Using a plant functional trait approach to increase buffer zone efficiency and reduce diffuse agricultural pollution

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Declaration

I hereby declare that the content of this thesis is my own work, except where reference are made to other sources, and that it was not previously presented for a higher degree elsewhere.

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Abstract

Buffer zones are vegetated strips made up of predominantly herbaceous species often containing a hedgerow or other woody layer. They are used as a barrier between agricultural fields and watercourses. Buffer zones are an important part of diffuse pollution prevention systems in agricultural environments. However, during extreme weather events, buffer zones can fail and pollution from sediment, phosphorus and nitrogen still occurs.

A conceptual model was employed to identify plant functional traits that could be used to enhance the resistance and resilience of buffer zones to overland flow and sediment transfer. Five grassland plants species were phenotyped and then subjected to flume experiments, soil strength and hydrological measurements at two different growth stages. We then used a mixture of species and functional groups in a field plot experiment under simulated overland flow with sediment addition to assess the processes in the field. Finally, we examined the soil physical and hydrological processes in three different established buffer types.

Significant relationships between root, leaf and morphological traits and saturated hydraulic conductivity, sediment capture, soil aggregate stability and overland flow resistance in the mesocosm experiment were found. However, these differences were not evident in the field plot experiment due to the heterogeneity of the landscape and environmental conditions. In addition, there were significant differences between the soil physical and hydrological properties between the established buffers and the crop area and between the different buffer types.

This work demonstrates that functional traits can be used to influence surface runoff and soil physical and hydrological processes in a lab-based setting, however this may not necessarily translate to a field setting, especially over short growing periods. This work does show that broad-leaved trees can affect both the physics and hydrology of the soil even when they are relatively immature.

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1.1 Literature Review

1.1.1 Population and Land Use

The world population currently stands at just over 7 billion and is predicated to rise to 9.7 billion by 2050 before peaking at 11 billion by 2100 (United Nations, 2019). The UK population is over 66 million people with over 55 million in England alone (ONS, 2019). This trend of a growing population, along with a change in diet and an increase in consumption of natural products, puts the already changing climate under pressure. A growing population has an increasing demand for food, fibre and medicine, therefore there is increased land use for agriculture leading to agricultural land being used ever more intensively (IPCC, 2019). The UK currently uses 56% of its land for agriculture, in England and Wales it is 70% (Alasdair, 2017). Creating new agricultural land is unfeasible in the UK where land is being used for expanding urban settlements and increasing the national transport infrastructure (Gardi et al., 2015). This means the current agricultural land needs to produce more food in possibly less space and ensure there is a thriving and vibrant rural community that can earn a decent living (Holden et al., 2017). However, this needs to happen without further damage to the environment if we are to meet our international targets and commitments.

1.1.2 Agriculture and Soil Erosion

Soil is essential to human life as it produces food, fibre, clean drinking water and contributes to climate regulation, but soil degradation is commonplace across most of the world (Boardman et al., 2006, IPCC, 2019). Soil erosion is a natural process that occurs through detachment of soil particles through water, wind or gravitational forces (Boardman et al., 2006, Boardman et al., 2019, Boardman, 2013, Holden et al., 2017, Verheijen et al., 2012). Globally soil erosion from agricultural fields is 10 to 20 times (on no-till fields) greater than known soil formation rates and 100 times greater on conventional tillage fields (IPCC, 2019). The rate of soil loss is unsustainable for continued food security and climate regulation (IPCC, 2019, Boardman et al., 2019). Consequently, much of the soil that is lost from the fields then becomes a pollutant and causes environmental and financial problems for drinking water resources, biodiversity and society (Boardman et al., 2019, Boardman, 2013, Holden et al., 2017, Ockenden et al., 2014, Rickson, 2014).

Soil erosion is less pronounced on well vegetated and natural areas, but due to the nature of agriculture many areas are regularly cultivated and left as bare ground between sowing and as crops mature (Stevens et al., 2009). There are three main environmental drivers of soil erosion: water, wind and gravity (Abdollahi et al., 2015, Verheijen et al., 2012).

Water: - The effect of rainfall on unprotected soils causes surface sealing and crusting because of this further rain then disturbs the surface of the soil ensuring particles become detached. The crusting and sealing of soils reduce soil surface roughness and encourages overland water flow. This can then encourage the development of rills and gullies a process were the soil is washed away (Boardman et al., 2006, Ola et al., 2015). High frequency and a high quantity of rain can cause impactful soil erosion not just the high intensity rainfall events (Quinton et al., 2001).

Wind: - This process effects already damaged soils, soils lacking in organic matter or sandy, dry soils (Boardman, 2013, Boardman et al., 2006, Verheijen et al., 2012).

Gravity: - The angle of slope and length of slope can accelerate the other soil erosion processes likewise cultivation on slopes can be a major cause of soil erosion (Boardman et al., 2006, Quinton and Catt, 2004).

Many variables can affect the type and intensity of soil erosion in the agricultural environment: abiotic, biotic and behavioural (Boardman, 2013, Idowu et al., 2002, Rickson, 2014). Soil type plays an important role in soil erodibility. Along with climatic variability, rainfall frequency and intensity, drought and drying/wetting extremes and topography, elevation of field and farm can also affect the risk of soil erosion (Quinton et al., 2001).

Finally, farmer behaviour is one of the most important aspects as it will be affected by available subsidies for certain practices, pressure from market forces, crop types grown, animals farmed, machinery used and culture (Harrison et al., 2019). Ploughing, planting and harvesting times will affect soil erosion rates as wet/windy weather conditions when ploughing and planting takes place have a negative effect on soil stability (Boardman, 2013, Rickson, 2014). Soils that are lacking in soil organic matter (SOM) due to intensive cultivation are also more prone to soil erosion (Rickson, 2014). All of the environmental and societal pressures that cause soil erosion in agricultural environments inevitably lead to complex environmental issues, including water pollution from agricultural diffuse pollution.

1.1.3 Agricultural Diffuse Pollution

Diffuse pollution is defined as pollution from multiple, dispersed and unknown sources (Harrison et al., 2019) and is also referred to as non-point source pollution. Agricultural diffuse pollution is the main source of nitrogen and sediment pollution of freshwater in the UK, and second only to water treatment works in terms of being the source of phosphorus pollution (Harrison et al., 2019, Holden et al., 2017, Ockenden et al., 2014). This pollution costs the UK in excess of £260 million per year (Rolls and Sunderland, 2014) and prevents it from meeting it obligations under the Water Framework Directive (200/60/EC).

The water framework directive obligates the EU member states to maintain its freshwater systems in good ecological and chemical status. The amount of freshwater systems meeting this target in England is 24%, Wales is 36%, Scotland at 63% and Northern Ireland at 22% (Holden et al., 2017). These numbers represent population and agricultural density along with the types of agriculture practised in the country (Alasdair, 2017).

The pollution of surface freshwater is responsible for increased costs in cleaning drinking water, reduced quality bathing waters, reduction in freshwater invertebrates, and the consequence that has for other species (Ockenden et al., 2017) including lowering feeding rates and lifespan of molluscs and other aquatic species, and preventing salmon and trout spawning due to sedimentation over gravel beds in rivers (Collins and Anthony, 2008). If phosphorus inputs are continued at high enough levels then eutrophication can occur (Haygarth et al., 2005). Eutrophication causes toxic algal blooms and can be hazardous to not only biodiversity, but also human health (Haygarth et al., 2005).

Studies suggest that 60% of nitrates (N) and 25% of phosphorus (P) in water bodies in the UK come from agricultural diffuse pollution (Holden et al., 2017). Collins and Anthony (2008) found that as much as 75% of sediments that pollute water in England and Wales come from agricultural sources. This along-side pesticides and microbiological organisms from manure can affect the ability of freshwater ecosystems to function at a catchment level (Collins and Anthony, 2008).

The Phosphorus transfer continuum as described by Haygarth et al. (2005) explains the processes of phosphorus diffuse pollution from source to environmental impact. This continuum allows insight into how soil erosion causes diffuse pollution in agricultural areas.

The study soils are often of high phosphorus content due to the anthropogenic inputs from mineral fertiliser, farmyard manure or slurry this is the 'source' (Haygarth et al., 2005). The phosphorus is mobilised through either solubilisation or detachment (Haygarth et al., 2005). Soil detachment is caused by rain splash erosion, overland water flow, tillage/harvesting and wind erosion (Quinton et al., 2001). Delivery of the phosphorus via the soil sediment particles is through gravity down slope into receiving water courses aided through overland water flow or wind (Haygarth et al., 2005). Impacts on receiving water courses are documented earlier in this section. However, they are widespread and uncertain due to scale, difficulties in measurements and landscape heterogeneity (Haygarth et al., 2005)

Alongside the damage done to the surface freshwater and coastal environment from soil erosion and diffuse agricultural pollution there are many instances of agricultural run-off that form part of flooding events. This not only cause water flooding, but muddy flooding that transfers large amounts of soils/sediments along with their associated pollutants into towns and homes (Boardman et al., 2019). This type of large-scale run-off is associated with non-vegetated fields, farm tracks and yards and the connectivity of the landscape (Boardman et al., 2019). This has serious environmental and financial consequences for rural communities and the wider public and needs to be addressed at source. Therefore, it is important to work with farmers and land managers to investigate and implement on-farm solutions that reduce soil erosion, reduce land connectivity and prevent diffuse pollution from soil erosion and sediment transport.

1.1.4 On-Farm Solutions to Soil Erosion and Diffuse Pollution from Soil

The most effective way to reduce diffuse pollution through soil erosion is to stop or reduce soil erosion occurring. There are numerous examples within the literature around no-till farming methods, reducing machinery size, using winter cover crops, changing planting and harvesting practices and ploughing around the contours of slopes (Gooday et al., 2014, Panagopoulos et al., 2011, Quinton et al., 2006, Quinton and Catt, 2004, Stevens and Quinton, 2009, Stevens et al., 2009). Any method that reduces mechanical disturbance, physically protects soil from weathering and encourages the build-up of soil organic matter is helpful to reduce soil loss from agricultural fields (Cardinali et al., 2014, Boardman, 2013, Stevens and Quinton, 2009, Stevens et al., 2009).

Despite best agricultural management practices that are intended to protect soil from erosion there are still many soil erosion events in agricultural environments (Stevens and Quinton, 2009, Stevens et al., 2009). The changing climate and more extreme weather events will only increase these erosion events in the future (IPCC, 2019). Therefore, it is still necessary to investigate ways to reduce the amount of soil and other pollutants entering watercourses.

Boardman et al. (2019) discuss the connectivity of the agricultural landscape and its impact on soil erosion effects. A highly connected landscape can increase the risk and consequence of soil erosion, runoff and flooding (Boardman et al., 2019, Ockenden et al., 2014). Research around soil erosion looks to field size, topography and edge of field barriers to reduce the loss of water and soil from the agricultural environment (Quinton and Catt, 2004, Ockenden et al., 2014). Edge of the field soil capture methods help to reduce the connectivity of the landscape, and therefore reduce diffuse pollution.

One edge of the field capture method investigated by Ockenden et al. (2012) and Ockenden et al. (2014) focused on small-scale wetlands in non-productive or existing wet areas of agricultural fields. These unlined ponds intercepted run-off and sediments during times of bare soils and heavy rainfall. They captured sediment, preventing it entering watercourses and enabling the re-use of the sediment as a soil replacement on eroded fields. There was reduction of sediment loads into watercourses where the wetlands were utilised, especially on sandy and silty soils (Ockenden et al., 2012, Ockenden et al., 2014). This study suggests that small-scale wetlands are a relatively affordable method to reduce sediment loads into watercourses when other best management practices failed or were impractical. However, small-scale wetlands are only one of a suite of edge of the field capture methods that have a positive impact on diffuse pollution levels from agricultural land (Stevens and Quinton, 2009, Stevens et al., 2009).

The edge or infield capture method is used across the agricultural environment with field margins, beetle banks, stiff grass hedges and vegetated buffer zones employed to reduce the spread of fertilisers, pesticides and reduce sediment-laden runoff (Biddulph et al., 2017, Gooday et al., 2014). A more detailed account of vegetated buffer zones, the focus of this project, is given in the following section.

1.1.5 Physics of Overland Water Flow

The mass of overland flow is strongly related to amount of rainfall, the angle and length of the slope and the soil type (Boardman et al., 2006, Quinton and Catt, 2004). The higher the volume and the longer the time frame of rainfall events increases the likelihood of infiltration excess, overland flow (Quinton et al., 2001). When this occurs on hill slopes, then there is overland waterflow. A steep and long slope will produce high water velocity which increases the likelihood of soil erosion (Wong 2011, Rickson, 2014). The likelihood of soil erosion is linked to water velocity and soil particle type. The Hjulström Curve (Figure 1.1) describes the relationship between water velocity and the detachment, transport and deposition of soil particles from the different soil types and different soil particle sizes (Fryirs et al., 2012). Small soil partials and high water velocity increases the likelihood of soil detachment and transport as velocity reduces or soil particle size increases this reduces the likelihood of erosion and transport and increases the likelihood of deposition (Fryirs et al., 2012).

The amount of kinetic energy created by the mass of the overland flow interacting with the soil types directly affects the transport capacity of the eroded soil particles by the overland water flow (Wong, 2011, Fryirs et al., 2012). As larger amount of soil particles are present in the overland flow then more soil erosion is likely to occur as there is more friction (Boardman et al., 2006). However, as overland water flow meets resistance in the form of hydraulic roughness caused by surface irregularities, stones and vegetation it reduces the energy of the flow by increasing the friction and creating drag (Dosskey et al., 2007, Kervroedan et al., 2019, Kervroedan et al., 2018).

In order for the hydraulic roughness to create sufficient resistance effective to reduce the sediment laden overland flow being transported into water courses the vegetation or other resistance needs to create conditions that reduce velocity and encourage deposition of sediments (Gatel et al., 2016, Abu-Zreig et al., 2004, Dosskey et al., 2007, Owens et al., 2007, Kervroedan et al., 2019, Kervroedan et al., 2018). These conditions are highly variable not only at a landscape scale, but often at field scale and depend on water velocity, soil particle size, infiltration capability, slope angle and slope length and the surface roughness of the vegetation (Wong,2011; Figure 1.1).

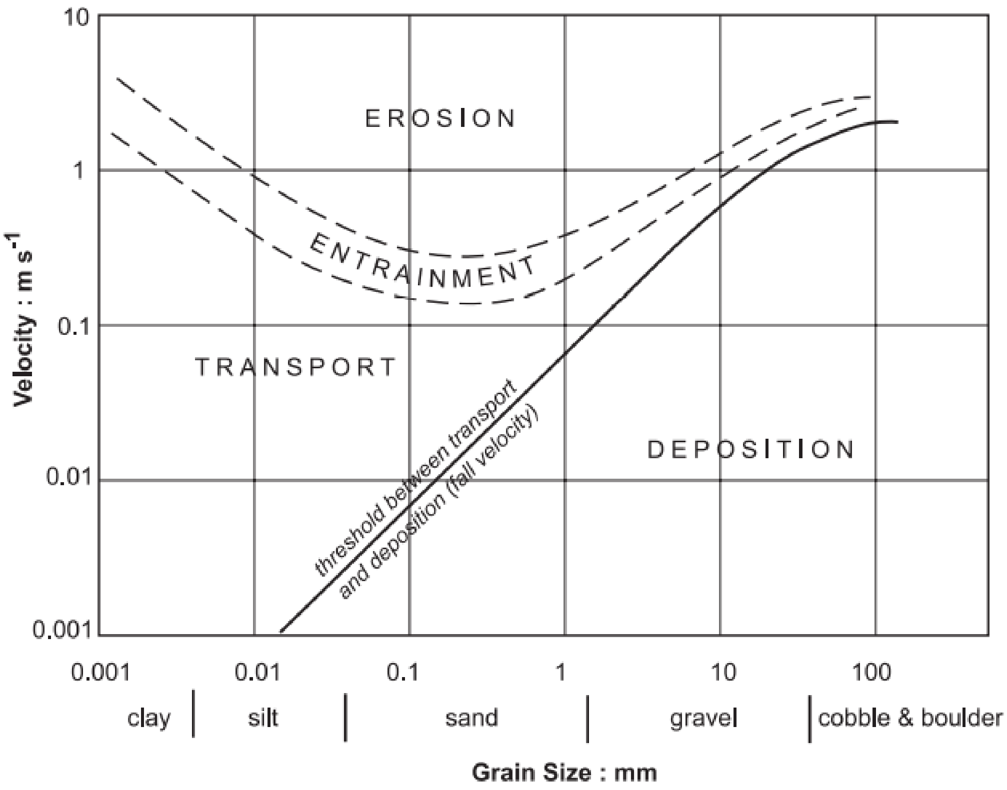


Figure 1.1 The Hjulström Curve Diagram shows the process and phases of sediment erosion, transport and deposition (Fryirs et al., 2012)

1.1.6 Vegetated Buffer Zones

Vegetated buffer zones (VBZ) are areas of non-cropped land adjacent to agricultural or pastoral fields situated between the fields and watercourses or pathways to watercourses (Abu-Zreig et al., 2004, Borin et al., 2010, Pan et al., 2017). Buffers are comprised of perennial vegetation that is present for at least 12 months (Haddaway et al., 2016) and consist of an herbaceous layer dominated by native grasses and often include a hedgerow or other woody layer (Haddaway et al., 2016). Other non-cropped edge of the field areas are often maintained for biodiversity or gamebird cover, but tend to have a wider variety of vegetation including annual plants and are chosen for a particular socio-economic or biodiversity gain (Haddaway et al., 2016).

VBZ are a physical barrier between the field and the receiving watercourse. The VBZ slows the water velocity because of the increased surface roughness and the increased infiltration capacity provided by the above and below ground characteristics of the vegetation (Gatel et al., 2016, Abu-Zreig et al., 2004, Dosskey et al., 2007, Owens et al., 2007, Kervroedan et al., 2019, Kervroedan et al., 2018). The slowing of the water flow allows for deposition of sediments and the delayed transport of dissolved nutrients, enabling plant uptake and sorption (Franco and Matamoros, 2016, Otto et al., 2012). VBZ have also been shown to reduce the leeching of nutrients into ground water through filtering and plant uptake (Vought et al., 1995). The consensus is that VBZ reduce the passage of P and N into watercourses by reducing the transfer of N and P rich sediments, through capture in dense and rough vegetation (Ali and Reineking, 2016, Otto et al., 2008, Owens et al., 2007), deposition, absorption, plant uptake and microbial uptake (Mander et al., 1997).

VBZ comprising of perennial grass strips with woody vegetation (hedgerows or willow species) were researched in an agricultural landscape in Italy (Borin et al., 2010, Borin et al., 2005). They were found to have success in reducing runoff by 33%, N by 44% and P by 50% in a young buffer strip (under 3 years old) compared to no buffer strip (Borin et al., 2010). In buffer strips older than three years, the study found that suspended solids were reduced by between 70-90%, N 70-95% and P 60-98% compared to no buffer strip (Borin et al., 2010, Borin et al., 2005; Table 1.1). In the study by Vought et al. (1995) it was found that a 10-meter buffer reduced the sediment bound P load by 95%. In the Syversen (2005) study, in a Nordic climate with its associated snow-melt overland flow, they found that particulates were reduced by 81 to 91%, N by 37-80% and P by 60-89% when using a buffer. They also found that a forested buffer zone captured more particulates than a grass buffer (Syversen, 2005) however Hefting et al. (2005) found no difference between forested and grassed buffer zones for reducing nitrogen travel through the buffer. There is variation in the ability of VBZ to carry out pollution reduction services.

The percentage amount of N and P discharged from VBZ varies between studies and between regions (Borin et al., 2004, Borin et al., 2010, Borin et al., 2005). Sheppard et al. (2006) found that some VBZ were a source of P discharge into watercourses due to elevated P levels within the buffer soils. This P discharge stems from the continued input into the buffer and lack of P extraction (Sheppard et al., 2006). It can be concluded that VBZ do not eliminate the transfer of N and P into watercourses but do have a significant impact on the sediment and nutrient load entering watercourses.

The variation in the VBZ performance is due to the complex interactions between the climate, the topography, slope gradient, ratio of source to receiving VBZ, soil type, crop type and management practices (Vought et al., 1995, Haddaway et al., 2016, Syversen, 2005, Gatel et al., 2016). The width of the VBZ, the type of vegetation and its' position in the landscape also affects its ability to carry out the required services (Borin et al., 2004, Syversen, 2005, Pan et al., 2017, Carluer et al., 2017, Lind et al., 2019). Likewise, the ratio of field or source to the VBZ can affect its capacity and its ability to reduce overland flow (Lafrance et al., 2013). As can be seen there has to be a tailored approach to situating and specifying VBZ depending on the needs of the landowner, the catchment and the individual land parcel.

Research on VBZ has focused on width, position and the wider agricultural landscape features (Schmitt et al., 1999). It is clear that crop cover, topography, soil type and climate play an important role in the effectiveness of the buffer strip (Carluer et al., 2016, Fernandes and Guiomar, 2016; Table 1.1). There has also been recent focus on vegetation type and to some extent combinations that are most effective at reducing the discharge of sediments, nutrients and agrochemicals (Haddaway et al., 2016). However, the focus on individual species or groups of species is not always the case and vegetation types tend to be grouped together.

Table 1.1 Vegetated Buffer Zone Studies

VBZ Type	**Size/Location/Age**	**Pollutant Type**		**Pollution reduction**	**Reference**
Various	Riparian 9 to 11 metres	Sediment		75%	(Lind et al., 2019)
Grass strips and Willow/hedgerow	Edge of Field Under 3 years to over 3 years	Sediment Runoff N P		70%-90% 33% 44%-95% 50%-98%	(Borin et al., 2010, Borin et al., 2005)
Hedgerows Trees Herbaceous	Riparian/upland 10 metres	P		95%	(Vought et al., 1995)
Forest Grass	Edge of Field	N P Sediment		37%-80% 60%-89% 81%-91&	(Syversen, 2005)
Grass	Flume Experiment (various slopes) 5 metres	Sediment		40%-72%	(Pan et al., 2010)
Trees/shrubs Grass Sorghum	Edge of Field 7.5 and 15 metres	Sediment Total P N		76%-93% 55%-79% 24%-48%	(Schmitt et al., 1999)

In studies on VBZ vegetation types are often divided into trees and herbaceous vegetation or a mixture of herbaceous vegetation with a woody layer of hedgerow. The study of specific herbaceous plants and combinations of different herbaceous plants for use in VBZ is limited for the UK and more often based in more extreme climatic areas (Ali and Reineking, 2016, Mekonnen et al., 2016). The European studies often focus on woody species individually and herbaceous species as a group. When specific grass species are studied, the rationale for the species focuses on what is easily grown or what is commonly found in agricultural areas (Lee et al., 2000, Pan et al., 2010). There is, however, a move to focus on individual grass and herb species and their distinct characteristics, by using a plant functional trait approach to designing VBZ (Kervroedan et al., 2019, Kervroedan et al., 2018).

1.1.7 Plant Functional Traits

The term plant functional traits refers to the characteristics of the plant including the phonological, morphological and physiological characteristics (Bardgett et al., 2014). Functional traits represent the ecology and life history strategies of the plants (Bardgett et al., 2014, Nock et al., 2016). Plants are grouped by functional groups, and functional traits can be used to inform conservation strategies and give insight into ecological processes (Nock et al., 2016, Bardgett et al., 2014). Using this approach could enable a better understanding of the functions, weaknesses and strengths of the VBZ vegetation.

Studies have demonstrated that specific plant traits effect ecosystem processes and in turn are affected by environmental conditions (Carluer et al., 2016, Suter and Edwards, 2013, Otto et al., 2008, Mekonnen et al., 2016). Plants exhibit traits according to environmental conditions and these traits are characteristic of the ability of the plant to thrive, persist or colonise a habitat or adapt if the conditions change; these traits are known as response traits (Guittar et al., 2016, Kleyer and Minden, 2015). Plants also demonstrate traits that influence the surrounding environment and can change ecosystem properties (Nock et al., 2016, Mekonnen et al., 2016, Diaz et al., 2004, Eviner and Chapin, 2003, De Baets et al., 2011). These traits are known as effect traits and can affect ecosystem services from a human perspective (Lavorel and Grigulis, 2012, Diaz et al., 2004, Eviner and Chapin, 2003). The effect and response traits have complex interactions and determine the life history and fitness of the plant to particular environments (Nock et al., 2016, Mekonnen et al., 2016).

Plant traits can be divided into 'hard' and 'soft' traits (Diaz et al., 2004, Nock et al., 2016). Hard traits have been found to be difficult to quantify and measure (Diaz et al., 2004), whereas soft traits are easier to measure on a smaller and more practical level. For example, measuring the dispersal capabilities of a plant species is difficult; it is challenging to understand all of the processes and then to measure them (Nock et al., 2016). However, using soft traits like seed mass, seed size and, number of seeds allows the researcher to understand the plants dispersal process and compare it with other species (Nock et al., 2016).

Traits can broadly be divided into five categories:

- **Whole plant traits** include life history, growth form, life span, functional guild, height, branching architecture and salt tolerance (Carluer et al., 2017, Perez-Harguindeguy et al., 2013, Grime, 1974).

- **Leaf traits** include leaf area, leaf dry matter, specific leaf area, leaf economic spectrum, rate of photosynthesis, rate of decomposition (Nock et al., 2016, Diaz et al., 2004).
- **Stem traits** include stem specific density (Perez-Harguindeguy et al., 2013, Kahmen and Poschlod, 2008, Dabney et al., 1995, Dunn and Dabney, 1996, Evans et al., 2007).
- **Below ground traits** include root length, specific root length, root dry matter content, root architecture, nutrient uptake strategy and symbiosis (Mekonnen et al., 2016, Fry et al., 2018, Bardgett et al., 2014, Bardgett, 2017, Klimesova et al., 2018, De Baets et al., 2007, Vannoppen et al., 2017).
- **Regeneration traits** include dispersal; vegetative spread; seed mass, size and amount; capacity to regenerate after disturbance (Perez-Harguindeguy et al., 2013, Eviner and Chapin, 2003).

Plant traits can affect environmental processes and ecosystem services through the ways in which they interact with abiotic processes (Dhital and Tang, 2015, Eviner and Chapin, 2003). Vegetative cover, and the benefits to soil erosion prevention has long been known, researched and used for soil stabilization (Westoby and Wright, 2006). Plant traits influence carbon and nutrient cycling through different nutrient acquisition strategies (Westoby and Wright, 2006), decomposability of leaves and chemical excretions from roots (Nock et al., 2016, Diaz et al., 2004). More recent research focus is with how plants and their traits can be used to enhance various aspects of vegetated buffer zones. There is potential to utilize plant traits to deliver ecosystem services in VBZ and refine existing ways that vegetation is used in VBZ. Identifying the traits that will affect the processes that are of interest will rely upon knowledge of how each is involved in the environmental process or function. Choosing the relevant traits to measure will depend on what the research aims are and the resources available.

1.1.8 Aboveground Plant Traits and Vegetated Buffer Zones

There are numerous studies investigating aboveground plant traits and how they interact with overland flow, sedimentation and nutrient removal. The study by Dabney et al. (1995) focuses on the stem strength and flexibility of stiff stemmed grass species used in grass hedges. They found that the strength of the stem was important to create a barrier to waterflow which enabled the water to pool and the deposition of sediment. They concluded that there was little filtering within vegetation and all sediment deposition happened at the edge of the grass hedge, so tall stiff stemmed grasses were considered ideal for planting in these hedges (Dabney et al., 1995). Conversely, there are other studies suggesting there are plant traits that encourage the filtering of sediments within the vegetated buffer zone.

In the study by Mekonnen et al. (2016), looking at the sediment trapping abilities of native grasses in Ethiopia, they found that the number and density of grass tillers had a positive effect on the sediment trapping efficiency of the grass strip. Showing that plant architecture, not just stem strength was an important plant trait for vegetated buffer zones (Mekonnen et al., 2016). Other studies have examined the impact of plant leaves and how, as well as creating ground cover that protects from weather erosion, they can increase hydraulic roughness and slow overland water flow.

The studies by Kervroedan et al. (2019), (2018) showed that different leaf and stem traits (leaf area, stem density) increased the hydraulic roughness of the buffer thus slowing the water flow and allowing sediment deposition. They found that large leaf area and high stem density reduced runoff through acting as a hydraulic brake and reducing soil erosion and sediment passage (Kervroedan et al., 2019, 2018). These studies suggest that leaf area, stem strength and density and plant architecture are all important traits within a vegetated buffer zone. However, they do not focus on the belowground traits or how they may affect the soil hydrology or physical strength.

1.1.9 Belowground Plant Traits and Vegetated Buffer Zones

There have been numerous studies in the last 10 years looking at the belowground processes of vegetation and their effects on soil structure, hydrology and soil strength (Gould et al., 2016, De Baets and Poesen, 2010, De Baets et al., 2007, De Baets et al., 2011, Sandercock et al., 2017, Vannoppen et al., 2016, Vannoppen et al., 2015, Bardgett, 2017, Bardgett et al., 2014, Fry et al., 2018, Orwin et al., 2010). The evidence is that different root architecture, root traits, mycorrhizal associations and type and amount of root exudates effect soil health and soil function.

Root diameter has a significant effect on soil strength fine, fibrous roots increase soil strength and soil aggregate stability through binding the soil particles and increasing the strength of the soil matrix (Bardgett et al., 2014, Gould et al., 2016, Orwin et al., 2010). Roots exudates are known to increase soil aggregate stability and soil microbes feed on root exudates and produce polysaccharides which act as a glue that binds aggregates and increases the hydrophobicity protecting them against water damage (Vannoppen et al., 2015, Bardgett et al., 2014). Vannoppen et al. (2015) and De Baets et al. (2007) found that soil type interacted with root type; sandy soils suffered less erosion with tap rooted species while clay soils responded better to fine, binding roots.

Part of erosion reduction features include a reduction of overland water flow (as in buffer zones) therefore roots types that increase soil hydraulic conductivity are suited for buffer zones and river dykes (Vannoppen et al., 2016, Vannoppen et al., 2015). Grass roots with high specific root length have a fast turnover and can create channels in the soil that increases water infiltration into the soil (Bardgett et al., 2014). It has been shown though that roots with a larger diameter increase soil hydraulic conductivity but have a detrimental effect on soil aggregate stability (Gould et al., 2016).

1.2 Study Rationale

There is a depth of research focusing on the ways in which pollution prevention techniques can be used within agricultural environments. There are many different methods and many reasons why each are used. Vegetated buffer zones are widely used and offer protection to watercourses from diffuse agricultural pollution. There are many studies looking at pollution prevention through VBZ, where they are situated in the catchment, their width and whether herbaceous or forested VBZ are most effective. However, vegetated buffer zones do fail and there are still water pollution issues around the UK due to sediments and nutrients in overland water flow entering surface waters. Understanding how to Increase the capacity and efficiency of vegetated buffer zones through a plant functional trait approach could enable better pollution prevention in an existing resource without high costs or a drastic change in approach. This research will focus on how vegetated buffer zones can reduce the passage of sediments as agriculture accounts for 75% of sediment pollution in UK water courses (Collins and Antony 2008) and sediment movements are linked to the transport of phosphorus from soil to water (Haygarth et al. 2005).

Hypotheses:

1. Plant functional traits will vary across species and functional groups and at different plant growth stages.
2. Plant functional traits will affect the delivery of sediment across the vegetated buffer zone.

3. Plant functional traits will affect the velocity of overland water flow across the buffer zone.
4. Plant functional traits will affect the hydraulic and physical properties of the buffer zone soils.
5. There will be a significant difference between species and functional groups for the measured overland flow, sediment delivery and soil physical and hydraulic properties.

1.3 Thesis Structure

This study will investigate specific herbaceous species to document their traits and compare them to a conceptual model of a VBZ. It will test the effectiveness of these species using a mesocosm run-on experiment and finally look at species and functional group combinations and their ability to reduce run-off and capture sediments in a field experiment.

Chapter 2 is focused on individual plants in a microcosm experiment. Plants were grown to three different growth stages: established, mature and degenerate and above and belowground traits were tested at each stage. The traits were then evaluated against a conceptual model of a vegetated buffer zone and differences between species, functional group and growth stages discussed.

Chapter 3 begins to test the assumptions of chapter 2 by growing species in monocultures for a mesocosm run-on experiment. Species were tested at two growth stages: mature and established. The mesocosms were subjected to 30-minute run-on simulations (5 l minute^{-1}) and runoff coefficients were measured at the beginning and end of the simulation. A sediment solution (5 g l^{-1}) was added at the 20-minute point and sediment discharge was collected for 5 minutes. Total dried sediment mass was measure at the end. Plant traits were measure for the mesocosms height before and after run-on, leaf and root traits were also measured. Post-run-on measurements were carried out 5 days afterwards and included saturated hydraulic conductivity, bulk density and three measures of soil aggregate stability. Tests for correlations between simulation and post simulation results and species plant traits were then explored.

Chapter 4 starts looking at species and functional group mixes in a field setting to explore the differences between mono-cultures, pairs and trios of grass species as well as mixtures of functional groups during a 30-minute run-on simulation (5 l $minute^{-1}$). Runoff coefficients were measured at peak flow and sediment trapping ability was measured by adding a sediment solution (5 g l^{-1}) and sampling at 5-minute intervals for 20-minutes. Total dried sediment was recorded, and sediment concentration was calculated. Post run-on simulation measurements included aboveground dry mass, root density, soil bulk density and field-saturated hydraulic conductivity. Results were examined for treatment differences.

Chapter 5 was part of a large multi-year field experiment on buffers at Rothamsted (North Wyke) and included taking soil samples and field-saturated hydraulic conductivity measurements on grass buffers, willow buffers and broad-leaved native tree buffers as well as the crop area containing fodder maize. The soil was tested for three measurements of soil aggregate stability. Results were examined for differences between treatments and correlation between treatment 1 (Fast wetting) of soil aggregate stability and field-saturated soil hydraulic conductivity.

Chapter 6 provides general discussion, limitations of the study and suggestions for further work.

2.1 Investigating plant functional traits to increase the efficiency and capacity of vegetated buffer zones

Using plant functional trait diversity to enable better water quality protection by enhancing the ability of vegetated buffer zones in agricultural fields could be a low cost, effective and socially acceptable method for reducing diffuse agricultural pollution (Collins et al., 2016). The reduction of phosphorus (P) and nitrogen (N) discharge into watercourses could potentially be achieved by slowing overland water flow, by using vegetative barriers (Eviner and Chapin, 2003, Dunn and Dabney, 1996, Evans et al., 2007). This will reduce further soil erosion of buffers and banks (Fattet et al., 2011) and allow sediment deposition to occur (Mekonnen et al., 2016, Bardgett et al., 2014, Ola et al., 2015, Gould et al., 2016). Slowing the flow may also enable better water infiltration into the soil by encouraging water pooling and keeping water in the buffer for longer (Dunn and Dabney, 1996, Dabney et al., 1995, Meyer et al., 1995). In addition having a diverse selection of plants root traits could increase infiltration pathways into the soil (Bardgett et al., 2014, Gould et al., 2016, Berendse et al., 2015, Dhital and Tang, 2015, Fattet et al., 2011, De Baets et al., 2007). Root trait choice could reduce soil erosion by increasing soil aggregate stability and shear strength (Bardgett et al., 2014, Gould et al., 2016, Berendse et al., 2015, Dhital and Tang, 2015, Fattet et al., 2011, De Baets et al., 2007). Using a trait approach could lead to increased protection of soil from rain splash and wind erosion (Westoby and Wright, 2006) and increase the rate of P and N removal through plant uptake using fast growing, high P uptake plant species (Kleyer and Minden, 2015).

