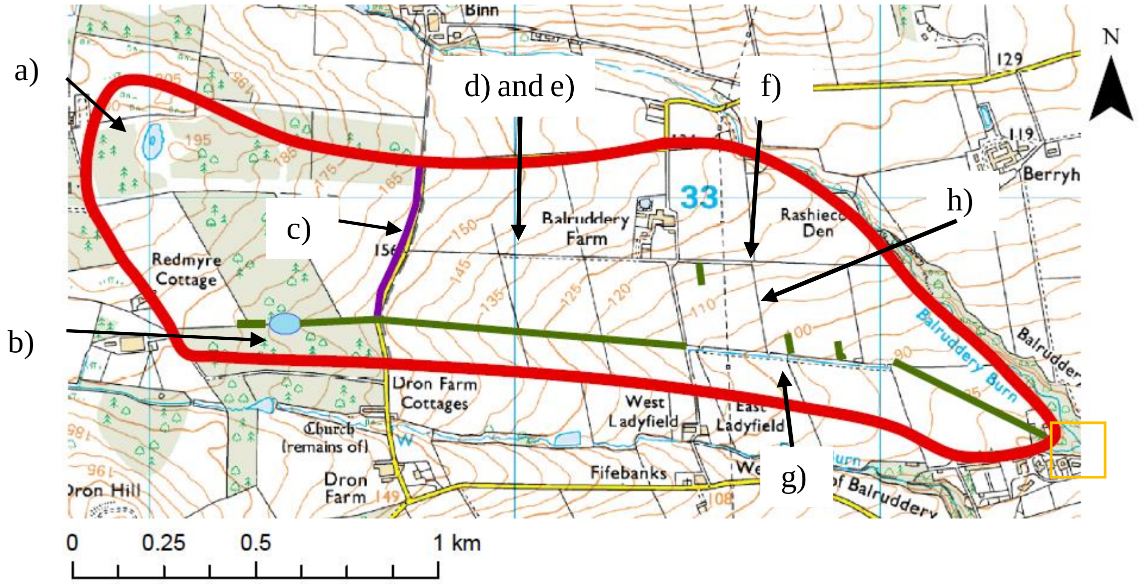


Figure 5.1 - Map of Balruddery catchment (red boarder) with known drainage network (green lines) joining Balruddery Burn on the eastern edge of the farm. Road side drainage ditches (purple line) and unmapped lake (blue oval) that contributed drainage network. The monitoring station is located in the south east of the catchment (orange box).

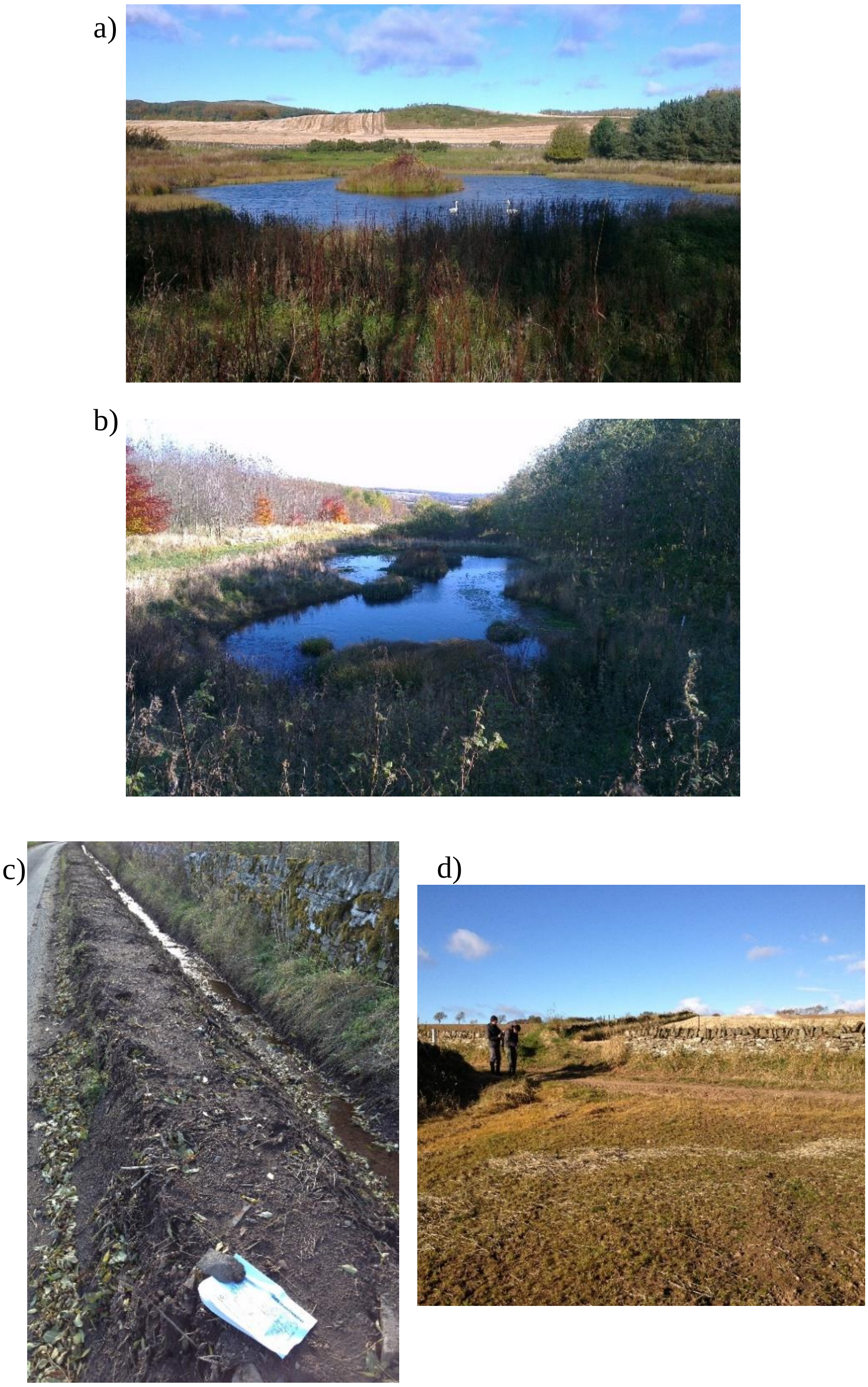


Figure 5.1 cont. – a) Natural lochan located in the north western corner of the catchment, the hill in the background illustrated the catchment watershed. b) Unmapped wild fowl pond view eastwards towards Balruddery Farm. c) Roadside ditches recently dredged and generating a substantial supply of readily mobilised sediment. d) Sediment splay resulting from concentrated runoff spilling from farm track.

Figure 5.1 cont. – e) Long term landscape change shown by approximately 1 m height difference between fields caused by a topographic step remitting from upslope deposition behind the wall. f) Farm tracks provided connectivity between fields for fluvial processes with gully formation in the field below (during an event, (d) is the result of these events). g) Gully formation along farm track with finer material removed and entering open channel to the right. h) Combination of farm access and water flow seen in f) resulted in depositional area at bottom of slope with excess water entering open channel.

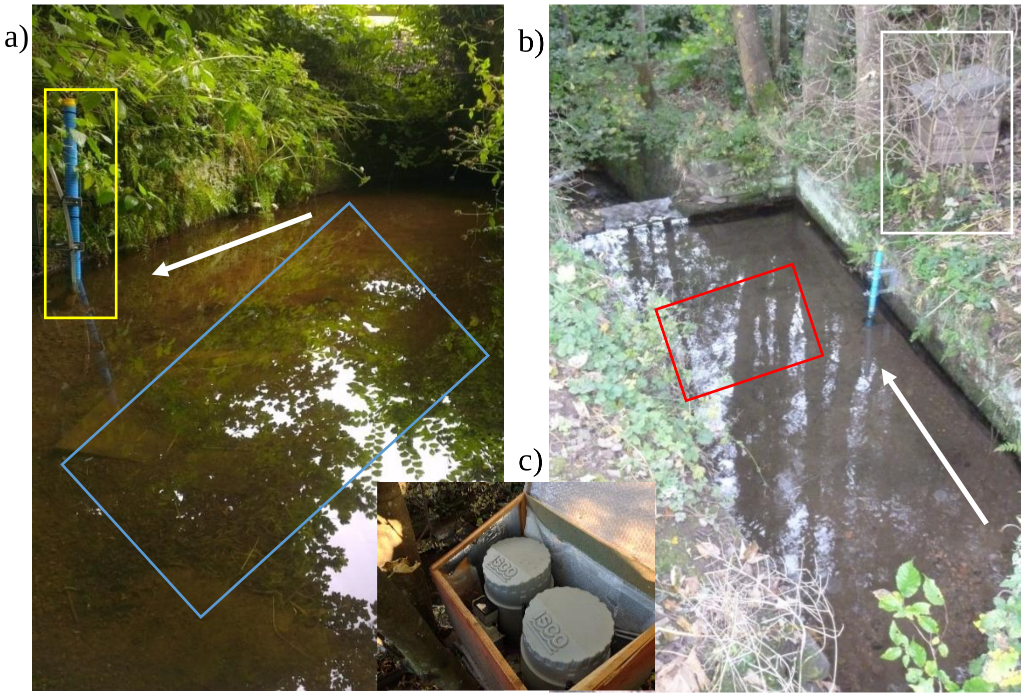


Figure 5.2 - a) In the culvert looking towards the farm outflow (arrow indicates main flow) with stilling pond (blue), pressure transducer, turbidity meter (yellow). b) Above the culvert showing the weir in the background, bed sampling area (red) with monitoring station on bank (white). (c) Inside monitoring station containing two automatic water samplers with data logger for pressure transducer and turbidity meter.

5.2.2 Study Objectives and Instruments

A long term monitoring protocol was established to collect water, sediment and seed data. The monitoring began on 1st January 2012 and ended 1st January 2013. The following sections explain the sampling and monitoring protocol for each water, sediment and seed dataset. Protocol validation was done by support staff at the University of Dundee and The James Hutton Institute who were able to successfully collect and process samples.

5.2.2.1 Water

Prior to monitoring, a pressure transducer was installed on the south eastern side of the stilling pond (Figure 5.2a). The pressure transducer (Keller Series 26W) was attached to a data logger (Newlog V2 – Universal Data Logging Module manufactured by Technolog) to provide constant monitoring of the water depth within the stilling pond. Data was recorded in 30 minute time steps to provide sufficient resolution of data across the year. The water depth (measured in cm from a stage board) was measured weekly, at a fixed time, from the top of the culvert opening. Figure 5.3 illustrates the correspondence of the pressure transducer between observed water depth pressure transducer responses (%).

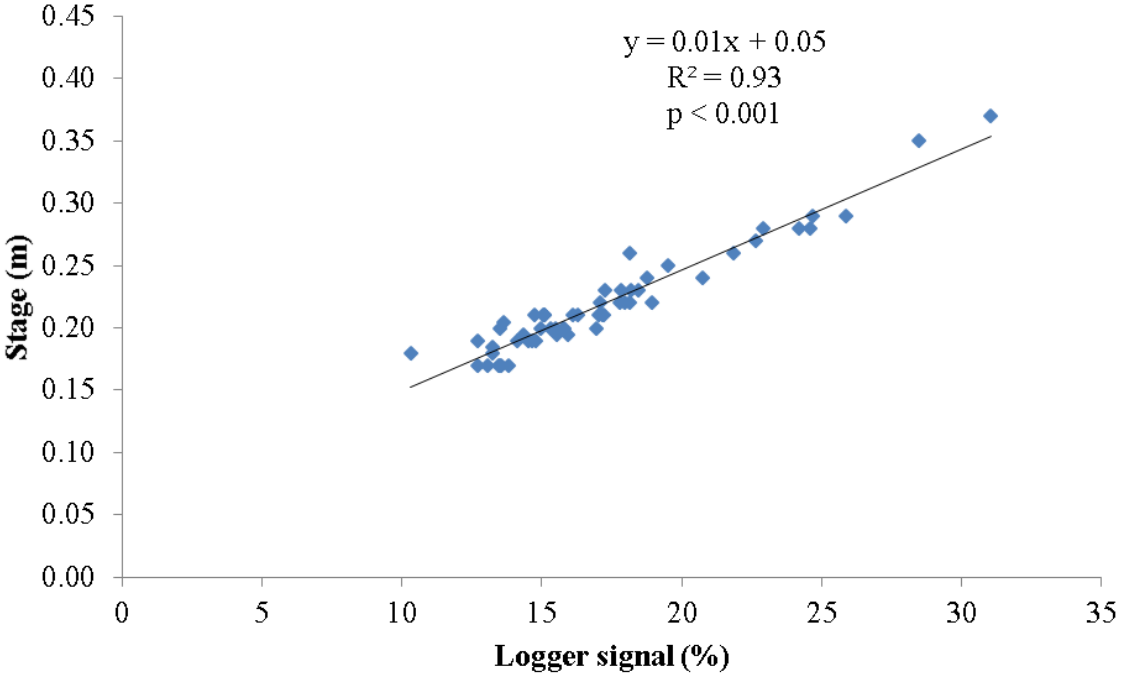


Figure 5.3 – Relationship between the pressure transducer responses to known water depths in 2012. (r^2=0.93, p<0.001).

Logger data was downloaded every week in 2012. Discharge was calculated using a stage-discharge obtained from a high flow calibration programme. During events discharge was measured using a handheld Acoustic Doppler Velocimeter (ADV manufactured by Sontek, Series 26W). The ADV is based on the Doppler effect and gave a highly accurate (±0.25 cm s^{-1}) velocity measurement (Sontek, 2012). Sampling was done over a cross-section of the channel in order to measure multiple velocities for discharge calculations. Discharge was determined from repeated measurements across a range of stage measurements to generate a calibration curve (Figure 5.4). This calibration enabled the determination of discharge from the pressure transducer data logger record.

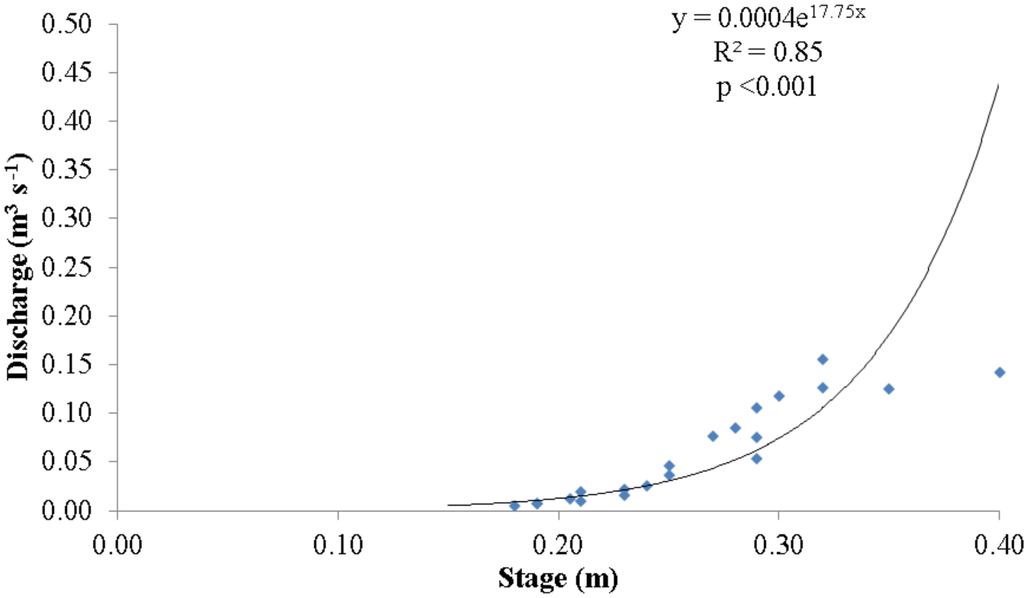


Figure 5.4 - Stage/discharge relationship derived from cross sectional gauging using the ADV (r^2= 0.86, p<0.001)

5.2.2.2 Sediment

Monitoring suspended solids concentration (SSC) was achieved using a turbidity meter (Partech IR100 Infrared Light Attenuation sensor). The turbidity meter was installed in the same position as the pressure transducer. Calibrating the turbidity meter required the use of an ISCO 6712 automatic water sampler. Figure 5.5 illustrates the calibration curve for using the turbidity meter and ISCO water samples. The automatic water sampler took a 1 L sample every 30 minutes when the water depth exceeded 20 cm. Sampling was achieved using a sensor that would trigger the peristaltic pump when the sensor was in contact with water. The sampler had a capacity of 24 x 1 L bottles allowing continuous sampling over 12 hours. This configuration allowed the recording of events over different durations. The sampler was checked weekly and samples were returned to the laboratory and stored in a refrigerator (4°C) to prevent algae growth prior to processing.

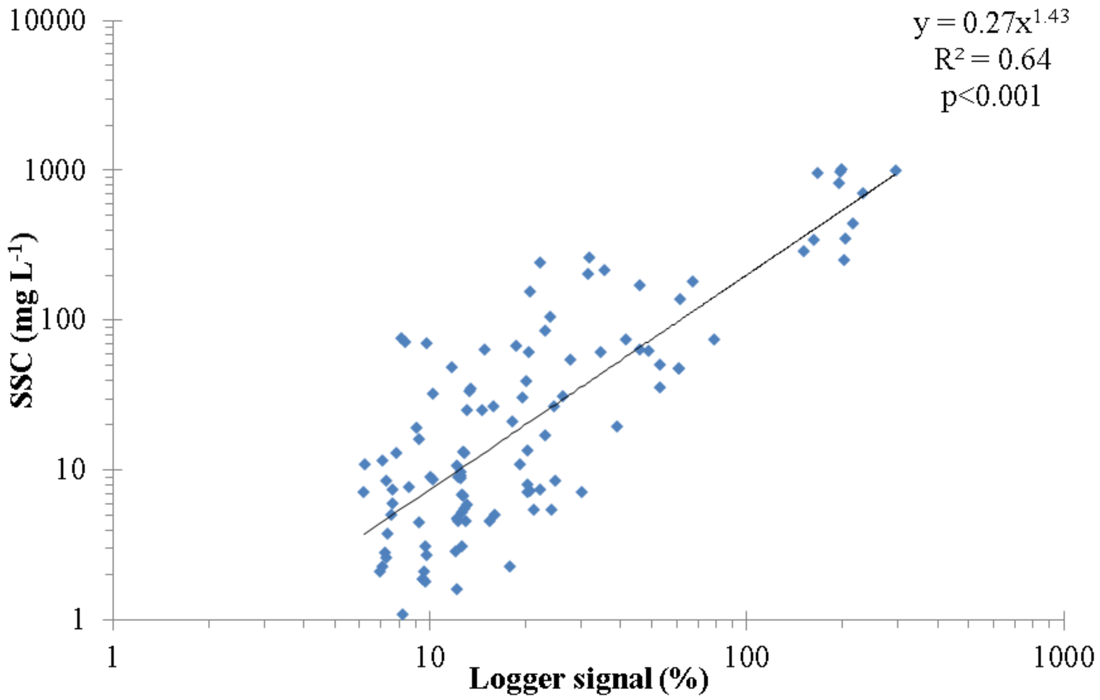


Figure 5.5 - Data logger measurements to SSC calibration curve derived from water samples taken during events in 2012 (r^2= 0.64, p<0.001)

During processing, each bottle was left to stand for 24 hours to allow the sediment to settle. However, particles less than 2 µm in size were unlikely to settle out. Sediment concentrations were determined using a vacuum pump to remove water, leaving solids on pre-weighed filter papers (Fisher brand 47mm diameter glass fibre filtration paper MF300). Prior to filtration, excess water was poured from the bottle to improve the efficiency of vacuum pump. Once a sample had been through the vacuum pump, the filter paper was placed in a drying oven at 40°C overnight. The dried sediment weight (mg/L) was used to calibrate the data logger. Sediment load was calculated by multiplying SSC by discharge. Deposition of sediment was recorded in a settling tray (38.5 cm x 33 cm x 11.5 cm) that was attached to the stream bed. The amount of sediment in the tray was emptied weekly and returned to the laboratory where the dry mass was weighed.

5.2.2.3 Seed

In contrast to water and sediment data, seed data were generated from a single weekly bed sample which was taken from a fixed 0.12 m^2 area (outlined in Figure 5.2) during the weekly site maintenance, logger download and bottle collection. Each sample was approximately 1 kg in mass following removal of organic debris (e.g. leaves, twigs). The samples were stored in sealable plastic bags and placed in a fridge until required.

Determining seed content of a bed sample required using a germination process. Prior to germination of a sample, 10 g of sediment was dried overnight at 40°C to determine the dry sediment mass for expressing the number of seeds per kilogram of sediment. The remainder of the sample was placed in a glasshouse for germination in the same conditions as used to germinate field samples in Section 2.2.2.2 to identify seeds. Following germination the seeds were identified using the taxonomic conventions of Ritchie and Ritchie (2003).

5.2.3 Accounting for missing data (HEC-HMS)

Achieving the aims and objectives required a complete time series of both discharge and SSC. However, missing data in a time series is not an uncommon problem in river monitoring (Shaw, 2011). Therefore, the use of a hydrological model was appropriate to estimate the amount of discharge because of rainfall in the catchment. Using the results of the model would allow relationships between discharge and SSC to be used to fill in missing SSC data. The HEC-HMS (Hydrolic engineering Center – Hydrologic Modeling System) model was developed by the US army Corps of Engineers for use in understanding hydrological situations (Feldman, 2000). The model uses an analytical model to calculate runoff based rainfall data under a given set of parameters (Halwatura and Najim, 2013).

Parameterisation of the HEC-HMS model required inputting data on vegetation canopies, surface storage, losses, unit transformations, base flow and catchment size. For vegetation canopy and surface storage, an initial storage was set at 5% with a maximum storage of 20 mm. Vegetation canopy represents the amount of rainfall interception for the catchment whilst surface storage represents the amount stored in surface depressions prior to runoff generation. Vegetation canopy was based on information provided by Lewis *et al.* (2013) whilst surface storage was estimated from the fluvial audit (Section 5.2.1). An initial loss of 10 mm with a constant rate of 30 mm hr^{-1} were used based on hydraulic conductivity by Grabowski (2010). Impervious surface covered 2% of the catchment and added to the loss component of the model. Data transformation used the soil conservation service unit hydrograph with a lag time of 30 minutes. This represented the rainfall to discharge conversion in the model. Finally, the baseflow component consisted of two ground water sub components (GW1 and GW2). GW1 had an infiltration rate of 0.004 m^3 s^{-1} for 24 hours after rainfall. This was based on the base flow observed at the monitoring station. GW2 had an infiltration rate of 0.0096 m^3 s^{-1} for 72 hours with two reservoirs. This represented the deeper movement of ground water from GW1 through to bedrock.

To account for missing SSC data, a SSC-discharge relationship was established using the top 5% of the observed discharge and SSC data (Shaw, 2010). Using the 5% of data that was above baseflow conditions allowed for a relationship to be identified between discharge and SSC but still contained substantial variability (Figure 5.6).

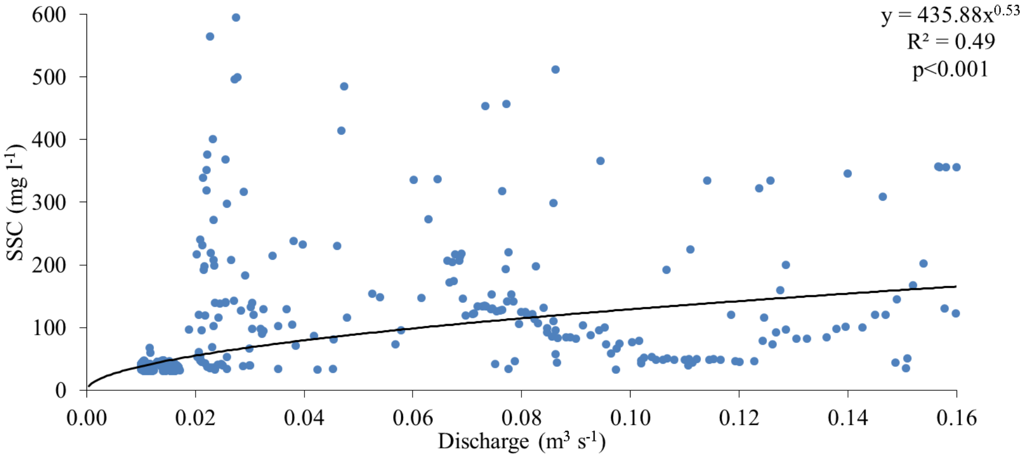


Figure 5.6- Sediment rating curve derived from top 5% discharge and SSC data.

5.2.4 *Statistical Analysis*

Unbalanced analysis of variance (ANOVA) of seed data was undertaken to test for differences between low and high discharge and SSC determined by the average of each variable. This was necessary because the number of events in each category was not the same. Regression analysis was used to determine the strength of relationships between the discharge, SSC and seed data collected for each complete week of 2012. The Shannon-Weiner index was used to measure diversity of seed flux and was calculated in the same manner as outlined in 2.2.3. Using the Nash Sutcliffe model efficiency (Nash and Sutcliffe 1970) provided an assessment of the HEC-HMS model output:

$$NSE = 1 - \frac{\sum(q_{obs} - q_{sim})^2}{\sum(q_{obs} - \overline{q_{obs}})^2} \qquad (5.1)$$

Where q_{obs} was observed discharge and q_{sim} was modelled discharge at each time step, $\overline{q}_{obs}$ was the mean observed discharge. The equation would give a range from -∞ to 1 where a negative value would show the model a worse fit and 1 being a perfect fit.

Seed concentration per kg of sediment was calculated as:

$$SC_s = \frac{1}{SS} \times SN \tag{5.2}$$

Where SC_s is seed concentration in seeds per kg, *SS* is the sample mass in kg and *SN* is the number of seeds. To convert to seed flux, the number of seeds deposited per unit area of bed requires:

$$SC_t = M \times SC_s \tag{5.3}$$

Where SC_t is the seed concentration in the tray and *M* is the sediment mass in the tray in (kg). To express seeds numbers for the entire bed load the number of seeds per m^2 is needed:

$$SF_a = \frac{1}{a} \times SC \tag{5.4}$$

Where SF_a is seed flux expressed as seeds m^{-2}, *a* is the area of the sampling point (0.12 m^2). This give the SF_a for the single sample point but to express as the total seed flux in the bedload:

$$SF = SF_a \times 8.84 \tag{5.5}$$

Where *SF* is the total seed flux (number of seeds). The total area of the culvert was 8.84 m^2. To clarify the calculations, the sample for the 24th April 2012 was calculated based on a 0.9kg sample being taken that contained 153 seeds:

Seed concentration in grab sample:

$$\frac{1}{0.9\,kg} \times 153 \text{ seeds} = 170 \text{ seeds kg}^{-1}$$

Seed concentration in tray:

$$0.208\,kg \times 170 \text{ seeds/kg} = 35 \text{ seeds}$$

Therefore seed density is:

$$\frac{1}{0.121 m^2} \times 35\ seeds = 277.77 \text{ seeds m}^{-2}$$

To calculate the seed flux for the entire bed in one week:

$$277.77 \times 8.84 = 2455 \text{ seeds}$$

5.3 Results

5.3.1 Discharge

Monitoring of the outflow resulted in a partial time series for 2012 time series, which was completed using rainfall data from within the catchment to model the missing data (Figure 5.7). For 19 hours between 22nd and 23rd December, no data (observed or modelled) was acquired due to instrument failures at both the weather station and stream monitoring station. The modelled data accounted for 3 months of missing data as a result of instrument failures. Figure 5.8 provides model validation using the Nash Sutcliffe model efficiency coefficient to compare observed and modelled values during events. The model also accounts for two periods of discharge that exceeded the stage-discharge relationship on 6th August for 4 hours and 20th – 21st December for 24 hours.

The pattern of observed discharge prior to 24th April remained constantly lower than the remainder of the year. Average discharge for between 1st January and 1st May was 0.009 $m^3 s^{-1}$, which was lower than the average observed discharge of 0.024 $m^3 s^{-1}$. This constant state was the result of low antecedent conditions within the catchment coupled with only 45% of the rainfall expected compared to the average for the same time period. Modelled discharge showed 10 events should have passed through the catchment with the amount of rainfall, although these modelled events are likely to be over estimates because of the low antecedent conditions present in the catchment.

The largest observed events for the year were during the summer period on 22nd and 30th June, 18th July, and 6th August with discharge of over 0.15 $m^3 s^{-1}$. During the summer events were approximately 3 times larger than 1st January - 1st May, which is unusual for an arable catchment since crop cover would have been high. Modelled values are approximately double the observed events showing that some storage in the catchment was occurring like caused by the crop cover. However, rainfall was higher and more frequent than 1st January - 1st May likely causing the difference in both dataset between the two periods. Between 14th August and 11th September, the model appears to underestimate discharge by missing a series of observed events. Rainfall data for the period suggests low (0.2 mm) but regular rainfall, however observed discharge compared to previous months disputes modelled outcome suggesting rainfall data might be inaccurate.

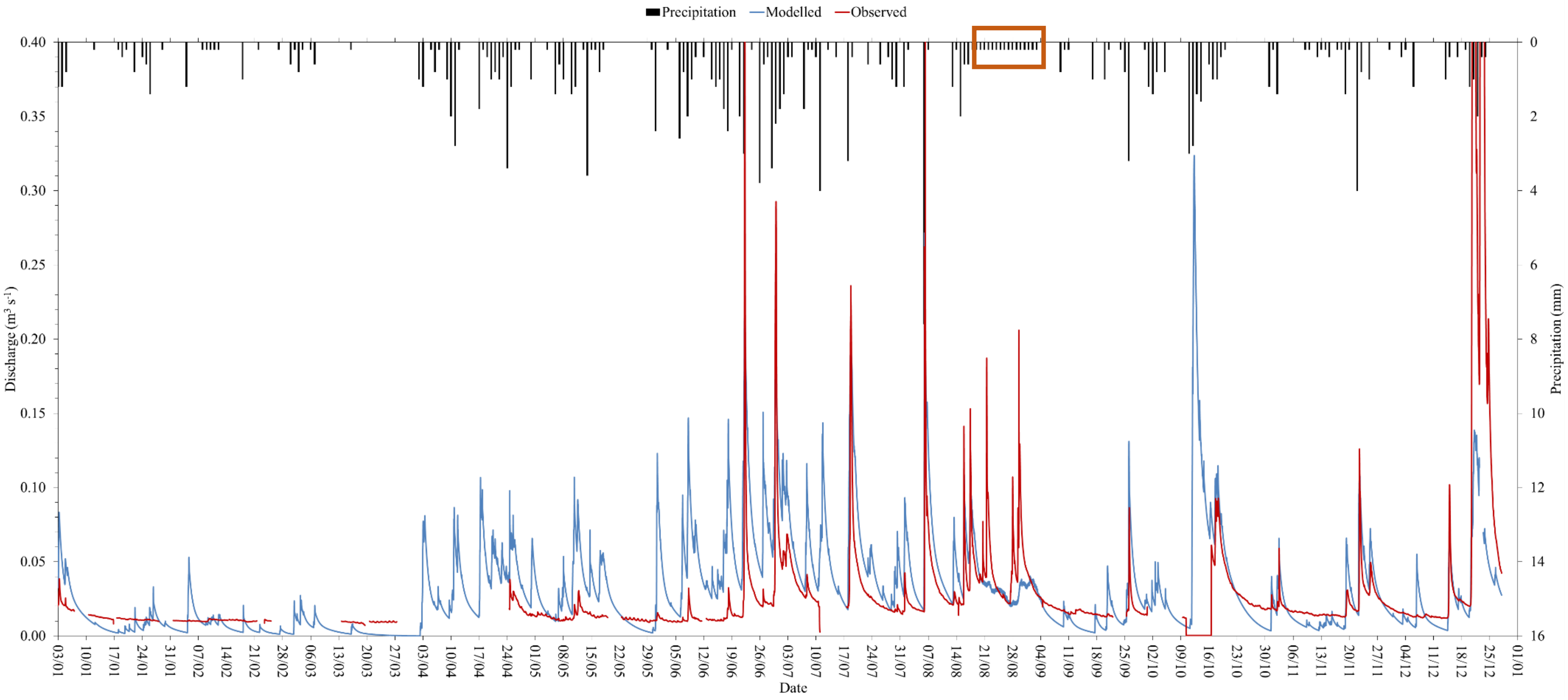


Figure 5.7 - Time series of observed (red) and modelled (blue) instantaneous discharge with precipitation data for 2012. Highlighted period between 14th August and 9th September shows malfunction in weather station affecting precipitation data.

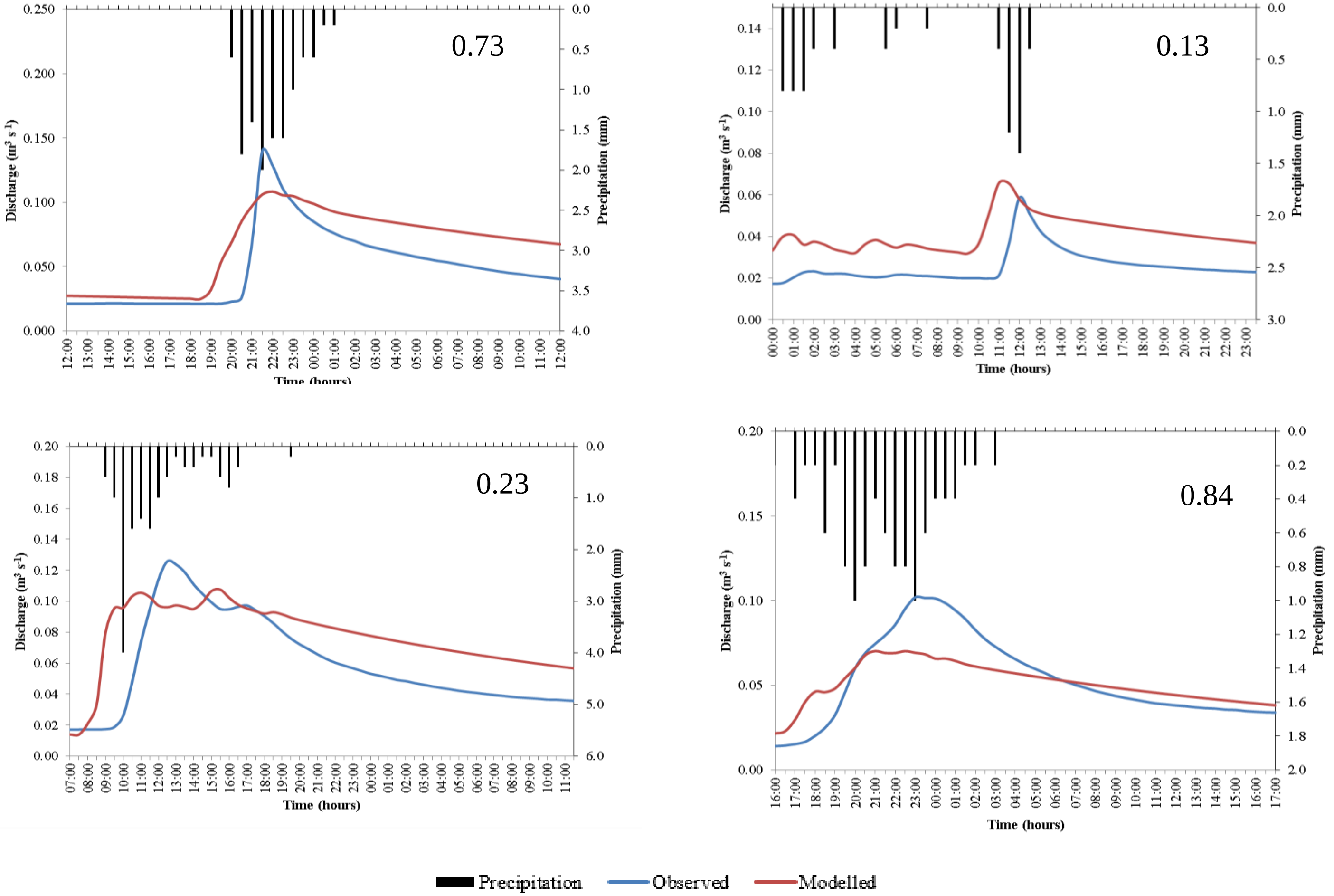


Figure 5.8 – Hydrographs for (a) 15th – 16th August, (b) 2nd November, (c) 22nd – 23rd November and (d) 14th December. Nash Sutcliffe model efficiency coefficient, shown in upper right corners, shows reliability of model against observed data.

Discharge events beyond 11th September were less frequent but similar in magnitude to events in the summer period. The modelled data for 9th – 16th October calculated the largest event during the year. From the events preceding and post this period, the modelled results are likely be reliable although the event might be similar to on 7th August in magnitude. Modelled events during this period showed good correspondence with observed events although this could be because crops that had been harvested allowing rainfall to generate runoff quicker than in the summer period.

5.3.2 Suspended Solid Concentration and Sediment load

The pattern of observed SSC showed that events were short and flashy rather than long and gentle events modelled by the SSC-discharge relationship (Figure 5.9). The main reason for the pattern observed by the SSC pattern is that sediment is readily available and passes through the monitoring station before discharge (Figure 5.10). The maxima SSC preceded the maxima precipitation was between 0 and 2.5 hours showing a rapid response to rainfall. This was reflected in Figure 5.9 with corresponding peaks in precipitation and SSC. Modelled SSC underestimated SSC maxima compared to all observed SSC maxima by approximately 2 – 5 times. Also, modelled events had long falling limbs and higher base SSC than observed which was caused by 95% of the year having observed SSC of <30 mg L^{-1}.

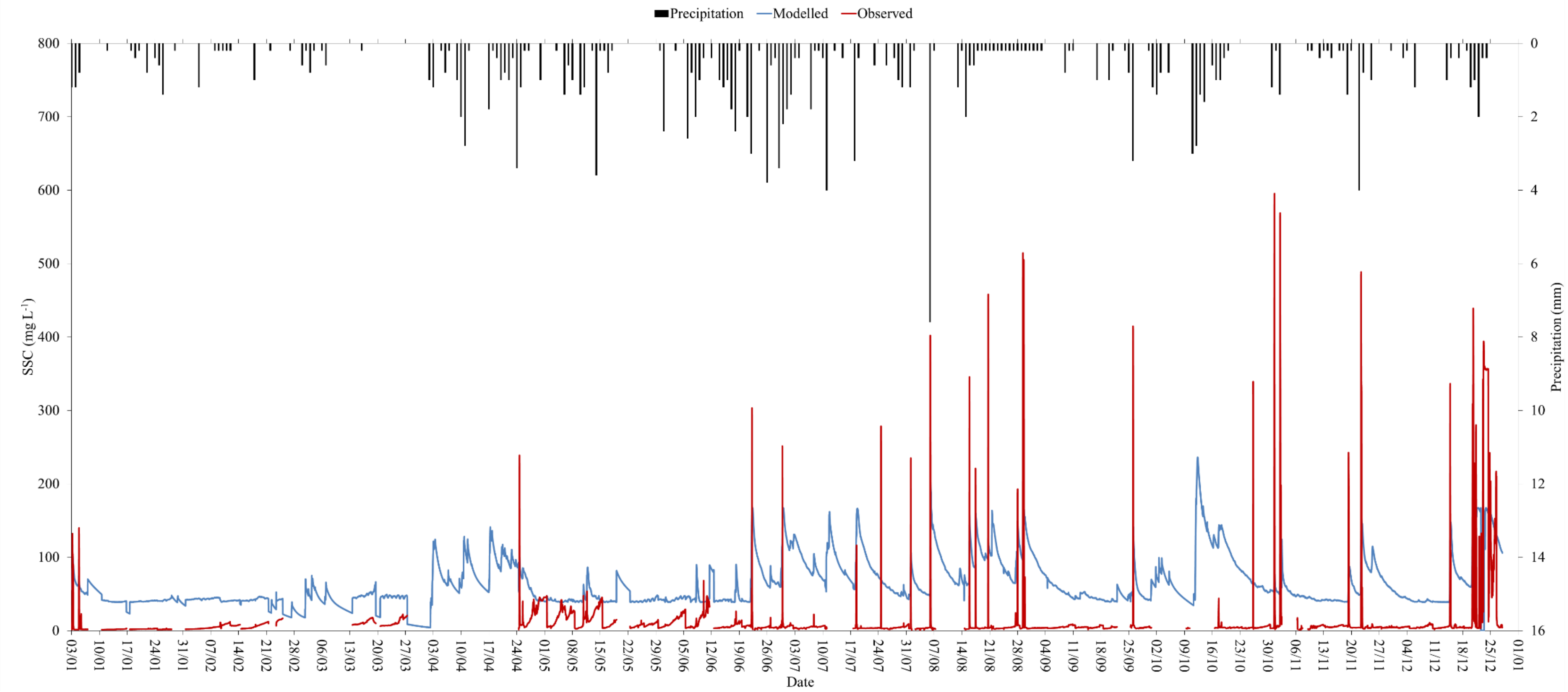


Figure 5.9 - Time series of observed (red) and modelled (blue) instantaneous SSC derived from turbidity measurements with precipitation data for 2012.

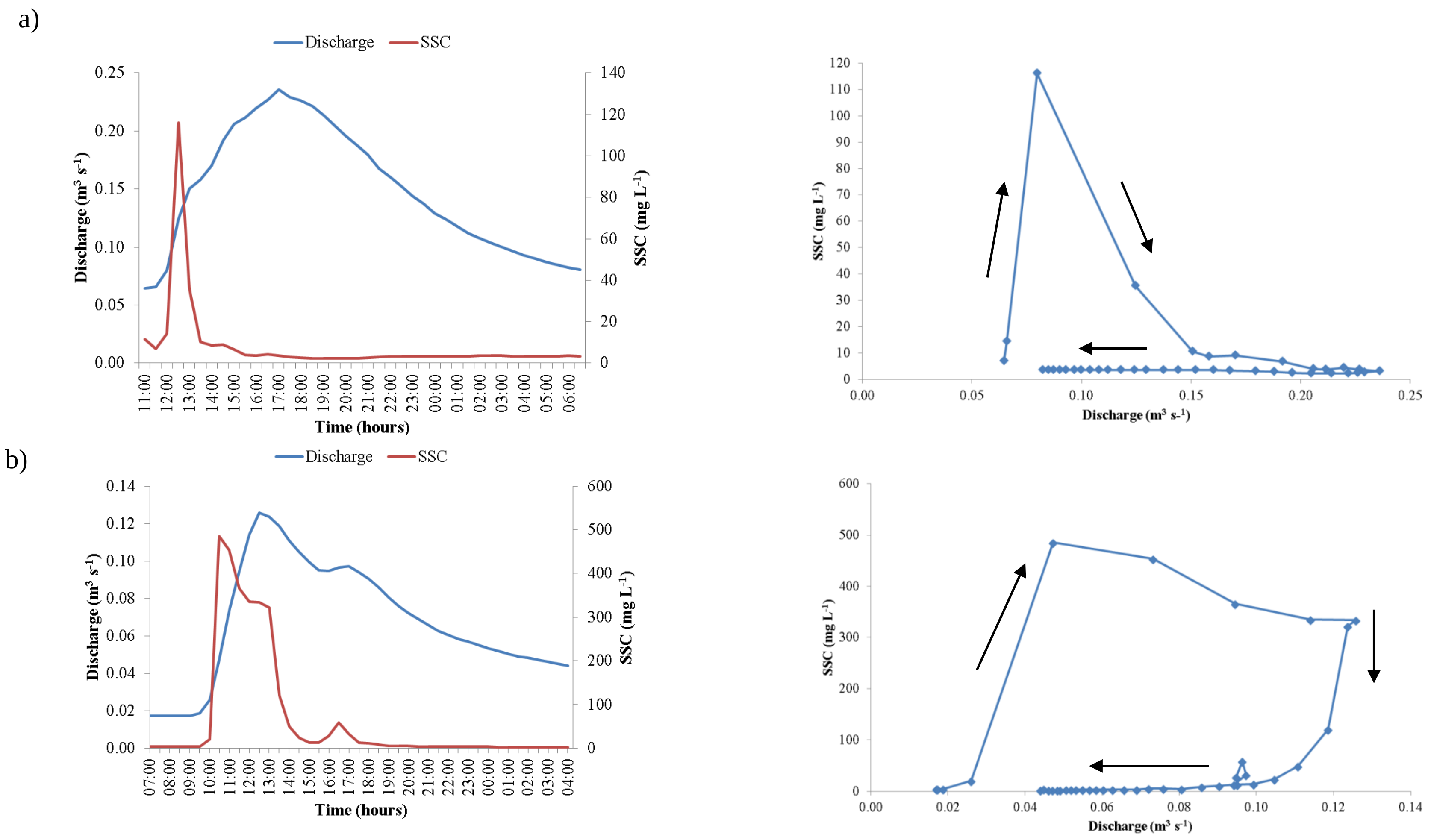


Figure 5.10 - Discharge and SSC hydrographs (left) and hysteresis loops (right) for (a) 18th – 19th July and (b) 22nd – 23rd November. Arrows on show time as in hydrographs.

Sediment load for both observed and observed plus modelled scenarios was calculated by the product of discharge and SSC for the year (Figure 5.11). The total observed sediment load was 15.38 t whilst modelled sediment load was 32.75 t. Expressed as a sediment loss for the catchment, observed sediment load gave 12.91 t km^{-2} yr^{-1} and modelled sediment load gave 26.63 t km^{-2} yr^{-1}. Given that the observed data is incomplete (missing approxiamtely 25% of the year), the 12.91t km^{-2} yr^{-1} sediment load estimate can be rejected. The unusual patterns around 28th February, 27th March – 4th April, and 9th October where there were rapid drops in modelled sediment load where due to no precipitation occuring causing discharge and SSC to drop. The annual pattern shows the difference in sediment load around 24th April where an appropriate order of magnitiude change occurs between the low antecedant conditions from the start of the year and the remainder of the year. The low farm activity of the summer months compared to harvest and re-seeding in October does not translate into the sediment load indicating that land use was not affecting the catchment flux.

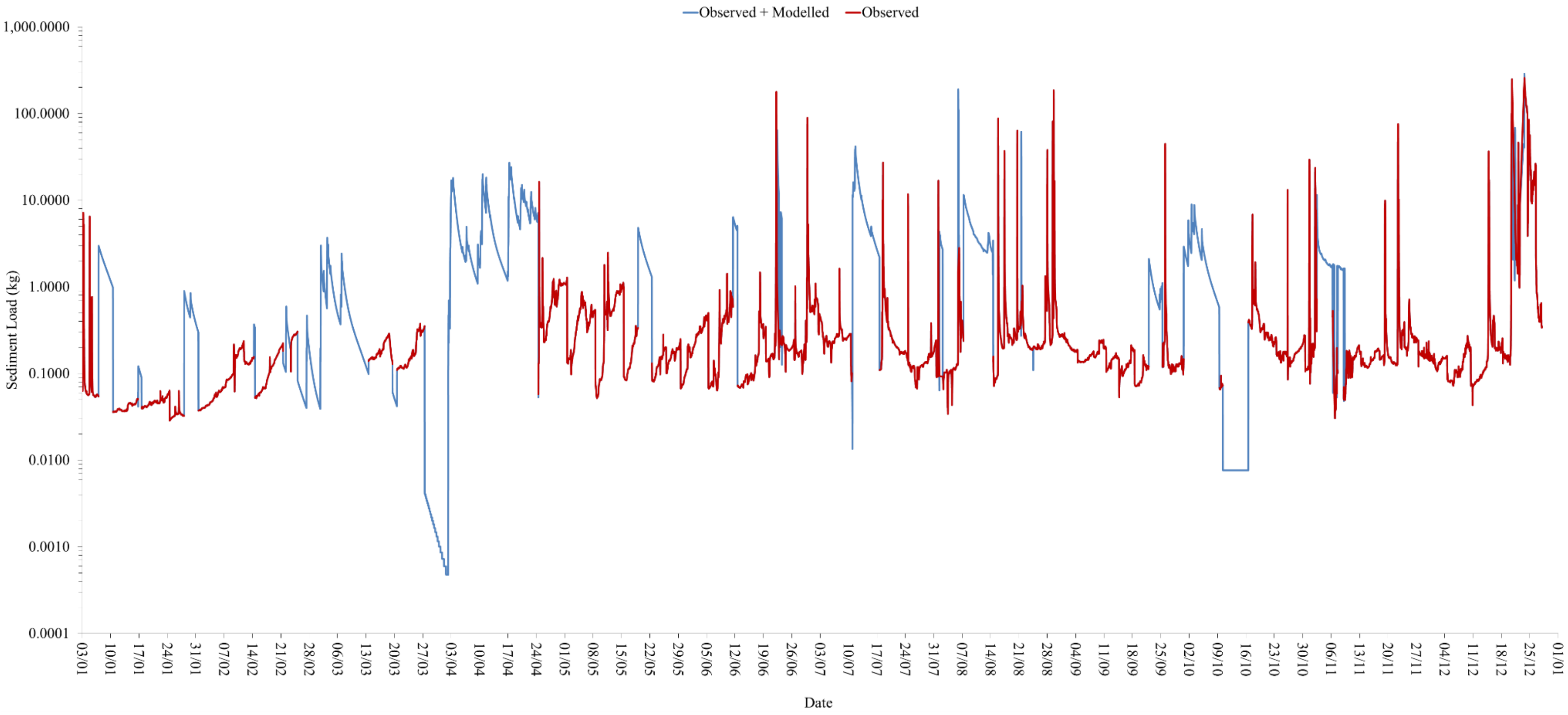


Figure 5.11 - Time series of observed (red) and observed plus modelled (blue) instantaneous sediment load for 2012. Periods with no observed data have been filled with modelled data to provide a sediment load estimate

5.3.3 Seed Flux

Weekly samples of bed sediment from the waterway resulted in a one year time series of seed flux from the catchment area (Figure 5.12). The average seed grab count in 2012 was 180 seeds kg^{-1} with two distinct peak periods of seed flux between 17th April - 19th June and 21st August – 4th December. The maximum seed concentration was 7670 seeds kg^{-1} for the week beginning 16th October whilst the minimum concentration was 7 seeds kg^{-1} beginning 18th December. The number of species ranged between 1 to 11 per sample. Comparing the seed grabs to the discharge and sediment load shows that the lowest seed concentration occurred in the same week that the largest event occurred. Relationships between seed concentrations are further investigated in Section 5.3.4.

Further exploration of the seed species data (Figure 5.13) shows that the proportion of seed from arable species increased throughout 2012. There was a difference ($p<0.001$) between two seed flux peaks regarding seed species sources. In the 1st peak, an average of 12.27% the seeds were from arable seed species however, in the 2nd peak , an average of 34.91% the seeds were from arable species.

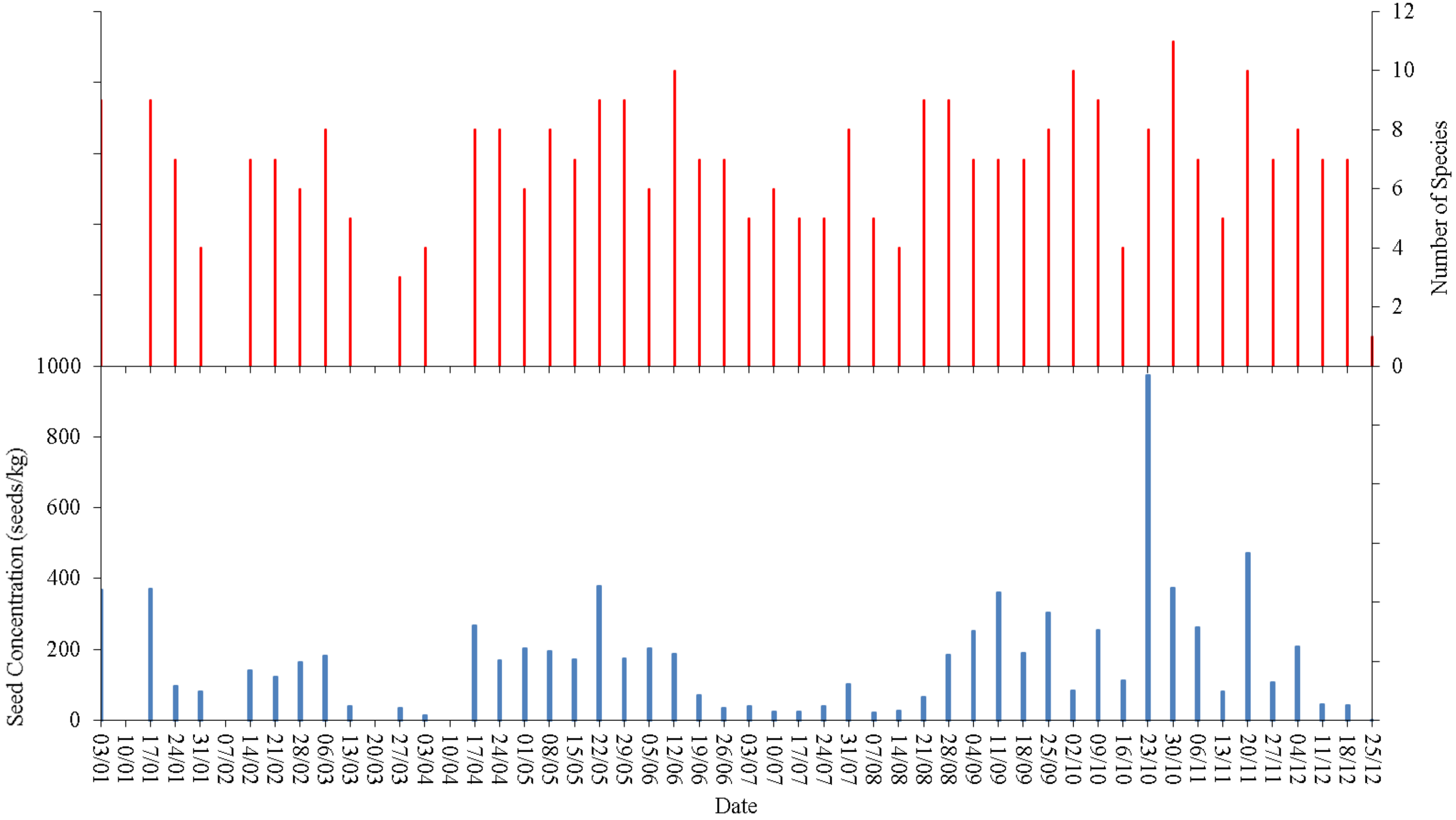


Figure 5.12 - Time series of seed concentration (seeds/kg) from bed sediment for 2012 expressed as seeds/kg in lower panel. Upper panel shows number of species within each week. Peak seed concentrations were in two periods from 17th April - 19th June and 21st August – 11th December. No samples were collected for 10th January or 7th February and no seeds were germinated in samples 20th March and 10th April.

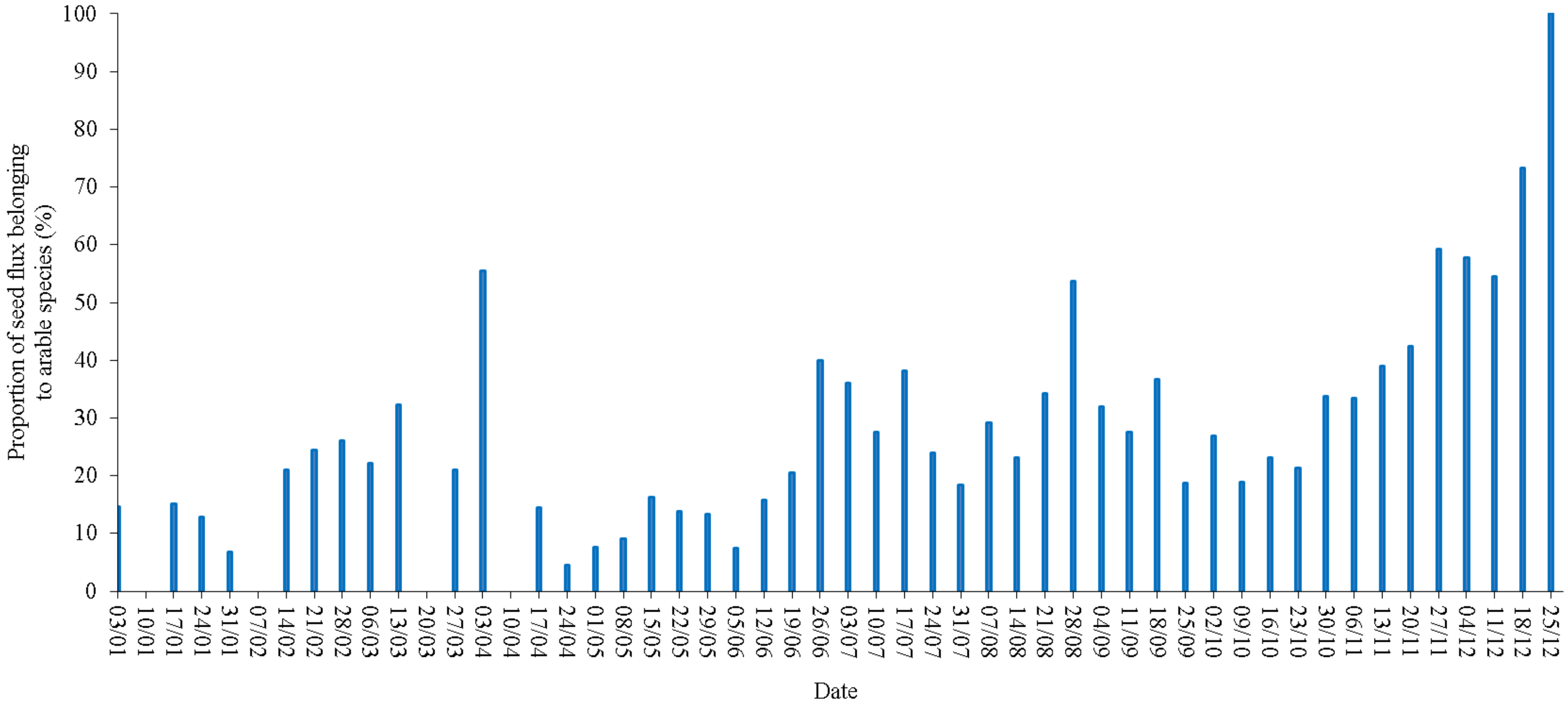


Figure 5.13 - Time series of proportion of seed from arable species in 2012. The first seed flux peak between 17th April and 19th June shows fewer arable seeds than the second peak between 21st August and 11th December No sample was collected for 10th January or 7th February and no seeds were germinated in samples 20th March and 10th April.

By using the sediment yield from the settling tray, a seed flux was calculated for the bed sediment (Figure 5.14). Settling tray data was unavilable prior to 13th March meaning no seed densities were calculated. Out of the 42 weeks available, the greatest seed flux was 84015 seeds week^{-1} from the week ending 16th October. However, 7th August (seed flux 19764 seeds week^{-1}) and 16th October were extremely different from all the others as seed grabs had less seeds than the seed flux. This disparity with the rest of the seed samples was because the tray contained over 10 kg of sediment compared to the average 0.8kg. The average seed flux was 4017 seeds week^{-1} for 2012. Samples taken on 26th June, 3rd & 24th July, 7th & 28th August, 4th September and 16th October were all above the average seed flux.