Many functional traits of plants are discussed in the literature including stem density, leaf economies, evapotranspiration rates, nutrient uptake rates and plant strategies (CSR; (Carluer et al., 2016, Roscher et al., 2013). There is debate about how these traits can be utilised for specific functions within buffer zones or in soil erosion prevention (Dhital and Tang, 2015). However, studies of specific plants and combinations of different plants for use in soil erosion and water protection are limited for the UK and more often based in more extreme climatic areas (Ali and Reineking, 2016, Mekonnen et al., 2016). When the studies are in temperate climates/European countries, they focus on how woody species as individuals and grassland species as a group reduce P and N output and sediment discharge from vegetated buffer zones (Lee et al., 2000).

2.1.1 Root Traits

Gould et al. (2016) identified function traits of specific grassland species and their effect on soil aggregate stability, general soil structure and soil hydrology. The fine and dense rooting strategies of the grass species specifically *L. perenne* and *A. odoratum* increased aggregate stability in monoculture and mixed species experiments. This was reportedly due to root mass, root length and the superficial rooting nature of the grass species. However, plots that contained legumes showed reduced aggregate stability, but greater hydraulic conductivity (Gould et al., 2016). These results were mirrored by Ola et al. (2015) who found that a dense mat of roots at the soil surface, as produced by *L. perenne* and *A. capillaris,* improved soil strength and decreased erodibility, but they also inhibited infiltration and in turn increased runoff. Decaying root structures were shown to greatly enhance soil infiltration pathways and increase hydraulic conductivity. This underlines the need for functional root diversity to best enhance positive root trait effects on diffuse pollution reduction.

2.1.2 Stem and Leaf Traits

Numerous studies have looked at aboveground traits for retaining sediment within vegetated buffer zones and found that overall denser vegetation helped to reduce sediment transfer and therefore helped to mitigate soil erosion (Ali and Reineking, 2016, Owens et al., 2007, Abu-Zreig et al., 2004, Delectic, 2001). Morphological traits were associated with the plants ability to trap sediments in the buffer zones. Delectic (2001) found that size, density and thickness of grass blades had a positive association with increased sediment capture in vegetated buffer zones.

Examining stem strength and flexibility traits could be give insight into species ability to withstand concentrated overland flow and how the species recovers in the aftermath of run-on events (Dunn and Dabney, 1996, Evans et al., 2007). If species can resist water flow it is thought that water flow can be impeded, slowed and sedimentation can occur due to backwater pooling (Dabney et al., 1995, Dunn and Dabney, 1996, Evans et al., 2007). Studying stem strength and density can also enable understanding of plant trade-offs between growth speed and strength/stability and the hydraulic capacity of a species (Chave et al., 2009, Dwyer and Mason, 2018).

2.1.3 Nutrient Acquisition Traits

The growth rate hypothesis suggests that rapid growth requires more P than N (Kleyer and Minden, 2015), so species offering this trait could enable the removal of P from the buffer through mowing and biomass removal. Nutrient acquisition traits are correlated with many of the easily tested leaf (specific leaf area (SLA), leaf economic spectrum) and root traits (specific root length (SRL), root tissue density (RTD)). Knowing these values could enable better predictions of nutrient use for the different species and inform buffer plant selection (Perez-Harguindeguy et al., 2013).

2.1.4 Plant Traits for Vegetated Buffer Zones

To understand the traits required to create a successful vegetated buffer zone it is first required to understand the processes and interactions of the buffer zone and the overland flow. Water and mobilised sediment are transported from the agricultural/pastoral field into the buffer zone and further into watercourses through ditches or tracks. The water could be impeded by the buffer zone vegetation and begin to pool at the edge creating a backwater effect, where it can infiltrate into the soil and the process of sediment deposition begins (Dunn and Dabney, 1996, Kervroedan et al., 2018). There can be a slowing of the water flow to provide opportunity for infiltration in the vegetated buffer zone and deposition in the vegetation or the water and mobilised sediment can continue flowing over the buffer and into the receiving watercourse (Figure 2.1). Of course, all of these processes often occur together, and they are influenced by region, climate, topography, soil type and gradient (Borin et al., 2005).

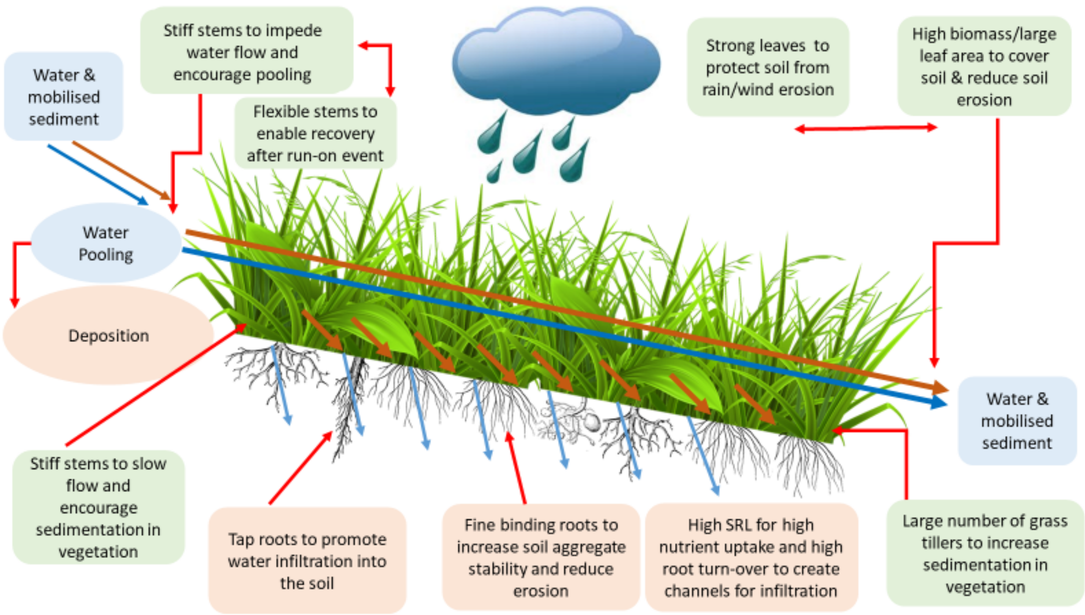


Figure 2.1 Buffer zone processes and the roles of plant functional traits.

In an attempt to quantify the effect and impact the traits could have on the buffer zone services the physiological traits required for performing the vegetative buffer zone functions are shown in Figure 2.1 and a trait and buffer function matrix is shown below (Table 2.1).

The buffer plants require high relative growth rate and high nutrient uptake to persist in the buffer zone. It is useful to measure this using simple plant trait measurements such as SRL, SLA, stem specific density (SSD) and plant height. These traits are used across many studies and allow for comparison across species, functional groups and studies (Bardgett, 2017, Gould et al., 2016, 2019, Kervroedan et al., 2018). High values for these functional traits give a valuable insight into how these plants would perform in vegetated buffer zones their competitiveness, ability to resist disturbance and their nutrient uptake characteristics (Diaz et al., 2004, Perez-Harguindeguy et al., 2013).

The plant architecture in terms of height, grass tillers, tussock forming or creeping growth form is also useful to make assumptions on how the plant can protect soil from rain and wind erosion (Westoby and Wright, 2006). Leaf dry matter content (LDMC) as a proxy for measuring the toughness of leaves enables simple measurements to determine the ability of the plant to resist and be resilient to overland flow including the sediments and debris carried with it (Kervroedan et al., 2019). In order for the grass species to resist and be resilient to overland flow and create the conditions to slow the flow, cause water pooling and sedimentation they need to have high strength and flexibility (Kervroedan et al., 2018, Dunn and Dabney, 1996). These traits can be measured using methods developed by Dunn and Dabney (1996) they investigate the stiffness and elasticity of grass stems in order to best design grass hedges. The five measurements are the moment of inertia, modulus of elasticity, yield strength, bending angle and SSD. Species water use is measured through SRL and SSD trait measurements. High SSD and high SRL values indicates high water (and nutrient) uptake (Perez-Harguindeguy et al., 2013).

Table 2.1 Buffer Services and Trait Matrix- Grey N/A or no impact, green medium impact, red high impact; ↑ Impact if value is high; ↕ Impact if value is high and/or low; ↓ Impact if value is low.

Buffer Function / Plant Trait	Infiltration	Nutrient use	Soil protection	Soil strength	Slowing water flow	Plant resilience
Height		↑	↑		↑	
Number of tillers			↑		↑	?
Leaf Dry Matter Content		?	↑		?	?
Specific Leaf Area		↑	↑		?	?
Stem Specific Density		↑	↑		↑	↑
Moment of Inertia			↑		↑	↓
Modulus of elasticity			↑		?	↑
Yield Strength			↑		↑	?
Bending Angle			↑		↑	?
Root Dry Matter Content	?	↑		?		?
Specific Root Length	?	↑		?		?
Root Tissue Density	↓	↓		?		?
Average Root Diameter	↕	?		↓		?

2.1.5 Study Rationale

Although there is work around individual aspects of sedimentation using vegetation (Dabney et al., 1995), root architecture for soil aggregate stability (Gould et al., 2016, Ola et al., 2015) and vegetation for erosion (Westoby and Wright, 2006) there is no combined study that allows insight into the mixture of plant traits needed to maximise buffer zone effectiveness. Therefore, the aim of this research is to identify a suite of plant functional traits that will enable the vegetated buffer zone to reduce the amount of sediment and nutrient discharge from agricultural fields into watercourses.

Hypotheses:

1. Plant function traits will differ between species, functional groups and growth stages.
2. Different species/functional groups will have traits most appropriate for providing different buffer services.

2.2 Methods

2.2.1 Selecting Species

Five native species commonly found in agricultural settings were used for all the experiments in this study. The species were chosen for their wide geographical range and ability to thrive on a wide variety of soil and habitat types. Using Grime (1974) CSR triangle theory of competitor, stress tolerant and ruderal it was noted that the species will need to be mainly competitors due to the high fertility soils but withstand some element of disturbance. Ellenberg indicator values (Hill, 1999) for nutrients, reaction and moisture were consulted to ensure the species could tolerate a high nutrient and high moisture environment (Table 2.2).

Selected plants were a mixture of the three main plant functional groups, graminoid, herb and legume. As vegetated buffer zones typically have a high concentration of grass species, three species were grass (*Lolium perenne, Dactylis glomerate*, *Schedonorus arundnaceus*), one herb (*Plantago lanceolata*) and one legume (*Trifolium repens*) were selected (Figure 2.2).

Figure 2.2. Study Species from left to right: *Lolium perenne, Dactylis glomerate, Schedonorus arundnaceus, Plantago lanceolate, Trifolium repens*.

Table 2.2 Ellenberg Indicator Values for Moisture, Nitrogen and Reaction for the five study species (Hill, 1999)

Species	**Moisture**	**Nutrients**	**Reaction**
Lolium perenne	5	6	6
Dactylis glomerata	5	7	6
Schedonorus arenaceo	6	7	6
Plantago lanceolata	5	6	4
Trifolium repens	5	6	5

2.2.2 Growing and Maintaining Plants

All the plants were grown in an unheated greenhouse at Lancaster University, Lancaster, UK. The first batch of seeds were sown in February 2017, but numerous sowings took place throughout spring 2017 to ensure there were enough plants at each growth stage for destructive sampling. Each batch of seeds sown had time of sowing, time of sprouting and time of re-potting recorded; seeds planted later in the spring took less time to germinate and slightly less time to become large enough to pot on. Seeds were broadcast into seed trays half filled with John Innes No. 2 compost and covered with a thin layer of compost, wet thoroughly and placed in larger trays containing water to be watered by capillary action. When the seedlings were large enough to handle, they were potted on to plug trays and then potted on to 3 litre pots filled with a sandy loam topsoil. Soil was sieved to 10 mm before planting and each pot and soil quantity was weighed and recorded to ensure consistency. Each test required five replicates for each species, at each growth stage. Three additional plants were grown to check root and above ground biomass growth rate and pot suitability. Plants were checked regularly and potted on to larger pots when necessary with dates recorded, soil weighed, and all variables kept consistent. Pots were kept in large trays containing water in an unheated greenhouse and rotated weekly to prevent bias from heat/cold or shading factors. Water was added to bottom of trays every two days or when needed.

Plants were tested at three different growth stages: established, mature and degenerate. Each species arrived at these stages at different times.

- Established Stage: 4 Weeks after planting into large pots. Each species planted at appropriate times according to growth rate.
- Mature Stage: when at least three out of five plants were flowering.
- Degenerate Stage: finished flowering and setting seed and at least three of the plants have leaves that were turning brown and dying.

2.2.3 Plant traits

Plant traits were measured using the published methods by Perez-Harguindeguy et al. (2013) and Dunn and Dabney (1996).

2.2.4 Leaves

The plants were harvested at the appropriate time (see growing methods) and it was ensured all tests on the leaves were carried out within three days. The leaves were removed from each plant and measured using leaf area meter (Areameter AM 200). Total leaf area for each plant was recorded (mm; except for degenerate plants where it was not possible to measure total leaf area due to the nature of the degenerate leaves). The degenerate plants were measured for SLA using 10 green leaves from each plant. Leaf dry matter content was measured using total leaf mass.

The fresh leaves weighed and recorded (g) using Navigator XL balance before drying in the oven at 60°C for 72 hours. Leaf dry mass was recorded (g) and the calculations for Specific leaf area (SLA) and leaf dry matter content (LDMC) were taken using equations 1 and 2.

$$SLA = \frac{L_a}{M_d} \qquad (1)$$

Where:

L_a is Leaf Area (mm)

M_d is Oven Dried Mass (mg)

SLA is Specific Leaf Area

$$LDMC = \frac{M_d}{M_f} \qquad (2)$$

Where:

M_d is Oven Dried Mass (mg)

M_f is Fresh Mass (g)

LDMC is Leaf Dry Matter Content

2..2.5 Plant above ground architecture

Plant architecture described using total plant height (mm) by extending plant material to full height and measuring from stem base. Leaf shape was described using standards from Hickey et al. (1997). Grass species tillers counted and recorded at each stage.

2.2.6 Stems

Stem tests carried were carried out within five days of harvest. Stem traits were measured on the grass species only. This is because *Plantago* has no stem and *Trifolium* has a creeping growth form that means many of the stems are parallel to the ground and would be unlikely to contribute in the same way. The water displacement method was used to measure volume of the stem in cm^3 (Perez-Harguindeguy et al., 2013), the stem was then dried in an oven at 70 °C for 72 hours. Oven dried stem mass was recorded (g). Stem specific density (SSD) was calculated using equation 3.

$$SSD = \frac{M_d}{V} \quad (3)$$

Where:

M_d is Oven Dried Mass (g)

V is volume (cm^3)

SSD is Stem Specific Density

Stem strength and flexibility for grass species at mature and degenerate stages were measured using methods from Dun and Dabney (1996). Moment of inertia (*I*), modulus of elasticity (*E*), yield strength (*y*) and bending angle at elastic limit of stems (*v*) calculated for each species.

The moment of inertia was measured by measuring the inside and outside dimensions of both ends (Figure 2.3) of the stem and recorded (mm) using a calliper and then using equation 4.

$$I = \frac{\pi}{64}(d_1^4 - d_a^4) \tag{4}$$

Where:

d_1 is mean of the outside dimension (mm)

d_a is mean the inside dimension (mm).

I is Moment of Inertia

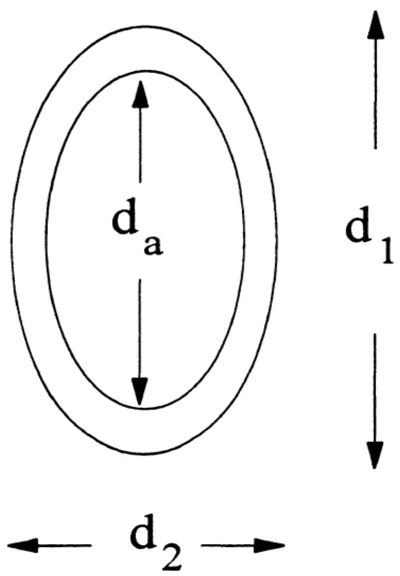


Figure 2.3 Measuring the stem for the moment of inertia calculation taken from Dunn and Dabney (1996).

The modulus of elasticity, yield strength and bending angle at yield point was measured by wrapping the grass stem in a single layer of cling film and securing in a clamp using blue tack to prevent crushing and breakage (Dunn and Dabney, 1996). A graduated board was placed behind the grass stem and a paper basket was attached one third of the way along the stem (Figure 2.4 & 2.5). Gradually weights were added recording each time the degree of deflection until the deflection was no longer proportional to the weight added or the stem did not go back to its original position after the load was removed. The maximum weight was recorded along with its corresponding deflection angle.

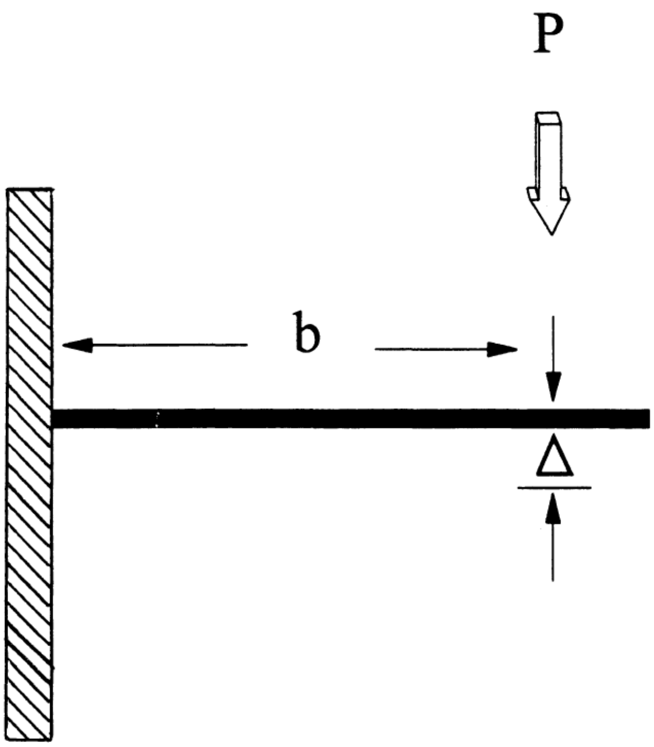


Figure 2.4 Measuring the modulus of elasticity, bending angle at yield point and yield strength. *P*= Load (weight), *b*= length along the stem and Δ= deflection of the stem taken from Dunn and Dabney (1996).

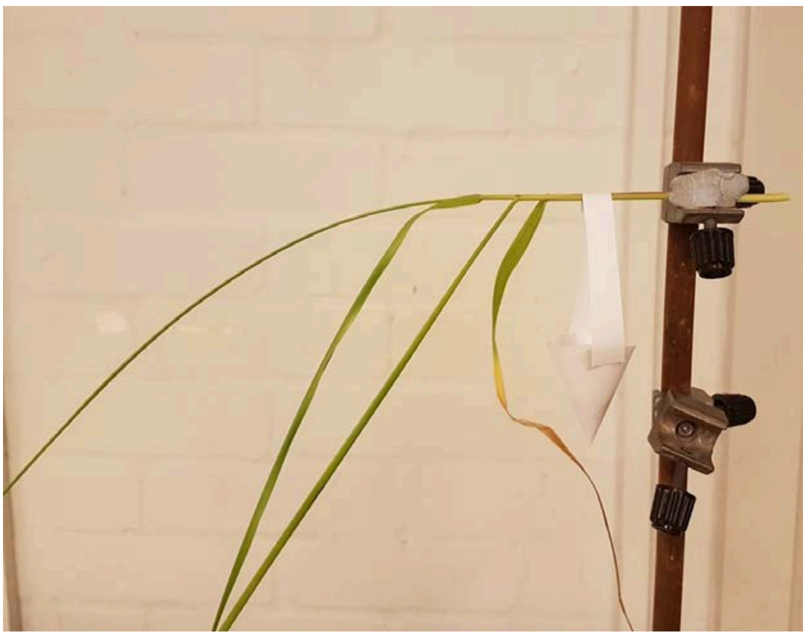


Figure 2.5 Measuring grass stems for modulus of elasticity, yield strength and bending angle at yield point.

Modulus of elasticity was calculated using equation 5 and result recorded in GPa, bending angle at yield point was calculated using equation 6 and recorded in degrees, finally yield strength was calculated using equation 7 and the result was recorded in MPa (Dunn and Dabney, 1996).

$$E = \frac{Pb^3}{3I\Delta} \tag{5}$$

Where:

E is Modulus of Elasticity (GPa)

P is Load (g)

B is length along the stem (cm)

Δ is deflection of the stem (degrees)

$$V = \arctan\left(\frac{\Delta}{b}\right) \tag{6}$$

Where:

b is length along the stem (cm)

Δ is deflection of the stem (degrees)

V is bending angle at yield point

$$Y = \frac{3d_1E\Delta}{2b^2} \tag{7}$$

Where:

d_1 is mean of the outside dimension of Stem (mm)

E is Modulus of Elasticity (GPa)

b is length along the stem (cm)

Δ is deflection of the stem (degrees)

Y is Yield Strength (MPa)

2..2.7 Roots

Roots were harvested within seven days of above ground biomass harvest. Pots were covered with tinfoil to prevent re-shooting of plants after leaf and stem harvest and the soil allowed to dry for two to three days. Connected root mass was removed and then remaining soil systematically searched through to remove all root fragments. Soil was washed from roots using a sieve, tweezers and water. The below ground fresh biomass was recorded (g). The roots were suspended in a tray filled with water ensuring they were fully elongated and not crossing. They were then scanned using the Epson Expression 11000 XL scanner and analysed using Winrhizo Pro 2013e 32-Bit for root length (cm), average root diameter (mm) and root volume (cm^3). Roots were then placed in a drying oven at 70 °C for 72 hours and oven dried mass was recorded (g). Root dry matter content (RDMC) was calculated using equation 8. Specific root length (SRL) calculated using equation 9 and root tissue density (RTD) using equation 10.

$$RDMC = \frac{M_d}{M_f} \quad (8)$$

Where:

M_d is Oven Dried Mass (mg)

M_f is Fresh Mass (g)

$RDMC$ is Root Dry Matter Content

$$SRL = \frac{R_l}{M_d} \quad (9)$$

Where:

R_l is Root Length (m)

M_d is Oven Dried Mass (g)

SRL is Specific Root Length

$$RTD = \frac{M_d}{R_v} \tag{10}$$

Where:

M_d is Oven Dried Mass

R_v is Root Volume

RTD is Root Tissue Density

2.2.8 Statistical Analysis

The results were analysed to see the differences for each trait at each different growth stage using R version 3.3.3 (R CoreTeam, 2018, R StudioTeam, 2016). Linear models were built using lm function and residuals tested for normality using plot function and Hist(resid). An anova and summary function were used to test differences before a Tukey post-hoc test was used. Any data sets that residuals did not conform to a normal distribution were tested using the non-parametric test Kruskal-Wallis and Tukey's Post-Hoc test. Results were plotted in Bar Charts using ggplot2 (Wickham, 2016).

2.2.9 Limitations of the Study and Further Work

The species were grown together in the same conditions and in the same growing medium, so the recorded traits although sometimes variable should be robust enough to make comparisons for the species in these circumstances (Burton et al., 2017) .However, these were lab conditions and these traits will likely vary due to nutrient availability, light/shade, competition and other environmental conditions when grown out in the field. Trait meanings and proxies are all from established and respected sources and there are numerous studies looking at some of these traits in the context of vegetated buffer zones (De Baets et al., 2007, 2019, Kervroedan et al., 2018).

2.3 Results

2.3.1 Plant Architecture

There was a significant difference in height (Figure 2.6) between the species at the established stage. All of the grass species were significantly taller than the forbs (P<0.01). There was no significant difference between *Plantago* and *Trifolium* (p>0.05). At the mature stage the grasses *Dactylis* and *Schedonorus* (P<0.01) were significantly taller than the other species (P<0.01). At the degenerate stage the difference between *Dactylis* and *Schedonorus* was less significant (p<0.05). *Lolium* was significantly smaller than Schedonorus (p<0.05) and Dactylis (p=0.054).

There was a significant difference in tiller numbers at both the mature and degenerate stages (P=<0.01; P=<0.01, Figure 2.7). *Lolium* had significantly more tillers than *Dactylis* and *Schedonorus* at both growth stages (P=<0.01) and *Schedonorus* had significantly more tillers than *Dactylis* at the degenerate stage (P=<0.05).

Table 2.3 Mean above and below-ground biomass (g) at each stage established (a), mature (b) and degenerate (c) and leaf shape.

Species	**(a)Above**	**(b) Above**	**(c) Above**	**(a) Below**	**(b)Below**	**(c) Below**	**Leaf Shape**
Lolium Perenne (LP)	0.82	84.62	52.5	0.31	48.32	48.32	Linear
Dactylis glomerata (DG)	0.44	173.38	87.45	0.16	132.26	132.26	Linear
Schedonorus arenaceous (SA)	0.43	134.15	101.18	0.15	98.44	98.43	Linear
Plantago lanceolata (PL)	5.58	43.58	97.75	2.39	32.25	48.43	Lanceolate
Trifolium repens (TR)	1.43	39.76	80.93	0.78	4.95	12.09	Trifololate

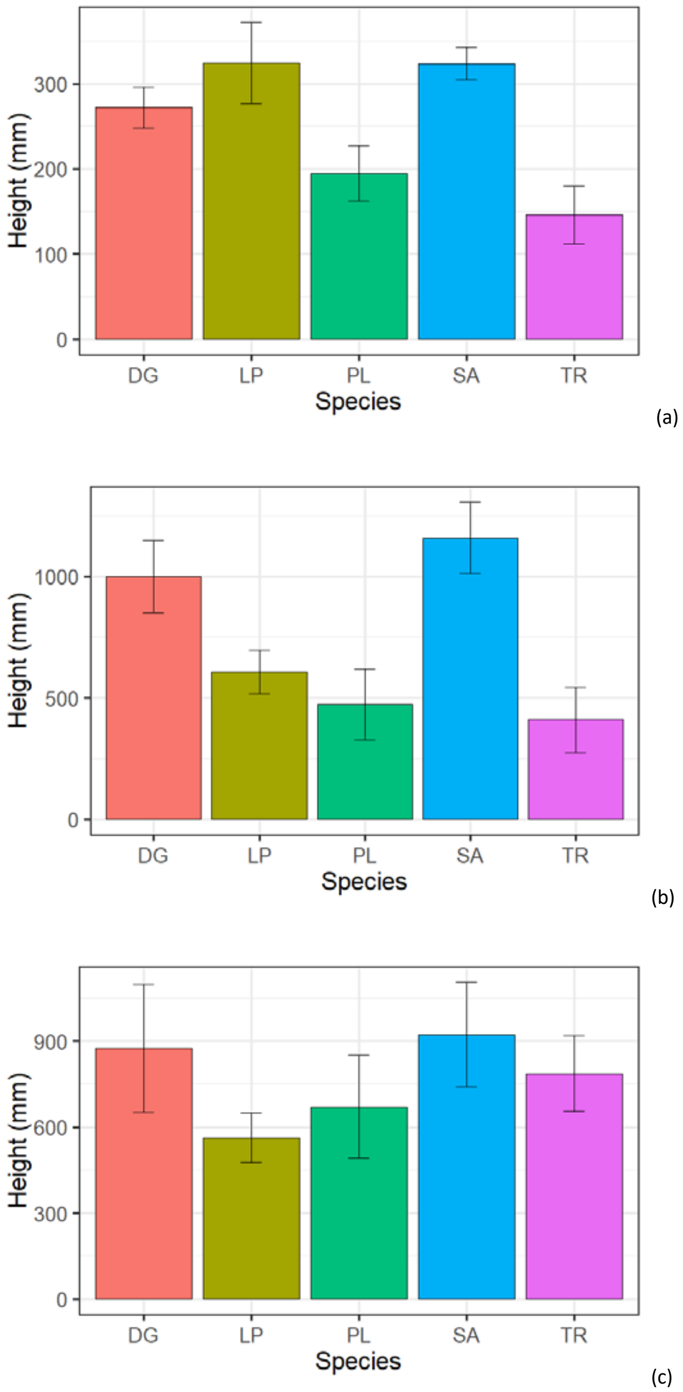


Figure 2.6 Bar Charts of height (mm) (Mean +/- standard deviation) for each of the five species (n=25) at three growth stages: (a) established, mature (b) and degenerate (c).

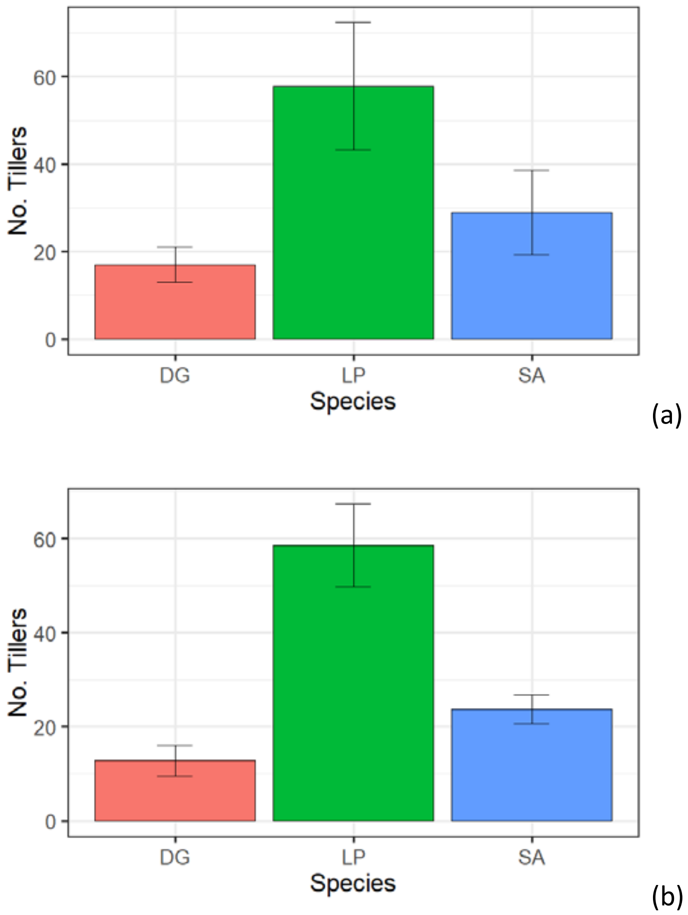


Figure 2.7 Bar Charts (Mean +/- standard deviation) of the number of tillers for three species (n=15) at two growth stages: mature (a) and degenerate (b).

2.3.2 Leaves

There are significant differences between the leaf dry matter content of the species at all growth stages (Figure2.8). At the established stage *Dactylis* and *Schedonorus* have significantly higher leaf dry matter content than *Plantago* (P=<0.05, P=<0.05 P<0.01). At the mature stage *Dactylis* had significantly higher leaf dry matter content than *Plantago* (P=<0.01) and *Trifolium* (P=<0.01), *Lolium* had significantly higher leaf dry matter content than *Plantago* (P=<0.01) and *Trifolium* (P=<0.01) and *Schedonorus* had significantly higher leaf dry matter content than *Trifolium* (P=<0.05, P=<0.01). At the degenerate stage *Trifolium* had significantly higher leaf dry matter content than *Dactylis* P<0.01).

There was a significant difference between the specific leaf area of the different species at all three growth stages (Established P=<0.01; Mature P=<0.01; Degenerate P=<0.01, Figure 2.9). At the established stage *Lolium*, *Plantago* and *Trifolium* have significantly higher specific leaf area than *Dactylis* and *Schedonorus* (P=<0.01). *Plantago* and *Trifolium* have significantly lower specific leaf area than *Lolium* (P=<0.01) and *Plantago* had significantly higher specific leaf area than *Trifolium* (P=<0.01). At the mature stage *Trifolium* had significantly higher specific leaf area than the three grass species (P=<0.05) and *Plantago* had significantly higher specific leaf area than *Lolium* and *Dactylis*. There was no significant difference between *Schedonorus*, *Dactylis* and *Lolium* (P=>0.05). In the degenerate stage *Trifolium* and *Schedonorus* have significantly (P<0.01) lower specific leaf area than *Dactylis*.

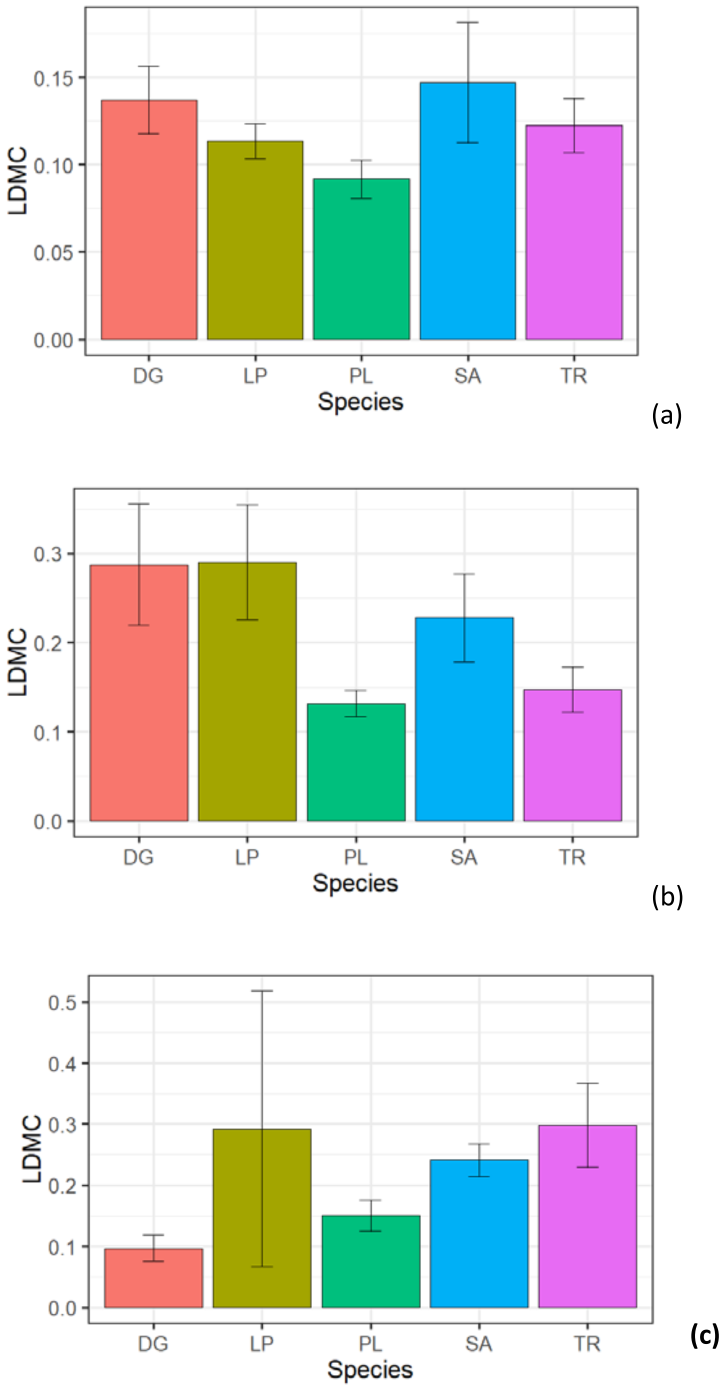


Figure 2.8 Bar Charts (Mean +/- standard deviation) of leaf dry matter content (LDMC, dry weight (mg)/fresh weight (g) =LDMC) for each of the five species (n=25) at three growth stages: established (a), mature (b) and degenerate(c).

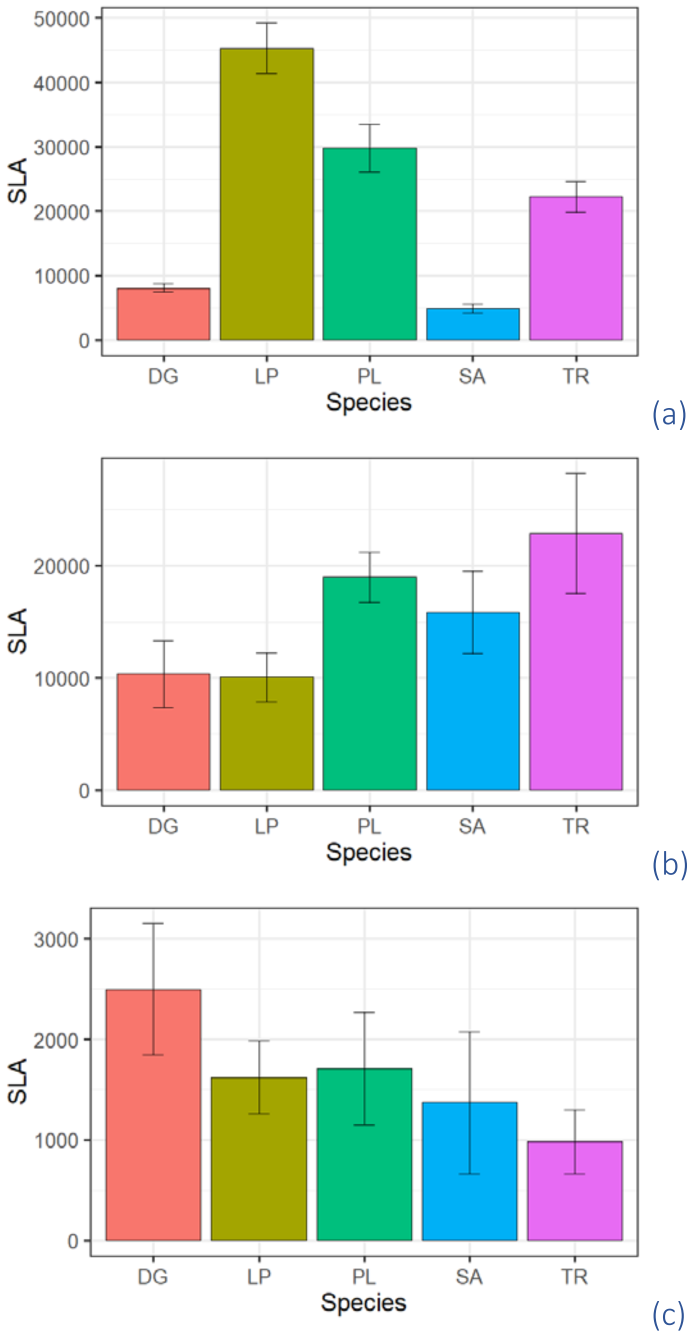


Figure 2.9 Bar Charts (Mean +/- standard deviation) of specific leaf area (SLA, leaf area (mm)/dry weight (mg) =SLA) for five species (n=25) at three growth stages: established (a), mature (b) and degenerate (c).

2.3.3 Stem

There was no significant difference in stem specific density at the established stage, but there was a significant difference at the mature and the degenerate stages (established P=>0.05; mature P=<0.01; degenerate P=<0.05; Figure 2.10). At the mature stage *Dactylis* had significantly higher stem specific density than *Lolium* and *Schedonorus* (P=<0.01, P=<0.05). At the degenerate stage *Schedonorus* had a significantly lower stem specific density than *Lolium* (P=<0.05). There was no difference between *Dactylis* and *Schedonorus* or *Dactylis* and *Lolium* (P=>0.05).

The moment of inertia (mm^4) was lower for *Lolium* at the mature stage, but not significantly. There was no significant difference between the other species or between the species at the degenerate stage (mature P=0.056, degenerate P=>0.05; Figure 2.11).

There was no significant difference of the modulus of elasticity between the species at the mature stage. At the degenerate stage *Lolium* had a significantly higher modulus of elasticity than *Schedonorus* (P=<0.01) and *Dactylis* (P=<0.01; mature P=>0.05; degenerate P=<0.01; Figure 2.12).

There was a significant difference between the bending angle at yield point for the species at the mature stage *Lolium* had a greater angle than *Dactylis* (P=<0.05) and *Schedonorus* (P=<0.05). There was a significant difference also at the degenerate stage *Schedonorus* had a smaller bending angle than both *Lolium* (P=<0.01) and *Dactylis* (P=<0.05; mature P=<0.05; degenerate P=<0.01; Figure 2.13).

The yield strength of the stems at the mature stage have no significant difference. At the degenerate stage *Lolium* had significantly higher yield strength than *Dactylis* (P=<0.01) and *Schedonorus* (P=<0.01; mature P=>0.05; degenerate P=<0.01; Figure2.14).

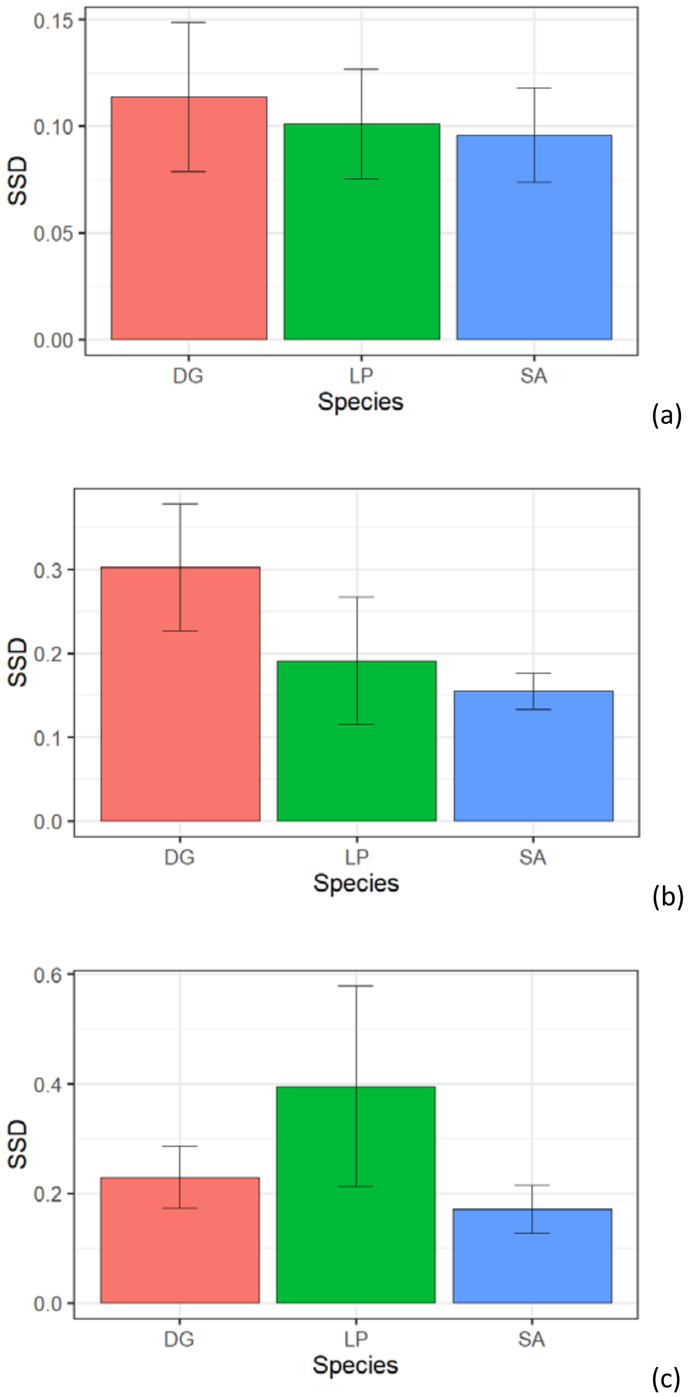


Figure 2.10 Bar Charts (Mean +/- standard deviation) of stem specific density (SSD) for five species (n=15) at three growth stages: established (a), mature (b) and degenerate (c).

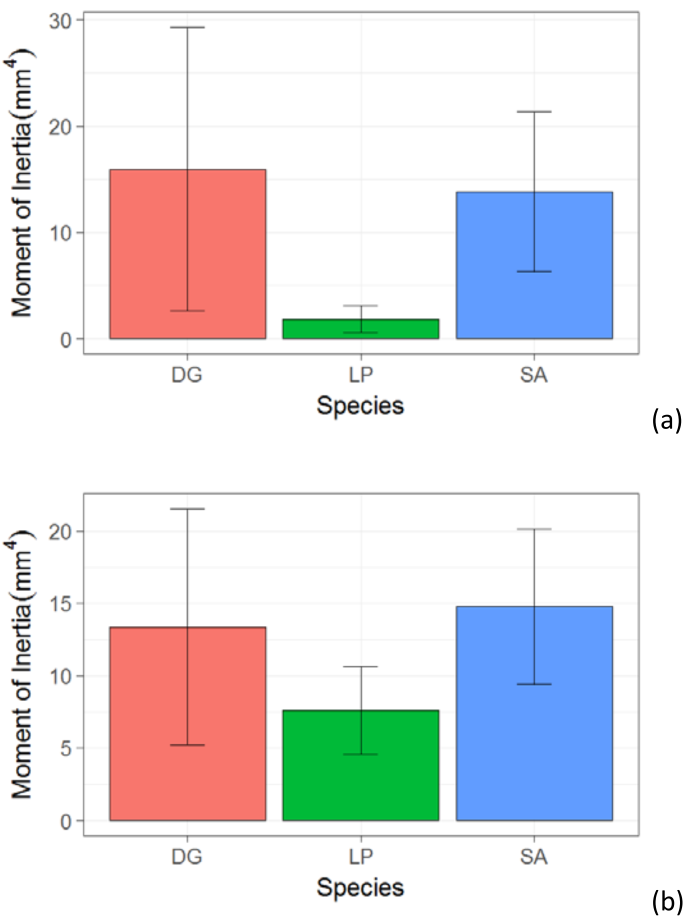
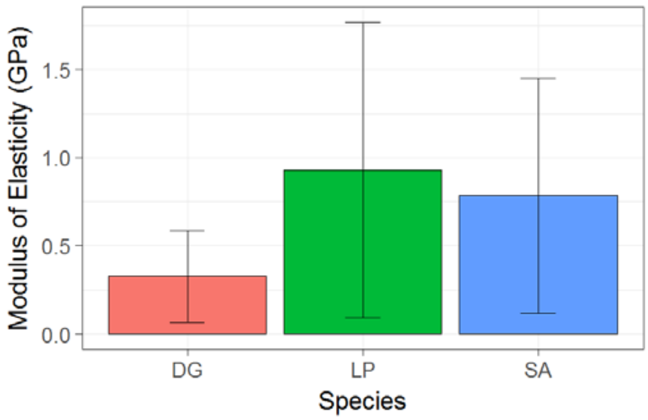
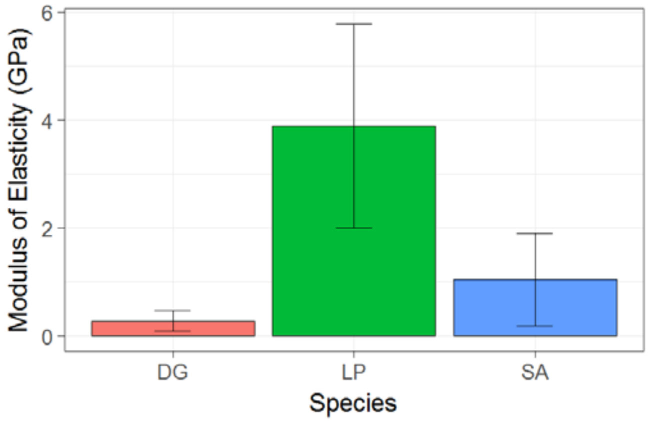


Figure 2.11 Bar Charts (Mean +/- standard deviation) of the Moment of Inertia (mm^4) for three species (n=15) at two growth stages: mature (a) and degenerate (b).

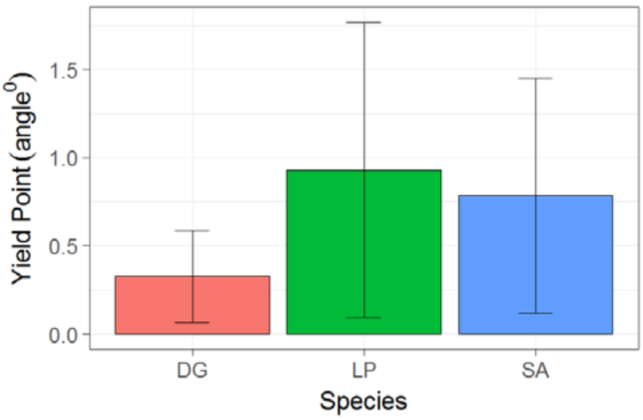


(a)

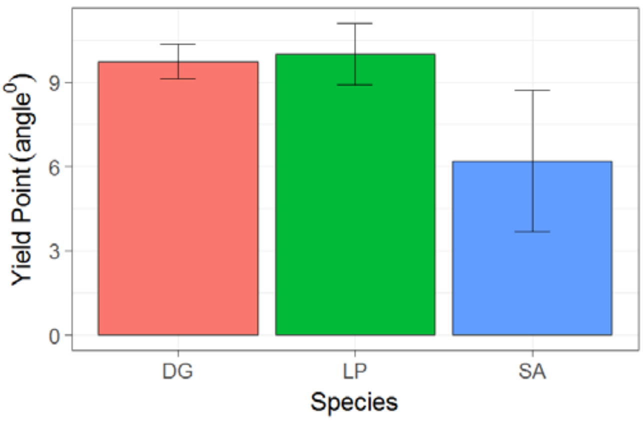


(b)

Figure 2.12 Bar Charts (Mean +/- standard deviation) of the Modulus of Elasticity (GPa) for three species (n=15) at two growth stages: mature (a) and degenerate (b).

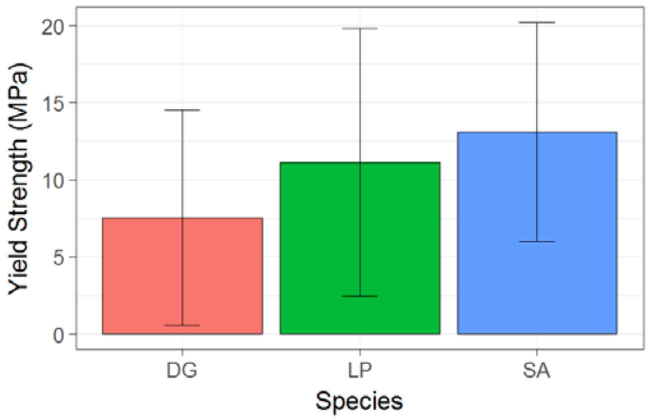


(a)

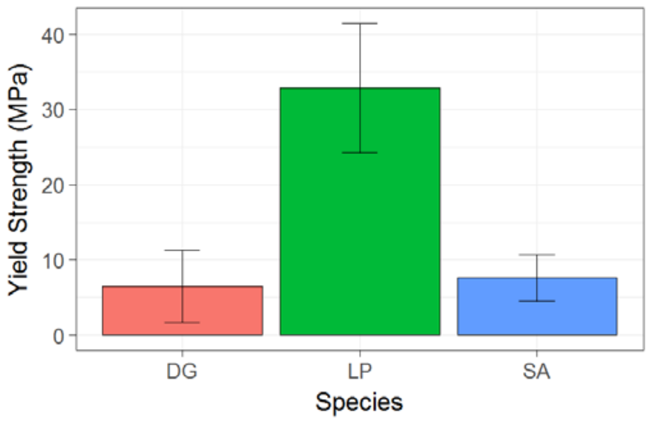


(b)

Figure 2.13 Bar Chart (Mean +/- standard deviation) of Bending Angle at Yield Point for three species (n=15) at two growth stages: mature (a) and degenerate (b).



(a)



(b)

Figure 2.14 Bar Chart (Mean +/- standard deviation) of the Yield Strength (MPa) of three species (n=15) at two growth stages: mature (a) and degenerate (b).

2.3.4 Roots

There was a significant difference in root dry matter content between species at all three growth stages (established P=<0.01; mature P=<0.01; degenerate P=<0.01; Figure 2.15). At the established stage *Lolium* had significantly lower root dry matter content than all of the other species (P=<0.05). At the mature growth stage *Plantago* had the lowest amount of root dry matter content (P=<0.01) and *Dactylis* had significantly higher root dry matter content than all of the other species (P=<0.01). At the degenerate stage *Dactylis* had the highest root dry matter content (P=<0.01) there was no significant difference between the other species.

There was a significant difference between the specific root length at each growth stage (established P=<0.01, mature P=<0.01), degenerate P=<0.01, Figure 2.16).

At the established stage *Dactylis* had higher specific root length than *Plantago* and *Trifolium* (P=<0.01), *Lolium* and *Schedonorus* have higher specific root length than *Plantago* (P=<0.01). At the mature stage *Plantago* and *Trifolium* have higher specific root length than the other three species (P=<0.05), *Schedonorus* had a higher specific root length than *Dactylis* (P=<0.05). At the degenerate stage *Lolium* had a higher specific root length than all of the other species (P=<0.01) and there was no significant difference between the other species.

There was a significant difference between average root diameter between the species at all three stages (established P=<0.01, mature P=<0.01, degenerate P=<0.01, Figure 2.17). *Plantago* and *Trifolium* have a significantly higher average root diameter than the three grass species (P=<0.01) at the established stage. At the mature stage *Trifolium* and *Plantago* have significantly higher average root diameter than *Dactylis* and *Lolium* (P=<0.01), *Trifolium* had higher average root diameter than *Schedonorus* (P=<0.05) and *Schedonorus* had higher average root diameter than *Lolium* (P=<0.01). At the degenerate stage *Trifolium* had a larger average root diameter than all of the grass species (P=<0.05), *Plantago* had a larger average root diameter than *Dactylis* and *Lolium* (P=<0.01) and *Schedonorus* had a larger average root diameter than *Lolium* P=<0.01).

There a significant difference in root tissue density at all of the stages (established P= <0.01, mature P=<0.01, degenerate P=<0.01, Figure 2.18). At the established stage, *Trifolium* had significantly lower root tissue density than *Lolium* and *Schedonorus* (P=<0.01). At the mature stage *Dactylis* had significantly higher root tissue density than all of the other species (P=<0.01). At the degenerate stage *Plantago* had higher root tissue density than all of the other species (P=<0.01).

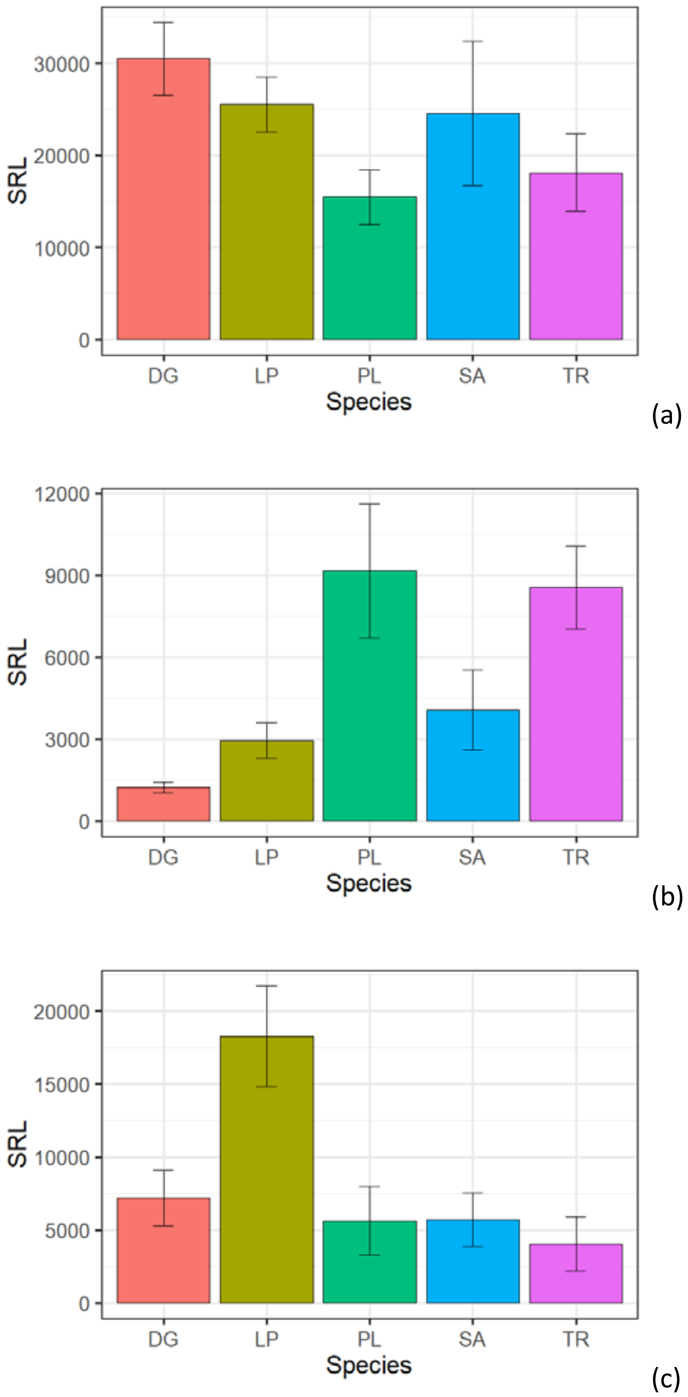
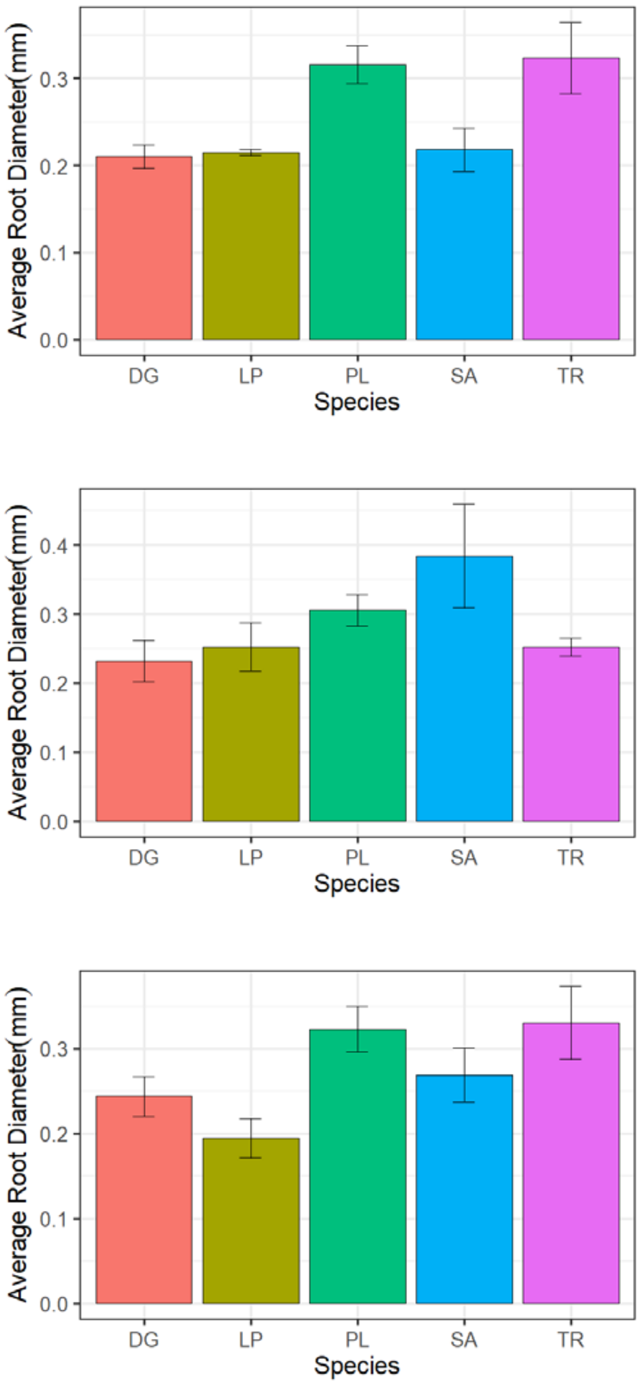


Figure 2.16 Bar Charts (Mean +/- standard deviation) for specific root length (SRL) five species (n=25) at three growth stages: established (a), mature (b) and degenerate (c).

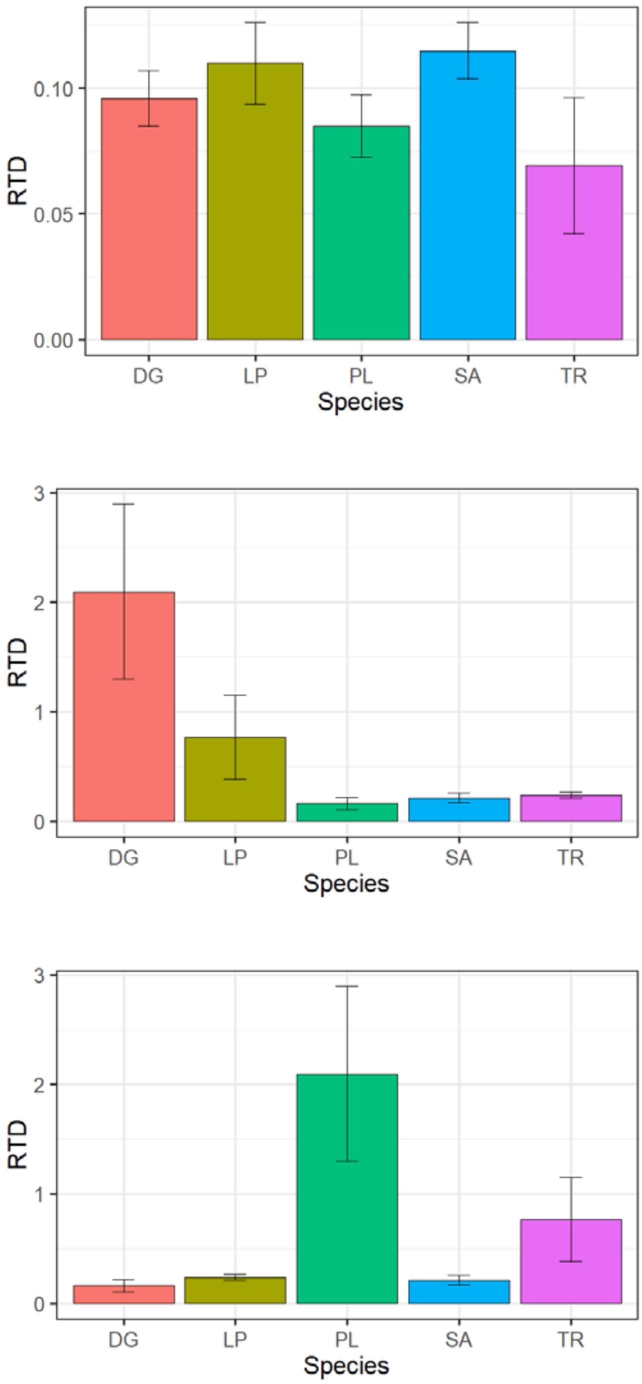


(a)

(b)

(c)

Figure 2.17 Bar Charts (Mean +/- standard deviation) for average root diameter (mm, ARD) for five species (n=25) at three growth stages: established (a), mature (b) and degenerate (c).



(a)

(b)

(c)

Figure 2.18 Bar Charts (Mean +/- standard deviation) for root tissue density (RTD) for five species (n=25) at three growth stages: established (a), mature (b) and degenerate (c).

2.4 Discussion

The proposed hypotheses can be accepted. The five species performed quite differently at the different growth stages. The established stage tests were useful to understand the plants establishment strategies while the mature and degenerate stage results illuminated how the species were able or not to perform services in the buffers. The grass species, *Lolium* and *Dactylis*, seemed to have traits more suited to slowing the flow, capturing sediments and protecting the soil. Furthermore, they had root traits reported to increase soil aggregate stability. The forbs both had root traits that are thought to encourage infiltration, while they provided ground cover and structural diversity.

2.4.1 Aboveground architecture

The grasses were taller than the forbs at all stages indicating that grasses could form a better barrier and give more resistance to overland flow than the forbs (Eviner and Chapin, 2003, Dunn and Dabney, 1996, Evans et al., 2007). The growth strategy of the grass species also speaks to the fact they will have a faster uptake of nutrients (Kleyer and Minden, 2015). This rapid growth strategy is associated with high phosphorus (P) use (Kleyer and Minden, 2015) this will enable removal of P from the buffer by cutting and removing biomass (Vought et al., 1995). *Lolium* was the shortest of the grass species tested but did have a significantly larger number of tillers than the other grasses at all stages tested. This shows that its growth strategy is more suited to turf forming which has been reported to enable the high capture and deposition of sediments (Mekonnen et al., 2016, Pan et al., 2017). These traits make *Lolium* the favoured grass species for sediment capture, even though its growth form suggests that it will not be an effective water barrier (Pan et al., 2017).

The forbs were lower growing across the growth stages, but *Trifolium* had a creeping habit that covered the soil, and this could be useful for sediment capture and soil protection (Mekonnen et al., 2016). Therefore, height must be used in conjunction with canopy complexity and growth form diversity within the species and between the species to enable it to be a useful trait indicator. This diversity could enhance the buffer plants ability to capture sediment and slow the water flow during a run-off event (de Bello et al., 2010).

The grass species had higher above ground plant biomass at the mature and degenerate stages this suggest good canopy cover and is a good indicator that the species will encourage infiltration and reduce soil erosion through limiting the rain splash damage of the soil (de

Bello et al., 2010, Burylo et al., 2012). Preventing this damage allows the soil to retain its hydraulic conductivity and reduce the risk of soil erosion from the buffer. It also provides a greater surface roughness that slows water flow and encourages sediment deposition (Kervroedan et al., 2018).

2.4.2 Leaves

The greater leaf dry matter content of the grasses could enable the leaves to better protect the soil surface and be more resistant to damage from overland flow and the debris it may carry, as species with high leaf dry matter content are less vulnerable to herbivores and leaf breakage (Owens et al., 2007). High leaf dry matter content could also affect roughness and density of the leaves and in turn have a positive effect on their ability to capture sediments (Delectic, 2001, Kervroedan et al., 2019). In the degenerate stage *Trifolium* has higher LDMC than the other species this suggests that there will be differences across the growing season. In a study by Pan et al. (2017) they found that *Trifolium* captured more sediment in a flume experiment than *Dactylis* especially at a later season growth stage. The better sediment capturing ability could be because of the higher leaf dry matter content increasing the surface roughness. This makes the case for a diverse planting scheme to ensure this is reflected in the ability of the buffer to function across the seasons (Berendse et al., 2015).

The forbs had higher SLA at the mature stage (the main growing season) indicating that they could exploit nutrient and water resources better than the grass species at this growth stage (Perez-Harguindeguy et al., 2013, Dwyer and Mason, 2018, Burton et al., 2017). These values reduced in the degenerate stage when the plants were senescing, and this is the time when extreme weather events become more likely (Boardman et al., 2006). At this stage *Dactylis* had significantly higher specific leaf area; it also started the senescence later than the other species. *Dactylis* has standing green biomass across winter meaning the leaves and stems are still present and able to continue to slow the flow, create surface roughness and capture sediments after other species have significantly reduced aboveground biomass (Pan et al., 2017, Kervroedan et al., 2019). Therefore, time of maturity and time of senescence could be a contributing factor to the species ability to carry out buffer services and should be a factor in the species choice (Berendse et al., 2015).

2.4.3 Stems

Stem strength, flexibility and density were measured to understand how the species could perform at impeding water flow to encourage pooling, but also the flexibility and elasticity to enable recovery from run-on events (Dabney et al., 1995, Meyer et al., 1995, Kervroedan et al., 2018). *Dactylis* had the highest stem specific density at the mature growth stage which implies that it has the strongest stem (Dwyer and Mason, 2018, Perez-Harguindeguy et al., 2013). This seems to be supported by the species erect and tuft forming habit. Numerous studies have suggested that this stiffness or strength is one of the leading traits that reduce water runoff speed, create backwater pooling and then in turn allow for deposition of sediments (Kervroedan et al., 2019, Kervroedan et al., 2018, Dunn and Dabney, 1996, Dabney et al., 1995, Meyer et al., 1995). However, Pan et al. (2010) found that other species captured more sediments than *Dactylis* at an advanced growth stage, so even though stem strength is a central trait for sediment capture and slowing the flow other factors such as leaf size, shape or roughness are an important consideration for this service in the buffer.

The moment of inertia and yield strength measurements were used to approximate how quickly the species would bend and allow water flow over the top, the modulus of elasticity and bending angle measurements investigated how the stems respond to heavy water flow and thus the species ability to recover from the event (Dabney et al., 1995, Dunn and Dabney, 1996). At the mature stage, *Lolium* had a lower moment of inertia than the other species. This suggests that *Lolium* would be less able to resist overland flow than the other species tested and would probably flatten more quickly in a run-on event, yet it also had a higher bending angle meaning that even after being flattened it should be able to recover and continue to function within the buffer (Dunn and Dabney, 1996). *Lolium* offers a significantly higher modulus of elasticity and higher yield strength at the degenerate stage than the other grass species demonstrating that it could recover from a run-on event without significant damage to the plant, but become easily bent over and not create a sturdy barrier to enable pooling and deposition.

2.4.4. Roots

Root dry matter content and specific root length are used as measures for describing the plants ability at nutrient and water uptake (Perez-Harguindeguy et al., 2013). High specific root length and a low root tissue density indicates the species can exploit nitrogen and water resources quickly and effectively (Bardgett et al., 2014). This suggests that their high specific root length values would make *Dactylis* and *Lolium* good candidates for this service in the buffer. Likewise, the forbs both showed high values for specific root length at the mature stage showing that they would make useful buffer species. In a study by De Deyn et al. (2009), it was found that the addition of herbs and legumes to grassland communities enabled better storage of carbon, less leaching of nitrogen, and better soil water storage. This shows that although specific root length is a valuable indicator of water and nutrient uptake there is a need for functional root diversity to enable influence over water and nutrient dynamics in the buffer (de Bello et al., 2010).

Root diameter and root length have a measurable and significant effect on soil erosion, soil aggregate stability, soil bulk density and soil hydraulic conductivity (de Bello et al., 2010, De Baets et al., 2007, Helsen et al., 2016, Berendse et al., 2015, Dupuy et al., 2005, Gould et al., 2016). The forbs had higher average root diameter throughout the growth stages that suggests that their root structures will promote better water infiltration into the soil, but this could also increase soil bulk density (Gould et al., 2016, Bardgett et al., 2014). Water infiltration is an important factor for reducing water runoff and hence sediment and nutrient transport through the buffer, it also reduces the risk of soil erosion in the buffer (Schmitt et al., 1999, Holly and Larson, 2016).