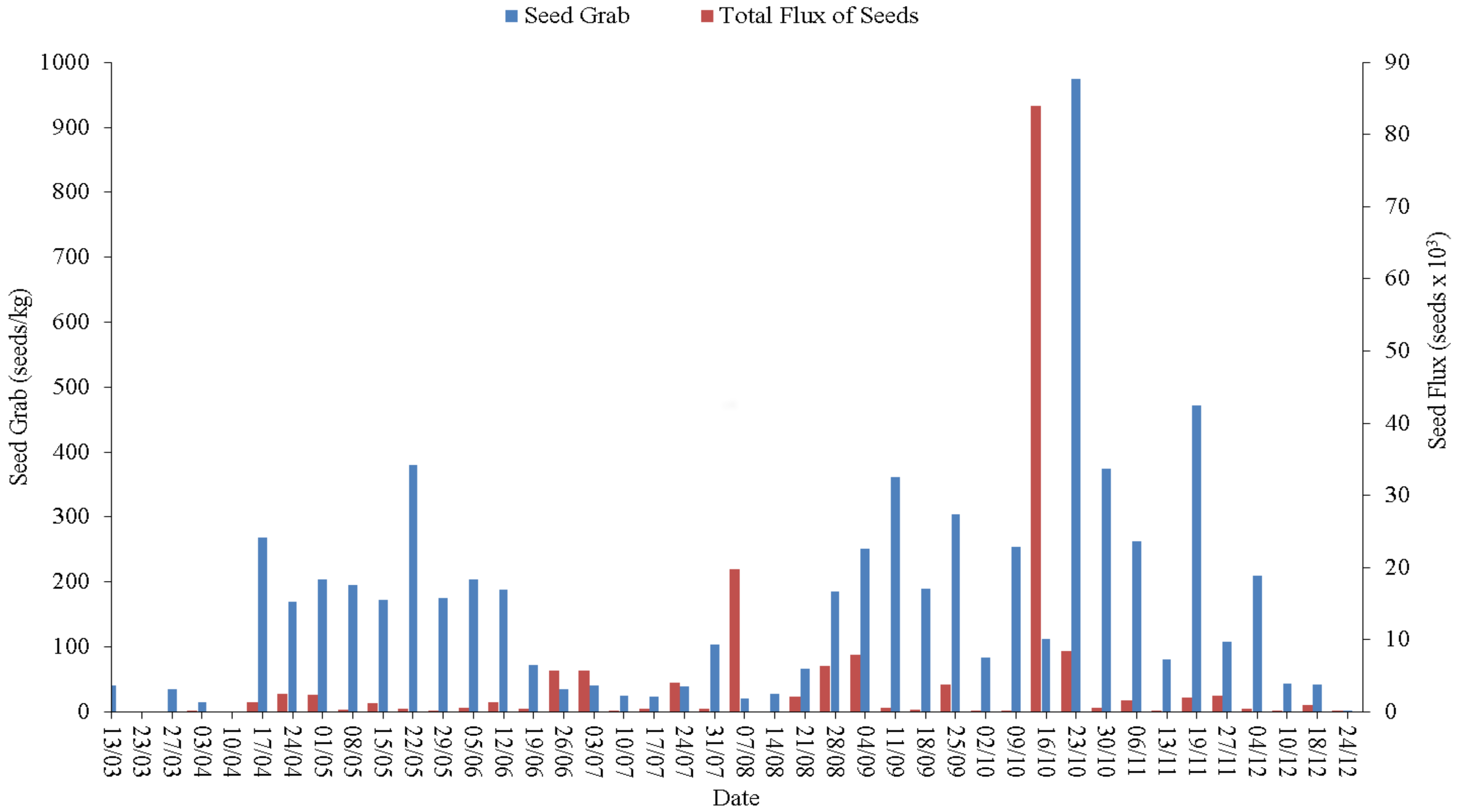


Figure 5.14 - Time series of seed concentration (seeds/kg) and seed flux (seeds/m^2) from bed sediment for 2012. Sediment yield from tray was only available from 13th March. Peak seed concentrations were in two periods from 17th April - 19th June and 21st August – 11th December. Seed flux peaks in the week prior to 16th October. No seeds were germinated in samples for 23rd March , 10th April, 24 December and no sediment yield was recorded for 14th August.

5.3.4 Relationships of seed data with discharge and sediment load

Due to the missing data, regression analysis of seed data to discharge and sediment load was split into observed data and observed plus model groups (Figure 5.15). Observed data contained 26 weeks of data as a result of the missing data. The observed plus model contained 42 weeks of data due to missing tray data. Discharge and seed flux were positively related by a power relationship for both observed ($r^2 = 0.61$, $p<0.001$). Observed plus modelled data showed no relationship ($r^2= 0.15$, $p = 0.614$). Discharge and number of species had no relationship for observed data ($r^2= 0.03$, $p = 0.33$). Observed plus modelled data showed a very weak power relationship ($r^2= 0.14$, $p = 0.017$). From these findings, discharge was shown to be clearly important in transporting seeds. Of the two relationships, the observed data had the better relationship with seed flux as the modelled discharges were likely to be an over estimate as previously discussed. Conversely, observed plus modelled data had the better relationship with seed species meaning a higher discharge resulted in less species loss.

Sediment load and seed flux were found to have positive relationships although observed data had a power relationship ($r^2= 0.54$, $p<0.001$) whilst observed plus modelled had a no relationship ($r^2= 0.08$, $p<0.935$). Both observed data ($r^2 =0.02$, $p = 0.35$) and observed plus modelled ($r^2= 0.02$, $p = 0.304$) showed no responses between sediment load and number of seed species. Relationships using observed data for sediment load and seed flux showed similarity to discharge relationships. However, the observed plus modelled relationships were much stronger for sediment load and seed flux, which could indicate that these are more accurately representing the processes of seed transport.

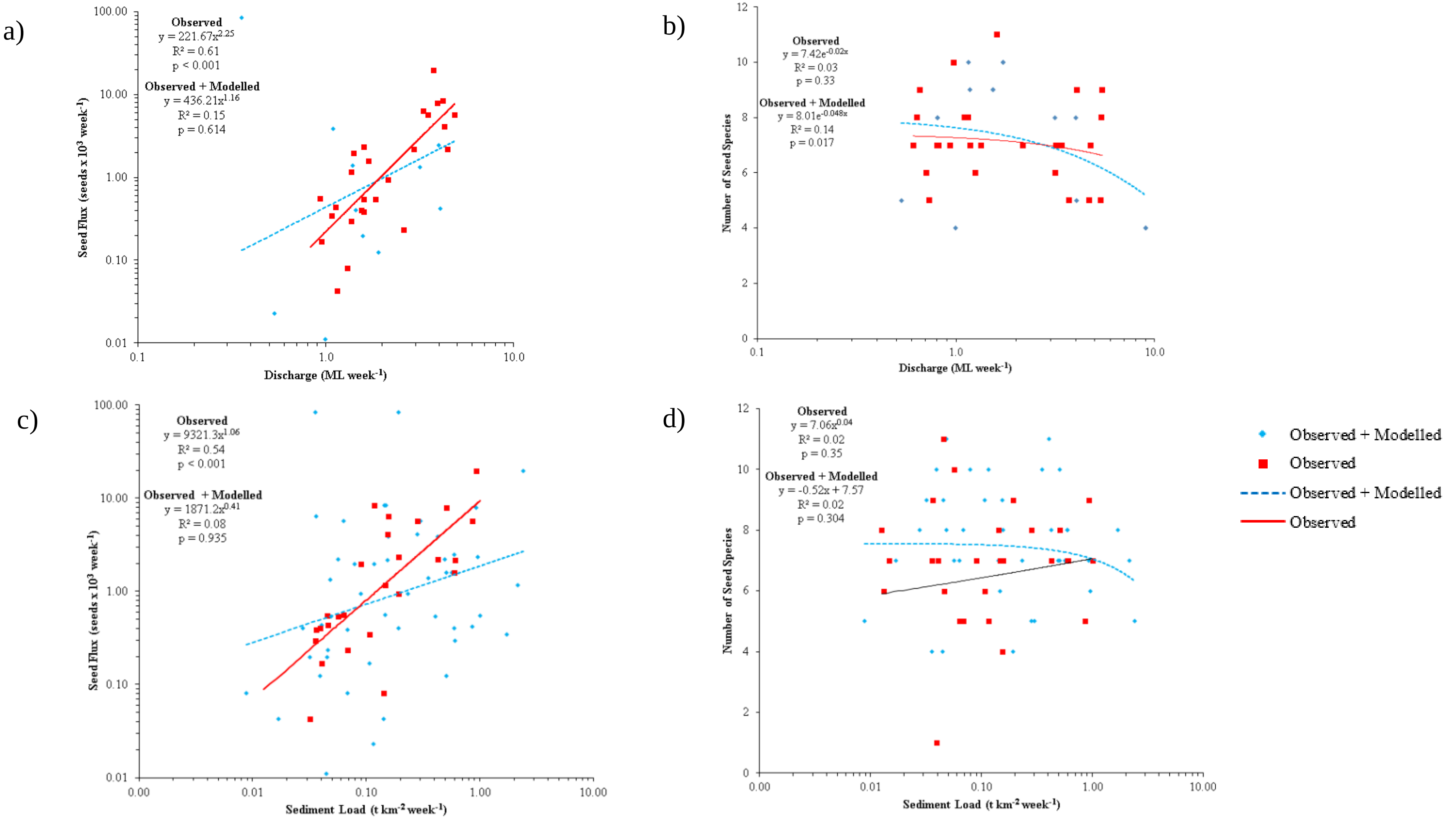


Figure 5.15 - Regression analysis of discharge against seed flux (a), number of seed species (b), and sediment load against seed flux (c) and number of seed species (d).

5.4 Discussion

The establishment of a hydrometric station at the outlet of Balruddery farm allowed for the monitoring of discharge, sediment and seed fluxes to determine the fate of weeds seeds at the catchment scale. The important finding was that seeds were being removed from the catchment along with a range of species. Both observed and observed plus modelled data suggested that sediment load was a better indicator of seed flux than discharge. This relationship demonstrated that soil erosion is important within the Balruddery catchment at transporting seeds within sediment rather than runoff or discharge.

Between 17th April and 19th June seed grabs corresponded with an increasing weed cover. This factor was important because there was a high availability of weed seeds via seed rain, which allowed the seeds to be transported whilst crop cover was low, meaning the soil was less protected from erosive processes (Lewis *et al.*, 2013). Similarly, crop cover was high during the summer months resulting in low numbers of seeds being transported despite high rainfall. Between 14th August and 4th December, seed grabs showed a rise and fall in seed numbers with a peak in the sample collected on 23rd October. This was important as seed rain inputs would have been low but farm activity was intensive as a result of harvest and field preparation (Lewis *et al.,* 2013). Harvest time and soil tillage were likely to have displaced individual seeds and patches of weed seeds (Marshall and Brian 1999, Blanco-Moreno *et al.,* 2004, Humston *et al*., 2005, Boyd and White 2009). As a result of differences in seed availability, weed seeds were more prone to dispersal and subsequent transport into the channel by a range of rainfall events.

From observations in Chapter 4 and data in this study , the hypothesis is that in the event of heavy rainfall in the middle of the farming season, when ground cover was high (due to crops) and farming operations were low (crop growing), seed flux may be controlled by storm frequency and subsequent discharge in the channel. On the other hand, during periods at the start or end of the season when soil is disturbed by farming activities, seeds from the seedbank become available for transport by lower rainfall amounts. The greater availability of seeds means channel seed fluxes can equal or exceed those during the crop growing season. (Lewis *et al.*, 2013).

The measurement of SSC and subsequent calculation of sediment load with modelled data meant the catchment sediment load was estimated to be 26.63 t km^{-2} yr^{-1}. Other small catchments (<10 km^2) (cf. Walling and Webb, 1987; Russell *et al.*, 2001) report values of between 37 and 122 t km^{-2} yr^{-1}. The difference between Balruddery catchment and other catchments could be due to the annual precipitation in 2012 (764.8 mm) being less than the 10 year regional average (JHI Invergowerie site 824.87 mm). In addition, Balruddery catchment drainage is culverted except for a 550m long channel meaning the connectivity between the farm and culvert site is likely to be low. By assuming the seed density for the total seedbank in 2012 for the field in Chapter 3 (18,248,494 seeds ha^{-1}) was the same across the 116 ha of farmland, and assuming a soil bulk density of 1 kg m^{-3} an annual seed flux can be calculated. The modelled sediment load of 32.63 t km^{-2} yr^{-1} represented a 0.022% loss from Balruddery Farm equating to a 462 437 seeds yr^{-1} loss. The loss estimates are much lower than the approximate 1% loss given in other catchment sediment budgets (Walling *et al.*, 2006; Department for Environment, 2008; Verheijen *et al.*, 2009). The broad estimates for seed losses assume a uniform contribution from every field within the catchment, whereas seeds are likely to be prevented from entering the channel by germination, predation, seed mortality and tillage redistribution (Grime *et al.*, 1981, Hulme *et al.*, 1998, Davis *et al.*, 2011, Petit *et al.*, 2013). Furthermore, the estimates do not account for the non-arable species observed in the seed flux that might be present in field edges, non-arable land (e.g. tracks or embankments) or channel banks. The input to the channel from other sources was observed on several occasions where daily rainfall exceeded 30 mm. An additional issue was the lack of knowledge of the exact source of the seeds (fields, field margins, channel banks) as well as where the seed entered the channel. Further investigation would be required to understand the exact source of seeds prior to entering the channel and the mechanisms that transported the seeds into the channel. A possible method would be to use ceramic beads as a surrogate seed similar to those used by Mohler *et al.* (2006).

5.5 Conclusions

This chapter aimed to determine the fate of weed seeds at the catchment scale over the course of a single year. This was achieved by establishing a monitoring station at the outflow of Balruddery Farm to conduct routine monitoring of discharge, sediment and seeds flux. During this monitoring period the source of seed input over the year was assessed. As a result of monitoring, applying the HEC-HMS model and an SSC-discharge relationship sediment load was estimated to be 32.63 t km^{-2}yr^{-1} which represented a loss of 0.034 % from the catchment with an estimated 595 287 seeds yr^{-1} loss to the channel network. Although overestimating the actual number of seeds lost, the percentage of sediment loss from the catchment was over two orders of magnitude smaller than suggested by other studies.

Monitoring the catchment outflow found that there was significant relationships between seed flux with both discharge and sediment load. Both observed data and observed plus modelled data showed sediment load to have the greater loss of seeds numbers ($r^2 = 0.89$, $p<0.001$) and species ($r^2 = 0.14$, $p = 0.004$). This fact was probably due to the farm activity, and changes in crop cover influencing the amount of available material for transport. Time series data showed seed flux corresponding with farming activity. Moreover, the exact source of seeds and how the seeds enter the channel remains unclear. Further work would be required to understand the amount and sources of seeds entering waterways to determine any management implications for within and outside of the catchment area. A longer monitoring period would improve the understanding of the hydrological conditions for the catchment area. Furthermore, sampling of suspended material and comparison to discharge, sediment load and bed samples might improve the understanding of the pattern of seed dispersal throughout the year

Chapter 6: Summary, Conclusions, Further work and Implications for arable management

6.1 Introduction

This thesis set out to advance the understanding of how soil erosion influences the weed seedbank in temperate arable environments. Literature suggested a tentative relationship between erosion and seedbank degradation but no empirical evidence had been presented for a relationship. This study sought to answer three key questions:

1. What is the nature (rates and timing) of seedbank transport by erosion and sediment transport processes with the relative contribution from tramline sources?
2. What is the amount, composition, timing and frequency of seed movement at different spatial scales?
3. What is the extent to which the transportation processes are linked to the sources, pathways and fate of sediments and what are the consequences for the seedbank and its ecological function?

This chapter unites the findings of the empirical work of this thesis and reflects on the results in relation to the research questions above. Figure 6.1 uses the different spatial scales (plot, field and catchment) of erosion processes that affected weed seeds. A summary of the key findings is provided before further work is described to suggest future research avenues to answer questions that remain from the experimental work.

6.2 Summary of spatial scale processes for soil erosion and seedbanks

6.2.1 Within field

As illustrated in Figure 6.1, individual seeds are initially dispersed by seed rain (1) onto the soil surface by a range of different dispersal mechanisms and abiotic processes (2 – 3), which can occur more than once before a seed enters the seedbank (Vander Wall and Longland, 2004; Benvenuti, 2007; Cousens *et al.*, 2008). Assuming the seed remains viable after the initial dispersal mechanism(s) (4 - 5), the seed will enter the seedbank awaiting germination conditions (6). The first important control on waterborne soil erosion is the presence of crop/vegetation cover (7) because this will control the amount and rate of transport (Question 1 & 2). The aim of Chapter 4 was to determine the specific environmental controls on seed mobility using portable field rainfall simulations.

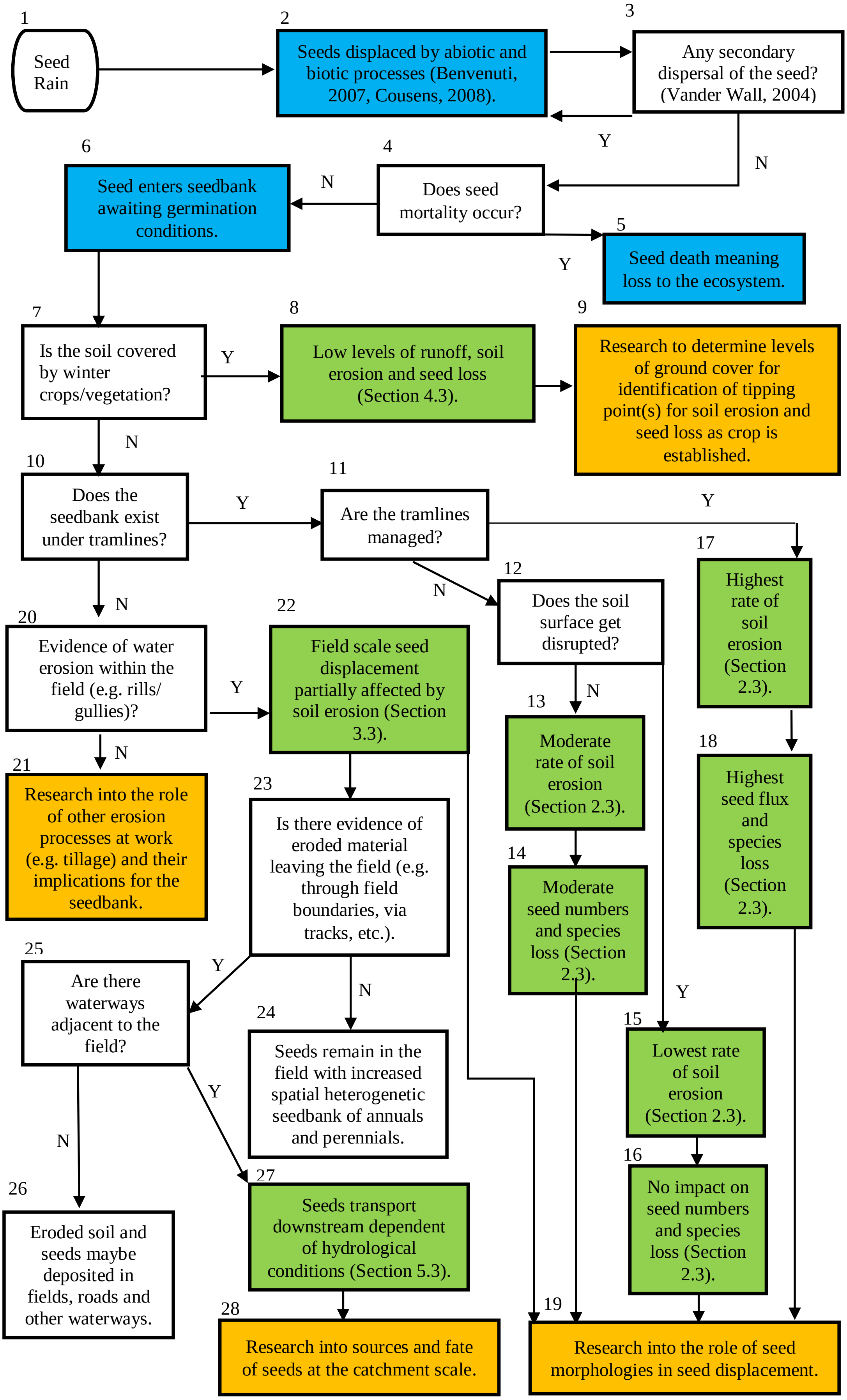


Figure 6.1 - Conceptual framework of seed movement by soil erosion from an individual seed scale to the catchment scale. White boxes contained questions, blue are information boxes, green show results of the thesis and orange are further research area with Y and N meaning Yes and No to questions respectively.

The results of the simulations found that the presence of vegetation protected the soil surface from rainfall that would instigate erosion (8). At the same time, vegetation cover can affect weed germination rates because of competition for water and light (Baskin and Baskin, 2006). However, seedbank densities and diversity may be higher in the cropped area than in tramlines because erosion losses are lower than from tramlines due to the vegetation providing protection from rainfall. Removing the ground cover at the small scale of the rainfall simulator (0.25 m x 0.25 m) found size-selective removal of soil particles and, for the first time, seeds caused by differences in seed morphologies and rill formation. Different seed morphologies change the hydrodynamics of seeds whilst rill formation changes the runoff velocity by concentrating runoff, which generates a greater detachment/transport force. However, a short intense event transported a greater amount of seeds under crop than on bare ground because of the greater seed availability. There is a need for further work to determine the levels of ground cover required to identify tipping point(s) for soil erosion and seed loss (9). This is important because arable fields do not have crop cover all year round. Farmers could manage the soil by using conservation tillage, delayed cultivations, or using mixed crop covers to prevent erosion of the soil and seedbank transport between periods of crop cover (Leys *et al.*, 2007).

Tramlines lack the protection of vegetation cover that the rest of the arable field can have once the crop is established (10). Tramlines have previously been identified as channels of soil erosion that can be managed to limit erosion and diffuse pollution (Withers *et al.*, 2006; Silgram *et al.*, 2007; Silgram *et al.*, 2010). Chapter 2 described the monitoring of soil erosion and subsequent transport of seeds under different tramline management strategies over three winter seasons (11 – 19). The key finding from the tramline study was that seed numbers were correlated with sediment load rather than runoff. Rain onto unmanaged tramlines caused the highest rates of soil erosion (6150 – 16 300 kg ha^{-1}) and, as demonstrated for the first time, seedbank loss in terms of both density (0.34 – 1.86 seeds m^{-2}) and number of species (13 – 20 species) (17 – 18). Conservation techniques such as low pressure tyres produces moderate rates of soil erosion (1400 – 5000 kg ha^{-1}) (13), seed flux (0.08 - 0.25 seeds m^{-2}) and species loss (9 – 12 species) (14). When the tramline was disrupted by a spiked harrow, the path for overland flow was interrupted resulting in the lowest erosion rates (400 – 6400 kg ha^{-1}) (15), seed flux (0.21 – 1.29 seeds m^{-2}) and species loss (6 – 12 species) (16). The important finding from the tramline study was that seed numbers were correlated with sediment load rather than runoff. Crucially, cultivation and accelerated soil erosion increases hydrochory above natural baseline levels. In addition, managing the tramlines was found to affect the diversity of transported seeds (seed numbers + seed species) more than number of seed species. These findings can aid farmers to make informed decisions about managing tramlines to prevent loss of soil and seed from the field. Further work is required to monitor the mobility of different seed morphologies under different environmental conditions (19). It is recommended that the use of rainfall simulations are necessary to explore differential seed mobilities.

6.2.2 Field

At the field scale, soil erosion can still occur in the form of rills and gullies where water flow is concentrated beyond tramlines (20) the thesis focussed on water-borne erosion, but the results presented suggest that other forms of erosion may also cause losses of seeds from the seedbank (21). Radionuclide tracing techniques allow for the observation and quantification of erosion rates at the field scale. Chapter 3 described using ^{137}Cs in a tracing study aimed at assessing the spatial pattern and rates of erosion over decadal timescales and exploring the significance for the seedbank at the field scale. The key finding of the study was that there were statistically significant relationships between the erosion rates and the seedbank densities. Grid A had a weak negative significant relationship ($r^2 = 0.13$, $p = 0.029$) and Grid B had a weak positive significant relationship ($r^2 = 0.12$, $p = 0.036$). However, erosion had a differential effect on the individual seed species (22). Investigation of individual seed species found that *Epilobium sp.* seed density had a negative relationship ($r^2 = 0.35$, $p <0.001$) whilst *Veronica arvensis* seed density had a weak positive relationship ($r^2 = 0.11$, $p = 0.043$) with erosion rates in 2011. *Capsella bursa-pastoris* seed density had a negative relationship to erosion rates in 2012 in Grid A ($r^2 = 0.15$, $p = 0.019$) whilst in Grid B had a positive relationship ($r^2 = 0.13$, $p = 0.029$). This selectivity of erosion for different species may be related to differences in seed morphology between species which is likely to affect their transportability. *Epilobium sp.* has hairs to aid in the seed dispersal, particularly by wind, whilst *Veronica persica* and *Capsella bursa-pastoris* use mucilage to bind to the soil. In addition, the seed sizes less than 2 mm have been shown to be susceptible to transport. The ecological significance of the seed morphologies is that having selective transport alters the competitiveness of the seedbank under vegetation cover leading to ecosystem change. Furthermore, the relationships identified are all weak indicating that erosion was an unrecognised underlying long term process that was being masked by the annual farming cycle. Further work would be required to understand the role of seed morphologies in seed transport at the field scale (19).

The spatial distribution of the soil erosion and seed species showed some overlap where eroding areas had lower seed density compared to deposition areas that had higher seed densities. This finding was not statically validated due to the sampling grid missing most of the basal deposition in the field. Important for farmers when managing the entire field is to consider the tillage practice and herbicide application for the field as this will affect both erosion rates and seedbank composition. Evidently, further work is needed to quantify the impact of erosion processes on the seedbank at the field scale and how management practice affects both erosion rates and seedbanks.

6.2.3 Catchment

Although the majority of soil erosion and deposition occurs within fields, between 20 and 50% of eroded sediment can leave the field and 1% be transported as suspended sediment in water courses annually (Walling *et al.*, 2006; DEFRA, 2008; Verheijen *et al.*, 2009). The pathways that transport sediment can also transport seeds beyond the field (23) although the majority would remain in the field (24) given the findings of Chapter 3. If there is evidence of eroded material leaving the field then the seeds could be deposited in aquatic (25) or terrestrial environments (26). Importantly, there is little understanding of the fate of seeds at the catchment scale if they enter waterways. However, the findings of Chapter 5 which aimed to develop a monitoring protocol for seeds from an arable catchment address this gap by quantifying, for the first time, seed flux in a waterway.

In the course of a single year, the seedbank of farm (18×10^6 seeds ha^{-1}) could be lowered by 0.022 % per year. Assuming a farm wide seedbank density and soil bulk density, a seed loss estimate would be 4.6×10^5seeds yr^{-1}. Although a simplification of the catchment, the estimates demonstrates that seeds are leaving the catchment in large amounts. At the catchment scale, observed plus modelled data show a strong positive relationship with discharge ($r^2 = 0.5$, $p < 0.001$) and sediment load ($r^2 = 0.89$, $p < 0.001$). The responses of seed numbers corresponded with storm events in the catchment that were able to transport available sediment into the channel. For seed species, observed plus modelled data sets found no relationship with discharge ($r^2 = 0.11$, $p = 0.17$) but a weak negative relationship with sediment load ($r^2 = 0.14$, $p = 0.004$). The implication of the relationships is that the number of seeds is associated with hydrological conditions within the catchment but seed species are not associated. These findings could have significant impacts at the landscape scale downstream where seeds deposited during high discharge events could germinate into weeds and alter local ecosystems.

6.3 Connectivity between spatial scales for seedbank and erosion

Connectivity within the environment is when physical or perceived boundaries to a process or system are lowered or removed between environments, scales or communities (Dutcher *et al.*, 2007). Often connectivity is used in catchment scale studies to disentangle complex systems and understand the individual components of the system (Lexartza-Artza and Wainwright, 2011). Similarly, connectivity between the field, farm and landscape scales influence the dispersal of weed seeds and composition of seedbanks at each scale (Petit et al 2013). This thesis has highlighted the extent to which transport processes by soil erosion affected the sources, pathways and fate of sediments and seeds. Understanding this is key to determining how soil erosion affects weed seedbanks across scales. Through the empirical data collected there was connectivity between scales for the seedbank as a result of soil erosion.

Starting at the small plot scale of the rainfall simulator (Chapter 4) the majority of seeds were transported from within the cropped area under short intense simulated storms. This is connected to the larger plot scale of the tramlines (Chapter 2) where a tramline plot consisted of two tyre wheelings and a sown inter-wheeling area. The majority (77%) of the tramline plot was cropped and was not physically affected by machinery. This means that in these cropped areas, seeds would be more readily available to be transported downslope likely due to the lack of soil compaction. Observations during rainfall simulations showed that seeds were transported in cropped area by splash rather than runoff but in a tramline plot runoff was generated down the tramlines. Therefore, the seeds collected in the gutters were from rain splash directly transporting seeds and sediment into the gutter or transported into the tramlines first and subsequently into the gutter.

The establishment of tramlines as conduits for sediment and seed transport means that there is connectivity between the plot and field scales. Evidence from the fluvial audit in Chapter 5 showed that runoff carrying sediment and seeds was easily transported by runoff between fields through connective pathways such as tracks. The fluvial audit highlighted the normal slope-channel coupling was distorted by underground drains and culverts that attenuates the importance of tracks and roads as either sources, conduits or barriers to sediment and seed movement. Similarly, field walls are important impediments to soil redistribution. At the field scale, the crop will be able to intercept rainfall meaning that erosion is driven by surface flows (for example Figure 5.1f) that form rills and gullies. As established previously, weed seed availability is much higher under crop making the transport of seeds by surface wash at the field scale an important process. Chapter 3 found that at the field scale, seed flux ranges between 2 – 2.5 % annually. However, the sediment budget concept from Lewis *et al.* (2013) indicates that in field deposition of eroded sediment is between 20 and 50%. Therefore, the seedbank is being re-distributed by erosion processes at the field scale with the majority remaining in the field.