However, this infiltration facilitation may be at the expense of soil aggregate stability (Gould et al., 2016). Numerous studies have explored root traits and their ability to increase soil aggregate stability and it has been found that thin, expansive root systems lead to better stability in pot, mesocosm and field experiments across arrange of systems including grasslands and dyke structures (Berendse et al., 2015, Gould et al., 2016, Bardgett et al., 2014, De Baets et al., 2007, Vannoppen et al., 2016). The grass species *Lolium* and *Dactylis* in this study had lower average root diameter across the growth stages indicating that their root traits were well suited to binding and reinforcing the soil and would work well to perform this service in the buffer. Conversely, the large amount of thin, binding roots in the top few centimetres of soil has been found to reduce the permeability of the soil and reduce hydraulic conductivity (Bardgett et al., 2014, De Baets et al., 2007, Gould et al., 2016).

These results highlight that there are trade-offs between traits and the ecosystem services that the planting is trying to address as no one species had all of the desirable traits to maximise the effectiveness of a vegetated buffer zone. This supports the work of Berendse et al. (2015) showed that increased diversity of species, functional groups and traits can mitigate against these trade-offs and protect against species loss and unwanted trait effects.

This consequently makes the argument for root diversity by multi-trait and species planting in the buffer to ensure soil strength and permeability is maintained.

2.4.5 Conclusions

For the species investigated the plant traits needed to form a successful VBZ are not found in one species that could be grown in a monoculture, but will require different species and different functional groups. *Lolium* has good ground coverage, has fast nutrient and water up take capabilities. It has strong and flexible stems to provide resilience and resistance to overland flow and long, fibrous roots that should reinforce and strengthen soil aggregate stability and soil sheer strength. However, *Lolium* is low growing and does not provide structural diversity and standing aboveground biomass in winter, so *Dactylis* would made an excellent accompaniment as it has contrasting growth strategy. Adding herbs into the planting should help bring structural and belowground diversity that could enable better water infiltration and different temporal resource efficiency.

3.1 Assessing species and plant trait performance under an overland flow simulation.

Use of mesocosm based, overland flow laboratory experiments are a common and well-established method of investigation, especially for examining the interactions of vegetation, soil type, sediment load and water run-on (Vannoppen et al., 2017, Abu-Zreig et al., 2004, Kervroedan et al., 2018, 2019). There are many studies using various flume sizes from large flumes (2.5m^2 surface area; Fu et al., 2019b) to relatively small samples (0.0324m^2; De Baets et al., 2011, Knapen et al., 2008) each allowing the researcher to understand the process of overland flow in their particular area of interest and at different scales.

Using laboratory-based flume simulations allows the investigator to examine aspects of the process without the interference of the many different natural processes that make it unclear how the mechanisms work and the logistical difficulties of field experiments (Abu-Zreig, 2001). Using a flume allows the researcher to repeat a process with high accuracy for different soil types or plant species (De Baets et al., 2007, Knapen et al., 2008). The gradient, overland flow volume or amount of added sediment can be changed while other aspects stay the same to allow an understanding of how each feature interacts or affects the outcome (Wang et al., 2019a). This allows a very detailed view of a particular process and allows the researcher to make assumptions on interactions.

An array of questions have been asked by a range of researchers from their flume experiments from looking at aboveground vegetation and how or if it increases the hydraulic roughness (Kervroedan et al., 2019, Kervroedan et al., 2018) to root systems and their ability to reduce soil erosion (De Baets et al., 2011, Vannoppen et al., 2017). There are many other studies focusing on how water moves across the landscape and how soil detachment processes occur with overland water flow as a driver (Knapen et al., 2008, Wang et al., 2019b). Many of the studies look at either aboveground or belowground plant and water processes, but not both. This helps the researcher to separate processes but neglects the interactions between them. Kervroedan et al. (2019) ensured the soil was saturated in order to remove water infiltration from the experiment and Vannoppen et al. (2015) removed all above ground vegetation to focus solely on roots. Both of these studies are discussed in the following sections.

3.1.2 Aboveground Processes

It has been proven that well vegetated areas are less likely to suffer soil erosion (Boardman et al., 2006). How vegetation affects the rate of overland water flow and the mobilised sediment is a question that has been studied in a flume experiment by Kervroedan et al. (2019). the study by Kervroedan et al. (2018) looked specifically at the surface roughness created by the different leaf and stem traits of the vegetation, they focused solely on aboveground processes and found that the leaf area and leaf density had a significant effect on hydraulic roughness and thus slowed the flow and captured sediments (Kervroedan et al., 2018). However, they did not find any significant effect of stem density on hydraulic roughness. Conversely, other studies have shown that stems are integral to slowing the flow and helping the deposition of sediments in grass dominated edge of the field strips (Dabney et al., 1995, Dabney et al., 2004, Meyer et al., 1995)

In the flume studies by Meyer et al. (1995) and Dabney et al. (1995) they found that grass hedges, made up of tall grass species with stiff stems, caused a backwater effect and water pooling that allowed the deposition of sediments with the slowing of the water flow. The sediment trapping ability varied with grass species, flow rate and sediment particle size (Meyer et al., 1995). Higher flow reduced sediment trapping and smaller particles were less likely to be trapped at the edge of the grass (Dabney et al., 1995). This was in contrast to the studies by Kervroedan et al. (2019) and Kervroedan et al. (2018) they did not find that the grasses helped to filter the sediments. It seems likely that the type and height of the grass species affected the way the studies were carried out and how the water and mobilised sediments reacted to the grass.

Although the aboveground processes are undoubtedly important in slowing runoff and capturing sediments the belowground processes and plant traits can affect saturated hydraulic conductivity and other soil physical properties (Vannoppen et al., 2017, Vannoppen et al., 2015, De Baets et al., 2007). Therefore, water infiltration and soil stability process and the plant trait drivers are worth studying. The next section will focus on belowground plant traits specifically the roots and how these affect the general soil matrix, soil aggregate stability and the hydraulic conductivity of the soil.

3.1.3 Belowground Processes

The study by Vannoppen et al. (2015) investigated the effects of root type and root properties on soil erosion through concentrated overland flow. They found that plant roots modify the soil and allow for changes to both mechanical and hydrological processes within the soil. This means that soils can be strengthened and have increased hydraulic capacity due to the types of and mixtures of roots because of the input of soil organic matter, root exudates and the binding of the soil matrix (Figure 3.1).

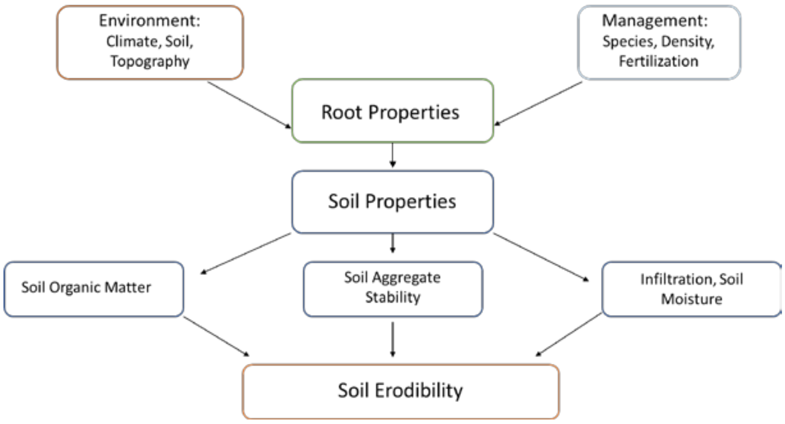


Figure 3.1 The interaction between Environment, Management and Root Properties and Soil Erosion Susceptibility adapted from Vannoppen et al. (2015).

This work was followed by an overland flow experiment to look for ways to quantify the relationship between soil processes and root types (Vannoppen et al., 2017). They found that all root types reduced soil erosion compared to bare soil, but fibrous roots reduced erosion more compared to tap roots (Vannoppen et al., 2017). However, this finding was strongly dependant on soil types, the fine, fibrous root systems worked better in non-cohesive soils, whereas the tap roots worked better in more cohesive soils (Vannoppen et al., 2017; Figure 3.1). These findings show that there is no one size fits all for planning which plant species would be best for the reduction in soil erosion.

Slowing the water flow over vegetated buffer zones is a way of reducing sediment load into watercourses (Dabney et al., 1995). The longer the water is within the field or buffer there is a higher chance that sediment deposition will occur (Meyer et al., 1995). Using vegetation as a physical barrier to the water has been discussed above, however there is research that suggests that belowground plant traits can increase water infiltration and thus slow the water flow (De Baets et al., 2011).

Song et al. (2017) found that fibrous plant roots, although good for soil cohesion and stability had a negative impact on soil hydraulic conductivity whereas tap rooted species had a positive influence. However, it is difficult to attribute this to specific root traits as land use affects species traits (Bardgett, 2017) and affects soil hydraulic conductivity (Chandler et al., 2018). Land use also affects the diversity and abundance of soil fauna that in turn can influence soil hydraulic conductivity (Chandler et al., 2018). There are many factors that affect the way water moves across and through the soil and it is important to understand the role vegetation and more specifically the plants and their traits have in this process. Identifying the specific traits that have an effect on specific buffer services will enable a better understanding of species and functional groups that will perform these services effectively.

3.1.4 Study Rationale

Following on from Chapter 2 investigating plant functional traits to increase the efficiency and capacity of vegetated buffer zones. This study aims to assess the accuracy of the conceptual model by carrying out single species laboratory-based, overland flow simulations. These will use the same five species that were phenotyped in chapter 2, to gain a better understanding of the influence of the plant traits on the overland flow processes.

Hypotheses:

1. There will be significant differences between species for runoff coefficients, saturated hydraulic conductivity, total sediment mass and soil aggregate stability.
2. There will be significant correlations between runoff coefficients, total dried sediment mass, saturated hydraulic conductivity, soil aggregate stability and above/belowground plant traits.

3.2 Methods

3.2.1 Selecting Species, Growing and Maintaining Plants

The five species grown were selected and trait tested in the previous chapter (chapter 2). The species used were *Lolium perenne*, *Dactylis glomerata*, *Schedonorus arundinaceus*, *Plantago lanceolata* and *Trifolium repens*.

Plants were grown in an open-ended poly tunnel in ten wooden frames (1020 mm by 780 mm by 300 mm) lined with waterproof plastic membrane (Figure 3.2). Pea gravel was situated at the bottom of the boxes for drainage (100 mm) and topped with 200 mm of sandy-loam topsoil (sieved to 10 mm). Seeds were sown 3 g m $^{-2}$ and lightly raked. All seeds were sown in April 2018.

Plants were watered every other day (or daily in very hot weather) using an overhead sprinkler system. Plants were fertilised every four weeks, using miracle grow plant food. Weeding was carried out every two days for the first month after sowing and then weekly for a further month. Weeding stopped when the plants were well established to prevent disturbance to the soil in preparation for testing. There were four repeats of five species at two growth stages (n=20 for each growth stage).

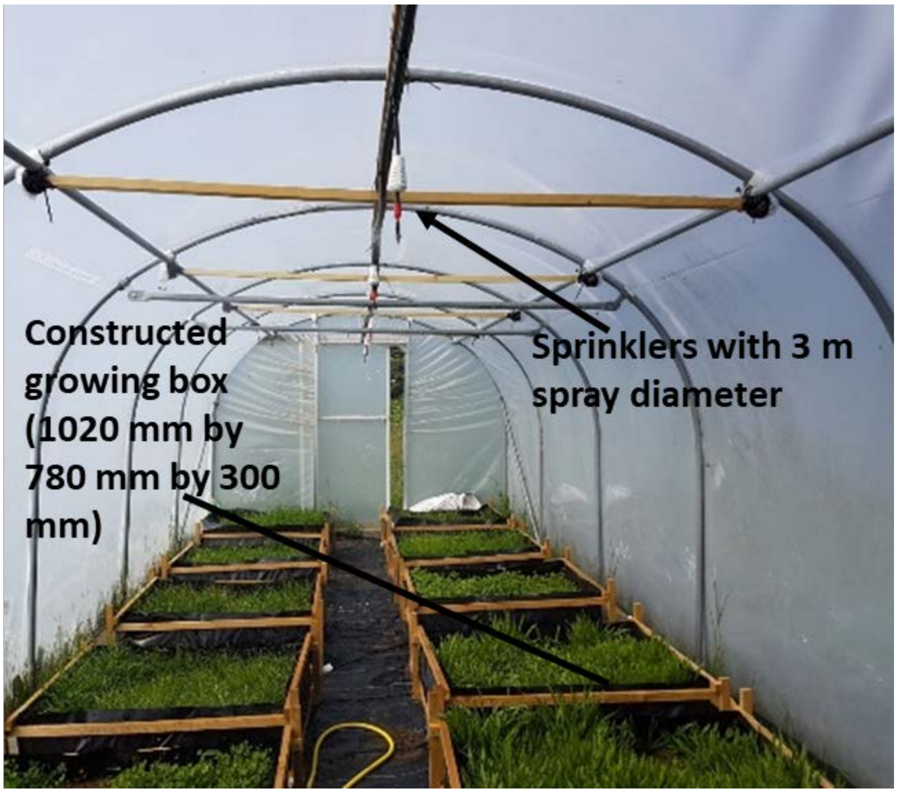


Figure 3.2 Growth boxes (1020 mm by 300 mm) in poly tunnel showing growth conditions.

3.2.2 Harvesting Plants

Plants were harvested and tested at two growth stages the same as Chapter 2:

- Mature: when 50% of plants were flowering.
- Degenerate: when plants have finished flowering and 50% of plants were beginning to senesce (flowering had finished, and leaves were turning brown).

Plants were harvested as turfs (500 mm by 250 mm) using a frame and a knife (Figure 3.3). The turfs were transferred into the prepared run-on box for transport and were kept well-watered until the experiment was carried out. All run-on experiments were carried out within two days of harvest.

Figure 3.3 *Dactylis glomerata* and *Lolium perenne* turfs after harvesting showing different soil attributes.

3.2.3 Run-on Experiments

After harvesting turfs were placed in purpose built run-on boxes (Figure 3.4). The boxes were 500 mm long, 250 mm wide and 300 mm deep. Boxes were rectangular with a 'V' shaped section at one end containing outflow pipe at the top and bottom of the box. The pipes allowed for collection of overland flow and infiltration water. The boxes contained 100 mm of gravel. They were set at a 6.5-degree angle; upslope of the box was a wooden ramp onto which the weir/spill box discharged to create the overland flow simulation (Figure 3.4). Overland flow simulations were designed to replicate vegetated buffer zones during a run-on/overland flow event (Table 3.1). Ideas for these methods were taken and adapted from Abu-Zreig et al. (2004) and Habibiandehkordi et al. (2015a).

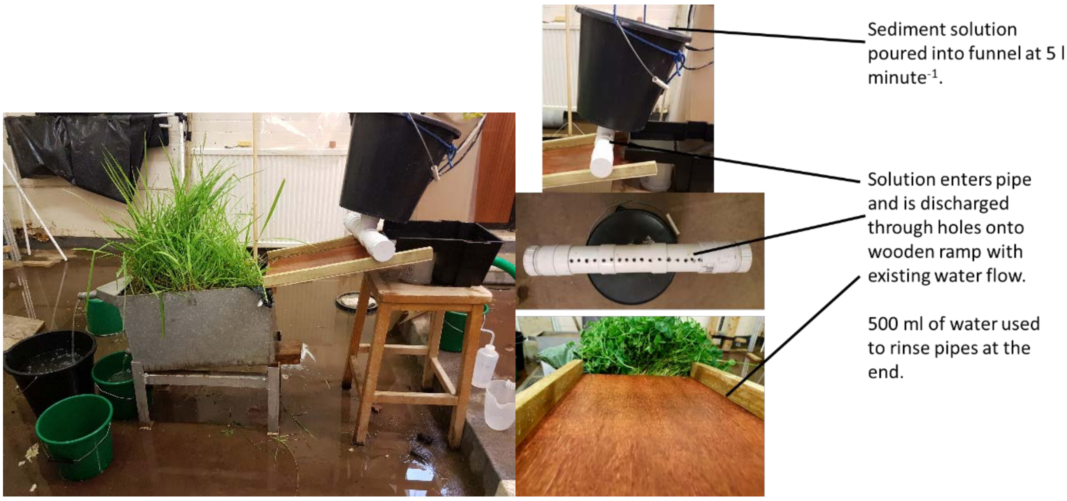


Figure 3.4 Run-on box containing *Dactylis glomerata* turf with ramp and weir box and sediment shower.

The flow rate was 5 l minute^{-}1 and the run-on simulation lasted for 30 minutes. Run-off velocity was recorded for five minutes at the beginning of the simulation at 0-5 minutes and then again at the end of the simulation at 25-30 minutes. Runoff coefficient was calculation as a percentage of outflow.

Sediment retention in vegetation was assessed through adding a sediment solution to the flow at the 15-minute point. The sediment solution consisted of 5 g l^{-1} of the same sandy-loam soil (sieved to 2mm) that the plants were grown in and added in 5 litres of water (total sediment load was 25 g). The soil was sieved, weighed and added to the water 24 hours before use. The sediment solution was agitated and poured into the 'sediment shower' (Figure 3.4) and the sediment solution merged into the overland flow. All overland flow was collected and left to settle overnight. Afterwards the water was poured away and the sediment was transferred to the oven at 105°c until weight was constant (this usually took three days). Total sediment mass was weighed and recorded in grams.

Vegetation sward height was measured before the run-on simulation, after the run-on simulation and then again five days later to assess the ability of the vegetation to withstand the overland flow and its ability to recover from the overland flow.

Table 3.1 Overland Flow Simulation details and measurements

Measurement	**Rate/Units**	**Sampling Interval**
Flow Rate	5 l minute^{-1}	For 30 minutes
Runoff Coefficient	Percentage (%) of run-on	At 0-5 and 25-30 minutes
Total Dried Sediment Mass	g	Between 15-20 minutes
Sward Height	mm	Before, after and 5 days after

3.2.4 Post Run-on Measurements

Five days post run-on simulation the above ground vegetation characteristics were measured (Table 3.2). All plant trait measurements were carried out using the methods stated in chapter 2 of this thesis (Table 3.3). Ten green leaves were used for measuring specific leaf area and leaf dry matter content. All leaves and stems were then harvested and dried to calculate above ground biomass (g).

Following the above ground vegetation measurements, the saturated hydraulic conductivity of each turf was measured in-situ. The simplified falling head method was used according to methods by Angulo-Jaramillo et al. (2016). An infiltration ring with a 200 mm diameter was pushed 50 mm into the soil after all vegetation had been removed. A soil moisture reading was taken just outside of the ring using a moisture meter. Next, 1 litre of water was poured gently into the ring and was timed in seconds how long it took to completely infiltrate into the soil. This was achieved when no more water was visible on the surface of the soil. Finally, a further soil moisture reading was taken from inside the infiltration ring and K_{fs} was calculated using equation 1.

$$K_{fs} = \frac{\Delta\theta}{(1-\Delta\theta)t_a}\left[\frac{D}{\Delta\theta} - \frac{(D+(1/a^*))}{1-\Delta\theta}\,1\mathrm{n}\left(1+\frac{(1-\Delta\theta)D}{\Delta\theta(D+(1/a^*))}\right)\right] \quad (1)$$

Where

D is the depth of water in ring,

$\Delta\theta$ is the post-test moisture level (inside ring) minus the pre-test moisture level (outside of the ring),

$a^*$is the saturation potential coefficient (based on soil type),

t_a is time in seconds.

Following the saturated hydraulic conductivity testing, three soil cores were taken from each turf (volume: 331,830 mm^3). The first core was used to measure soil bulk density, the second for assessing root traits and the third for soil aggregate stability. For the soil bulk density calculation soil was extracted in the core, stones above 3mm were removed and then soil was dried at 105°c until mass stopped changing (typically around three days). Soil bulk density was calculated using equation 2.

$$D_{b=\frac{M_d}{V}} \tag{2}$$

Where

D_b is soil bulk density;

M_d is Oven dried mass;

V is the volume of the core.

The second core was used to assess root traits and root dry mass. Roots were washed and measured for root dry matter content, specific root length, average root diameter, root volume and root tissue density using methods described in Chapter 2 of this thesis. The final core was used to measure soil aggregate stability.

Three treatments were used to assess the soil aggregate stability of the soil when exposed to different stressors (ISO, 2012). The stressors were: fast wetting by immersion in water, designed to test the soil stability when dry material is subjected to fast wetting like irrigation and heavy rainfall (Treatment 1); slow wetting by capillary action, tests the dry soils reaction to slow wetting for example moderate rainfall (Treatment 2); mechanical disaggregation through shaking in ethanol which examines the behaviour of wet soil when subjected to mechanical disturbance (Treatment 3, Table 3.2, Figure 3.5). Mean weighted diameter was calculated using equation 3.

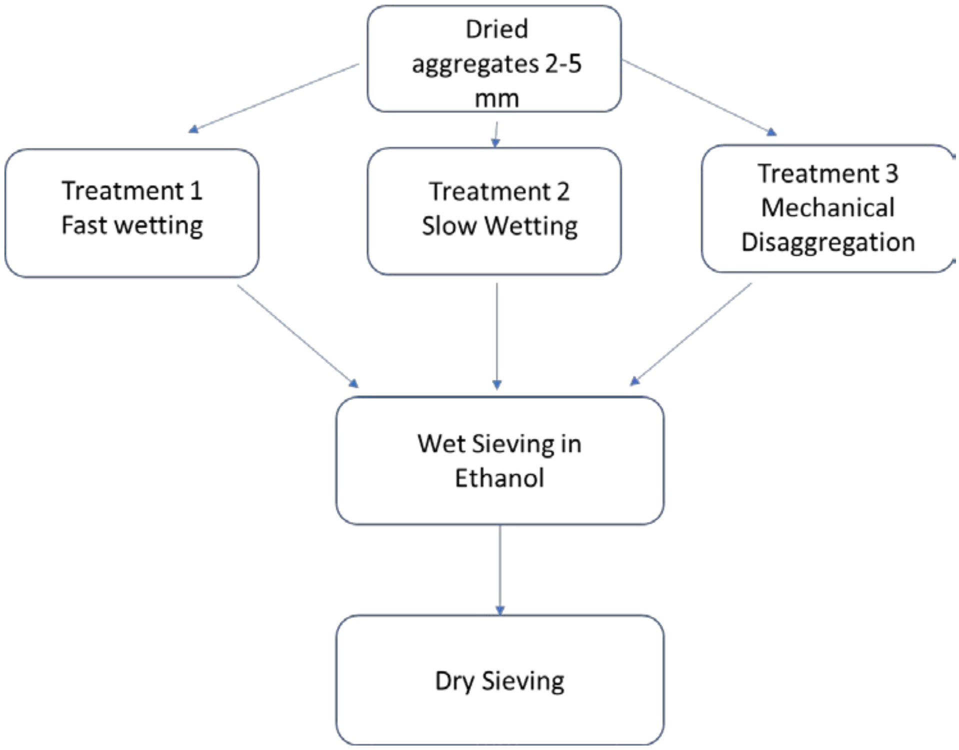


Figure 3.5 Flow diagram showing the soil aggregate stability protocol.

$$\text{MWD} = \sum(\bar{d} * w)/100 \quad (3)$$

Where

$\bar{d}$ is the mean diameter between two sieves;

w is the weighted percentage of the particles retained on the sieve (ISO, 2012).

Table 3.2 Methods for assessing soil aggregate stability for three treatments (ISO, 2012)

Treatment	**Soil**	**Method**
Treatment 1- Fast Wetting	5 g	• Oven dry aggregates 24 hours, 40ºc • Immerse in 50 ml of deionized water for 10 minutes • Remove water • Carry out wet sieving
Treatment 2- Slow Wetting	5 g	• Oven dry aggregates 24 hours, 40ºc • Place on filter paper on top of 30 mm high, moist, foam block • Leave for 60 minutes • Remove and carryout wet sieving
Treatment 3- Mechanical Disaggregation	5 g	• Oven dry aggregates 24 hours, 40ºc • immerse in 50 ml of ethanol for 30 minutes • Remove ethanol • Place in flask with 200ml deionized water • Over end flask 10 times • Leave to settle for 30 minutes • Remove aggregates and carry out wet sieving
Wet Sieving	N/A	• Place remaining aggregates on 50 μm sieve • Immerse in ethanol • Turn sieve 5 times • Remove aggregates for air drying • Place air dried aggregates in oven 105°c for 24 hours
Dry Sieving	N/A	• Place dried aggregates on column of sieves (2 mm, 1 mm, 0.5 mm, 0.2 mm, 0.1 mm, 0.05 mm) • Rotate gently for 30 seconds • Weigh and record aggregates on each sieve • Use equation 3 to find MWD (mm)

Table 3.3 Post run-on details and measurements

Measurement	Rate/Units
Specific Leaf Area	mg mm^{2-1}
Leaf Dry Matter Content	mg g^{-1}
Aboveground biomass	Dried mass (g)
Saturated Hydraulic Conductivity	K_{fs} mm $hour^{-1}$
Soil Bulk Density	Ratio oven dried mass to volume (g mm^{3-1})
Soil Aggregate Stability	Mean weighted diameter (MWD, mm)
Root Dry Matter Content	mg g^{-1}
Specific Root Length	m g^{-1}
Root Volume	cm^3
Average Root Diameter	mm
Root Tissue Density	Root Dry Mass/Root Volume (g cm^{3-1})

3.2.5 Statistical Analysis

Data were analysed using a principle component analysis to investigate the variance, associations and correlations of the species traits and run-on processes (R Studio Team, 2016, R Core Team, 2018). Data were analysed for significant correlations between plant traits (as the predictor variable) and the different run-on measurements (as the outcome variable) in R version 3.5 (R Core Team, 2018, R Studio Team, 2016). All aboveground traits were tested against all above ground run-on processes. All belowground traits were tested against saturated hydraulic conductivity and soil aggregate stability measurements. The above and belowground processes were tested against each other (where appropriate), which led to the belowground traits being tested against aboveground processes. Results were displayed using scatter plots created in ggplot2 (Wickham, 2016).

3.3 Results

3.3.1 Mature Growth Stage

3.3.1.1 Aboveground Processes

There was a significant positive correlation between total sediment mass in outflow and the height of the sward at the beginning of the run-on simulation ($p < 0.05$, $R^2 = 0.18$; Figure 3.6) and at the end of the run-on simulation ($P<0.05$, $R^2 = 0.21$; Figure 3.6). There was a larger total sediment mass in the outflow when the sward height was taller before the run-on simulation and after the run-on simulation.

The runoff coefficient in the minutes 0-5 of the run-on simulation was positively correlated with the specific leaf area of the species ($P<0.05$, $R^2 = 0.24$; Figure 3.7). There was a significant positive correlation between root dry matter content and the run-off coefficient in minutes 0-5 ($P<0.05$, $R^2 = 0.21$; Figure 3.7). There was a significant difference in the runoff coefficient between the species at the beginning of the run-on simulation ($P<0.01$, $R^2 = 0.50$; Figure 3.8). Trifolium had the largest runoff coefficient at 0-5 minutes of the simulation, significantly higher than all of the other species. There was no significant difference of the runoff coefficient between the species at 25-30 minutes of the simulation.

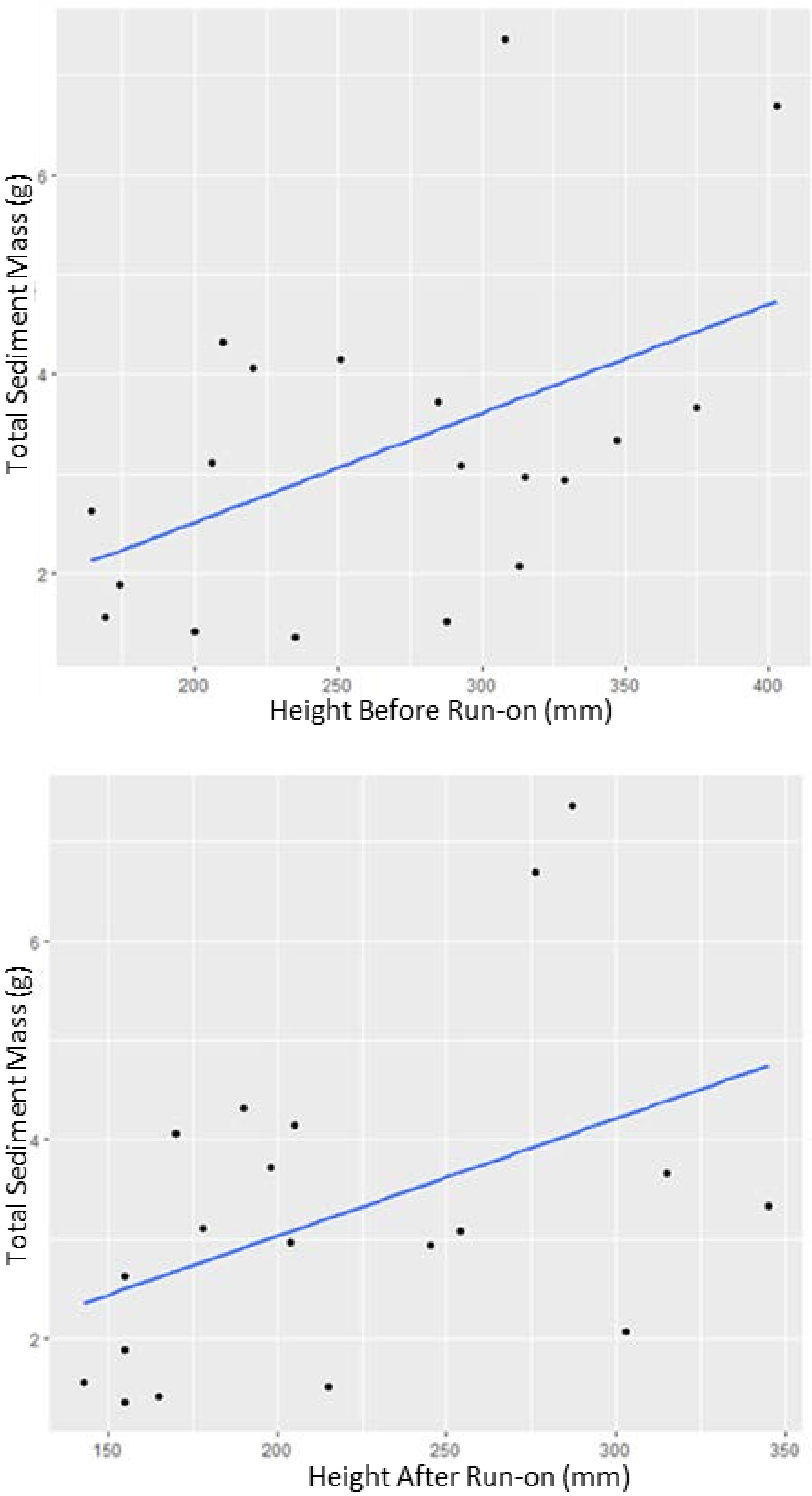


Figure 3.6 Correlation between Total Sediment Mass (g) in the Outflow and Sward Height (mm) before and After the Run-on Simulation at the mature growth stage (n=19).

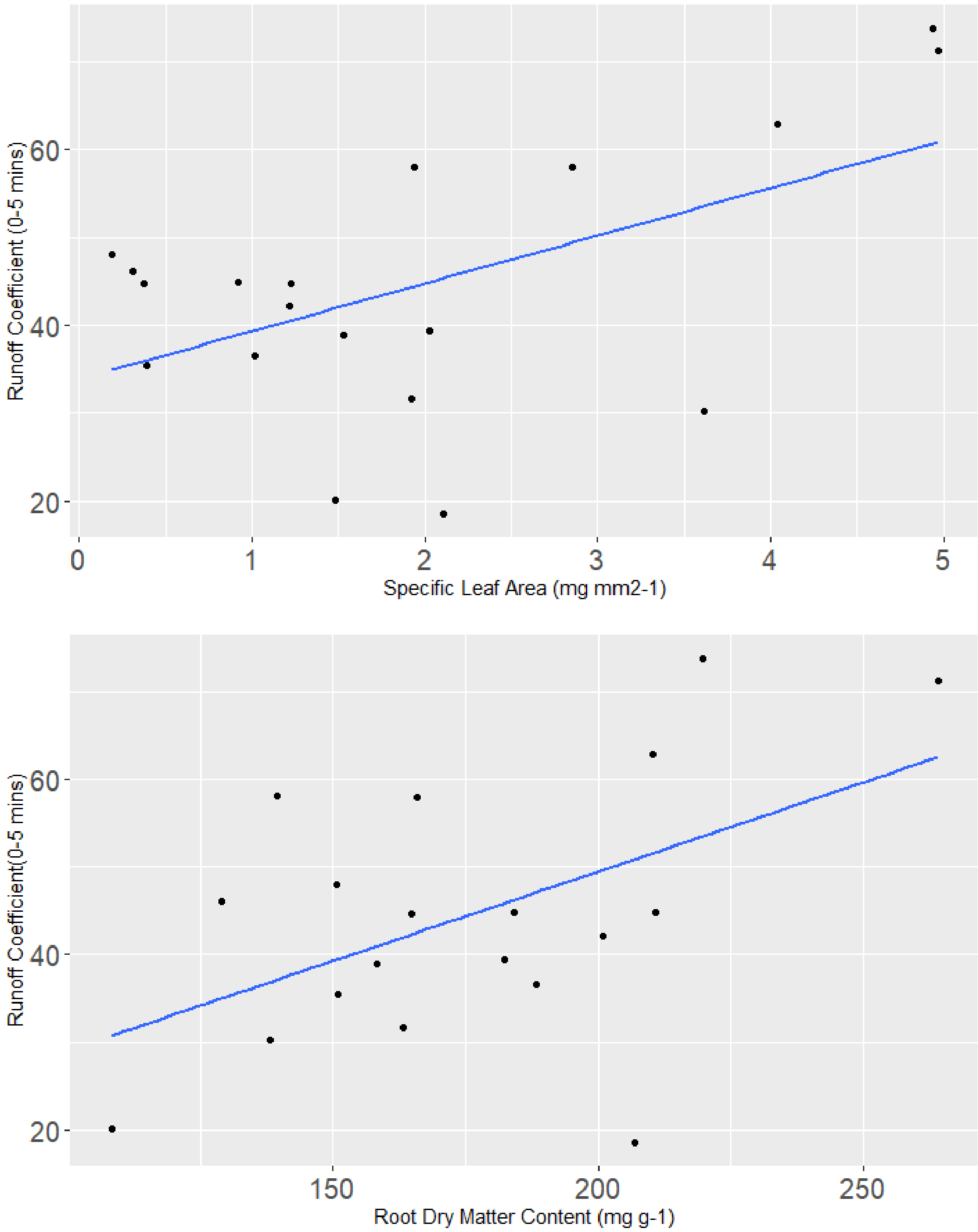


Figure 3.7 Correlation between Specific Leaf Area (mg mm^{2-1}), Root Dry Matter Content (mg g^{-1}) and runoff coefficient at mature growth stage (n=19).

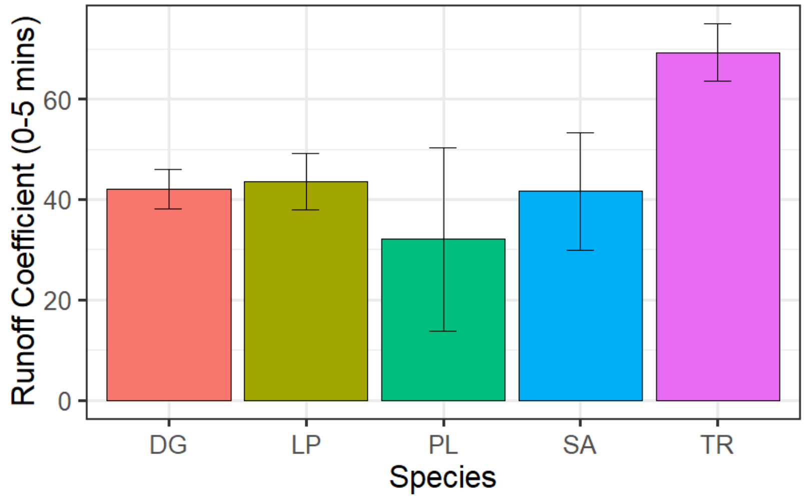


Figure 3.8 Bar Chart (Mean +-Standard Deviation) Run-off Coefficient at the mature growth stage (n=19). DG= *Dactylis glomerata*, LP= *Lolium perenne*, PL= *Plantago lanceolata*, SA= *Schedonorus arundinaceus*, TR= *Trifolium repens*.

3.3.1.2 Belowground Processes

Field saturated hydraulic conductivity (K_{fs}) was significantly positively correlated with root dry matter content ($P<0.05$, $R^2 = 0.29$; Figure 3.9) and average root diameter ($P<0.01$, $R^2 = 0.36$; Figure 3.9). Saturated hydraulic conductivity (K_{fs}) was significantly negatively correlated with specific root length ($P<0.01$, $R^2 = 0.36$; Figure 3.10) and actual root length ($P<0.01$, $R^2 = 0.33$; Figure 3.10).

There was a significant negative correlation between average root diameter (mm) and mean weighted diameter (mm) from treatment 2 (slow wetting; $P<0.01$, $R^2 = 0.38$; Figure 3.11). There was a significant positive correlation between specific root length (m g^{-1}) and the mean weighted diameter (mm) of aggregates from treatment 2 (slow wetting; $P<0.01$, $R^2 = 0.39$; Figure 3.11).

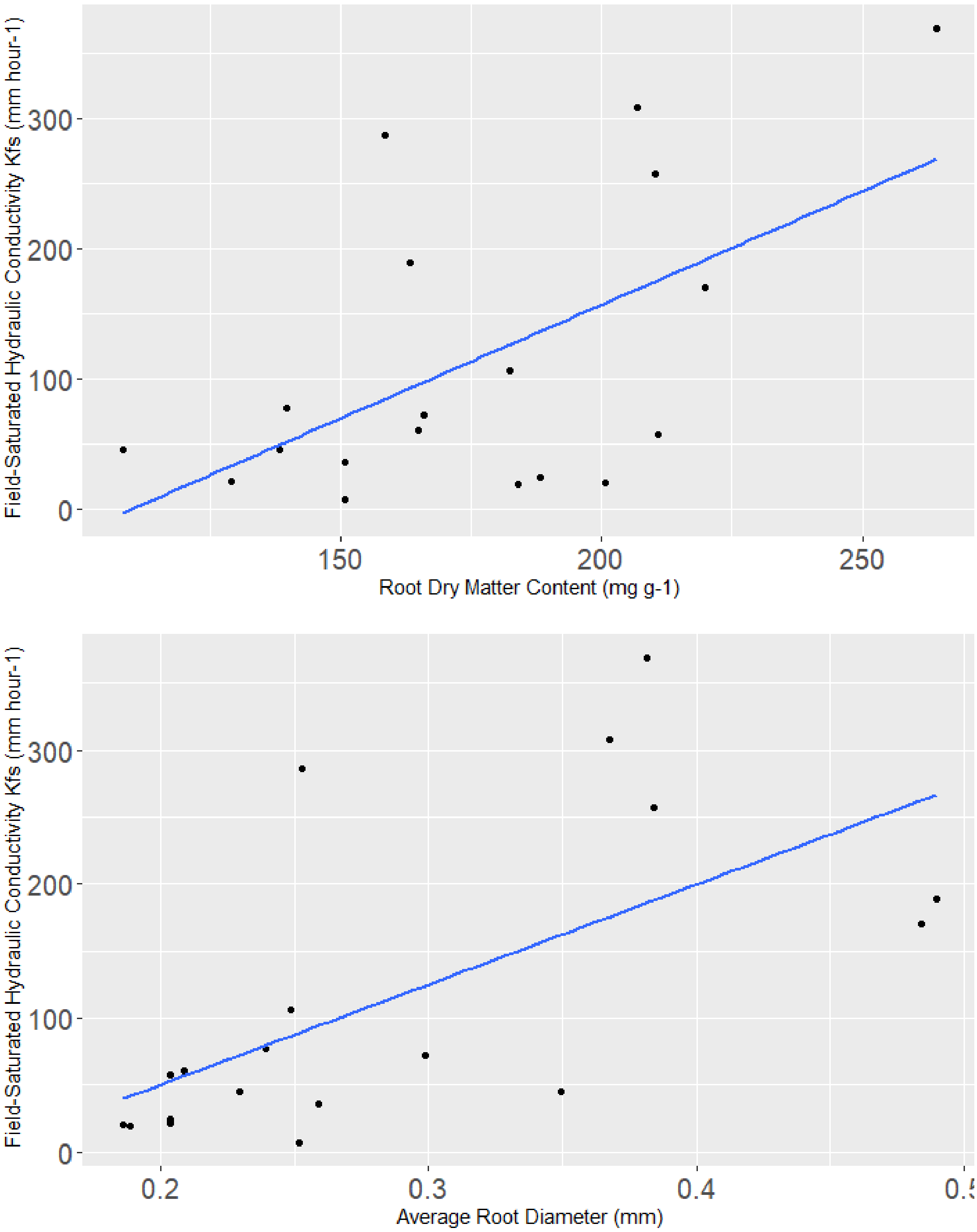


Figure 3.9 Correlation between Root Dry Matter Content (mg g^{-1}), Average Root Diameter (mm) and Field-Saturated Hydraulic Conductivity, K_{fs} (mm $hour^{-1}$) at the mature growth stage (n=19).

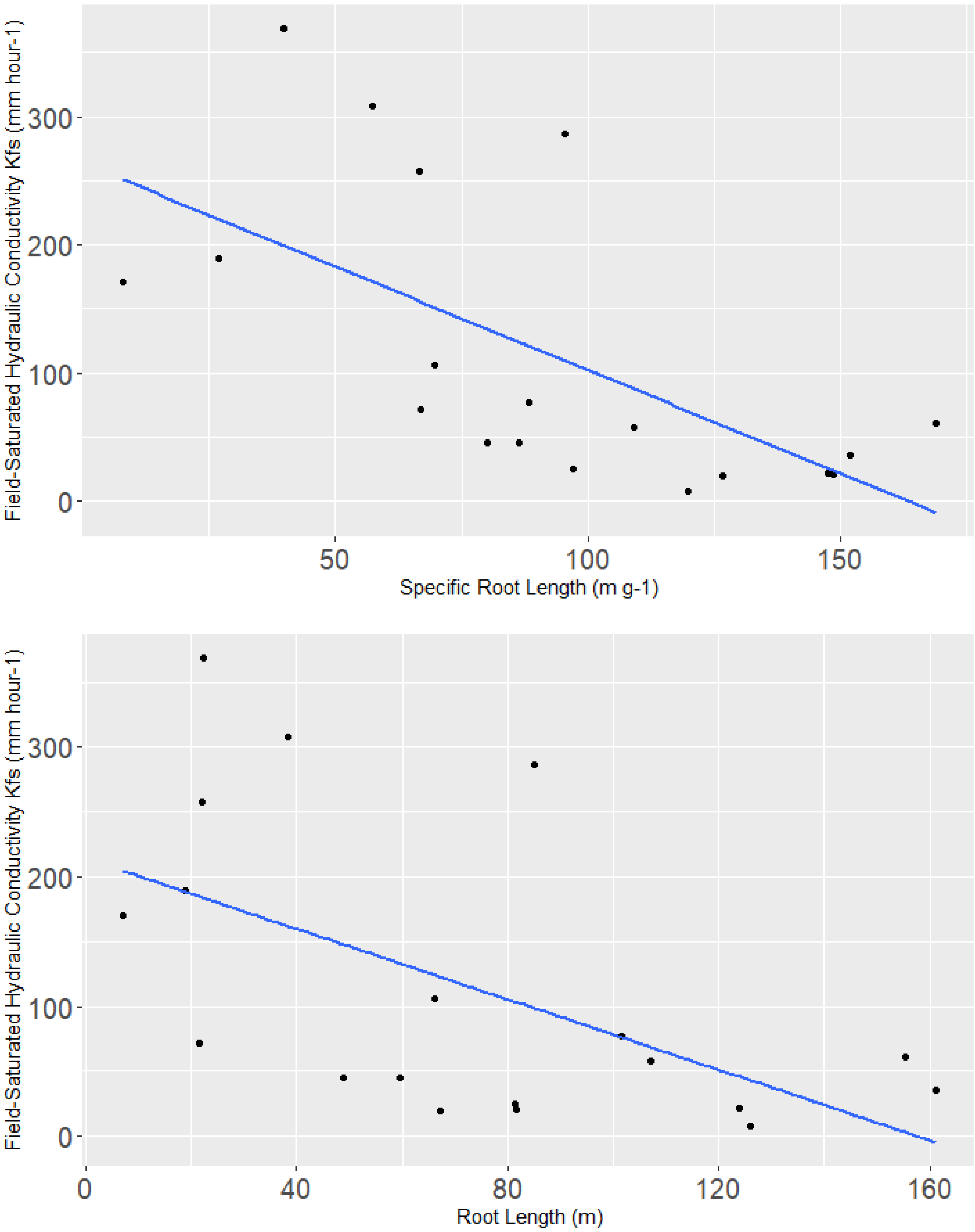
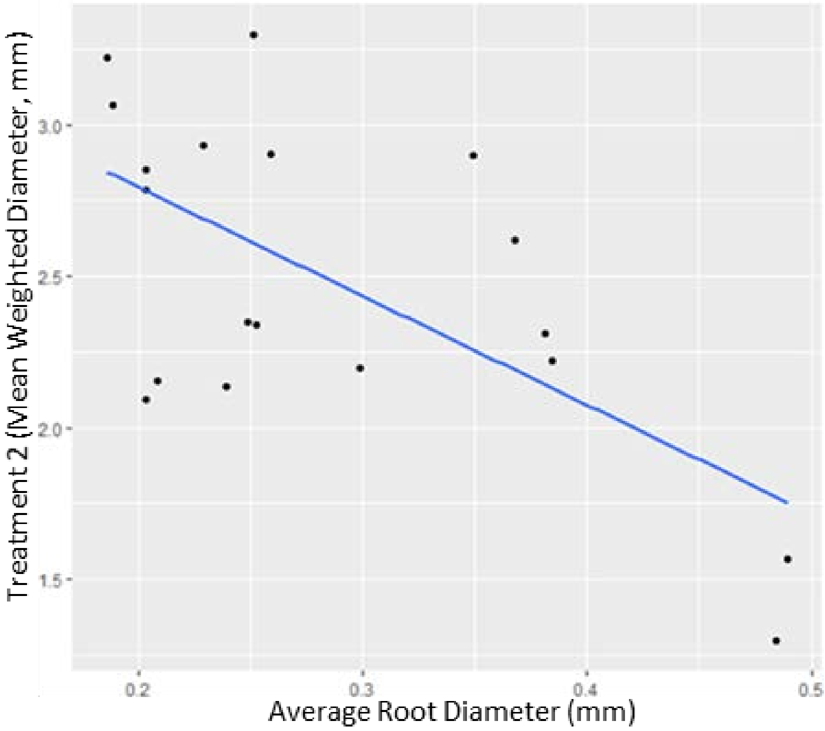
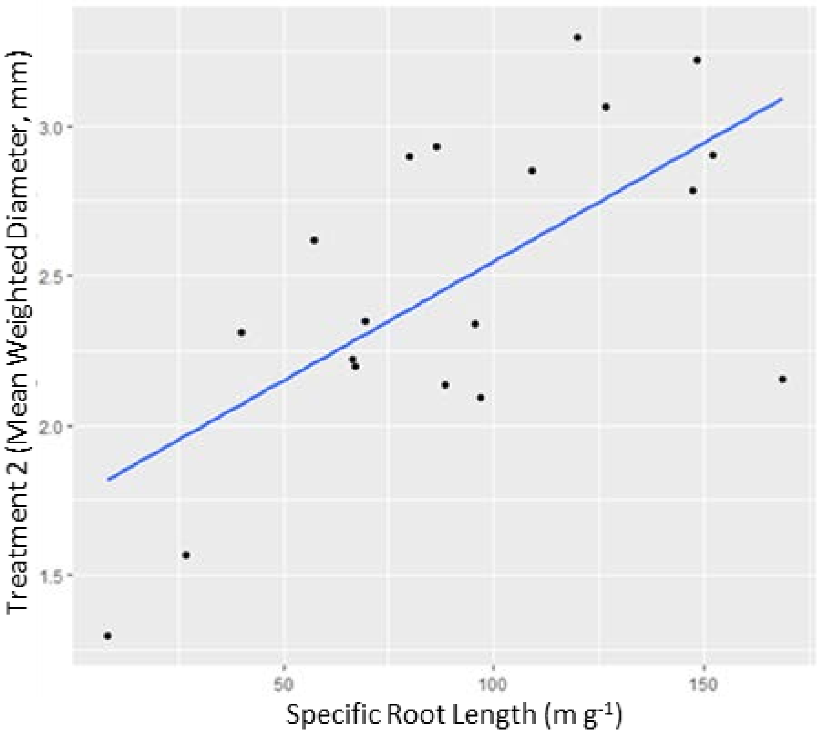


Figure 3.10 Correlation between Specific Root Length (m g^{-1}), Root Length (m) and Field-Saturated Hydraulic Conductivity, K_{fs} (mm $hour^{-1}$) at the mature growth stage (n=19).





3.11 Correlation between Average Root Diameter (mm), Specific Root Length (m g^{-1}) and Soil Aggregate Stability (Mean Weighted Diameter mm, Treatment 2) at the mature growth stage.

3.3.2 Degenerate Growth Stage

3.3.2.1 Aboveground Processes

There was a significant positive correlation between the total sediment mass (g) in the outflow and the height (mm) of the sward before and after the run-on simulation ($P<0.05$, $R^2 = 0.24$, $P<0.05$, $R^2 = 0.24$; Figure 3.12). The runoff coefficient in minutes 25-30 of the run-on simulation was positively correlated with the sward height (mm) at the end of the simulation ($P<0.05$, $R^2 = 0.19$; Figure 3.13).

The runoff coefficient at minutes 0-5 and 25-30 was negatively correlated with K_{fs} (mm hour^{-1}, $P<0.01$, $R^2 = 0.58$, $P<0.01$, $R^2 = 0.54$; Figure 3.14). The higher the saturated hydraulic conductivity the lower runoff coefficient. There was a significant difference of runoff coefficients between the species at 0-5 minutes and 25-30 minutes ($P<0.01$, $R^2 = 0.71$, $P<0.01$, $R^2 = 0.65$; Figures 3.15). *Dactylis* and *Plantago* have a significantly lower runoff coefficient than *Lolium* and *Schedonorus* at minutes 0-5. At minutes 25-30 Plantago had a significantly lower run-off coefficient than *Lolium* and *Schedonorus* and *Dactylis* had significantly lower runoff coefficient than *Schedonorus*.

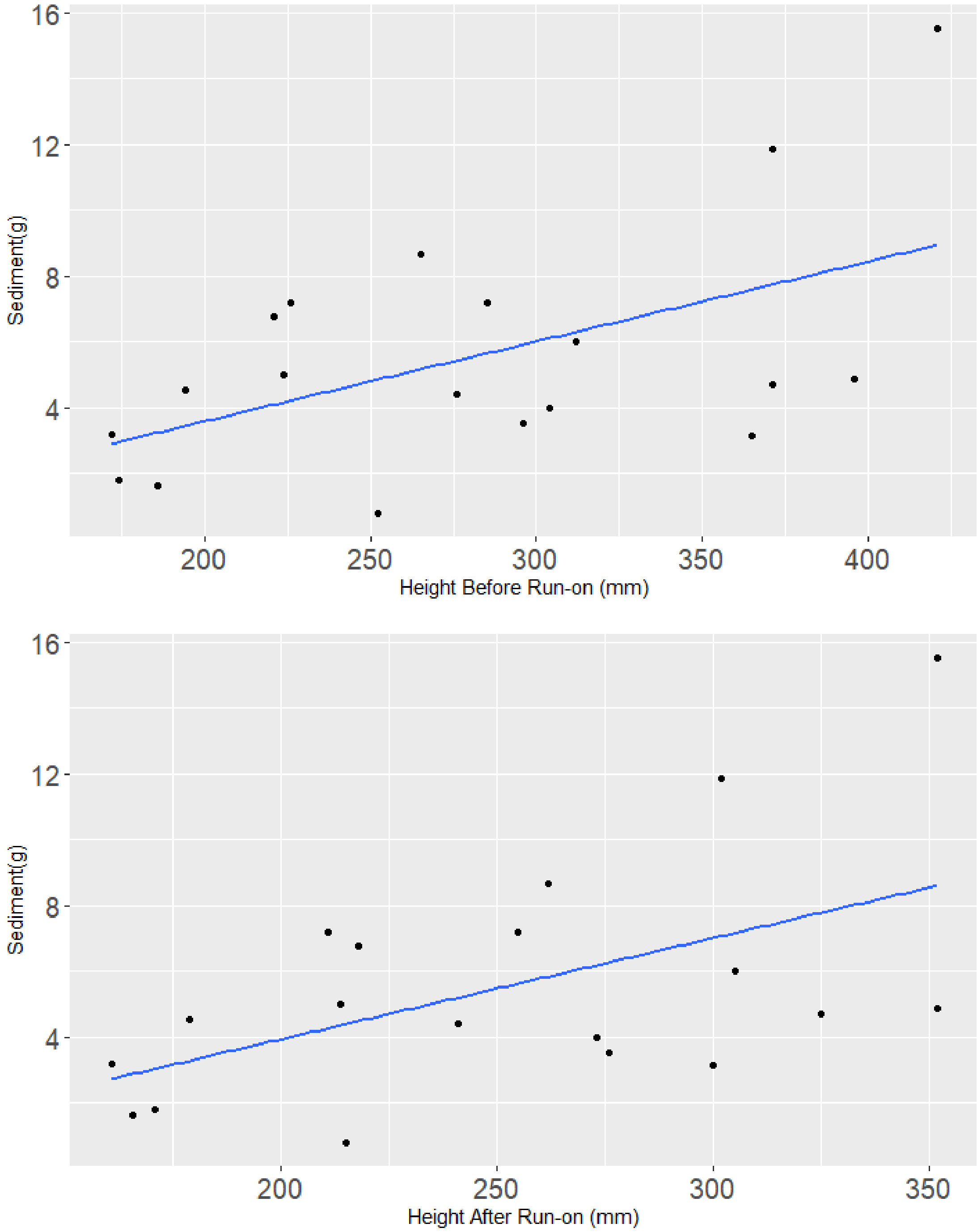


Figure 3.12 Correlation between Sward Height before and After Run-on Simulation and Total Sediment Mass (g) in outflow at the Degenerate Growth Stage (n=19).

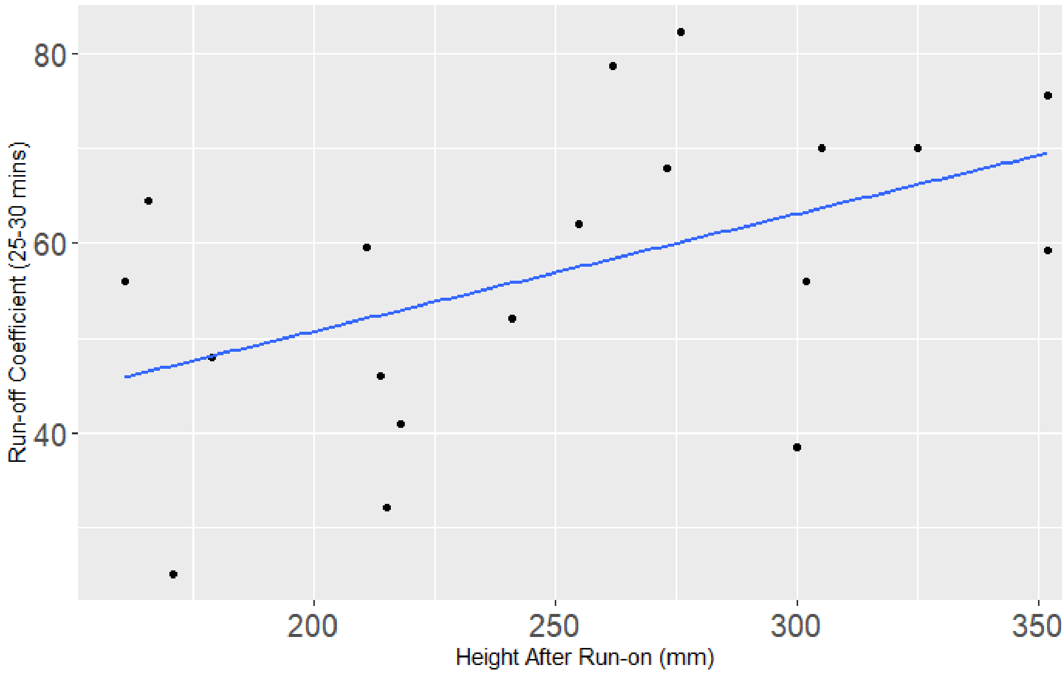


Figure 3.13 Correlation between Sward Height after Run-on (mm) and Runoff Coefficient (25-30 minutes) at the degenerate growth stage (n=19).

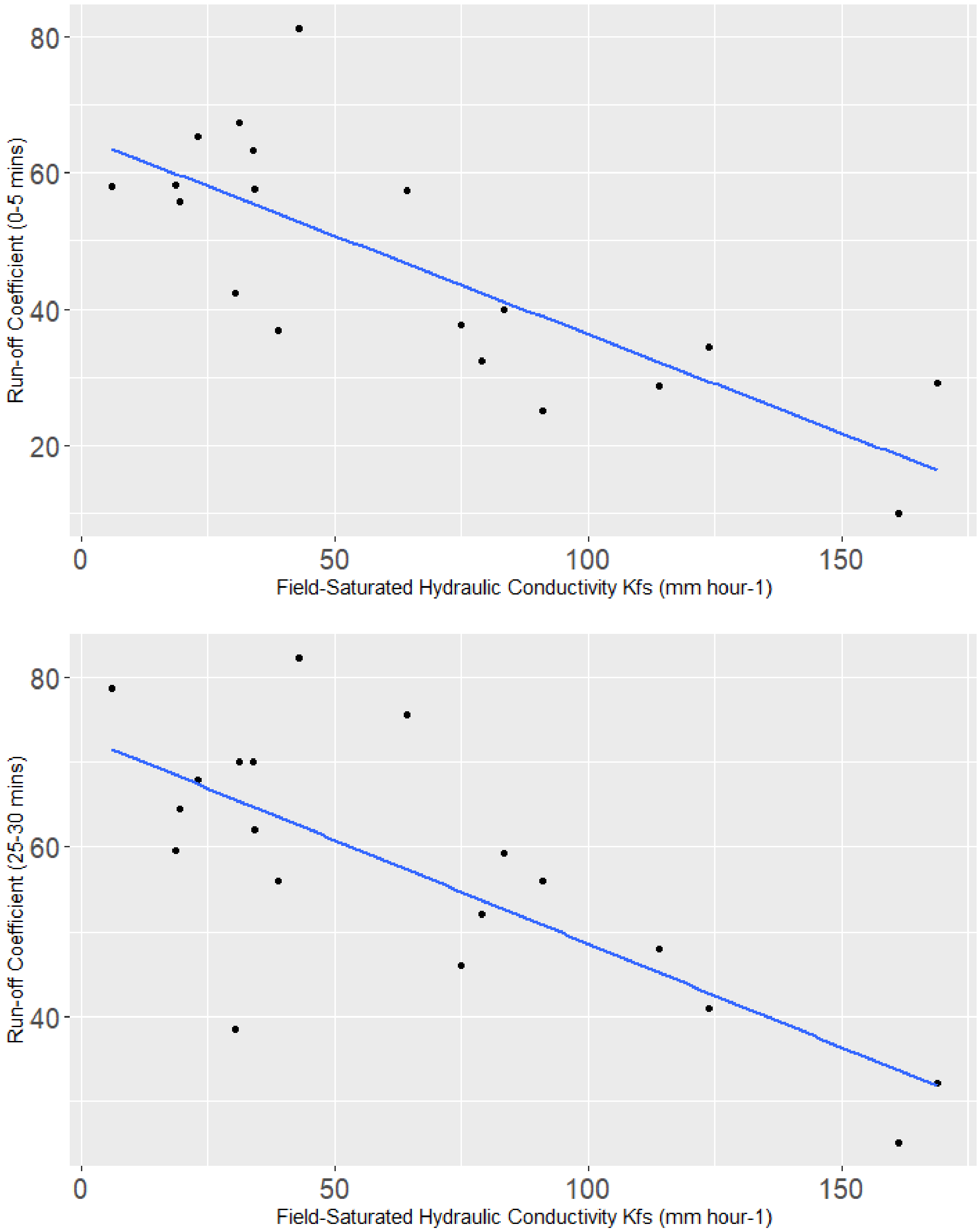


Figure 3.14 Correlation between K_{fs} (mm hour^{-1}) and Runoff Coefficient (0-5 and 25-30 minutes) at the degenerate growth stage (n=19).

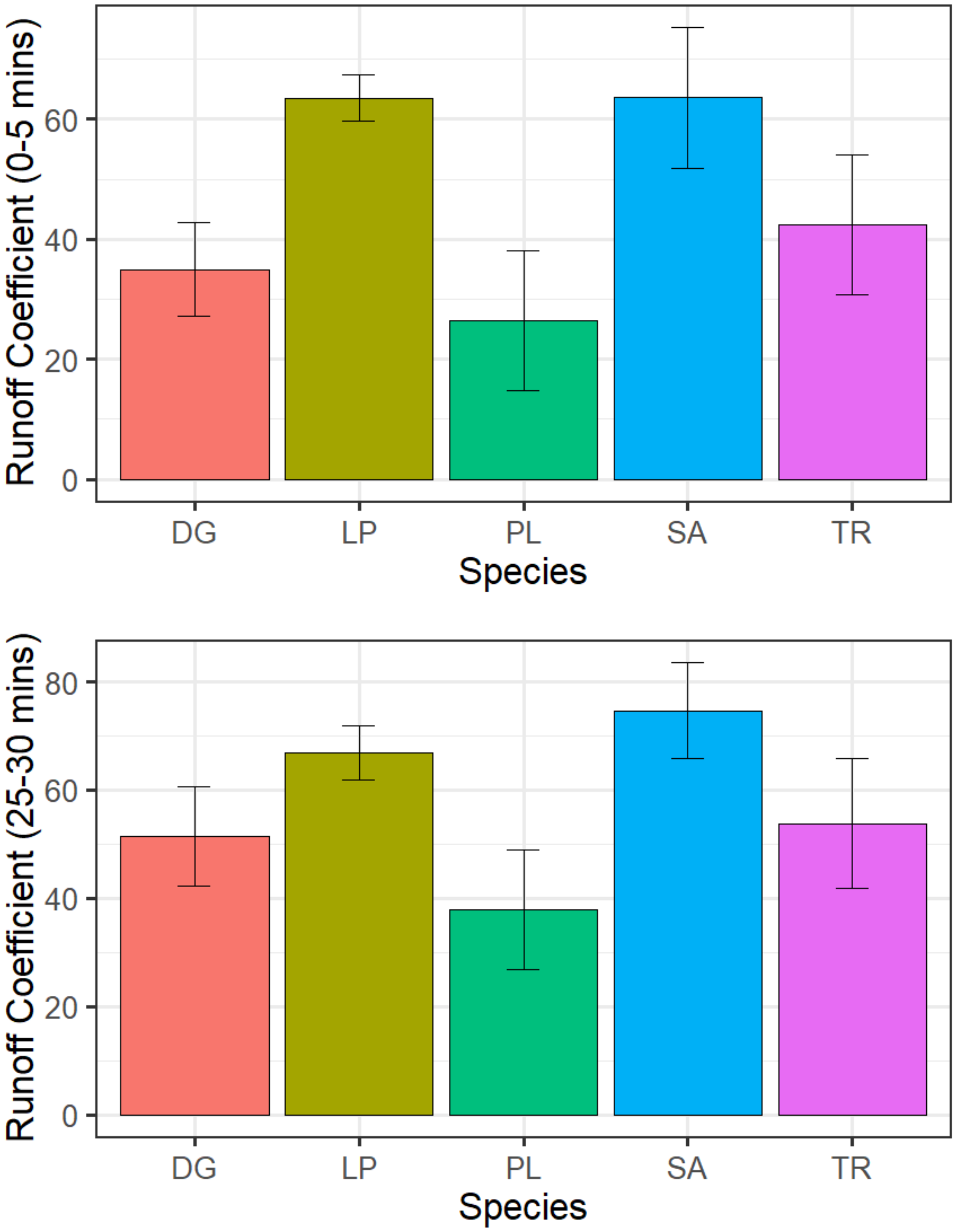


Figure 3.15 Bar Chart (Mean +-Standard Deviation) Runoff Coefficient (0-5 and 25-30 minutes) at the degenerate growth stage (n=19).

3.3.2.2 Belowground Processes

Runoff coefficient at minutes 0-5 and 25-30 are positively correlated with root volume (cm^3, $P<0.01$, $R^2 = 0.31$, $P<0.05$, $R^2 = 0.24$; Figure 3.16). Root volume was also negatively correlated with K_{fs} (mm $hour^{-1}$, $P<0.05$, $R^2 = 0.22$, Figure 3.16).

There was a significant positive correlation between root dry matter content (mg $g^{-}1$) and mean weighted diameter (mm) from treatment 3 (mechanical disaggregation, $P<0.05$, $R^2 = 0.21$; Figure 3.17). There was a significant difference between the mean weighted diameter (mm) of the species in treatment 1 and 2 (fast wetting and slow wetting, $P<0.05$, $R^2 = 0.32$, $P<0.05$, $R^2 = 0.36$; Figure 3.18). There was a difference for treatment 3 but it was not significant ($P=0.059$, Figure 3.18). *Plantago* had the largest mean weighted diameter for all treatments. The difference was significant for *Schedonorus* for treatment 1 and *Trifolium* in treatment 2.

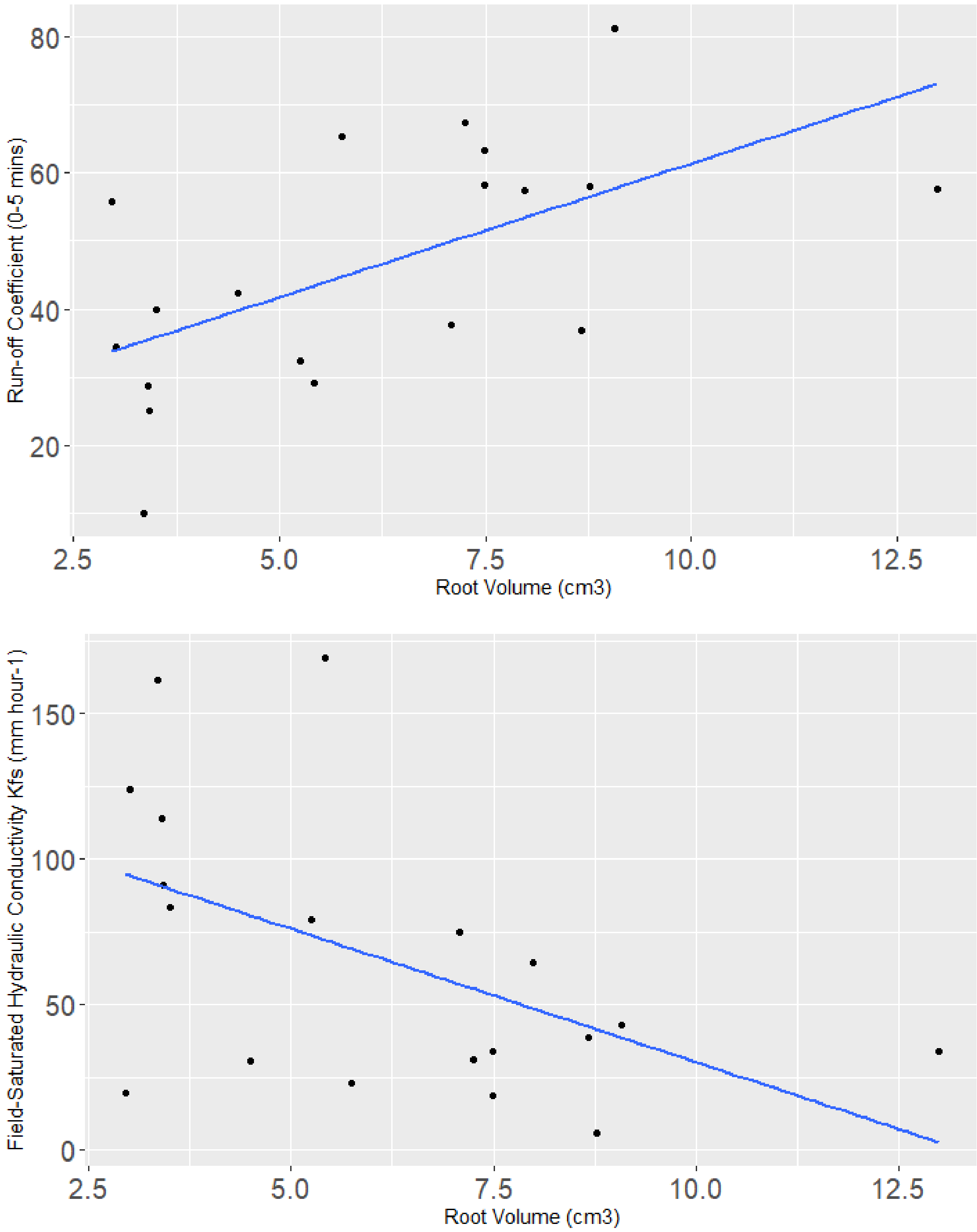


Figure 3.16 Correlations between Root Volume and Runoff Coefficients and Field-Saturated Hydraulic Conductivity, K_{fs} (mm $hour^{-1}$) at the Degenerate Stage (n=19).

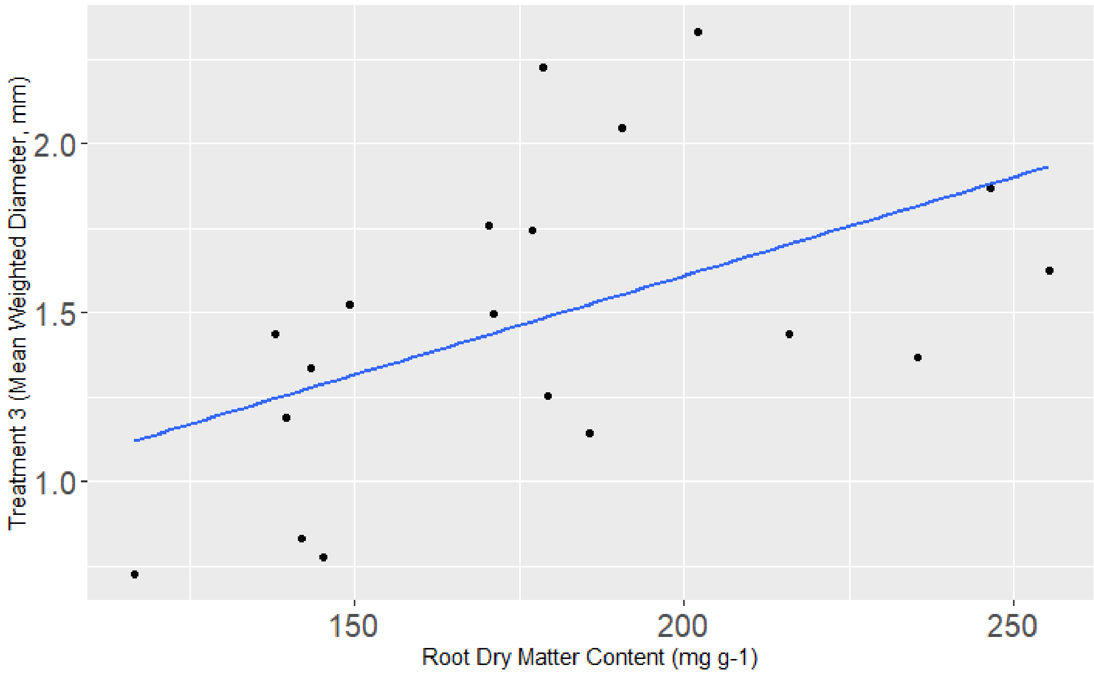


Figure 3.17 Correlation between Root Dry Matter Content (mg g^{-1}) and Soil Aggregate Stability (Mean Weighted Diameter mm, Treatment 3) at the degenerate growth stage.