At the catchment scale, connectivity between the fields and waterways or bodies that transport/store suspended sediment is important for the redistribution of soil and seeds. Quantification of the seed flux was less than 0.1%, which is the same amount as eroded sediment movement, at the catchment scale. However, these figures show the first empirical indication of landscape scale weed seedbank dynamics through a spatial scale connective pathway from within fields, across fields and farm by sediment transport.

6.4 Significance and Implications of Findings

The findings of this thesis are significant for the research, farming and policy communities. Prior to this research, soil erosion and weed seedbanks were viewed as independent research communities. However, there was a tentative link between soil erosion and seedbank movement based on literature evidence (Jiao *et al.*, 2009, Lewis *et al.*, 2013). The significant finding of this thesis was that seed are being transported as a result of soil erosion over different spatial and temporal scales. Importantly, seedbanks are not the only biological component of arable systems, therefore the findings of this thesis could lead the way for investigations into relationships between erosion and other biological components such as earthworms or nematodes (Blanchart *et al*, 2004,Baxter *et al.*, 2013). The other key significant finding of the thesis was the amount and diversity of seeds being transported at different scales. The implications to farmers are issues with lowered crop yield and competition from weeds (Hawes *et al.*, 2010). The implications for researchers would be more focused on the significance of the diversity of seeds being transported. This thesis has identified that seed morphology plays a role in the transportability of a seed. However, the removal of selective species could be altering the agro-ecosystem by the mobilisation of functional groups that provide specific ecophysiological traits that improve productivity within the crop (Hawes *et al*. 2009). Research into the functional implications of the thesis findings is important to understand arable ecosystem change.

Farming intensification after World War II caused runoff and soil erosion to become problems for both farmers and policy makers who were aiming to protect the wider environment (Evans, 2010). Policy developments at the European scale such as the Common Agricultural Policy (EC, 1999), the Water Framework Directive (EC, 2000) and the Soil Thematic Strategy (EC, 2012) have aimed at minimising soil erosion through financial incentives, research and education of land managers. European policy integration within the UK has been a devolved matter for England, Wales, Northern Ireland and Scotland resulting in individual soil policies (Evans, 2010).

An important part of soil, and wider environmental policy, is the increasing focus on biodiversity and functionality. In Europe, the implementation of the 1992 International Convention on Biological Diversity meant that farmers should take action to conserve species and populations on the farm (Gerowitt *et al.*, 2003). Furthermore, the Common Agricultural Policy offers financial support for maintaining minimum ecological standards (Gerowitt *et al.,* 2003). In terms of weeds, a balance is required between biodiversity and productivity in order to maintain important ecological function and services (Bohan and Haughton 2012). At the landscape scale, the balance of biodiversity and productivity is important because of the complexity of the landscape scale enables a greater biodiversity of weeds (Roschewitz *et al.*, 2005).

Important to both soil erosion and biodiversity policies is the need for evidence-based research to monitor, model and manage agro-ecosystem environments (Evans, 2010). Moreover, the inter-disciplinary nature of this thesis provides evidence that raises awareness of an overlapping policy area that soil erosion can affect ecosystem development through the mobilisation of the weed seedbank. The empirical findings of this thesis have demonstrated that policy needs to be multi-disciplinary to be effective at different spatial scales due to connectivity within the arable ecosystems. Hypothetically, the decline in the arable weed seedbank and the rise of soil erosion due to farming intensification have been influential to agro-ecosystems in the last 50 years (Evans 2010, Hawes *et al.,* 2012, Lewis *et al.,* 2013). Underpinning both weed seedbanks and soil erosion is farm management at the within field, field and farm scales. This thesis has quantified the links between soil erosion and seedbanks at all three spatial scales, which are controlled by a single farm owner. Vitally at the farm (defined as Balruddery Farm in this thesis) and landscape boundary lies the need for wider co-ordination between farms and other land users through policy advancement in order to minimise erosion and biodiversity impacts.

Given the findings of this thesis, there are important recommendations that can be made to farmers to aid in controlling the movement of weed seeds by erosion. The most effective management practice would be to prevent detachment by rainfall and subsequent transport by runoff of soil because the seeds are transported within the soil. Erosion management can be categorised into agronomic, soil or mechanical methods but a combination is required to achieve good erosion management (Morgan, 2005). Agronomic methods include the use of mulching, cover crops and crop rotations primarily to protect the soil surface from detachment and runoff (Morgan, 2005, Smets *et al.* 2008). Soil management would require changes to tillage practices such as minimum or sustainable tillage practices (see Chapter 3 for description of sustainable tillage). In addition, reducing compaction of the soil would allow water to infiltrate into the soil and prevent runoff. A simple low cost solution, outlined in Chapter 2, is to change tractor tyres to lower pressure tyres which decrease runoff by 80% and sediment transport by 95% in tramlines. Finally, mechanical methods that divert or store runoff such as terraces, drainage or barriers can be expensive but highly effective over the long term (Morgan, 2005).

6.5 New Directions and Potential Research Areas

Throughout the thesis, gaps in the current knowledge have been highlighted where new work is required to improve the understanding of the erosion processes affecting arable weed seedbanks. The main research area found there was a greater need for understanding small-scale mechanics (e.g. rain splash erosion, seed transport resistance from appendages) that contribute to observed processes. Although this was partially achieved with rainfall simulations, further work to investigate the full extent of what seed morphologies role is on a seed’s transportability by water is necessary. Understanding the timing and conditions of seed transport is crucial to the short and long term movement within the argo-ecosystem and wider landscape. For example, how could different amounts and types of ground cover affect the seed transportability by erosive processes? Improving this mechanistic understanding will further enhance this new research area.

Further scope exists for quantification of the ecological significance of seed transport by erosion. Sediment budgets provide conceptual frameworks that are useful in assessing gains and losses of sediment at field or catchment scales. A similar framework could be established for seed fluxes to give an insight into the ecological significance of a field or catchment to the wider ecological environment. Figure 6.2 shows a conceptual seed balance model. The model is based on the average seedbank density for 2011/2012 for Steading field in Chapter 2. Seed rain was calculated assuming the maximum germination rate of 10% for each species and then multiplied by the average number of seeds per plant based on Fitter and Peat (1994) and Home Grown Cereals Authority (2014). The majority of seed losses occurs as a result of seed morality caused by predation and environmental conditions (Watson *et al.*, 2003; Westerman *et al.*, 2003; Navntoft *et al.*, 2009; Davis *et al.*, 2011; Westerman *et al.*, 2011). It is important to note that the large range could mask other possible seed fates (e.g. displacement by tillage) that has not been quanitfied. The next largest loss of seed is via germination although this loss is offset by the production of seed rain to regenerate the seedbank (Lewis *et al.*, 2013). Seeds transported by erosion processes account for under 3% of the total movement in the seedbank budget. This is a relatively small amount compared with the other processes but was previously unregonised. The signifcance being that hydrochory (seed dispersal by water) is a well established mechanism for seed dispersal yet the specific pathways, distaces and scales were not well understood (Benvenuti , 2007, Petit *et al.*, 2013). Therefore, the amount and diversity of seed ransport might be small comapred to other ecological processes but erosion identifies connective pathways between spatial parts of the seedbank (e.g. hill crest, slope and footslope). The full extent of a seed budget requires further research in order to improve estimates of the inputs from seed rain and losses across different arable systems.

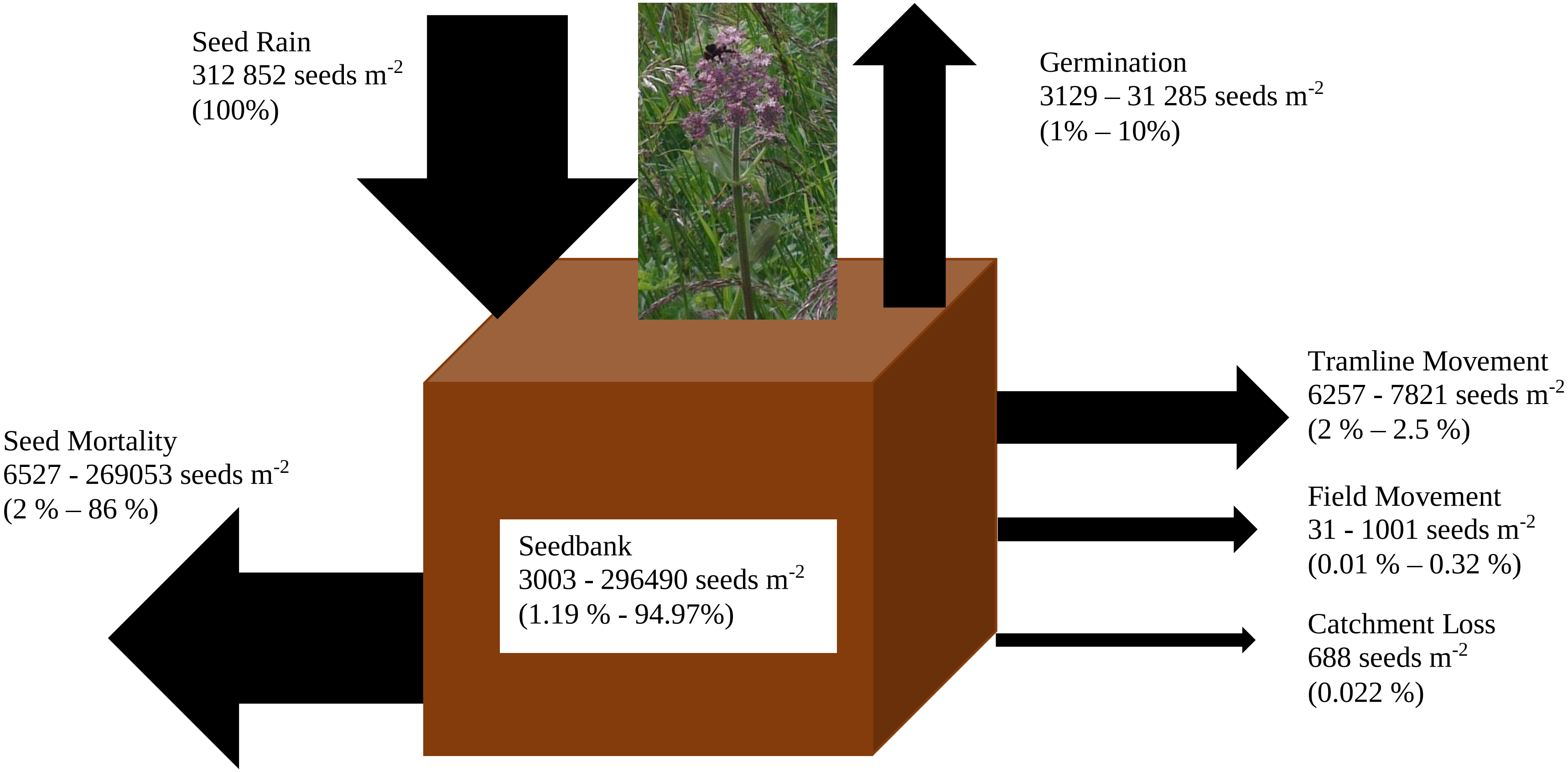


Figure 6.2 – Conceptual seedbank budget using seedbank density for 2011/2012 in Steading field (average 377 seed m^{-2}).

Another area of research that is opened up by the findings of this thesis is the potential contribution of weed seedbanks to soil carbon. Soil erosion and carbon have been studied at the global (Lal, 2003; Van Oost *et al.*, 2007) and UK level (Quinton *et al.*, 2006; Kuhn *et al.*, 2012; Dungait *et al.*, 2013). This thesis has highlighted the importance of erosion to the movement of seeds within fields and loss of seeds in sediment from fields. It was shown that the loss of seed can be high and therefore has the potential to represent a significant loss of carbon, which could contribute to carbon sources and sinks. From this thesis, carbon can be calculated based on the seed mass with the assumption that the seed is completely comprised of carbon. Using the seed fluxes from tramlines identified in Chapter 2, seed carbon loss (seed mass multiplied by seed number) is 0.244 – 45.873 g ha^{-1}. This range is a first estimate and is affected by seasonal differences in storm events, tramline managements. Using the average seed flux for 2012, the average annual loss of carbon based on seed mass would be 2.33 g of the total seed carbon of Balruddery Farm using the same assumptions outlined in Section 5.4. Further work is required to demonstrate the significance of this potential by showing a loss of carbon caused by soil erosion.

6.6 Conclusion

The original aim was to advance the understanding of soil erosion on the weed seedbanks in arable agricultural environments, which was achieved through a field based experimental approaches. Initial focus on the effects of tramline erosion on the seedbank led to further investigation of plot, field and catchment scale mechanisms. The findings of these experiments showed that the effect of soil erosion on the seedbank is scale dependent as increasing spatial scales diminishes the effect. This is likely due to an increasing system complexity where other natural and anthropogenic factors are affecting seedbank dynamics. However, there are limitations to the findings which have been outlined in the previous sections that should be considered. Despite these limitations, there is scope for further refinement of these experiments to clarify the findings. Furthermore, there is substantial scope, presented in the previous section, which offers new research areas that with additional work will develop and confirm the findings in this study for informing sustainable agricultural management and policy.

References

Al-Ghazal AA (2002) Effect of tractor wheel compaction on bulk density and infiltration rate of a loamy sand soil in Saudi Arabia.*Emirates Journal of Food and Agriculture*. 14. 24 - 33

Albrecht H (2003) Suitability of arable weeds as indicator organisms to evaluate species conservation effects of management in agricultural ecosystems. *Agriculture, Ecosystems & Environment*. 98: 201-211.

Albrecht H (2005) Development of arable weed seedbanks during the 6 years after the change from conventional to organic farming. *Weed Research.* 45: 339-350.

Albrecht H and Auerswald K (2009) Seed traits in arable weed seed banks and their relationship to land-use changes. *Basic and Applied Ecology*. 10: 516-524.

Alignier A and Petit S (2012) Factors shaping the spatial variation of weed communities across a landscape mosaic. *Weed Research.* 52: 402-410.

Andreasen C and Skovgaard IM (2009) Crop and soil factors of importance for the distribution of plant species on arable fields in Denmark. *Agriculture, Ecosystems & Environment.* 133: 61-67.

Baessler C and Klotz S (2006) Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agriculture, Ecosystems & Environment.* 115: 43-50.

Banwart S (2011) Save our soils. *Nature.* 474: 151-152.

Baskin CC and Baskin JM (2006) The natural history of soil seed banks of arable land. *Weed Science.* 54: 549-557.

Batey T (2009) Soil compaction and soil management – a review. *Soil Use and Management*. 25: 335-345.

Baxter C. Rowan JS, McKenzie BM and Neilson R (2013) Understanding soil erosion impacts in temperate agroecosystems: bridging the gap between geomorphology and soil ecology using nematodes as a model organism. *Biogeosciences*. 10:7133 – 7145.

Bekker RM, Bakker JP, Ozinga WA and Thompson K (2003) Seed traits: essential for understanding seed longevity. In: Bekker RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management.* Warwick: Association of Applied Biologists. 1 -10 .

Bell JS, Nolan AJ and Donnelly D (2009) *The Soils of Balruddery Farm*. Aberdeen: The James Hutton Institute

Benvenuti S (2007) Weed seed movement and dispersal strategies in the agricultural environment. *Weed Biology and Management*. 7: 141-157.

Bernal-Lugo I and Leopold AC (1998) The dynamics of seed mortality. *Journal of Experimental Botany*. 49: 1455-1461.

Blanchart E, Albrecht A, Brown G, Decaëns T, Duboisset A, Lavelle P, Mariani L. and Roose E (2004) Effects of tropical endogeic earthworms on soil erosion. *Agriculture, Ecosystems and Environment*. 104: 303-315.

Blanco-Moreno JM, Chamorro L, Massales RM, Recasens J and Sans FX (2004) Spatial distribution of Lolium rigidum seedlings following seed dispersal by combine harvesters. *Weed Research*. 44:375-387.

Boardman J (2006) Soil erosion science: Reflections on the limitations of current approaches. *Catena*. 68: 73-86.

Bohan DA, Powers SJ, Champion G, Haughton AJ, Hawes C, Squire G, Cussans J and Mertens SK. (2011) Modelling rotations: can crop sequences explain arable weed seedbank abundance? *Weed Research*. 51: 422-432.

Bohan DA and Haughton AJ (2012) Effects of local landscape species richness on in-field weed metrics across the Great Britain scale. *Agriculture, Ecosystems and Environment*. 208 - 215

Boix-Fayos C, Martínez-Mena M, Arnau-Rosalén E, Calvo-Cases A, Castillo V and Albaladejo J (2006) Measuring soil erosion by field plots: Understanding the sources of variation. *Earth-Science Reviews*. 78: 267-285.

Boyd NS and White S (2009) Impact of wild blueberry harvesters on weed seed dispersal within and between fields. *Weed Science*. 57:541-546.

Bracken LJ and Croke J (2007) The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*. 21: 1749-1763.

Brazier R (2004) Quantifying soil erosion by water in the UK: a review of monitoring and modelling approaches. *Progress in Physical Geography*. 28: 340-365.

Brenchley WE (1918) Buried weed seeds. *The Journal of Agricultural Science* 9: 1-31.

Brenchley WE and Warington K (1933) The Weed Seed Population of Arable Soil: II. Influence of Crop, Soil and Methods of Cultivation Upon the Relative Abundance of Viable Seeds. *Journal of Ecology*. 21: 103-127.

Brombacher A and Eppink LAAJ. (1991) *Applications and constraints of the mini-rainfall simulator after Kamphorst*, Wageningen: Wageningen Agricultural University.

Buhler DD, Hartzler RG and Forcella F. (1997) Implications of Weed Seedbank Dynamics to Weed Management. *Weed Science*. 45: 329-336.

Castro LG, Cogo NP and Volk LBD (2006) Alterations in soil surface roughness by tillage and rainfall in relation to water erosion. *Revista Brasileira De Ciencia Do Solo*. 30: 339-352.

Cerdà A and García-Fayos P (2002) The influence of seed size and shape on their removal by water erosion. *Catena*. 48: 293-301.

Cerdan O, Govers G, Le Bissonnais Y, Van Oost K, Poesen J, Saby N, Gobin A, Vacca A, Quinton J, Auerswald K, Klik A, Kwaad FJPM, Raclot D, Ionita I, Rejman J, Rousseva S, Muxart T, Roxo MJ and Dostal T. (2010) Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. *Geomorphology*. 122: 167-177.

Chambers JC and MacMahon JA (1994) A Day in the Life of a Seed: Movements and Fates of Seeds and Their Implications for Natural and Managed Systems. *Annual Review of Ecology and Systematics*. 25: 263 - 292.

Chambers JC, MacMahon JA and Haefner JH (1991) Seed Entrapment in Alpine Ecosystems: Effects of Soil Particle Size and Diaspore Morphology. *Ecology*. 72: 1668-1677.

Chamen T, Alakukku L, Pires S, Sommer C, Spoor G, Tijink F and Weisskopf P (2003) Prevention strategies for field traffic-induced subsoil compaction: a review: Part 2. Equipment and field practices. *Soil and Tillage Research*. 73: 161-174.

Chappell A and Thomas AD (2002) Modelling to reconstruct recent wind erosion history of fields in eastern England. In: Lee JA and Zobeck TM (eds) *ICAR5/GCTE-SEN Joint Conference*. Lubbock, USA, 309-311.

Chee-Sanford J and Fu X. (2010) Investigating the role of microorganisms in soil seedbank management. . In: Méndez-Vilas J (ed) *Current research, technology* *and education topics in Applied Microbiology and Microbial Biotechnology Vol 1.* Badajoz: Formatex Research Centre.

Collins AL, Zhang Y, McChesney D, Walling DE, Haley SM and Smith P (2012) Sediment source tracing in a lowland agricultural catchment in southern England using a modified procedure combining statistical analysis and numerical modelling. *Science of The Total Environment*. 414: 301-317.

Conn JS (2006) Weed seed bank affected by tillage intensity for barley in Alaska. *Soil and Tillage Research.* 90: 156-161.

Cousens R, Dytham C and Law R (2008) *Dispersal in plants: a population perspective,* Oxford: Oxford University Press.

Csontos P (2007) Seed banks: ecological definitions and sampling considerations. *Community Ecology*. 8 : 75 -85.

Csontos P and Tamás J (2003) Comparisons of soil seed bank classification systems. *Seed Science Research.* 13: 101-111.

Cuttle S, Macleod C, Chadwick D, Scholefield D, Haygarth P, Newell-Price P, Harris D, Shepard M, Chambers B and Humphrey R (2007) An Inventory of Methods to Control Diffuse Water Pollution from Agriculture (DWPA). London :DEFRA

Dabney SM, Delgado JA and Reeves DW (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis*.32: 1221-1250.

Davis A, Schutte B, Iannuzzi J and Renner K (2008) Chemical and Physical Defense of Weed Seeds in Relation to Soil Seedbank Persistence. *Weed Science*. 56: 676-684.

Davis AS, Daedlow D, Schutte BJ and Westerman PR. (2011) Temporal scaling of episodic point estimates of seed predation to long-term predation rates. *Methods in Ecology and Evolution.* 2: 682-890.

Davis AS, Renner KA and Gross KL (2005) Weed seedbank and community shifts in a long-term cropping systems experiment. *Weed Science.* 53: 296-306.

Davison P, Hutchins MG, Anthony SG, Betson M, Johnson C and Lord EI (2005) The relationship between potentially erosive storm energy and daily rainfall quantity in England and Wales. *Science of the Total Environment*. 344: 15 – 25.

Dawson JJC, Soulsby C, Tetzlaff D, Hrachowitz M, Dunn SM and Malcolm IA (2008) Influence of hydrology and seasonality on DOC exports from three contrasting upland catchments. *Biochemistry*. 90: 93-113.

De Cauwer B, D'Hose T, Cougnon M, Leroy B, Bulcke R and Reheul D (2011) Impact of the quality of organic amendments on size and composition of the weed seed bank. *Weed Research* 51: 250-260.

De Cauwer B, Reheul D, Nijs I and Milbau A (2008) Management of newly established field margins on nutrient-rich soil to reduce weed spread and seed rain into adjacent crops. *Weed Research*. 48: 102-112.

Deasy C, Quinton JN, Silgram M, Bailey AP, Jackson B and Stevens CJ (2009) Mitigation Options for Sediment and Phosphorus Loss from Winter-sown Arable Crops. *Journal of Environmental Quality*. 38: 2121-2130.

Deng W, Jeng DS, Toorop PE, Squire GR and Iannetta PP (2012) A mathematical model of mucilage expansion in myxospermous seeds of Capsella bursa-pastoris (shepherd's purse). . *Annals of Botany*. 109: 419-427.

Department for Environment, Food and Rural Affairs (DEFRA) (2002) *Directing the Flow – Priorities for Future Water* London: DEFRA.

Department for Environment, Food and Rural Affairs (DEFRA) (2008) *Documenting soil erosion rates on agricultural land in England and Wales: Phase 2*. London: DEFRA.

Dobbie KE, Bruneau PMC and Towers W (2011) *The State of Scotland's Soil*. Natural Scotland. Available on at www.sepa.org.uk/land/land_publications.aspx [Accessed 12.10.2012].

Dungait JAJ, Ghee C, Rowan JS, McKenzie BM, Hawes C, Dixon ER, Paterson E and Hopkins DW (2013) Microbial responses to the erosional redistribution of soil organic carbon in arable fields. *Soil Biology & Biochemistry*. 60: 195-201.

Dutcher DD, Finley JC, Luloff AE and Johnson JB (2007) Connectivity With Nature as a Measure of Environmental Values. *Environment and Behavior*. 39: 474-493.

EC (1999) On Support for Rural Development from the European Agricultural Guidance and Guarantee Fund. Council Regulation (EC) No. 1257/1999, European Commission: Brussels.

EC (2000) Establishing a Framework for Community Action in the Field of Water Policy. Directive 2000/60/EC of the European Parliament and of the Council.

EC (2012) The implementation of the Soil Thematic Strategy and ongoing activities. COM (2012) 46. European Commission: Brussels.

Environment Agency (2007) *The Unseen Threat to Water Quality. Diffuse Water Pollution in England and Wales Report – May 2007* London:Environment Agency.

Estevez B, Domon G & Lucas E (2000) Use of landscape ecology in agroecosystem diversification towards phytoprotection. *Phytoprotection* 81: 1–14.

Evangeliou N, Balkanski Y, Cozic A and Møller AP (2013) Global transport and deposition of ^{137}Cs following the Fukushima nuclear power plant accident in Japan: emphasis on Europe and Asia using high−resolution model versions and radiological impact assessment of the human population and the environment using interactive tools. *Environmental Science and Technology*. 47: 5803 – 5812.

Evans R (2010) Runoff and soil erosion in arable Britain: changes in perception and policy since 1945. *Environmental Science and Policy*. 13: 141-149.

Evans DM, Pocock MJO, Brooks J and Memmott J (2011) Seeds in farmland food-webs: Resource importance, distribution and the impacts of farm management. *Biological Conservation.* 144: 2941-2950.

Feast PM and Roberts HA (1973) Note on the Estimation of Viable Weed Seeds in Soil Samples. *Weed Research.* 13: 110-113.

Feld, CK, Martins da Silva, P, Sousa, JP, de Bello, F, Bugter, R, Grandin, U, Hering, D, Lavorel, S, Mountford, O, Pardo, I, Pärtel, M., Römbke, J, Sandin, L, Jones, KB & Harrison, PA (2009) Indicators of biodiversity and ecosystem services: a synthesis across ecosystems and spatial scales. *Oikos* 118: 1862-1871.

Feldman AD (2000) Hydrologic Modeling System HEC-HMS, Technical Reference Manual. U.S. Army Corps of Engineers, Hydrologic Engineering Center, HEC, Davis, CA, USA.

Fiener P, Seibert SP and Auerswald K (2011) A compilation and meta-analysis of rainfall simulation data on arable soils. *Journal of Hydrology* 409: 395-406.

Firbank LG (1999) Genetically modified crop Farm-Scale Evaluations. London: DEFRA.

Firbank LG, Heard MS, Woiwod IP, Hawes C, Haughton AJ, Champion GT, Scott RJ, Hill MO, Dewar AM, Squire GR, May MJ, Brooks DR, Bohan DA, Daniels RE, Osborne JL, Roy DB, Black HIJ, Rothery P and Perry JN (2003) An introduction to the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*. 40: 2-16.

Fitter AH and Peat HJ (1994) The Ecological Flora Database. *Journal of Ecology*. 82 : 415 - 425

Forcella F (2003) Debiting the seedbank: priorities and predictions. In: Bekker RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management.* Warwick: Association of Applied Biologists, 151-162.

Foster IDL, Owens PN and Walling DE (1996) Sediment yields and sediment delivery in the catchments of Slapton Lower Ley, South Devon, UK. *Field Studies*. 8: 629-661.

Fried G, Petit S, Dessaint F and Reboud X (2009) Arable weed decline in Northern France: Crop edges as refugia for weed conservation? *Biological Conservation.* 142: 238-243.

Fryirs KA and Brierley GJ (2012) Geomorphic Analysis of River Systems: An approach to reading the landscape. Chichester:Wiley-Blackwell

Fullen MA (2003) Soil erosion and conservation in northern Europe. *Progress in Physical Geography*. 27: 331-358.

Gabriel D, Thies C and Tscharntke T (2005) Local diversity of arable weeds increases with landscape complexity. *Perspectives in Plant Ecology, Evolution and Systematics*. 7: 85-93.

García-Fayos P and Cerdà A (1997) Seed losses by surface wash in degraded Mediterranean environments. *Catena*. 29: 73-83.

García-Fayos P, Bochet E and Cerdà A (2010) Seed removal susceptibility through soil erosion shapes vegetation composition. *Plant Soil*. 334: 289-297.

Gerowitt B, Bertke E,Hespelt S-K and Tute C (2003) Towards multifunctional agriculture – weeds as ecological goods? *Weed Research*. 43 : 227 - 235

Gibson RH, Nelson IL, Hopkins GW, Hamlett BJ and Memmott J. (2006) Pollinator webs, plant communities and the conservation of rare plants: arable weeds as a case study. *Journal of Applied Ecology*. 43: 246-257.

Golosov VN (2002) Special Consideration for Areas Affected by Chernobyl Fallout. In: Zapata F (ed) *Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides.* London: Kluwer Academic Publishers, 67 - 96.

Goodson JM, Gurnell AM, Angold PG and Morrissey IP (2003) Evidence for hydrochory and the deposition of viable seeds within winter flow-deposited sediments: The River Dove, Derbyshire, UK. *River Research and Applications.* 19: 317-334.

Govers G, Quine TA, Desmet PJJ and Walling DE (1996) The Relative Contribution of Soil Tillage and Overland Flow Erosion to Soil Redistribution on Agricultural Land. *Earth Surface processes and Landforms*. 21: 929 – 946

Grabowski R (2010) *Time monitoring of volumetric soil water content and saturated hydraulic conductivity and their relationship with topography during maize cropping*. Dissertation. UNESCO Centre Dundee University.

Grashof-Bokdam CJ and van Langevelde F (2005) Green veining: landscape determinants of biodiversity in European agricultural landscapes. *Landscape Ecology*. 20:417-439

Grime JP, Mason G, Curtis AV, Rodman J and Band SR (1981) A Comparative Study of Germination Characteristics in a Local Flora. *Journal of Ecology*. 69: 1017-1059.

Grundy AC, Mead A and Burston S (2003a) Does weed seed sowing density significantly effect weed emergence response to burial depth? In: Bekker RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management.* Warwick: Association of Applied Biologists, 39 - 46.