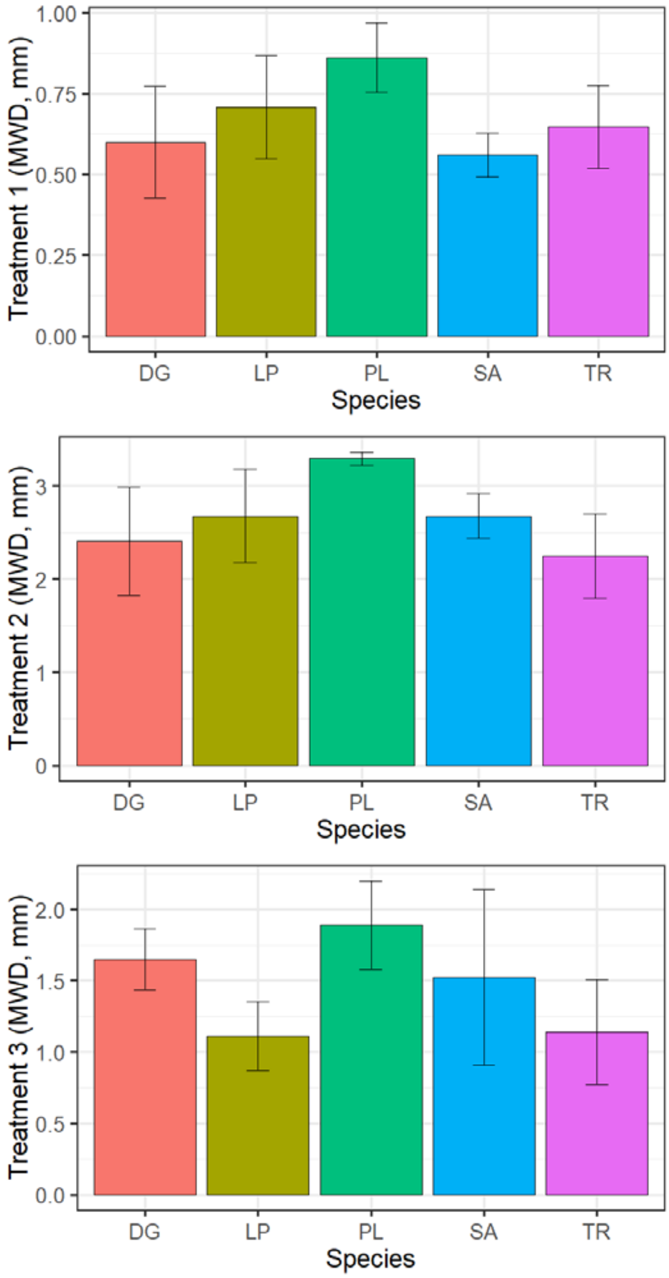


Figure 3.18 Bar Chart (Mean +-Standard Deviation) Soil Aggregate Stability (Mean Weighted Diameter mm, Treatment 1, 2 & 3) at the degenerate growth stage (n=120 per test).

3.4 Discussion

There were a variety of plant traits that were suited to encouraging sedimentation, slowing water flow or facilitating water infiltration into the soil (increasing the saturated hydraulic conductivity of the soil). Some of the differences in the provision of these buffer services were at the species level, however, many others were correlated with specific trait values rather than being grouped as species, therefore the hypotheses can be partially accepted. Certain species stood out from the others due to having traits that were suitable for a variety of buffer services both above and belowground. There were also some trade-offs between services and traits which shows that a variety of species with a variety of traits could be the best solution to enhancing the vegetated buffer zone.

3.4.1 Total Sediment Mass and Run-off Coefficient

Plant height (before and after the run-on simulation) was positively correlated with total sediment mass in outflow at the mature and degenerate growth stages. There was also a positive correlation with runoff coefficients. There was no correlation between total sediment mass and the runoff coefficients at the beginning and end of the run-on simulation even though they both positively correlated with sward height; this indicates that other factors influenced the sediment load and run-off coefficients.

The results from this study show that a low sward height was better than a tall sward height for reducing sediment load and for slowing water flow. This implies that tall, stiff stemmed grasses are not necessarily the only way to reduce sediment load and reduce the speed of runoff. The results in this study align with the results from Haddaway et al. (2016), Kervroedan et al. (2019) and Zhang et al. (2019) that say the vegetation density at the height of the water flow is the most important trait for sediment capture and the slowing of the water flow.

It is known that the presence of vegetation reduces soil erosion as it protects the soil from rain splash erosion and creates a strong soil matrix through root anchorage (De Baets et al., 2011, Sandercock et al., 2017, Vannoppen et al., 2017). There is also evidence that vegetation can reduce the passage of mobile sediments through buffer zones (Abu-Zreig et al., 2004, Abu-Zreig, 2001). There are mixed theories and a mixture of evidence to relate this reduction to vegetation types and indeed the traits or attributes of the vegetation (Abu-Zreig et al., 2004, De Baets et al., 2009, Kervroedan et al., 2018, Dabney et al., 1995, Dabney et al., 2004, Meyer et al., 1995). Research by Dabney et al. (1995), Meyer et al. (1995) has suggested that tall stiff stemmed grasses were best for slowing water flow and reducing sediment transfer. They argue that sediment deposition is achieved by delaying the water at the edge of the buffer and creating water pools, which in turn allows for the deposition (Dabney et al., 1995, Meyer et al., 1995). They suggest that there was very little filtering of sediments by and within the vegetation (Dabney et al., 1995). However, the findings from this study do not support this and suggest that sediment filtering does happen within the vegetation.

Previous studies have defined vegetation density using stem density, stem diameter, leaf area and stem specific density measurements (Kervroedan et al., 2018, 2019). The evidence suggests that the vegetation density at the height of the water flow increases the surface roughness of the buffer thus reducing the velocity of the water and allowing deposition of the sediments (Kervroedan et al., 2018, 2019). These studies have also found there is a positive correlation with surface roughness and specific leaf area. Despite, this evidence there were no significant relationships between total sediment mass and run-off coefficients and the stem traits of any of the grass species in this study. However, only the grass species were subjected to trait measurements on the stems as the forb and legume species were without traditional stem structures indicating that plant architecture is a consideration.

The runoff coefficients were significantly different between species at three out of the four measurement time points. *Plantago* and *Dactylis* had significantly smaller runoff coefficients than the other species at the degenerate stage and *Trifolium* had the highest runoff coefficients at the mature stage. These species differences raise questions about what above ground processes could be driving the slowing of the water flow. *Plantago* has no stem, but forms a tight, upright rosette of long leaves that create a large amount of vegetative cover just above soil level. *Dactylis* has flattened wide stems that tiller to form tufts. Although it had lower tiller numbers than the other grass species, at both growth stages, the stems were robust and have a low modulus of elasticity and a high moment of inertia (Dunn and Dabney, 1996; Chapter 2). These traits could be mimicking the tall stiff grass hedges described by Dabney et al. (1995), Meyer et al. (1995) but closer to the soil surface. These species attributes at the soil surface could contribute to the overall vegetation density at the height of the water flow acting like a hydraulic brake (Kervroedan et al., 2019) and be a critical factor in slowing the water flow and reducing the runoff coefficient (Fu et al., 2019a, Pan et al., 2017). Despite the above ground traits having an influence on the sediment capture and runoff coefficients the soil was not saturated during the run-off simulations, so it is important to explore the effect that the water infiltration into the soil had on the runoff coefficient and the sediment load.

3.4.2 Belowground Processes

3.4.2.1 Saturated Hydraulic Conductivity, Root Traits and Run-off Coefficients

The field saturated hydraulic conductivity rate (K_{fs}) of the soil had a negative correlation with the runoff coefficient at three out of the four time points measured. This suggests that K_{fs} made a significant contribution to the reduction of the runoff coefficient. This echoes the results of the studies by Mekonnen et al. (2016) and Zimmermann et al. (2013) that water infiltration into the soil is one of the key factors that affect runoff. The more water that enters the soil and is retained within the soil will reduce the water velocity and encourage deposition of sediments (Abu-Zreig, 2001). This is an important attribute for successful buffer services (Burylo et al., 2012). However, this process is not homogeneous, but dependent on differing soil types and soil structure, land use and critically the vegetation type (Chandler et al., 2018, Ramezani et al., 2019, Wang et al., 2019a, Vannoppen et al., 2015, De Baets et al., 2011).

The traits of the vegetation affect the soil hydraulic conductivity at different levels; for example, the vegetation coverage protects the soil surface from rain splash damage and maintains the soil physical structure (Quinton and Catt, 2004, Boardman, 2013). Likewise, the root systems of the vegetation influence the soil structure through the physical or chemical processes that influences the infiltration rate of the soil (Gould et al., 2016, Bardgett, 2017, De Baets et al., 2011). Understanding the implications and mechanisms to this increased or reduced field saturated hydraulic conductivity is central to increasing infiltration and reducing runoff.

The average root dimeter has a positive correlation with the field saturated hydraulic conductivity of the soil at the mature growth stage. This is in line with other studies on herbaceous vegetation (Gould et al., 2016, Bardgett et al., 2014, Archer et al., 2002) and follows some of the factors that increase infiltration under trees (Chandler et al., 2018, Agnese et al., 2011). Large root diameters create channels in the soil and, as in the case of *Trifolium,* have adventitious qualities that form spreading root penetrations that increase water pathways (De Baets et al., 2007). It has been observed that taproots also increase infiltration pathways into the soil (Song et al., 2017). These types of roots are generally associated with forbs and legumes in the UK, and these results are similar to results reported in studies looking at hydraulic conductivity in mixed species plots in grassland and land reclamation studies (Pan et al., 2017, Song et al., 2017, Ramezani et al., 2019).

Root dry matter content is positively correlated with the field saturated hydraulic conductivity at the mature growth stage. Conversely, it was also positively correlated with the runoff coefficient at the mature growth stage. This seems contradictory as saturated hydraulic conductivity rate was negatively correlated with the runoff coefficient. It is likely there is a species effect that complicates the result for root dry matter content. *Trifolium* has high root dry mater content (Gould et al., 2016), which could explain the apparent contradiction in the trend with high root dry matter content as Trifolium had the largest runoff coefficient. This highlights that although hydraulic conductivity is an important mechanism for reducing runoff, if the aboveground traits are not well suited to impeding the water flow then the hydraulic conductivity rate does not compensate. These results suggest a compromise on infiltration ability could be necessary to reduce the runoff coefficient.

The other measured root traits were all negatively correlated with field saturated hydraulic conductivity. Specific root length and actual root length at the mature growth stage inhibited the soil saturated hydraulic conductivity. Species or individuals with high specific root length exhibit high nutrient and water uptake attributes and have a high turnover of individual roots (Perez-Harguindeguy et al., 2013). It is thought that a high turnover of roots could be a good trait for increasing hydraulic conductivity because decaying roots leave empty root passages and increase soil organic matter (De Baets et al., 2007). However, these attributes did not increase hydraulic conductivity as was expected. A possible explanation for this could be connected to functional groups of the species with high specific root length. The species in this study with high specific root length were graminoids and all had fibrous root systems (Grime, 2007). It is known that fibrous root systems accumulate a large amount of roots near the surface of soils (Grime, 2007) this inhibits water infiltration and can reduce soil hydraulic conductivity (Gould et al., 2016, Vannoppen et al., 2017, Vannoppen et al., 2015). Root length is correlated with specific root length therefore the same mechanisms apply for this trait as specific root length. High specific root length and high root length does not necessarily inhibit water infiltration specifically, however high specific root length is a trait of the species that follow the rooting strategy that does.

The root trait that had the most influence over infiltration and runoff coefficients in the degenerate growth stage was root volume. There was negative correlation with hydraulic conductivity and a positive correlation with the runoff coefficients. A large volume of roots impeded the passage of water into the soil and therefore increased the runoff coefficient. This was again linked with the functional group of the plant with the graminoids having a larger root volume than the herbs and therefore could be linked to the grass rooting strategies (Grime, 2007, Bardgett, 2017). However, this does not explain everything, as the graminoids were not consistently poor at reducing runoff or facilitating water infiltration, so there are other aspects not necessarily understood from this study. There could also be an issue with the limited space of the mesocosm experiment. The plants were grown in limited space and at the degenerate stage; this could be an influencing factor with a fast-growing species with large root mass. That being said the species were not root bound and were not displaying stress traits when harvested. Nevertheless, it is important to factor in the differences in a mesocosm and in a field context.

3.4.2.2 Soil Aggregate Stability Measurements and Root Traits

The average root diameter was negatively correlated with the mean weighted diameter (mm, MWD) of the aggregates in treatment 2 (slow wetting/micro cracking). Gould et al. (2016) also found that species that are known for having large average root diameter such as *Trifolium* were negatively correlated with aggregate stability. Species that have roots with a large average diameter tend to invest more in root formation and have higher root dry matter content and higher root tissue density, thus creating less root length (Birouste et al., 2014) which seems to have an effect on the formation of aggregates (Vannoppen et al., 2017). Specific root length and average root diameter are negatively correlated so it follows that the specific root length, at this growth stage, was positively correlated with the MWD in treatment 2. There is evidence from multiple studies (Gould et al., 2016, Vannoppen et al., 2017, Pérès et al., 2013, Le Bissonnais et al., 2018); that fine, fibrous roots have a positive influence on soil aggregates and these results are comparable. As mentioned previously the species with high specific root length are graminoids and thus have fine, fibrous roots confirming that this root trait is compatible with increasing soil aggregate stability. These root traits are known for being resource competitive (Grime, 2007) and it is likely they may produce large amounts of exudates increasing polysaccharides which are soil binding agents and increase microbial activity, that can also bind soil particles (Liu et al., 2005). The polysaccharides and the short lifespan of the roots, that have high specific root length, increase soil organic matter (SOM) in the soil. This also increases the soil aggregate stability as the SOM and the polysaccharides bind micro-aggregates into macro-aggregates (Liu et al., 2005, Pérès et al., 2013).

Root dry matter content at the degenerate growth stage is positively correlated with the MWD of the aggregates after treatment 3. Root dry matter content is indicative of a resource conservative plant trait (Bardgett et al., 2014) and is a proxy for root tissue density (Birouste et al., 2014). This translates to root strength, so it is possible that strong roots can mitigate against mechanical disaggregation through their binding processes. In the study by Le Bissonnais et al. (2018) looking at effects of plant traits across different soil types/climate factors they found that root dry matter content did have a positive effect on soil aggregate stability, but at only one of the sites. This correlation was not shown at the mature growth stage and should be taken with caution as the positive trait associations at the mature stage were with root traits indicative of rapid resource- acquisition species.

Although these results align, with other similar studies for root trait outcomes, many other root traits that were tested do not follow the same pattern and although these ones do, they do not correspond exactly. In the study by Gould et al. (2016) they found that the root traits mostly correlated with either treatment 1, (slaking/fast wetting) or in some cases treatment 3 (mechanical disaggregation). Whereas in this study none of the root traits correlated with treatment 1 and most of the traits discussed above were both correlated with treatment 2 (micro cracking/slow wetting). These results are likely to be related to the soil type used in the different studies as different root systems alter the structure differently in cohesive and non-cohesive soils (Vannoppen et al., 2015). The soil used in this study had extremely low MWD (in the 0.4 to 0.8mm category) in treatment 1 showing that the soil was "unstable", is likely to suffer "very frequent" surface crusting and runoff and interrill erosion is "frequent in all situations" (ISO, 2012). These differences in the way traits drive the soil aggregate stability across different sites/experiments align with the study by Le Bissonnais et al. (2018) that found that the root traits were important at site level but did not necessarily correspond across different soil and climatic conditions. For these reasons, it seems that the tested root traits did not show any correspondence with the MWD, however there was a significant species difference for treatments 1 and 2 and a difference for treatment 3.

Plantago and *Lolium* had significantly larger MWD than the other species for treatments 1 and 2. *Plantago* also had a larger MWD of aggregates after treatment 3 but it was not statistically significant (P=0.056). In the study by Martin et al. (2012) they found that the roots of *Plantago* was the principle driving force in the formation of soil aggregates and soil aggregate stability. The study looked at different fungal inoculations to the root and where there were no inoculations and just the roots, it was consistently positively correlated with MWD (Martin et al., 2012, Wu et al., 2014). In the studies by De Baets et al. (2011) and Gould et al. (2016) it was found that grass species (graminoids) had a positive effect on soil aggregate stability, however this study shows that not all graminoids species exhibit the same ability and other factors may be responsible for the influence on the MWD.

3.4.3 Conclusions

This study set out to identify the plant functional traits that were advantageous for carrying out services in a vegetated buffer zone. The research has shown that for slowing the water flow and reducing sediment load that sward height was important. It seems more importantly, that vegetation density at the height of water flow increased the surface roughness and created a hydraulic brake. This allowed for deposition of the sediment and reduced the runoff coefficient. As well as vegetation density it was clear that having a high saturated hydraulic conductivity rate was also important, but it was not the only factor and that it didn't compensate for unsuitable aboveground vegetation. There were trade-offs for some of the traits between high hydraulic conductivity and low soil aggregate stability. It is, however, important to note that high soil aggregate stability is an important soil health parameter and high soil aggregate stability ensures resistance to surface sealing and the blocking of soil pores that in turn can reduce saturated hydraulic conductivity.

Given that plant height is an important trait the ideal species as a buffer plant would need low growing dense vegetation or dense vegetation at the height of the overland flow. Wide stems or dense rosettes seem to be a good option. Roots that had a large average root diameter and high root dry matter content to encourage water infiltration into the soil, but fibrous roots that have a high specific root length to increase soil aggregate stability. Not all of these traits may be available in a single species so using a mixture of species should allow for the best buffer plants. The species that performed the best in this experiment were *Plantago* followed by the grass species *Lolium* and *Dactylis.*

4.1 Examining how plant species mixes and functional group mixes affect the sediment trapping and runoff reduction of vegetated buffer zones

Vegetated buffers zones are areas of non-cropped land adjacent to agricultural or managed pastoral fields (Borin et al., 2010, Pan et al., 2017). Vegetated buffer zones help protect surface waters from diffuse agricultural pollution by providing a barrier between cropped land and water bodies or pathways to water bodies (Haddaway et al., 2016, Dosskey et al., 2008, Dosskey, 2001). Vegetated buffer zones can reduce the passage of overland water flow containing sediments, chemical fertilisers and pesticides (Borin et al., 2010, Borin et al., 2005, Dosskey, 2001). This happens by using the natural hydraulic roughness of the buffer vegetation to slow the water flow and increased hydraulic conductivity of the buffer through the root systems of the vegetation (Kervroedan et al., 2019, Vannoppen et al., 2017). The reduction and slowing of the water flow allows for the deposition of sediments and the removal or degradation of other chemical additions (Franco and Matamoros, 2016, Ali and Reineking, 2016, Owens et al., 2007).

There are many studies examining the performance of buffers in relation to buffer type, width and some looking at age of vegetation and vegetation management (Borin et al., 2004, Syversen, 2005, Hefting et al., 2005, Vought et al., 1995). There is extensive research looking at the differences between grassed buffers and buffers planted with trees, and work focussing on stiff grass hedges (Lee et al., 2000, Pan et al., 2010, Dabney et al., 1995, Meyer et al., 1995). However, there are few studies examining the composition of herbaceous vegetation in vegetated buffer zones (Kervroedan et al., 2019, Kervroedan et al., 2018). Therefore, there is less evidence on whether a mixture of herbaceous species and functional groups could improve the vegetated buffer zone services.

4.1.1 Field Plot Studies

Many of the studies of vegetated buffer zones have measured existing buffers or were part of long-term buffer projects that were able to continue measurements over a number of years allowing the investigation of how age and species maturity affect buffer services (Borin et al., 2005, Dosskey et al., 2007, Schmitt et al., 1999, Dosskey, 2001). Other studies created plots to study the buffer process in order to have more focus on vegetation or buffer additions (Habibiandehkordi et al., 2015b, Kervroedan et al., 2019, Fu et al., 2019b). Creating plots limits the number and length of experiments, but it enables investigation of particular vegetation and vegetation characteristics and allows the researcher to manipulate vegetation composition.

As well as differences in plot designs there are different ways in which data from the experiments are collected. Some studies use the crops in the field or bare plots above the buffer plots and wait for natural rainfall and runoff to look at how the buffers work (Borin et al., 2005, Dosskey et al., 2007, Haddaway et al., 2016). However, rainfall is unreliable, so it is good practice to simulate the overland flow and simulate sediment runoff (Habibiandehkordi et al., 2015b, Kervroedan et al., 2019, Fu et al., 2019b). This method facilitates the measurement discharge and the nutrients and/or sediment concentration during experiments.

4.1.2 Study Rationale

There are few studies that look specifically at the mixture of species and the few that do, focus on woody species in comparison to herbaceous species (Haddaway et al., 2016). When there is a focus on herbaceous species there seems to be a bias towards grass species, in particular stiff grassed hedges in studies in the USA (Dabney et al., 1995, Wilson et al., 2019, Meyer et al., 1995). There are few studies that focus solely on the interaction between grass, forb and legume species and the run-on, and they do not attempt to qualify how these species should be mixed to create a better buffer (Kervroedan et al., 2019). In the previous two chapters, the focus was on plant traits and if and how these affect the ability of the buffer zone to reduce the passage of sediments, slow overland water flow and increase soil hydraulic conductivity in controlled experiments. In this field plot study with simulated overland flow, the focus is on whether the mixture of species or functional groups effect the buffer performance in a field setting and how the lab studies translate to a field setting.

Hypotheses:

1. There will be significant differences between treatments for runoff coefficients and sediment concentration.
2. There will be a significant difference between treatments for soil hydraulic conductivity.

3. Sward height will be correlated with sediment concentration
4. Root traits will be correlated with soil hydraulic conductivity.

4.2 Methods

4.2.1 Site Description

The study site was situated on arable land on Aikbank Farm in Calthwaite, between Penrith and Carlisle, England (NY 347725, 540593, Figure 4.1). The study site was in a six-meter margin adjacent to a winter sown, barley field. The margin was previously planted with a game-bird cover crop, which was ploughed into the soil in preparation for the experiment (September 2018). The margin sloped in a generally uniform way away from the arable field at a mean slope of 4.5 (+- 0.5) degrees. The soils were texture, slowly permeable and had impeded drainage and are described as loamy clayey, slowly permeable with impeded drainage (Cranfield University, 2020; Figure 4.2).

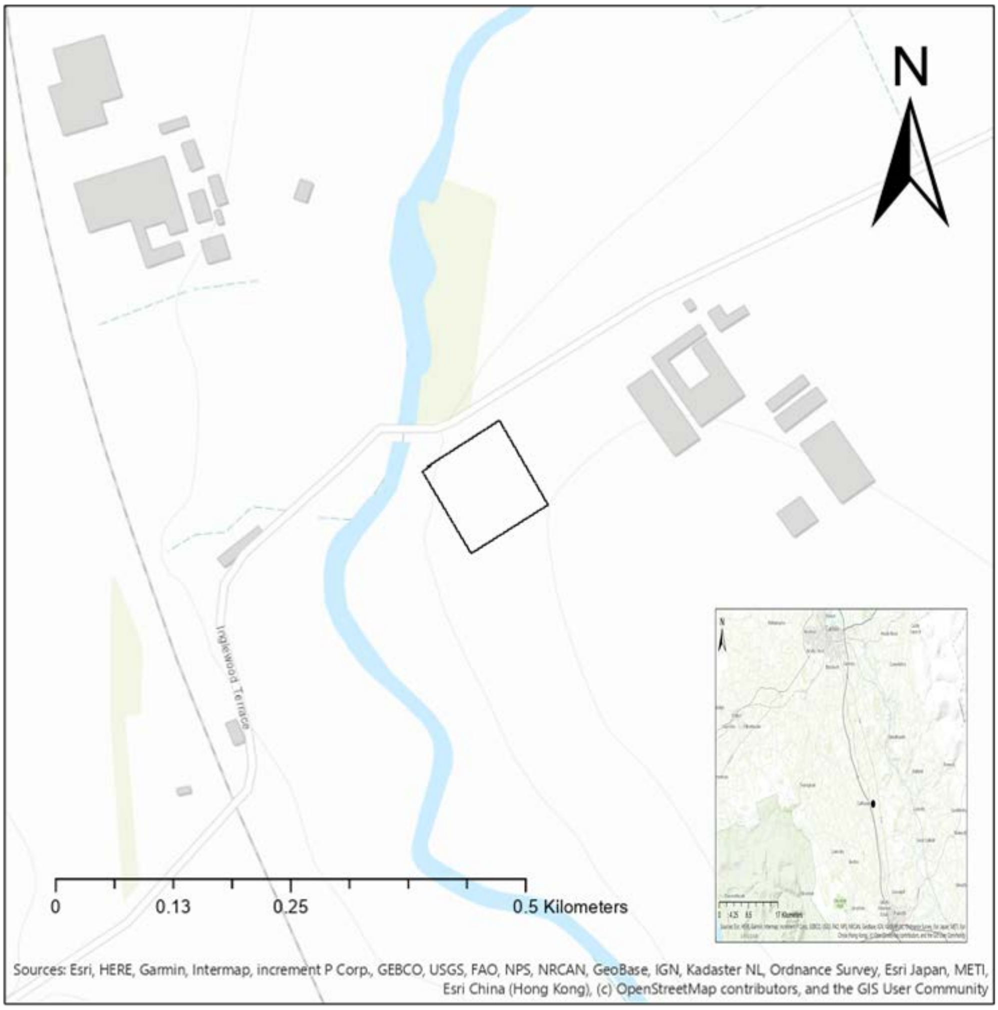


Figure 4.1 Location of Field Site (inset) and Location of the Experiment.

Figure 4.2 Soil Profile to ~460 mm showing Organic and A horizon to ~400mm and water-logged B horizon to ~460 mm.

4.2.2 Species, Planting Design and Plot Creation

The species used in this study were the same as used in the previous chapters (*Lolium perenne, Dactylis glomerata, Schedonorus arundinaceus, Plantago lanceolata and Trifolium repens*). Ten treatments contained different planting regimes: - Single grass species (3), pairs of grass species (3), all grass species, all grass with forb and all grass with the legume (Figure 4.3). Plants were grown from seed and seeds were sown at 3 g m^{-2} in September 2018. Plants were rain fed. Weeding took place once between October 2018 and December 2018, and four times between January 2019 and August 2019.

Plots were 500 mm by 1000 mm facing down the slope. There was 2 m between plots and 3 m between blocks. There were four repeats of each treatment set out as a randomised block design with each block situated below the other (Figure 4.3)

B	D	A	E	C	F	G	H	I	J
I	G	J	F	H	A	B	E	D	C
D	A	I	E	G	H	B	F	C	J
J	A	I	D	C	F	G	B	H	E

A- All Grass Species
B- All Grass and *Plantago*
C- All Grass and *Trifolium*
D- *Lolium* and *Schedonorus*
E- *Lolium* and *Dactylis*
F- *Dactylis* and *Schedonorus*
G- *Lolium*
H- *Dactylis*
I- *Schedonorus*
J- All Species

Figure 4.3 Planting Design, Layout and Key

4.2.3 Run-on Experiment

The experiment took place in August 2019 over 10 days. The experiment ran for 30 minutes per plot using 150 litres of water at a rate of 5 l minute^{-1} equivalent to 300 mm hour^{-1} The plots were hydrologically isolated by metal sheets dug 120 mm into the ground at either side of the plot (Figure 4.4, image 1 & 2). The header tank held 100 l of water and maintained a steady flow when it contained 75 l therefore the tank was kept at over 75 l for the entire 30 minutes. The header tank discharged into the weir box which spilled onto the ramp to create overland flow onto the plots (Figure 4.4, image 3 & 4). For measurements and water collection a trench was dug at the bottom of the plot and a collector plate inserted into the soil with a gutter pipe angled to direct runoff to the collection bottle (Figure 4.4, image 5.).

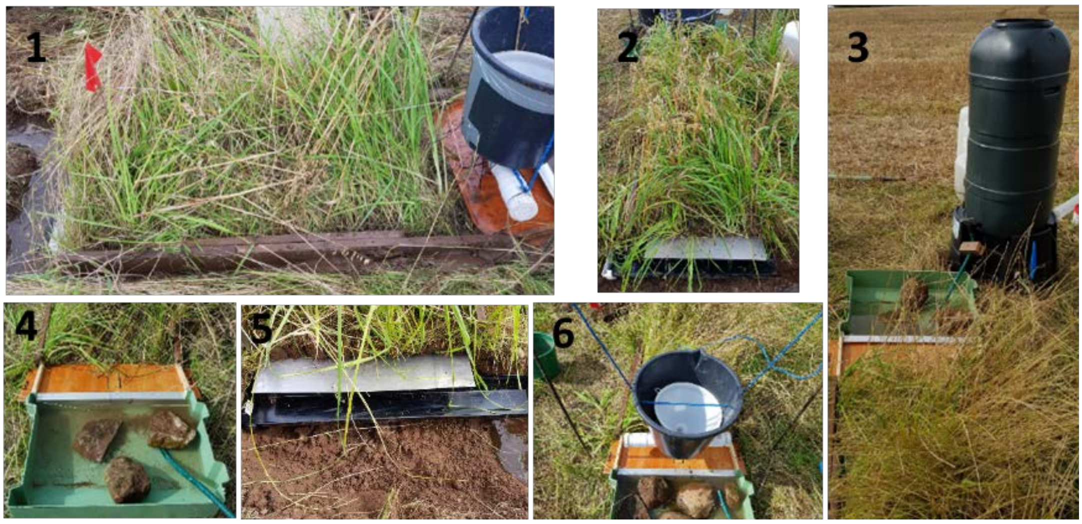


Figure 4.4 Run-on Experiment 1. View of plot with isolation sheets. 2. Full length of plot with collector plate. 3. Header tank discharging into weir box. 4. Weir box and ramp. 5. Collector plate and gutter. 6. Sediment shower suspended over ramp.

4.2.3.1 Sediment Addition

Sediment retention in vegetation was assessed through adding a sediment solution to the flow after 11 minutes. Sediment was added at a concentration of 5g l^{-1}, 10 litres of sediment solution was added over a five-minute period using same application method as chapter 3 (Figure 3.3, 4.4, image 6). The sediment suspension was created using field soil, dried and sieved to 0.5 mm then soaked in the 10 litres of water overnight and then mixed by turning over end 10 times before application.

4.2.3.2 Data Collection

Sward height was measured before and after the run-on simulation. Time to runoff was measured by timing from the beginning of run-on to when first runoff was observed. Time at peak flow was found by determining the volume of discharge for 1 minute at intervals of 5 minutes until the peak flow was reached. This was carried out on three practice plots before the experiment. A mean time was used to determine volume of runoff at peak flow for the other plots (l minute^{-1}). After the peak flow was reached the sediment solution was added. Sediment was collected in 250 ml bottles from the gutter and started 1 minute after sediment additions began. Three further sediment samples were taken at 5 minute intervals (Table 4.1).

Table 4.1 Run-on Simulation details and measurements

Measurement	**Rate/Units**	**Sampling Interval**
Flow Rate	l minute^{-1}	For 30 minutes
Time to Runoff	Seconds	From beginning of run-on to runoff
Runoff coefficient at Peak Flow	Percentage (%) of Run-on	At 10 minutes
Sediment Concentration	mg ml^{-1} second^{-1}	At 11 minutes and then three more times at 5-minute intervals
Sward height	mm	Before and after

4.2.4 Post Run-on measurements

The aboveground biomass was sampled the same day as the run-on simulations. A 1000 mm by 200 mm area of vegetation was removed, bagged and dried in an oven at 62 ^{o}C for 72 hours and then weighed (g) to obtain dry mass.

Following the above ground vegetation measurements, the saturated hydraulic conductivity of each plot was determined. The simplified falling head method was used according to methods by Angulo-Jaramillo et al. (2016) and was explained in detail in chapter 3 (the infiltration ring had a 300 mm diameter for the field experiment).

Following the saturated hydraulic conductivity measurement, two soil cores were taken from each plot (100 mm depth, volume: 144.3 mm^3). The first core was used to measure soil bulk density, the second for assessing root density. For the soil bulk density calculation soil was extracted in the core, stones above 3 mm were removed (and their volume recorded) and then soil was dried at 105 °C until mass stopped changing (typically around three days). Soil bulk density was calculated using equation 1, minus the volume of removed stones. Root density was measured by washing all roots from the collected core and obtaining dry mass (g). Root density was calculated using equation 2.

$$D_{b=\frac{M_d}{V}} \tag{1}$$

Where

D_b is soil bulk density;

M_d is Oven dried mass;

V is the volume of the core.

$$R_{d=\frac{M_d}{V}} \tag{2}$$

Where

R_d is root density;

M_d is Oven dried mass;

V is the volume of the core.

4.2.5 Statistical Analysis

Data were analysed for differences between treatments using R version 3.5.1 (R Studio Team, 2016, R Core Team, 2018). Data were tested for a normal distribution using Hist and box functions and any data that were significantly different from a normal distribution were log10 transformed. Linear models were built using lm function in R (R Studio Team, 2016, R Core Team, 2018). Data were also analysed in lme4 (Bates et al., 2015) by building a linear model with the random effect of Block to explore if this had any effect on results. Results were displayed using box and whisker plots using ggplot2 (Wickham, 2016) to enable the variation of data to be accurately shown.

4.3 Results

There was no significant difference between treatments for runoff coefficient at peak flow ($p>0.05$, Figure 4.4) or time to runoff ($p>0.05$, Figure 4.4). There was no significant treatment difference for field saturated hydraulic conductivity (K_{fs} mm hour^{-1}, $P>0.05$, Figure 4.6), treatments C and D were lower and had less variation than the other treatments. There was no significant difference between treatments for sediment concentration ($P>0.05$, Figure 4.6). Adding block as a random effect did not change the significance.

There was no significant difference between treatments for sward height before or after run-on simulation ($P>0.05$, Figure 4.7), aboveground dry biomass ($P>0.05$, Figure 4.8), root density ($P>0.05$, Figure 4.8) or soil dry bulk density ($P>0.05$, Figure 4.9).