Grundy AC, Mead A and Burston S (2003b) Modelling the emergence response of weed seeds to burial depth: interactions with seed density, weight and shape. *Journal of Applied Ecology*. 40: 757-770.

Gulden R and Shirtliffe S (2009) Weed Seed Banks: Biology and Management. *Weeds, Herbicides and Management*. 2: 49 - 52.

Gunton RM, Petit S and Gaba S (2011) Functional traits relating arable weed communities to crop characteristics. *Journal of Vegetation Science*. 22: 541-550.

Gurnell A, Thompson K, Goodson J and Moggridge H (2008) Propagule deposition along river margins: linking hydrology and ecology. *Journal of Ecology*. 96: 553-565.

Gurnell AM, Boitsidis AJ, Thompson K and Clifford NJ (2006) Seed bank, seed dispersal and vegetation cover: Colonization along a newly-created river channel. *Journal of Vegetation Science* 17: 665-674.

Halwatura D and Najim MMM (2013) Application of the HEC-HMS model for runoff simulation in a tropical catchment. *Environmental Modelling & Software*. 46: 155 -162.

Han L, Jiao J, Jia Y, Wang N, Lei D and Li L (2011) Seed removal on loess slopes in relation to runoff and sediment yield. *Catena.* 85: 12-21.

Hancock GR and Evans KG (2010) Gully, channel and hillslope erosion – an assessment for a traditonally managed catchment. *Earth Surface Processes and Landforms*. 35: 1468 - 1479

Harper JL (1977) *Population biology of plants.* London: Academic Press.

Hawes C, Haughton AJ, Bohan DA and Squire GR (2009) Functional approaches for assessing plant and invertebrate abundance patterns in arable systems. *Basic and Applied Ecology*. 10: 34-42.

Hawes C, Haughton AJ, Osborne JL, Roy DB, Clark SJ, Perry JN, Rothery P, Bohan DA, Brooks DR, Champion GT, Dewar AM, Heard MS, Woiwod IP, Daniels RE, Young MW, Parish AM, Scott RJ, Firbank LG and Squire GR (2003) Responses of plants and invertebrate trophic groups to contrasting herbicide regimes in the Farm Scale Evaluations of genetically modified herbicide-tolerant crops. *Philosophical Transactions of the Royal Society Series B.* 358: 1899-1913.

Hawes C, Squire GR, Hallett PD, Watson CA and Young M (2010) Arable plant communities as indicators of farming practice. *Agriculture, Ecosystems & Environment.* 138: 17-26.

He Q and Walling DE (1996) Interpreting the particle size effect in the adsorption of ^{137}Cs and unsupported Pb by mineral soils and sediments. *Journal of Environmental Activity*. 30: 117 - 137.

Heard MS, Hawes C, Champion GT, Clark SJ, Firbank LG, Haughton AJ, Parish AM, Perry JN, Rothery P, Roy DB and Scott RJ (2003a) Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. 2. The effects on individual species *Philos Trans R Soc Lond B Biol Sci.* 358: 1833-1846.

Heard MS, Hawes C, Champion GT, Clark SJ, Firbank LG, Haughton AJ, Parish AM, Perry JN, Rothery P, Scott RJ, Skellern MP, Squire GR and Hill MO (2003b) Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. 1. Effects on abundance and diversity. *Philos Trans R Soc Lond B Biol Sci.* 358: 1819-1832.

Home Grown Cereals Authority (2014) The Encyclopaedia of Arable Weeds. Available at http://web.adas.co.uk/WeedManager/ [Accessed on 03/04/2014]

Howe HF and Smallwood J (1982) Ecology of seed dispersal. *Annual Review of Ecology and Systematics.* 13: 201 - 248.

Hughes A (2012) Disturbance and Diversity: An ecological chicken and egg problem. *Nature Education Knowledge*. 3: 48.

Humston R, Mortensen DA and Bjornstad ON (2005) Anthropogenic forcing on the spatial dynamics of an agricultural weed: the case of the common sunflower. *Journal of Applied Ecology*.42: 863 – 872.

Hulme PE (1998) Post-dispersal seed predation and seed bank persistence. *Seed Science Research.* 8: 513-519.

Hyvönen T and Huusela-Veistola E (2008) Arable weeds as indicators of agricultural intensity - A case study from Finland. *Biological Conservation* 141: 2857-2864.

Hyvönen T, Ketoja E, Salonen J, Jalli H and Tiainen J (2003) Weed species diversity and community composition in organic and conventional cropping of spring cereals. *Agriculture, Ecosystems & Environment*. 97: 131-149.

Iserloh T, Fister W, Seeger M, Willger H and Ries JB (2012) A small portable rainfall simulator for reproducible experiments on soil erosion. *Soil and Tillage Research.* 124: 131-137.

Iserloh T, Ries JB, Arnáez J, Boix-Fayos C, Butzen V, Cerdà A, Echeverría MT, Fernández-Gálvez J, Fister W, Geißler C, Gómez JA, Gómez-Macpherson H, Kuhn NJ, Lázaro R, León FJ, Martínez-Mena M, Martínez-Murillo JF, Marzen M, Mingorance MD, Ortigosa L, Peters P, Regüés D, Ruiz-Sinoga JD, Scholten T, Seeger M, Solé-Benet A, Wengel R and Wirtz S (2013) European small portable rainfall simulators: A comparison of rainfall characteristics. *Catena.* 110: 100-112.

Jiao J, Zou H, Jia Y and Wang N (2009) Research progress on the effects of soil erosion on vegetation. *Acta Ecologica Sinica.* 29: 85-91.

Jones A, Panagos P, Barcelo S, Bouraoui F, Bosco C, Dewitte O, Gardi C, Erhard M, Hervás J, Hiederer R, Jeffery S, Lükewille A, Marmo L, Montanarella L, Olazábal C, Petersen J-E, Penizek V, Strassburger T, Tóth G, Van Den Eeckhaut M, Van Liedekerke M, Verheijen F, Viestova E and Yigini Y (2012) *The State of Soil in Europe*. Ispra: European Union

Jones N and Naylor R (1992) Significance of the seed rain from set-aside. In: Clarke J (ed) *Set aside* Farham: British Crop Protection Council, 91-96.

Jones NE, Archer L and Boatman ND (2003) Methods of determining weed seed inputs to the seed bank on arable land. In: Bekker RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management* Warwick: Association of Applied Biologists, 171-178.

Jong ED, Begg CBM and Kachanoski RG. (1983) Estimates of soil erosion and deposition for some saskatchewan soils. *Canadian Journal of Soil Science.* 63: 607-617.

Kamphorst A (1987) A small rainfall simulator for the determination of soil erodibility. *Netherlands Journal of Agricultural Science* 35: 407-415.

Kuhn NJ, Armstrong EK, Ling AC, Connolly KL and Heckrath G (2012) Interrill erosion of carbon and phosphorus from conventionally and organically farmed Devon silt soils. *Catena.* 91: 94-103.

Lal R (2003) Soil erosion and the global carbon budget. *Environment International* 29: 437-450.

Lamour A and Lotz LAP (2007) The importance of tillage depth in relation to seedling emergence in stale seedbeds. *Ecological Modelling.* 201: 536-546.

Le Roux G and Marshall WA (2011) Constructing recent peat accumulation chronologies using atmospheric fall-out radionuclides. *Mires and Peat*. 7. 1 - 14

Lewis TD, Rowan JS, Hawes C and McKenzie BM (2013) Assessing the significance of soil erosion for arable weed seedbank diversity in agro-ecosystems. *Progress in Physical Geograph.y* 37: 622-641.

Lexartza-Artza I and Wainwright J (2011) Making connections: changing sediment sources and sinks in an upland catchment. *Earth Surface Processes and Landforms*. 36: 1090-1104.

Leys A, Govers G, Gillijns K and Poesen J (2007) Conservation tillage on loamy soils: explaining the variability in interrill runoff and erosion reduction. *European Journal of Soil Science*. 58: 1425-1436.

Loreau M, Mouquet N and Gonzalez A (2003) Biodiversity as spatial insurance in heterogeneous landscapes. *Proceedings of the National Academy of Sciences*. 100: 12765-12770.

Marshall EJP and Arnold GM. (1994) Weed seed banks in arable fields under contrasting pesticide regimes. *The Annals of Applied Biology* 125: 349-360.

Marshall EJP and Brain P (1999) The horizontal movement of seeds in arable soil by different soil cultivation methods. *Journal of Applied Ecology*. 36:443–454.

Marshall EJP, Brown VK, Boatman ND, Lutman PJW, Squire GR and Ward LK (2003) The role of weeds in supporting biological diversity within crop fields. *Weed Research*. 43: 77-89.

McFarlane D, Loughran R and Campbell B (1992) Soil erosion of agricultural land in Western Australia estimated by cesium-137. *Soil Research*. 30: 533-546.

Mennan H and Zandstra BH (2006) The Effects of Depth and Duration of Seed Burial on Viability, Dormancy, Germination, and Emergence of Ivyleaf Speedwell (Veronica hederifolia). *Weed Technology*. 20: 438-444.

Merkus HG. (2009) *Partile Size Measurements: Fundamentals, Practice, Quality*. Dordrecht Springer.

Met Office (2013) *UK Climate Summaries*. Available at: http://www.metoffice.gov.uk/climate/uk/. [Accessed on 26/09/2013]

Michelin. (2013) *Michelin Xeobib*. Available at: http://www.michelin-agricultural-tyres.co.uk/.Web Page [Accessed on 20/04/2013]

Mohler CL (1993) A Model of the Effects of Tillage on Emergence of Weed Seedlings. *Ecological Applications*. 3: 53-73.

Mohler CL, Frisch JC and McCulloch CE (2006) Vertical movement of weed seed surrogates by tillage implements and natural processes. *Soil and Tillage Research*. 86: 110-122.

Moles AT, Ackerly DD, Tweddle JC, Dickie JB, Smith R, Leishman MR, Mayfield MM, Pitman A, Wood JT and Westoby M (2007) Global patterns in seed size. *Global Ecology and Biogeography*. 16: 109-116.

Moles AT, Ackerly DD, Webb CO, Tweddle JC, Dickie JB and Westoby M (2005) A Brief History of Seed Size. *Science*. 307: 576-580.

Moonen AC and Bàrberi P (2004) Size and composition of the weed seedbank after 7 years of different cover-crop-maize management systems. *Weed Research*. 44: 163-177.

Morgan RPC (2005) *Soil Erosion and Conservation*. Oxford: Blackwell.

Morvan X, Saby NPA, Arrouays D, Le Bas C, Jones RJA, Verheijen FGA, Bellamy PH, Stephens M and Kibblewhite MG (2008) Soil monitoring in Europe: A review of existing systems and requirements for harmonisation. *Science of The Total Environment*. 391: 1-12.

Müller F, Gnauck A, Wenkel K-O, Schubert H and Bredemeier M, 2010 *Theoretical Demands for Long-Term Ecological Research and the Management of Long-Term Data Sets*. In Müller F, Baessler C, Schubert H, Klotz S (eds) Long-Term Ecological Research : Between Theory and Application. Springer, New York Pages 11 - 27

Nakanishi H (2002) Splash seed dispersal by raindrops. *Ecological Research*. 17: 663-671.

Nash JE and Sutcliffe JV (1970) River flow forecasting through conceptual models. 1. A discussion of principles. *Journal of Hydrology*. 10 : 282 - 290

Natural England (2013) *Environmental Stewardship*. Available at: http://www.naturalengland.org.uk/. [Accessed on 01/09/2013]

Navntoft S, Wratten SD, Kristensen K and Esbjerg P (2009) Weed seed predation in organic and conventional fields. *Biological Control*. 49: 11-16.

Newson M (1997) Time, scale and change in river landscapes: the jerky conveyor belt. *Landscape Research*. 22: 13-23.

Owens PN, Walling DE and He Q (1996) Spatial variability of caesium-137 inventories at reference sites: an example from two contrasting sites in England and Zimbabwe. *Applied Radiation and Isotopes*. 47: 699-707

Parsons AJ (2012) How useful are catchment sediment budgets? *Progress in Physical Geography*. 36: 60-71.

Parsons AJ and Foster IDL (2011) What can we learn about soil erosion from the use of 137Cs? *Earth-Science Reviews*. 108: 101-113.

Pennock DJ and Appleby PG (2003) Sample Processing. In: Zapata F (ed) *Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides*. London: Kluwer Academic Publishers, 59 - 67.

Petit S, Alignier A, Colbach N, Joannon A, Coeur D and Thenail C (2013) Weed dispersal by farming at various spatial scales. A review. *Agronomy for Sustainable Development*. 33: 205 -217

Perry JN, Rothery P, Clark SJ, Heard MS and Hawes C (2003) Design, analysis and statistical power of the Farm-Scale Evaluations of genetically modified herbicide-tolerant crops. *Journal of Applied Ecology*. 40: 17-31.

Quine TA, Van Oost K, Walling DE and Owens PN (2006) *Scoping study of soil loss through wind erosion, tillage erosion and soil co-extracted with root vegtables*. London: DEFRA

Quine TA and Walling DE (1991) Rates of soil erosion on arable fields in Britain: quantitative data from caesium- 137 measurements. *Soil Use and Management*. 7: 169 – 176

Quine TA, Walling DE, Chakela QK, Mandiringana OT and Zhang Z (1999) Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from caesium-137 measurements. *Catena*. 36:115 - 142

Quinton JN, Catt JA, Wood GA and Steer J (2006) Soil carbon losses by water erosion: Experimentation and modeling at field and national scales in the UK. *Agriculture Ecosystems & Environment*. 112: 87-102.

Riksen M, Brouwer F and de Graaff J (2003) Soil conservation policy measures to control wind erosion in northwestern Europe. *Catena*. 52: 309-326.

Ritchie JC and Ritchie CA (2003) *Bibliography of ^{137}Cs studies*. United States Department of Agriculture :ARS

Roberts HA and Feast P (1973) Emergence and Longevity of Seeds of Annual Weeds in Cultivated and Undistrubed Soil. *Journal of Applied Ecology*. 10: 133-143.

Robinson RA and Sutherland WJ (2002) Post-War Changes in Arable Farming and Biodiversity in Great Britain. *Journal of Applied Ecology*. 39: 157-176.

Roller A, Beismann H and Albrecht H (2003) The influence of soil cultivation on the seedbank of GM-herbicide tolerant and conventional oilseed rape. In: Bekker

RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management.* Warwick: Association of Applied Biologists.

Roschewitz I, Gabriel D, Tscharntke T and Thies, C (2005) The effects of landscape complexity on arable weed species diversity in organic and conventional farming. *Journal of Applied Ecology*. 42: 873 - 882

Rowan JS (1999) Particle Size Preparation Protocol. University of Dundee:Dundee

Rowan JS, Black S and Franks SW (2012) Sediment fingerprinting as an environmental forensics tool explaining cyanobacteria blooms in lakes. *Applied Geography*. 32: 832-843.

Royal Botanical Gardens (2008) *Seed Information Database*. Available at: http://data.kew.org/sid/sidsearch.html. [Accessed on 13.6.11]

Russell MA, Walling DE and Hodgkinson RA (2001) Suspended sediment sources in two small lowland agricultural catchments in the UK. *Journal of Hydrology*. 252: 1-24.

Ryan MR, Smith RG, Mirsky SB, Mortensen DA and Seidel R (2010) Management Filters and Species Traits: Weed Community Assembly in Long-Term Organic and Conventional Systems. *Weed Science*. 58: 265-277.

Scottish Government (2012) *SRDP 2014 - 2020 Report of the Agri-Environment-Climate Working Group*. Available at http://www.scotland.gov.uk. [Accessed on 06/12/2013].

Six J, Bossuyt H, Degryze S and Denef K (2004) A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil & Tillage Research*. 79: 7 -31

Shannon CE and Weaver W (1949) *The Mathematical Theory of Communication,* Urbana: University of Illinois Press.

Shaw EM, Beven KJ, Chappell NA and Lamb R (2011) *Hydrology in Practice*. Oxon: Spon Press.

Silgram M, Jackson B, Quinton J, Stevens C and Bailey A (2007) Can tramline management be an effective tool for mitigating phosphorus and sediment loss? *The 5th International Phosphorus Workshop (IPW5).* Silkeborg, Denmark, 287-289.

Silgram M, Jackson DR, Bailey A, Quinton J and Stevens C (2010) Hillslope scale surface runoff, sediment and nutrient losses associated with tramline wheelings. *Earth Surface Processes and Landforms*. 35: 699-706.

Singer MB and Dunne T (2001) Identifying eroding and depositional reaches of valley by analysis of suspended sediment transport in the Sacramento River, California. *Water Resources Research*. 37: 3371-3381.

Slattery MC and Burt TP (1995) Size characteristics of sediment eroded from agricultural soil: dispersed versus non-dispersed, ultimate versus effective. In: Hickin EJ (ed) *River Morphology*. Chichester: John Wiley & Sons, 1 - 17.

Slattery MC and Burt TP (1997) Particle size characteristics of suspended sediment in hillslope runoff and stream flow. *Earth Surface Processes and Landforms*. 22: 705-719.

Small IF, Rowan JS and Duck RW (2003) Long-term sediment yield in Crombie Reservoir catchment, Angus; and its regional significance within the Midland Valley of Scotland. *Hydrological Sciences Journal*. 48: 619 - 636.

Smets T, Poesen J and Knapen A (2008) Spatial scale effects on the effectiveness of organic mulches in reducing soil erosion by water.*Earth-Science Reviews*. 89: 1-12.

Smith LM, II and Kok LT (1984) Dispersal of Musk Thistle (Carduus nutans) Seeds. *Weed Science*. 32: 120-125.

Sontek (2012) *Flowtracker Handheld-ADV*. Available at http://www.sontek.com/flowtracker.php [Accessed on 28/09/2013]

Spokas K, Forcella F, Archer D and Reicosky D (2007) SeedChaser: Vertical soil tillage distribution model. *Computers and Electronics in Agriculture*. 57: 62-73.

Squire G (2012) Generic crop and weed cover curves estimated from unpublished data gathered as part of the Farm-Scale Evaluations of GMHT crops. (Personal Communitcation

Squire GR, Brooks DR, Bohan DA, Champion GT, Daniels RE, Haughton AJ, Hawes C, Heard MS, Hill MO, May MJ, Osborne JL, Perry JN, Roy DB, Woiwod IP and Firbank LG (2003) On the rationale and interpretation of the farm-scale evaluations of genetically-modified herbicide-tolerant crops. *Philos Trans R Soc Lond B Biol Sci*. 358: 1779-1799.

Squire GR, Rodger S and Wright G. (2000) Community-scale seedbank response to less intense rotation and reduced herbicide input at three sites. *The Annals of Applied Biology* 136: 47-57.

Syvitski, JPM and Milliman, JD (2007) Geology, Geography, and Humans Battle for Dominance over the Delivery of Fluvial Sediment to the Coastal Ocean. *The Journal of Geology*. 115: 1-19.

The Jame Hutton Institute (JHI) (2011a) *A Handbook of Field Sampling Protocols for Biodiversity Indicator Monitoring*. Dundee: The Jame Hutton Institute

The Jame Hutton Institute (JHI) (2011b) *Arable Seed Identification system*. Available at: http://asis.scri.ac.uk/ [Accessed on 13/6/2011]

Thompson K, Bakker J and Bekker R (1997) *The Soil Seed Banks of North West Europe: methodology, density and longevity*, Cambridge: Cambridge University Press.

Thompson K, Band SR and Hodgson JG (1993) Seed Size and Shape Predict Persistence in Soil. *Functional Ecology*. 7: 236-241.

Tørresen KS, Skuterud R, Tandsæther HJ and Hagemo MB. (2003) Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop Protection*. 22: 185-200.

Tyler AN, Davidson DA and Grieve IC (2001) In situ radiometric mapping of soil erosion and field-moist bulk density on cultivated fields. *Soil Use and Management*. 17: 88-96.

Van Oost K, Govers G, De Alba S and Quine TA (2006) Tillage erosion: a review of controlling factors and implications for soil quality. *Progress in Physical Geography*. 30: 443-466.

Van Oost K, Quine TA, Govers G, De Gryze S, Six J, Harden JW, Ritchie JC, McCarty GW, Heckrath G, Kosmas C, Giraldez JV, da Silva JRM and Merckx R (2007) The Impact of Agricultural Soil Erosion on the Global Carbon Cycle. *Science*. 318: 626-629.

Vander Wall SB and Longland WS (2004) Diplochory: are two seed dispersers better than one? *Trends in Ecology & Evolution*. 19: 155-161.

Venable DL and Brown JS (1988) The Selective Interactions of Dispersal, Dormancy, and Seed Size as Adaptations for Reducing Risk in Variable Environments. *The American Naturalist*. 131: 360-384.

Verheijen FGA, Jones RJA, Rickson RJ and Smith CJ (2009) Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews.* 94: 23-38.

Wallbrink PJ, Walling DE and He Q (2002) Radionuclide measurement using HPGe Gamma Spectrometry. In: Zapata F (ed) *Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides.* London: Kluwer Academic Publishers, 67 - 96.

Walling DE and Collins AL (2008a) The catchment sediment budget as a management tool. *Environmental Science & Policy*. 11: 136-143.

Walling DE, Collins AL, Jones PA, Leeks GJL and Old G (2006) Establishing fine-grained sediment budgets for the Pang and Lambourn LOCAR catchments, UK. *Journal of Hydrology*. 330: 126-141.

Walling DE, Collins AL and Stroud RW (2008b) Tracing suspended sediment and particulate phosphorus sources in catchments. *Journal of Hydrology*. 350: 274-289.

Walling DE, He Q and Appleby PG (2002a) Conversion Models for Use In Soil-Erosion, Soil-Resdistribution and Sedimentation Investigations. In: Zapata F (ed) *Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides.* London: Kluwer Academic Publishers, 67 - 96.

Walling DE, He Q and Whelan PA (2003) Using 137Cs measurements to validate the application of the AGNPS and ANSWERS erosion and sediment yield models in two small Devon catchments. *Soil and Tillage Research.* 69: 27-43.

Walling DE and Quine TA (1990) Calibration of caesium-137 measurements to provide quantitative erosion rate data. *Land Degradation & Development.* 2: 161-175.

Walling DE and Quine TA (1991) Use of ^{137}Cs measurements to investigate soil erosion on arable fields in the UK: potential applications and limitations. *Journal of Soil Science*. 42: 147-165.

Walling DE and Quine TA (1992) The use of caesium-137 measurements in soil erosion surveys. *Erosion and Sediment Transport Monitoring Programmes in River Basins.* Oslo, Norway, 143 - 152.

Walling DE, Russell MA, Hodgkinson RA and Zhang Y (2002b) Establishing sediment budgets for two small lowland agricultural catchments in the UK. *Catena.* 47: 323-353.

Walling DE and Webb BW (1987) Suspended load in gravel-bed rivers: UK experience. In: Thorne CR, Bathurst JC and Hey RD (eds) *Sediment Transport in Gravel-Bed Rivers.* Chichester: Wiley, 691 - 723.

Walling DE, Zhang Y and He Q (2007) Models for Converting Measurements of Environmental Radionuclide Inventories (137Cs, Excess 210Pb, and 7Be) to Estimates of Soil Erosion and Deposition Rates (Including Software for Model Implementation). International Atomic Energy Agency. Available online at http://www-naweb.iaea.org/nafa/swmn/Helpfile.pdf. [Accessed on 22/7/13]

Watson SJ, Mauchline AL, Brown VK and Froud-Williams RJ (2003) Post-dispersal losses of Stellaria media and Polygonum aviculare seeds in spring barley (*Hordeum vulgare*). In: Bekker RM, Forcella F, Grundy AC, et al. (eds) *Seedbanks: Determination, Dynamics & Management.* Warwick: Association of Applied Biologists, 203-208.

Webster R and Lark M (2013) *Field Sampling for Environmental Science and Management.* Oxford: Routledge.

Westerman PR, Dixon PM and Liebman M (2009) Burial rates of surrogate seeds in arable fields. *Weed Research.* 49: 142-152.

Westerman PR, Liebman M, Heggenstaller AH and Forcella F (2006) Integrating Measurements of Seed Availability and Removal to Estimate Weed Seed Losses Due to Predation. *Weed Science.* 54: 566-574.

Westerman PR, Luijendijk CD, Wevers JDA and Van Der Werf W (2011) Weed seed predation in a phenologically late crop. *Weed Research* 51: 157-164.

Westerman PR, Wes JS, Kropff MJ and Van Der Werf W (2003) Annual losses of weed seeds due to predation in organic cereal fields. *Journal of Applied Ecology*. 40: 824-836.

Wild A (1993) *Soils and the Environment: An Introduction,* Cambridge: Cambridge University Press.

Wiles L and Schweizer E (2002) Spatial dependence of weed seed banks and strategies for sampling. *Weed Science*. 50 :595 - 606

Wilson BJ and Lawson HM (1992) Seedbank persistence and seedling emergence of seven weed species in autumn-sown crops following a single year's seeding. *Annals of Applied Biology*. 120: 105-116.

Withers PJA, Hodgkinson RA, Bates A and Withers CM (2006) Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. *Soil Use and Management.* 22: 245-255.

Zapata F, Garcia-Agudo E, Ritchie, JC and Appleby, PG (2003) In: Zapata F (ed) *Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides.* London: Kluwer Academic Publishers, 1 - 14

Zhang W, Ricketts TH, Kremen C, Carney K and Swinton SM (2007) Ecosystem services and dis-services to agriculture. *Ecological Economics.* 64: 253-260.

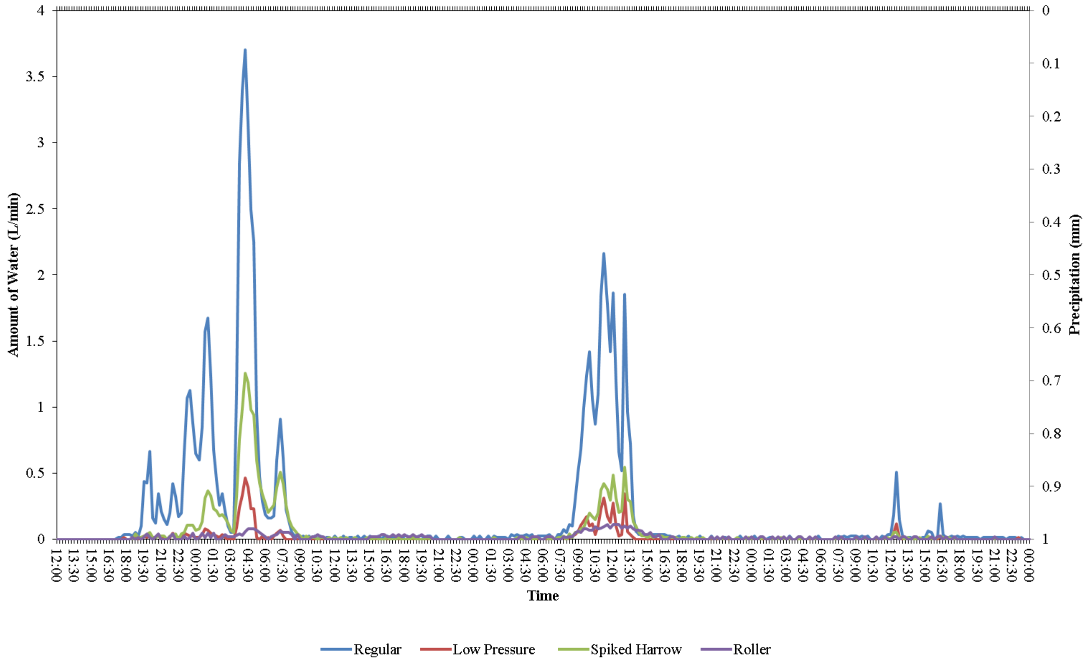
Zhongming W, Lees BG, Feng J, Wanning L and Haijing S (2010) Stratified vegetation cover index: A new way to assess vegetation impact on soil erosion. *Catena.* 83: 87-93.

Zobeck TM (2004) Rapid soil particle size analyses using laser diffraction *Applied Engineering in Agriculture*. 20: 633 - 639.

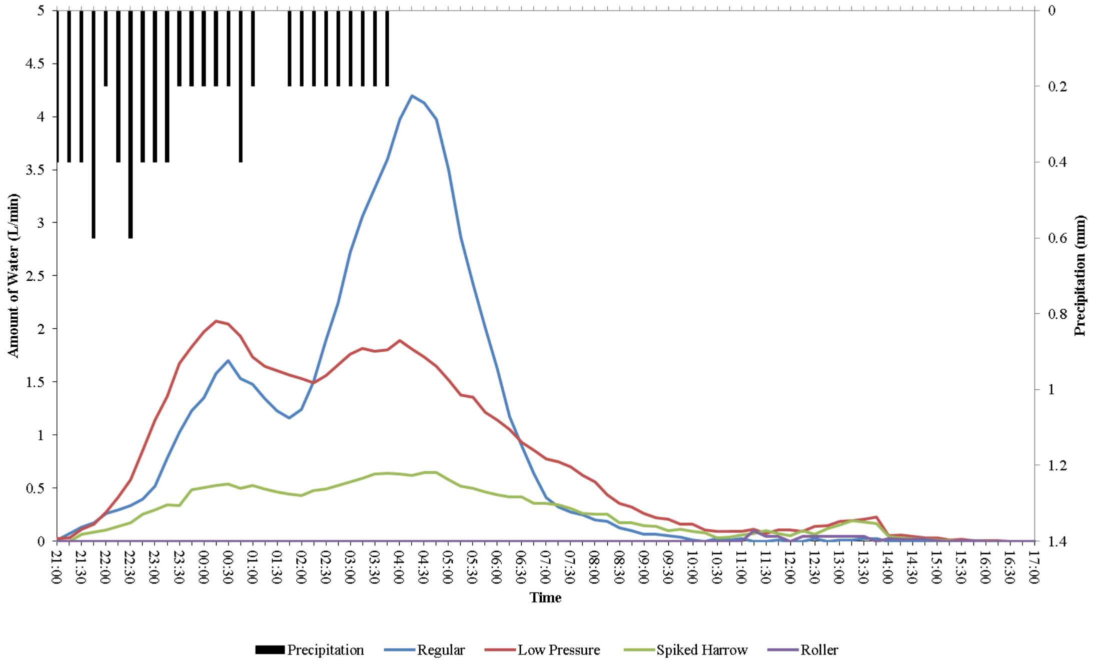
Appendix A: Tramline Hydrographs

2010/11

Event 1: 11th December 2012 at 12:00 until 14th December at 00:00

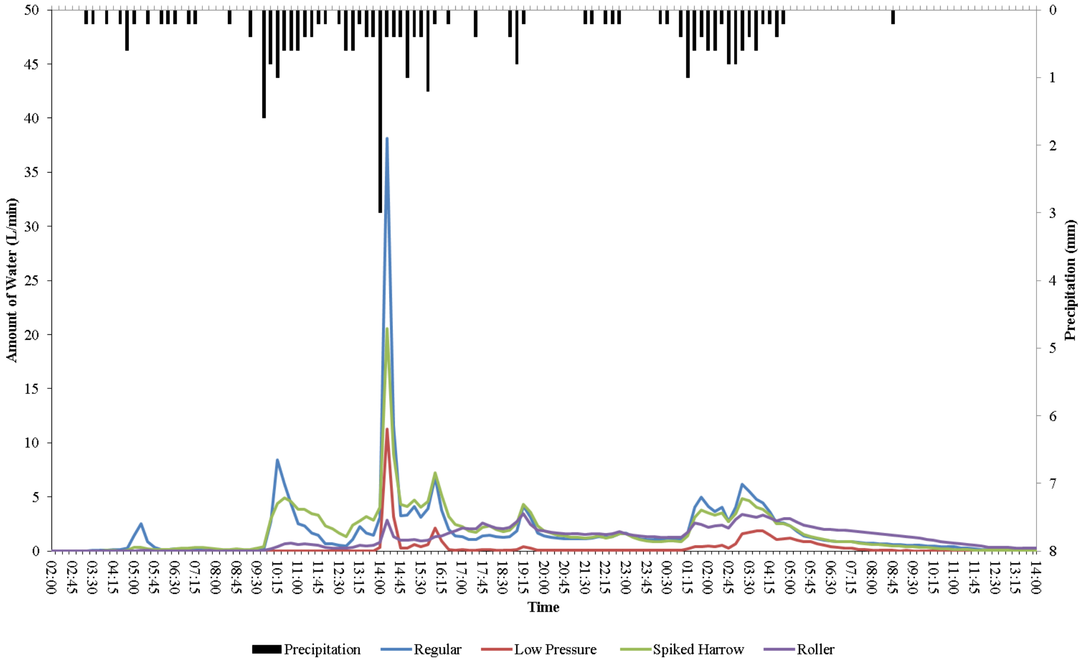


Event 2: 11th January 2011at 21:00 until 12th January at 17:00

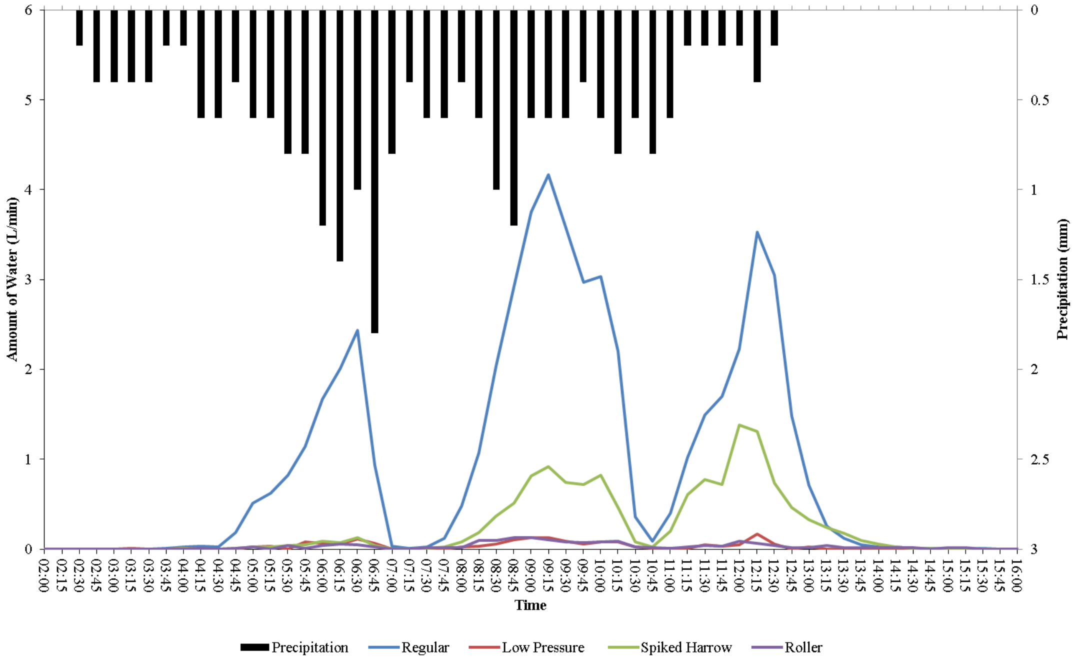


Event 3: No data due to instrument failure

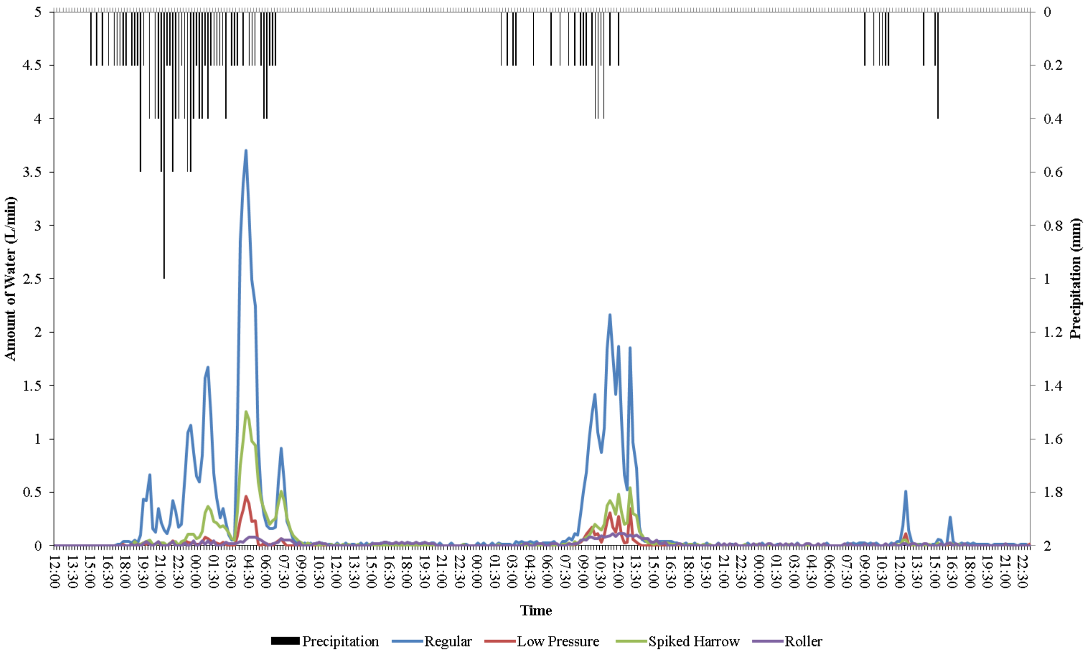
Event 4: 15th January 2011 at 02:00 until 16th January 2011 at 14:00



Event 5: 7th February 2011 at 02:00 until 16:00

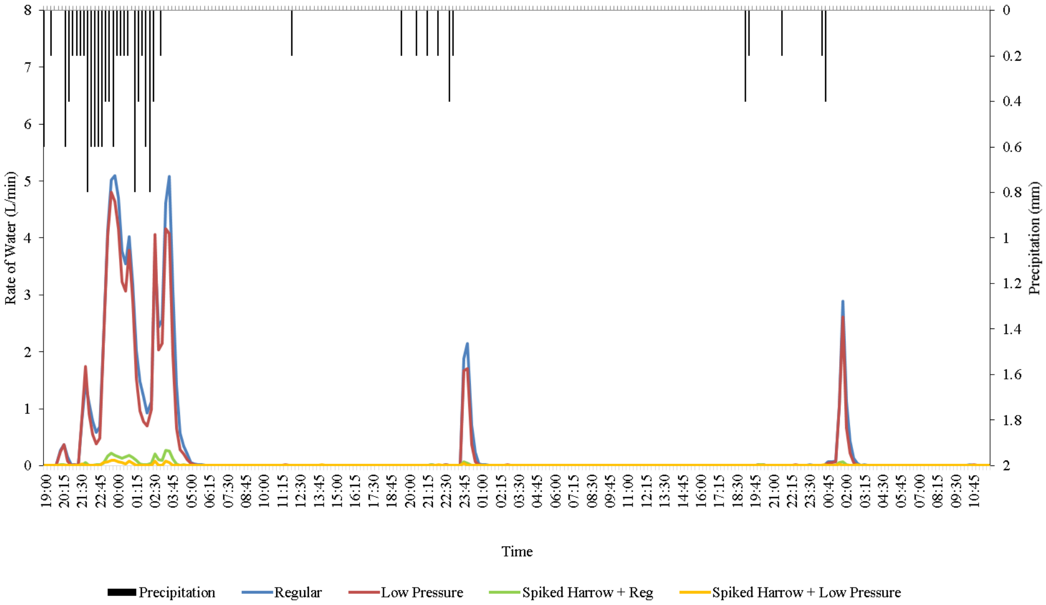


Event 6: 11th February 2011 at 12:00 until 14th February 2011 at 23:00

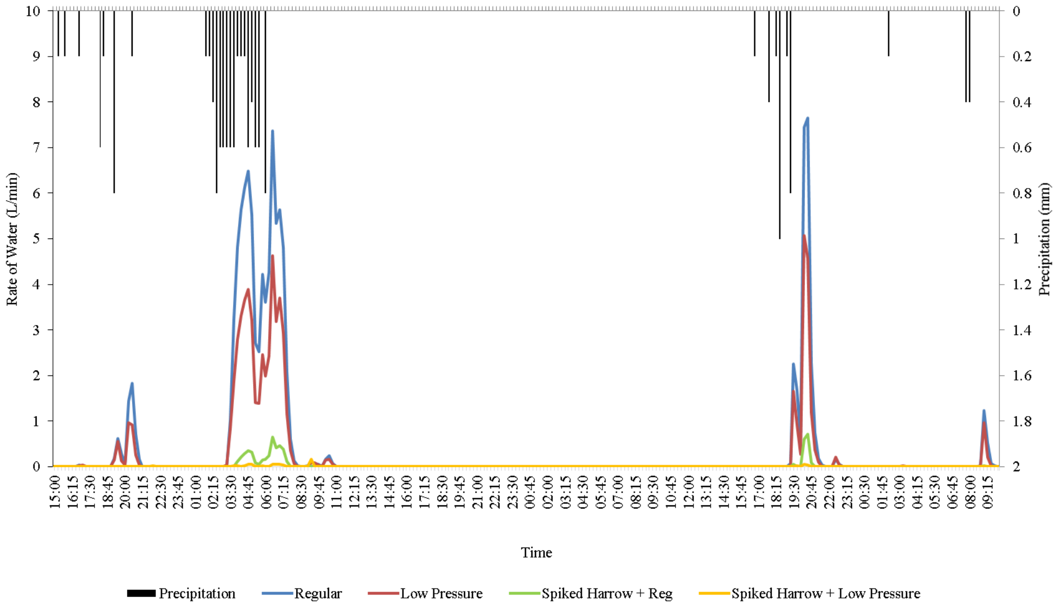


2011/12

Event 7: 28th November 2011 at 19:00 until 1st December at 11:45

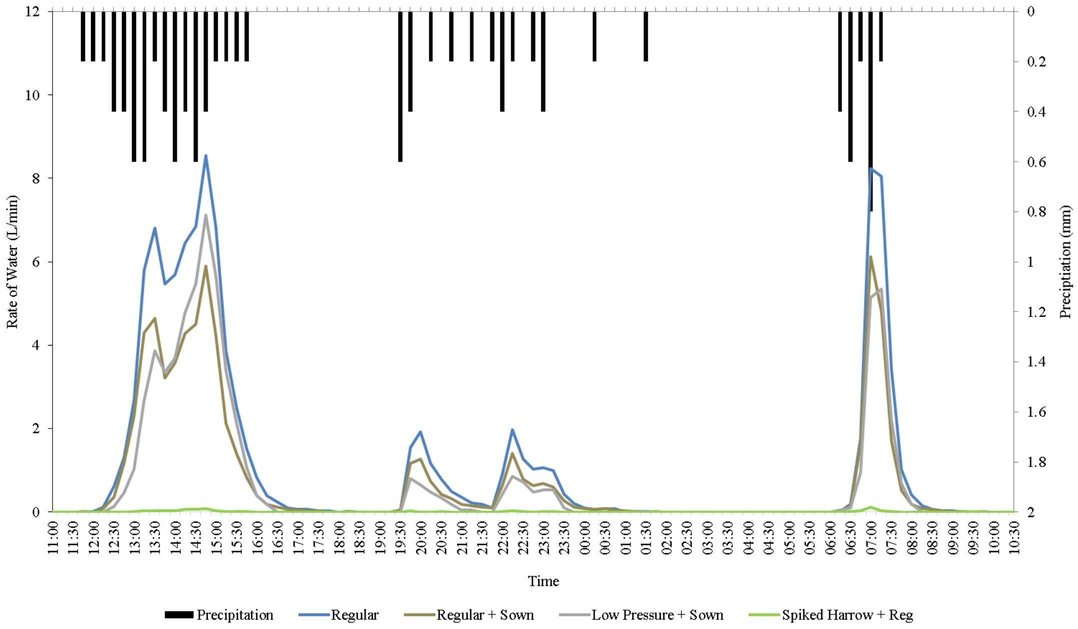


Event 8: 2nd January 2012 at 15:00 until 5th January 2011 at 10:00

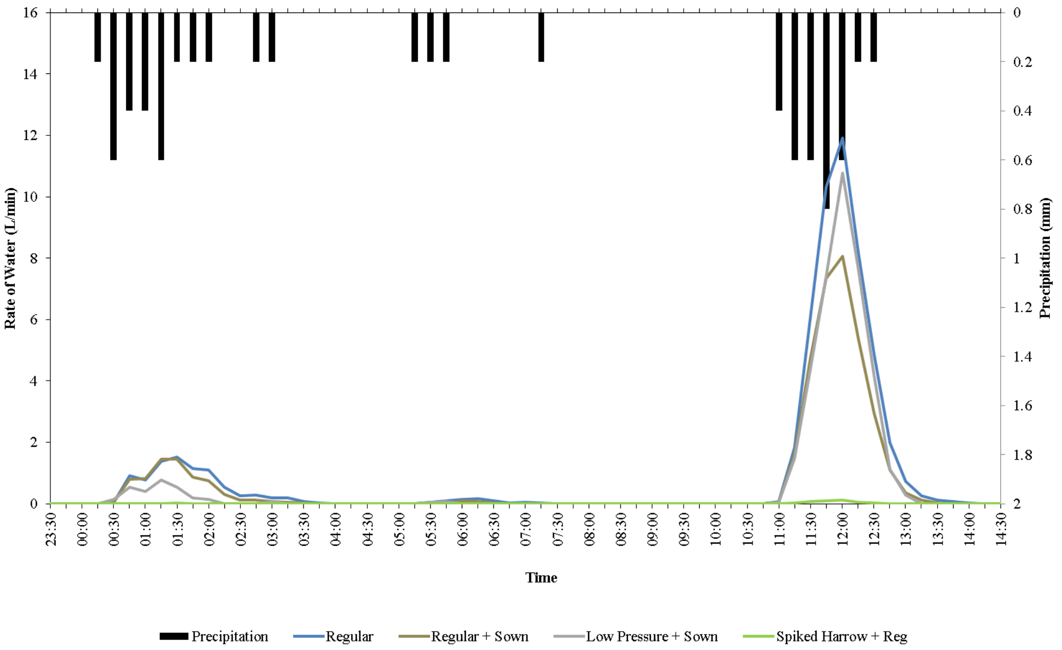


2012/13

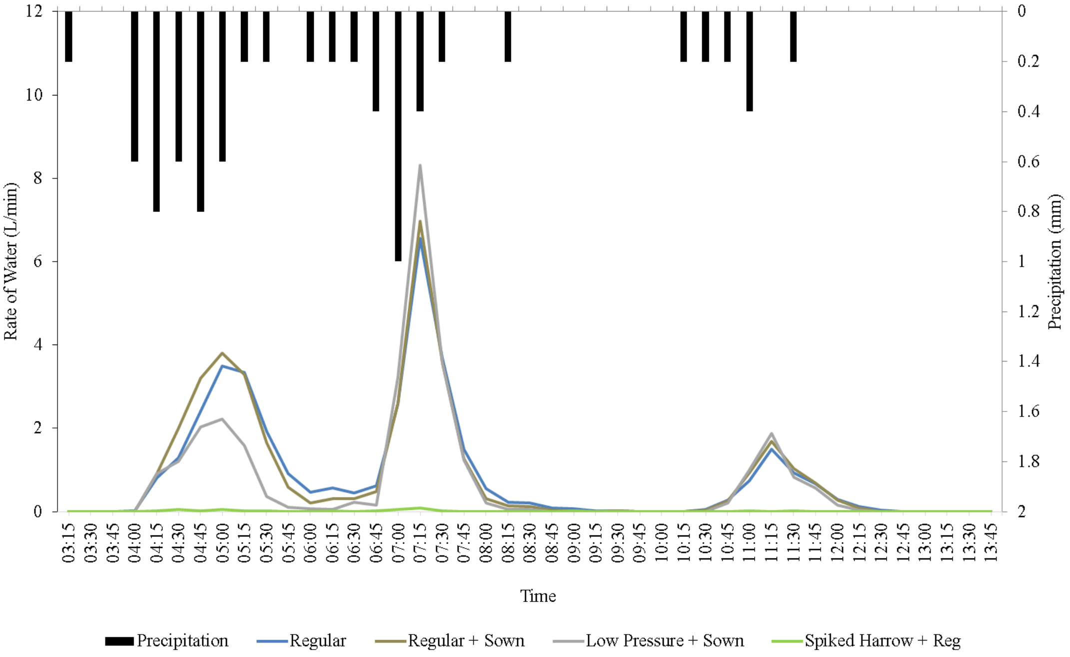
Event 9: 17th October 2012 at 11:00 until 18th October at 10:30



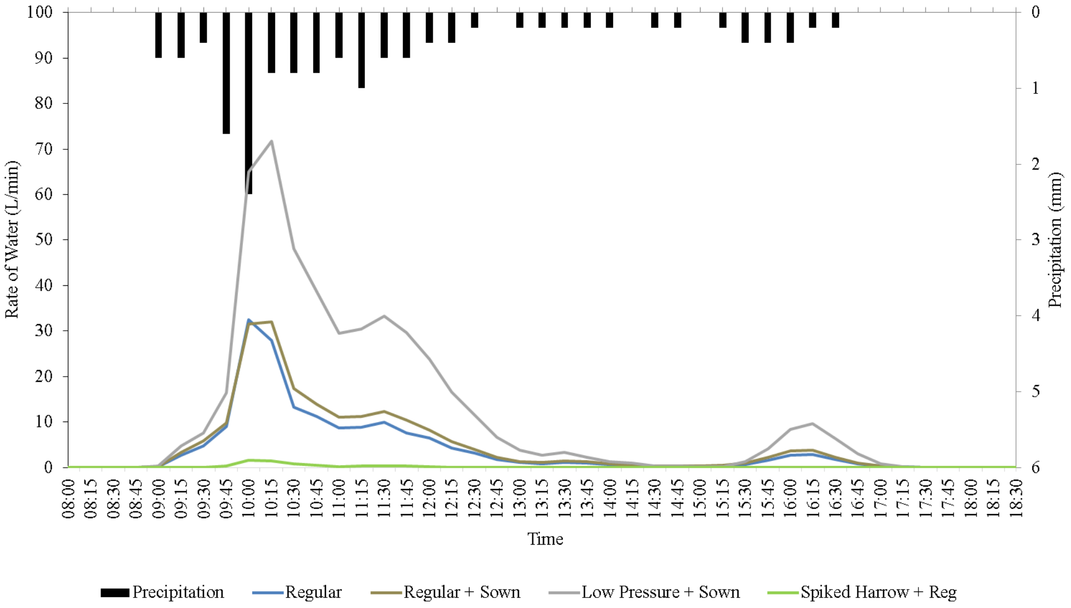
Event 10: 1st November 2012 at 23:30 until 2nd November 2012 at 14:30



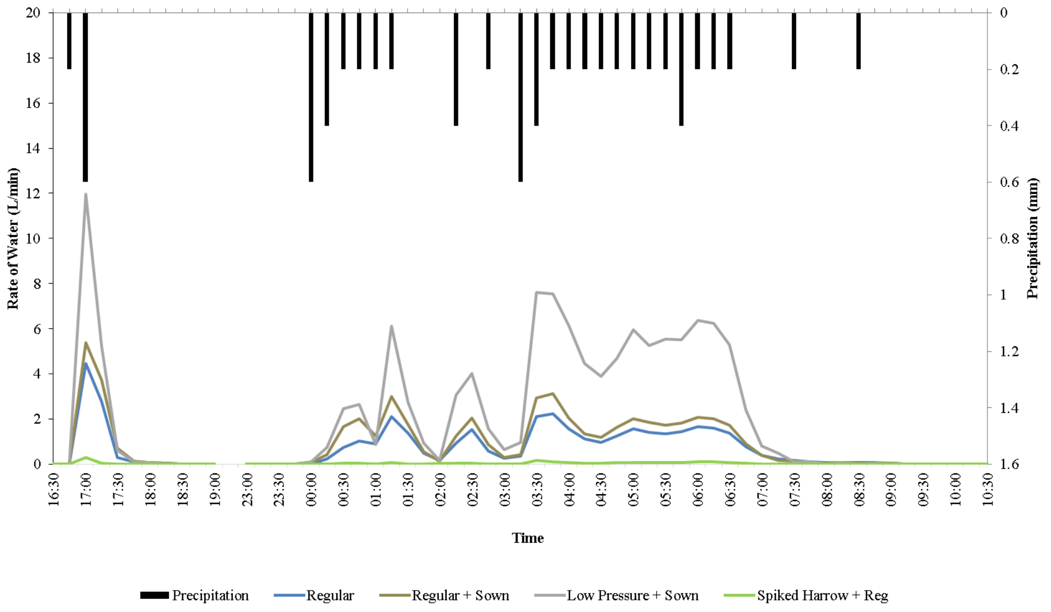
Event 11:19th November 2012 at 03:15 until 13:45



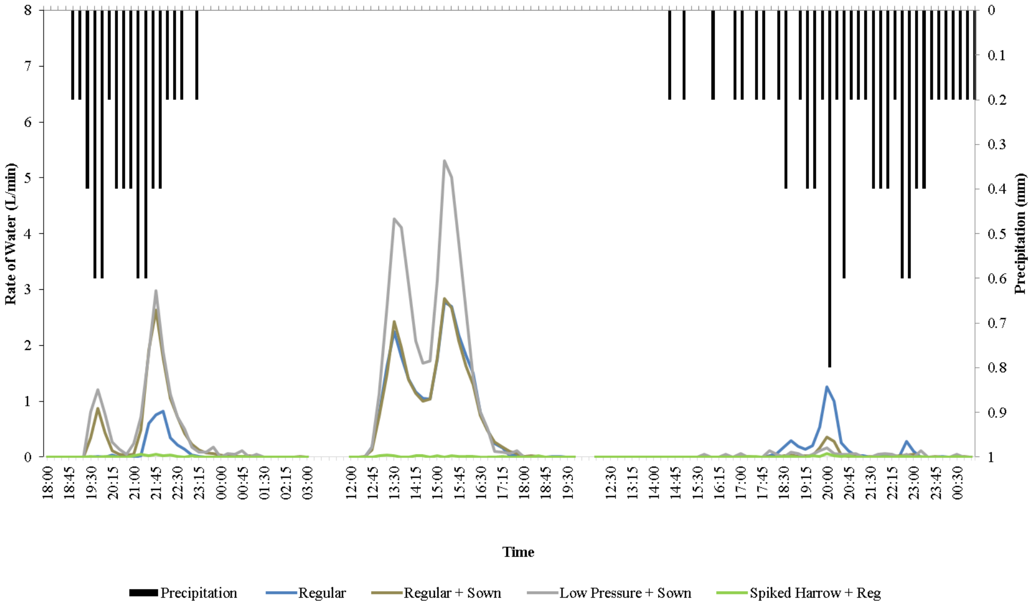
Event 12: 22nd November 2012 at 08:00 until 18:30



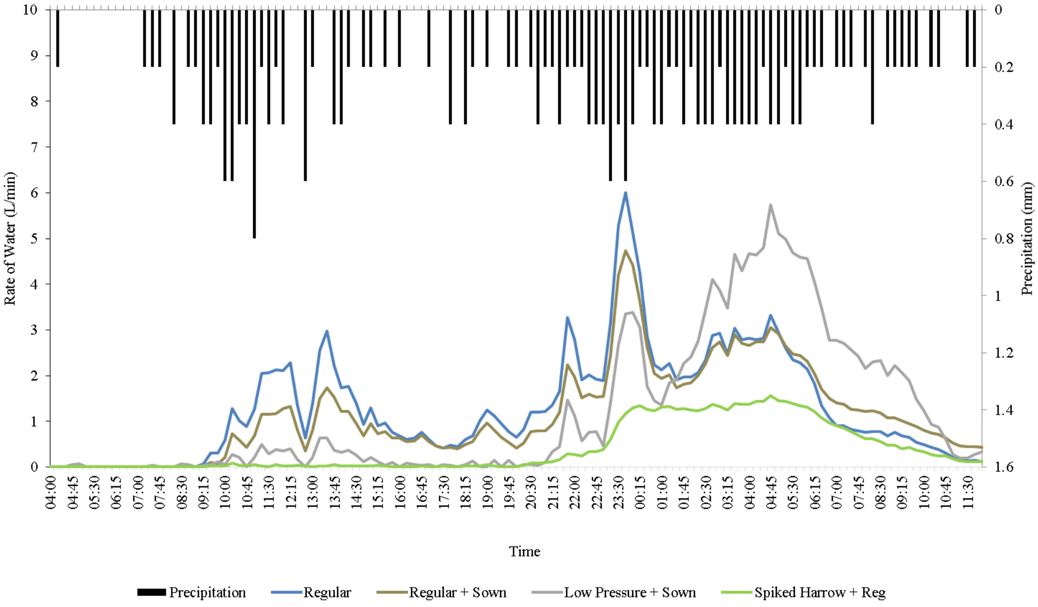
Event 13: 25th November 16:30 until 19:00, and 24th November at 23:00 until 25th November at 13:30



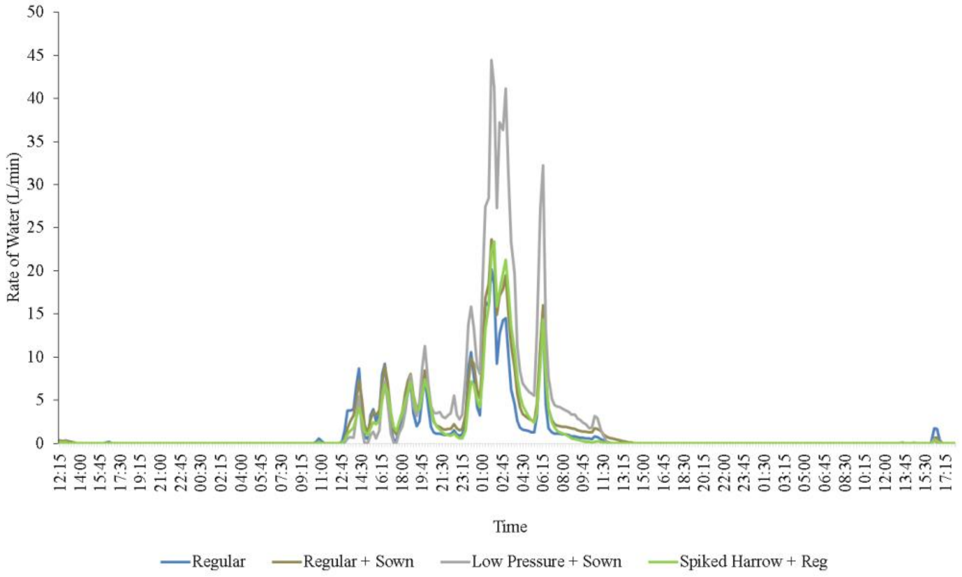
Event 14: 6th December 2012at 18:00 until 7th December at 03:00, 8th December at 12:00 until19:30, and 14th December at 12:00 until 15th December at 01:00