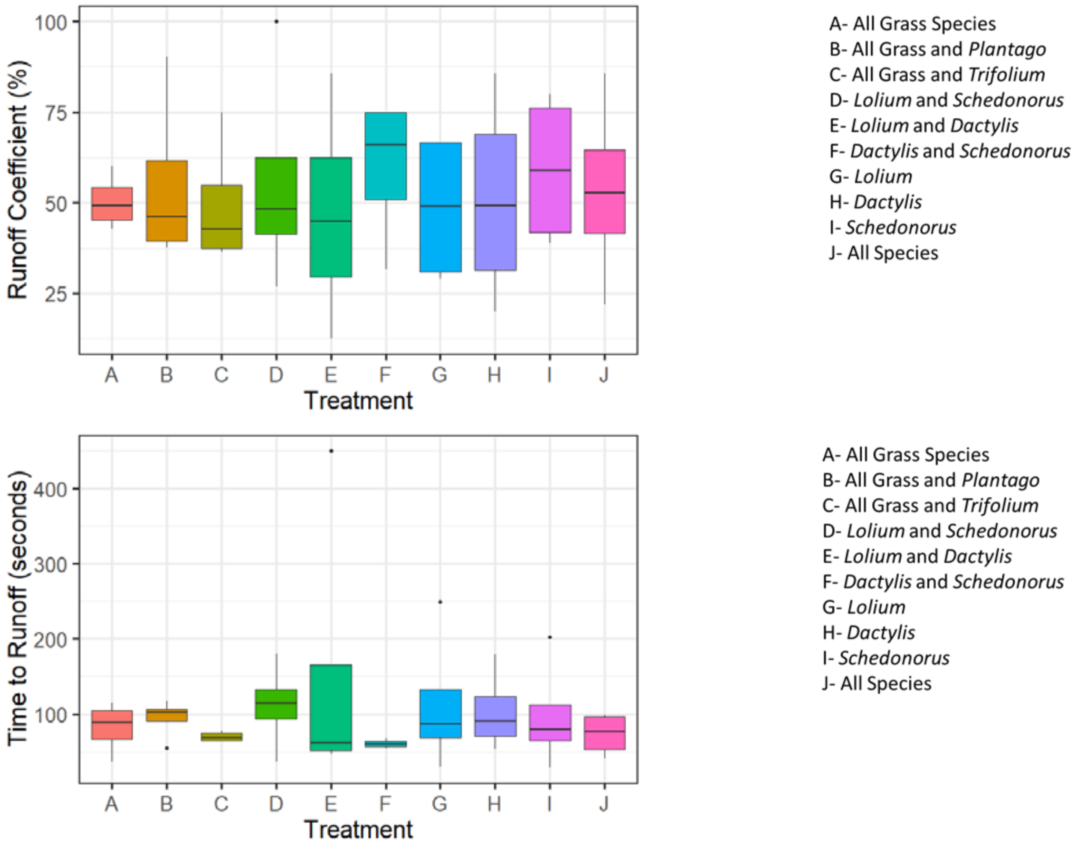


Figure 4.4 Box and Whisker plots for Run-off Coefficient at Peak Flow and Time from run-on to runoff (n=40; median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

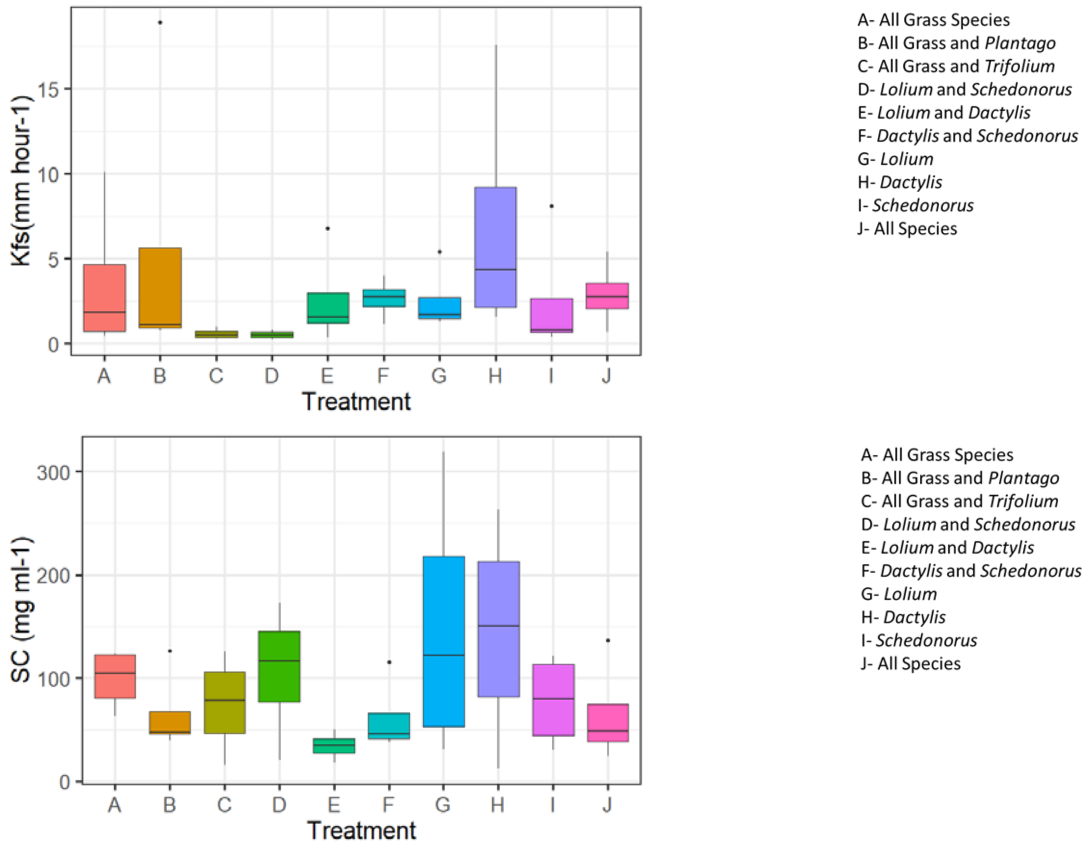


Figure 4.6 Box and Whisker plots for Field Saturated Hydraulic Conductivity (K_{fs} mm hour^{-1}) and sediment concentration(SC mg ml^{-1}; n=40; median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

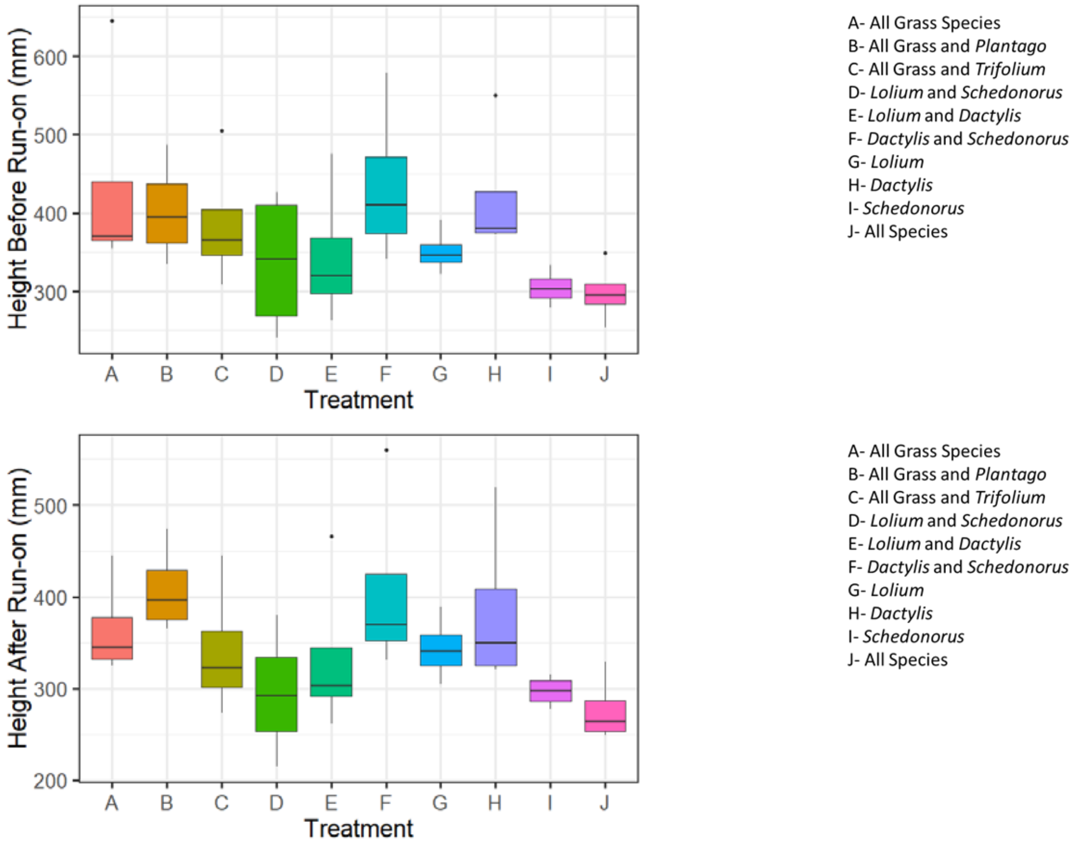


Figure 4.7 Box and Whisker plots for Sward Height Before and After Run-on Simulation (n=40; median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

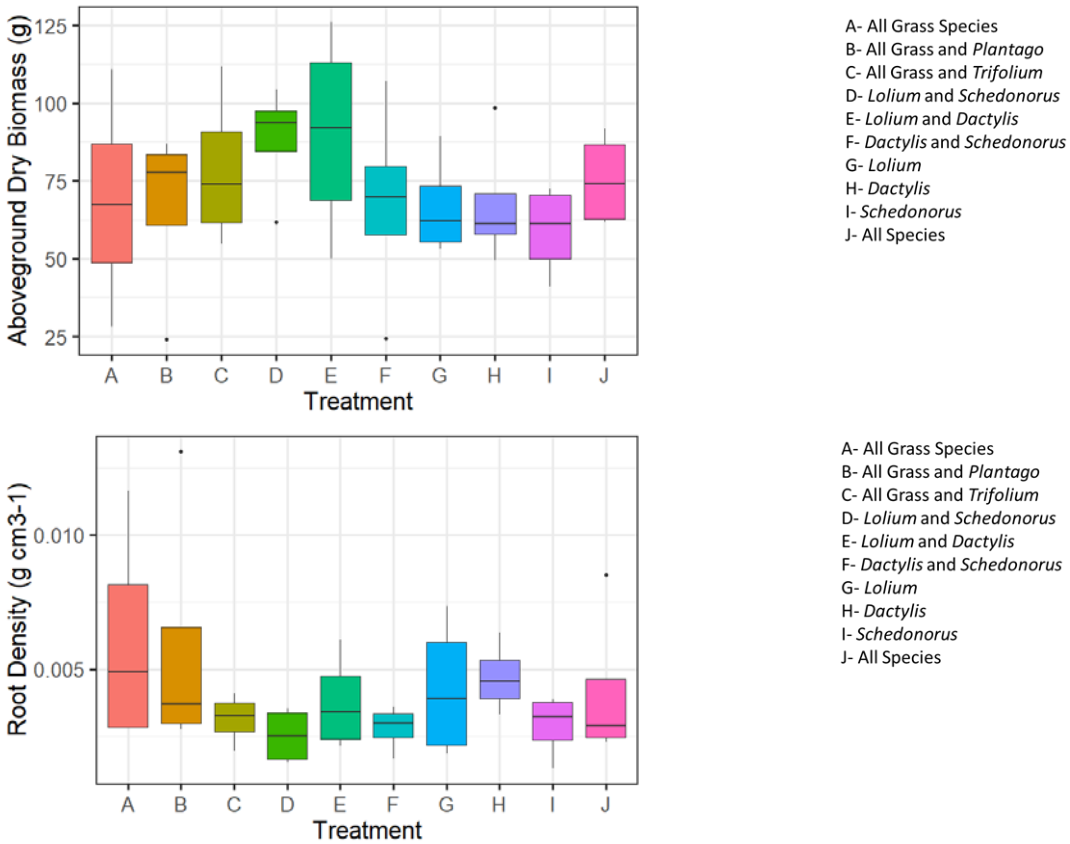


Figure 4.8 Box and Whisker plots for Aboveground Dry Biomass (g) and Root Density (g cm^{3-1}; n=40; median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

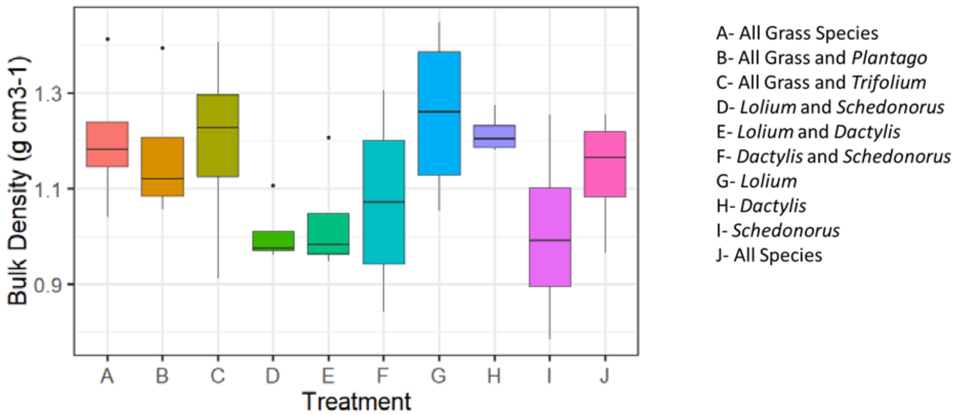


Figure 4.9 Box and Whisker plot for Soil Bulk Density (g cm^{3-1}; n=40; median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

4.4 Discussion

Contrary to expectations this study found no significant differences between the treatments for any of the tests carried out and all treatments had similar above and below ground biomass, therefore the hypotheses are rejected. All treatments slowed the water flow, and all captured some sediments. In the previous chapter there were clear differences for runoff coefficients, sediment retention and saturated hydraulic conductivity due to species and plant trait differences. However, this field plot experiment did not show these differences between species or the species mixes. The lack of treatment effects are probably due to the similarity in the plant functional traits in the experiment. Plant traits are known to modify the soil and aboveground processes (Nock et al., 2016, De Baets et al., 2011) but are also subject to the environmental conditions (Bardgett, 2017, Guittar et al., 2016, Kleyer and Minden, 2015). It seems possible that the environmental conditions had a higher influence on the plant traits than the traits were able to exert on their environment in the time they had to grow and the environmental conditions.

4.4.1 Runoff Coefficients and Sediment Concentration

All buffer plots and all treatments were well grown and had high vegetation cover. Vegetation cover was above 80% on all plots. This uniformly high vegetation cover seems likely to be the main reason that there was a consistent runoff coefficient across the treatments (median between 45% and 65%, Figure 4.4). Vegetation density at the height of water flow delaying the water, enabling the water to settle in soil depressions and allowing the water to infiltrate into the soil explains the high-water retention rate within the buffer plots (Ali and Reineking, 2016, Morgan, 2005). This supports evidence from previous studies that have found that vegetation cover and vegetation density are key for slowing and reducing runoff and sediment delivery (Morgan, 2005). Rey (2003) found in a study of a catchment in France with large gullies that they stopped producing sediments when the low growing, herbaceous vegetation cover exceeded 50%. They found that all vegetation slowed down the delivery of sediments and as little as 33% cover interrupted the sediment delivery (Rey, 2003). In a study by Mekonnen et al. (2016) they trialled native, stiff stemmed grasses (in Ethiopia) to assess their suitability for edge of field sediment trapping. They found that grasses with a high tiller number and high density coupled with high root depth were the best combination for retaining sediments (Mekonnen et al., 2016). Vegetation cover and vegetation density are clearly important for reducing runoff coefficients and reducing sediment concentration by increasing the hydraulic roughness of the surface (Kervroedan et al., 2019). However, other factors are likely to influence buffer performance such as plant litter, soil structure and hydraulic conductivity.

As differences between the treatments were not evident, it could be related to the buffer plot age. The plots only completed one growing season before the field overland flow simulation this could have affected the plots ability to slow water flow and reduce sediments. In the study by Dosskey et al. (2007) they compared the age and performance of different plots, they also looked at the differences between grassed plots and plots containing trees. The age of the buffer plots influenced how they performed in reducing the passage of sediments and nutrients (Dosskey et al., 2007). They found that buffer plots that were over three years old had a greater vegetation density and this was key to slowing the water flow through the buffer (Dosskey et al., 2007). As the plots age the increased root density and root turnover should produce more soil pores and possibly increase soil hydraulic conductivity. The aboveground vegetation will be supplemented with plant litter and the plants will develop a more diverse structure which should allow for differentiation between treatments. (Dosskey et al., 2007, Schmitt et al., 1999) It could be that the field plots in this study would have more differentiation between treatments if they were tested again after further growing seasons due to litter accumulation and improved soil structure through root development (Schmitt et al., 1999).

4.4.2 Saturated Hydraulic Conductivity

Surprisingly, no differences were found between the treatments for field saturated hydraulic conductivity. This could help to explain the lack of difference for the runoff coefficients and sediment concentration. In the previous chapter, there was a significant correlation between runoff coefficients and the field saturated hydraulic conductivity as well as significant correlations between root traits and species type. These contradictory results are likely be due to the difficulties associated with upscaling from lab to field and the uncertainties with plot scale experiments (Alaoui et al., 2011). These inconsistencies include soil type, soil structure, soil depth, moisture content, animal activity and vegetation shading (Haruna et al., 2018).

The differences between species and the correlations between root traits and saturated hydraulic conductivity shown in chapter 3 was not evident in the field experiment. These differences are possibly due to the differences in soil type. The field soil has a higher clay content then the soil used in the lab experiments which was a sandy loam. There is evidence that roots have a more pronounced effect on sandy soils than soils containing higher clay percentages (Vannoppen et al., 2017, Vannoppen et al., 2016, Vannoppen et al., 2015). Therefore, it is possible that the root mass and architecture of the different species in the different treatments were less affective at increasing soil aggregate stability and increasing soil pores to facilitate increased saturated hydraulic conductivity.

A possible explanation for the low saturated hydraulic conductivity (Figure 4.6) could be the soil moisture in the field. There was a mean of 35% moisture content before the saturated hydraulic conductivity testing. Between 52% and 97% (mean of 80.4%) of the pore space contained water prior to the saturated hydraulic conductivity testing. Rainfall was 159.4 mm for the month of August (MetOffice, 2020) which was 169.5% of the previous 10-year mean for August. Each plot had been subjected to the run-on simulation the week before which saw 150 l of water run over or into the plot. This could have possibly influenced the low saturated hydraulic conductivity rates. Bagarello and Sgroi (2007) found that soils with high moisture content had reduced saturated hydraulic conductivity due to soil swelling that reduced soil pore space. However, a number of land use, management and other variables, not just vegetation, can affect saturated hydraulic conductivity (Haruna et al., 2018, Chandler et al., 2018).

In a study by Chandler et al. (2018) looking at the differences in saturated hydraulic conductivity under different vegetation regimes (trees and pasture) and between tree species there were significant differences between saturated hydraulic conductivity for pasture and trees and differences between the different tree species. Different land management obscured these differences (grazed or non-grazed). The ungrazed forests had significantly higher saturated hydraulic conductivity than the pasture and the *Pinus sylvestris* had a significantly higher rate than the *Acer psuedoplatanus.* Yet these differences were lost when all of the systems were grazed showing that the management played a role in the saturated hydraulic conductivity rates of these systems (Chandler et al., 2018). It is thought that the higher intensity of previous land use affects the soil hydraulic conductivity and increases the time to recovery (Lozano-Baez et al., 2019, Soracco et al., 2019). The study site is part of an agricultural field under regular cultivation, therefore these observed effects of the land use intensity and the effect it has saturated hydraulic conductivity and on time to recovery (Lozano-Baez et al., 2019, Chandler et al., 2018) could explain the lack of differences between the saturated hydraulic conductivity in this study.

As the study plots were ploughed and seeded in September 2018 and the vegetation took time to provide full soil coverage it is likely that soil aggregate stability was reduced due to exposure to rain splash and wind causing the soil physical structure to decline (Morgan, 2005). When soil aggregates stability is reduced this causes fine particles to block soil pores and reduce the saturated hydraulic conductivity (Knapen et al., 2008). Once soil structure is compromised slaking can occur and this blocks pores further reducing hydraulic conductivity (Kumar et al., 2012). It has been shown that tillage has a negative effect on the aggregate stability of the soil (Kahle et al., 2013) which has knock on effects to the saturated hydraulic conductivity. Therefore, time since the last tillage management on the buffer plots could have been too short for the treatments to have affect from root action or organic matter input.

4.4.3 Conclusion

The aim of this study was to investigate the differences between species and functional group mixes and their ability to reduce overland water flow and increase sediment retention in vegetated buffer zones. It was hypothesised that a mixture of species and functional groups would create conditions that would help to reduce overland water flow, encourage sedimentation and increase soil saturated hydraulic conductivity. The results from this study did not show any differences between the ten treatments for any of the measured parameters. It did show that the vegetation reduced the overland flow by 55% in some instances which corroborate results from other studies on vegetated buffer zones showing that a high vegetation cover will reduce runoff and sediment passage through the buffer. The lack of differences between the above and belowground vegetation traits between treatments seems to contribute to the lack of difference in the overland flow, sediment concentration and saturated hydraulic conductivity.

The lack of significant differences between treatments is possibly due to the previous land management, the buffer plot age and the size of the plots. Larger plot size would help to reduce the effect of soil and slope heterogeneity on the experiment. Similarly, multiple growing seasons would allow the vegetation to have a stronger effect on soil through litter development, root turnover and organic matter inputs. Finally, using different flow rates on numerous repeats to explore the effectiveness of the buffers at different overland flow intensity could answer further questions around capacity of the buffers at different intensity of overland flow.

5.1 Impacts of different vegetation types in vegetated buffer zones on soil aggregate stability and field saturated hydraulic conductivity

Vegetated buffer zones are areas of non-cropped land between agricultural or pastural fields and water courses or pathways to water courses (Borin et al., 2010). Vegetated buffer zones help to reduce the passage of sediments, nutrients and pesticides from cropped land to the aquatic environment (Borin et al., 2005, Dosskey, 2001). They do this through reducing the velocity of the water flow over the buffer through increased hydraulic roughness and increased water infiltration. Extensive research has shown that vegetated buffer zones reduce diffuse pollution from agriculture (Dosskey, 2001, Dosskey et al., 2008, Dosskey et al., 2007, Borin et al., 2004, Borin et al., 2005), however pollution from sediments, nutrients and agro-chemicals are still found in the aquatic environment.

The type of vegetation in vegetated buffer zones differs depending on circumstance, culture or preference of the farmer (Haddaway et al., 2016, Borin et al., 2010). Many buffer zones in the UK consist of herbaceous vegetation dominated by fast growing grasses and a hedgerow or another form of woody layer (Dosskey et al., 2008, Dosskey et al., 2007, Schmitt et al., 1999). Buffers comprising of broad-leaved native trees can be desirable as riparian vegetation due to their ability to stabilize banks and their shading properties (Borin et al., 2010). Fast-growing woody species such as willows that can be coppiced and used for, amongst other things, biofuel are increasingly popular (Borin et al., 2010). There is still uncertainty which buffer type is best for increasing infiltration and preventing soil loss.

In the study by Chandler and Chappell (2008) it was shown that the saturated hydraulic conductivity of soil within 3 m of an oak tree was 2.3 to 3.4 times higher than open pasture. It is established that the higher saturated hydraulic conductivity under trees and within woodland is due to root depth and diameter and organic matter input from litter (Chandler and Chappell, 2008, Kumar et al., 2012). The difference between areas containing trees or grass/pasture can however be reduced by the land use of the site, for example grazing reduces the hydraulic conductivity of soils (Chandler et al., 2018). The intensity and type of land use can also affect the soil physical properties that in turn affect the saturated hydraulic conductivity of the soil (Chandler et al., 2018, Agnese et al., 2011, Vannoppen et al., 2017, Vannoppen et al., 2015).

Soil physical structure is a key part of soil health and is important for carbon storage, nutrient cycling and erosion prevention (Bardgett et al., 2014, Gould et al., 2016, Le Bissonnais et al., 2018). If soils have strong aggregate stability, they are less likely to suffer from erosion and are more productive (Barthes and Roose, 2002). If aggregate stability is degraded then hydraulic conductivity is reduced, because soil pores become blocked and crusts can form at the surface of the soil (Vannoppen et al., 2015). This increases erosion risk further by increasing water ponding at the surface because water is prevented from moving through the soil profile. Consequently, the potential for overland water flow is higher and the risk of soil erosion is further increased (Knapen et al., 2008). Soil aggregate stability can be compromised by flood events, heavy rainfall, irrigation, tillage and poaching/compaction by livestock/vehicles (Boardman, 2013). Soil aggregates are formed through a combination of microbial activity, soil organic matter (SOM), root exudates and root physical structures (Liu et al., 2005, Pérès et al., 2013, Wu et al., 2014). These factors affect the soil aggregates differently and to different magnitudes dependant on soil type and the quantities of clay or sand (Le Bissonnais et al., 2018). All vegetation cover increases soil strength, soil physical structure and reduces erosion, however what is less clear is which type of vegetated buffer zone will reduce erosion in specific landscape types and conditions.

5.1.2 Study Rationale

The study is part of an ongoing study at Rothamsted Research's North Wyke farm in Devon, UK, researching vegetated buffer zones with different types of vegetation and the effect they have on the hydrology and water quality during overland flow events. The aims of this study are to investigate if there are any significant differences between the buffer types for three measures of soil aggregate stability and soil saturated hydraulic conductivity, including if soil aggregate stability influences the saturated hydraulic conductivity of the buffer and crop area. It will also explore the differences between the crop area and the buffer types for one measurement of soil aggregate stability and saturated hydraulic conductivity.

Hypotheses:

1. There will be significant differences between plot treatments for saturated hydraulic conductivity.
2. There will be significant differences between plot treatments for the three measures of soil aggregate stability.

3. There will be significant differences between the buffer plots and the crop area for soil aggregate stability and saturated hydraulic conductivity.

5.2 Methods

5.2.1 Site location and Description

The experimental site was part of a five-year buffer zone project started in 2016 and coordinated by Rothamsted Research at their North Wyke Farm. The site is in Devon close to the town of Okehampton (SX 269510, 97494 Figure 5.1). The buffer zones were previously pasture and the soil is slightly acid loamy and clayey with slightly impeded drainage (Cranfield University, 2020) classified as a Hallsworth Series clayey pelo-stragnogley soil formed in 'head' from clay shale (Harrod and Hogan, 2008).

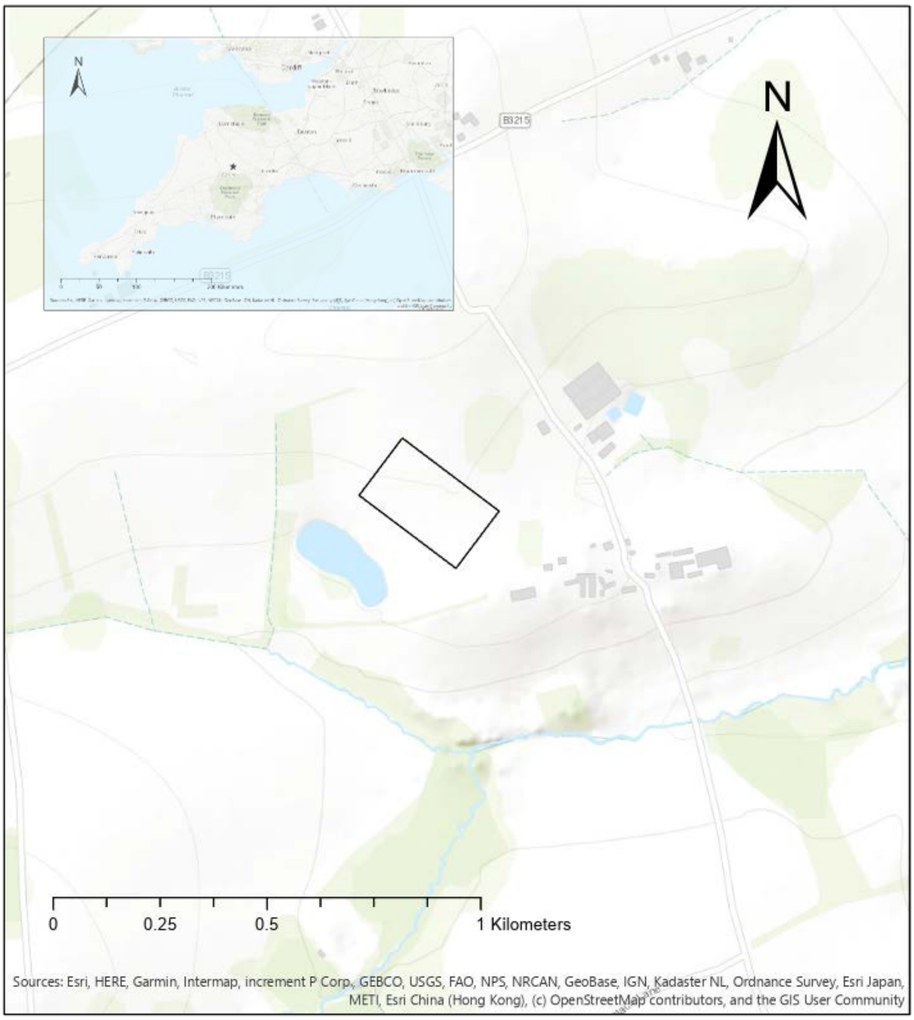


Figure 5.1 Location of field site (inset) and experiment

5.2.2 Plot design and previous experiments

Nine experimental buffer zone plots (12 m by 12 m) along with three controls were arranged in a randomised block design (Figure 5.2). Three plots were planted with a novel grass species (*Festulolium loliaceum* cv. Prior), three planted with willow (*Salix* cultivars Endurance, Terra nova, Mourne, Cheviot and Hambleton) and three planted with broadleaved native trees (*Corylus avellane, Tilia cordata, Quercus robur, Castanea sativa, Ulmus glabra*), referred to in this study as grass, willow or wood plots respectively. Native herbaceous vegetation had grown amongst the grass in the grass plots and had formed an herbaceous understory in the willow and wood plots. Plots were established in the spring of 2016. Existing vegetation was cleared using herbicide before the planting of the buffers and the grass plots were harrowed prior to seeding. The cropped area above the vegetated buffer plots was initially planted with improved grassland for silage production and then converted to fodder maize in the spring of 2019.

Plots had been tested for runoff capacity, water quality as well as soil chemical and physical properties as part of a long-term study into vegetated buffer zone performance.

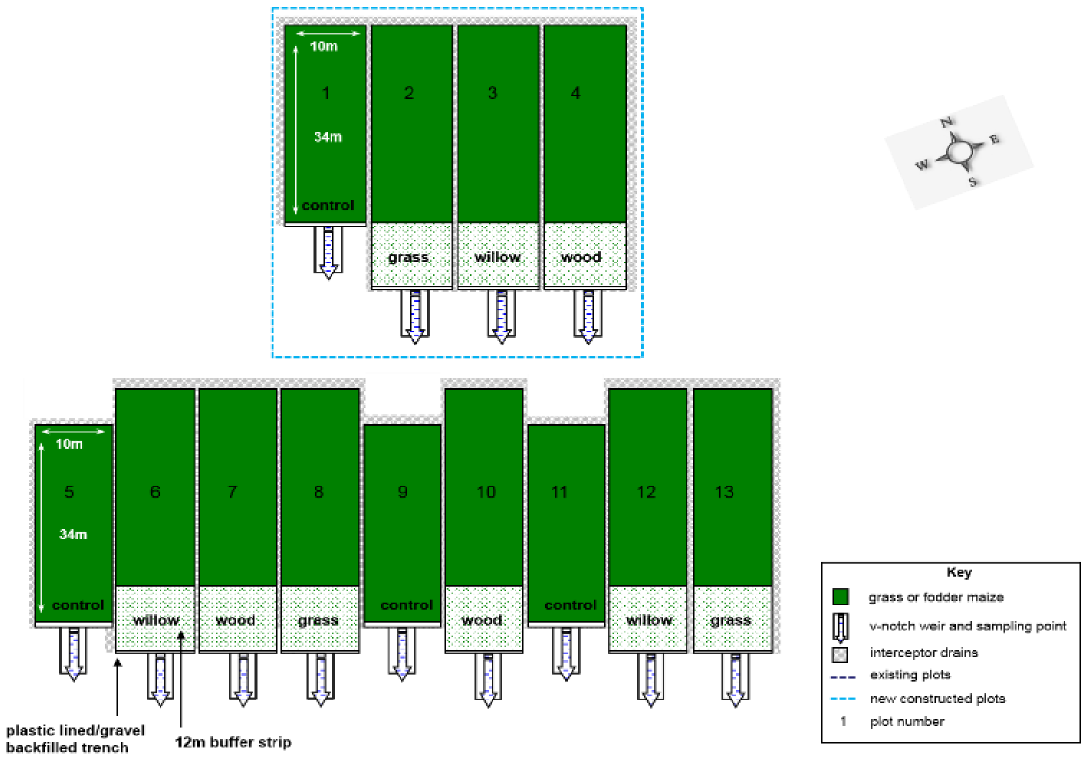


Figure 5.2 Plot design and layout (Collins et al., 2018)

5.2.3 Experimental design and data collection

Data for this study were collected using five samples located within the buffer zone of each plot. Sampling locations were randomised as far as possible, but care was taken not to sample the compacted area used as a path for gas sampling. Data were collected for field saturated hydraulic conductivity and three measures of soil aggregate stability (Figure 5.3).

The simplified falling head method was used to calculate field saturated hydraulic conductivity according to methods by Angulo-Jaramillo et al. (2016). An infiltration ring with a 300 mm diameter was pushed 50 mm into the soil after all vegetation had been removed. A soil moisture reading was taken just outside of the ring using a theta probe (moisture meter, Figure 5.3). Next, 2 litres of water was poured gently into the ring and was timed in seconds how long it took to completely infiltrate into the soil. This was achieved when no more water was visible on the surface of the soil. Finally, a further soil moisture reading was taken from inside the infiltration ring and K_{fs} was calculated using equation 1.

$$K_{fs} = \frac{\Delta\theta}{(1-\Delta\theta)t_a}\left[\frac{D}{\Delta\theta} - \frac{(D+(1/\alpha^*))}{1-\Delta\theta}\ln\left(1+\frac{(1-\Delta\theta)D}{\Delta\theta(D+(1/\alpha^*))}\right)\right] \quad (1)$$

Where:

D is the depth of water in ring,

$\Delta\theta$ is the post-test moisture level (inside ring) minus the pre-test moisture level (outside of the ring),

α^* is the saturation potential coefficient (based on soil type),

t_a is time in seconds.

Soil aggregate stability was tested for the different buffer types and the cropped area (ISO, 2012). Cropped areas were sampled and tested for soil aggregate stability using the fast wetting treatment only, due to time constraints. Three treatments were used to assess the soil aggregate stability of the buffer soil when exposed to different stressors (ISO, 2012). The stressors are fast wetting by immersion in water, designed to test the soil stability when dry material is subjected to fast wetting like irrigation and heavy rainfall (Treatment 1). Slow wetting by capillary action this tests the dry soils reaction to slow wetting for example moderate rainfall (Treatment 2). Mechanical disaggregation through shaking in ethanol this examines the behaviour of wet soil when subjected to mechanical disturbance (Treatment

3). Detailed methods are explained in Chapter 3 (Table 3.2 Figure 3.5). Mean weighted diameter was calculated using equation 2.

$$\text{MWD}= \sum(\bar{d} * w)/100 \qquad (2)$$

Where

$\bar{d}$ is the mean diameter between two sieves;

w is the weighted percentage of the particles retained on the sieve (ISO, 2012).