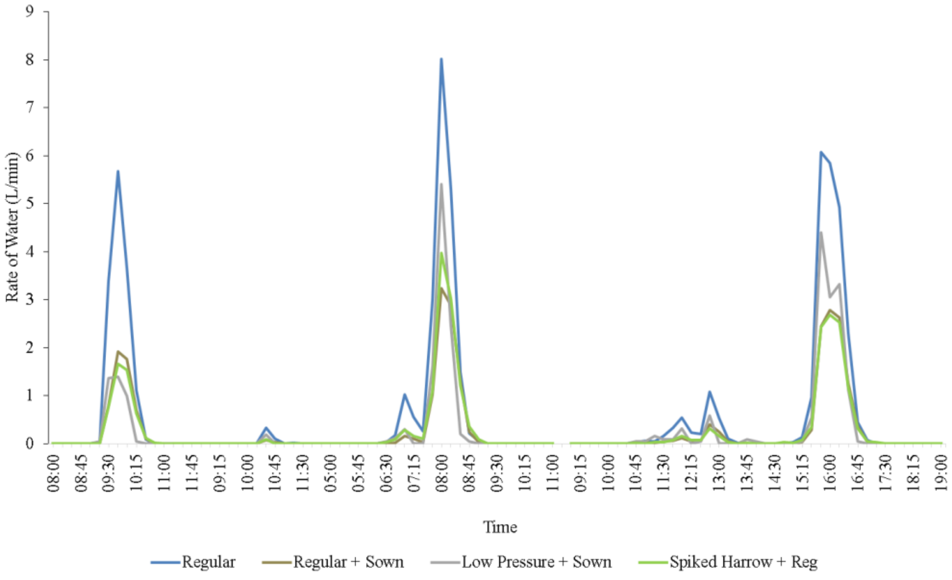
Event 15: 20th December 2012 at 04:00 until 21st December at 12:00



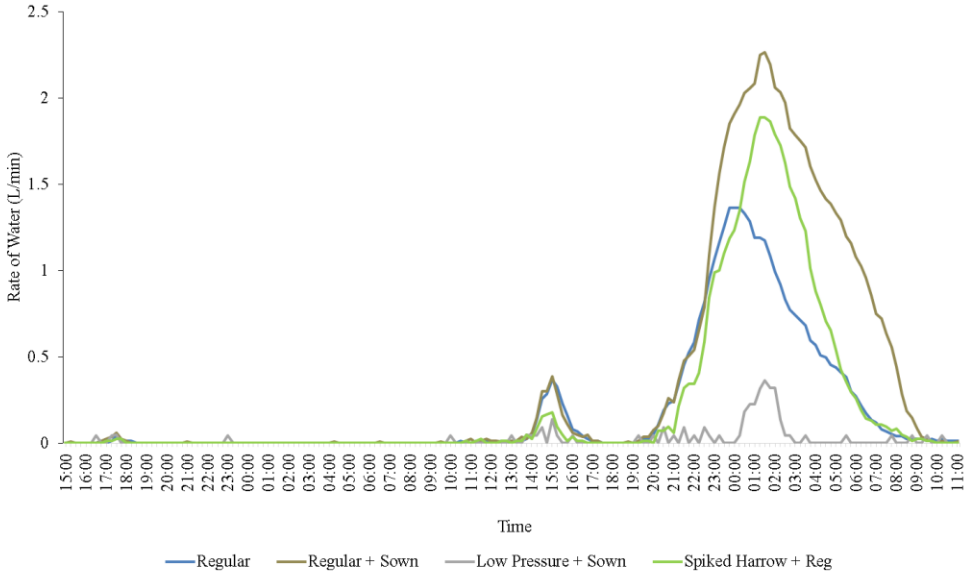
Event 16: 21st December 2012 at 12:15 until 24th December at 18:00 (no precipitation data available)



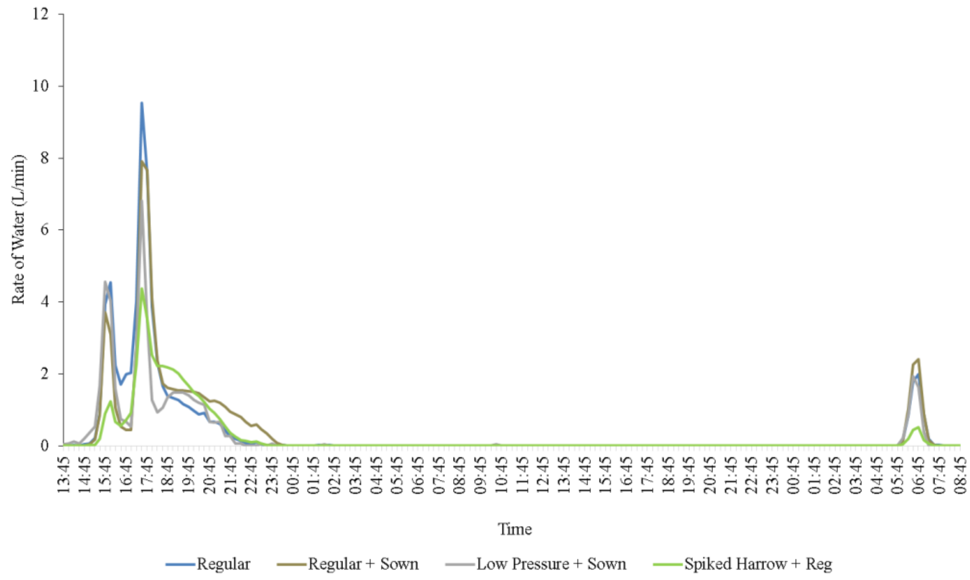
Event 17: 29th December 2012 at 08:00 until 2nd January 2013 at 11:00, and 7th January 2013 at 09:00 until 19:00 (no precipitation data was available)



Event 18: 27th January 2013 at 15:00 until 29th January at 11:00 (no precipitation data was available)

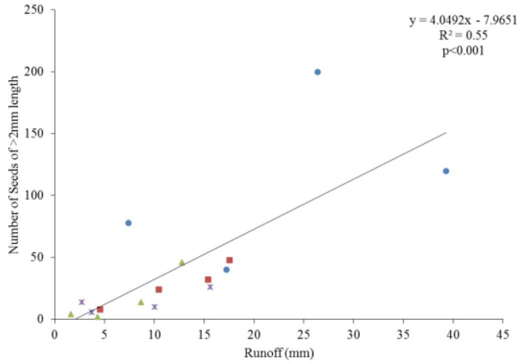


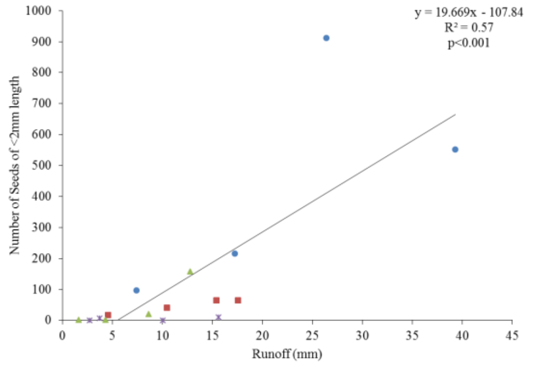
Event 19: 29th January 2013 at 13:45 until 31st January at 08:45 (no precipitation data was available)

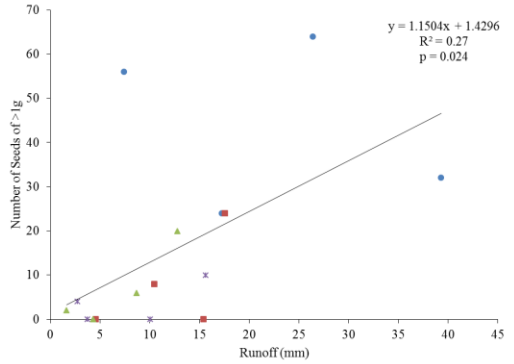


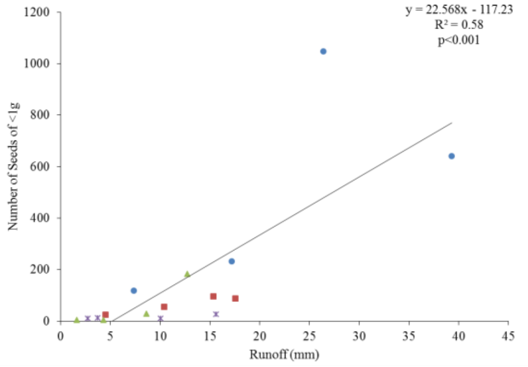
Appendix B: Scatter Plots for Different Seed Morphologies against Runoff and Sediment Load From Tramlines in 2010/11, 2011/12 and 2012/13

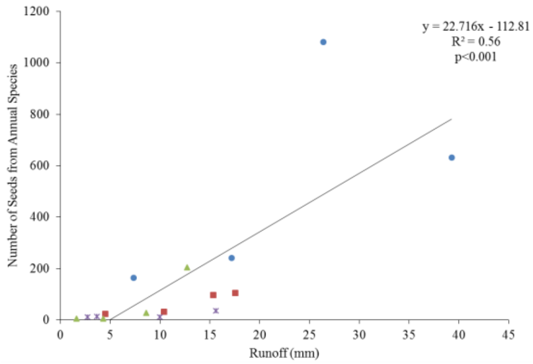
2010/11 - Runoff

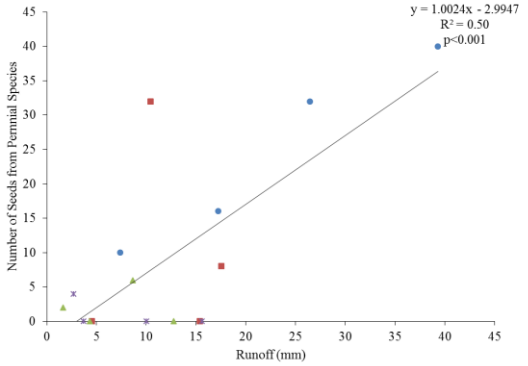




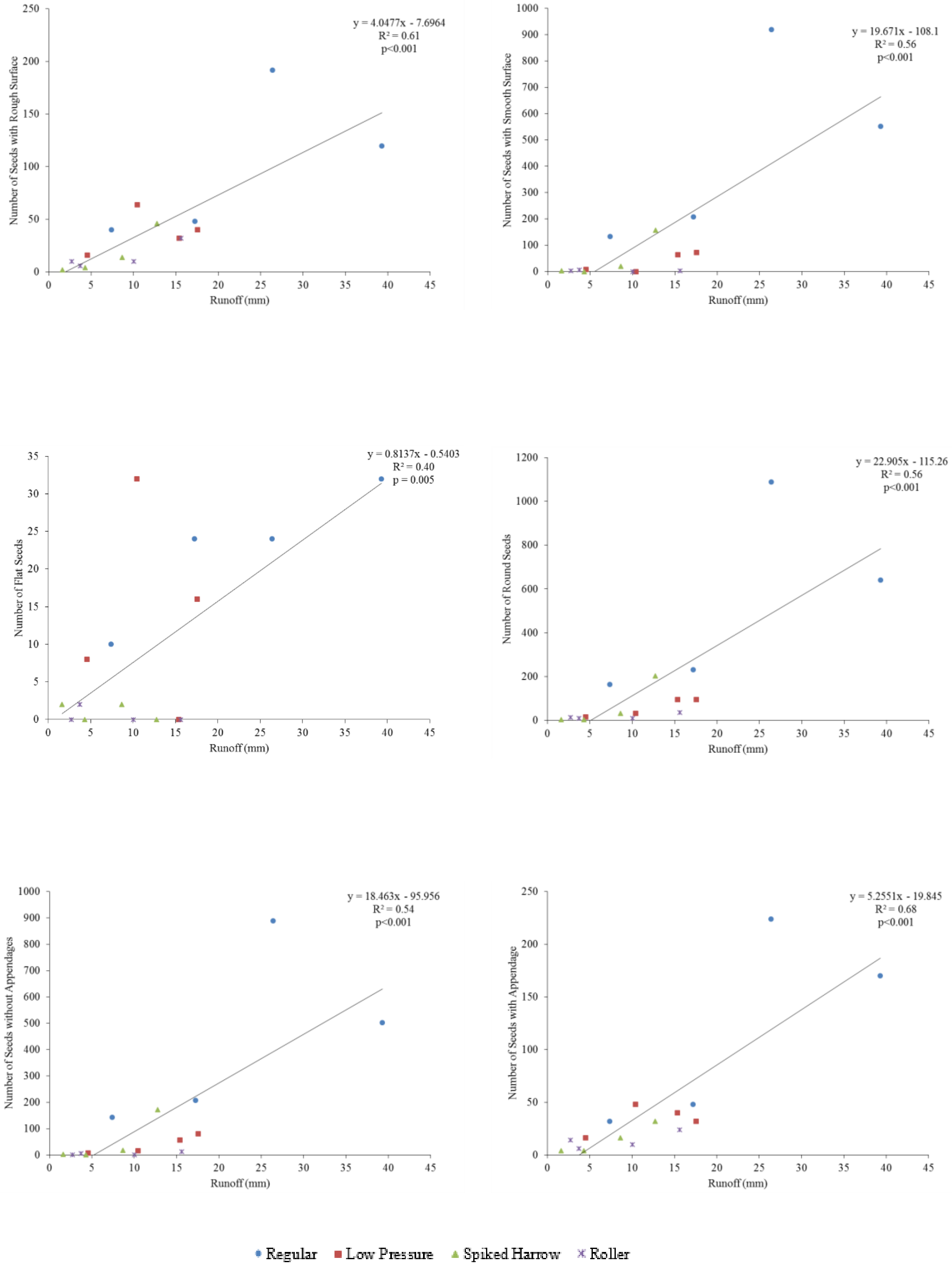




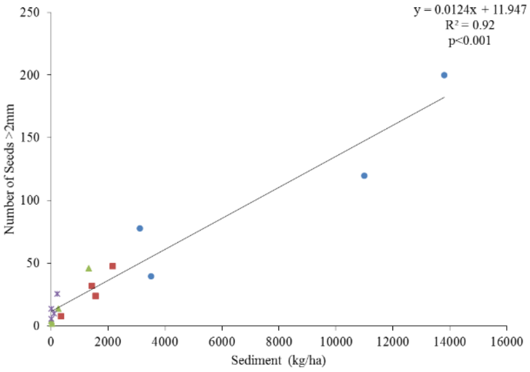


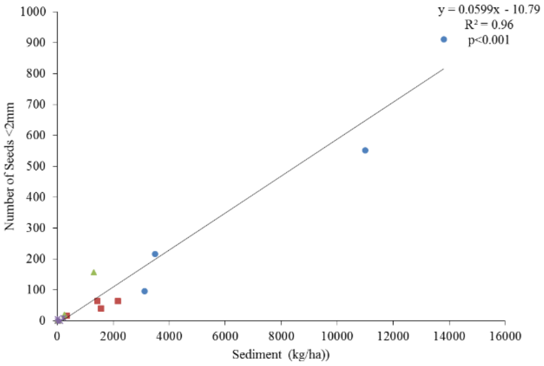


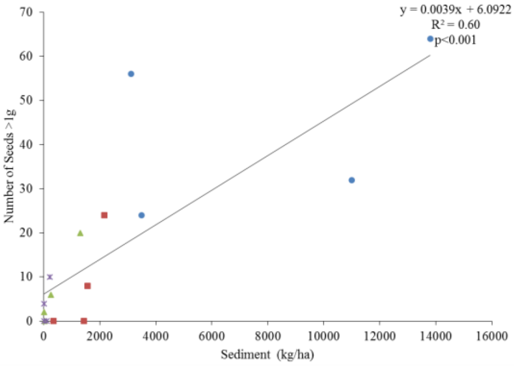
● Regular ■ Low Pressure ▲ Spiked Harrow ✕ Roller

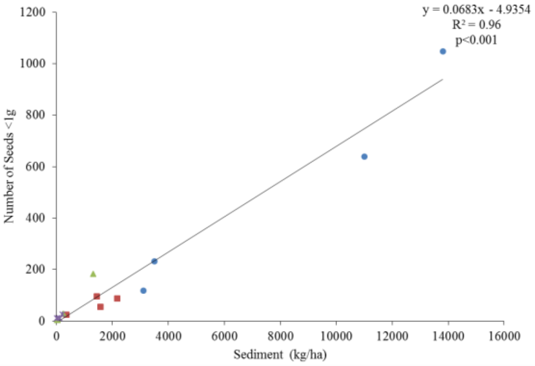

Number of Seeds with Rough Surface
Runoff (mm)
y = 4.0477x - 7.6964
R² = 0.61
p<0.001
Number of Seeds with Smooth Surface
Runoff (mm)
y = 19.671x - 108.1
R² = 0.56
p<0.001
Number of Flat Seeds
Runoff (mm)
y = 0.8137x - 0.5403
R² = 0.40
p = 0.005
Number of Round Seeds
Runoff (mm)
y = 22.905x - 115.26
R² = 0.56
p<0.001
Number of Seeds without Appendages
Runoff (mm)
y = 18.463x - 95.956
R² = 0.54
p<0.001
Number of Seeds with Appendage
Runoff (mm)
y = 5.2551x - 19.845
R² = 0.68
p<0.001
Regular
Low Pressure
Spiked Harrow
Roller

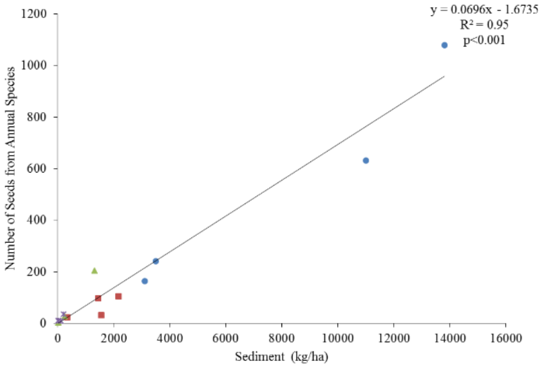
2010/11 - Sediment

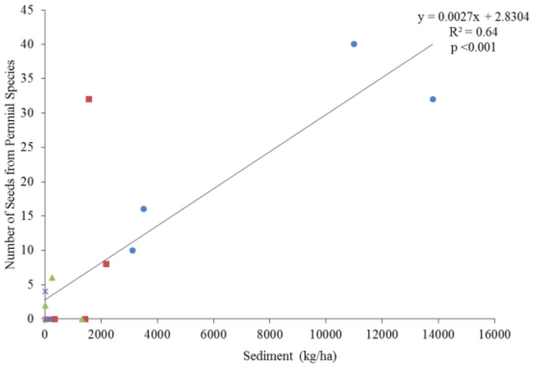






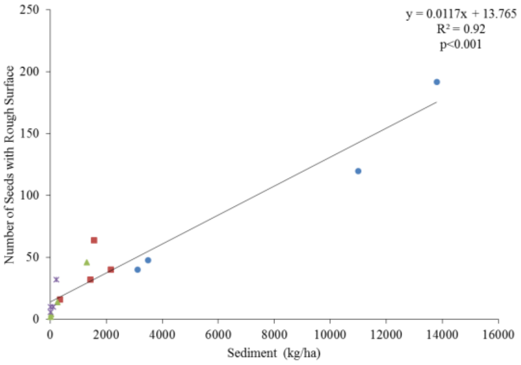


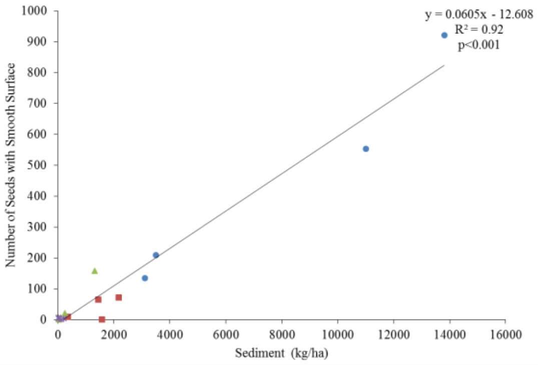


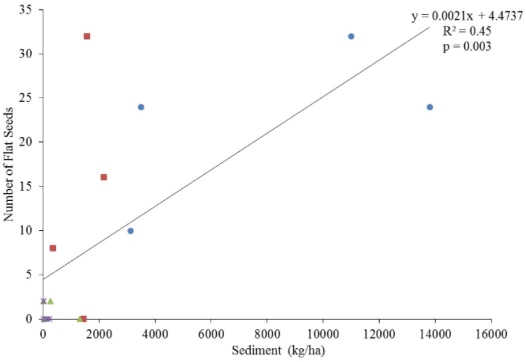


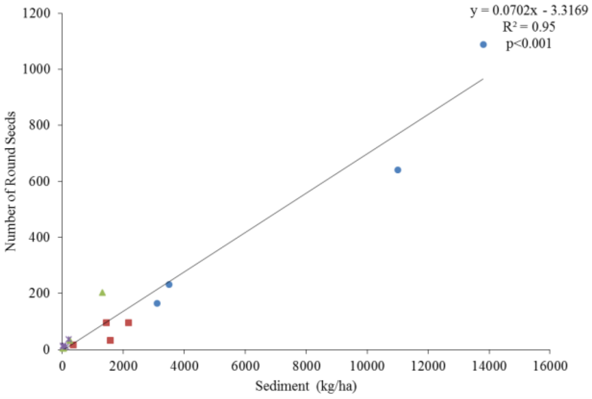
● Regular ■ Low Pressure ▲ Spiked Harrow ✕ Roller

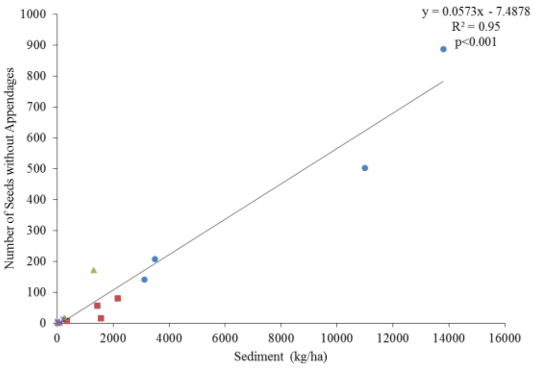
2010/11 - Sediment

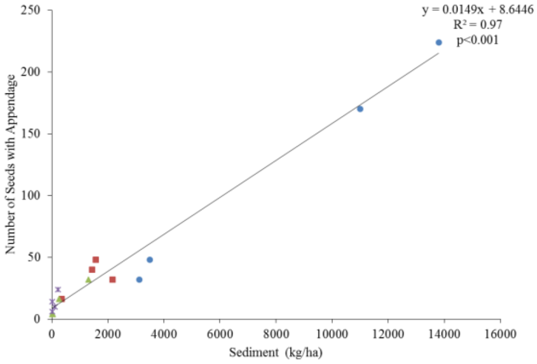






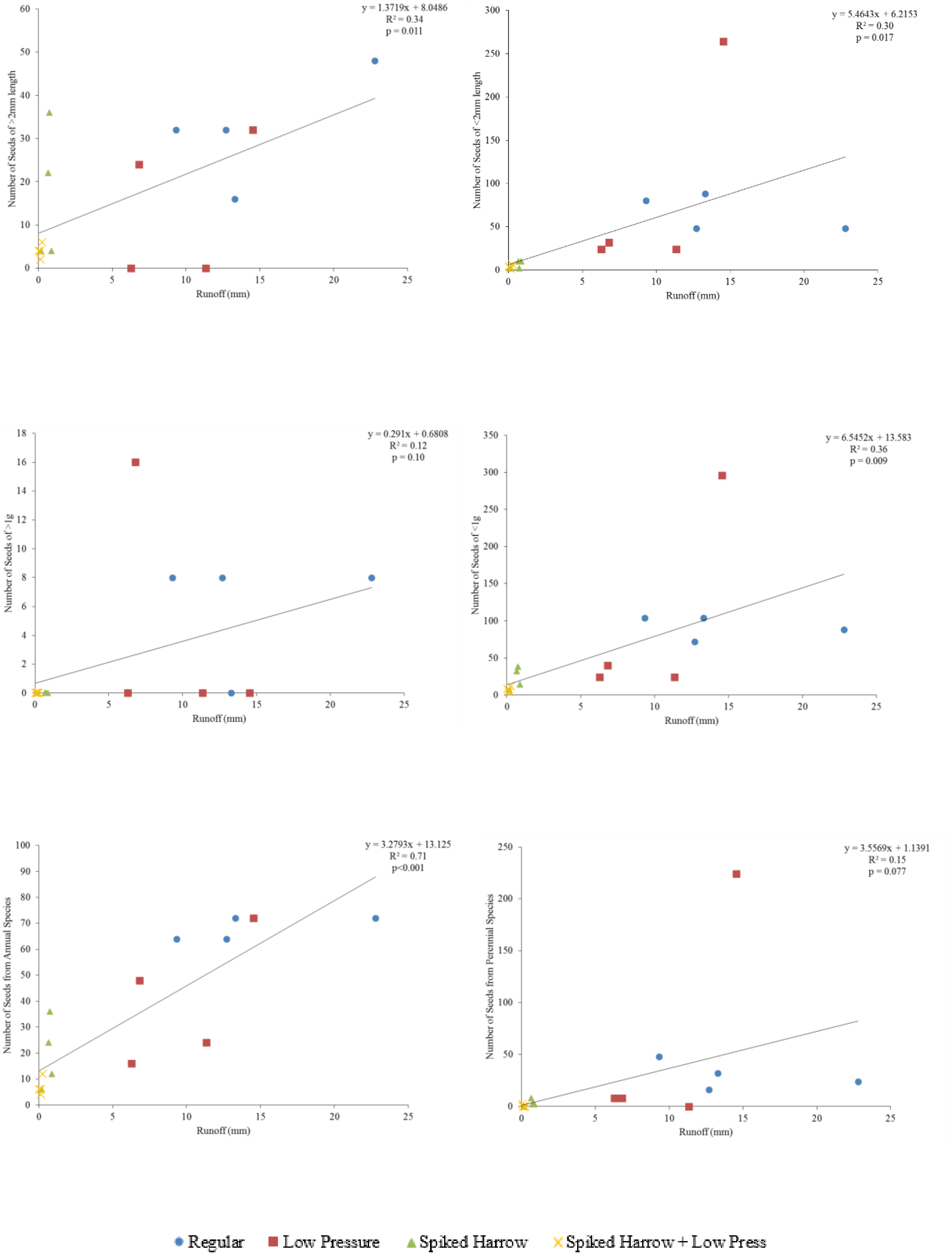




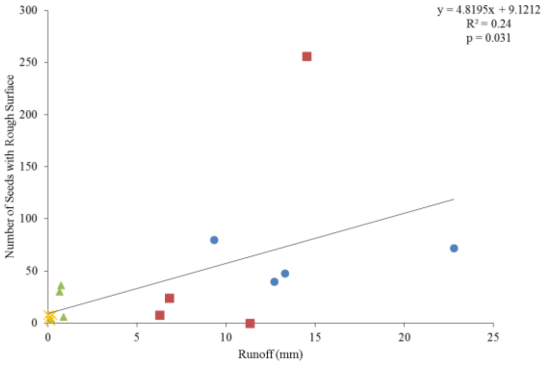


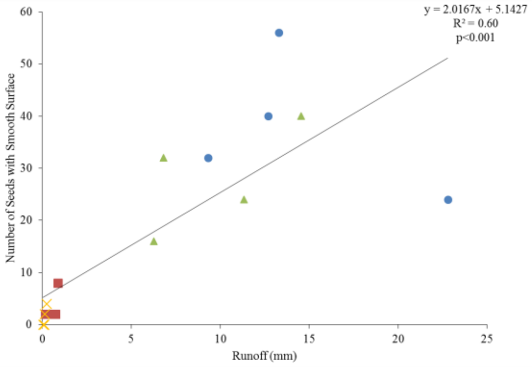
● Regular ■ Low Pressure ▲ Spiked Harrow ✕ Roller