Figure 5.3 Soil sample for soil aggregate stability and equipment for testing field saturated hydraulic conductivity.

5.2.4 Statistical Analysis

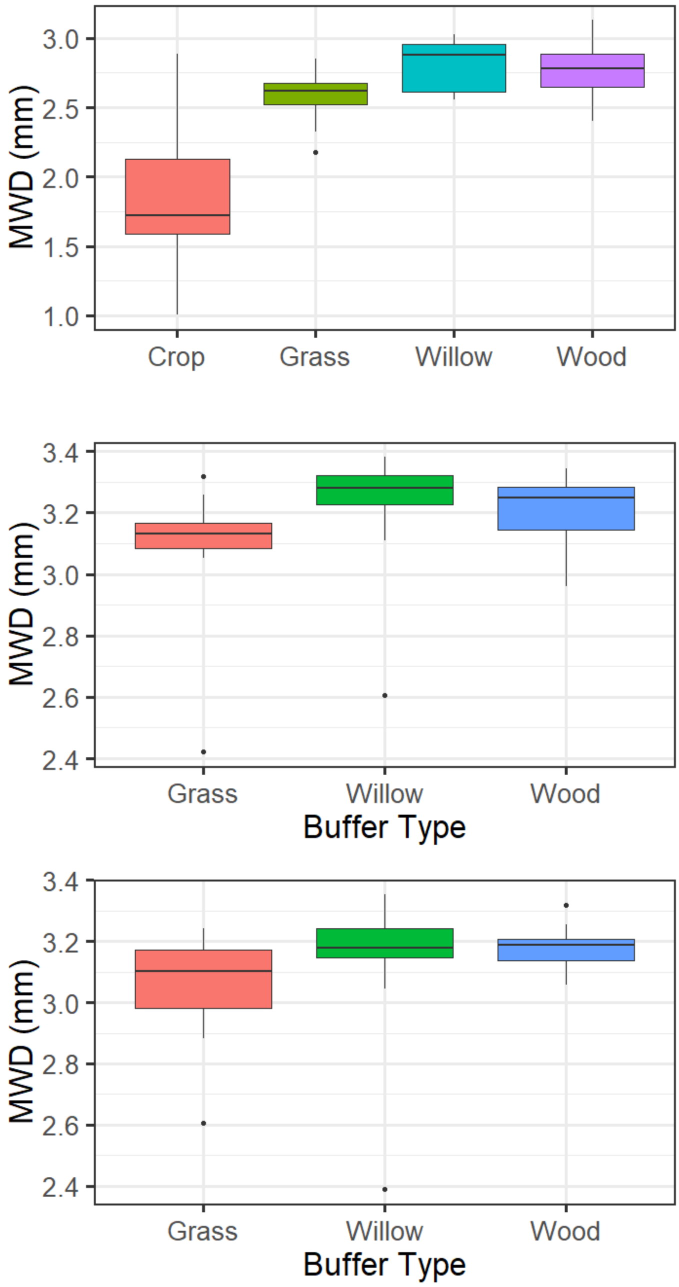
Data were analysed for differences between buffer and crop treatments using R version 3.5.1 (R Studio Team, 2016, R Core Team, 2018). Data were tested for a normal distribution using Hist and box functions. Where data was not significantly different from a normal distribution or could be transformed to be closer to a normal distribution, linear models were built using lm function in R (R Studio Team, 2016, R Core Team, 2018). Data that were significantly different from a normal distribution were analysed using the Kruskal.Test function in R (R Studio Team, 2016, R Core Team, 2018). Results were displayed using box and whisker plots and scatter graphs using ggplot2 (Wickham, 2016) to enable the variation of data to be accurately shown.

5.3 Results

There was a significant difference between the crop area and all the buffer zone types for the mean weighted diameter (soil aggregate stability) for treatment 1 (fast wetting, $P<0.01$, Figure 5.4). All vegetated buffer zones had higher mean weighted diameter than the cropped area. The grass buffer zone treatment had significantly lower ($P<0.05$, Figure5.4) mean weighted diameter than the wood buffer for treatment 2 (slow wetting). There was no significant difference between the buffer types for treatment 3 (mechanical disaggregation, $P>0.05$, Figure 5.4).

There was a significant difference between the crop area and all the buffer zone types for the field saturated hydraulic conductivity (K_{fs} mm hour^{-1}, $P<0.01$, Figure 5.5). The wood buffer had a significantly higher saturated hydraulic conductivity rate than the grass buffer ($P<0.05$). The willow buffer had a higher mean rate than the grass buffer, but it was not significant ($P=0.09$). There was no significant difference between the wood and willow buffer ($P>0.05$, Figure 5.5).

There was a significant correlation between the mean weighted diameter of the soil aggregates after treatment 1 (fast wetting) and the field saturated hydraulic conductivity (K_{fs} mm hour^{-1}, $P<0.01$, $R^2= 0.48$, Figure 5.6).



(a)

(b)

(c)

Figure 5.4 Box and Whisker plots for Soil aggregate stability (mean weighted diameter, MWD, mm) for three treatments. Fast wetting n=73 (a), slow wetting n= 39 (b) and mechanical disaggregation n= 40 (c); (median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

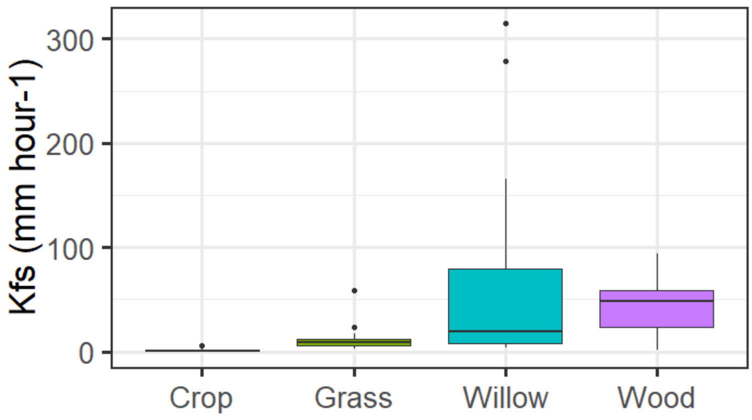


Figure 5.5 Box and Whisker plots of Field Saturated Hydraulic Conductivity (K_{fs} mm hour^{-1}; n= 53, median=horizontal line; box boundaries=lower quartile (25%), upper quartile (75%); whiskers=highest & lowest values; dots = outliers).

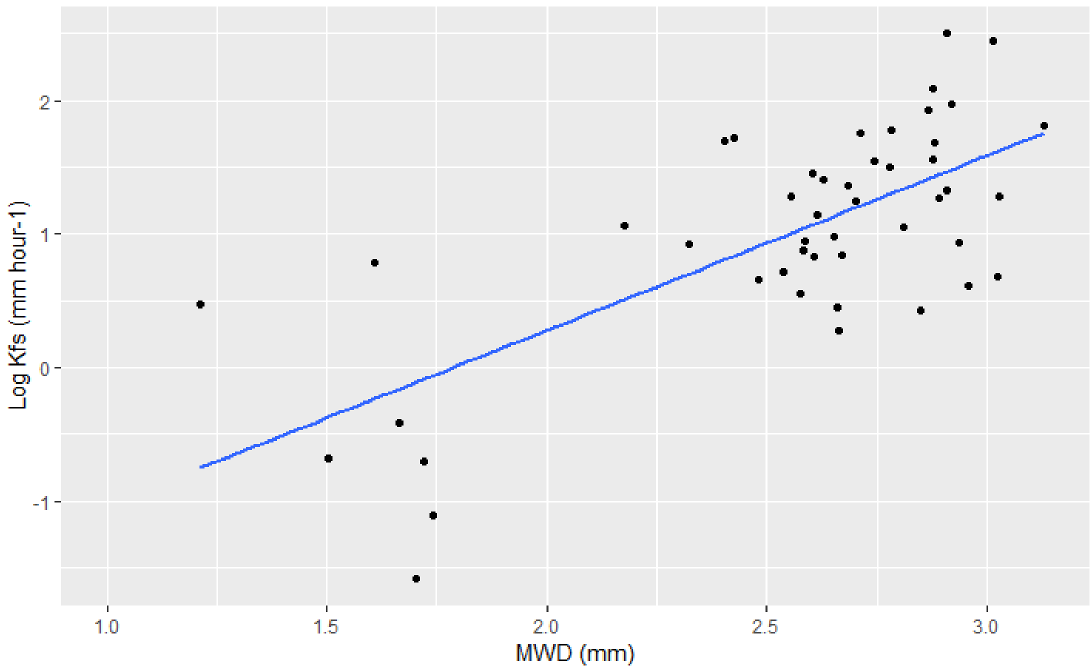


Figure 5.6 Scatter plot showing a correlation between soil aggregate stability mean weighted diameter (mm) for treatment 1 (fast wetting) and the log10 of field saturated hydraulic conductivity (K_{fs} mm hour^{-1}).

5.4 Discussion

The main finding from this study is that all vegetated buffer zone types had a significantly higher saturated hydraulic conductivity and significantly higher soil aggregate stability than the upslope cropped area, therefore hypothesis 3 can be accepted. There were also differences between the grass buffer and the buffers containing wood and willow. This shows that vegetated buffer zones are effective at increasing infiltration and are likely to reduce overland water flow and reduce soil erosion and degradation, this means hypothesis 1 can be accepted. The wood buffer outperformed the grass buffer for saturated hydraulic conductivity and the mean weighted diameter of soil aggregates for treatment 2 slow wetting, therefore hypothesis 2 can be accepted.

5.4.1 Field Saturated Hydraulic Conductivity

All buffer types had significantly higher field saturated hydraulic conductivity than the crop area. This result shows that soils with a high vegetative cover promote better soil hydraulic conductivity than bare ground (the cropped area had been ploughed and set to fodder maize the month before the experiments were carried out. De Baets et al., 2011). These results are consistent with results from other studies examining soil hydraulic properties (De Baets et al., 2007, De Baets et al., 2011, Sandercock et al., 2017, Vannoppen et al., 2016). The reason is that vegetative cover protects the soil from rain-splash action and maintains its structure, so the soils do not slake and block the soil pores (Gyssels et al., 2005). Living and decayed roots create channels and pores within the soil and promote increased hydraulic conductivity (Gyssels et al., 2005, Gould et al., 2016). There are numerous studies looking at the impact of roots on saturated hydraulic conductivity (Chandler and Chappell, 2008, Chandler et al., 2018, De Baets et al., 2007, Sandercock et al., 2017, Vannoppen et al., 2017, Vannoppen et al., 2015). It is known that tap roots increase hydraulic conductivity compared to fibrous root systems in studies with herbaceous plants and this could correspond to the likely large root mass and volume of the wood and willow buffers relative to the grass buffers (De Baets et al., 2007, Vannoppen et al., 2017, Gould et al., 2016). There will be considerably more organic matter input from leaf litter in the wood and willow buffers which has been shown to enhance hydraulic conductivity (Chandler and Chappell, 2008).

The wood buffer had significantly higher saturated hydraulic conductivity than the grass buffer. The willow buffer also had higher saturated hydraulic conductivity but compared to the grass buffer there was no significant difference (P=0.09). These results are consistent with results from Chandler and Chappell (2008) that showed the influence of a large broad-leaved tree on the saturated hydraulic conductivity of a parkland habitat in contrast to the grassland area. In the study it was shown there was a very large zone of influence of the tree (up to 11 m) where the saturated hydraulic conductivity was significantly increased (Chandler and Chappell, 2008). The differences were explained by the greater volume and diameter of the roots compared to the grass areas. The higher soil organic matter of the wood and willow buffers could also explain the higher saturated hydraulic conductivity (Agnese et al., 2011).

Studies have shown that deeper root systems create more micropores and increase saturated hydraulic conductivity (Kumar et al., 2012). However, the trees in this experiment were planted in the spring of 2016 so were still small and there were large areas of natural regrowth vegetation. The willow buffer was planted at the same time and despite significantly more growth and a more complete canopy, the results were more variable and there were no significant differences between the willow buffer and the other buffers.

There is some evidence to suggest that natural regeneration of native vegetation could have contributed to the increased hydraulic conductivity of the wood buffers (Wang et al., 2012). In a study on the drylands of the Loess plateau in China, it was found that natural re-generation of herbaceous and shrub vegetation significantly increased the saturated hydraulic conductivity of the soil compared to planted grasses and tree communities (Wang et al., 2012). However, the conditions are different in this study and in contrast there are studies that suggest the intensity of the current or previous land use has a greater influence on the restoration of the saturated hydraulic conductivity (Lozano-Baez et al., 2019, Chandler et al., 2018, Kumar et al., 2012).

The difference in buffer vegetation establishment could have been the cause of some of the variation. The grass plots were created by herbicide application, harrowing and then reseeding while the wood and willow plots were created using an herbicide and then direct planting. The harrowing of the grass plots could cause the destruction of some of the soil structure thus reducing the saturated hydraulic conductivity (Kahle et al., 2013). However, the grass plots had significantly higher saturated hydraulic conductivity than the crop areas, so structure was restored from the harrowing, but had not increased to the rate of the other plots. This shows vegetation has a strong effect on improving the soil structure and increasing the saturated hydraulic conductivity.

5.4.2 Soil Aggregate Stability

All soils in this study under all treatments were classified as "stable" or "very stable" according to the international standard (ISO, 2012) showing that the soil had good structure partly due to the high clay content (LeBissonnais, 1996). All the buffer types had a higher mean weighted diameter than the crop area under treatment 1 (fast wetting), showing that the aggregates in the buffers were more resistant to the action of water and more resistant to slaking. The buffers all had more vegetative cover than the crop area. This protects the soil, provides a source of organic matter and suggests that there was a higher root presence within the soil (De Baets et al., 2011, Liu et al., 2005, Sandercock et al., 2017). Roots have a mechanical, biological and chemical effect on aggregate formation through enmeshing the soil, hydrophobic root exudates protecting aggregates from water stress and the stimulation of microbial activity (De Baets et al., 2011, Vannoppen et al., 2017, Vannoppen et al., 2015, Bardgett, 2017, Martin et al., 2012, Pérès et al., 2013).

There was a significant positive correlation between the mean weighted diameter (mm) of the soil aggregates after treatment 1 (fast wetting) and the field saturated hydraulic conductivity. These results reflect the findings of the study by Vannoppen et al. (2015) which looked at the erosion preventing ability of plant roots through increasing aggregate stability. They found that high aggregate stability prevents slaking of the soil and blocking of soil pores thus reduces hydraulic conductivity. As well as plant roots, the influence of recent tillage could influence the soil aggregate stability and then the saturated hydraulic conductivity (Kahle et al., 2013). Although there is evidence that tillage can have a positive effect on saturated hydraulic conductivity through loosening of the top layer of soil (Schluter et al., 2018), if the soil has undergone tillage this can cause a breakdown of the soil aggregates. If the soil remains bare, with little above or below ground vegetation, rain splash can then cause slaking of the soil and the reduction of saturated hydraulic conductivity (De Baets et al., 2011, LeBissonnais, 1996, Schluter et al., 2018).

The mean weighted diameter (mm) of the soil aggregates after treatment 2 (slow wetting) in the wood buffer was significantly higher than the grass buffer. These results are likely to be associated with the root traits of the wood species and the understory vegetation. The roots of broad-leaved tree species are associated with increased soil strength and are often used to increase the soil matrix strength for banks and dykes (Krzeminska et al., 2019). The influence of root mycorrhizal associations, root exudates and the leaf litter quality could all contribute to the increased stability against the stressor of slow wetting (Tang et al., 2011, Reid and Goss, 1981, Wu et al., 2014, Pérès et al., 2013). Even though the wood buffer had higher saturated hydraulic conductivity and a higher mean weighted diameter for treatment 2 (slow wetting), the wood buffer was immature, and differences may become more pronounced as the trees mature, the canopy closes and the root mass increase (Agnese et al., 2011, Niu et al., 2019).

5.4.3 Conclusion

The aim of this research was to investigate if there were differences in saturated hydraulic conductivity and soil aggregate stability (three treatments/stressors) between the different vegetated buffer zone treatments and the crop areas. This study showed that vegetated buffer zones have higher saturated hydraulic conductivity and more stable soil aggregates than the upslope cropped areas. This is due to the protection from the above ground vegetation and the stabilizing effects of the plant roots. The wood buffer consistently had higher hydraulic conductivity and better soil aggregate stability for treatment 2 than the grass buffer. All buffer types benefited the soil structure and soil hydrology of the field site. Further research is necessary to understand the soil processes within the buffers when the wood buffer has mature trees and after the willow buffer has been coppiced and regrown.

6.1 General Discussion

This thesis aimed to identify if vegetated buffer zones could be improved through increasing infiltration capacity, slowing overland water flow and improving sediment capturing ability using a plant functional trait approach. There were three main (chapters 2 to 4) which include microcosm experiments, a mesocosm experiment and a field experiment. The fourth experiment, presented in chapter 5, focuses on measurements of soil aggregate stability and saturated hydraulic conductivity for an existing, multi-year buffer project.

The study focused on sediment delivery through overland water flow because it was found to be a large proportion of diffuse pollution from agricultural land (Collins and Anthony, 2008). The study hypotheses (Table 6.1) focused on above and belowground plant traits and their ability to affect runoff coefficients, sediment concentrations in overland flow, soil hydraulic conductivity and soil aggregate stability. The main takeaways from the study were (Figure 6.1):

- Plant functional traits can affect the buffer services when tested in controlled conditions (pot/mesocosm), however these findings were not repeated when scaled into a field study (under one year's growth).
- Recent tillage, soil type and general environmental conditions had a stronger effect than plant traits on the performance of buffer services related to soil hydraulic and physical properties.
- Tillage affected the buffer services through soil aggregate breakdown and hence reduced hydraulic conductivity. Further research is needed to assess the timescale from tillage that plant traits begin to influence the soil physical and hydraulic structures.
- Root traits do influence soil aggregate stability with high SRL and low average root diameter positively influencing the mean weighted diameter (mm) of soil aggregates however not equally or in every circumstance. In the mesocosm study (Chapter 3) and the field study (Chapter 5) Treatment 2 (slow wetting) was affected by root traits, however Treatment 1 was unaffected by the root traits these findings are different to other studies and shows that root effects on soil aggregate stability is highly dependent on soil type and environmental conditions and time.

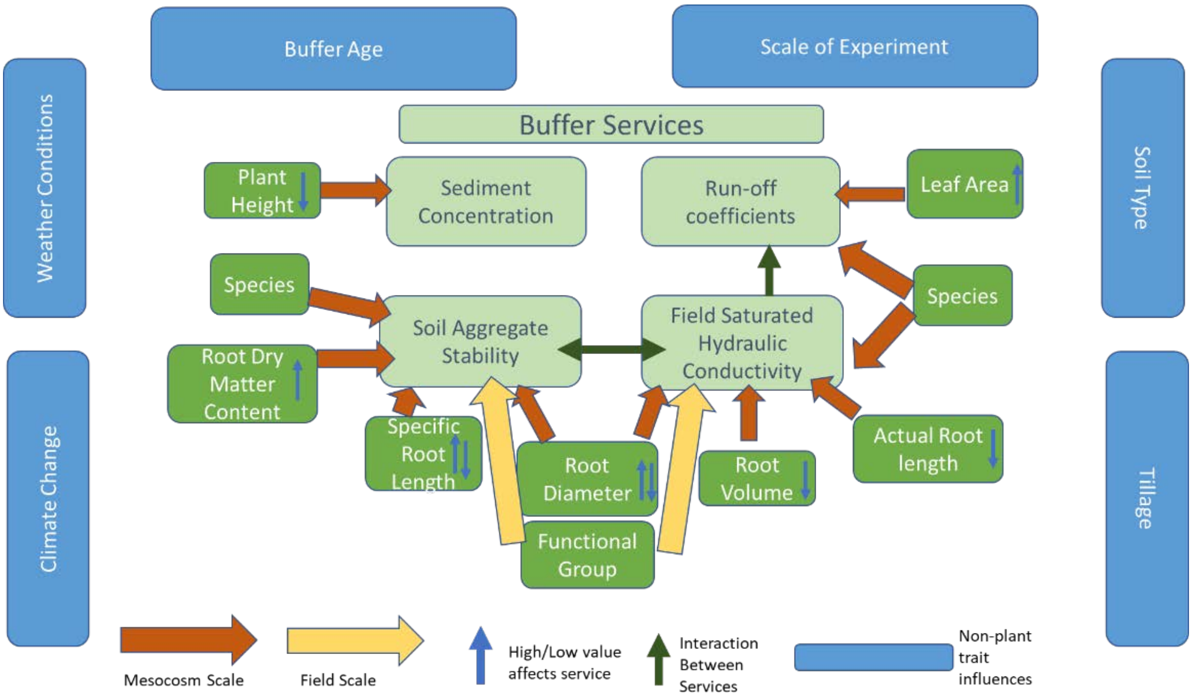


Figure 6.1 Conceptual Model: How plant functional traits and other influences affect buffer zone services across three different experiments and two different scales (Field and Mesocosm)

Table 6.1 Study Hypotheses across the different scales

Hypotheses	**Scale-Pot**	**Scale-mesocosm**	**Scale-Field**
Plant functional traits will vary across species and functional groups and at different plant growth stages.	Accept	Accept	Reject
Plant functional traits will affect the delivery of sediment across the vegetated buffer zone.	Not Measured	Accept	Reject
Plant functional traits will affect the velocity of overland water flow across the buffer zone.	Not Measured	Accept	Reject
Plant functional traits will affect the hydraulic and physical properties of the buffer zone soils.	Not Measured	Accept	Partially accept
There will be a significant difference between species and functional groups for the measured overland flow, sediment delivery and soil physical and hydraulic properties.	Not Measured	Accept	Partially accept

The first experiment, presented in chapter 2 (microcosm experiment), examined the functional traits of five common grassland species (*Lolium perenne, Dactylis glomerate***,** *Schedonorus arundnaceus*, *Plantago lanceolata*, *Trifolium repens*) at three growth stages (established, mature, degenerate). These species were chosen due to their abundance in agricultural areas, their ability to be competitive in a high nutrient and highly disturbed environment. Various above and belowground plant traits were measured and analysed against a conceptual model of a vegetated buffer zone.

The second experiment, in chapter 3, used the same five species grown in mono-culture mesocosms and subjected them to a 30-minute, lab based overland flow experiment at two different growth stages (mature, degenerate). Measurements for runoff and sediment mass were combined with plant trait measurements to examine the plant trait drivers of the runoff process and compare it with the model in chapter 2. Post runoff measurements included saturated hydraulic conductivity, three measures of soil aggregate stability and dry bulk soil density. These measurements were used to investigate the influence below ground traits had on soil physical and hydrological processes.

The third experiment in chapter 4 again used the same five species to look at the effect of single grass species, mixes of grass species and mixes of grass, legume and forb species in the field when subjected to simulated overland flow. Measurements included time to runoff, peak flow and sediment concentration in outflow. Post-run-on experiments were dry bulk soil density and saturated hydraulic conductivity. Differences between treatments, number of species and number of functional groups were explored as well as above and belowground plant traits.

The final experiment, presented in chapter 5, was a field experiment in established buffers containing a novel grass species, willow cultivars and broad-leaved tree species. Soil aggregate stability and saturated hydraulic conductivity measurements were taken from the buffers (3 buffer repeats, 5 samples for each buffer) and the crop areas. Differences between buffer types, between the buffers and the crop area and correlations between soil aggregate stability and saturated hydraulic conductivity measures were investigated.

The overall findings show that there were a variety of species and functional traits that influence the buffer processes and these traits vary amongst and within functional groups. There were some significant correlations between specific functional traits and sediment capture, slowing the water flow, saturated hydraulic conductivity and soil aggregate stability in the mesocosm experiment. However, these findings did not translate to the field experiment where it seemed that the heterogeneity of the landscape and other environmental factors reduced the differences between the species traits. Conversely, in chapter 5, there were significant differences between the buffer types for the soil physical and hydraulic processes.

6.1.1 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity is an important part of overland flow management (Morgan, 2005, Chandler et al., 2018). When water flow exceeds the hydraulic conductivity of the soil this causes runoff increasing the risk of soil erosion (Morgan, 2005). Overland water flow increases sediment, nutrient and pesticide pollution in surface water bodies (Rickson, 2014). This thesis examined ways in which plant functional traits can be used to increase rate of saturated hydraulic conductivity in vegetated buffer zones.

There were species and trait associations with saturated hydraulic conductivity echoing work by Gould et al. (2016) and De Baets et al. (2011). Large average root diameter increased the saturated hydraulic conductivity in the mesocosm experiments in chapter 3. Conversely, a high specific root length reduced saturated hydraulic conductivity as did large root volume and large actual root length. The large root diameter in this study were associated with the forbs while high specific root length is a common trait of grass species that have fine, fibrous roots where the root mass is close to the surface of the soil this restricts water flow and reduces saturated hydraulic conductivity (Gould et al., 2016). It has been suggested that species with high specific root length have a high turnover of roots which leave channels and increase soil organic matter which increase saturated hydraulic conductivity (Bardgett et al., 2014, De Baets et al., 2007) , however this does not appear to be the case in this study. The mesocosm study demonstrated that root traits do have an influence on saturated hydraulic conductivity, however, these differences were not seen in the field plot experiment in chapter 4.

The differences between the results for mesocosm and field plots were probably due to differences in soil type, the heterogeneity of the landscape and possibly the environmental conditions that had a stronger influence on the soil hydraulic conductivity than the plant traits (De Baets et al., 2007, Vannoppen et al., 2017, Vannoppen et al., 2015, Bardgett et al., 2014). In chapter 4 the field plots showed no plant trait differences either, therefore it is possible that a longer growing time would change the saturated hydraulic conductivity rates (Dosskey et al., 2007, Schmitt et al., 1999). Further growing time could enable the different species and trait affects to become more pronounced through differences in root turnover creating pore space in the soil and subsequently altering the saturated hydraulic conductivity rates (Bardgett et al., 2014). The previous land management could have also impacted the hydraulic conductivity as the plots were at the edge of an arable field and were ploughed before the experiment and then left with little vegetative cover while the vegetation developed over the winter months.

The field study in chapter 5 highlighted how the difference in functional groups can affect the hydraulic conductivity of soil and confirmed the effect on soil aggregate breakdown and lack of vegetation cover on saturated hydraulic conductivity rates within the same field. In this study the wood buffer had the highest saturated hydraulic conductivity rate even though the trees were relatively immature. There was little difference between the wood and willow buffer, but the willow buffers were further developed and had a more complete canopy, therefore it raises the question regarding how the wood buffer will differ in future when it has reached maturity.

There was a positive correlation between saturated hydraulic conductivity and the mean weighted diameter of the aggregates for treatment 1 (mm, soil aggregate stability, fast wetting) this result highlights the importance of soil aggregate stability on saturated hydraulic conductivity and potential infiltration excess overland flow (Vannoppen et al., 2015). Bare ground subject to rain splash damage causes slaking, blocking soil pores and reducing saturated hydraulic conductivity (Boardman, 2013). All the buffer types had a higher saturated hydraulic conductivity rate than the recently ploughed crop area that had low vegetation cover. This result was expected and showed the importance of vegetative cover and tillage on soil structure and hydraulic conductivity and helps to explain the results in chapter 4.

6.1.2 Soil Aggregate Stability

This study shows that different species and different plant functional traits affect soil aggregate stability differently. In chapter 3 we saw that there were not only species differences for the different treatments designed to look at different stressors, but also specific trait values correlated with aggregate stability. In chapter 2 the trait value positively correlated with soil aggregate stability (treatment 2 Slow wetting) was specific root length while average root diameter was negatively correlated with treatment 2. This is the opposite to the correlations for soil hydraulic conductivity and shows that the picture was not necessarily straightforward for the trait types preferred for enhancing vegetated buffer zones. The roots with high specific root length and low average root diameter were advantageous for increasing the mean weighted diameter of the aggregates but inhibited the saturated hydraulic conductivity rate which shows there are trade-offs and no one size fits all approach.

The more conclusive results for species differences were in the degenerate growth stage (chapter 3) where there was a significant difference for all three soil aggregate treatments. *Plantago* had the highest mean weighted diameter for each treatment. *Plantago* has a relatively high specific root length indicating that it produces a large amount of root exudates which are good at forming and protecting soil aggregates (Gould et al., 2016, Bardgett et al., 2014). It is also worth noting that it has been shown by De Baets et al. (2007) and Vannoppen et al. (2015) that tap roots are effective at reducing erosion in sandy soils and this could be a contributing factor to that process. These results begin to explore the trade-offs between root traits and the way in which they can affect the soil.

The field experiment in chapter 5 confirmed the importance of tillage and vegetation cover for soil aggregate stability as all buffer types had higher soil aggregate stability than the recently ploughed and sparsely vegetated crop area. Vegetation cover protects the soil from rain splash damage while leaf/plant litter and root exudates increase soil organic matter with a positive effect on soil aggregate stability (Le Bissonnais et al., 2018, Morgan, 2005, Boardman et al., 2006). The grass buffers had significantly lower mean weighted diameter for treatment 2 (slow wetting) than the wood buffer and there were no significant differences between the buffers for the other treatments. The wood buffer could have influenced the soil aggregate stability through organic matter input through leaf litter or possibly through root volume (Wu et al., 2014, Liu et al., 2005, Pérès et al., 2013). Furthermore, this result could have been impacted by the method of buffer creation as the grass buffers were harrowed before seeding while the willow and wood buffer just had herbicide application, were then directly planted and had a natural re-growth understorey.

6.1.3 Surface Runoff

There were clear and significant differences between species and traits and the runoff coefficients in chapter 3. Runoff coefficients and dried sediment mass in the outflow were positively correlated with sward height. The runoff coefficients were also correlated with some root traits and in turn with the saturated hydraulic conductivity. There were some differences across growth stages with less influence of root traits in the degenerate growth stage.

In the mesocosm experiment in chapter 3 the main traits that affected the runoff coefficient and the amount of dried sediment mass in the outflow was the height of the sward. Showing that high vegetation density at the height of (this shallow runoff) was key to increasing sedimentation and slowing the overland water flow. The stems and leaves of the vegetation increase hydraulic roughness and provided a hydraulic brake that slowed the flow and allowed sedimentation (Kervroedan et al., 2018, 2019). These results are consistent with other studies looking at overland flow in vegetated buffer zones (Kervroedan et al., 2019, Fu et al., 2019a, Pan et al., 2010, Pan et al., 2017).

The two species that influenced the runoff coefficients consistently across the experiments were *Plantago* and *Dactylis.* Although, runoff coefficients did not correlate with any of the measured stem traits (stem specific density, modulus of elasticity, yield strength, moment of inertia) the density or shape of the stem were likely to be the reason that they increased the hydraulic roughness and slowed the water flow (Fu et al., 2019a, Kervroedan et al., 2018). The aboveground biomass showed no correlation with runoff coefficients or sediment mass or sediment concentration in the mesocosm or field experiment. Showing that biomass itself was less important to reducing runoff than the density and architecture of the vegetation.

In the field plot study, the different treatments showed no significant differences between runoff coefficients, time to runoff or sediment concentration. The traits that had helped to reduce runoff in the mesocosm experiment did not affect the field experiment probably due to the heterogeneity of the slope and soil surface in the field and the effect of the environmental conditions on the plant traits. There was no significant difference between the root density of any of the treatments in the field. Root traits and root volume influenced the saturated hydraulic conductivity in the mesocosm experiment. Saturated hydraulic conductivity is a key process that reduces the runoff coefficients and sediment transfer through vegetated buffer zones Therefore, this could explain the lack of differences between the treatments for runoff coefficients and sediment concentration.

6.2 Vegetated Buffer Zones and Climate Change

Climate change is predicted to bring changing weather patterns, and, in the UK, it could result in draughts and extreme rain events (IUCN 2018). Long dry spells followed by heavy and prolonged rainstorms can cause soil erosion through reduced hydraulic conductivity and rain splash detachment of soil particles this increase the chance of soil erosion and overland water flow (Quinton et al., 2001)

Extreme weather events along with increased pressure on agricultural land to produce more food in a changing market with political uncertainty (DEFRA, 2018, Agriculture Act 2020) will increase the risk of agricultural diffuse pollution from sediments.

Vegetated buffer zone already form part of diffuse pollution prevention in arable landscapes are increasing in pastoral landscapes with fencing of water courses etc (Collins et al.,2016). In a study by Collins et al. (2016) there was evidence that farmers used vegetated buffer zones as part of their pollution prevention systems and were positive about increasing their use on their land. Along with reducing diffuse pollution vegetated buffer zones can increase soil carbon on agricultural land and meet targets set out by the government in their 25-year plan for the environment (DEFRA, 2018).

From this study the evidence suggests that reducing tillage in the creation of vegetated buffer zones will enable them to perform better when they are first established. Therefore, it seems that also reducing compaction and disturbance on vegetated buffer zone will be of benefit for the buffer services.

Using an appropriate mixture of herbaceous species on grassed buffer zones to ensure there is a diversity of above and belowground traits will enable the variety of traits to encourage sedimentation and reduce water velocity by increasing hydraulic roughness. Having a variety of root traits that will increase organic matter, create and maintain soil pores and increase hydraulic conductivity. Planting trees and allowing understory vegetation to develop naturally will have benefits for reduce pollution prevention and the increase of carbon storage on agricultural land.

6.3 Further Work

Further work should focus on including more species and further trait tests to increase knowledge for a variety of plants and enabled more processes to be investigated. Considering root exudates, plant nutrient use and decomposition would have given greater insight about the species and explain further the effect they have on the belowground buffer processes especially soil aggregate stability, saturated hydraulic conductivity and the effect of soil carbon and soil organic matter. A long-term study to assess how long it takes after tillage, for soil aggregate stability to recover under different planting regimes and different soil types would inform vegetated buffer zone creation and planting techniques.

An additional understanding of the aboveground traits will be beneficial to differentiate between the specific plant trait effects on overland flow and the general ground cover because despite numerous stem and leaf trait measurements there was difficulty in understanding which were associated with reduced flow. Examining how planting density and basal soil cover influence the overland flow and sediment delivery could expand this understanding further. This work could also include isolating above or belowground traits to separate how they interact with the run-on simulations.

Using larger plots for the field study as well as allowing the plots to grow for more than one season would have possibly produced clearer results and been closer to natural conditions. This work could include the use of different flow volumes with multiple run-on events and a wider variety of species and functional group types. Additionally, understanding the differences in traits between the broad-leaved trees and the willow cultivars and assessing if these differences effect the above and belowground processes in the vegetated buffer zone could inform buffer zone planting regimes more effectively.

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Appendix 1 Glossary of Terms

Plant Functional Traits- characteristics of the plant including the phonological, morphological and physiological characteristics

Specific leaf Area- The ration of area to dry mater of a plant leaf

Leaf Dry Matter Content- The dry, non-water content of plant leaves

Specific Root Length- The ratio of root length to root dry matter

Root Dry Matter Content- The dry non-water content of plant roots

Average Root Diameter- The average diameter of a set of measured roots

Modulus of elasticity- A measure of a stiffness of an object

Moment of inertia- The force it takes to stop an objects rotation around the axis

Angle at bending point- The angle when the object will no longer return to it's original form

Yield strength- The amount of weight it takes to stop the object returning to it's original form

Tillers- The way that grass grows using vegetative spread

Vegetated Buffer Zones (VBZ)- are areas of non-cropped land adjacent to agricultural or pastoral fields situated between the fields and watercourses or pathways to watercourses

Runoff coefficient- The percentage of water leaving the mesocosm/field plot during the run-on simulation