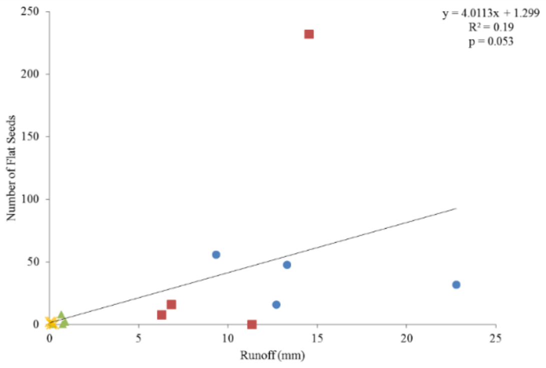
2011/12 – Runoff

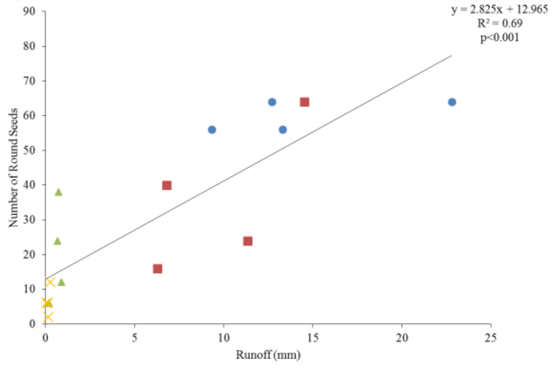


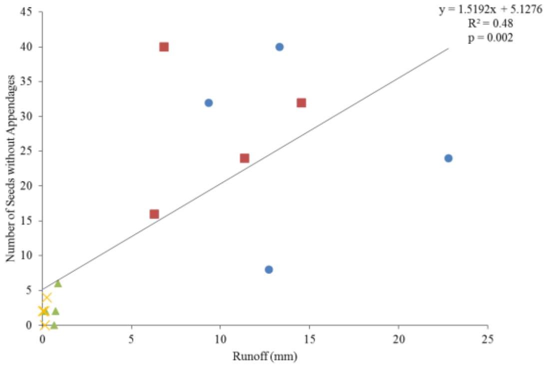
2011/12 – Runoff

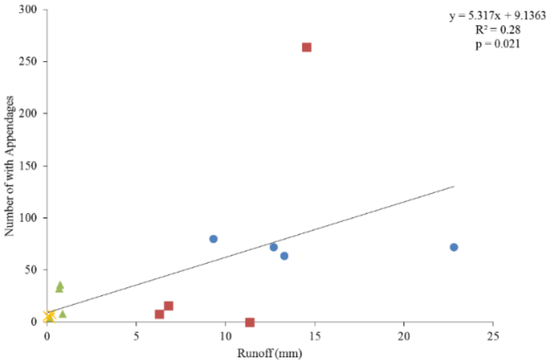






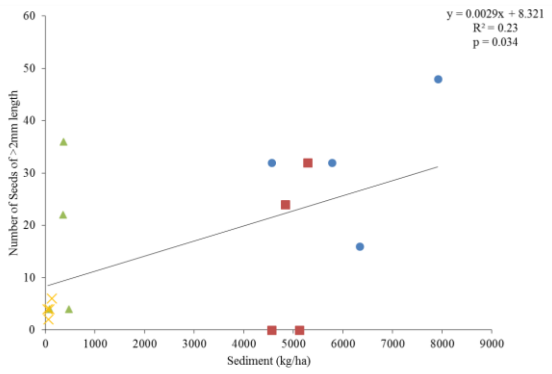


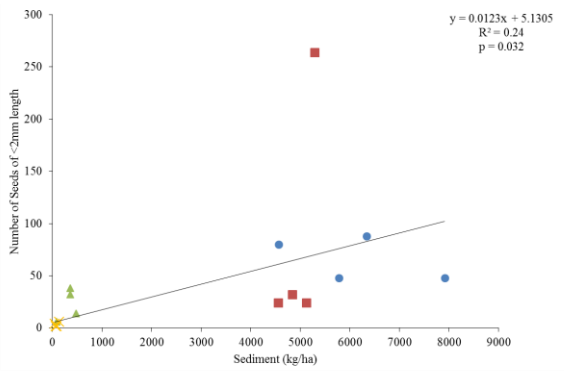


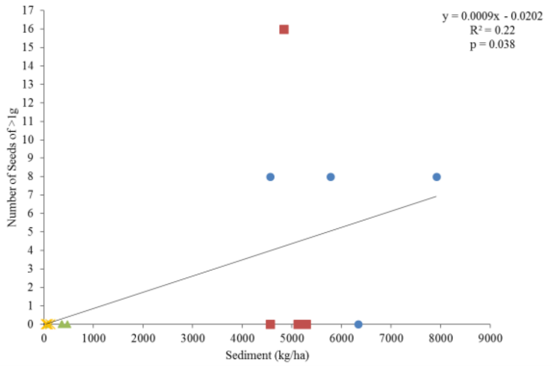


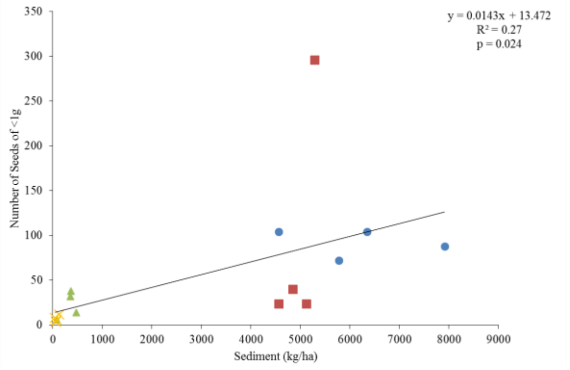
● Regular ■ Low Pressure ▲ Spiked Harrow × Spiked Harrow + Low Press

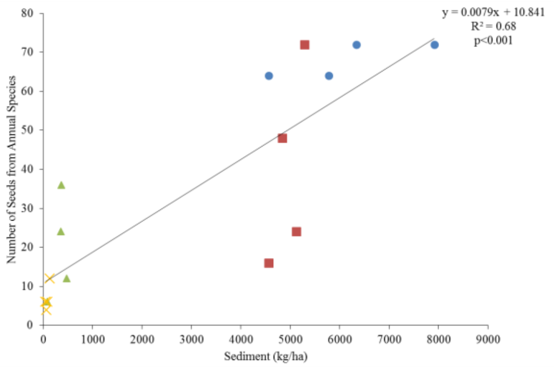
2011/12 - Sediment

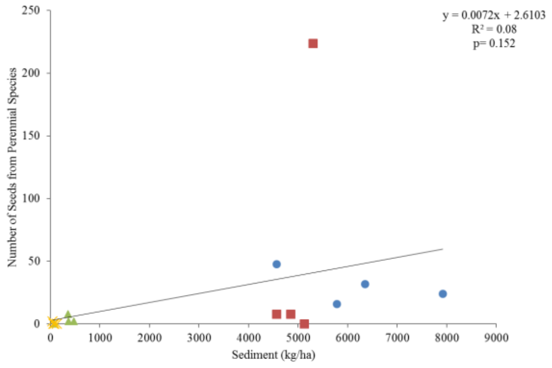






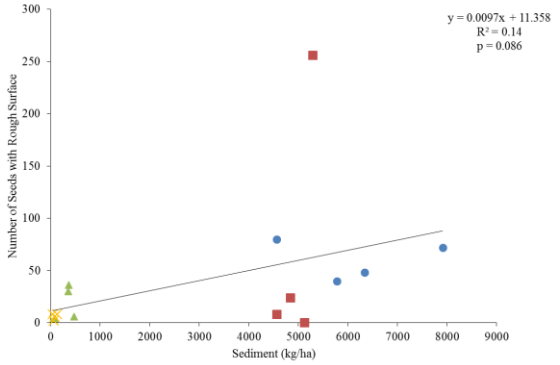


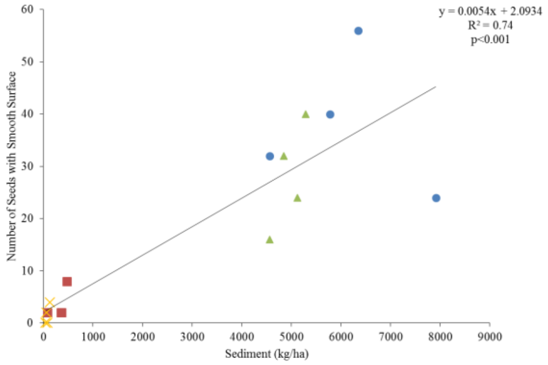


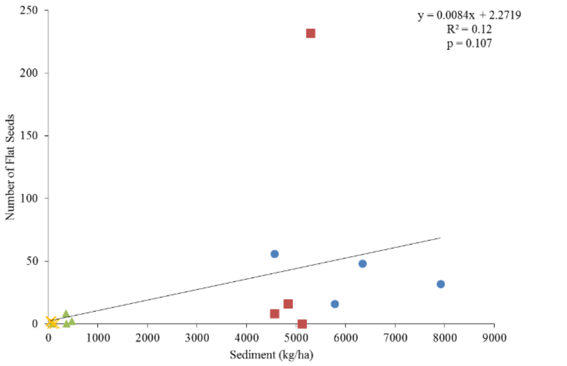


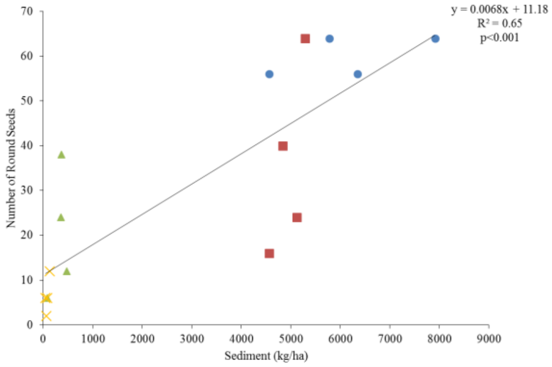
● Regular 🟥 Low Pressure ▲ Spiked Harrow ✕ Spiked Harrow + Low Press

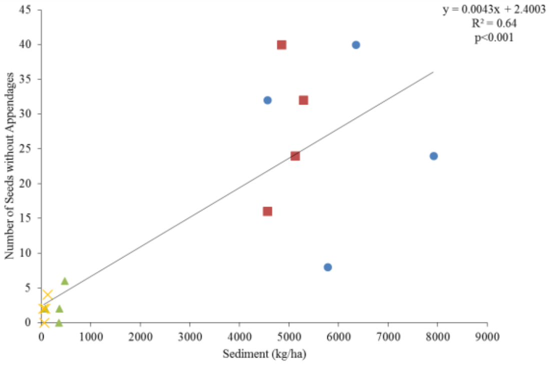
2011/12 - Sediment

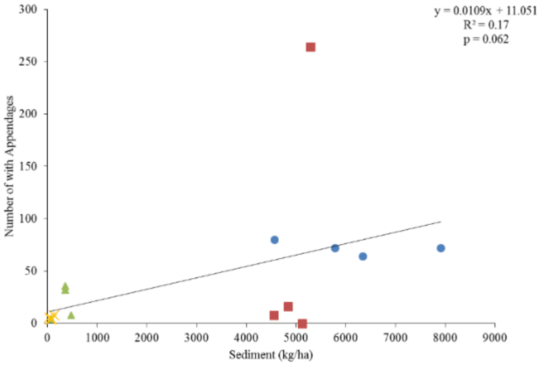






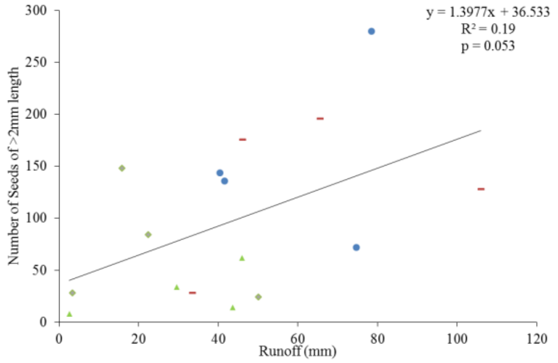


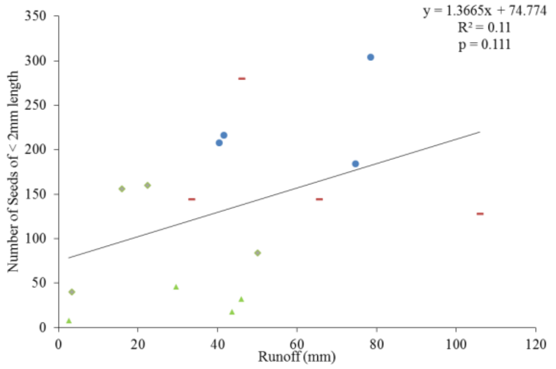


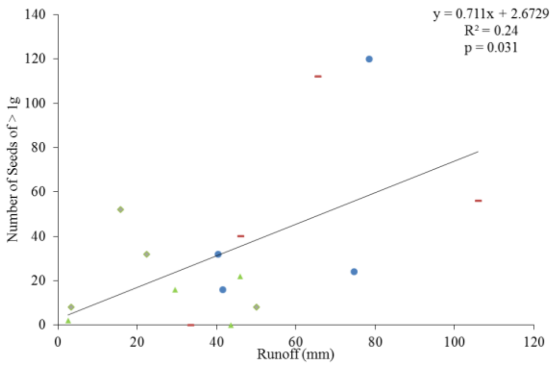


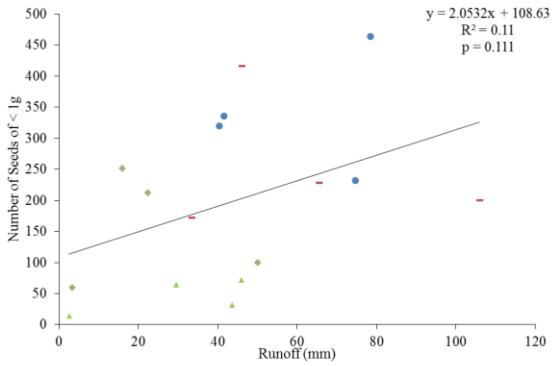
● Regular ■ Low Pressure ▲ Spiked Harrow × Spiked Harrow + Low Press

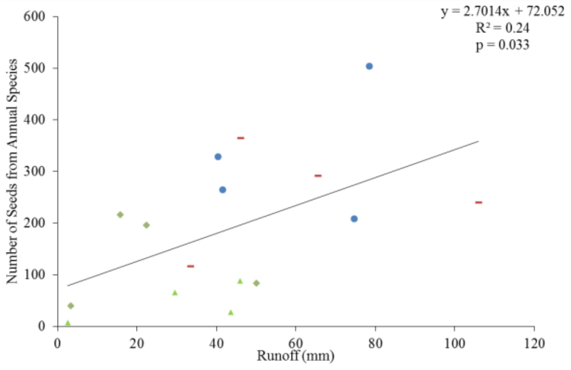
2012/13 – Runoff

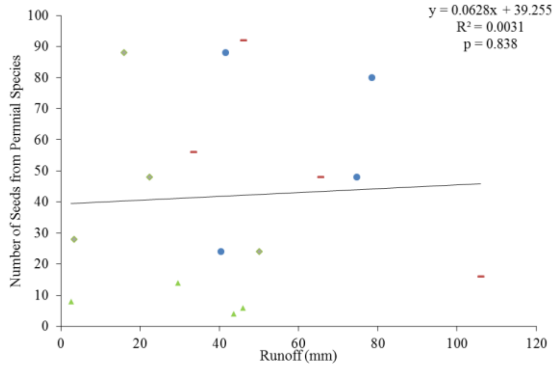






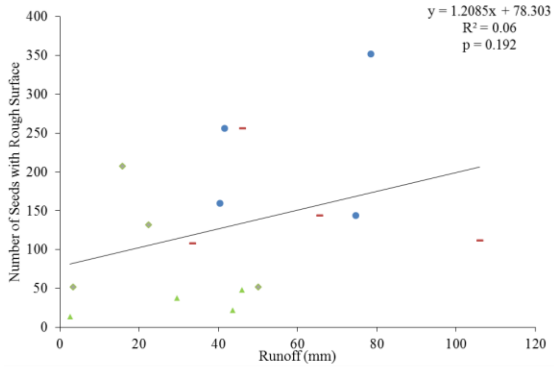


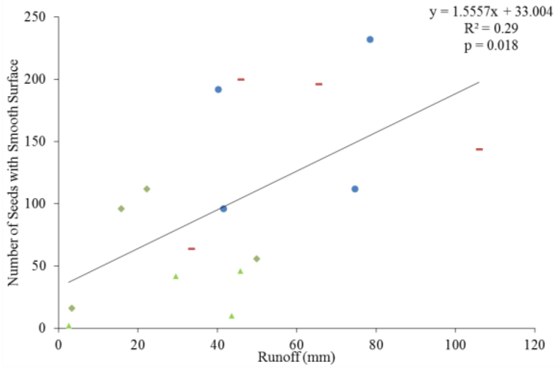


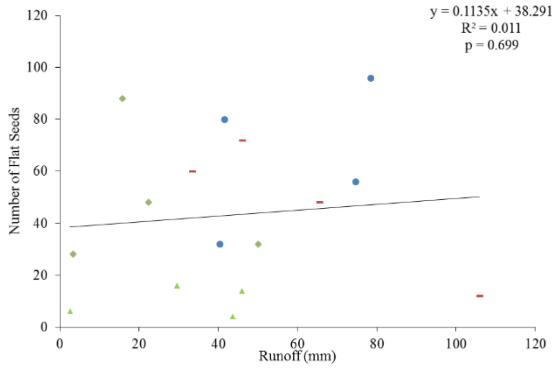


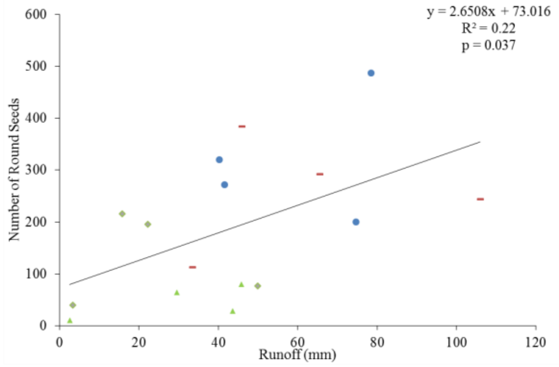
● Regular – Regular + Sown ◆ Low press + Sown ▲ Spiked Harrow + Reg

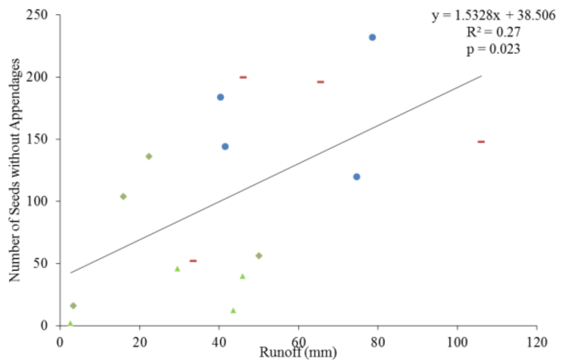
2012/13 - Runoff

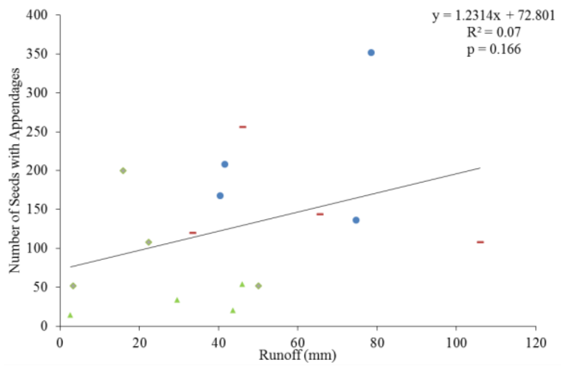






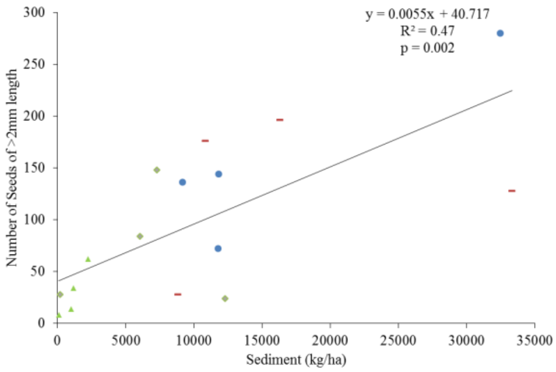


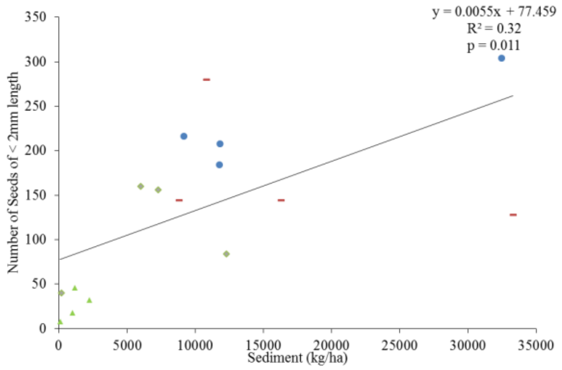


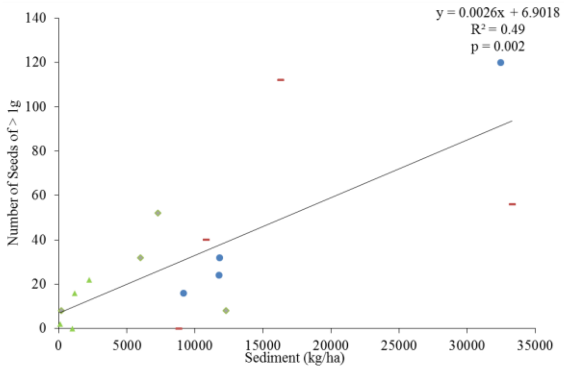


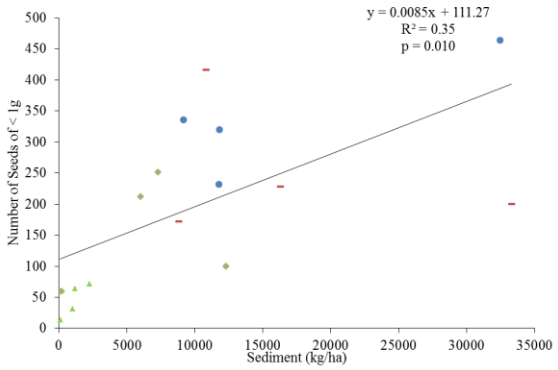
● Regular – Regular + Sown ◆ Low press + Sown ▲ Spiked Harrow + Reg

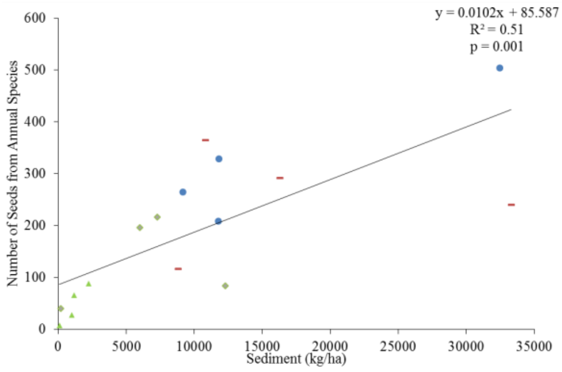
2012/13 - Sediment

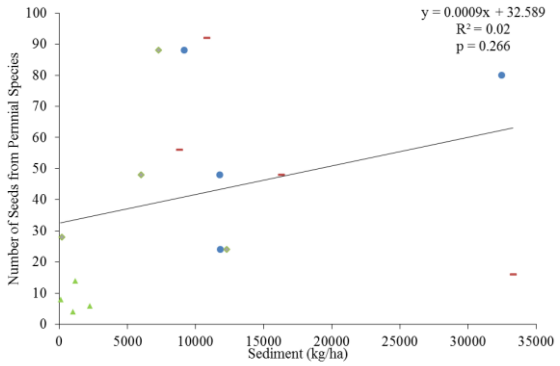






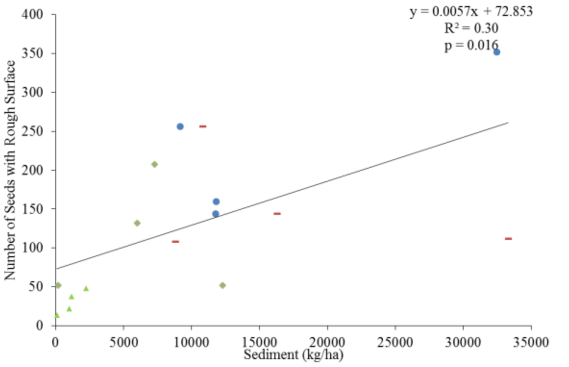


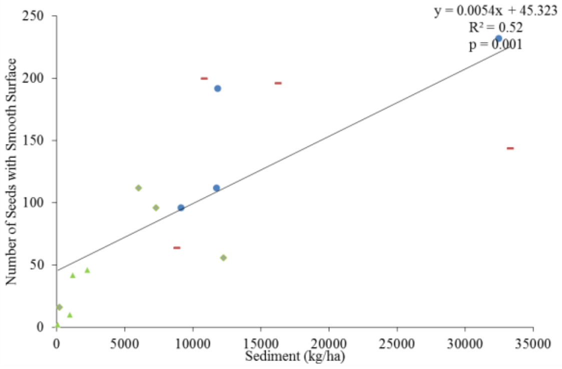


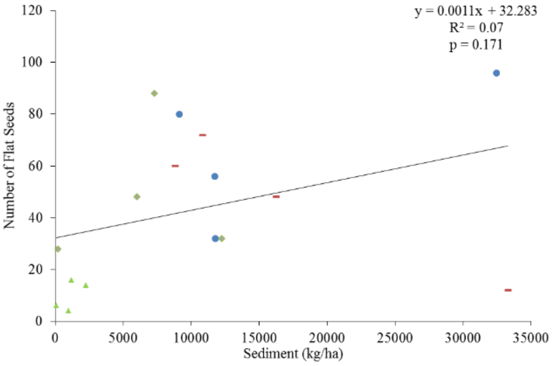


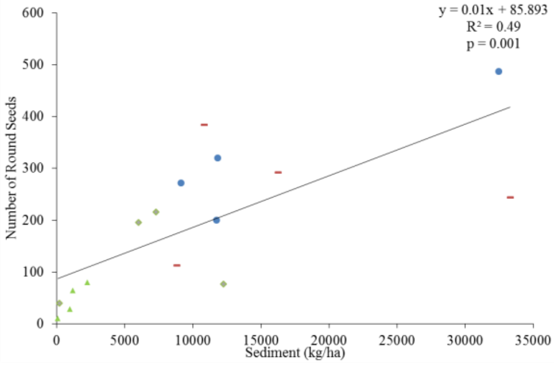
● Regular – Regular + Sown ◆ Low press + Sown ▲ Spiked Harrow + Reg

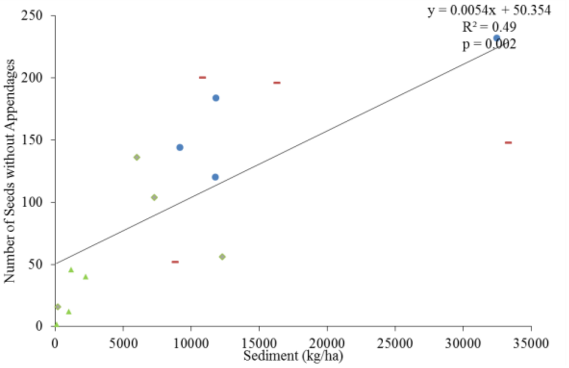
2012/13 - Sediment

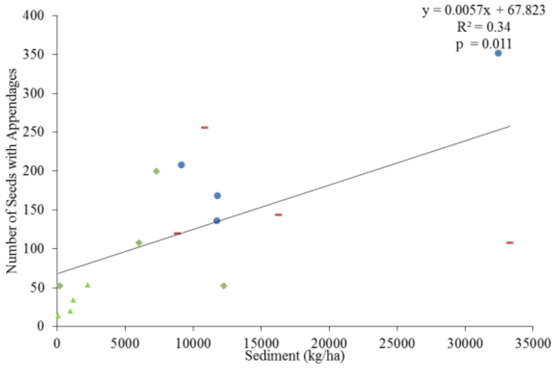








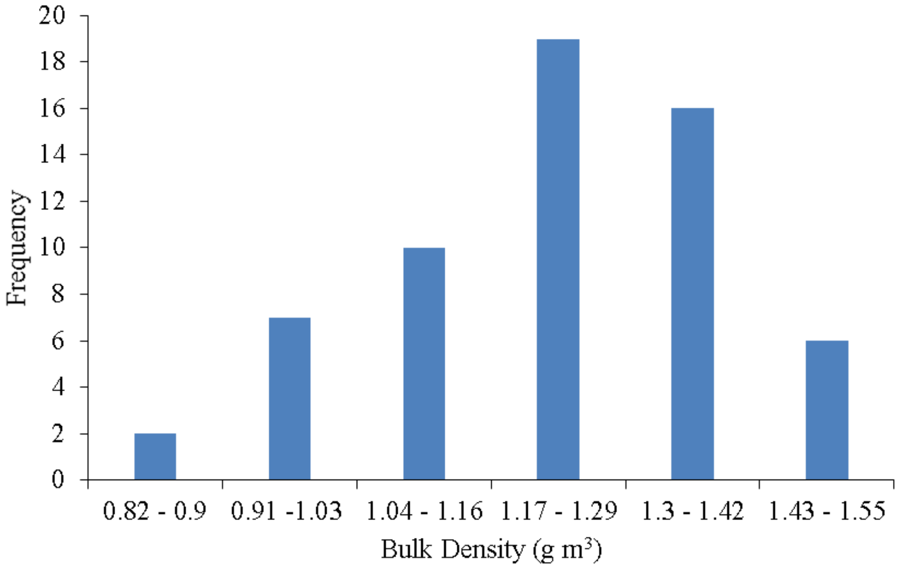




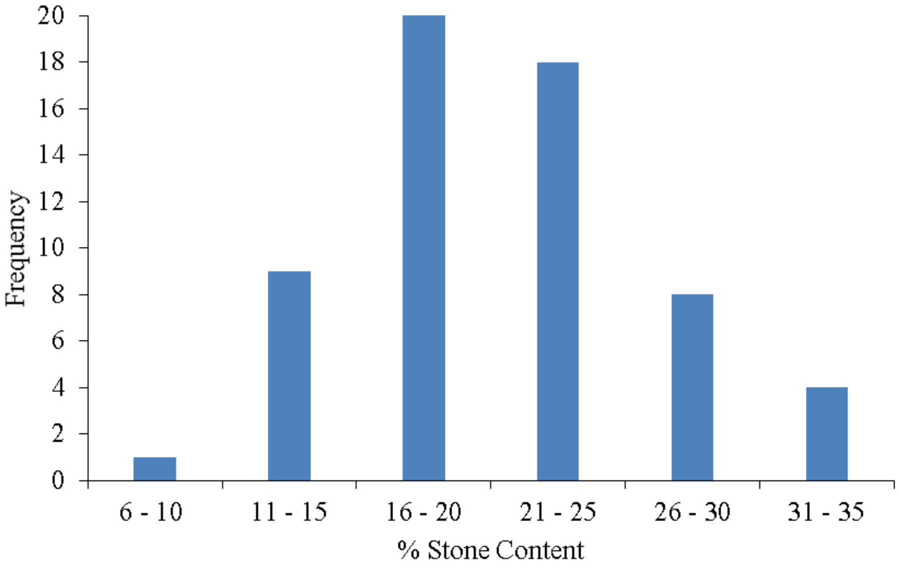
● Regular – Regular + Sown ◆ Low press + Sown ▲ Spiked Harrow + Reg

Appendix C: Frequency Distribution of Bulk Density and Stone Content for Middle East Field

Bulk Density



Stone Content



Appendix D: ^{137}Cs Inventories Reference Site Values

Reference Cores:

Core Number	**Core Mass without stones (kg)**	**137 Cs Inventory (Bq m^{-2})**
1	1.15	2033
2	1.42	2320
3	1.24	2339
4	1.34	2367
5	1.34	1745
6	1.4	2753
7	0.93	1376
8	1.41	2695
9	1.2	1205

Core Mass vs ^{137}Cs Inventories: