CRANFIELD UNIVERSITY

Corina Lees

Controlling soil erosion in a changing climate: evaluating suitable plant species in grassed waterway design

SCHOOL OF WATER, ENERGY, ENVIRONMENT AND AGRIFOOD

PhD
Academic Year: 2017 - 2022

Supervisor: Dr Robert Simmons
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD

ABSTRACT

Soil erosion is a global problem which needs mitigating due to the on-site and off-site impacts it causes. Soil erosion is set to become an even greater problem due to climate change. Climate change is likely to increase the intensity, frequency and duration of precipitation events. This change in precipitation will increase flow erosivity and thus increase the chance of soil detachment. Grass-based erosion mitigation features will have to be able to withstand a higher volume of water as runoff volumes will increase due to climate change. An increased surface runoff rate will increase sediment transport capacity leading to more soil erosion when coupled with an increased detachment rate therefore solutions for the future need to be researched.

Grass-based erosion mitigation features such as swales, buffer strips and grassed water ways (GWWs) have been shown to be effective. In this study, *Festulolium Bx511* (F2), *Festulolium cv Prior* (F1) and a mixture of *Festuca rubra* and *Lolium perenne* (C) were used in mixtures and monocultures to investigate their efficacy in mitigating erosion.

Experiment 1 used growth rooms under different climatic conditions, a summer scenario (22°C) and an autumn scenario (15°C). There were also different rainfall scenarios, drought (No rainfall), normal (100 % rainfall based on average rainfall (1981 – 2010) average rainfall (1981 – 2010) data from the Met Office) and excess (200 % of average rainfall (1981 – 2010) based on data from the Met Office) to see how they would affect the plant traits needed for erosion control. For summer establishment conditions the normal rainfall value was 49.2 mm, and the excess rainfall was 98.4 mm. For autumn establishment conditions the normal rainfall was 81.9 mm, and the excess value was 163.8 mm. A plant trait ranking system was devised, the species which showed promise were taken forward and used within hydraulic flume experiments to assess actual soil erosion mitigation potential.

Plant traits linked to erosion control include both above ground (% cover, plant height, number of stems, number of tillers, stem diameter (mm), stem area

density (mm^2 mm^{-2}), above ground biomass (g) and below ground traits (root total length (cm), root total surface area (cm^2), root diameter (mm) and total root length (cm) of ≤0.25 mm diameter. Climate change is likely to change how grass plant traits are manifest due to the differing climatic conditions. Therefore, any solutions currently promoted that utilise grass monocultures and mixtures for erosion mitigation features such as GWWs may need to be revised to mitigate for climate change. Conclusions from Experiment 1 include that species selection for soil erosion control features such as GWWs must consider potential rainfall and temperature conditions during the grass establishment for optimal erosion control. There were, however, two species combinations which could be considered as year-round candidates, Fest_1+Fest_2+C and C.

Experiment 2 was a hydraulic flume experiment where the inflow rates used were 0.2 – 1.4 l s^{-1}. Significant differences in the following plant traits; number of stems, number of tillers, stem diameter (mm), stem area density (mm^2 mm^{-2}), total root length (≤0.25 mm ⌀), total root surface area (cm^2), and root diameter (mm) were observed between different treatments. Conv had a significantly higher number of stems as compared to all other experimental treatments. Fest_1 had a significantly higher number of tillers, stem diameter and stem area density as compared to all other treatments. Fest_1+Fest_2+C had a significantly higher total root length (≤0.25 mm ⌀) as compared to Conv. Fest_1+2 had a significantly higher total root surface area than the Fest_1 and Fest_1+Fest_2+C experimental treatments. Fest_1+Fest_2 had a significantly higher root diameter as compared to the Fest_1+Fest_2+C experimental treatment. However, significant differences did not manifest in sediment concentration. In conclusion, it did not matter if grass species monocultures or mixtures were used as there were no significant differences in sediment concentration between the experimental grass treatments.

Experiment 3 was also a hydraulic flume experiment where the inflow rates used were 0.2 – 2.6 l s^{-1}. In this experiment there was a lowered seeding rate (L) and a recommended seeding rate used (N). There were significant differences in plant traits and also in sediment concentration. The critical thresholds for the

Environment Agency (EA) major event classification of 1000 mg l^{-1} to be reached were determined for Experiment 3. There were several experimental grass treatments which did not breach the limit set out by the EA (Conv N, Fest_1+2 L, Fest_1 N and Conv L). In conclusion the Conv L, Fest_1 N and Fest_1+2 L species treatments should be recommended for farmers for use in soil erosion mitigation features such as grassed waterways.

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Keywords: *Festulolium*: *Festulolium Bx511*; *Festulolium cv Prior*; *Festuca rubra*; Grassed water way; *Lolium perenne;* Plant traits; Soil erosion mitigation.

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I am dedicating this thesis to Peter Lees who encouraged me to pursue my dreams. May he rest in peace.

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LIST OF ABBREVIATIONS

AGBM	Above ground biomass
BGBM	Below ground biomass
Conv	Conventional mixture of *Lolium perenne* and *Festuca rubra*
DW	Dry Weight
EA	Environment Agency
Fest_1	*Festulolium cv Prior*
Fest_2	*Festulolium Bx511*
Fest_1+Fest_2	Mixture of *Festulolium cv Prior* and *Festulolium Bx511*
Fest_1+2+Conv	Mixture of *Festulolium cv Prior*, *Festulolium Bx511* and Conventional mixture.
FW	Fresh Weight
g	Acceleration due to gravity
GWW	Grassed Waterway
Ha	Hectare
KE	Kinetic Energy
L	Lowered seeding rate of 60%
N	Recommended seeding rate
pw	Water density
r	Hydraulic Radius
s	Slope angle
SAD	Stem Area Density
S.E.	Standard Error
t	tonnes
yr	Year

1 Introduction and Literature Review

Abstract

Soil erosion is a global problem which has both on-site impacts (loss of soil from agricultural land) and off-site impacts (enrichment of water bodies with nutrients leading to eutrophication and costs associated with sediment loading). Soil erosion is set to become an even greater problem due to climate change. Climate change is likely to increase the intensity, frequency, and duration of precipitation events as well as increase temperatures. These changes in precipitation are likely to increase flow erosivity causing an increased soil detachment rate and increase runoff volume resulting in more soil erosion occurring. Grass-based erosion mitigation features such as bunds, swales, grass buffer strips and grassed water ways (GWWs) exist and have been shown to reduce run-off and sediment loading. These rely on grass plant traits to be effective at reducing soil erosion as they increase surface roughness (Hewlett et al., 1987), imparting a frictional component to flow and decrease the flow velocity (Gavrić et al., 2019) as well as increase soil shear strength (Ali & Osman 2008). Specific plant traits include both above ground (% cover, sward height (cm), number of stems, number of tillers, stem diameter (mm), stem area density (mm^2 mm^{-2}) and below ground traits (root total length, root total surface area (cm^2), root diameter (mm) and root length (cm) of (≤0.25 mm ⌀) Climate change is likely to change how grass plant traits are manifest due to the differing climatic conditions, for example in periods of drought the plant height can decrease by as much as 52% (Deleglise et al., 2015) and above ground biomass (AGBM) can also decrease (Fariaszewska 2020). Therefore, any solutions currently promoted that utilise grass monocultures and mixtures for erosion mitigation features such as GWWs may need to be revised to mitigate for climate change. More research is needed to investigate how key plant traits associated with monocultures and mixtures of novel and conventional grass mixes are affected by climate change scenarios. This is because these plant traits will affect the flow velocity and flow shear stress which influence the erosivity of flow and the soil erosion potential of the grass species mixture or monoculture chosen.

1.1 Soil Erosion; A Global Challenge

Within the UK soil loss has been shown to range between 32 – 506 t ha^{-1} (Boardman et al., 2009). Quine and Walling (1991) also reported soil losses in the UK of 0.61 – 10.5 t ha^{-1} yr^{-1}. Further, Boardman (2013) also reports that erosion can be up to 3 t ha^{-1} yr^{-1} for a sandy loam soil with a vegetation cover of grass. However, soil erosion is a problem which is not limited to the UK, it is a global problem (Boardman 2009; Verheijen et al., 2009; Burylo et al., 2012; Boardman 2013; Pimentel & Burgess 2013; Kroese et al., 2020). Soil loss from agricultural land has been shown to be more than >20 t ha^{-1} yr^{-1} in France (Boardman et al., 2018). Finally, Wilkinson & McElroy (2007) report a soil erosion rate of 75 Gt y^{-1} in the USA. Silgram et al., (2010) found sediment loss ranged from 0.003 – 4. 8 t ha^{-1} and Mishra et al., (2022) found sediment loss ranged from 3.23-7.73 Mg ha^{-1} y^{-1}. Tolerable soil loss rates for either vegetated or unvegetated soils range from 0.3 – 1.4 t ha^{-1} which shows that the rates are being exceeded and therefore further research needs to be done in this area (Verheijen et al., 2009).

Soil erosion causes both on-site (Pimentel & Burgess 2013) and off-site impacts (Collins et al., 2007; Collins et al., 2009; Kroese et al., 2020; National Audit Office 2020), and it therefore needs to be researched and mitigated against as much as possible. The effects of soil erosion are particularly prevalent on agricultural land with ≥80% of agricultural land adversely affected by soil loss (Pimentel & Burgess 2013). A loss of soil on agricultural land results in a threat to future food security due to lowered soil fertility (Borreli et al., 2020). An already expanding population and lowered resource capital for agricultural land means that farms need to become more efficient at producing food. This will not be possible if soil erosion is allowed to continue at its current rate.

Soil erosion will also result in the degradation of nearby waterbodies due to increased nutrient and suspended sediment loads (National Audit Office 2020). An increased sediment loading and associated decrease in water quality has been reported by Collins et al., (2007), Collins et al., (2009) and Wilkinson & McElroy (2007). In the UK, up to 70% of waterbody sediment loads come from agricultural land (National Audit Office 2020). This percentage is similar to what is seen in Africa where 75% of sediment loads come from agricultural land (Kroese et al., 2020). Soil erosion may result in eutrophication and cause fish death which can devastate the whole freshwater ecosystem. Suspended sediment can be calculated using turbidity measurements whereby the clarity of water is assessed by the scattering of light (Kitchener et al., 2017) or by using a metric set out for the level of suspended solids in water bodies (Environment Agency 2016). In the UK there are classifications that the Environment Agency (2016) has set that show when a major event has occurred. Anything above 1000 mg l^{-1} is seen as a major event (Category 1) which will contribute to the devastation of freshwater ecosystems due to persistent or extensive effects (Environment Agency 2016). Within this classification persistent is an effect which is still ongoing 7 days from the event of contamination (Environment Agency 2016). Alternatives to using this classification could be to use the category 2 or category 3 events where the suspended solid concentrations of soil in waterbodies are above 500 mg l^{-1} and 250 mg l^{-1} respectively (Environment Agency 2016). Category 3 events are considered to have minimal effects on water quality (Environment Agency 2016). Therefore, any sediment concentrations which are higher than this should be avoided.

With climate change the EA limit of 1000 mg l^{-1} (2016) is likely to be breached more often. This is due to the increased frequency, intensity, and duration of predicted rainfall events (Baxter et al., 2013; Wright et al., 2015; Zuazo & Pleguezuelo 2008). Climate change, in terms of increased durations and intensities of rainfall, will result in a higher chance of soil erosion occurring due to both an increased flow erosivity and an increased surface runoff rate (Almeida et al., 2021). Further, with warmer wetter winters and hotter drier summer predicted (Met Office, 2018a), the effect of climate change on erosion rates will vary throughout the year. In the summer when it is drier it is likely to result in an increased soil loss due to low soil moisture content (Baruti 2004) and in the winter when it is wetter this may result in a reduction in soil shear strength due to too high soil moisture contents (Byran 2000). Therefore, grass traits and their ability to prevent soil erosion needs to be researched in different seasonal scenarios.

1.2 Mitigation of Soil Erosion

1.2.1 Role of Vegetation

The role of vegetation in soil erosion mitigation is vital (Fiener & Auerswald 2006; Boardman 2013; Boger et al., 2018; Li & Pan 2018). Vegetation can mitigate against all soil erosion processes by contributing to surface roughness (Hewlett et al., 1987), reducing flow velocity (Gavrić et al., 2019) and increasing soil shear strength (Ali & Osman 2008). Bare soil will provide no frictional component to flow, neither will it provide enmeshment via root hairs, for example, nor will it be a barrier to slow down flow velocity (Gavrić et el., 2019) and reduce flow shear stress. Root traits will enhance the shear strength of the soil (Ali & Osman 2008). Studies such as Boardman (2013) reported an increase in erosion rates for bare soil (10 – 45 t ha^{-1}) as opposed to vegetated soil (0.1- 3 t ha^{-1}). For further information about the part vegetation plays in the mitigation of soil erosion, there is a conceptual diagram which describes the role of vegetation in controlling for soil erosion in more detail in chapter 2, Figure 2-1.

There are many ways in which vegetation can be used to mitigate soil erosion. These include bunds, buffer strips (Boger et al., 2018; Li & Pan 2018), swales (Leroy et al., 2016; Gavrić et al., 2019) and grassed water ways (GWWs) (Hewlett et al., 1987; Prosser et al., 1995; Fiener & Auerswald 2006) etc.

1.2.2 Grassed Water Ways

GWWs are one way in which vegetation can be used to mitigate soil erosion (Prosser at al., 1995; Mekonnen et al., 2014; Rickson 2014; Staton & Bosch 2015). Fiener & Auerswald (2005) found that a GWW reduced soil erosion by 77 – 97 %. GWWs are specifically designed and established where there are soil erosion problems present due to large volumes of overland water flow. Typical overland flow values are in the range of 0 – 20 mm (Smith et al., 2011; Zhu et al., 2022). In order to design and establish a GWW the location where erosion is evident will first need to be assessed. An example of how a GWW is established is one at the Scheyern Experimental Farm, for a period of 8.5 years natural vegetation growth with no maintenance was allowed to establish (Fiener &

Auerswald 2005). GWWs help to facilitate movement of water off land without there being erosion problems and can also reduce water runoff by between 10 – 90 % (Fiener & Auerswald). This reduction in runoff occurs due to the high infiltration capacity of GWWs. GWWs can be used to prevent erosion by scouring and detachment of soil in situ. GWWs can also act as a sediment trap which will reduce the offsite impacts of erosion. GWWs can also be used to alleviate off-site impacts that soil erosion can cause as they will result in less nitrogen and phosphorous contaminating nearby water bodies (Alewell 2020). GWWs are also effective at preventing and reducing soil erosion by way of depositing entrained sediment and preventing scouring as well as rill and gully formation. GWWs are usually situated on natural flow pathways in order to limit the damage of overland flow including the higher levels of shear stress which are expected at these points of convergence (Prosser et al., 1995). As GWWs are located on natural flow convergence pathways (Prosser et al., 1995) this would allow for the water to be slowed down through increased hydraulic retention times due to the frictional component that the vegetation above ground traits provide.

1.2.3 Specific Grass Traits that promote erosion mitigation

Specific above ground grass traits which influence soil erosion are above ground biomass (Morgan & Rickson 1995) number of stems (Morgan & Rickson 1995), number of tillers, stem diameter, stem area density (Morgan & Rickson 1995; De Baets et al., 2009), % emergence, plant height (Hewlett et al., 1987), % canopy cover and % ground cover (Morgan & Rickson 1995). Above ground traits such as % cover and above ground biomass will limit the effects of rainsplash on detachment as they facilitate the dissipation of the kinetic energy (KE) of the raindrops (Morgan & Rickson 1995). Therefore, less detachment will take place as the rain drop KE will not be enough to detach soil particles. Further, an increased stem area density (SAD) and number of stems will result in less soil erosion occurring by way of reducing detachment by overland flow (Morgan & Rickson 1995; De Baets et al., 2009). According to Morgan & Rickson (1995) the required stems per unit area in order to reduce soil erosion by overland flow is >10,000 stems per m^2. An increased number of stems per unit area will increase sediment trapping efficiency (Mekonnen et al., 2016). Above ground plant traits will impart a frictional component to water flow (Al-Hamdan et al., 2012), lowering flow velocity and/or flow shear stress resulting in a lowered flow erosivity.

If the flow velocity is reduced the flow erosivity will also be reduced meaning that the facilitation of sedimentation within soil erosion mitigation features will occur (Fiener & Auerswald 2006; Gavrić et al., 2019; Zhang et al., 2019). This is due to the fact that the flow has less energy so will be more likely to deposit soil particles and aggregates and less likely to detach them. A grass sward will decrease flow velocity due to the increased surface roughness (Hewlett et al., 1987). Flow velocity will influence whether or not soil erosion will take place, the higher the flow velocity the more likely it is that soil erosion will occur (Gavrić et al., 2019). The maximum permissible velocity for a sandy loam soil type is 0.53 - 0.6 m s^{-1} (FAO 1988; National Engineering Handbook 2007; Plainwater 2015). Details on the maximum permissible flow velocity that different grass species have are shown in Table 1-1. Grass species which have been investigated previously are Ryegrass (Ramos et al., 2016), Vetch (Ramos et al., 2016), tall fescue (New York Stormwater Management Design Manual 2015), red fescue (New York Stormwater Management Design Manual 2015) and Bermuda grass (National Engineering Handbook 2007). A gap in the knowledge is that the grass species *Festulolium cv Prior* and *Festulolium Bx511* have not had their maximum permissible flow velocities determined yet.

Specific below ground grass traits which influence soil erosion are root total surface area (De Baets et al., 2007; Vanoppen et al., 2015), root length, root diameter (Hai 2012; Mekonnen et al., 2016), and total root length (cm) of (≤0.25 mm ⌀) (Liang et al., 2017). Below ground plant traits are important as they provide mechanical reinforcement of the soil (Liang et al., 2017) and promote soil cohesion leading to an increased aggregate stability (De Baets et al., 2007; Vanoppen et al., 2015). Flow shear stress is used as a measure of the erosivity. Flow shear stress needs to overcome soil shear strength in order for soil erosion to occur and the shear strength of soil with roots in will be higher than that of soil which does not have roots in (Ali & Osman 2008). Root diameter has been shown to affect the shear strength of soil, as root diameter (Hai 2012) increases so does root tensile strength resulting in an increased shear strength of the soil. Flow shear stress will influence whether soil erosion will take place or not, the higher the shear stress the more likely it will be for soil erosion to occur as it will be more likely for the shear strength of the soil to be exceeded (Leonard & Richard (2004).

Many grass species will have all of the above plant traits, but they might not be expressed in a way which will allow for a reduction in soil erosion to occur, and some grass species will be suited to different environmental conditions as opposed to others. Therefore, it would be wise to consider mixtures as well as monocultures to ensure that erosion mitigation is optimised. Both Blanco-Canqui et al., (2004) and Berendse et al., (2015) have found that a higher species diversity yielded less sediment. Berendse et al., (2015) was investigating both grass species and dicot species whereas Blanco-Canqui et al., (2004) studied grass only. However, it should be noted that plants may behave differently when planted alongside others as Bingcheng et al., (2010) found when planting switchgrass and milkvetch together. Milkvetch had a greater root density near the soil surface when grown with switchgrass as opposed to when it was grown as a monoculture (Bingcheng et al., 2010). Therefore, altering the grasses capacity to mitigate soil erosion.

Seasonal variations in precipitation and temperature and other climatic conditions (Met Office 2018a; Met Office 2018b) will also affect grass growth and plant traits effecting grass species viability for soil erosion mitigation features (Lees et al., 2020). For example, drought has been shown to influence plant height by decreasing it as much as 52% (Deléglise et al., 2015) which effects the surface roughness (Manning's n value) imparted to water flow. This means that grasses grown for longer periods of time in drought conditions may be better suited for erosion control, at least in terms of plant height only, as lodging will be less likely to occur if plant height is shorter. However, other plant traits also have to be taken into consideration, Fariaszewska (2020) found that above ground biomass (AGBM) decreased for certain grass species following a period of drought meaning that if that was the only plant trait which effected soil erosion control would result in the grass species of *Festulolium*, *Lolium* and *Festuca* all being less effective at soil erosion mitigation. This would be due to there being a decreased frictional component imparted to flow (Hewlett et al., 1987). Sardans & Penuelas (2013) also reported that prolonged periods of drought would reduce plant growth in terms of AGBM as well as cover in the Mediterranean. Therefore, there would be less of a reduction in flow velocity and more chance of detachment entrainment and transport occurring. Further, there would be more chance of detachment via rainsplash due to there being less chance that raindrop KE will be dissipated (Morgan & Rickson 1995). Also, with climate change set to increase the frequency, duration and intensity of rainfall events (Baxter et al., 2013; Wright et al., 2015; Zuazo & Pleguezuelo 2008). According to IPCC (2013) mean precipitation rates can increase by as much as 50% by the year 2100. Soil erosion will increase as well as run-off rates due to increased intensity of rainfall events (Almeida et al., 2021). With these changing conditions leading to an increased chance of soil erosion research needs to be undertaken on how species plant traits which will influence soil erosion mitigation will change due to climate change.

Table 1-1: Vegetation type and either flow velocities or maximum permissible flow velocities.

Vegetation Type	Soil loss/Sediment Concentration	Flow velocity ($m\ s^{-1}$)	Maximum permissible flow velocity ($m\ s^{-1}$)
[1]Long natural grasses	NDA	NDA	1.83
[1]Short natural grasses	NDA	NDA	1.22
[1]Bunch Grasses	NDA	NDA	1.22
[2]Ryegrass residue	Average 0.47 $g\ l^{-1}$	Mean 0.063	NDA
[2]Vetch residue	Average 5.2 $g\ l^{-1}$	Mean 0.086	NDA
[2]Ryegrass below ground only	Average 6.66 $g\ l^{-1}$	Mean 0.108	NDA
[2]Vetch below ground only	Average 14.55 $g\ l^{-1}$	Mean 0.132	NDA
[3]Tall fescue	NDA	NDA	0-5 % 1.52 5-10 % 1.22 >10% 0.99
[3]Grass and legume mixture	NDA	NDA	0-5 % 1.22 <10 % 0.91
[3]*Red fescue*	NDA	NDA	0.7
[3]*Senices lespedoza*	NDA	NDA	0.7
[3]*Annual lespedoza*	NDA	NDA	0.7
[3]Reed Canarygrass	NDA	NDA	0-5% 1.52 5-10% 1.22 >10% 0.91

[4]Milligen (site)	NDA	NDA	7
[4]Booneg 1 (site)	NDA	NDA	8-9.5
[4]Booneg 2 (site)	NDA	NDA	8-9.5
[4]Booneg 3 (site)	NDA	NDA	8
[4]Booneg 4 (site)	NDA	NDA	8
[5]Bermudagrass on sandy silt	NDA	NDA	1.83
[5]Bermudagrass on silt clay	NDA	NDA	2.44
[5]Kentucky blue grass on sandy silt	NDA	NDA	1.52
[5]Kentucky blue grass on silt clay	NDA	NDA	2.13
[6]Plastic grass	0-8.65 %	11.5-14.6	NDA
[6]Plastic grass	0-10.5 %	21.4-24.8	NDA
[6]Plastic grass	0-12.2 %	23.9 -28.8	NDA
[6]Plastic grass	0-12.2 %	11.5-28.9	NDA
[6]Plastic grass	0-11.2 %	13.8-17.3	NDA
[6]Plastic grass	0-13 %	22.7-29.6	NDA
[6]Plastic grass	0-13 %	27-34.5	NDA
[6]Plastic grass	0-13 %	13.8-34.5	NDA

NDA (No data available)

[1]Plainwater 2015 [2]Ramos et al., 2016 [3]New York Stormwater Management Design Manual 2015 [4]Bijlard et al., 2016 [5]National Engineering Handbook 2007 [6]Pan et al., 2015

1.3 Thesis Outline

This thesis is written in the format of papers, an approved style for Cranfield University. The introduction, methods, results, and discussion sections are presented within each chapter. Due to similarity in the experimental approach, there is some unavoidable repetition of methods between chapters. The three experimental chapters (Chapters 2, 3 and 4) are three laboratory-based experiments. Chapter 2 is focused on finding out which plant species monocultures and mixtures can withstand different climatic conditions including drought and flooded conditions as well as determining a plant trait ranking system with regards to soil erosion mitigation. Chapter 3 is focused on a hydraulic flume experiment where grass was cut to two different sward heights 1.0 cm and 3.0 cm. This was to investigate whether different sward heights effected soil erosion mitigation potential. Chapter 4 is also a hydraulic flume experiment focused on finding the critical shear stress and flow velocities for the EA 1000 mg l^{-1} limit being reached for roots and shoots treatments as well as roots only treatments. Chapter 5 focused on applying and further evaluating the plant trait ranking system devised in Chapter 2 by using data generated from Chapters 3-4. It also looks at potential impacts of the plant trait ranking system on management practices. Chapter 6 is focused on the wider applications as an outcome of this thesis. Chapter 7 looks at the general conclusions as an outcome from this thesis.

The papers presented here are organised around the below research objectives and contributions of authors to each chapter are described in Table 1-2.

1.4 Knowledge Gaps

It is imperative that research is done into soil erosion mitigation features such as GWWs due to a number of factors. The first being that sediment concentrations are sometimes greater than the 1000 mg l^{-1} Environment Agency limit for a Class 1 event to occur, therefore any solutions for grass species mixtures or monocultures which have already been found are not viable. Although it is not a direct measure of soil erosion from a GWW, the output of overland flow from a GWW may end up within nearby waterbodies, thus the 1000 mg l^{-1} limit is helpful in determining which grass species to use. It also allows for an easy comparison of sediment concentrations associated with the experimental treatments within this study. Deletic (2005) and Wilson et al., (2011) found sediment concentrations to be between 300 – 750 mg l^{-1} and 690- 1700 mg l^{-1} respectively which is of a similar range to the 1000 mg l^{-1} limit. However, the knowledge gained from this study is only from a small mesocosm size (0.2 x 0.1 x 0.1 m) and the sediment concentrations observed may be less than what reaches waterbodies due to the ability for GWWs to trap sediment. Moreover, when overland flow reaches the river, sediment concentrations can be higher than 1000 mg l^{-1} as shown by Luo et al., (2020) who obtained a sediment concentration of 40,000 – 160,000 mg l^{-1} when using 10.0 x 1.0 x 0.5 m experimental soil plots. The *festulolium* varieties *cv Prior* and *Bx511* monocultures and mixtures have not had their critical flow velocities and shear stress determined in the context of this EA limit in the context of this EA limit. Therefore, this thesis aims to address this gap in knowledge. Further, climate change is likely to exacerbate soil erosion due to the increased intensity, frequency and duration of rainfall. There are also predicted changes in temperature due to climate change. Therefore, solutions need to be found for grass species mixtures of monocultures which will be able to withstand all these different climatic conditions and still retain the plant traits necessary for soil erosion mitigation. It is not yet known how *Festulolium cv Prior* and *Festulolium Bx511* will manifest plant traits in monocultures as opposed to mixtures. Nor is it known how these species will manifest plant traits within different climatic conditions. Therefore, *festulolium cv Prior* and *festulolium Bx511* were grown in monocultures and mixtures at different temperatures and under drought and flooded conditions to see if they will still exhibit the traits needed for erosion control. Therefore, this thesis also addresses this gap in knowledge. Another gap in knowledge is that it is unknown how roots and shoots vs roots only will affect species mixtures and monocultures viability at being used within a GWW. .

1.5 Research Aims & Objectives

The work presented in this thesis aimed to evaluate suitable grass species monocultures and mixtures to be used in GWW design in a changing climate. This aim was completed by the following objectives.

- 1. Develop a statistically robust method to rank grass species treatments by converting numerical physical plant trait data into comparative scores. Grass species can then be ranked by their ability to control for soil erosion by water.
- Evaluate how plant traits related to the control of soil erosion by water are affected by monocultures and mixtures as well as establishment season and rainfall scenarios.
- Assess how the most promising species mixtures and monocultures from Experiment 1 performed in terms of soil erosion control when subjected to concentrated flow events.
- Define when the critical shear stress and critical flow velocity for selected species mixtures and monocultures reaches the 1000 mg l^{-1} major incident limit set out by the EA.

- Assess the accuracy of the plant trait ranking system at predicting soil erosion.

Table 1-2: Disclosure and dissemination from the thesis

	Chapter 1	Chapter 2	Chapter 3	Chapter 4	Chapter 5	Chapter 6	Chapter 7
		Objective 1	Objective 2	Objective 3	Objective 4		
Publications		Published in the EJSS Special Issue: STARS: Innovations in Soil Science to Address Global Grand Challenges. https://doi.org/10.1111/ejss.13045	Will be submitted to Geoderma	Will be submitted to Geoderma	Will be submitted to Soil Use and Management		
Corina Lees	Structure and writing	Literature review, experimental design, structure, and writing	writing-original draft, conceptualization, methodology, validation, formal analysis, investigation	writing-original draft, conceptualization, methodology, validation, formal analysis, investigation	writing-original draft, conceptualization, methodology, validation, formal analysis, investigation	writing-original draft, conceptualization, methodology, validation, formal analysis, investigation	Discussion, structure, identification of contributions to knowledge and key conclusions, and writing
R.W Simmons	Guidance on structure, editing	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Guidance on structure, editing
R.J.R Rickson	Guidance on structure, editing	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Supervision, writing-review and editing, review of analysis	Guidance on structure, editing

1.6 References

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P. & Borrelli, P. (2020). Global phosphorus shortage will be aggravated by soil erosion. Nature *Communications*, 11, 4546.

Al-hamdan, O.Z., Pierson Jr, F.B., Nearing, M.A., Stone, J.J., Williams, C.J., Moffet, C.A., Kormos, P.R., Boll, J. & Weltz, M.A. (2012). Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modelling. *Earth surface processes and landforms*, 37, 157-168.

Ali, F.H. & Osman, N. 2008. Shear Strength of a Soil Containing Vegetation Roots. *Soils and Foundations*, 48 (4), 587-596. doi: 10.3208/sandf.48.587

Almeida, W.S., Seitz., Oliveira, L.F.C. & Carvalho, D.F. (2021). Duration and intensity of rainfall events with the same erosivity change sediment yield and runoff rates. *International Soil and Water Conservation Research*, 9 (1), 69-75.

Baxter, C., Rowan, J. S., McKenzie, B. M. & Neilson, R. (2013). Understanding soil erosion impacts in temperate agroecosystems: Bridging the gap between geomorphology and soil ecology. *Biogeosciences Discussions*, 10, 7491-7520.

Berendse, F., Ruijven, J., jongejans, E. & Keesstra, S. (2015). Loss of Plant Species Diversity Reduces Soil Erosion Resistance. *Ecosystems*, 18, 881-888.

Bijlard, R., Steendam, G.J., Verhagen, H.J. & Meer, J.V.D. 2016. Determining the critical velocity of grass sods for wave overtopping by a grass pulling device. *Coastal Engineering proceedings,* 1 (35). doi: https://doi.org/10.9753/icce.v35.structures.20.

Bingcheng, X., Feng-Min, L. & Lun, S. (2010). Seasonal root biomass and distribution of Switchgrass and Milk vetch intercropping under 2:1 row replacement in a semiarid region in Northwest China. *Communications in Soil Science and Plant Analysis*, 41 (16), 1959-1973.

Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H. & Alberts, E.E. (2004). Grass Barriers for Reduced Concentrated Flow Induced Soil and Nutrient Loss. *Soil Science Society of America Journal*, 68 (6), 1963-1972.

Boardman, J., Shepheard, M.L., Walker, E. & Foster, I.D.L. (2009). Soil erosion and risk-assessment for on- and off-farm impacts: A test case using the Midhurst area, West Sussex, UK. *Journal of Environmental Management*, 90 (8), 2578-2588. doi: 10.1016/j.jenvman.2009.01.018

Boardman, J. (2013). Soil Erosion in Britain: Updating the Record. *Agriculture*, 3, 418-442. doi: 10.3390/agriculture3030418

Boardman, J., Vandaele, K., Evans, R. & Foster, I.D.L. (2018). Off- site impacts of soil erosion and runoff: Why connectivity is more important than erosion rates. *Soil Use and Management*, 35 (2), 245-256. doi: 10.1111/sum.12496

Boger, A. R., Ahiablame, L., Mosase, E. & Beck, D. (2018). Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. *Environmental Science: Water Research & Technology*, 4, 478-486.

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L. & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences of the United States of America*, 117 (36), 21994-22001. doi: 10.1073/pnas.2001403117

Burylo, M., Rey, F., Mathys, N. & Dutoit, T. (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms*, 37, 1463-1470.

Collins, A.L. & Walling, D.E. (2007). Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes*, 1448-1459. doi: 10.1002/hyp.6269

Collins, A.L. & Anthony, S.G., Hawley, J. & Turner, T. (2009). The potential impact of projected change in farming by 2015 on the importance of the agricultural sector as a sediment source in England and Wales. *Catena*, 79, 243-250. doi: 10.1016/j.catena.2009.05.007

De Baets, S., Poesen, J., Knapen, A. & Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms,* 32 (9), 1323-1345.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34 (10), 1374-1392

Deléglise, C., Meisser, M., Mosimann, E., Spiegelberger, T., Signarbieux, C., Jeangros, B. & Buttler, A. (2015). Drought-induced shifts in plants traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. *Agriculture, Ecosystems & Environment*, 213, 94-104.

Deletic, A. (2005). Sediment transport in urban runoff over grassed areas. *Journal of Hydrology*, 301, 108-122. doi: 10.1016/j.jhydrol.2004.06.023

Environment Agency, 2016. *Incidents and their classification: the Common Incident Classification Scheme (CICS)*. Environment Agency. pp 38-39.

FAO, 1988. *Watershed management field manual - Slope treatment measures and practices".* FAO technical paper 13/3, FAO, Roam.

Fariaszewska, A., Aper, J., Van Huylenbroeck, J., De Swaef, T., Baert, J. & Pecio, L. (2020). Physiological and biochemical responses of forage grass varieties to mild drought stress under field conditions. *International Journal of Plant Production*, 14, 335-353.

Fiener, P. & Auerswald, K. (2006). Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research*, 87 (1), 48-58.

Gavrić, S., Leonhardt, G., Marsalek, J. & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment*, 669, 431-447.

Govers, G. (1990). *Empirical relationships for the transport capacity of overland flow*. Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987), 189, 45-63.

Grabowski, R.C., Droppo, I.G. & Wharton, G. (2011). Erodibility of cohesive sediment: The importance of sediment properties. *Earth-Science Reviews*, 105 (3-4), 101-120. doi: 10.1016/j.earscirev.2011.01.008

Hai, T.L. (2012). *Root characteristics of some grass species on the sea dikes in Viet Nam*. Communications on Hydraulic and Geotechnical Engineering. PhD Thesis. Delft University of Technology. Available from: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.875.4710&rep=rep1&type=pdf [Accessed on 20 January 2022]

Hewlett, H. W. M, Boorman, L. A. & Bramley, M. E (1987). *Guide to the design of reinforced grass waterways*. London, the United Kingdom: Construction Industry Research and Information Association (CIRIA).

Houlbrooke, D.J., Thom, E.R., Chapman, R. & McLay, C.D.A. (1997). A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. *New Zealand Journal of Agricultural Research*, 40, 429-435. doi: 10.1080/00288233.1997.9513265

IPCC (2013). *Summary for policymakers*. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, (108-112). Cambridge, England: Cambridge University Press.

Kitchener, B.G.G., Wainwright, J., Parsons, A.J. (2017). A review of the principles of turbidity measurement. *Progress in Physical Geography*, 41 (5), 620-642. doi: 10.1177/0309133317726540

Kroese, J.S., Batista, P.V.G., Jacobs, S.R., Breuer, L., Quinton, J.N. & Rufino, M.C. (2020). Agricultural land is the main source of stream sediments after conversion of an African montane forest. *Scientific Reports*, 10, 14827. doi: 10.1038/s41598-020-71924-9

Lees, C., De Baets, S., Rickson, R.J. & Simmons, R.W. (2020). Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study. *European Journal of Soil Science*, 72, 2381-2397.

Leonard, J. & Richard, G. (2004). Estimation of runoff critical shear stress for soil erosion from soil shear strength. *Catena*, 3, 233-249.

Leroy, M, Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I. & Marcotte, S. (2016). Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of The Total Environment*, 566-567, 113-121.

Li, C. & Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90-103.

Liang, T., Bengough, A.G., Knappett, J.A., MuirWood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & Meijer, G.J. (2017). Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. Ecological Engineering, 109B, 207-227.

Lick, W. & McNeil, J. (2001). Effects of sediment bulk properties on erosion rates. *Science of the Total Environment*, 266 (1-3), 41-48. doi: 10.1016/s0048-9697(00)00747-6

Luo, M, Pan, C. & Liu, C. (2020). Experiments on measuring and verifying sediment trapping capacity of grass strips. *CATENA*, 194, 104714. doi: 10.1016/j.catena.2020.104714

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L. & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755-763.

Met Office (2018a). Ross-on-Wye climate. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/public/weather/climate/gcnpm68t8

Met Office (2018b). Land projection maps: Probabilistic projections. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/land-projection-maps

Mishra, P.K., Rai, A., Abdelrahman, K., Rai, S.C. & Tiwari, A. (2022). Land Degradation, Overland Flow, Soil Erosion, and Nutrient Loss in the Eastern Himalayas, India. *Land*, 11 (2), 179. doi: 10.3390/land11020179

Montgomery, D. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences*, 104 (33), 13268-13272.

Morgan, R. P. C. & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach,* London: E & FN Spon.

National Audit Office (2010). *Tackling diffuse water pollution in England* (online), London: National Audit Office Retrieved from https://www.nao.org.uk/wp-content/uploads/2010/07/1011188.pdf

National Engineering Handbook. (2007). *United States Department of Agriculture*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail//?cid=nrcs141p2_024573 Part 654, Chapter 8.

New York stormwater management design manual, 2015. Available from: https://www.dec.ny.gov/chemical/29072.html. Appendix L.

Pan, C., Shangguan, Z. & Ma, L. (2015). Assessing the dye-tracer correction factor for documenting the mean velocity of sheet flow over smooth and grassed surfaces. *Hydrological processes*, 29 (26), 5369-5382. doi: https://doi.org/10.1002/hyp.10565

Pimentel, D. & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, 3 (3), 443– 463.

Plainwater, 2015. Shear Stress & Permissible Velocity. *New York State Stormwater Management Design Manual* (January, 2015). Available from: https://plainwater.com/water/shear-stress-permissible-velocity/

Prosser, I. P., Dietrich, W. E. & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology, 13 (1–4), 71– 86.

Quine, T. A. & Walling, D. E. (1991). Rates of soil erosion on arable fields in Britain: Quantitative data from Caesium 137 measurements. *Soil Use and Management*, 7 (4), 169-176.

Ramos, J.C., Bertol, I., Barbosa, F.T., Bertól, C., Mafra, A.L., Miquelluti, D.J. & Júnior, J.M. (2016). Water erosion in surface soil conditions: runoff velocity, concentration and D50 index of sediments in runoff. *Scientia Agricola*, 73 (3), 286-293. doi: https://doi.org/10.1590/0103-9016-2015-0110

Rickson, R.J. (2014). Can control of soil erosion mitigate water pollution by sediments? *Science of The Total Environment*, 468-469, 1187-1197. doi: 10.1016/j.scitotenv.2013.05.057

Sardans, J. & Penuelas, J. (2013). Plant-soil interactions in Mediterranean forest and shrublands: impacts of climatic change. *Plant Soil*, 365, 1-33. doi: 10.1007/s11104-013-1591-6

Shit, P.K., Pourghasemi, H.R. & Bhunia, G.S. (2020). Effects of Grass on Runoff and Gully Bed Erosion: Concentrated Flow Experiment. *In book: Gully Erosion Studies from India and Surrounding Regions,* pp 221-233.

Smith, M.W., Cox, N.J. & Bracken, L.J. (2011). Modeling depth distributions of overland flows. *Geomorphology*, 125 (3), 402-413.

Staton, M. & Bosch, B. (2015). *Grassed waterways can help maintain soil quality and productivity*. Michigan State University. Available from: https://www.canr.msu.edu/news/grassed_waterways_can_help_maintain_soil_quality_and_productivity [Accessed 3rd December 2021]

USDA. (2022). *Soil Bulk Density Moisture/Aeration*. USDA. Available from: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053260.pdf [Accessed on 1 March 2022].

Vannoppen, W., Vanmaercke, M., De Baets, S. & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666-678.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J. & Smith, C.J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, 94 (1-4), 23-38.

Wilkinson, B.H. & McElroy, B.J. (2007). The impact of humans on continental erosion and sedimentation. GSA Bulletin, 119 (1-2), 140-156. doi: 10.1130/B25899.1

Wilson, H.M, Cruse, R.M. & Burras, C.L. (2011), Perennial grass management impacts on runoff and sediment export from vegetated channels in pulse flow runoff events. *Biomass and Bioenergy*, 35 (1), 429 – 436. doi: 10.1016/j.biombioe.2010.08.059

Wright, A. J., Ebeling, A., Kroon, H., Roscher, C., Weigelt, A., Buchmann, N. & Eisenhauer, N. (2015). Flooding disturbances increase resource availability and productivity but reduce stability in diverse plant communities. *Nature Communications*, 6, 60-92.

Zhang, B., Zhang, G., Yang, H. & Zhu, P. (2019). Temporal variation in soil erosion resistance of steep slopes restored with different vegetation communities on the Chinese loess plateau. *Catena*, 182, 104170.

Zhu, Y., Zhang, Y., Yang, J., Nguyen, B.T. & Wang, Y. (2022). A novel method for calculating disturbed water depth and flow velocity of stormwater runoff during the heavy rainfall events. *Journal of Hydrology*, 612, Part A, 128064.

Zuazo, V. H. D. & Pleguezuelo, C. R. R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, 28 (1), 65-86.

2 Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study

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2.1 Abstract

Grassed waterways are used to mitigate the offsite transport of sediment generated by soil erosion. This study used a novel trait-based ranking approach as a method to screen potential candidate grass monocultures and mixes based on their theoretical performance in reducing (a) detachment via rainsplash, (b) detachment via scouring due to concentrated flow and (c) sediment transport and deposition processes. Selected grass species were grown under simulated UK summer and autumn establishment conditions under three different replicated rainfall scenarios: drought, normal rainfall and excess rainfall. The grass species used were the novel hybrid species *Festulolium cv Prior* (Fest_1) and *Festulolium Bx511* (Fest_2) and a conventional mixture of *Lolium perenne* and *Festuca rubra* (Conv). Monocultures and mixtures of these species were studied. Plant traits pertinent to control of soil erosion by water were measured. Aboveground traits included plant height, percentage ground cover, aboveground biomass, stem diameter, stem area density and number of tillers. Below ground traits included total root length, root total surface area, belowground biomass, root diameter and % fine roots ≤0.25 mm ⌀. For summer conditions, the species treatments that had the highest overall soil erosion mitigation potential were Conv, Fest_1 + 2 + Conv and Fest_2. For autumn conditions, the best treatments were Fest_1 + 2, Fest_1

+ 2 + Conv and Conv. The Fest 1 + 2 + Conv had more desirable traits for erosion control than mono Festulolium treatments for the autumn conditions. The conventional mixture had more desirable traits for erosion control than mono Festulolium treatments in both climate scenarios. The results indicate that the trait-based ranking approach utilised in this study can be used to inform rapid screening of candidate grass species for soil erosion control.

2.2 Highlights

• How to select the most suitable grass species for soil erosion control under changing climate conditions?

• A novel scoring system based on plant traits associated with soil erosion mitigation was developed.

• Fest_1 + 2 and Conv treatments expressed traits strongly associated with maximum soil erosion mitigation.

• Species selection for grassed waterways should consider the establishment growing season and expected rainfall.

2.3 Keywords

climate change, *Festuca rubra*, *Festulolium*, grassed waterways, *Lolium perenne*, plant traits, soil erosion mitigation

2.4 Introduction

2.4.1 Soil erosion and impact of climate change

Soil erosion is a global problem (Burylo, Rey, Mathys, & Dutoit, 2012) and 80% of the world's agricultural land has moderate–severe rates of erosion (Pimentel & Burgess, 2013). Agricultural diffuse pollution in the UK has negative effects on water quality and accounts for 70% of sediments found within water bodies (National Audit Office, 2010). Grass species are frequently used for erosion control in in-field structures such as grassed waterways (GWWs), swales (Boger et al., 2018; Leroy et al., 2016; Gavrić, Leonhardt, Marsalek, & Viklander, 2019) and vegetated strips (Boger et al., 2018; Li & Pan, 2018). GWWs are situated on natural flow pathways and are designed to withstand the high shear stresses imparted to soil by concentrated flow (Prosser, Dietrich, & Stevenson, 1995). By reducing the velocity and thus erosivity of flow, GWWs reduce particle detachment, entrainment and transport, and facilitate sedimentation within the GWW (Fiener & Auerswald, 2006; Zhang, Zhang, Yang, & Zhu, 2019). Climate change is predicted to increase the risk of soil erosion due to an increase in the magnitude, duration and frequency of extreme storm events (Baxter, Rowan, McKenzie, & Neilson, 2013; IPCC, 2013; Routschek, Schmidt, & Kreienkamp, 2014; Wright et al., 2015; Zuazo & Pleguezuelo, 2008). The UK is predicted to have warmer, wetter winters and hotter, drier summers (Met Office, 2018a). Therefore, grass species used in soil erosion control will have to tolerate higher temperatures, drought conditions and rainfall events of higher intensity, duration and frequency (IPCC, 2013).

2.4.2 Plant traits affecting soil erosion in GWWs

Figure 2-1 depicts the soil erosion processes operating in GWWs: detachment by rainsplash, detachment by overland flow, entrainment and transport in overland flow, and deposition (Morgan & Rickson, 1995). Detachment is the first phase of soil erosion and can occur by rainsplash or overland flow. Subsequently, detached soil particles can be entrained in overland flow. The entrained soil particles are transported downslope and deposited, when the flow transport capacity is no longer able to carry them (Govers, 1990). Figure 2-1 also illustrates how plant traits are expected to influence the soil erosion process. Vegetation traits affecting detachment by rainsplash are % ground cover and aboveground biomass as they facilitate dissipation of kinetic energy from rainfall (Morgan & Rickson, 1995). Aboveground traits affecting detachment by concentrated flow include stem area density (Morgan, 2007), where a stem density of >10,000 stems per m^2 reduces detachment by flow (De Baets et al., 2009; Morgan & Rickson, 1995). The % germination, and number and distribution of tillers will also influence the uniformness of the ground cover, with clumping of grass (Morgan, 2007) leading to convergence of erosive flow paths. Critical belowground plant traits that reduce detachment include the total length of the fine roots (≤0.25 mm

⌀) acting as mechanical reinforcement (Liang et al., 2017). Mean root diameter, total length of roots (Mekonnen, Keesstra, Ritsema, Stroosnijder, & Baartman, 2016) and total root surface area are also important as they influence both soil cohesion and aggregate stability (De Baets, Poesen, Knapen, & Galindo, 2007; Vannoppen, Vanmaercke, De Baets, & Poesen, 2015). By increasing surface roughness (Hewlett et al., 1987) and reducing flow velocities (Gavrić et al., 2019), a grass sward reduces entrainment and transport capacity and increases deposition of sediment. Decreasing flow velocities promotes sedimentation due to increased hydraulic retention (Gavrić et al., 2019), which is determined by stem area density (SAD), which is determined by number of stems and stem diameter per unit area. Mekonnen et al., (2016) found that SAD increased the sediment trapping efficiency of vegetation. Plant height influences the Manning's n coefficient, which expresses roughness imparted to the flow by the vegetation (Hewlett et al., 1987).

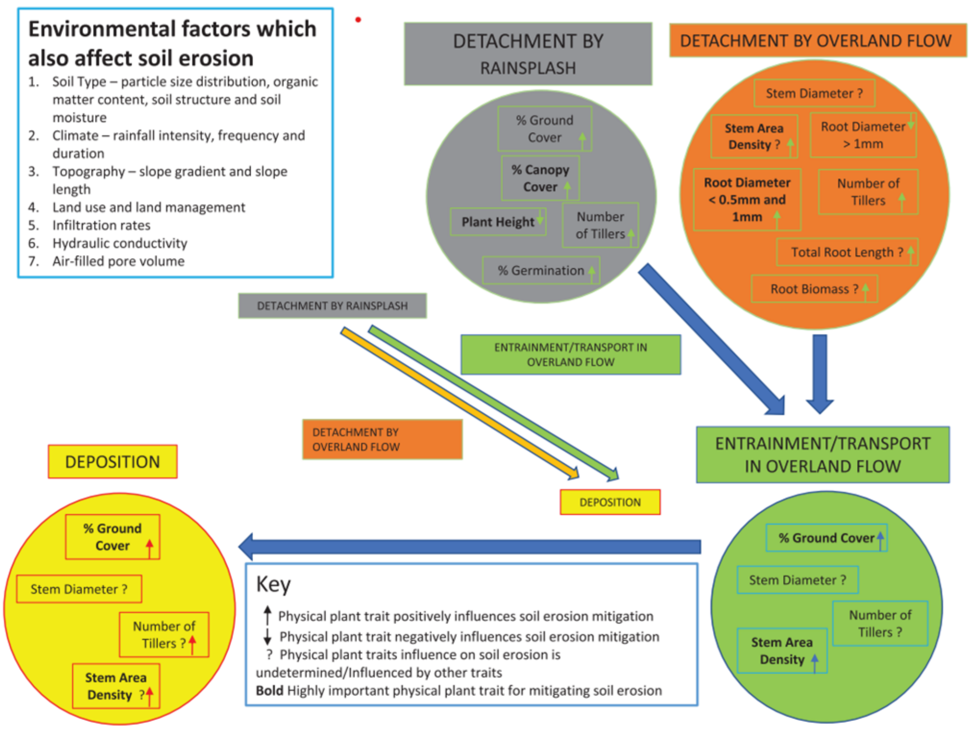

Figure 2-1 Soil erosion processes as affected by plant traits

Previous studies have tried to develop methods to select suitable species for erosion control (De Baets et al., 2009; Ghestem et al., 2014). These studies, however, have not justified the conversion of numerical plant trait data into selection criteria. A key objective of this study is to develop a statistically robust method to rank grass species treatments by converting numerical physical plant trait data into comparative scores. This is to allow ranking of the effectiveness of a grass species monoculture and mixtures in reducing soil erosion by water to be ranked. This can then inform the selection of suitable grasses for further laboratory or field-based studies. There is also a paucity of knowledge on the potential of the novel Festulolium Bx511 and Festulolium cv Prior grass species for erosion control, particularly in relation to climate change induced water stress. Furthermore, for the Festulolium varieties, little is known about the plant trait response when grown as a monoculture compared to when it is grown in a species mix. This study, through the use of a novel trait based ranking approach, evaluates the potential of novel grass species compared to conventional species for mitigating soil erosion by concentrated flow in GWWs, considering both their aboveground and belowground bioengineering traits. A further objective of this study is to evaluate how plant traits related to the control of soil erosion by water at an early establishment stage are affected by species diversity (monocultures and mixes), establishment season and rainfall scenarios. We hypothesize that plant diversity will improve the bioengineering traits for soil erosion mitigation. We also hypothesize that novel grass species exhibit higher trait-based ranking scores for future soil erosion mitigation than the conventional grass mix.

2.5 Methodology

2.5.1 Microcosm preparation

An erodible sandy loam topsoil (63% sand, 22% silt and 15% clay) from arable land near Ross-on-Wye (UK) was used to fill PVC microcosms (external diameter of 68.8 mm and a height of 180.0 mm). The soil Eardiston association, known to be at high risk of water erosion (Evans, 1990; Hollis & Hodgson, 1974). The microcosms were similar in size to those used by Gutteridge, Zhang, Jenkyn, and Bateman (2005) and Singh, Munro, Potts, and Millard (2007). The size of the microcosm allowed for plant traits to be analysed at individual species level and the plants were not pot bound after 6 weeks of growth. Furthermore, the microcosm size was appropriate to study the influence of the individual vegetation traits on the erosion process at the point at which individual particles/small aggregates are detached from the soil mass at the mm^2 or cm^2 scale.

The soil had a pH of 5.17, soil organic matter content of < 5.0 mm sieve. All microcosms were packed to a dry bulk density (BD) of 1.27 g cm^{-3}, simulating BDs indicative of arable soils in Herefordshire (UK). A total of 168 microcosms were packed. Treatments consisted of seven plant species treatments, two establishment scenarios and three rainfall scenarios. Each treatment combination was replicated in quadruplicate.

2.5.2 Establishment scenarios

A walk-in growth room (Reiskirchen-Lindenstruth, Germany) in the Cranfield University Soil Management Facility was used to simulate summer and autumn establishment conditions for Ross-on-Wye. For the summer establishment condition, the growth room temperature and humidity were set at 22°C and 78%, indicative of the mean July conditions for Hereford between 1981 and 2010 (Met Office, 2018a). For the autumn establishment condition, the growth room temperature and humidity were set at 15°C and 81%, indicative of the mean October conditions for Hereford between 1981 and 2010 (Met Office, 2018a). CO_2 levels for both conditions were ambient.

2.5.3 Rainfall scenarios

The mean rainfall (1981–2010) in Ross-on-Wye for July is 49.2 mm (Met Office, 2018b). This is generated from 8 days of rainfall of >1 mm (Met Office, 2018a). Therefore, for the “Normal” rainfall scenario (Norm_R) during summer establishment, a total of 49.2 mm of water was added in equal amounts on eight occasions over 4 weeks, after a 2-week establishment period. For the 2-week establishment period, a uniform amount of water was given to every treatment. The IPCC (2013) reports the mean change in precipitation could be as much as 50% more by the year 2100. For the Excess rainfall scenario (Excess_R), 98.4 mm was added in equal amounts on eight different occasions. To replicate drought conditions, a no rainfall scenario (Drought) was applied for 4 weeks, after the 2-week establishment period. For the autumn establishment condition, the mean rainfall (1981–2010) in Ross-on-Wye for October is 81.9 mm over 12 rain days >1 mm (Met Office, 2018a). Over the course of the 4-week experiment, 81.9 mm was added on 12 separate occasions for the Norm_R treatment. For the Excess_R treatment, double this amount was added, and for the Drought treatment, no additional water was added after the 2-week establishment period.

2.5.4 Species treatments and seeding rates

As shown in Table 2-1, the species treatments chosen were a conventional mixture of *Lolium perenne* and *Festuca rubra*, which is often used in GWWs within the UK. A further two novel hybrid species, *Festulolium cv Prior* (L. perenne and F. pratensis cross) and *Festulolium Bx511* (L. perenne and F. mairei cross), were selected. These two novel hybrid species were chosen due to their ability to resist climate change: Festuloliums such as Bx511 have been bred to be drought tolerant and withstand climate change conditions (Humphreys et al., 2006) and *Festulolium cv Prior* is flood tolerant (Macleod et al., 2013). Therefore, it is postulated that Festulolium varieties are better adapted to warmer, wetter autumns and winters, and to hotter, drier summers (Humphreys et al., 2006; MacLeod et al., 2013). These species were chosen for their reported resilience under future climate change conditions (IPCC, 2013; Routschek et al., 2014). Within each microcosm, seeds were placed on top of the soil, avoiding edge effects (>0.5 cm away from the edge) at equal spacing. Subsequently, 10 mm of the test soil was placed on top of the seeds and gently compressed to ensure good soil–seed contact. The number of seeds per microcosm and equivalent seeding rates (kg ha^{-1}) are given in Table 2-1. The seeding rates were chosen taking into account the cost to the farmer for implementing the novel Festulolium varieties and through personal communications from J. Harper, IBERS, Aberystwyth (14 March, 2018) and P. Brown, Frontier Agriculture (21 March, 2018). The microcosms were placed into water baths to allow wetting up through capillary rise. After germination of the grass seeds, all microcosms were watered equally by maintaining a water depth of 40 mm in each water bath during the 2-week establishment phase. After this 2-week establishment period, all grass stems were cut to 30 mm to promote tillering and to replicate studies of grass sward management (mowing and grazing regimes) (Deléglise et al., 2015; Pirchio et al., 2018). The rainfall scenarios were then imposed: no rainfall (Drought), normal rainfall (Norm_R) and twice the normal amount of rainfall (Excess_R).

Table 2-1: Grass Species Treatments and Seeding Rates

Treatment code	Grass species	Monoculture or mixture	Seeding rate[a] (kg ha^{-1})	Seeding rate (seeds per pot)
Fest-1	*Festulolium* cv Prior	Mono	50	5
Fest-2	*Festulolium* Bx511	Mono	50	6
Conv	Conventional mix consisting of *Lolium perenne* (75%) and *Festuca rubra* (25%)	Mixture (×2)	100	23
Fest-1 + 2	*Festulolium* cv Prior	Mixture (×2)	30	3
	Festulolium Bx511		30	3
Fest-1 + Conv	Conventional mix	Mixture (×3)	50	11
	Festulolium cv Prior		30	3
Fest-2 + Conv	Conventional mix	Mixture (×3)	50	11
	Festulolium Bx511		30	3
Fest-1 + 2 + Conv	Conventional mix	Mixture (×4)	50	11
	Festulolium Bx511		30	3
	Festulolium cv Prior		30	3

[a]Seeding rates are based on personal communications from J. Harper, IBERS, Aberystwyth (14 March, 2018) and P. Brown, Frontier Agriculture (21 March, 2018).

2.5.5 Experiment Design and Statistical Analysis

For both the autumn and summer establishment conditions, a complete randomized block design was adopted with rainfall scenario as blocks. Within each block, species treatments were randomly distributed and replicated in quadruplicate. To test the experimental hypotheses, for each establishment condition, results were analysed for statistical differences using a two-way factorial ANOVA with species treatment and rainfall scenario as independent variables and the selected plant traits as dependent variables. Where significant differences ($p < .05$) were observed, *post-hoc* Fisher least significant difference (LSD) analysis was applied (Statistica 13.2 Dell Inc.). Subsequently, to eliminate co-dependence before the plant traits were entered into the scoring system, a Pearson's rho correlation test was performed, and any co-dependent variables removed.

2.5.6 Plant Trait Based Ranking Approach

The plant trait-based ranking approach adopted in this study was adapted from Unagwu (2017). The highest and lowest values for each plant trait formed the range of the ranking system (Figure 2-2). The range for each trait was then divided equally into seven class intervals as there were seven different species that could be statistically different from each other (Figure 2-2). Using the % cover data as a worked example, the class range was 2% to 20%, with a class interval of 2.57% (Figure 2-2). The class intervals were then labelled 1–7, with 7 having the best erosion control potential. This process was followed for all plant traits with class intervals being trait specific.

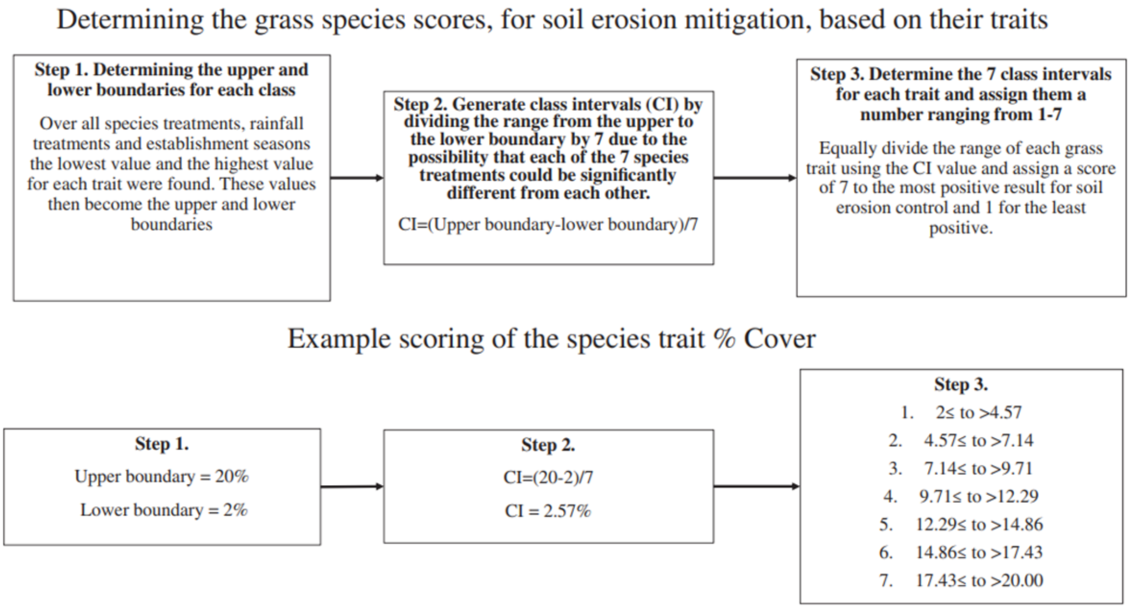

Figure 2-2 Schematic of the determination of boundaries, intervals and scoring values for each plant trait, with a worked example of the % cover grass trait.

The plant trait scores are shown in Tables 2-4. Trait values that were not significantly different (p<.05) following *post-hoc* Fisher LSD analysis fell within the same class category. Where trait values were close to a class boundary and were statistically similar, a conservative approach was taken and these were placed in the lower (worse) class. All scores for each plant trait were then summed to obtain a species-specific treatment score for each of the three erosion processes (detachment (by rainsplash and overland flow), entrainment/transport and deposition), establishment condition and rainfall scenarios (Tables 2-4). For each erosion process, scores for the Drought and Excess_R scenarios were calculated as a variance from the Norm_R. This was done because suitable species for future erosion control should tolerate both extreme dry and wet establishment conditions. The variance scores of Drought and Excess_R from the Norm_R were then added together to give a final ranking. To reflect the relative magnitude and contribution of the different soil erosion processes operating in a GWW, weightings to the scores were added: 10% for potential ability to control detachment via rainsplash, 60% for control of detachment via concentrated flow, and 30% for control of entrainment/transport and deposition. This gave a total ‘erosion mitigation potential’ score per species treatment (Table 5).

Table 2-2: Plant trait data and scores as related to their theoretical ability to control detachment by rainsplash for all species, rainfall and establishment season.

		Summer conditions						Autumn conditions					
Rainfall	Species	G% germination	C%	PH (cm)	SAD ($mm^2\ mm^{-2}$)	AGB (g)	Ts score	G% germination	C% cover	PH (cm)	SAD ($mm^2\ mm^{-2}$)	AGB (g)	Ts score
Dry	Fest_1	80 (5)	4 (1)	45.0 (4)	0.004 (1)	0.43 (2)	**13**	70 (3)	5 (2)	24.6 (6)	0.003 (1)	0.22 (1)	**13**
	Fest_2	71 (5)	5 (1)	42.9 (5)	0.004 (1)	0.51 (2)	**14**	75 (4)	5 (2)	27.3 (5)	0.004 (1)	0.91 (1)	**13**
	Conv	78 (5)	11 (4)	42.5 (5)	0.012 (2)	0.88 (5)	**21**	82 (4)	9 (4)	18.9 (7)	0.004 (1)	0.26 (1)	**17**
	Fest_1 + 2	88 (5)	5 (1)	43.3 (5)	0.004 (1)	0.46 (2)	**14**	71 (3)	6 (2)	25.7 (6)	0.003 (1)	0.26 (1)	**13**
	Fest_1 + Conv	78 (5)	8 (3)	37.1 (6)	0.004 (1)	0.50 (2)	**17**	54 (3)	8 (3)	20.7 (7)	0.004 (1)	0.29 (1)	**15**
	Fest_2 + Conv	79 (5)	9 (3)	31.3 (6)	0.003 (1)	0.41 (2)	**17**	43 (3)	9 (5)	24.6 (6)	0.003 (1)	0.34 (1)	**16**
	Fest_1 + 2 + Conv	89 (5)	9 (3)	34.4 (6)	0.005 (1)	0.49 (2)	**17**	73 (3)	10 (6)	25.1 (6)	0.004 (1)	0.33 (1)	**17**
Normal	Fest_1	95 (5)	8 (3)	55.8 (1)	0.008 (1)	0.90 (6)	**16**	75 (5)	6 (2)	26.4 (5)	0.002 (1)	0.23 (1)	**14**
	Fest_2	92 (5)	12 (6)	42.9 (3)	0.015 (4)	0.86 (4)	**22**	79 (5)	7 (2)	25.9 (5)	0.002 (1)	0.29 (1)	**14**
	Conv	81 (5)	10 (4)	36.6 (6)	0.005 (1)	0.51 (3)	**19**	91 (7)	12 (7)	17.4 (7)	0.002 (1)	0.21 (1)	**23**
	Fest_1 + 2	100 (5)	9 (4)	48.2 (3)	0.016 (5)	0.76 (4)	**21**	75 (5)	7 (2)	25.7 (5)	0.003 (1)	0.25 (1)	**14**
	Fest_1 + Conv	74 (5)	11 (5)	43.4 (5)	0.014 (3)	0.88 (5)	**23**	63 (3)	10 (4)	25.6 (5)	0.004 (1)	0.32 (1)	**14**
	Fest_2 + Conv	83 (5)	15 (7)	36.0 (6)	0.009 (2)	0.82 (4)	**24**	43 (3)	11 (6)	23.5 (6)	0.005 (1)	0.33 (1)	**17**
	Fest_1 + 2 + Conv	75 (5)	11 (5)	44.6 (4)	0.006 (1)	0.73 (4)	**19**	66 (3)	11 (5)	25.8 (5)	0.003 (1)	0.34 (1)	**15**
Excess	Fest_1	85 (5)	6 (2)	50.0 (3)	0.007 (1)	0.71 (4)	**15**	55 (4)	5 (2)	23.4 (6)	0.003 (1)	0.18 (1)	**14**
	Fest_2	96 (5)	10 (4)	48.6 (3)	0.009 (3)	1.21 (7)	**22**	63 (4)	7 (2)	26.6 (4)	0.002 (1)	0.25 (1)	**12**
	Conv	88 (5)	14 (6)	44.6 (4)	0.007 (1)	0.96 (6)	**22**	88 (7)	13 (5)	18.6 (7)	0.004 (1)	0.27 (1)	**21**
	Fest_1 + 2	79 (5)	8 (3)	48.3 (3)	0.008 (2)	0.72 (4)	**17**	75 (5)	8 (2)	24.0 (6)	0.003 (1)	0.25 (1)	**15**
	Fest_1 + Conv	75 (5)	12 (5)	43.1 (5)	0.010 (4)	0.82 (5)	**24**	53 (4) (4)	8 (2)	24.3 (5)	0.003 (1)	0.25 (1)	**13**
	Fest_2 + Conv	74 (5)	15 (7)	34.8 (6)	0.005 (1)	0.96 (6)	**25**	58 (4)	13 (6)	26.0 (5)	0.004 (1)	0.37 (1)	**17**
	Fest_1 + 2 + Conv	73 (5)	12 (5)	46.6 (3)	0.009 (2)	0.96 (6)	**21**	83 (5)	14 (7)	23.1 (6)	0.004 (1)	0.31 (1)	**20**

Percentage germination (G%); percentage ground cover (C%); plant height (PH (cm)); stem area density (SAD ($mm^2\ mm^{-2}$)); aboveground DW biomass (ABG (g)); values in parentheses are trait scores. Identical trait scores mean no statistical differences in actual values; Ts is the total score.

Table 2-3 Plant trait data and scores as related to their theoretical ability to control detachment by overland flow for all species, rainfall and establishment season

		Summer conditions								Autumn conditions							
Rainfall	Species	PH (cm)	#St	SAD ($mm^2\ mm^{-2}$)	AGB (g)	RL(m) ≤ 0.25 mm	RSA (cm^2)	RDiam (mm)	Ts	PH (cm)	#St	SAD ($mm^2 mm^{-2}$)	AGB (g)	RL(m) ≤ 0.25 mm	RSA (cm^2)	RDiam (mm)	Ts
Dry	Fest_1	45.0 (4)	6 (2)	0.004 (1)	0.43 (2)	11.3 (4)	132 (3)	0.28 (1)	**17**	24.6 (6)	4 (2)	0.003 (1)	0.22 (1)	3.83 (1)	73.8 (2)	0.31 (6)	**19**
	Fest_2	42.9 (5)	5 (2)	0.004 (1)	0.51 (2)	4.41(1)	60.4 (1)	0.88 (1)	**13**	27.3 (5)	5 (2)	0.004 (1)	0.91 (1)	7.31 (1)	120 (2)	0.31 (6)	**18**
	Conv	42.5 (5)	6 (3)	0.012 (2)	0.88 (5)	0.99 (1)	17.2 (1)	0.38 (1)	**18**	18.6 (7)	16 (6)	0.003 (1)	0.26 (1)	5.81 (1)	91.2 (2)	0.28 (6)	**24**
	Fest_1 + 2	43.3 (5)	4 (2)	0.004 (1)	0.46 (2)	5.39 (1)	83.2 (2)	0.28 (1)	**14**	25.7 (6)	5 (2)	0.003 (1)	0.26 (1)	3.58 (1)	75.0 (2)	0.32 (6)	**19**
	Fest_1 + Conv	37.1 (6)	4 (2)	0.004 (1)	0.50 (2)	7.99 (2)	66.3 (1)	0.26 (1)	**15**	20.7 (7)	11 (4)	0.004 (1)	0.29 (1)	4.29 (1)	63.9 (2)	0.29 (6)	**22**
	Fest_2 + Conv	31.3 (6)	5 (2)	0.003 (1)	0.41 (2)	8.19 (3)	68.5 (1)	0.26 (1)	**16**	24.6 (6)	13 (4)	0.003 (1)	0.34 (1)	6.35 (1)	107 (2)	0.30 (6)	**21**
	Fest_1 + 2 + Conv	34.3 (6)	6 (2)	0.005 (1)	0.49 (2)	11.8 (5)	86.0 (2)	0.25 (1)	**19**	25.1 (6)	14 (5)	0.003 (1)	0.33 (1)	6.99 (1)	105 (2)	0.32 (6)	**22**
Normal	Fest_1	55.8 (1)	10 (7)	0.008 (1)	0.90 (6)	0.69 (1)	16.4 (1)	0.47 (1)	**18**	26.4 (5)	4 (2)	0.002 (1)	0.23 (1)	2.85 (1)	169 (4)	0.46 (6)	**20**
	Fest_2	42.9 (3)	8 (5)	0.015 (4)	0.86 (4)	8.98 (3)	96.6 (2)	0.33 (1)	**22**	25.9 (5)	5 (2)	0.002 (1)	0.29(1)	7.35 (1)	241 (6)	0.40 (5)	**21**
	Conv	36.6 (6)	4 (1)	0.005 (1)	0.51 (3)	5.71 (1)	58.9 (1)	0.28 (1)	**14**	17.4 (7)	16 (6)	0.001 (1)	0.21 (1)	5.77 (1)	193 (4)	0.34 (3)	**23**
	Fest_1 + 2	48.2 (3)	8 (6)	0.016 (5)	0.76 (4)	0.92 (1)	16.6 (1)	0.39 (1)	**21**	25.7 (5)	5 (2)	0.002 (1)	0.25 (1)	7.07 (1)	220 (5)	0.40 (5)	**20**
	Fest_1 + Conv	43.4 (5)	7 (3)	0.014 (3)	0.88 (5)	0.56 (1)	15.2 (1)	0.42 (1)	**19**	25.6 (5)	12 (4)	0.004 (1)	0.32 (1)	8.68 (1)	317 (7)	0.47 (7)	**26**
	Fest_2 + Conv	36.0 (6)	7 (4)	0.009 (2)	0.82 (4)	1.03 (1)	13.8 (1)	0.34 (1)	**19**	23.5 (6)	12 (4)	0.004 (1)	0.33 (1)	20.7 (5)	307 (7)	0.34 (3)	**27**
	Fest_1 + 2 + Conv	44.6 (4)	8 (6)	0.006 (1)	0.73 (4)	1.03 (1)	16.4 (1)	0.34 (1)	**18**	25.8 (5)	13(4)	0.003 (1)	0.34 (1)	15.9 (4)	318 (7)	0.37 (4)	**26**
Excess	Fest_1	50.0 (3)	7 (5)	0.007 (1)	0.71 (4)	1.70 (1)	36.5 (1)	0.39 (1)	**16**	23.4 (6)	3 (1)	0.003 (1)	0.18 (1)	5.88 (1)	174 (1)	0.37 (3)	**14**
	Fest_2	48.6 (3)	7 (5)	0.009 (3)	1.21 (7)	2.51 (1)	39.1 (1)	0.38 (1)	**21**	26.6 (4)	4 (1)	0.002 (1)	0.25 (1)	3.70 (1)	196 (2)	0.44 (7)	**17**
	Conv	44.6 (4)	6 (3)	0.007 (1)	0.96 (6)	2.34 (1)	20.0 (1)	0.31 (1)	**17**	18.6 (7)	18 (7)	0.004 (1)	0.27 (1)	9.96 (1)	303 (5)	0.35 (2)	**24**
	Fest_1 + 2	48.3 (3)	6 (4)	0.008 (2)	0.72 (4)	2.11 (1)	34.7 (1)	0.35 (1)	**16**	24.0 (6)	5 (1)	0.003 (1)	0.25 (1)	7.14 (1)	259 (4)	0.38 (4)	**18**
	Fest_1 + Conv	43.1 (5)	7 (5)	0.010 (4)	0.82 (5)	1.24 (1)	21.4 (1)	0.36 (1)	**22**	24.3 (5)	10 (4)	0.003 (1)	0.25 (1)	9.56 (1)	235 (3)	0.39 (5)	**20**
	Fest_2 + Conv	34.8 (6)	9 (7)	0.005 (1)	0.96 (6)	0.92 (1)	13.8 (1)	0.35 (1)	**23**	26.0 (5)	14 (6)	0.004 (1)	0.37 (1)	10.2 (1)	359 (7)	0.40 (6)	**27**
	Fest_1 + 2 + Conv	46.6 (3)	8 (6)	0.009 (2)	0.96 (6)	1.68 (1)	22.9 (1)	0.35 (1)	**20**	23.1 (6)	14 (5)	0.004 (1)	0.31 (1)	8.71 (1)	340 (6)	0.39 (5)	**25**

Plant height (PH (cm)); number of stems (#St); stem area density (SAD ($mm^2\ mm^{-2}$)); aboveground DW biomass (ABG (g)); root length of roots ≤0.25 mm in diameter (RL (m)); root surface area (RSA); mean root diameter (RDiam (mm)); values in parentheses are trait scores. Identical trait scores mean no significant differences in actual values; Ts is the total score.

Table 2-4 Plant trait data and scores as related to their theoretical ability to control sediment transport and encourage deposition for all species, rainfall and establishment season

		Summer conditions					Autumn conditions				
Rainfall	**Species**	**% C**	**PH (cm)**	**SAD (mm^2 mm^{-2})**	**AGB (g)**	**Ts**	**% C**	**PH (cm)**	**SAD (mm^2 mm^{-2})**	**AGB (g)**	**Ts**
Dry	Fest_1	4 (1)	45.0 (4)	0.004 (1)	0.43 (2)	**8**	5 (2)	24.6 (6)	0.003 (1)	0.22 (1)	**10**
	Fest_2	5 (1)	42.9 (5)	0.004 (1)	0.51 (2)	**9**	5 (2)	27.3 (5)	0.004 (1)	0.91 (1)	**9**
	Conv	11 (4)	42.5 (5)	0.012 (2)	0.88 (5)	**16**	9 (4)	18.6 (7)	0.004 (1)	0.26 (1)	**13**
	Fest_1 + 2	45 (1)	43.3 (5)	0.004 (1)	0.46 (2)	**9**	6 (2)	25.7 (6)	0.003 (1)	0.26 (1)	**10**
	Fest_1 + Conv	8 (3)	37.1 (6)	0.004 (1)	0.50 (2)	**12**	8 (3)	20.7 (7)	0.004 (1)	0.29 (1)	**12**
	Fest_2 + Conv	9 (3)	31.3 (6)	0.003 (1)	0.41 (2)	**12**	9 (5)	24.6 (6)	0.003 (1)	0.34 (1)	**13**
	Fest_1 + 2 + Conv	9 (3)	34.4 (6)	0.005 (1)	0.49 (2)	**12**	10 (6)	25.1 (6)	0.004 (1)	0.33 (1)	**14**
Normal	Fest_1	8 (3)	55.8 (1)	0.008 (1)	0.90 (6)	**11**	6 (2)	26.4 (5)	0.002 (1)	0.23 (1)	**9**
	Fest_2	12 (6)	42.9 (3)	0.015 (4)	0.86 (4)	**17**	7 (2)	25.9 (5)	0.002 (1)	0.29 (1)	**9**
	Conv	10 (4)	36.6 (6)	0.005 (1)	0.51 (3)	**14**	12 (7)	17.4 (7)	0.002 (1)	0.21 (1)	**16**
	Fest_1 + 2	9 (4)	48.2 (3)	0.016 (5)	0.76 (4)	**16**	7 (2)	25.7 (5)	0.003 (1)	0.25 (1)	**9**
	Fest_1 + Conv	11 (5)	43.4 (5)	0.014 (3)	0.88 (5)	**18**	10 (4)	25.6 (5)	0.004 (1)	0.32 (1)	**11**
	Fest_2 + Conv	15 (7)	36.0 (6)	0.009 (2)	0.82 (4)	**19**	11 (6)	23.5 (6)	0.005 (1)	0.33 (1)	**14**
	Fest_1 + 2 + Conv	11 (5)	44.6 (4)	0.006 (1)	0.73 (4)	**14**	11 (5)	25.8 (5)	0.003 (1)	0.34 (1)	**12**
Excess	Fest_1	6 (2)	50.0 (3)	0.007 (1)	0.71 (4)	**10**	5 (2)	23.4 (6)	0.003 (1)	0.18 (1)	**10**
	Fest_2	10 (4)	48.6 (3)	0.009 (3)	1.21 (7)	**17**	7 (2)	26.6 (4)	0.002 (1)	0.25 (1)	**8**
	Conv	14 (6)	44.6 (4)	0.007 (1)	0.96 (6)	**17**	13 (5)	18.6 (7)	0.004 (1)	0.27 (1)	**14**
	Fest_1 + 2	8 (3)	48.3 (3)	0.008 (2)	0.72 (4)	**12**	8 (2)	24.0 (6)	0.003 (1)	0.25 (1)	**10**
	Fest_1 + Conv	12 (5)	43.1 (5)	0.010 (4)	0.82 (5)	**19**	8 (2)	24.3 (5)	0.003 (1)	0.25 (1)	**9**
	Fest_2 + Conv	15 (7)	34.8 (6)	0.005 (1)	0.96 (6)	**20**	13 (6)	26.0 (5)	0.004 (1)	0.37 (1)	**13**
	Fest_1 + 2 + Conv	12 (5)	46.6 (3)	0.009 (2)	0.96 (6)	**16**	14 (7)	23.1 (6)	0.004 (1)	0.31 (1)	**15**

Percentage ground cover (C%); plant height (PH (cm)); stem area density (SAD (mm^2 mm^{-2})); aboveground DW biomass (ABG (g)); values in parentheses are trait scores. Same trait scores mean that the actual values were not statistically different; Ts is the total score.

Table 2-5: Total species scores for summer and autumn establishment for control of (1) rainsplash, (2) detachment by overland flow, (3) transport and deposition, weighted 10%, 60%, 30%, respectively, to reflect the relative contribution of each phase to overall erosion process

Rainfall conditions during establishment	Species	Detachment by rainsplash			Detachment by overland flow			Transport and deposition			All soil erosion phases
		Drought	Excess	Weighted total	Drought	Excess	Weighted total	Drought	Excess	Weighted total	Overall weighted total
Summer	Fest_1	-3	-1	−0.4	7	−9	−1.2	−3	−1	−1.2	**−2.8**
	Fest_2	8	0	0.8	10	−3	4.2	−8	0	−2.4	**2.6**
	Conv	0	3	0.3	5	3	4.8	2	3	1.5	**6.6**
	Fest_1 + 2	−7	−4	−1.1	−10	−7	−10.2	−7	−4	−3.3	**−14.6**
	Fest_1 + Conv	−6	0	−0.6	−7	2	−3	−6	1	−1.5	**−5.1**
	Fest_2 + Conv	−7	1	−0.6	−5	3	−1.2	−7	1	−1.8	**−3.6**
	Fest_1 + 2+ Conv	−2	2	0	0	4	2.4	−2	2	0	**2.4**
Autumn	Fest_1	−1	0	−0.1	−1	−6	−4.2	1	1	0.6	**−3.7**
	Fest_2	−1	−2	−0.3	−3	−4	−4.2	0	−1	−0.3	**−4.8**
	Conv	−6	−2	−0.8	1	1	1.2	−3	−2	−1.5	**−1.1**
	Fest_1 + 2	1	1	0.2	−1	−2	−1.8	1	1	0.6	**−1**
	Fest_1 + Conv	−1	−1	−0.2	−4	−6	−6	1	−2	−0.3	**−6.5**
	Fest_2 + Conv	1	0	0.1	−6	0	−3.6	−1	−1	−0.6	**−4.1**
	Fest_1 + 2+ Conv	−2	5	0.3	−6	−1	−4.2	2	3	1.5	**−2.4**

2.5.7 Above Ground Plant Trait Measurements

Percentage germination was measured after the 2-week establishment phase. All the individual stems in each treatment were counted. For the 4-week post-establishment period, percentage ground cover (% ground cover) and plant height (PH) were measured. Mean PH (cm) was measured using a graduated scale on three randomly chosen stems from each microcosm. Mean PH (n = 3) was then calculated per microcosm. Post establishment, mean PH was measured at T-1 (Day 1), T-2 (Day 3), T-3 (Day 7), T-4 (Day 14) and T-5 (Day 28). Percentage ground cover (%) was measured using a quadrat, with 1cm^2 cells for each replicate at T-1, T-2, T-3, T-4 and T-5. At the end of the 4-week growth period, the following aboveground plant traits were measured: number of tillers, number of stems, stem diameter (mm) and aboveground biomass (fresh weight (FW) and dry weight (DW). In addition, the following belowground root traits were determined: belowground root biomass (BGB) (FW and DW), root diameter (mm), root total surface area (cm^2), total length (cm) of fine roots (≤0.25 mm ⌀) and total root length (cm). The number of tillers was determined for three randomly selected individual grass plants per replicate. Stem diameter (mm) was measured on three randomly selected stems per replicate on randomly chosen individual grass tillers using a digital Vernier gauge. As the surface area of the microcosms is known (37.2 cm^2) and both the number of stems and the stem diameter were measured, the stem area density (mm^2 mm^{-2}) (SAD) was calculated using the following equation:

Equation 2-1: $Stem\ Area\ Density = \textbf{Surface area of the stems} * \textbf{number of stems} / \textbf{surface area of the microcosm}$

For aboveground FW and DW, the grass was cut 0.2 cm above the soil surface to ensure that no soil was in the sample. The aboveground fresh biomass (AFW, g) was calculated by weighing all of the cut grass sample for each replicate. The grass was then oven dried at 65°C for 3 days and reweighed to give the aboveground DW biomass (ADW, g).

2.5.8 Determination of root traits

Grass root traits were measured after root washing, where samples were placed on a <500-μm sieve and any soil adhering to roots was gently washed away, leaving the main bulk of the roots. The sieve was then placed in shallow clear water and any remaining broken roots picked out manually and placed with the main bulk of the root sample to determine total fresh weight (FW, g). Subsequently, 0.1–0.2 g (0.89–20.10 %) of the FW root sample was taken as a subsample (see below), whereas the remaining roots were oven dried at 65°C for 3 days and then reweighed to give the belowground dry biomass (DW, g). The root subsample was used to calculate the total root length (cm) and root diameter (mm) distribution, using (WinRhizo software, Quebec, QC, Canada) (Regent Instruments, 2016). The root subsamples were stored at <4 °C in a 15% ethanol solution until they could be analysed. After the WinRhizo analysis, these subsamples were also oven dried at 65°C for 3 days and their weights added to the FW and DWs of the corresponding sample.

2.6 Results

2.6.1 Differences in above ground plant traits across treatments and rainfall scenarios

For brevity, only the summer scenario results are depicted as figures here. Autumn scenario results are shown in 8Appendix A. Significant differences in stem diameter were seen between species and between rainfall scenarios under autumn establishment ($p < .05$). Stem diameter was significantly higher for Fest_2 under Drought (1.94 mm) as opposed to Norm_R (1.46 mm) conditions. Under summer establishment, treatments with Festulolium varieties generally had a significantly larger stem diameter (2.06–3.98 mm) than treatments with Conv (0.95–2.31 mm) (Figure 2-3 (a)). For summer establishment, Fest_ 1 was associated with significantly more tillers under Norm_R (9.5) than under both Excess_R (6.88) and Drought (5.75) (Figure 2-3 (b)) conditions. Fest_2, Fest_1 + 2, Fest_1 + Conv, Fest_2 + Conv and Fest_1 + 2 + Conv had significantly fewer tillers under Drought than under Norm_R or Excess_R conditions. For autumn establishment, the aboveground biomass (AGB) for Fest_1 under Excess_R was significantly lower ($p < .05$) than Fest_2 + Conv under Norm_R, Excess_R or Drought (Table 2-2 Table 2-3 Table 2-4). For summer establishment, the Drought condition had significantly lower AGB ($p<.05$) compared to the Norm_R or Excess_R for all treatments, except the Conv (Figure 2-3). Fest_2 had significant differences between Drought (0.51 g), Norm_R (0.86 g) and Excess_R (1.21 g) conditions (Figure 2-3) The stem diameter and number of tillers were significantly different, yet no statistically significant differences were observed in stem area density for autumn establishment. For Fest 1 + Conv, stem area density was significantly lower under Drought (0.006 mm^2 mm^{-2}) when compared to Norm_R (0.012 mm^2 mm^{-2}) and Excess_R (0.015 mm^2 mm^{-2}) rainfall. For Fest_1, Conv, Fest_1 + 2, Fest_2 + Conv and Fest_1 + 2 + Conv, no significant differences in stem area density were found for the different rainfall scenarios.

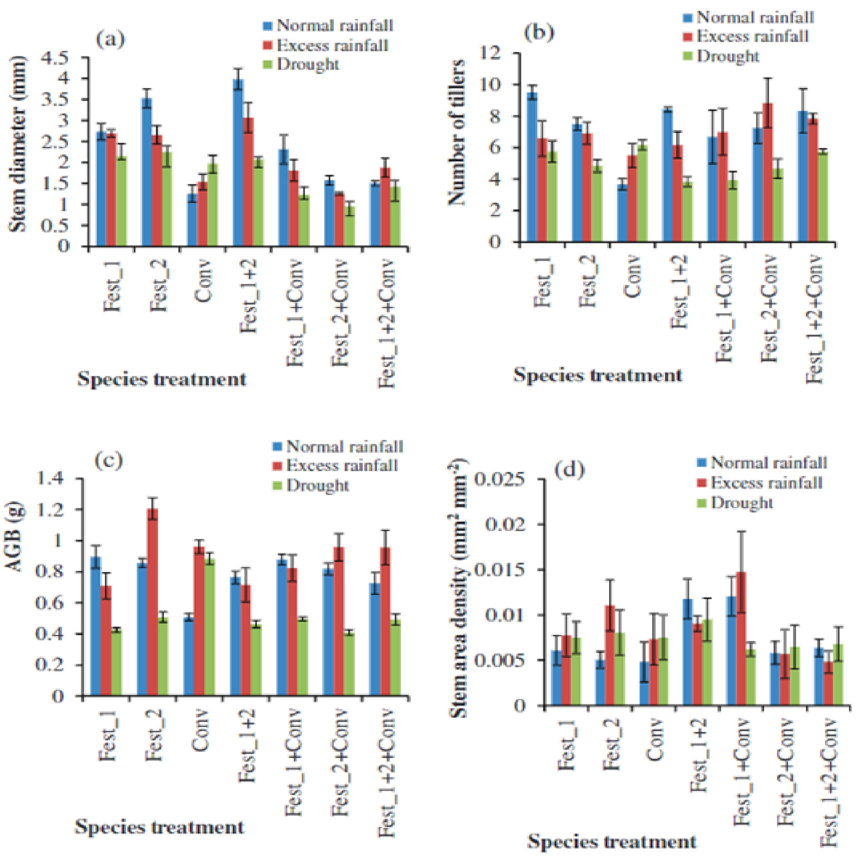

Figure 2-3: Aboveground plant traits, (a) stem diameter (mm), (b) number of tillers, (c) AGB (g) and (d) stem area density (mm^2 mm^{-2}), for summer establishment, according to species treatment and rainfall scenario. Error bars represent ±1 S.E.

2.6.2 Differences in below ground plant traits across treatments and rainfall scenarios

For summer establishment, total root length was significantly higher under Drought compared to Norm_R or Excess_R for Fest_1, Fest_1 + Conv, Fest_2 + Conv and Fest_1 + Fest_2 + Conv. (Figure 2-4). Fest_2 showed no significant differences in root length between the three rainfall scenarios under summer establishment. For autumn establishment, there were no statistical differences ($p > .05$) in the mean root diameter under Drought for all species treatments. Under summer establishment, Fest_1, Fest_1 + Conv and Fest_1 + 2 + Conv had significantly lower mean root diameters under Drought compared to Norm_R and Excess_R. For autumn establishment, the length of roots that were ≤ 0.25 mm diameter was significantly higher ($p<.05$) in Fest_2 + Conv and Fest_1 + 2 + Conv under Norm_R as opposed to the other rainfall scenarios. For summer establishment, all species treatments except for Fest_2 and Conv had a significantly higher total root length ≤ 0.25 mm in diameter under Drought. The belowground biomass (BGB), total root surface area and root to shoot ratio all followed a similar trend to the total root length and for brevity are not shown in Figure 2-4.

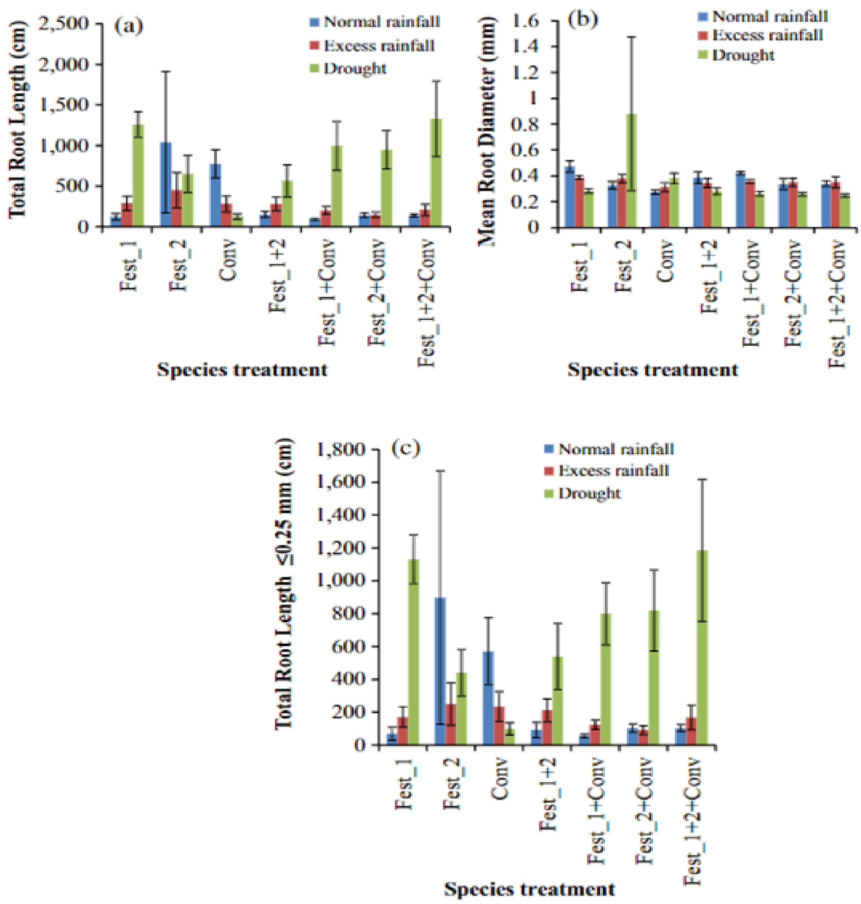

Figure 2-4: Belowground plant traits, (a) total root length (cm), (b) mean root diameter (mm) and (c) total root length≤0.25 mm in diameter (cm), for summer establishment, according to specie sand rainfall scenario treatments. Error bars represent ±1 S.E.

2.6.3 Elimination of co-dependent variables from the plant trait-based scoring approach

The following plant traits were significantly correlated with other traits (correlation coefficients >0.7; see Supplementary Information Tables 1 and 2)

1. Number of stems and % ground cover.

2. Stem diameter and stem area density.

3. Aboveground biomass (AGB) fresh and dry weight.

4. Belowground biomass (BGB) fresh and dry weight, total root length, total root surface area and root to shoot ratio.

Where co-dependence was found (0.7 or above), some variables effectively became redundant and were not put into the same scoring table. From the above list, stem area density, % ground cover, AGB, dry weight and total root surface area were retained for the plant trait-based scoring approach

2.6.4 Plant trait scores related to soil erosion control in GWWs

For all species treatments, rainfall scenarios and establishment season, the plant traits associated with control of the three soil erosion processes (Figure 2-1) were scored following the approach explained in 2.4 (Tables 2-4). The final treatment-specific plant trait scores are presented in Table 2-5. For detachment by rainsplash, the highest scoring species treatments under summer establishment conditions were: Conv (score = 21), Fest_2 + Conv (24) and Fest_2 + Conv (25) in the Drought, Norm_R and Excess_R regimes, respectively (Table 2-5). For the autumn establishment conditions, the highest scoring species treatments were: Conv (score = 17) = Fest_1 + 2 + Conv (17), Conv (23) and Conv (21) in the Drought, Norm_R and Excess_R regimes, respectively (Table 2-5). For detachment via concentrated flow, the highest scoring species treatments under the summer establishment conditions were: Conv (19), Fest_2 + Conv (22) and Fest_2 + Conv (23) in the Drought, Norm_R and Excess_R conditions, respectively (Table 2-3). For autumn establishment, the highest scoring species treatments were: Conv (24), Fest_2 + Conv (27) and Fest_2 + Conv (27) in the Drought, Norm_R and Excess_R conditions, respectively (Table 3). Finally, for the entrainment/transport and deposition phase, the highest scoring species treatments under summer establishment conditions were: Conv (16), Fest_2 + Conv (19) and Fest_2 + Conv (22) in the Drought, Norm_R and Excess_R conditions, respectively (Table 2-4). For the autumn scenario, the highest scoring species treatments were: Fest_1 + 2 + Conv (15), Conv (17) and Fest_1 + 2 + Conv (15) in the Drought, Norm_R and Excess_R conditions, respectively. The species that have the highest overall scores (for all erosion processes combined) under summer establishment were: Conv (7.1), Fest_1 + 2 + Conv (2.8) and Fest_2 (2.6) (Table 2-5). The equivalent scores for autumn establishment were: Fest_1 + 2 (0.8), Fest_1 + 2 + Conv (0.2) and Conv (−1.1). The Conv and Fest_1

+ 2 + Conv treatments were in the top three scores for both seasons, whereas the Fest_1, Fest_1 + Conv and Fest_2 + Conv treatments were consistently outside of the top three scores

2.7 Discussion

2.7.1 Aboveground Traits

Deléglise et al., (2015) found that drought significantly reduced vegetation height by as much as 52% as compared to normal conditions. The present study does not corroborate this, but Deléglise et al., (2015) assessed PH on a community basis and the drought period was longer than that used in the present study, which could explain these contradictory findings. One implication of Deléglise et al.'s (2015) findings was that grass species subjected to longer periods of drought had lower PHs, which may be beneficial in terms of soil erosion control (i.e., avoidance of lodging). This is on the assumption that other salient plant traits were not affected by drought. Under summer establishment, the Drought condition reduced stem diameter and AGB in all treatments except for the Conv treatment. Fariaszewska et al., (2020) found that AGB for Festuca, Lolium and Festulolium decreased following a period of drought, which concurs with the present study, where all the treatments containing Festulolium had a lower AGB under drought conditions. However, Conv, a mixture of *Festuca rubra* and *Lolium perenne*, did not conform to the findings of Fariaszewska et al., (2020). This may be because this species combination was not used by Fariaszewska et al., (2020) and also because the Conv had a high stem diameter and number of tillers in the drought condition, which will increase the AGB. Furthermore, the Conv treatment had a lower total root length < 0.25 mm and a lower total root length under Drought conditions, which suggests more resources were expended on aboveground growth.

2.7.2 Belowground Traits

Summer establishment and Drought conditions generally gave higher total root lengths compared with Normal or Excess rainfall. However, Fest_2 root lengths and roots <0.25 mm diameter were consistent under all rainfall scenarios, whereas Conv had a higher total root length and more roots of <0.25 mm in diameter under Normal rainfall. Macleod et al., (2013) found that Fest_1 had the largest overall root system size and distribution after 6 months, out of the species they tested. This is not the case with the present study, but this can be explained by the fact that the species monocultures and mixtures are different to those of Macleod et al., (2013).

2.7.3 Monocultures versus mixtures in GWWs

This study aimed to compare the theoretical efficacy of monocultures versus mixtures in controlling soil erosion in GWWs, based on their observed plant traits. According to the scoring system, the Conv treatment (mix of two species) showed the greatest potential to control soil erosion by water under summer establishment (Table 2-5). Furthermore, under autumn establishment, Fest_1 + 2 showed the highest soil erosion mitigation potential (mix of two species) (Table 2-5). None of the treatments with mixes of four species performed as well as this, suggesting that too many species may hinder the development of plant traits associated with soil erosion control potential. Our hypothesis that more species grown together would encourage erosion control traits has to be rejected. However, for autumn establishment, the Fest_1 + 2 + Conv treatment (a mixture of four species; Table 2-5), had a higher soil erosion mitigation potential than the monoculture of Festulolium (Table 2-5). Furthermore, the Conv treatment (a mixture of two species) had a higher score than that of the monoculture Festulolium species under both establishment seasons. This supports our hypothesis that it is not purely the number of species in a mixture, but the quality of the species traits of those grasses within the mixture, which will influence soil erosion control. Furthermore, a mixture of species will provide more ecological niches and genetic diversity compared to a monoculture (Chase and Myers, 2011), building plant resilience (and associated soil protection) in the face of external stresses such as pests, diseases, drought and/or waterlogging. Competition between species needs further exploration: if the present experiment was undertaken over a longer period of time, the rooting profile of the mixed species (and associated erosion control performance) may be very different due to the prolonged competition between species. This may affect the overall erosion resistance of communities. For example, Bingcheng, Feng-Min, and Lun (2010) found that rooting properties of Switchgrass and Milk Vetch were influenced when species were planted together: the roots grew differently within the root zone, with one species adopting a more flexible distribution strategy, and another species having roots at the same depth, but with a greater root density. From an erosion control perspective both have potential as they have a greater root density (De Baets & Poesen, 2010), and with a spreading out of roots there is less chance of sheet erosion or overland erosion occurring due to roots binding with the soil.

2.7.4 Establishment season and climate conditions for GWW establishment

One aim of this study was to determine if rainfall regime (drought, normal, excess) and establishment season (summer, autumn) affected the properties of grass species that affect soil erosion processes. The results show that establishment season (summer versus autumn) influences plant traits associated with erosion mitigation. The highest scoring species for summer establishment were: Conv, Fest_1 + 2 + Conv and Fest_2. For autumn establishment, the highest scores were Fest_1 + 2, Fest_1 + 2 + Conv and Conv. High-scoring species and treatments that were suitable for predicted climates of both extreme dry and extreme wet conditions from this study were: Fest_1 + 2 + Conv and Conv, which were both within the top three highest scores, regardless of establishment season or rainfall treatment. These species mixes are thus likely to be better adapted to a climate with warmer, wetter winters and hotter, drier summers (IPCC, 2013).

2.7.5 Scoring system of plant traits for GWW effectiveness

This study aimed to develop a novel plant trait-based scoring system to aid the screening of suitable grass species for control of soil erosion in GWWs. The method can also be used to identify individual plant traits that are performing the worst out of all the plant traits and whether this can be overcome easily by management intervention. For example, a low score for PH can be overcome by changing mowing frequency to ensure that optimum grass sward height is maintained. Similarly, a low score for % cover can be improved by increasing the seeding rate and fertiliser regime (yet this increases establishment costs). Traits such as root diameter and root surface area can be manipulated through appropriate species selection. As erosion processes in GWWs vary over time and space, the weightings used in the proposed scoring method (to reflect different soil erosion processes in operation) can be changed to identity the most appropriate species selection for any given site conditions.

De Baets et al., (2009) previously developed a method to compare species effectiveness at controlling soil erosion that focused on selecting plant species to control rill and gully erosion, formed by the processes of detachment by overland flow, entrainment and transport of sediment. Ghestem et al., (2014) developed a scoring method based on root properties only, which also does not look at the process of soil erosion by water as a whole. The present study expands these approaches by also theoretically including the process of soil detachment by rainsplash. The present study allows for variable weighting of all erosion processes to reflect their dominance at any given time and/or place, which is not possible with the approaches taken by De Baets et al., (2009) or Ghestem et al., (2014). To explore these issues further, a sensitivity analysis was undertaken to test the robustness of the weighting method used. When the weightings for detachment via scouring and entrainment/transport and deposition were changed from either 70:20% or 20:70%, Conv remained the optimum species treatment for overall plant trait score for summer establishment. However, for autumn establishment, the optimum species treatment was Fest_1 + 2 + Conv for the ratios 20:70% (i.e., where transport and deposition dominate over flow detachment) up to 45:45%. However, for the ratios 50:40% to 70:20% (where flow detachment dominates), Fest_1 + 2 was the optimum species treatment. There are some caveats to the scoring method used in this study, as only physical plant traits were used to assess suitability of different species in the control of erosion. Other factors that influence soil erosion processes, such as evapotranspiration and soil properties such as hydraulic conductivity, were not included. These factors need to be considered and can easily be added to the scoring scheme by future researchers.

2.8 Conclusions

This paper presents a novel plant trait-based scoring method that allows the comparison of different grass species, based on standardized scores that are associated with the control of soil erosion processes in GWWs. The method was used to compare the performance of different plant species (as monocultures and in mixtures) when established in summer or autumn, and subjected to three different rainfall scenarios, using a short-term, microcosm trial. The grass species treatments that showed the greatest potential for soil erosion mitigation, based on engineering plant traits, under summer establishment were the conventional grass mix (Conv), Fest_1 + 2 + Conv and Fest_2. For autumn establishment, the most suitable species were the Fest_1 + 2, Fest_1 + 2 + Conv and the Conv grass mix. Thus the season in which the GWW is established needs to be considered when selecting species or a mixture of species for soil erosion control. However, Fest_1 + 2 + Conv and Conv performed well when planted in either summer or autumn, and would therefore be suitable year-round options. Thereafter, local factors such as slope and land management will need to be considered before implementing and designing grassed waterways. The scoring method can be adapted to incorporate other factors affecting erosion processes and for other soil erosion control features, such as buffer strips and swales.

2.9 References

Baxter, C., Rowan, J. S., McKenzie, B. M., & Neilson, R. (2013). Understanding soil erosion impacts in temperate agroecosystems: Bridging the gap between geomorphology and soil ecology. *Biogeosciences Discussions*, 10, 7491–7520. https://doi.org/10.5194/bgd-10-7491-2013

Bingcheng, X., Feng-Min, L., & Lun, S. (2010). Seasonal root biomass and distribution of Switchgrass and Milk vetch intercropping under 2:1 row replacement in a semiarid region in Northwest China. *Communications in Soil Science and Plant Analysis*, 41(16), 1959–1973. https://doi.org/10.1080/00103624.2010.495806

Boger, A. R., Ahiablame, L., Mosase, E., & Beck, D. (2018). Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. *Environmental Science: Water Research & Technology*, 4, 478–486. https://doi.org/10.1039/C7EW00230K

Burylo, M., Rey, F., Mathys, N., & Dutoit, T. (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms*, 37, 1463–1470. https://doi.org/10.1002/esp.3248

Chase, J. M. & Myers, J. A. (2011). Disentangling the importance of ecological niches from stochastic processes across scales. *Philosophical Transactions of the Royal Society B*, 336 (1576), 2351–2363. https://doi.org/10.1098/rstb.2011.0063

De Baets, S., & Poesen, J. (2010). Empirical models for predicting the erosion-reducing effects of plant roots during concentrated flow erosion. *Geomorphology*, 118(3–4), 425–432. https://doi.org/10.1016/j.geomorph.2010.02.011

De Baets, S., Poesen, J., Knapen, A., & Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms*, 32(9), 1323–1345. https://doi.org/10.1002/esp.1470

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J., & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34(10), 1374–1392. https://doi.org/10.1002/esp.1826

Deléglise, C., Meisser, M., Mosimann, E., Spiegelberger, T., Signarbieux, C., Jeangros, B., & Buttler, A. (2015). Drought induced shifts in plants traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. *Agriculture, Ecosystems & Environment*, 213, 94–104. https://doi.org/10.1016/j.agee.2015.07.020

Evans, R. (1990). Soils at risk of accelerated erosion in England and Wales. *Soil Use and Management*, 6(3), 125–131.

Fariaszewska, A., Aper, J., Van Huylenbroeck, J., De Swaef, T., Baert, J., & Pecio, L. (2020). Physiological and biochemical responses of forage grass varieties to mild drought stress under field conditions. *International Journal of Plant Production*, 14, 335–353. https://doi.org/10.1007/s42106-020-00088-3

Fiener, P., & Auerswald, K. (2006). Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research*, 87(1), 48–58. https://doi.org/10.1016/j.still.2005.02.035

Gavrić, S., Leonhardt, G., Marsalek, J., & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment*, 669, 431–447. https://doi.org/10.1016/j.scitotenv.2019.03.072

Ghestem, M., Cao, K., Ma, W., Rowe, N., Leclerc, R., Gadenne, C., & Stokes, A. (2014). A framework for identifying plant species to be used as ‘ecological engineers’ for fixing soil on unstable slopes. *PLoS One*, 9(8), e95876. https://doi.org/10.1371/journal.pone.0095876

Govers, G. (1990). *Empirical relationships for the transport capacity of overland flow*. Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987), 189, 45–63.

Gutteridge, R. J., Zhang, J. P., Jenkyn, J. F., & Bateman, G. L. (2005). Survival and multiplication of Gaeumannomyces graminis var. tritici (the wheat take-all fungus) and related fungi on different wild and cultivated grasses. *Applied Soil Ecology*, 29(2), 143–154. https://doi.org/10.1016/j.apsoil.2004.11.003

Hewlett, H. W. M, Boorman, L. A. & Bramley, M. E (1987). *Guide to the design of reinforced grass waterways*. London, the United Kingdom: Construction Industry Research and Information Association (CIRIA).

Hollis, J. M., & Hodgson, J. (1974). *Soils in Worcestershire I (Kidderminster*). Harpenden, England: Soil Survey of England and Wales.

Humphreys, M. W., Yadav, R. S., Cairns, A. J., Turner, L. B., Humphreys, J., & Skøt, L. (2006). A changing climate for grassland research. *New Phytologist*, 169(1), 9–26.

IPCC (2013). *Summary for policymakers*. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, (108–112). Cambridge, England: Cambridge University Press.

Leroy, M, Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I., & Marcotte, S. (2016). Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of The Total Environment*, 113–121. https://doi.org/10.1016/j.scitotenv.2016.05.027

Li, C., & Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90–103. https://doi.org/10.1016/j.jhydrol.2018.01.007

Liang, T., Bengough, A.G., Knappett, J.A., MuirWood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & G. J. Meijer. (2017). Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering*, 109B, 207–227. doi: 10.1016/j.ecoleng.2017.06.067

MacLeod, C. J. A., Humphreys, M. W., Whalley, R., Turner, L. B., Binley, A., Watts, C. W., Haygarth, P. M. (2013). A novel grass hybrid to reduce flood generation in temperate regions. *Scientific Reports*, 3, 1–7. https://doi.org/10.1038/srep01683

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L., & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755–763. https://doi.org/10.1016/j.catena.2016.08.036

Met Office (2018a). *Ross-on-Wye climate*. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/public/weather/climate/gcnpm68t8

Met Office (2018b). *Land projection maps: Probabilistic projections*. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/landprojection-maps

Morgan, R. P. C. (2007). *Vegetative-based technologies for erosion control*. In A. Stokes, I. Spanos, J. E. Norris, & E. Cammeraat (Eds.), Eco-and ground bio-engineering: The use of vegetation to improve slope stability. Developments in plant and soil sciences (Vol. 103). Dordrecht, The Netherlands: Springer.

Morgan, R. P. C., & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach*, London: E & FN Spon.

National Audit Office. (2010). Ta*ckling diffuse water pollution in England (online),* London: National Audit Office Retrieved from https://www.nao.org.uk/wp-content/uploads/2010/07/1011188.pdf

Pimentel, D., & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, 3(3), 443–463. https://doi.org/10.3390/agriculture3030443

Pirchio, M., Fontanelli, M., Frasconi, C., Martelloni, L., Raffaelli, M., Peruzzi, A., Grossi, N. (2018). Autonomous mower vs. rotary mower: Effects on turf quality and weed control in tall fescue Lawn. *Agronomy*, 8(2), 15. https://doi.org/10.3390/agronomy8020015

Prosser, I. P., Dietrich, W. E., & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology*, 13(1–4), 71–86. https://doi.org/10.1016/0169-555X(95)00020-6

Regent Instruments (2016). *WinRHIZO 2016 Basic, Reg, Pro & Arabidopsis For Root Measurement*. Canada: Regent instruments Canada Inc.

Routschek, A., Schmidt, J., & Kreienkamp, F. (2014). Impact of climate change on soil erosion - a high-resolution projection on catchment scale until 2100 in Saxony/Germany. *Catena*, 121, 99–109. https://doi.org/10.1016/j.catena.2014.04.019

Singh, B. K., Munro, S., Potts, J. M., & Millard, P. (2007). Influence of grass species and soil type on rhizosphere microbial community structure in grassland soils. *Applied Soil Ecology*, 36(2–3), 147–155. https://doi.org/10.1016/j.apsoil.2007.01.004

Unagwu, B.O. (2017). *Application of organic amendments to restore soil health and productivity of a degraded soil (PhD thesis).* Cranfield University, Cranfield.

Vannoppen, W., Vanmaercke, M., De Baets, S., & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666–678. https://doi.org/10.1016/j.earscirev.2015.08.011

Wright, A. J., Ebeling, A., Kroon, H., Roscher, C., Weigelt, A., Buchmann, N.,Eisenhauer, N. (2015). Flooding disturbances increase resource availability and productivity but reduce stability in diverse plant communities. *Nature Communications*, 6, 60–92. https://doi.org/10.1038/ncomms7092

Zhang, B., Zhang, G., Yang, H., & Zhu, P. (2019). Temporal variation in soil erosion resistance of steep slopes restored with different vegetation communities on the Chinese loess plateau. *Catena*, 182, 104170. https://doi.org/10.1016/j.catena.2019.104170

Zuazo, V. H. D., & Pleguezuelo, C. R. R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, 28(1), 65–86. https://doi.org/10.1051/agro:2007062

3 Grass species selection to control concentrated flow erosion in grassed waterways

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3.1 Abstract

Grassed waterways are typically situated in natural flow paths and are designed to prevent scouring which can lead to rill or gully formation and to encourage sediment deposition. In the UK, climate change is predicted to lead to warmer, wetter winters and hotter, drier summers, as well as increased frequency of extreme rainfall events. Therefore, it is vital that grass species that are effective in reducing soil erosion in grassed waterways under a changing climate are studied. The aim of this study is to assess the efficacy of grass species to prevent soil erosion under concentrated flow conditions in grassed waterways. Experimental treatments included bare soil, a conventional grass mixture of *Lolium perenne* and *Festuca rubra* (100 kg ha^{-1}), (Conv) *Festulolium cv Prior* (50 kg ha^{-1}) (Fest_1), *Festulolium cv Prior* (30 kg ha^{-1}) and *Festulolium Bx511* (30 kg ha^{-1}) (Fest_1+2), and all species combined (30+ 30+50 kg ha^{-1}) (Fest_1+2+Conv). Treatments were established in macrocosms (1.2 x 1.0 x 0.5 m) in sandy clay loam soil. At 6-weeks post-Emergence, undisturbed mesocosms (0.3 x 0.1 x 0.1 m) of each experimental treatment were excavated in quadruplicate. Above ground plant traits were measured: ground cover (%), Emergence (%), number of stems, number of tillers, stem diameter (mm) and stem area density (mm^2 mm^{-2}). Below ground traits included: root diameter (mm), root total surface area (cm^2) , total length (cm) of fine roots (≤0.25 mm ⌀) and

total root length (cm). Sward height treatments were 1.0 cm or 3.0 cm. Each mesocosm was subjected to a concentrated flow event of increasing magnitude within a hydraulic flume (Advanced Soil and Sediment Erosion Testing Environment (ASSETE)). Inflow rates ranged from 0.2-0.6 l s^{-1} for bare soil treatments, 0.2-0.8 l s^{-1} for 3.0 cm sward treatments and 0.2-1.4 l s^{-1} for 1.0 cm sward treatments. This was due to the bare soil treatments being eroded by 0.6 l s^{-1} and because of constraints due to the hydraulic flume. Treatment performance was assessed in terms of reduction of flow shear stress, flow velocity and sediment concentration. No significant differences ($p<0.05$) were found in flow shear stress and flow velocity for experimental grass treatments for a 3.0 cm sward height. For 3.0 cm grass sward height experimental treatments, significant differences in flow shear stress were found for the 0.6 – 0.7 l s^{-1} inflow rates. Significant differences for flow velocity were found at inflow rates of 0.6 – 0.8 l s^{-1} for the 1.0 cm grass sward height treatments. Sediment concentration was significantly reduced in all grass treatments as compared to the bare soil control ($p<0.05$), but no significant differences were found between experimental grass treatments. The plant trait measurements were used to explain these results. Significant differences ($p<0.05$) were observed between species treatments for the number of stems, number of tillers, stem area density, root diameter, root total surface area and total length (cm) of fine roots (≤0.25 mm ⌀). These significant differences in plant traits did not manifest in significant differences in sediment concentration between the grass species treatments but could be used to explain minor differences observed in flow shear stress and flow velocity. This suggests that overall, specific plant traits, grass stand height or species composition (monoculture or mixture) did not affect flow characteristics or sediment concentrations.

3.2 Highlights

- Species monocultures and mixes were tested for soil erosion control via a hydraulic flume.

- Increasing magnitudes of concentrated flow were used to assess the ability of grass species treatments to mitigate soil erosion.

• Plant traits were analysed with regards to their effect on soil erosion mitigation indicators (flow shear stress and velocity, and sediment concentration).

• Differences in species monocultures and mixtures and plant traits did not affect sediment concentration.

3.3 Introduction

3.3.1 Concentrated flow erosion and its effects

Soil erosion is a problem which occurs globally and therefore it is of high importance (Morgan and Rickson, 1995; Burylo et al., 2012; Pimentel and Burgess, 2013; Amundson et al., 2015; Borrelli et al., 2020). Soil erosion processes involve the detachment, entrainment, transport, and deposition of soil particles (Morgan and Rickson, 1995). A study in the UK has shown soil loss from 24 - 383 m^3 ha^{-1} (Boardman 2009). Boardman (2013) also reports annual erosion rates of 10 – 45 t ha^{-1} for bare soil and 0.1 – 3 t ha^{-1} for grass on sandy loam soil in the UK. However, it is not just the UK that is subject to soil erosion. Montgomery (2007) reports surface lowering rates from 0.01 mm y^{-1} to < 10mm y^{-1}. Erosion rates in the US are as high as 75 Gt y^{-1} (Wilkinson & McElroy 2007). Soil loss has been shown to be 18.2 t ha^{-1} yr^{-1} in China (Liu et al., 2020). Soil loss rates on farmland are between <0.05 - >20 t ha^{-1} yr^{-1} in France (Boardman et al., 2018).

Concentrated water flow most often occurs on hillsides and usually forms in specific natural pathways. Soil erosion by concentrated flow has been exacerbated due to human activity and has detrimental impacts on agricultural land (Montgomery 2007; Restrepo & Syvitski (2006) Zhang et al., 2019; Borreli et al., 2020). These impacts can include negative environmental and economic outcomes (Montgomery, 2007; Morgan, 2005; Pimentel and Burgess, 2013; Borreli et al., 2020). On-site impacts on agricultural land include lowered soil fertility (Borreli et al., 2020). Offsite impacts (Wilkinson & McElroy 2007; Collins et al., 2007; Collins et al., 2009; Rickson 2014; Boardman et al., 2019; National Audit Office, 2020) include decline in water quality and sediment loading of localised water bodies (Wilkinson & McElroy 2007; Collins et al., 2007; Collins et al., 2009; National Audit Office, 2020). In the UK 76% of sediment loading is due to agricultural land and inappropriate management practices which promote erosion and generate runoff (Collins et al., 2009). Similarly, in Africa agricultural practices account for 75% of sediment loading (Kroese et al., 2020).

Soil erosion caused by concentrated flow can be mitigated by placing a grassed waterway (GWW) on natural flow pathways (Prosser at al., 1995; Mekonnen et al., 2014; Rickson 2014). GWWs can prevent the formation of rills and gullies which would have otherwise been formed (Dabney et al., 2004). The plant traits of the grass, both above and below ground, will affect slope hydrology and provide erosion control (Morgan and Rickson, 1995; Fiener & Auerswald 2003; Vannoppen et al., 2015).

GWWs have been shown to reduce the soil erosion risk on agricultural land, including on-site impacts (Zhang et al., 2019) and offsite impacts (Alewell 2020). GWWs not only decrease soil erosion, they will also result in less phosphorous (P) and nitrogen (N) reaching and contaminating water bodies (Alewell 2020), causing the degradation of freshwater ecosystems (National Audit Office 2010). However, not all GWWs will be the same, different monocultures or mixtures of species will be better suited for different environmental conditions, therefore each GWW must be designed for each specific location. Further, each site will have different natural flow pathways where the GWW will need to be placed in order to be most effective at preventing rill and gully formation. GWWs are specific to each site and therefore should be designed for the expected storm events (U.C. Cooperative Extension 2003)

Grasses which have been used in GWWs in the USA include red fescue (Festuca rubra), tall fescue (Festuca arundinacea), smooth brome (Bromus inermis), perennial ryegrass (Lolium perenne) (Staton & Bosch 2015), quack grass (Elytrigia repens), orchard grass (Dactylis glomerata) and oat grass (Arrhenatherum elatius) (Fiener 2003). Furthermore, differences in grass physical plant traits will influence their efficacy at erosion control within GWWs (De Baets et al., 2019; Mekonnen et al., 2016; Liang et al., 2017).

Grass species have specific physical plant traits which control the detachment and entrainment of soil and encourage deposition of suspended sediment (Lees at al., 2020). The traits which are pertinent to each soil erosion sub-process have been detailed and outlined in Lees et al., (2020). Grass traits which influence soil erosion processes in GWWs include % cover (Morgan and Rickson, 1995), grass sward height (cm), % germination, stem diameter (mm), number of stems, stem area density (mm^2 mm^{-2}) (De Baets et al., 2009), total root length (cm) (Mekonnen et al., 2016), total length of fine roots (≤0.25 mm ⌀) (cm) (Liang et al., 2017), root diameter (mm) (Hai, 2012) and root total surface area (cm^2) (Vannoppen et al., 2015).

Grass traits can also influence the soils' susceptibility to erosion (erodibility) (Lees et al., 2020; De Baets et al., 2009; Vannoppen et al., 2015), and thus the critical erosion thresholds will change for different grass species (as a function of their traits). Therefore, different species of grass will likely affect flow velocity and thus whether the critical flow velocity at which erosion initiates is actually reached.

Above ground grass traits apply a frictional component to the concentrated flow (Al-hamdan et al., 2012). Germination and emergence rates will contribute to the final % cover, number of stems, total number of tillers and the stem area density which all influence soil erosion (Morgan and Rickson, 1995; De Baets et al., 2009: Mekonnen et al., 2016; Liang et al., 2017). All above ground plant traits will dissipate the energy of flow, so critical thresholds needed to detach, entrain or transport sediment will not be reached. In fact, the reduction of flow energy (and associated transport capacity) due to vegetation may cause deposition of sediment already entrained in the flow. By increasing Mannings n, flow velocity and flow shear stress will decrease, reducing detachment, entrainment and transport of eroded soil and encouraging the deposition of sediment. If the shear stress is decreased, then there will likely be less soil erosion. The ability of the flow to cause erosion (erosivity) in this study is determined by both flow velocity and shear stress.

3.3.2 Climate change effects on erosion

Climate change will impact the frequency, intensity and duration of rainfall events (Baxter at al., 2013; IPCC 2013: Westra et al., 2014) resulting in soil erosion being more pronounced in the future. With an increase in intensity of rainfall events, both sediment yield and runoff rates increase (Almeida et al., 2021). Moreover, global temperatures are set to change, with in the UK, hotter, drier summers and warmer, wetter, winters predicted (Met Office, 2018). Consequently, the efficacy of conventional grass species currently being used in the UK in GWWs to reduce soil erosion via concentrated flow may be modified due to potential changes in key plant physical traits. For example, species of grass may not be able to survive in both waterlogged and drought conditions and as such some grass species may not be able to provide year-round erosion mitigation in GWWs. Novel Festulolium species can thrive in these conditions and as such are good candidates for erosion control in GWWs under a changing climate (Macleod, 2013). The Festulolium grass species investigated in this study have been taken forward from the findings of Lees et al., (2020), as they were shown to have plant traits suitable for erosion control in both flooded and drought conditions.

3.3.3 Scientific gap and objectives of this study

The scientific gap to be addressed by this study is to evaluate the efficacy of novel grass species either as monocultures or mixtures to withstand concentrated flow events of increasing magnitude. Blanco-Canqui et al., (2004) found that sediment load was higher in plots where there was only one species as opposed to plots where there were two species of grass. Berendse et al., (2015) also observed that higher species diversity yielded less sediment. The Festulolium varieties evaluated in this study namely Festulolium cv Prior and Festulolium Bx511 have shown good potential to be used in GWWs due to their plant physical traits (Lees et al., 2020) and ability to mitigate soil erosion (Macleod et al., 2013). Therefore, the aims of this study are to take these novel species, which are adapted to future climate conditions (drought, flooding and temperature changes), and to evaluate their suitability within GWWs as compared with a conventional grass mix. A further aim of this study is to see if differences in grass traits will significantly affect shear stress, flow velocity and sediment concentration.

This study also aims to address another evidence gap: does sward height (1.0 cm or 3.0 cm) (and thus grass management regime) affect the ability of the different grass treatments to control soil erosion.

3.4 Methodology

3.4.1 Species selection and seeding rates

The species treatments and their seeding rates, used within this study, were carried forward from the findings of Lees et al., (2020) (Chapter 2 of this thesis). This allows fair comparisons between the two studies and to provide validation for the devised species ranking system (Chapter 5 Plant Trait Ranking System). The novel grass species were previously selected for their ability to grow under flooded and drought conditions. They also had suitable plant traits to mitigate against soil erosion. As shown in Table 3-1, the species treatments comprised a conventional mixture of *Lolium perenne* (75 %) and *Festuca rubra* (25 %) (Conv), *Festulolium cv Prior* (Fest_1), *Festulolium cv Prior* and *Festulolium Bx511* (Fest_1+2), and *Festulolium cv Prior* with *Festulolium Bx511* and the conventional mixture (Fest_1+2+Conv). A bare soil treatment was used as a control.

Table 3-1: Treatment code, grass species, and seeding rates (kg ha^{-1})

Treatment Code	Grass Species	Seeding rate* (kg ha^{-1})
Bare soil control	n/a	n/a
Fest_1	*Festulolium cv Prior*	50
Conv	Conventional mixture consisting of *Lolium perenne* (75%) and *Festuca rubra* (25%)	100
Fest_1+2	*Festulolium cv Prior*	30
	Festulolium Bx511	30
Fest_1+2+Conv	Conventional Mix	50
	Festulolium Bx511	30
	Festulolium cv Prior	30

*Seeding rates are based on personal communications from J. Harper, IBERS, Aberystwyth (14 March, 2018) and P. Brown, Frontier Agriculture (21 March, 2018).

3.4.2 Macrocosm preparation

Five macrocosms (4 grass treatments and a bare soil treatment) (0.8 x 1.20 x 0.50 m) (Figure 3-1) were packed to a dry bulk density (BD) of 1.27 g cm^{-3} to simulate conditions of a specific farm in Ross-On-Wye where soil erosion is a problem. The BD is below the threshold (1.60 g cm^{-3}) which will restrict root growth for this type of soil and falls within the ideal BD for plant growth (<1.40 g cm^{-3}) (USDA 2022). The same BD was used for all treatments as it can affect soil erodibility (Lick & McNeil 2001; Grabowski et al., 2011). Bulk density was also kept constant between treatments as it affects plant traits such as root length, root dry weight, number of tillers and grass yield, which can all influence soil erosion mitigation (Houlbrooke et al., 1997). The soil texture was a sandy clay loam, 20%

clay, 28% silt and 52% sand. Once all the soil was packed within the macrocosm the surface was levelled.

Figure 3-1: Experimental macrocosm set up.

Prior to seeding, the surface of each macrocosm was divided into 12 different sections and the seeds weighed out for each section to ensure uniform coverage. Clumping of grass cover can lead to concentrated flow paths which would increase soil erosion (Morgan 2007). After seeding, a further 1.0 cm of soil was applied on top of the seeds before being gently compressed to ensure a good seed/soil contact.

The grass was grown outside for 4 weeks, following a 2-week establishment period (Lees et al., 2020) under UK summer conditions from June 17th to the end of July 2019. According to the Met Office (2022), the maximum temperature for June and July 2019 was 24.1^{o}C and the minimum temperature for June and July 2019 was 10.8 ^{o}C at the closest weather station (Cambridge NIAB). The seeding of the macrocosms was staggered to allow for the same growth period for each treatment (as the treatments could not be tested for erosion control performance at the same time). The macrocosms received the same volume of water (2.5 l), twice a day. This allowed a volumetric soil moisture content of at least 15% to be maintained across all experimental treatments. Within each macrocosm, the soil moisture content at 0.1 m depth intervals to 0.4 m below the surface was measured, at least weekly, using a Delta-T PR2 profile probe (Delta-T) (Appendix A).

3.4.3 Mesocosm preparation

After 6 weeks, sub-samples were excavated using stainless-steel mesocosms (0.3 x 0.1 x 0.1 m) (Figure 3-2), which comprised of a stainless-steel insert and a perforated stainless-steel base, prior to testing in the Advanced Soil and Sediment Erosion Testing Environment (ASSETTE) hydraulic flume (Figure 3-3 & Figure 3-4).

Figure 3-2 Sub-samples using stainless-steel inserts for the bare soil treatment.

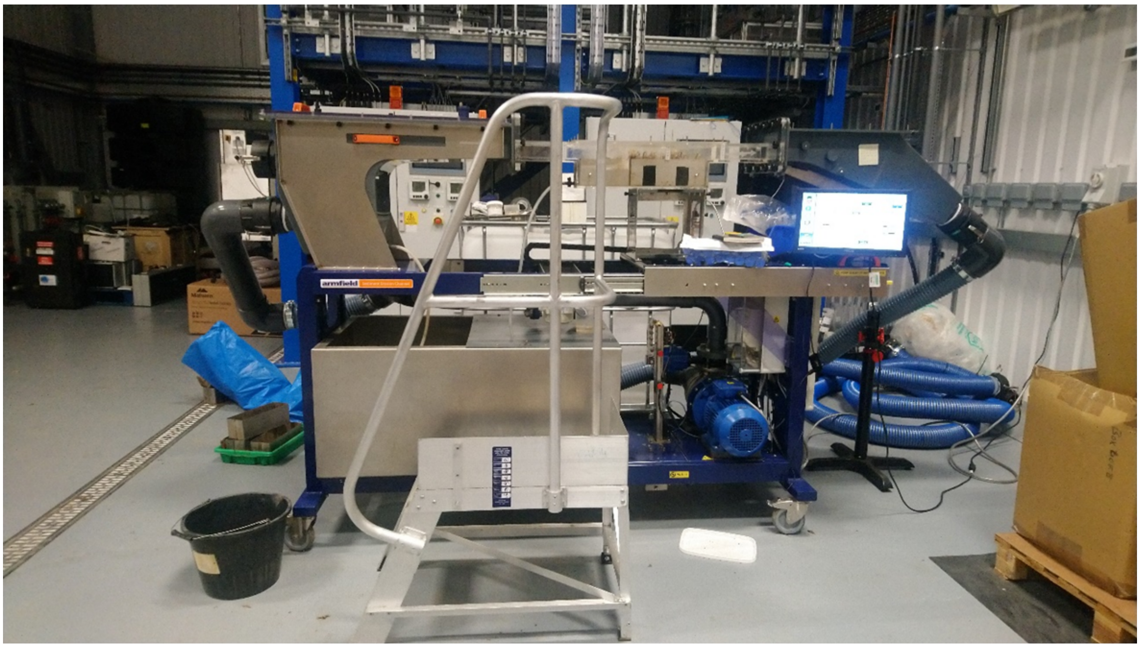

Figure 3-3: Hydraulic flume experimental set up.

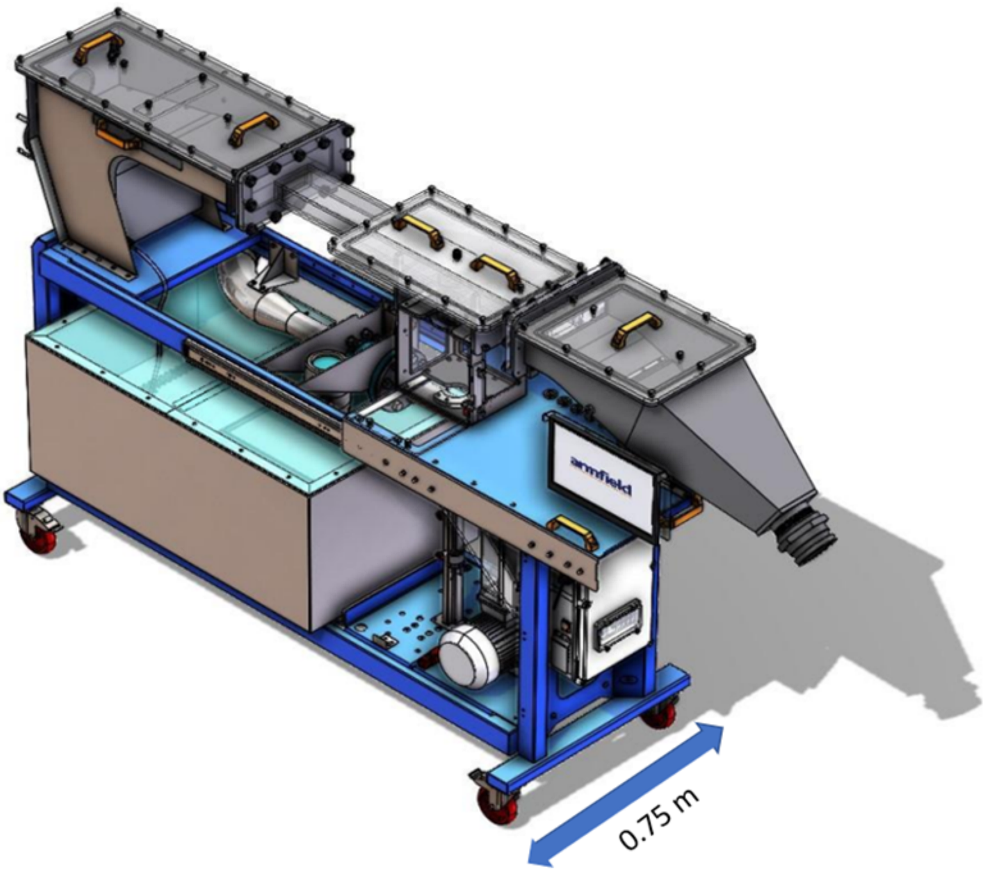

Figure 3-4 Technical drawing of hydraulic flume (Armfield 2019).

The stainless-steel insert was carefully hammered into the macrocosm. Soil around one side of the insert was removed, and a perforated base inserted and secured. Once removed, the mesocosm was saturated for 7 hours before being left to drain overnight prior to testing to ensure that all treatments were tested at approximately field capacity moisture content. It was important that all mesocosms had the same initial soil moisture state as a decrease in soil moisture at rooting depth can cause an increase in soil loss (Baruti 2004). On the other hand, if the soil moisture content increases too much this will result in a decrease in soil shear strength (Bryan 2000). There were two grass sward height treatments, 1.0 cm and 3.0 cm to investigate how management practices (such as mowing regime) and over-grazing by livestock can influence soil erosion.

3.4.4 Emergence

Emergence (%) was measured by counting how many seeds were broadcast in a random selection of 3 of the 12 sections within the macrocosm. This was to check that the grass would grow in a uniform sward to avoid the likelihood of flow concentrations and vortex erosion associated with patchy vegetation (Morgan and Rickson 1995; Morgan 2007). The number of seeds was then compared to the number of emerging seedlings in that corresponding area after the 2-weekestablishment period. Mean germination (%) (n=3) was determined for each macrocosm.

3.4.5 Number of Stems

The total number of stems was counted manually for each mesocosm. From this, stem area density could be determined. A high stem area density (SAD) of >10,000 stems m^{-2} is enough to reduce soil detachment by concentrated flow (Morgan 2007).

3.4.6 Number of Tillers, Stem Diameter and Stem Area Density

The number of tillers and stem diameter (mm) were determined by randomly selecting five individual grass plants per treatment replicate following the method of Liu et al., (2018). This represented between 5 – 10 % of the plants per mesocosm, depending on the seeding density. The number of tillers per plant was counted manually and stem diameter was measured using a digital Vernier gauge (Liu et al., 2018). For both grass sward heights, the stem diameter was measured as close to the soil surface as possible, at a height of ≤5 mm, so that the soil was not disturbed, following the method of De Baets et al., (2009) who also measured stem diameter at the base. This was to ensure that measurement of stem diameter was comparable between treatments at the place where the vegetation was likely to have greatest effect on flow properties. The stem diameter was measured to determine the SAD ($mm^2\ mm^{-2}$). SAD, as well as stem diameter and number of tillers are indicators of the frictional component imparted to flow by the vegetation, resulting in a dissipation of flow energy. This can lead to reduced detachment and runoff capacity of flow for transport (Stagge et al., 2012), and even sedimentation (Gavrić et al., 2019) due to the increased sediment trapping efficiency (Mekkonen et al., 2016).

Stem area density was calculated using the following equation (Lees et al., (2020), after De Baets et al., (2009)).

Equation 3-1:

$$\boldsymbol{Stem\ Area\ Density} = \frac{\boldsymbol{surface\ area\ of\ stems\ (mean\ stem\ diameter) * number\ of\ stems}}{\boldsymbol{area\ of\ microcosm}}$$

3.4.7 Root traits

After each mesocosm had been tested in the hydraulic flume (ASSETTE), three cylindrical soil cores (0.46 m cm internal diameter 0.1 m long) were taken at equidistances along the length of the mesocosm. The roots were washed using a pressure sprayer, then sieved following the method of Genney et al., (2000), using a 500 µm sieve. Root traits were measured using the methods described in Lees et al., (2020).

For every soil core, a subset of the roots (0.1 - 0.2 g) were image-processed using WinRhizo software (Regent Instruments, 2016). Roots were stored at <4^{o}C in a 15 % ethanol solution before analysis (Bainard et al., 2010). The following root traits were determined for each core: root diameter (mm), root total surface area (cm^2) (De Baets et al., 2007), total length (cm) of fine roots (≤0.25 mm ⌀) according to Liang et al., (2017), and total root length (cm) (Mekonnen et al., 2016). The means for all below ground traits were determined (n=3). These root traits are closely related to erosion processes as they provide soil mechanical reinforcement by increasing soil cohesion, soil / root adhesion and aggregate stability through root exudates (Vanoppen et al., 2015).

3.4.8 Hydraulic flume set up

Each mesocosm was subject to an incrementally increasing concentrated flow event using a hydraulic flume ASSETTE (Figure 3-). The flume was used at a constant slope gradient of 5 degrees. This is because slope gradient will affect the erosivity of flow due to gravity and slope gradient is directly linked to soil erosion (Zhang et al., 2015). Indeed, during pre-testing, a slope gradient of 0 degrees generated low flow velocities and minimal soil erosion. Each mesocosm was placed into the flume and all joints were sealed with Vaseline to ensure a seamless interface between the mesocosms and flow bed of the ASSETTE. Another blank stainless-steel insert (0.2 x 0.1 x 0.1 m) was placed next to the experimental treatment to facilitate insertion and extraction of the mesocosms. Both inserts were level with each other to ensure flow over them was not interrupted.

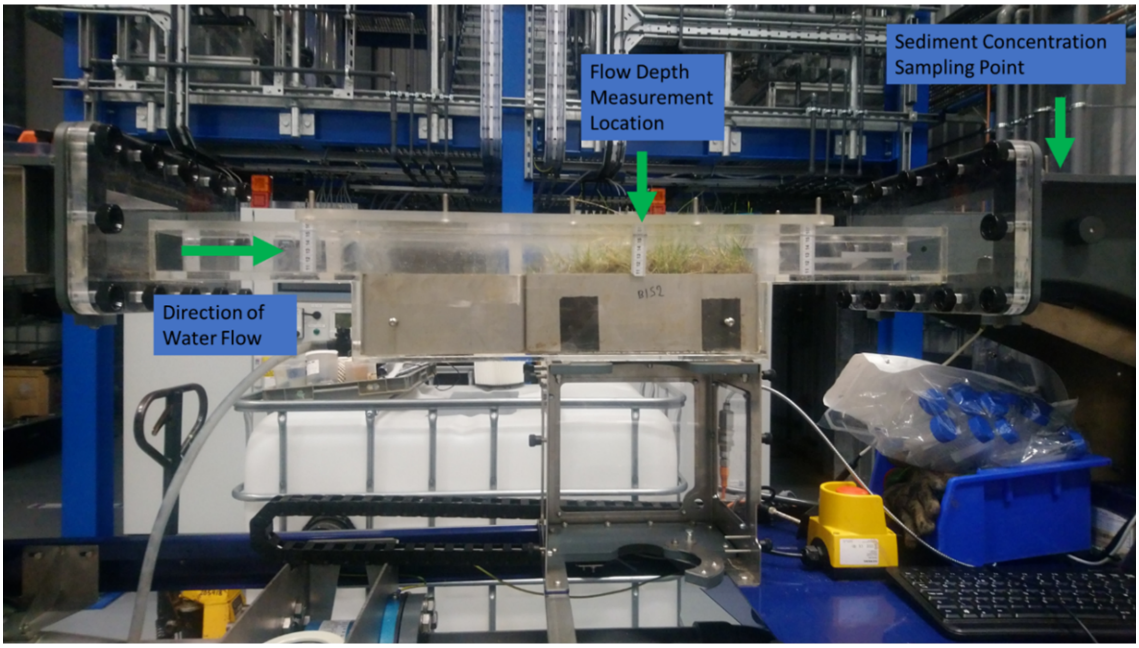

Figure 3-5: Photo of the hydraulic flume ASSETTE with the flow depth measurement location at the middle of the sample (0.15 m), direction of water flow and the sediment concentration sampling point.

During the experimental runs, it became apparent that not all inflow rates could be used for all treatments (Table 3-2). The bare soil (B) treatment replicates were subjected to a continuous flow event of 5 mins duration, with inflow rates ranging from 0.2 - 0.6 l s^{-1} The inflow rate was raised in increments of 0.1 l s^{-1} at 1 min intervals. All bare soil treatments were completely eroded at the inflow rate of 0.6 l s^{-1}, therefore the flow event was ended at that point. The 0.01 m grass sward height treatments were subjected to a continuous flow event of 7 min duration with inflow rates ranging from 0.2 – 1.4 l s^{-1} with the inflow rates being raised at one-minute intervals in increments of 0.2 l s^{-1} (Table 3-2). The 3.0 cm grass sward height treatments were subjected to a continuous concentrated flow event of 7 min duration with inflow rates ranging from 0.2 – 0.8 l s^{-1}, raised at one-minute intervals in increments of 0.1 l s^{-1} (Table 3-2). When the 3.0 cm treatments were undertaken, the grass sward reduced the flow velocity and increased flow depth, resulting in the flume nearly overtopping. Consequently, the inflow rate could not be increased any further due to the physical constraints of the flume design.

Table 3-2: Flow rate conditions for the different vegetation treatments

	Flow rate (l s^{-1})									
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.2	1.4
Bare soil	✓	✓	✓	✓	✓					
1.0 cm sward height	✓		✓		✓		✓	✓	✓	✓
3.0 cm sward height	✓	✓	✓	✓	✓	✓	✓			

3.4.9 Shear stress and flow velocity calculations

Flow depth (cm) was determined for each inflow rate using a GoPro camera, and a graduated scale taped to the side of the flume at the middle of the mesocosm sample (i.e. 15.0 cm from the leading edge of each mesocosm sample). Using the captured HD video, flow depth was measured so that shear stress and flow velocity could be calculated to estimate the impact of the grass treatments on these flow characteristics. The water depth was measured for each incremental increase in inflow rate at :15 seconds :30 seconds, and :45 seconds, mean water depth (cm) at each incremental increase in inflow rate was then determined (n=3) for each experimental sample, of which there were 4 replicates, and used to calculate flow shear stress and flow velocity.

Shear stress (Pa) was calculated using the following equation which has been used in a number of studies (Lave & Avouac 2001; Montieth & Pender 2005; Knapen et al., 2007; Khodashenas et al., 2008; Schwendel et al., 2010; Somsook et al., 2021; Cheng & Zhang 2022; Liu et al., 2022; Lou et al., 2022; Sun et al., 2022; White et al., 2022; Xiao et al., 2022; Ye et al., 2022; Lou et al., 2023). As well as being used for field studies (Sun et al., 2022; Ye et al., 2022; Lou et al., 2023) the equation has previously also been applied to flume studies (Montieth

& Pender 2005; Liu et al., 2022; White et al., 2022). Parameters are defined as pw as water density (1000 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), R is the hydraulic radius, and S is the slope angle of soil surface.

Equation 3-2: $\boldsymbol{Shear\ Stress\ (Pa) = pwgRS}$

The Hydraulic radius was calculated using the following equation. Manning's n was assumed to be 0.03 as that was the median value for uniform very short grass swards (<50 mm) taken from Morgan & Rickson (2005).

Equation 3-3: $\boldsymbol{Hydraulic\ radius = \frac{flow\ velocity\ x\ mannings\ n}{(slope^{0.5})^{1.5}}}$

Flow velocity (m s^{-1}) was calculated using the following equation, the width of the flume (m) and the inflow rates (l s^{-1}) were known. The water depth (m) and flume dimensions were used to calculate the cross-sectional area of flow.

Equation 3-4: $\boldsymbol{Flow\ Velocity\ (m\ s^{-1}) = Inflow\ rate(l\ s^{-1}) / Cross\ sectional\ area\ (m^2)}$

3.4.10 Sediment Concentration

Sediment samples were collected during each continuous concentrated flow event. At each inflow rate two water samples were taken down flow of the mesocosm using 50 ml centrifuge tubes (Location marked on Figure 3-). These water samples were subsequently filtered through pre-weighed No. 42 Whatman filter papers that had been previously oven dried for 24 hours at 105°C. The mass (g) of any sediment collected on the filter paper was determined following oven drying for 24 hours at 105°C.

3.4.11 Statistical Analysis

All results (i.e. plant traits, flow shear stress, flow velocity, sediment concentration) were normalised and subject to a one-way ANOVA and a Fisher LSD *post-hoc* test was undertaken, if significant differences ($p \leq 0.05$) were found (Appendix B). It was expected that any significant differences in plant traits would result in significant differences in flow shear stress, flow velocity, and/or sediment concentration.

3.5 Results

3.5.1 Above ground plant traits

The mean number of stems in the Conv treatment (194) was significantly higher than all other treatments (Table 3-3: Means for stems, tillers and stem diameter (n=4), and SAD (n=1) for % Emergence, (n=12) for % ground cover, above ground plant traits, between experimental grass treatments.. Fest_1 had a significantly higher SAD (214 mm^2 mm^{-2}) than all other treatments. Conv had a significantly greater mean number of tillers (4.27) compared to all other treatments. In terms of number of tillers, the Fest_1+2, Fest_1+2+C, and Fest_1 treatment were statistically similar (mean values of 2.8, 2.88, 2.88 respectively). Fest_1 (1.58 mm) had a significantly greater mean stem diameter than all other treatments including Conv (1.12 mm). The Fest_1+2 and the Fest_1+2+Conv treatments showed no significant difference in mean stem diameter (1.35 mm and 1.37 mm respectively).

Table 3-3: Means for stems, tillers and stem diameter (n=4), and SAD (n=1) for % Emergence, (n=12) for % ground cover, above ground plant traits, between experimental grass treatments.

Sample	Number of Stems	Number of Tillers	Stem Diameter (mm)	% Emergence	% Ground Cover	SAD (mm^2, mm^{-2})
Fest_1	113^{b}	4.27^{b}	1.58^{c}	67.9^{a}	29.8^{a}	214^{c}
Conv	195^{c}	2.88^{a}	1.12^{b}	50.3^{a}	24.1^{a}	87.9^{b}
Fest_1+2	138^{a}	2.80^{a}	1.35^{a}	69.8^{a}	28.5^{a}	149^{a}
Fest_1+2+ Conv	147^{a}	2.88^{a}	1.37^{a}	60.6^{a}	33.0^{a}	148^{a}

For each above ground trait, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*) Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*, Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*).

3.5.2 Below ground plant traits

Fest_1+2+Conv had a significantly higher total root length (343 cm) than Conv (291 cm) (Table 3-4). Fest_1+2+Conv had a significantly higher total root length ≤ 0.25cm ⌀ (209 cm) than Conv (155 cm) (Table 3-4). The Fest_1 treatments were not statistically different to the Fest_1+2 treatments (184 and 197 cm) for total root length ≤ 0.25cm in diameter. The Fest_1+2 treatments had a significantly higher mean total root surface area (37 cm^2) compared to the Fest_1 (30 cm^2) and Fest_1+2+Conv (30 cm^2) treatments. Fest_1+2+Conv had a significantly lower mean root diameter (0.33 cm) than Fest_1+2 (0.41 cm) (Table 3-4).

Table 3-4: Below ground plant traits (n=4): total root length (cm), total root length (cm) (<0.25cm in diameter); total root surface area (cm2); and mean root diameter (cm) for the 4 grass treatments.

Treatment	Total Root Length (cm)	Total Root Length (cm) (<0.25cm ⌀)	Total Root Surface Area (cm^2)	Mean Root Diameter (cm)
Fest_1	324[a]	184[ab]	30[a]	0.36[ab]
Conv	291[a]	155[a]	31[ab]	0.39[ab]
Fest_1+2	344[a]	197[ab]	37[b]	0.41[b]
Fest_1+2+Conv	343[a]	209[b]	30[a]	0.33[a]

For each below ground trait, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*, Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*).

3.5.3 Flow shear stress for bare soil treatment

The shear stress for the bare soil treatments ranged from 0.47 Pa at a flow rate of 0.6 l s^{-1} to 1.75 Pa at a flow rate of 0.4 l s^{-1} (Table 3-5). The greatest variations in shear stress occurred at the 0.5 l s^{-1} (0.42 S.E) and 0.4 l s^{-1} (0.35 S.E.) flow rates. The shear stress for the bare soil control treatments has also been linked to the sediment concentration (Section 3.3.1 and Section 3.3.2).

Table 3-5: Mean (n=4) shear stress (Pa) for each inflow rate (l s^{-1}), at the middle of the sample, for the bare soil treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at different inflow rates (l s^{-1})				
Treatment	0.2 (l s^{-1})	0.3 (l s^{-1})	0.4 (l s^{-1})	0.5 (l s^{-1})	0.6 (l s^{-1})
Bare Soil	*0.57 (± 0.22)	*0.93 (± 0.25)	1.75 (± 0.35)	1.19 (± 0.42)	0.47 (± 0.07)

*Sample size n=3

3.5.4 Flow shear stress for the 1.0 cm sward height treatment

For the 1.0 cm grass sward height treatment flow shear stress generally increased as inflow rates increased (Table 3-6). The greatest variance was found within the Fest_1+2 treatment for inflow rates of 1.2 (±0.21 S.E.) and 1.4 l s^{-1} (±0.23 S.E.). Flow shear stress ranged from 0.06 Pa (Fest_1+2 at 0.2 l s^{-1}) – 0.74 Pa (Fest_1+2 at 1.4 l s^{-1}). However, following a One-Way ANOVA there were no significant differences in shear stress between the 1.0 cm grass sward height treatments for any inflow rates. Flow shear stress has also been linked to the sediment concentration for the 1.0 cm sward height (Section 3.3.1).

Table 3-6: Mean (n=4) shear stress (Pa) for each inflow rate (l s^{-1}), at the middle of the sample, for grass species treatments at 1.0 cm sward height. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at different inflow rates (l s^{-1})						
Treatment*	0.2 (l s^{-1})	0.4 (l s^{-1})	0.6 (l s^{-1})	0.8 (l s^{-1})	1.0 (l s^{-1})	1.2 (l s^{-1})	1.4 (l s^{-1})
Conv	0.11[a] (±0.02)	0.24[a] (±0.03)	0.28[a] (±0.02)	0.39[a] (±0.04)	0.48[a] (±0.06)	**0.49[a] (±0.13)	
Fest_1+2+Conv	0.09[a] (±0.02)	0.18[a] (±0.02)	0.23[a] (±0.01)	0.30[a] (±0.01)	0.41[a] (±0.03)	**0.55[a] (±0.07)	***0.52[a] (±0.01)
Fest_1+2	**0.06[a] (±0.01)	0.24[a] (±0.09)	0.36[a] (±0.15)	0.44[a] (±0.14)	0.53[a] (±0.16)	0.66[a] (±0.21)	0.74[a] (±0.23)
Fest_1	**0.09[a] (±0.03)	**0.20[a] (±0.04)	**0.30[a] (±0.02)	**0.39[a] (±0.02)	**0.53[a] (±0.04)	**0.59[a] (±0.10)	**0.65[a] (±0.15)

*Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, *Festulolium cv Prior* and *Festulolium Bx511*, Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*), at the middle of the sample. For each inflow rate, values followed by the same letter are not significantly different (p <0.05) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. **Sample size is n=3. ***Sample size is n=2

3.5.5 Flow shear stress for the 3.0 cm sward height treatment

For a grass sward height of 3.0 cm, the flow shear stress was determined for all inflow rates 0.2-0.8 l s^{-1} (Table 3-7). Flow shear stress ranged from 0.06 Pa (Fest_1 at 0.2 l s^{-1}) to 0.27 Pa (Fest_1 at 0.7 l s^{-1})). There were significant differences in flow shear stress at 0.6 – 0.7 l s^{-1} with the Fest_1 treatment associated with associated with a significantly higher shear stress as comparedcompared to all other 3.0 cm treatments. Flow shear stress has also been linked to sediment concentration for the 3.0 cm grass sward height (Section 3.3.2).

Table 3-7: Differences in mean (n=4) shear stress (Pa) for each inflow rate (l s^{-1}), at the middle of the sample, between the 3.0 cm sward height grass species treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at different inflow rates (l s^{-1})						
Treatment*	0.2 (l s^{-1})	0.3 (l s^{-1})	0.4 (l s^{-1})	0.5 (l s^{-1})	0.6 (l s^{-1})	0.7 (l s^{-1})	0.8 (l s^{-1})
Conv	0.07[a] (±0.01)	0.07[a] (±0.01)	0.08[a] (±0.01)	0.09[a] (±0.01)	0.11[a] (±0.00)	0.11[a] (±0.00)	
Fest_1+2+Conv	0.06[a] (±0.02)	0.09[a] (±0.02)	0.11[a] (±0.04)	0.11[a] (±0.02)	0.12[a] (±0.02)	0.13[a] (±0.02)	0.14[a] (±0.02)
Fest_1+2	0.06[a] (±0.01)	0.07[a] (±0.01)	0.09[a] (±0.01)	0.10[a] (±0.01)	0.11[a] (±0.01)	0.12[a] (±0.01)	**0.13[a] (±0.01)
Fest_1	**0.20[a] (±0.13)	**0.12[a] (±0.05)	**0.15[a] (±0.05)	0.16[a] (±0.03)	0.21[b] (±0.04)	0.27[b] (±0.08)	***0.16[a] (±0.01)

*Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*, Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*), at the middle of the sample. For each inflow rate, values followed by the same letter are not significantly different (p <0.05) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. ** Sample size is n=3. *** Sample size is n=2

At an inflow rate of 0.2 l s^{-1}, the 1.0 cm and 3.0 cm grass sward heights are directly comparable. The flow shear stress ranged from 0.06 – 0.74 Pa for 1.0 cm and 0.06 – 0.27 Pa for 3.0 cm (Table 3-6 and Table 3-7).

3.5.6 Flow velocity for the bare soil treatment

The flow velocity (m s^{-1}) for the bare soil treatments ranged from 0.52 at a flow rate of 0.6 l s^{-1} to 1.24 at a flow rate of 0.4 l s^{-1} (Table 3-8). The flow velocity was the most variable at flow rates 0.2 l s^{-1} (0.376) and 0.3 l s^{-1} (0.399).

Table 3-8: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate (l s^{-1}), at the middle of the sample for the bare soil treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Velocity (m s^{-1}) at different inflow rates (l s^{-1})				
Treatment	0.2 (l s^{-1})	0.3 (l s^{-1})	0.4 (l s^{-1})	0.5 (l s^{-1})	0.6 (l s^{-1})
Bare Soil	0.93 (±0.376)	1.20 (±0.399)	1.24 (±0.169)	0.94 (±0.225)	0.52 (±0.050)

3.5.7 Flow velocity for the 1.0 cm sward height treatment

For the 1.0 cm grass sward treatments, there were no significant differences in flow velocity at inflow rates of 0.2 – 0.4 l s^{-1} and 1.0 – 1.4 l s^{-1} ($p<0.05$) Table 3-9. However, there were significant differences in flow velocity at inflow rates of 0.6 – 0.8 l s^{-1} ($p<0.05$). At 0.6 l s^{-1}, Conv (0.38 m s^{-1}) and Fest_1 (0.39 m s^{-1}) had significantly greater flow velocities than the Fest_1+2 (0.31 m s^{-1}) and the Fest_1+2+Conv (0.33 m s^{-1}) treatments (Table 3-9). Further, at 0.8 l s^{-1} Conv (0.46 m s^{-1}) and Fest_1 (0.57 m s^{-1}) had significantly greater flow velocities than Fest_1+2 (0.45 m s^{-1}) and Fest_1+2+C (0.48 m s^{-1}).

The variance, within experimental treatment replicates, in flow velocity for the 1.0 cm sward height grass treatments ranged from 0.007 – 0.136 m s^{-1} Table 3-9. The significant differences at 0.6 – 0.8 l s^{-1} inflow rates might be due to the relatively low variance (0.007 – 0.034 m s^{-1}) as compared to the other inflow rates. This low variance might also be due to the plant traits being more suited to slow velocity and provide a frictional component against water flow. The values for flow velocity are the same or higher for Fest_1 and Conv for all inflow rates as opposed to all other experimental treatments, however, they might not be significantly higher in some cases due to increased variability within the Fest_1+2 treatment.

Table 3-9: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate (l s^{-1}), at the middle of the sample between the 1.0 cm grass sward treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow velocity (m s^{-1}) at different inflow rates (l s^{-1})						
Treatment	0.2 (l s^{-1})	0.4 (l s^{-1})	0.6 (l s^{-1})	0.8 (l s^{-1})	1.0 (l s^{-1})	1.2 (l s^{-1})	1.4 (l s^{-1})
Conv	0.20^{a} (±0.025)	0.33^{a} (±0.031)	0.38^{b} (±0.020)	0.46^{b} (±0.034)	0.53^{a} (±0.044)	0.54^{a} (±0.047)	
Fest_1	0.17^{a} (±0.020)	0.29^{a} (±0.026)	0.39^{b} (±0.010)	0.46^{b} (±0.010)	0.57^{a} (±0.019)	0.61^{a} (±0.041)	0.74^{a} (±0.010)
Fest_1+2	0.14^{a} (±0.007)	0.33^{a} (±0.080)	0.31^{a} (±0.017)	0.39^{a} (±0.029)	0.45^{a} (±0.110)	0.52^{a} (±0.038)	0.69^{a} (±0.136)
Fest_1+2+Conv	0.17^{a} (±0.024)	0.27^{a} (±0.020)	0.33^{a} (±0.010)	0.39^{a} (±0.007)	0.48^{a} (±0.025)	0.58^{a} (±0.054)	0.56^{a} (±0.011)

*Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). For each inflow rate, values followed by the same letter are not significantly different (p <0.05) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. (n=3) for Fest_1 at inflow rates of 0.2 – 1 l s^{-1}.

3.5.8 Flow velocity for the 3.0 cm sward height treatment

For the 3.0 cm sward height, no significant differences in flow velocity were observed for any of the grass treatments at inflow rates of 0.2 – 0.8 l s^{-1} (Table 3-10). There were no significant differences which might be explained by the low variance within the 3.0 cm sward height experimental grass treatments which ranged from 0.007 – 0.030 l s^{-1}. Sward height treatments of 3.0 cm would be more reliable than 1.0 cm sward height treatments in terms of flow velocity due to the lowered variance within experimental treatments.

Table 3-10: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate (l s^{-1}), at the middle of the sample, between the 3.0 cm grass sward treatment. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow velocity (m s^{-1}) at different inflow rates (l s^{-1})						
Treatment*	0.2 (l s^{-1})	0.3 (l s^{-1})	0.4 (l s^{-1})	0.5 (l s^{-1})	0.6 (l s^{-1})	0.7 (l s^{-1})	0.8 (l s^{-1})
Conv	0.14^a (±0.020)	0.15^a (±0.013)	0.16^a (±0.007)	0.17^a (±0.007)	0.19^a (±0.005)	0.20^a (±0.004)	0.24^a (±0.000)
Fest_1	0.17^a (±0.035)	0.21^a (±0.054)	0.18^a (±0.030)	0.26^a (±0.029)	0.23^a (±0.027)	0.24^a (±0.011)	0.26^a (±0.007)
Fest_1+2	0.14^a (±0.018)	0.15^a (±0.013)	0.17^a (±0.013)	0.18^a (±0.010)	0.20^a (±0.008)	0.21^a (±0.013)	0.23^a (±0.009)
Fest_1+2+Conv	0.13^a (±0.023)	0.17^a (±0.034)	0.15^a (±0.015)	0.20^a (±0.026)	0.21^a (±0.024)	0.22^a (±0.024)	0.24^a (±0.022)

*Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). (n=3) for Fest_1 at 0.3 (l s^{-1}).A One-Way ANOVA was used to determine statistical differences.

The only comparable inflow rate for the differing sward height treatments was 0.2 l s^{-1} as the experiment had been run for the same amount of time and everything was constant aside from the sward height.

3.5.9 Sediment concentration for the 1.0 cm sward height treatment

As expected, the sediment concentration (g l^{-1}) was significantly greater ($p<0.05$) for the bare soil control treatment as compared with all the 1.0 cm grass sward height treatments (Figure 3-4). Although the sediment concentration varied from

1.6 – 2 g l^{-1} for the 1.0 cm grass treatments, there were no significant differences ($p<0.05$) between the grass species.

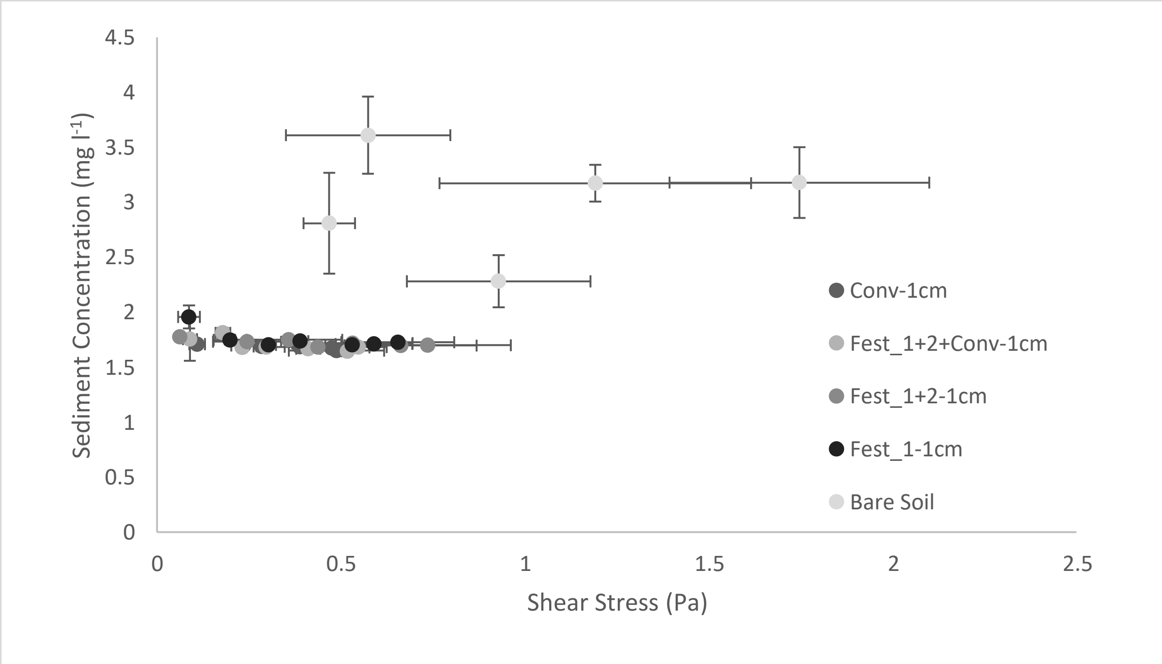

Figure 3-4: Mean (n=4) sediment concentration (g l^{-1}) and shear stress (Pa), at the middle of the sample, for the 1.0 cm grass sward height treatments Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*) and Fest_1 (*Festulolium cv Prior*) as compared with the bare soil control. Error bars represent ±1 S.E.

3.5.10 Sediment concentration for the 3.0 cm sward height treatment

As expected, the sediment concentration was significantly greater ($p<0.05$) for the bare soil control treatment as compared with all the 3.0 cm grass sward height treatments (Figure 3-5). There were no significant differences ($p<0.05$) between 3.0 cm grass sward height treatments.

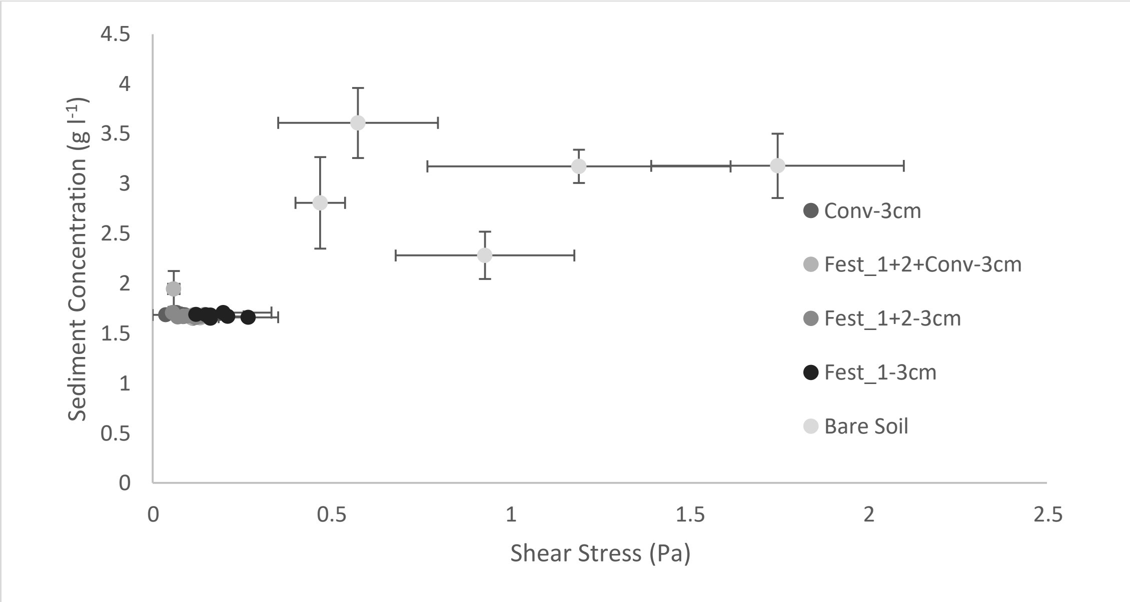

Figure 3-5: Difference in mean (N=4) sediment concentration (g l^{-1}) and shear stress (Pa) for the 3.0 cm grass sward treatment as opposed to the bare soil. Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra)*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*) and Fest_1 (*Festulolium cv Prior*). Error bars represent +/- 1 S.E.

3.5.11 Correlating plant traits with flow shear stress, flow velocity and sediment concentration

To explain the hydrological and erosion control performance of the different grass treatments, their plant traits were correlated with flow shear stress, flow velocity and sediment concentration. The data is shown in Appendix B. No strong (R = <0.7) positive or negative correlations were found between any plant trait and the shear stress results. Strong (R = >0.7) positive correlations were found between two plant traits (i.e. stem area density and number of stems) and flow velocity. No strong positive or negative correlations were found between plant traits and sediment concentrations.

3.6 Discussion

3.6.1 Plant physical parameters

It was expected that significant differences in plant traits known to affect flow characteristics and erosion processes would be reflected in significant differences in sediment concentration. This is because plant traits affect properties such as Mannings n (Hewlet et al., 1987) and soil shear strength (Ali & Osman 2008). It is interesting that this is not the case in the present study, as the significant differences between some plant traits are not reflected in flow properties or sediment results. Significant differences were found between the four grass treatments for number of stems, number of tillers, stem diameter, stem area density, root length <0.25 cm, root surface area and root diameter. All other plant traits were not significantly different. However, this has not manifested in significant differences in sediment concentration, which is not in line with previous research where different plant traits have influenced soil erosion. The differences in plant traits were not sufficient to result in differences here. This might be because there were no correlations found between plant traits and sediment concentration. However, it is more likely that because the mesocosm size was very small and that there was not a long enough period of growth time for larger differences to manifest between plant traits. The current research also suggested that it did not matter whether a species monoculture or mixture was used.

The flow velocity of Fest_1+2+C and Fest_1+2 treatments were significantly lower at 0.6 – 0.8 l s^{-1} flow input rates, than the Fest_1 and Conv treatments. Further, the shear stress was significantly higher in the Fest_1 treatment at 3.0 cm for the 0.6 – 0.7 l s^{-1} flow input rates. However, this significant difference was only for a small proportion of inflow rates from within this study. Although this was not manifest in differences in sediment concentration, the result may be explained by differences in plant traits. Yet, it must be said that there were no correlations between manifested plant traits and shear stress. The Conv treatment had a significantly higher number of stems (195) to all other treatments (113-147). In contrast, the Fest_1 treatment had a significantly lower number of stems as opposed to all other treatments. This data alone suggested that the Conv treatment would have a higher soil erosion mitigation potential than the Fest_1 as the number of stems helps to provide the frictional component which slows down and dissipates the energy of concentrated flows, increasing hydraulic retention, the amount of residence time runoff has (Gavrić et al., 2019) and therefore mitigating soil erosion. However, besides from the number of stems, other plant traits such as the stem diameter, SAD and number of tillers still needs to be considered as they will all contribute to providing a frictional component against water flow.

On the other hand, the Fest_1 treatment was associated with a significantly higher mean number of tillers (4.3) as opposed to all the other treatments (2.8-2.9). This is the opposite of what we would expect as this trait will increase hydraulic retention (Gavrić et al., 2019), however, the significant increase was only for a few of the inflow rates for Fest_1. If the water is slowed down, there would be a higher chance for deposition to occur and a lowered chance for entrainment and transport to occur. A higher number of tillers is better for soil erosion mitigation as it imparts a higher frictional component to the concentrated flow. Mganga et al., (2021) found the number of tillers in grass plants ranged from 18-40 which is much higher than was found within this study which may be because the growth times were different. Mganga et al., (2021) grew their grasses for a period of 9 months as opposed to the 6-week period used within this study. Further, the grass species used were *Cenchrus ciliaris*, *Enteropogon macrostachyus* and *Eragrostis superba* which differed from this study. However, their study did not contain any information on sediment concentration.

The mean stem diameter was significantly different between treatments in the current study. There were significant differences in stem diameter, being significantly higher for the Fest_1 and Conv treatments suggesting that the hydraulic retention would increase (Gavrić et al., 2019) as the frictional component provided by the stems would lower flow velocity, increasing residence times for water runoff. Therefore, making detachment less likely and deposition more likely. However, the shear stress was significantly higher in the Fest_1 treatment for a small proportion of inflow rates which is not as expected. For the

Fest_1 treatment the shear stress was significantly higher in the 3.0 cm sward height at 0.6 – 0.7 l s^{-1}, and for the Fest_1 and Conv treatments the flow velocity were significantly greater for 0.6 – 0.8 l s^{-1} for the 3.0 cm sward height. From the previous study (Lees et al., 2020), which used the same experimental treatments, the stem diameter ranged from 0.8 - 3.5 mm. Liu et al., (2018) found that Chinese rye grass (*Leymus Chinensis*) stems were on average 1.09 cm when no grazing occurred which is greater than what was found within this study. This difference may be because their sample sites were in the field, meaning that the grass had been established for more than 6-weeks. However, both Liu et al., (2018) and Lees et al., (2020) did not look at sediment concentration.

The SAD was significantly different and ranged from 88 - 214 cm^2 cm^{-2}. The greatest SAD was found in the Fest_1 treatment which had a significantly higher flow shear stress and flow velocity than the other treatments for 0.6 – 0.8 l s^{-1} in the 3.0 cm sward height. This infers some explanatory relationship here, however, this is not the relationship we would expect. This might be because the shear stress was higher in only a small proportion of inflow rates. Stem area density was not positively or negatively correlated to shear stress, but it was positively correlated with flow velocity at an flow rate (0.5 l s^{-1}). On the other hand, the SAD for Conv was significantly lower than that of all other treatments and Conv had a significantly greater flow velocity and shear stress at 0.6 – 0.8 l s^{-1} for the 3.0 cm sward height. The SAD provides a frictional component to the water flow due to providing a barrier against it and will reduce detachment by overland flow (Morgan 2007). An increased SAD also increases sediment trapping efficiency (Mekonnen et al., 2016). The frictional component provided by the Conv treatment was lower than that of other treatments, resulting in the greater flow velocity and shear stress. According to De Baets et al., (2009), SAD ranged from 0.0006 – 0.0055 cm^2 cm^{-2} but it was for different grass species, namely Mediterranean false brome (*Brachypodium retusum*) and alpine oatgrass (*Helictotrichon filifolium*). Therefore, in terms of soil erosion mitigation the species used within this study would be better as the SAD is more. The SAD has to be >10,000 stems m^{-1} (Morgan, 2007) to make a difference in terms of soil erosion mitigation via over land flow. Therefore, the SAD was lower in this study than the recommended in terms of soil erosion mitigation.

There were no significant differences in mean total root length which would suggest that there would be no difference in sediment concentration between the experimental grass treatments as root length helps to promote soil cohesion, adhesion and aggregate stability (Vannoppen et al., 2015). Macleod et al., (2013) found that Fest_1 had the largest overall root system size and distribution, which was determined via the scoring of rooting depth and rooting density, after 6 months, as opposed to other grass species, but this was not the case in this study. However, the grass species mixtures and monocultures were different, in this study *Festulolium cv Prior*, *Lolium perenne* and *Festuca rubra* were present, and in Macleod et al., (2013) cv AberStar, cv Bf993, cv AberEpic, cv Dovey, and cv 99/1 were used. In Macleod et al., (2013) Fest_1 had a higher root trait score than all other treatments, and had consistently the lowest run off generated, which showed that a larger root system was better in terms of erosion control. However, it did not have the largest root system and perform the best in terms of erosion control in this study. Therefore Fest_1 should be favoured over the other grass species in Macleod et al., (2013), but not over the grass species used within this study. However, the sediment concentrations all exceeded the EA guidelines for a major event (1000 mg l^{-1}) therefore they would all result in the degradation of water bodies if they were to be used in the field. However, as aforementioned the sediment concentration estimates may be higher than they were due to the sediment sampling method.

There were significant differences in mean total root length ≤ 0.25 cm in diameter, the experimental grass treatments ranged from 155 cm (Conv), which was significantly lower than 209 cm (Fest_1+2+Conv). Therefore, this suggests that the Fest_1+2+Conv would be better at soil erosion control due to an increased mechanical reinforcement of the soil (Mekonnen et al., 2016; Liang et al., 2017). However, the Fest_1+2+C and Conv treatment had no difference in sediment concentration as compared with the other treatments.

There were significant differences in root total surface area, with Fest_+1+2+Conv and Fest_1 being significantly lower than Fest_1+2. This implied that the Fest_1+2 treatment would be associated with a higher sediment concentration, leading to more erosion, as shallow roots will also help contribute to enmeshment (Zhou et al., 1998). Enmeshment is where soil microaggregates become attached to roots, increasing aggregate stability and therefore decreasing the chance for the aggregates to become detached. However, there was no difference in sediment concentration.

Mean root diameters were statistically different and ranged from 0.33 – 0.41 cm for Fest_1+2+Conv and Fest_1+2 respectively. This implied that the Fest_1+2+Conv treatment would be better at reducing soil erosion than the other treatments, because as root diameter increases the root tensile strength decreases (Hai, 2012) and thus the shear strength of the Fest_1+2 soil should be greater. However, that was not the case as there were no significant differences in sediment concentration and only minor significant differences in flow shear stress and flow velocity. Plant traits have been found to influence soil erosion and soil erosion potential in many studies (Morgan & Rickson 1995; Zhou et al., 1998; Fiener 2003; Hai, 2012; Vanoppen et al., 2015) and yet in this study differences in plant traits made no difference to the observed sediment concentration.

3.6.2 Flow shear stress

Any significant differences in plant traits for the 1.0 cm sward height were not reflected in significant differences in flow shear stress. This suggested that any of these experimental treatments could be used in GWWs, as the shear stress remained the same (as was the sediment concentration). However, an increased shear stress might not necessarily mean an increased sediment concentration. This is because the shear strength of the soil may have increased, resulting in plants having different critical shear stress and flow velocities as a function of their plant traits.

As there were no significant differences in shear stress for the 1.0 cm sward height treatment as opposed to the 3.0 cm sward height treatment this suggested that differences in vegetation traits were unable to influence flow shear stress when the grass was cut to 1.0 cm. Therefore, if a farmer knows that their fields are likely to be overgrazed or subject to high mechanical stress then any of the grass species used within this study would yield the same results in terms of shear stress of flow (0.06 – 0.65 Pa).

These values for shear stress are below values which have been shown to be critical shear stress values for grass (Xiao et al., 2014) and bare soil (Moody et al., 2005). For grass slopes, Xiao et al., (2014) observed a critical shear stress value of 2.85 N m^2 (2.85 Pa) which is much lower than the shear stress values obtained in this study. Moody et al., (2005) found critical shear stresses lower than 2.2 N m^2 (2.2 Pa) for different bare soil types, again, an order of magnitude lower than found in the current study. Therefore, there is a wide discrepancy in critical shear stress values obtained in the literature and the shear stress found within this study. As the shear stress is below the critical values found within the literature it should mean that there is little soil erosion in both grass treatments and bare soil treatments which is not in line with the results that were gained.

Significant differences in flow shear stress were found at 0.6 – 0.7 l s^{-1} between the 3.0 cm sward height treatments, with Fest_1 having a significantly higher flow shear stress. Due to these significant differences in flow shear stress it would therefore be expected that the erosivity of the concentrated flow event (Grabowski et al., 2011) would be affected. This would also suggest that the Fest_1 treatment would yield the most sediment and be the worst in terms of soil erosion control. However, there were no significant differences in sediment concentration, which might be explained by differences in soil shear strength, as affected by the root traits of the different treatments. Even if the shear stress of the flow is higher, it might not exceed the shear strength of the soil. Roots have been shown to increase the shear strength of soil (Ali & Osman 2008). It could be that the Fest_1+2+Conv, Con and the Fest_1+2 treatments have a higher soil shear strength, as opposed to the Fest_1 treatments. There was a significant differences in plant traits that could support this hypothesis: Fest_1+2 had a greater total root surface area (cm^2) than Fest_1. As root traits are known to stabilise soil by mechanical reinforcement (Mekonnen et al., 2016; Liang et al., 2017), this means that differences in sediment concentration should not be expected between treatments which show no significant differences between root traits.

3.6.3 Flow velocity

The results for flow velocity were similar to the results for shear stress, with there being no significant differences in flow velocity observed between the 1.0 cm sward height treatments. As the erosivity of flow indicators were not significantly different, this suggested that the sediment concentration would be much the same. Indeed, there are no significant differences in sediment concentration.

Significant differences in flow velocity occurred at 0.6 – 0.8 $l\ s^{-1}$ for the 3.0 cm grass sward height. This suggests that there would be differences in sediment concentration for these two inflow rates if the critical flow velocity for erosion to occur had been reached. Fest_1 and Conv were associated with significantly higher flow velocities when compared to Fest_1+2 and Fest_1+2+Conv.

3.6.4 Sediment concentration

There were significant differences ($p<0.05$) found between the bare soil control and all the grass treatments in terms of sediment concentration (Fig 2-3) with the bare soil control treatment associated with higher sediment concentrations than the grass treatments. This was as expected as the soil erosion mitigation tendencies of plant traits are well known (Morgan and Rickson 1995; Melville & Morgan 2006; De Baets et al., 2007; Mekonnen et al., 2014). Vegetation is widely used for soil erosion control in a number of different soil erosion mitigation features such as grass filter strips (Boger et al., 2018; Li & Pan 2018), swales (Boger et al., 2018) and GWWs (Prosser et al., 1995) as they reduce run off and soil loss (Melville & Morgan 2006). The observed reduction in sediment concentration for the vegetated treatments as opposed to the bare soil treatments may be due to the plant root traits increasing the shear strength of the soil (Ali & Osman 2008) as the flow velocities were not significantly different. This data can be used to influence management practices relating to these species' monocultures and mixtures as there were no significant differences in sediment concentration. This implied that a farmer could choose any of these species for their GWW. They were all better than the bare soil in terms of erosion control, yet the sediment concentrations for all the experimental grass treatments were over the Environment Agency (2016) acceptable limit of 1000 mg l^{-1}. As all the treatments exceed the limit for sediment concentration this means that they would have caused a major incident, resulting in the degradation of freshwater ecosystems, if they were being used in GWWs and other soil erosion mitigation features. However, this high sediment concentration might be due to the method in taking the sediment samples: there was a flush of suspended sediment when the flow increment was raised, and this was when the samples were consistently taken. Otherwise, the water remained clear. The method of collection might have resulted in an overestimation of sediment concentration.

There were no significant differences in sediment concentration for the experimental grass treatments which was not as expected. As there were significant differences in plant traits, significant differences in sediment concentration were expected. Finally, the mowing of grass could be to either 1.0 cm or 3.0 cm to achieve the same results for sediment concentration. The most economical and practical management practice could be used as it will give the same results for sediment concentration. However, the sediment concentrations still all exceeded the EA guidelines for a major event (EA 2016). This research allows a land manager better understanding of how to manage their GWW in terms of mowing regimes, as either 1.0 cm or 3.0 cm will be acceptable grass sward heights to aim for.

3.6.5 Recommendations

There were no significant differences in sediment concentration between the experimental grass treatments. Therefore, any of these experimental treatments will achieve the same effect within soil erosion mitigation features such as grassed waterways. However, all the sediment concentrations were above acceptable limits of 1000 mg/l, according to the Environment Agency (2016). This means that none of them can be recommended for erosion control features when they have been growing for that short a growth period. It could be that with time they would be able to withstand concentrated flow events better, using a geotextile in the early stages of growth. At the same time, the high sediment concentrations could be explained by the sampling method: the sediment samples were taken at the time when the flow input was incrementally increased, leading to a ‘flush’ or ‘pulse’ of sediment, suggesting the sediment concentration may be an overestimation for settled / steady state flow conditions. Therefore, further research including growing the grass for a longer period and using a greater range of inflow rates would be able to tease out any possible significant differences in sediment concentration, flow velocity or flow shear stress. The critical point at which erosion starts to occur can also be worked out in the future if the hydraulic flume inflow rates are raised at the smallest increment possible which will provide further evidence to farmers in their soil erosion feature management. It will aid them in choosing grasses with higher critical points at which erosion starts to occur.

3.7 Conclusions

Flow shear stress was significantly different at the 0.6 – 0.7 l s^{-1} inflow rates, and flow velocity was significantly different for the 0.6 – 0.8 l s^{-1} treatments for the 3.0 grass sward height only. At all other inflow rates and for all the 1.0 cm grass sward treatments, there was no significant difference in flow shear stress or flow velocity. The sediment concentration was significantly different between the bare soil control treatments and the experimental grass treatments. No significant differences were observed in sediment concentration between the experimental grass treatments. However, there were significant differences in the following plant traits, number of stems, number of tillers, stem diameter (mm), stem area density (mm^2 mm^{-2}), root length in cm of (<0.25cm ⌀), root surface area (cm^2) and root diameter (mm). Many previous studies have found that plant traits influence sediment concentration. However, this was not the case in this study. Any differences in plant traits manifested no significant differences in sediment concentration. Whether the grass was a monoculture or mixture it had no bearing on the observed sediment concentration. More research is needed on how these experimental treatments influence the soil erosion processes that happen within a GWW, for a longer time scale or used in conjunction with changing other factors, such as soil type, slope gradient and length of plot, which will influence soil erodibility and flow erosivity. As the sediment concentrations generated exceeded the EA acceptable limits, it is not advised that the treatments are relied upon as an erosion control measure after a limited amount of growth time. However, the soil was eroded in pulses as the inflow rates were increased and these pulses coincided with when sediment samples were taken.

3.8 References

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P., & Borrelli, P. (2020). Global phosphorus shortage will be aggravated by soil erosion. *Nature Communications*, 11, 4546. doi: 10.1038/s41467-020-18326-7

Al-hamdan, O.Z., Pierson Jr, F.B., Nearing, M.A., Stone, J.J., Williams, C.J., Moffet, C.A., Kormos, P.R., Boll, J. & Weltz, M.A. (2012). Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modelling. *Earth surface processes and landforms*, 37, 157-168. doi: 10.1002/esp.2227

Ali, F.H. & Osman, N. 2008. Shear Strength of a Soil Containing Vegetation Roots. *Soils and Foundations*, 48 (4), 587-596. doi: 10.3208/sandf.48.587

Almeida, W.S., Seitz., Oliveira, L.F.C. & Carvalho, D.F. (2021). Duration and intensity of rainfall events with the same erosivity change sediment yield and runoff rates. *International Soil and Water Conservation Research*, 9 (1), 69-75.

Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E. & Sparks, D. (2015). Soil and human security in the 21st century. *Science*, 348 (6235). doi: 10.1126/science.1261071

Armfield, 2019. *Sediment Erosion Flume S28*. Issue 3. Armfield.

Bainard, L.D., Kilronomos, J.N. & Hart, M.M. (2010). Differential effect of sample preservation methods on plant and arbuscular mycorrhizal fungal DNA. *Journal of Microbiological Methods*, 82 (2), 124-130. doi: 10.1016/j.mimet.2010.05.001

Baruti, J.H.M. (2004). *Study of Soil Moisture in relation to soil erosion in the proposed Tancitaro Geopark, Central Mexico: A case of the Zacandaro sub-watershed*. pp 64. Available from: https://webapps.itc.utwente.nl/librarywww/papers_2004/msc/ereg/baruti.pdf

Baxter, C., Rowan, J.S., McKenzie, B.M. & Neilson, R. (2013). Understanding soil erosion impacts in temperate agroecosystems: bridging the gap between geomorphology and soil ecology. *Biogeosciences Discuss*, 10, 7491-7520. doi: 10.5194/bgd-10-7491-2013

Berendse, F., Ruijven, J., jongejans, E. & Keesstra, S. (2015). Loss of Plant Species Diversity Reduces Soil Erosion Resistance. *Ecosystems*, 18, 881-888. doi: 10.1007/s10021-015-9869-6

Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H. & Alberts, E.E. (2004). Grass Barriers for Reduced Concentrated Flow Induced Soil and Nutrient Loss. Soil *Science Society of America Journal*, 68 (6), 1963-1972. doi: 10.2136/sssaj2004.1963

Boardman, J., Shepheard, M.L., Walker, E. & Foster, I.D.L. (2009). Soil erosion and risk-assessment for on- and off-farm impacts: A test case using the Midhurst area, West Sussex, UK. *Journal of Environmental Management*, 90 (8), 2578-2588. doi: 10.1016/j.jenvman.2009.01.018

Boardman, J. (2013). Soil Erosion in Britain: Updating the Record. *Agriculture*, 3, 418-442. doi: 10.3390/agriculture3030418

Boardman, J., Vandaele, K., Evans, R. & Foster, I.D.L. (2018). Off- site impacts of soil erosion and runoff: Why connectivity is more important than erosion rates. *Soil Use and Management,* 35 (2), 245-256. doi: 10.1111/sum.12496

Boardman, J., Vandaele, K., Evan, R. & Foster, R.D.L. (2019). Off-site impacts of soil erosion and runoff: why connectivity is more important than erosion rates. *Soil Use and Management*, 35 (2), 245-256. doi: 10.1111/sum.12496

Boger, A. R., Ahiablame, L., Mosase, E. & Beck, D. (2018). Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. *Environmental Science: Water Research & Technology*, 4, 478-486. doi: 10.1039/ C7EW00230K

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L. & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences of the United States of America*, 117 (36), 21994-22001. doi: 10.1073/pnas.2001403117

Bryan, R.B. (2000). Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, 32 (3-4), 385-415. doi: 10.1016/S0169-555X(99)00105-1

Burylo, M., Rey, F., Mathys, N. & Dutoit, T. (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms*, 37, 1463-1470. doi: 10.1002/esp.3248

Chen, B. & Zhang, X. (2022). Effects of slope vegetation patterns on erosion sediment yield and hydraulic parameters in slope-gully system. Ecological Indicators, 145, 109723. doi: 10.1016/j.ecolind.2022.109723

Collins, A.L. & Walling, D.E. (2007). Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes*, 1448-1459. doi: 10.1002/hyp.6269

Collins, A.L. & Anthony, S.G., Hawley, J. & Turner, T. (2009). The potential impact of projected change in farming by 2015 on the importance of the agricultural sector as a sediment source in England and Wales. *Catena*, 79, 243-250. doi: 10.1016/j.catena.2009.05.007

Dabney, S.M., Shields, F.D., Temple, D.M. & Langendoen, E.J. (2004). Erosion Processes in Gullies Modified by Establishing Grass Hedges. *American Society of Agricultural Engineers*, 47 (5), 1561-1571. doi: 10.13031/2013.17634

De Baets, S., Poesen, J., Knapen, A. & Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms*, 32 (9), 1323-1345. doi: 10.1002/esp.1470

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34 (10), 1374-1392. doi: 10.1002/esp.1826

Environment Agency, 2016. *Incidents and their classification: the Common Incident Classification Scheme (CICS)*. Environment Agency. pp 38-39.

FAO, 1988. *Watershed management field manual - Slope treatment measures and practices*. FAO technical paper 13/3, FAO, Roam.

Fiener, P. (2003). *Concept and effects of a multi-purpose grassed waterway - long-term measuring and mathemati-cal modeling of runoff reduction and sediment trapping*. University thesis.

Fiener, P & Auerswald, K. (2003). Effectiveness of Grassed Waterways in Reducing Runoff and Sediment Delivery from Agricultural Watersheds May 2003. *Journal of Environmental Quality*, 32, 927-36. doi: 10.2134/jeq2003.9270

Fiener, P. & Auerswald, K. (2006). Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research*, 87 (1), 48-58. doi: 10.1016/j.still.2005.02.035

Gavrić, S., Leonhardt, G., Marsalek, J. & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment*, 669, 431-447. doi: 10.1016/j.scitotenv.2019.03.072

Genney, D.R., Alexander, I.J. & Hartley, S.E. (2000). Exclusion of grass roots from soil organic layers by Calluna: the role of ericoid mycorrhizas. *Journal of Experimental Botany*, 51 (347), 1117-1125. doi: 10.1093/jexbot/51.347.1117

Govers, G., Everaert, W., Poesen, J., Rauws, G., De Ploey, J. & Lautridou, J.P. (1990). A long flume study of the dynamic factors affecting the resistance of a loamy soil to concentrated flow erosion. *Earth Surface Processes and Landforms*, 15 (4), 313-328. doi: 10.1002/esp.3290150403

Grabowski, R.C., Droppo, I.G. & Wharton, G. (2011). Erodibility of cohesive sediment: The importance of sediment properties. *Earth-Science Reviews*, 105 (3-4), 101-120. doi: 10.1016/j.earscirev.2011.01.008

Hai, T.L. (2012). *Root characteristics of some grass species on the sea dikes in Viet Nam. Communications on Hydraulic and Geotechnical Engineering*. PhD Thesis. Delft University of Technology. Available from: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.875.4710&rep=rep1&type=pdf [Accessed on 20 January 2022]

Houlbrooke, D.J., Thom, E.R., Chapman, R. & McLay, C.D.A. (1997). A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. *New Zealand Journal of Agricultural Research*, 40, 429-435. doi: 10.1080/00288233.1997.9513265

IPCC (2013). *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. United Kingdom: Cambridge University Press.

Khodashenas, S.R., Abderrezzak, K.E.K. & Paquier, A. (2008). Boundary shear stress in open channel flow. A comparison among six methods. *Journal of Hydraulic Research*, 46 (5), 598-609. doi: 10.3826/jhr.2008.3203

Knapen, A., Poesen, J., Gyssels, G. & Nachtergaele, J. (2007). Resistance of soils to concentrated flow erosion: A review. *Earth Science Reviews*, 80 (1-2), 75-109. doi: 10.1016/j.earscirev.2006.08.001

Kroese, J.S., Batista, P.V.G., Jacobs, S.R., Breuer, L., Quinton, J.N. & Rufino, M.C. (2020). Agricultural land is the main source of stream sediments after conversion of an African montane forest. *Scientific Reports*, 10, 14827. doi: 10.1038/s41598-020-71924-9

Lave, J. & Avouac, J.P. (2001). Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *Journal of Geophysical Research: Solid Earth*, 106, 26,311-26,787. doi: 10.1029/2001JB000359

Lees, C., De Baets, S., Rickson, R.J, & Simmons, R.W. (2020). Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study. *European Journal of Soil Science*, 72, 2381-2397. doi: 10.1111/ejss.13045

Li, C., & Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90-103. doi: 10.1016/j.jhydrol.2018.01.007

Liang, T., Bengough, A.G., Knappett, J.A., MuirWood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & Meijer, G.J. (2017). Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering*, 109 (B), 207-227. doi: 10.1016/j.ecoleng.2017.06.067

Lick, W. & McNeil, J. (2001). Effects of sediment bulk properties on erosion rates. Science of the Total Environment, 266 (1-3), 41-48. doi: 10.1016/s0048-9697(00)00747-6

Liu, B., Xie, Y., Li, Z., Liang, Y., Zhang, W., Fu, S., Yin, S., Wei, X., Zhang, K., Wang, Z., Liu, Y., Zhao, Y. & Guo, Q. (2020). The assessment of soil loss by water erosion in China. International Soil and Water Conservation Research, 8 (4), 430-439. doi: 10.1016/j.iswcr.2020.07.002

Liu, Z., Baoyin, T., Duan, J., Yang, G., Sun, J. & Li, X. (2018). Nutrient Characteristics in Relation to Plant Size of a Perennial Grass Under Grazing Exclusion in Degraded Grassland. *Frontiers in Plant Science*, 9, 295. doi: 10.3389/fpls.2018.00295

Liu, J.X., Wang, B., Duan, X.W., Yang, Y.F. & Liu G.B. (2022). Seasonal variation in soil erosion resistance to overland flow in gully-filled farmland on the Loess Plateau, China. *Soil and Tillage Research*, 218, 105297. doi: 10.1016/j.still.2021.105297

Lou, Y., Gao, Z., Sun, G., Wu, T., Zhou, F., Ai, J., Cen Y. & Xie, J. (2022). Runoff scouring experimental study of rill erosion of spoil tips. *CATENA*, 214, 106249. doi: 10.1016/j.catena.2022.106249

Lou, Y., Wang, W., Guo, M., Guo, W., Kang, H., Feng, L., Zhu, Y. and Yang, H. (2023). Vegetation affects gully headcut erosion processes by regulating runoff hydrodynamics in the Loess tableland region. *Journal of Hydrology*, 616, 128769. doi: 10.1016/j.jhydrol.2022.128769

MacLeod, C. J. A., Humphreys M.W., Whalley, R., Turner, L.B., Binley, A., Watts, C. W., Skøt, L., Joynes, A., Hawkins, S., King, I.P., O'Donovan, S. & Haygarth, P.M. (2013). A novel grass hybrid to reduce flood generation in temperate regions. *Scientific Reports*, 3, 1-7. doi: 10.1038/srep01683

Mekonnen, M., Keesstra, S.D., Stroosnijder, L., Baartman, J.E.M. & Maroulis, J. (2014). Soil Conservation Through Sediment Trapping: A Review. *Land Degradation and Development*, 26 (6), 544-556. doi: 10.1002/ldr.2308

Mekonnen, M., Keesstra, S.D., Ritsema, C.J., Stroosnijder, L. & Baartman, J.E.M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in northwest Ethiopia. *Catena*, 147, 755-763. doi: 10.1016/j.catena.2016.08.036

Melville, N., & Morgan, R.P.C. (2006). The influence of grass density on effectiveness of contour grass strips for control of soil erosion on low angle slopes. *Soil Use and Management*, 17 (4), 278-281.

Met Office (2018). *Ross-On-Wye Climate*. Met Office. URL https://www.metoffice.gov.uk/public/weather/climate/gcnpm68t8 [Accessed on 20 January 2018].

Met Office (2022) *Cambridge NIAB climate data*. Met Office. URL https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/cambridgedata.txt [Accessed on 11 February 2022].

Mganga, K.Z., Kaindi, E., Ndathi, A.J.N., Bosma, L., Kioko, T., Kadenyi, N., Musyoki, G.K., Wambua, S., Steenbergen, F. & Musimba, N.K.R. (2021). Plant

Morphoecological Traits, Grass-Weed Interactions and Water Use Efficiencies of Grasses Used for Restoration of African Rangelands. *Frontiers in Ecology and Evolution*, doi: 10.3389/fevo.2020.613835

Montieth, H. & Pender, G. (2005). Flume investigations into the influence of shear stress history on a graded sediment bed. *Water Resources Research*, 41 (12). doi: 10.1029/2005WR004297

Montgomery, D. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences*, 104 (33), 13268-13272.

Moody, J.A., Smith, J.D. & Ragan, B.W., (2005). Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires. *Journal of Geophysical Research Earth Surface*, 110 (F1), doi:10.1029/2004JF000141.

Morgan, R.P.C. (2005). *Soil Erosion and Conservation*. Third Edition. Blackwell publishing Ltd.

Morgan, R. P. C. (2007). *Vegetative-based technologies for erosion control*. In A. Stokes, I. Spanos, J. E. Norris, & E. Cammeraat (Eds.), Eco-and ground bio-engineering: The use of vegetation to improve slope stability. Developments in plant and soil sciences (Vol. 103). Dordrecht, The Netherlands: Springer

Morgan, R.P.C. & Rickson, R.J. (1995). *Slope stabilisation and erosion control: a bioengineering approach*. London: E & FN Spon.

Morgan, R.P.C. & Rickson, R.J. (2005). *Slope stabilisation and erosion control: a bioengineering approach*. 2nd Edition. London: E & FN Spon.

National Audit Office 2010. *Tackling diffuse water pollution in England [online].* National Audit Office. URL https://www.nao.org.uk/wp-content/uploads/2010/07/1011188.pdf [accessed on 26 July 2020].

Pimentel, D. & Burgess, M. (2013). Soil Erosion Threatens Food Production. *Agriculture*, 3 (3), 443-463. doi: 10.3390/agriculture3030443

Plainwater, 2015. *Shear Stress & Permissible Velocity*. New York State Stormwater Management Design Manual (January, 2015). Available from: https://plainwater.com/water/shear-stress-permissible-velocity/

Prosser, I.P, Dietrich, W.E. & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology*, 13 (1-4), 71-86. doi: 10.1016/0169-555X(95)00020-6

Regent Instruments (2016). *WinRHIZO 2016 Basic, Reg, Pro & Arabidopsis For Root Measurement*. Canada: Regent instruments Canada Inc.

Restrepo, J.D. & Syvitski, J.P.M., 2006. Assessing the Effect of Natural Controls and Land Use Change on Sediment Yield in a Major Andean River: The Magdalena Drainage Basin, Colombia. *Ambio*, 35 (2), 65-74.

Rickson, R.J. (2014). Can control of soil erosion mitigate water pollution by sediments? *Science of The Total Environment*, 468-469, 1187-1197. doi: 10.1016/j.scitotenv.2013.05.057

Schwendel, A.C., Death, R.S. & Fuller, I.C. (2010). The assessment of shear stress and bed stability in stream ecology. *Freshwater Biology*, 55 (2), 261-281. doi: 10.1111/j.1365-2427.2009.02293.x

Silgram, M., Jackson, D.R., Bailey, A., Quinton, J. & Stevens, C. (2010). Hillslope scale surface runoff, sediment and nutrient losses associated with tramline wheelings. Earth Surface Processes and Landforms, 35 (6), 699-706. doi: 10.1002/esp.1894

Somsook, K., Azhikoda, G., Duka, M.A. & Yokoyama, K. (2021). Riverbed fluctuation and erosion property of cohesive sediment based on long-term topographic surveys in a macrotidal estuary. *Regional Studies in Marine Science*, 45, 101848. doi: 10.1016/j.rsma.2021.101848

Stagge, J.H., Davis, A.P., Jamil, E. & Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research*, 46 (20), 6731-6742. doi: 10.1016/j.watres.2012.02.037

Staton, M. & Bosch, B. (2015). *Grassed waterways can help maintain soil quality and productivity. Michigan State University*. Available from: https://www.canr.msu.edu/news/grassed_waterways_can_help_maintain_soil_quality_and_productivity [Accessed 3rd December 2021].

Sun, L., Zhang, B., Yin, Z., Guo, H., Siddique, K.H.M., Wu, S. & Yang, J. (2022). Assessing the performance of conservation measures for controlling slope runoff and erosion using field scouring measurements. *Agricultural Water Management*, 259, 107212. doi: 10.1016/j.agwat.2021.107212

U.C. Cooperative Extension. (2003). *Estimated Costs & Potential Benefits for Non-engineered Grassed Waterways. U.C. Cooperative Extension*. Available from: http://awqa.org/wp-content/toolkits/Other/Non-EngGrassedWater.pdf [Accessed on 4 December 2021].

USDA. (2022). *Soil Bulk Density Moisture/Aeration*. USDA. Available from: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053260.pdf [Accessed on 1 March 2022].

Vannoppen, W., Vanmaercke, M., De Baets, S. & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews,* 150, 666-678. doi: 10.1016/j.earscirev.2015.08.011

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G. & Roberts, N.M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*, 52 (3), 522-555. doi: 10.1002/2014RG000464

White, K., She, Y. & Zhang, W. (2022). A comparison of shear stress estimation methods for a single geobag on a rough bed. *Geotextiles and Geomembranes*, 50 (6), 1230-1243. doi: org/10.1016/j.geotexmem.2022.09.001

Wilkinson, B.H. & McElroy, B.J. (2007). The impact of humans on continental erosion and sedimentation. *GSA Bulletin*, 119 (1-2), 140-156. doi: 10.1130/B25899.1

Xiao, H., Guo, P., Zhang, Q., Hu, H., Hong, H., Zhang, L., Yang, Y., Xia, Z., Li, M., Kang, H. & Zhang, G. (2022). Variation in soil properties and its influence on dynamic change of soil erosion resistance to overland flow in the water-level fluctuation zone of the Three Gorges Reservoir, China. *CATENA*, 213, 106141. doi: 10.1016/j.catena.2022.106141

Xiao, P., Yang, E. & Jiao, P. (2014). Effect of Grass on Reducing Runoff and Sediment and its Critical Flow Shear Stress. *Advanced Materials Research*, 1010-1012, 1145-1148. doi: 10.4028/www.scientific.net/AMR.1010-1012.1145

Ye, Y, Tan, X, Liu, Y., Zhou, C., Shi, F., Lee, Y, & Murphy M.A., 2022. The impact of erosion on fault segmentation in thrust belts: Insights from thermochronology and fluvial shear stress analysis (southern Longmen Shan, eastern Tibet). *Geomorphology*, 397, 108020. doi: 10.1016/j.geomorph.2021.108020

Zhang, Z., Sheng, L., Yang, J., Chen, X., Kong, L. & Wagan, B. (2015). Effects of Land Use and Slope Gradient on Soil Erosion in a Red Soil Hilly Watershed of Southern China. *Sustainability*, 7, 14309-14325. doi: 10.3390/su71014309

Zhang, B., Zhang, G., Yang, H. & Zhu, P. (2019). Temporal variation in soil erosion resistance of steep slopes restored with different vegetation communities on the Chinese Loess Plateau. *Catena*, 182, 104170. doi: 10.1016/j.catena.2019.104170

Zhou Y, Watts D, Li Y. & Cheng X. (1998). A case study of effect of lateral roots of Pinus yunnanensis on shallow soil reinforcement. Forest Ecology and Management 103, 107-120. *Catena*, 182. doi: 10.1016/j.catena.2019.1041

4 Critical flow velocity and shear stress thresholds for grass in grassed water ways

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4.1 Abstract

Soil erosion can have major off-site impacts on water bodies. A sediment concentration of over 1000 mg l^{-1} is defined by the Environment Agency (EA) in the UK as the critical threshold for a major event (category 1) for potentially devastating effects on the receiving water body (Environment Agency 2016). One way in which soil erosion can be mitigated against is by the installation of grassed waterway in concentrated flow paths. Grassed waterways reduce flow volume, flow velocity, and shear stress, by imparting a frictional component to the flow as a function of the grass traits, resulting in a lowered sediment concentration. An increased flow shear stress and flow velocity results in an increased risk of soil erosion occurring. However, the critical shear stress and flow velocity at which the EA 1000 mg l^{-1} sediment concentration threshold is exceeded is not known for the species treatments in this study. The species treatments are *Festulolium cv Prior,* a mixture of *Festulolium Bx511* and *Festulolium cv Prior*, a conventional mixture of *Lolium perenne* and *Festuca rubra*, and a mixture of all species combined. The recommended and a lowered (60%) seeding rate was used for each experimental grass treatment. A roots and shoots, and a roots only treatment was investigated for each experimental grass treatment. Above ground plant traits measured included stem area density, % ground cover, number of stems, number of tillers and stem diameter. Below ground plant traits measured included total below-ground biomass, root length, root diameter and root surface area. This study aims to establish the critical shear stress and flow velocity threshold for these species mixtures and monocultures by using a hydraulic flume. Increasing inflow rates (0.2 - 2.6 l s^{-1}) were used to simulate overland flows on a grass sward within a grassed waterway. Shear stress ranged from 0.01 – 0.71 Pa and flow velocity ranged from 0.04 – 0.80 m s^{-1}, both were determined for all inflow rates at increments of 0.1 l s^{-1}. Sediment concentration was also obtained for all inflow rate increments. There were significant differences found between the measured plant traits for the experimental grass treatments. These differences in plant traits might be able to explain the significant differences found in sediment concentration for the experimental grass treatments. Negative correlations were found between stem area density, % ground cover, and number of stems and the sediment concentration. This was as expected as they impart a frictional component to flow. The EA limit for a major event was exceeded for the majority of roots only treatments. The Fest_1+2+C L did not breach the 1000 mg l^{-1} limit in both the roots and shoots, and roots only treatments, therefore it should be recommended for use in grassed water ways as this treatment is effective at resisting concentrated flow events even when the above ground biomass is absent. Further, the Conv N, Fest_1+2 L, Fest_1 N and Conv L treatments did not exceed the 1000 mg l^{-1} limits for the roots and shoots treatments.

4.2 Introduction

Soil erosion occurs globally, causing both on-site and off-site impacts (Burylo et al., 2012; National Audit Office 2010; Pimentel and Burgess 2013). On-site impacts include the formation of rills (Ou et al., 2021) which can lead to gully formation on farms (Zhang et al., 2019). The prerequisites for formation of gullies depends upon certain soil qualities such as the bulk density and organic matter content (Ou et al., 2021). A rill will start to form when the shear stress of the flow is greater than the resistance of the soil (Knapen & Poesen 2009). Erosion by water is a main contributor to rill and gully formation as it is likely to follow specific pathways. Climate change means that the predicted rainfall events will be of increased intensity, frequency and duration (Baxter at al., 2013; IPCC 2013:

Westra et al., 2014) are likely to increase rill and gully formation due to them overcoming soil resistance.

There are many off-site impacts of soil erosion which include eutrophication of nearby water bodies (Ekholm & Lehtoranta 2012). Over 70% of the suspended sediment in water bodies in the UK is due to soil erosion from agricultural land (National Audit Office 2010). Further, 95% of the soil erosion in Wales and England comes from agricultural land which can lead to excess phosphate in water bodies (Inman & Consulting 2006). One way in which off-site impacts are assessed is by sediment concentration. The current Environment Agency (EA) classification of a Category 1 major event is a sediment concentration of 1000 mg l^{-1} (EA 2016). Any sediment concentration above 1000 mg l^{-1} can lead to a degradational environmental event for the water body.

Both on-site and off-site impacts can be mitigated against by the appropriate design and installation of a grassed water way (GWW) which are usually situated on natural flow pathways to help lessen the damage overland flows can cause (Prosser et al., 1995; Fiener and Auerswald, 2006; Zhang et al., 2019). Once grassed water ways are established on natural flow pathways (Prosser et al., 1995), they can change the characteristics of flow such as decreasing the flow erosivity. A decline in flow erosivity will result in a lowered entrainment rate and an increased deposition rate. GWWS will also reduce the sediment concentration of runoff entering water bodies and the EA limits will not be reached. This is due to the specific plant traits that GWWs provide (Lees et al., 2020). Above ground traits that can mitigate soil erosion include SAD (mm^2 mm^{-2}) (De Baets et al., 2009; Morgan and Rickson 1995; Morgan 2007), stem diameter (mm), number of stems, number of tillers and percentage cover, above ground biomass (g). Below ground traits that can mitigate soil erosion include total root length (cm) (Mekonnen et al., 2016), root length (cm) of (<0.25 cm ⌀) (Liang et al., 2017), below ground biomass (g), root surface area (cm^2) and root diameter (mm) (Vannoppen et al., 2015).

Plant traits which influence the frictional component imparted to flow by the grassed sward in GWWs, resulting in a lowered velocity and shear stress, include stem area density (Morgan and Rickson 1995), stem diameter, number of stems, number of tillers and % cover (De Baets et al., 2009: Mekonnen et al., 2016; Liang et al., 2017). Due to these above ground plant traits the concentrated flow energy dissipates, and the water depth increases, thus decreasing flow erosivity. This dissipation of flow energy will result in an increased sediment trapping efficiency (Mekkonnen et al., 2016) resulting in an increased sedimentation rate (Gavrić et al., 2019).

Aside from the reduction in flow velocity, flow shear stress can also be used as an indicator of the erosivity of flow (Winterwerp et al., 2012). An increased shear stress will result in an increased soil erosion rate (Winterwerp et al., 2012; Li et al., 2019). A higher shear stress can also increase the suspended sediment load. Li et al., (2009) stated that the critical shear stress for soil erosion under different grass species was 1.49 Pa. Therefore, any shear stress above this level could be considered erosive.

This study will critically evaluate and quantify the flow shear stress and flow velocity at which erosion takes place for different selected grass species treatments and a bare soil control. This will be done by investigating different grass species mixtures and monocultures to see when the EA classification of a Category 1 major event is exceeded (Environment Agency 2016). This will allow for the species traits to be linked to the lowest sediment concentrations. The critical flow shear stress and flow velocity needed for a 1000 mg l^{-1} (Environment Agency 2016) of sediment concentration to enter water bodies is not yet known for *Festulolilum cv Prior*, *Festulolium Bx511* and the conventional mixture. This study will investigate how each grass species mixture or monoculture will affect the erosivity of flow, as expressed by the flow shear stress and flow velocity.

This study will also investigate the effect of seeding rate on grass species treatment efficacy. There are only recommended seeding rates and these recommended rates are often not attributed to soil erosion control. It is not known if a lowered seeding rate will affect plant traits adversely resulting in elevated soil erosion rates. Two different types of treatments were tested, namely roots and shoots (0.03 m sward length), and roots only. This was to see how they will affect flow shear stress and flow velocity, and consequently sediment concentrations. This will allow for the contribution of above ground traits and below ground traits in terms of soil erosion mitigation to be determined. The data will also show the effect of roots on the erodibility of soil and the effect of shoots on flow erosivity.

4.3 Methodology

4.3.1 Macrocosm preparation

Nine macrocosms (0.8 x 1.2 x 0.5 m) were packed in total, 8 containing experimental grass treatments and 1 bare soil control treatment. Each macrocosm was packed to a dry bulk density of 1.27 g cm^{-3} in line with a specific soil textural class. Soil bulk density (BD) can influence soil erodibility (Lick & McNeil 2001; Grabowski et al., 2011) therefore it was standardised for all treatments. Further, the soil BD was <1.40 g cm^{-3} and therefore, root growth was not expected to be limited (USDA 2022). Another reason the soil BD was kept constant was due to high BD negatively effecting plant traits which are linked to soil erosion control such as root length, root dry weight and number of tillers (Houlbrooke et al., 1997). The soil texture was sandy clay loam, 20% clay, 28% silt and 52% sand. Following soil packing the soil was levelled. The grass was grown in these macrocosms for 8 weeks following a 2-week establishment period in an environmentally controlled glasshouse.

4.3.2 Species selection and seeding rates

The species treatments and the seeding rates used within this study were carried forward from Lees et al., (2020) and selected as the best performing in terms of soil erosion mitigation potential. This was to allow for easier comparisons between the two studies and to provide validation for the grass species ranking system. The novel grass species were previously selected for their ability to grow under flooded and drought conditions which help show that they can withstand climate change scenarios. As shown in Table 4-1, the species treatments comprised a conventional mixture of *Lolium perenne* (75 %) and *Festuca rubra* (25 %) (Conv), *Festulolium cv Prior* (Fest_1), *Festulolium cv Prior* and *Festulolium Bx511* (Fest_1+2), and *Festulolium cv Prior* with *Festulolium Bx511* and the conventional mixture (Fest_1+2+Conv). A bare soil treatment was used as a control.

Two seeding rates were used within this study, a recommended seeding rate (N) which was used in Lees et al., (2020) (Chapter 2 of this thesis), and 60% of the recommended seeding rate (L). This simulated the lowered % emergence and survival rate of the seedlings within the natural environment, for example, reduced % germination due to increased water stress and/or increasing temperatures (Yi et al., 2019).

Each macrocosm was divided into 12 uniform sections, the seeds were weighed out and broadcast for each section to ensure a uniform percentage coverage. A further 0.01 m (15.5 g) of soil was placed on top and gently compressed to ensure a good contact between the soil and the seeds.

Table 4-1: Treatment code, grass species and seeding rates (kg ha^{-1}).

Treatment Abbreviation	Experimental Grass Species	Recommended Seeding rate (N) (kg ha^{-1})	*Lowered seeding rate (L) (kg ha^{-1})
Fest_1	*Festulolium cv prior*	50	30
Conv	Conventional mixture consisting of *Lolium perenne* (75%) and *Festuca Rubra* (25%)	100	60
Fest_1+2	*Festulolium cv prior*	30	18
	Festulolium Bx511	30	18
Fest_1+2+C	Conventional Mix	50	30
	Festulolium Bx511	30	18
	Festulolium cv prior	30	18

*60% of recommended seeding rate. Seeding rates are based on personal communications from J. Harper, IBERS, Aberystwyth (14 March, 2018) and P. Brown, Frontier Agriculture (21 March, 2018).

4.3.3 Mesocosm preparation

Following the methodology adopted in 3.4.3, after 8 weeks growth following a 2-week germination period, whole plant sub-samples were transferred from the macrocosms to stainless-steel mesocosms (0.3 x 0.1 x 0.1 m), which comprised of a stainless-steel insert and a perforated stainless-steel base, prior to testing in the Advanced Soil and Sediment Erosion Testing Environment (ASSETTE) hydraulic flume. A stainless-steel insert was carefully hammered into the macrocosm. Soil around one side of the insert was subsequently excavated, and a perforated base inserted and secured with tape. Once removed the mesocosm was saturated for 7 hours during the day before being left to drain to field capacity overnight prior to testing to ensure that all treatments were tested at field capacity. This was done to ensure that the soil was in the same soil moisture state as a decrease in soil moisture can cause an increase in soil loss (Baruti 2004). There was one grass sward height treatment at 0.03 m to simulate roots and shoots and one where the grass sward was entirely removed to simulate roots only. Each treatment was replicated in quadruplicate.

4.3.4 Soil Moisture Content

Mean soil moisture content (n=3) was determined for each macrocosm. Within each macrocosm, the soil moisture content was determined at 0.1 m depth intervals up to 0.4 m, at least weekly, using a Delta-T PR2 profile probe (Delta-T) (Appendix A). This allowed for a soil moisture content of at least 15% to be maintained across all experimental treatments. Three readings were taken within each macrocosm with the PR2 profile probe twisted by 120°. The soil moisture content was taken over the course of the experiment to ensure uniformity between treatments.

4.3.5 Number of Stems

After the grass treatments were transferred from the macrocosms to the mesocosms the number of stems were counted for the stem area density (SAD) to be calculated. A high stem area density (SAD) of <10,000 stems m^2 is enough to reduce soil detachment by concentrated flow (Morgan 2007).

4.3.6 Number of Tillers, Stem Diameter and Stem Area Density

The number of tillers and stem diameter (mm) were determined by randomly selecting five individual grass plants per treatment replicate following Liu et al., (2018) The number of tillers per plant was counted manually and stem diameter was measured using a digital Vernier gauge (Liu et al., 2018). For the 0.03 m grass sward height, the stem diameter was measured as close to the soil surface as possible at the following height (≤5 mm) without disturbing the soil following De Baet et al., (2009) who also measured stem diameter at the base, this was to ensure that the stem diameter was measured at the same place on the grass stem. The stem diameter was measured so that the SAD could be determined. SAD, as well as stem diameter and number of tillers, impart a frictional component to water flow resulting in a dissipation of flow energy, causing sedimentation (Gavrić et al., 2019) due to an increased sediment trapping efficiency (Mekkonnen et al., 2016). Stem area density was calculated using the following equation which was used in De Baets et al., (2009) and Lees et al., (2020).

Equation 4-1: $$\textbf{\textit{Stem Area Density}} = \frac{\textbf{\textit{surface area of stems (mean stem diameter)}} * \textbf{\textit{number of stems}}}{\textbf{\textit{area of microcosm}}}$$

4.3.7 Root traits

After each mesocosm had been tested in the hydraulic flume (ASSETTE), three 0.046 m internal diameter cylindrical 0.1 m long soil cores, were taken at equidistance along the length of the mesocosm. The roots were washed using a pressure sprayer, sieve, and picked out using tweezers following Genney et al., (2000) using a <500 µm sieve. Root traits were measured post-root washing and were prepared in accordance with Lees et al., (2020).

After roots were weighted, they were processed using WinRhizo software (Regent Instruments, 2016). Roots were stored at <4^{o}C in a 15% ethanol solution until analysis (Bainard et al., 2010). The following root traits are important as they provide mechanical reinforcement by increasing aggregate stability and soil due to root cohesion (Vanoppen et al., 2015) and were determined for each core. These include root diameter, root total surface area (De Baets et al., 2007), total length (cm) of fine roots (≤0.25 mm ⌀) (Liang et al., 2017) and total root length (cm) (Mekonnen et al., 2016). Mean (n=3) values for the below ground traits was determined for each experimental replicate.

4.3.8 Hydraulic flume concentrated flow event

Each mesocosm was subject to an incrementally increasing concentrated flow event using the hydraulic flume (ASSETTE) (Figure 4-1). The flume was used at the same slope (5°) to ensure that the slope did not affect the erosivity of the flow. This is because the slope will affect soil erosion due to gravity affecting the experimental set up, in general an increased slope has been shown to exacerbate soil erosion (Zhang et al., 2015; Li et al., 2019). Further the slope was required to generate more erosive conditions in terms of flow velocity and flow shear stress. During pre-testing if no slope was applied then soil erosion was minimal, and no sediment was able to be collected. Each mesocosm was placed into the flume and all interfaces sealed with Vaseline to ensure a seamless interface between the mesocosms and flow bed and sides of the ASSETTE. Another blank stainless-steel insert (0.2 x 0.1 x 0.1 m) was placed next to the experimental treatment to facilitate insertion and extraction of the mesocosms. Both inserts were level with each other and sealed to ensure a uniform flow.

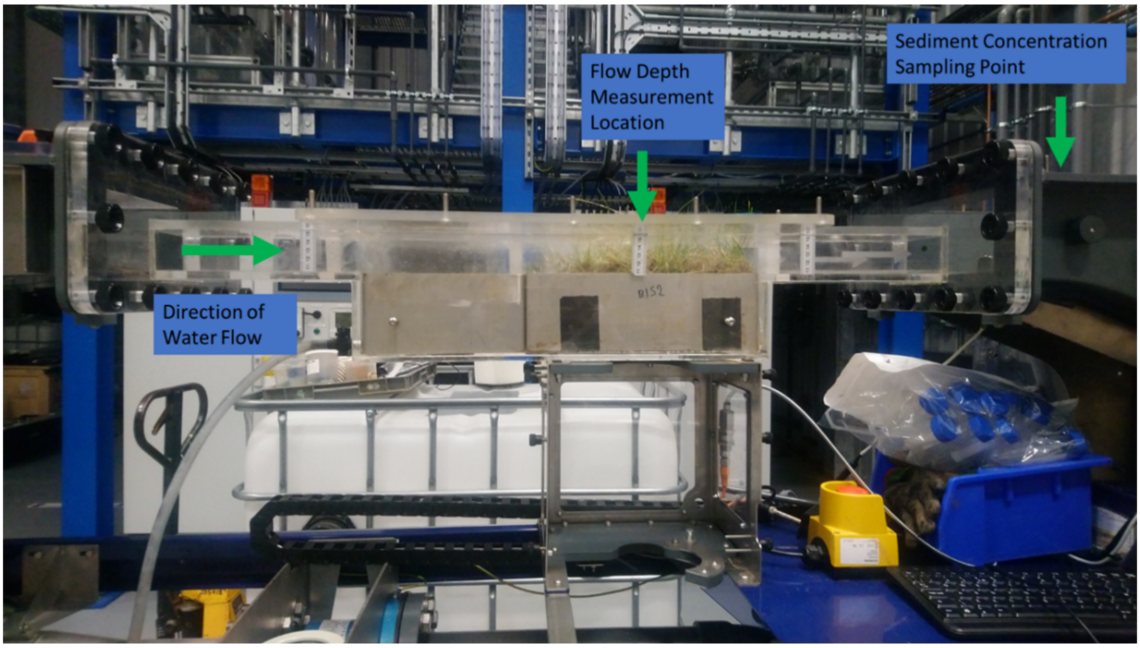

Figure 4-1: Photo of the hydraulic flume (ASSETTE) with the flow depth measurement location at the middle of the sample (0.15 m), direction of water flow and the sediment concentration sampling point.

For all treatments, inflow rates started at 0.2 l s^{-1} and were raised in increments of 0.1 l s^{-1} up to 2.6 l s^{-1}. Each inflow rate was implemented for 1.0 min before the inflow rate was ramped up. This meant that each experimental discharge lasted 26 minutes. The inflow rate was controlled by a computer attached the flume.The smallest increment in which the hydraulic flume could be ramped up by (0.1 l s^{-1}) was used so that the critical point at which soil erosion occurred could be determined. Due to climate change an increased magnitude and duration of rainfall is expected (Routschek et al., 2014; Wright et al., 2015) which is what this concentrated flow event is trying to simulate.

4.3.9 Determination of flow shear stress

Flow depth (m) was determined for each concentrated flow event run, via a graduated scale which was placed at the start of the mesocosm. Each concentrated flow event was filmed using a GoPro IV. This meant that the water depth levels could be determined after the event. For each inflow rate water depth was measured at the :30, :31 and :32 sec time stamp. Mean water depth (cm) was then determined to enable the flow velocity to be calculated.

Shear stress (Pa) was calculated using the following equation which has been used in a number of equation studies (Lave & Avouac 2001; Montieth & Pender 2005; Knapen et al., 2007; Khodashenas et al., 2008; Schwendel et al., 2010; Somsook et al., 2021; Cheng & Zhang 2022; Liu et al., 2022; Lou et al., 2022; Sun et al., 2022; White et al., 2022; Xiao et al., 2022; Ye et al., 2022; Lou et al., 2023).Parameters included pw as water density (1000 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), R is the cross-sectional area of the flume, and S is the slope angle of soil surface (5^{o}).

Equation 4-2: $\boldsymbol{Shear\ Stress\ (Pa) = pwgRS}$

The hydraulic radius was calculated using the following equation. Manning's n was assumed to be 0.3 as that is the median value for a short uniform grass swards taken from Morgan & Rickson (2005).

Equation 4-3: $\boldsymbol{Hydraulic\ Radius = \frac{flow\ velocity\ x\ mannings\ n}{(slope^{0.5})^{1.5}}}$

4.3.10 Determination of flow velocity

Flow velocity (m s^{-1}) was calculated following Equation 4-4, the width of the flume (m) and the inflow rates (l s^{-1}) were known. The flow depth (m) values at the start of the mesocosm were used to determine the cross-sectional area. Flow velocities which have caused soil erosion for grass have been shown to range between 0.108 **-** 0.61 m s^{-1} (Ramos et al., 2016; Shit et al., 2020). Therefore, flow velocities were desired to be at around this range.

Equation 4-4: $\boldsymbol{Flow\ Velocity\ = Inflow\ rate/Cross\ sectional\ area}$

4.3.11 Determination of sediment concentration

Sediment samples were collected during each incremental increase of each continuous concentrated flow event. At each inflow rate two water samples were taken down flow of the mesocosm using 50 ml centrifuge tubes. These water samples were subsequently filtered through No. 42 Whatman filter papers. The mass (g) of the soil and the filter paper weight was determined before the samples were oven dried for 24 hours at 105^{o}C. The samples were then reweighed. Before use, each filter paper was weighed before and after being oven dried for 24 hours at 105^{o}c. Therefore, any change in filter paper weight was accounted for.

4.3.12 Statistical analysis

Before statistical analysis data was transformed if there was not a normal distribution via a log10. All data was subject to a One-way ANOVA and a *post-hoc* Fischer LSD test was undertaken if significant differences ($p \leq 0.05$) were found (Appendix B). This was to determine whether there were any significant differences in plant traits for the different experimental grass species treatments which could then be linked to any differences in sediment concentration, flow shear stress or flow velocity. Any significant differences in shear stress or flow velocity or sediment concentration could then be determined and correlated with any significant differences in plant traits by way of Spearman's rank. The plant traits were also correlated against flow shear stress, flow velocity and sediment concentration to see if the plant traits had any bearing on these variables.

4.4 Results

4.4.1 Above ground traits (Roots and shoots)

For the roots and shoots above ground plant traits, the number of stems varied from 62 (Fest_1 L) to 142 (Conv N) (Table 4-2). The number of stems for Conv N (142) was significantly greater ($p<0.05$) than that of all other treatments except for Fest_1+2+Conv L (118). The number of tillers for the roots and shoots treatment ranged from 2.2 (Fest_1 N) to 3.4 (Fest_1 L). The number of tillers was significantly greater ($p<0.05$) in the Fest_1 L (3.4) treatment than for all other treatments except for Conv L (3.0) and Fest_1+2 L (2.8) treatments. The stem diameter (mm) for the roots and shoots treatments ranged from 1.35 (Conv L) to 2.21 mm (Fest_1+2 N). The stem diameter (mm) was significantly greater ($p<0.05$) for the Fest_1+2 N (2.21 mm) treatment than the Conv N (1.42 mm), Conv L (1.35 mm), Fest_1 N (1.66 mm) and Fest_1+2+Conv N (1.49 mm) treatments. The ground cover (%) for the roots and shoots treatments ranged from 11 (Fest_1+2 L) 23 % (Conv N). The ground cover (%) was significantly greater ($p<0.05$) in the Conv N (23 %) treatment as opposed to all other treatments. The SAD (mm^2 mm^{-2}) for the roots and shoots treatment ranged from 0.014 (Conv L) to 0.044 (Fest_1+2 N & Fest_1+2+Conv L). The SAD (mm^2 mm^{-2}) was significantly greater ($p<0.05$) for Fest_1+2 N and Fest_1+2+Conv L (0.044) as opposed to all other experimental treatments (Table 4-2).

Table 4-2: Differences in mean, (n=4) number of stems, number of tillers, stem diameter (mm) and SAD (mm^2 mm^{-2}), (n=12) for % ground cover, above ground plant traits, between experimental roots and shoots grass treatments. Values in parentheses indicate ±1 Standard Error (S.E).

Sample	Number of Stems	Number of Tillers	Stem Diameter (mm)	% Ground Cover	SAD (mm^2 mm^{-2})
Conv N	142[i] (±6.1)	2.6[bcde] (±.050)	1.42[abc] (±.099)	23[e] (±1.20)	0.022[bcde] (±.0025)
Fest_1+2+Conv N	99.0[cdef] (±8.1)	2.4[abcd] (±.216)	1.49[abc] (±.116)	16[cd] (±.29)	0.017[abcd] (±.0024)
Fest_1+2 N	114[efgh] (±9.9)	2.4[abc] (±.440)	2.21[g] (±.104)	14[abcd] (±1.84)	0.044[h] (±.0062)
Fest_1 N	69.0[ab] (±5.1)	2.2[ab] (±.206)	1.66[cde] (±.102)	14[abcd] (±.87)	0.015[ab] (±.0025)
Conv L	94.0[cde] (±3.2)	3.0[def] (±.081)	1.35[ab] (±.110)	15[abcd] (±1.66)	0.014[a] (±.0019)
Fest_1+2+Conv L	118[fghi] (±7.0)	2.4[abcd] (±.082)	2.14[fg] (±.195)	15[abcd] (±2.21)	0.044[gh] (±.0079)
Fest_1+2 L	83.0[bc] (±3.7)	2.8[cdef] (±.096)	1.95[efg] (±.035)	11[a] (±.71)	0.025[def] (±.0018)
Fest_1 L	62.0[a] (±4.2)	3.4[f] (±.096)	1.97[efg] (±.103)	12[abc] (±1.03)	0.019[abcde] (±.0028)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra,* Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra, Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), All treatments are at 60% of the normal recommended seeding rate. All treatments with an N are the normal recommended seeding rate. For each plant trait, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis

4.4.2 Below ground traits (Roots and shoots)

For the roots and shoots treatments below ground plant traits, the total root length (cm) ranged from 974 (Fest_1 N) to 1837 cm (Fest_1+2+Conv L) (Table 4-3). The total root length (cm) was significantly greater ($p<0.05$) for Fest_1_2+Conv L (1837 cm) as opposed to all other experimental roots and shoots treatments. For the roots and shoots treatments the total root length (cm) (<0.25cm in diameter) ranged from 526 (Conv L) to 959 cm (Fest_1+2+Conv L). The total root length (cm) (<0.25cm in diameter) for the Fest_1+2+Conv L (959 cm) treatment was significantly greater ($p<0.05$) than that for all other treatments except for Conv N (814 cm) and Fest_1+2+Conv N (803 cm). For the roots and shoots treatments the total root surface area (cm^2) ranged from 76 (Conv L) to 280 cm^2 (Fest_1+2+Conv L). The total root surface area (cm^2) for Fest_1+2+Conv L was significantly greater ($p<0.05$) than that of all other treatments except for Fest_1+2+Conv N. For the roots and shoots treatments the average root diameter (cm) ranged from 0.29 cm (Conv L) to 0.56 cm (Fest_1+2+Conv N). The average root diameter (cm) was significantly similar ($p<0.05$) for the following treatments, Fest_1+2+Conv N (0.56 cm), Fest_1+2 N (0.42), Fest_1+2+Conv L (0.48 cm), Fest_1+2 L (0.43 cm).

Table 4-3: Below ground plant traits (n=4), total root length (cm), total root length (cm) (<0.25cm⌀), total root surface area (cm^2) and average root diameter (cm) for the experimental roots and shoots treatment. Values in parentheses indicate ±1 Standard Error (S.E).

Sample	Total Root Length (cm)	Total Root Length (cm) (<0.25cm ⌀)	Total Root Surface Area (cm^2)	Average Root Diameter (cm)
Conv N	1372^{de} (±173)	814^{defg} (±100)	168^{cde} (±28)	0.38^{bcde} (±.021)
Fest_1+2+Conv N	1419^{de} (±103)	803^{defg} (±56)	226^{efg} (±39)	0.56^{f} (±.156)
Fest_1+2 N	1165^{d} (±52)	626^{bcd} (±30)	154^{de} (±10)	0.42^{cdef} (±.017)
Fest_1 N	974^{abc} (±87)	602^{abc} (±51)	106^{ab} (±12)	0.34^{ab} (±.012)
Conv L	836^{ab} (±49)	526^{ab} (±29)	76^{a} (±5.5)	0.29^{a} (±.009)
Fest_1+2+Conv L	1837^{f} (±66)	959^{g} (±40)	280^{g} (±15)	0.48^{df} (±.017)
Fest_1+2 L	1274^{de} (±108)	658^{bcde} (±59)	193^{ef} (±21)	0.47^{f} (±.019)
Fest_1 L	1000^{abc} (±122)	608^{ab} (±80)	116^{abc} (±16)	0.37^{bce} (±.017)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), All treatments are at 60% of the normal recommended seeding rate. All treatments with an N are the normal recommended seeding rate. For each plant trait, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis

4.4.3 Below ground traits (Roots only)

For the roots only treatments below ground plant traits, the total root length (cm) ranged from 865 (Fest_1 L) to 1864 cm (Fest_1+2+Conv L) (Table 4-4). The total root length (cm) was significantly greater ($p<0.05$) for the Fest_1+2+Conv L (1864 cm) treatments as opposed to all other experimental treatments except for Fest_1+2 L (1655 cm). For the roots only treatments the total root length (cm) (<0.25cm in diameter) ranged from 512 (Fest_1 L) to 977 cm (Fest_1+2+Conv L). The total root length (cm) (<0.25cm in diameter) was significantly greater ($p<0.05$) for the Fest_1+2+Conv L (977 cm) treatment as opposed to the Fest_1 (512 cm) treatment. For the roots only treatments the total root surface area (cm^2) ranged from 108 (Fest_1 L) to 285 cm^2 (Fest_1+2+Conv L) with the Fest_1+2+Conv L treatment being significantly greater than the Fest_1 L treatment. For the roots only treatments the average root diameter (cm) ranged from 0.38 (Conv L & Fest_1 N) 0.49 cm (Fest_1+2+Conv L) with the Fest_1+2+Conv L treatment being significantly greater ($p<0.05$) than that of the Fest_1 N and Conv L treatments.

Table 4-4: Below ground plant traits (n=4), total root length (cm), total root length (cm) (<0.25cm ⌀), total root surface area (cm^2) and average root diameter (cm) for the experimental roots only treatment. Values in parentheses indicate ±1 Standard Error (S.E).

Sample	Total Root Length (cm)	Total Root Length (cm) (<0.25cm ⌀)	Total Root Surface Area (cm^2)	Average Root Diameter (cm)
Conv N	1337^{de} (±182)	793^{defg} (±109)	181^{cde} (±27)	0.43^{cdef} (±.034)
Fest_1+2+Conv N	1651^{de} (±163)	876^{efg} (±101)	253^{efg} (±37)	0.48^{def} (±.039)
Fest_1+2 N	1433^{de} (±103)	777^{cdef} (±58)	225^{efg} (±29)	0.48^{df} (±.030)
Fest_1 N	1259^{cd} (±105)	759^{cdef} (±45)	160^{bcd} (±26)	0.38^{abc} (±0.031)
Conv L	1054^{bcd} (±70)	621^{bcde} (±26)	133^{bcd} (±39)	0.38^{abce} (±.078)
Fest_1+2+Conv L	1864^{f} (±77)	977^{g} (±56)	285^{fg} (±25)	0.49^{df} (±.039)
Fest_1+2 L	1655^{ef} (±87)	908^{fg} (±56)	226^{efg} (±16)	0.43^{bcdef} (±.013)
Fest_1 L	865^{a} (±79)	512^{a} (±51)	108^{ab} (±14)	0.39^{bcde} (±.021)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), All treatments with an L are at 60% of the normal recommended seeding rate, all treatments with an N are the normal recommended seeding rate. For each plant trait, values followed by the same letter are not significantly different (p <0.05) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis

4.4.4 Flow shear stress

The flow shear stress was measured for the roots and shoots treatments (Table 4-5 Table 4-6) and there were no significant differences ($p<0.05$) in flow shear stress between any experimental grass treatments for inflow rates of 1.5 – 1.9 and 2.1 – 2.3 l s^{-1}. Significant differences in flow shear stress were however observed between treatments for inflow rates of 0.2 – 1.5 l s^{-1}, 2.0 l s^{-1} and 2.4 – 2.6 l s^{-1} (Table 4-5 Table 4-6). The Fest_1+2 N consistently had the statistically lowest or joint statistically lowest value for flow shear stress as compared to all the other roots and shoots treatments when there were significant differences and therefore performed the worst in terms of reducing flow shear stress. For an inflow rate of 2.4 l s^{-1} Fest_1+2 N had a significantly lower ($p<0.05$) shear stress (0.01 Pa) than that of all other experimental roots and shoots treatments aside from Fest_1+2 L (0.01 Pa). At an inflow rate of 2.5 l s^{-1} Fest_1+2 N had a significantly lower ($p<0.05$) flow shear stress than most other treatments except for the Fest_1+2 L (0.01 Pa) and the Fest_1+2+C L (0.01 Pa) treatments which were statistically similar. At the highest inflow rate, 2.6 l s^{-1}, the flow shear stress for Fest_1+2 N (0.01 Pa) was significantly greater ($p<0.05$) than all other treatments except for Fest_1+2 L (0.02 Pa), Fest_1+2+C L (0.02 Pa) and Conv L (0.02 Pa) which it was statistically similar to. These findings suggested that the Fest_1+2 N treatment would yield less soil erosion and have a lower sediment concentration than most other treatments. The flow shear stress was also measured for the roots only treatments (Table 4-7 Table 4-8) and similarly, no significant differences ($p<0.05$) between experimental grass treatments for inflow rates of 1.5 and 2.5 - 2.6 l s^{-1}. For the low inflow rates, 0.2 – 1.4 l s^{-1} Fest_1+2 L was consistently associated with the significantly lowest flow shear stress as opposed to all other treatments suggesting that there would be less soil erosion and a lower sediment concentration for this treatment at these lower inflow rates of up to 1.4 l s^{-1}.

Table 4-5: Differences in mean flow shear stress (Pa) (n=4) for each inflow rate 0.2 – 1.3 (l s^{-1}), at the middle of the sample, between the roots and shoots grass sward treatment. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at specific flow rates (l s^{-1})											
Treatment	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Conv L	0.32^{abc} (±0.124)	0.30^{bc} (±0.115)	0.21^{bcd} (±0.078)	0.17^{ac} (±0.066)	0.16^{c} (±0.060)	0.12^{ac} (±0.046)	0.10^{a} (±0.037)	0.10^{bc} (±0.036)	0.08^{bc} (±0.030)	0.07^{bc} (±0.028)	0.06^{bc} (±0.023)	0.06^{bc} (±0.022)
Conv N	0.45^{bc} (±0.153)	0.38^{c} (±0.134)	0.27^{d} (±0.089)	0.26^{c} (±0.088)	0.20^{c} (±0.064)	0.16^{c} (±0.049)	0.16^{c} (±0.050)	0.15^{c} (±0.049)	0.14^{c} (±0.042)	0.12^{a} (±0.038)	0.11^{c} (±0.034)	0.10^{c} (±0.028)
Fest_1+2+Conv L	0.03^{a} (±0.006)	0.03^{a} (±0.003)	0.02^{a} (±0.003)	0.02^{b} (±0.004)	0.02^{a} (±0.003)	0.02^{b} (±0.002)	0.02^{b} (±0.002)	0.01^{a} (±0.001)	0.01^{a} (±0.001)	0.01^{a} (±0.001)	0.01^{a} (±0.001)	0.01^{a} (±0.001)
Fest_1+2+Conv N	0.16^{ab} (±0.037)	0.11^{ab} (±0.041)	0.09^{abc} (±0.041)	0.06^{ab} (±0.018)	0.06^{ab} (±0.016)	0.05^{ab} (±0.016)	0.05^{ab} (±0.013)	0.04^{ab} (±0.011)	0.04^{ab} (±0.010)	0.03^{ab} (±0.010)	0.03^{ab} (±0.010)	0.04^{ab} (±0.007)
Fest_1+2 L	0.11^{ab} (±0.035)	0.08^{ab} (±0.023)	0.07^{ab} (±0.023)	0.06^{ab} (±0.022)	0.06^{ab} (±0.017)	0.05^{ab} (±0.017)	0.05^{ab} (±0.014)	0.05^{ab} (±0.015)	0.04^{ab} (±0.013)	0.04^{ab} (±0.012)	0.04^{ab} (±0.011)	0.04^{ab} (±0.011)
Fest_1+2 N	0.04^{a} (±0.010)	0.03^{a} (±0.008)	0.02^{a} (±0.008)	0.02^{b} (±0.004)	0.02^{a} (±0.004)	0.02^{b} (±0.003)	0.02^{b} (±0.003)	0.01^{a} (±0.003)	0.01^{a} (±0.002)	0.01^{a} (±0.002)	0.01^{a} (±0.003)	0.01^{a} (±0.003)
Fest_1 L	0.71^{c} (±0.329)	0.36^{c} (±0.116)	0.26^{cd} (±0.094)	0.18^{ac} (±0.056)	0.12^{bc} (±0.036)	0.12^{ac} (±0.033)	0.09^{ac} (±0.027)	0.08^{ab} (±0.024)	0.07^{ab} (±0.022)	0.07^{abc} (±0.021)	0.05^{ab} (±0.014)	0.05^{ab} (±0.012)
Fest_1 N	0.33^{abc} (±0.013)	0.25^{bc} (±0.021)	0.19^{bcd} (±0.017)	0.18^{ac} (±0.009)	0.15^{bc} (±0.009)	0.13^{ac} (±0.007)	0.10^{ac} (±0.010)	0.10^{bc} (±0.009)	0.09^{bc} (±0.008)	0.08^{bc} (±0.004)	0.08^{bc} (±0.007)	0.07^{bc} (±0.004)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-6: Differences in mean flow shear stress (Pa) (n=4) for each inflow rate 1.4 – 2.6 (l s^{-1}), at the sample, between the roots and shoots grass sward treatment. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	0.05^{ac} (±0.020)	0.05^{a} (±0.017)	0.05^{a} (±0.016)	0.04^{a} (±0.014)	0.03^{a} (±0.008)	0.03^{a} (±0.007)	0.03^{abcd} (±0.008)	0.03^{a} (±0.007)	0.03^{a} (±0.006)	0.02^{a} (±0.005)	0.02^{abc} (±0.005)	0.02^{ab} (±0.005)	0.02^{ab} (±0.004)
Conv N	0.08^{c} (±0.022)	0.06^{a} (±0.018)	0.06^{a} (±0.015)	0.05^{a} (±0.014)	0.05^{a} (±0.012)	0.04^{a} (±0.011)	0.04^{c} (±0010)	0.04^{a} (±0.009)	0.03^{a} (±0.008)	0.03^{a} (±0.008)	0.03^{c} (±0.008)	0.03^{b} (±0.007)	0.03^{c} (±0.007)
Fest_1+2+Conv L	0.02^{ab} (±0.008)	0.03^{a} (±0.009)	0.02^{a} (±0.008)	0.02^{a} (±0.007)	0.02^{a} (±0.008)	0.02^{a} (±0.006)	0.02^{ad} (±0.005)	0.02^{a} (±0.006)	0.02^{a} (±0.006)	0.02^{a} (±0.004)	0.02^{ad} (±0.005)	0.01^{ac} (±0.003)	0.02^{ab} (±0.005)
Fest_1+2+Conv N	0.04^{ab} (±0.006)	0.04^{a} (±0.002)	0.04^{a} (±0.002)	0.04^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{abc} (±0.000)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{abc} (±0.001)	0.02^{ab} (±0.001)	0.02^{ac} (±0.001)
Fest_1+2 L	0.04^{ab} (±0.009)	0.03^{a} (±0.008)	0.03^{a} (±0.007)	0.03^{a} (±0.007)	0.02^{a} (±0.006)	0.02^{a} (±0.005)	0.02^{abd} (±0.005)	0.02^{a} (±0.005)	0.02^{a} (±0.006)	0.02^{a} (±0.004)	0.02^{abd} (±0.003)	0.02^{ac} (±0.003)	0.02^{ab} (±0.002)
Fest_1+2 N	0.02^{b} (±0.006)	0.03^{a} (±0.009)	0.02^{a} (±0.008)	0.02^{a} (±0.008)	0.02^{a} (±0.006)	0.02^{a} (±0.006)	0.01^{d} (±0.004)	0.01^{a} (±0.004)	0.01^{a} (±0.004)	0.01^{a} (±0.005)	0.01^{d} (±0.001)	0.01^{c} (±0.000)	0.01^{b} (±0.000)
Fest_1 L	0.04^{abc} (±0.008)	0.04^{a} (±0.004)	0.04^{a} (±0.004)	0.04^{a} (±0.004)	0.04^{a} (±0.002)	0.03^{a} (±0.002)	0.03^{abc} (±0.003)	0.03^{a} (±0.002)	0.03^{a} (±0.003)	0.03^{a} (±0.002)	0.03^{abc} (±0.002)	0.02^{ab} (±0.002)	0.02^{ac} (±0.002)

Fest_1 N	0.05[ac] (±0.001)	0.05[a] (±0.002)	0.05[a] (±0.002)	0.04[a] (±0.002)	0.04[a] (±0.002)	0.04[a] (±0.002)	0.04[bc] (±0.001)	0.03[a] (±0.002)	0.03[a] (±0.001)	0.03[a] (±0.001)	0.03[bc] (±0.001)	0.03[b] (±0.001)	0.02[ac] (±0.001)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-7: Differences in mean flow shear stress (Pa) (n=4) for each inflow rate 0.2 – 1.3 (l s^{-1}), at the sample, between the roots only treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at specific flow rates (l s^{-1})											
Treatment	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Conv L	0.30[a] (±0.052)	0.20[a] (±0.050)	0.19[a] (±0.053)	0.17[a] (±0.048)	0.16[a] (±0.044)	0.13[a] (±0.042)	0.10[a] (±0.035)	0.11[a] (±0.034)	0.10[a] (±0.030)	0.08[a] (±0.030)	0.08[a] (±0.030)	0.07[ab] (±0.021)
Conv N	0.53[c] (±0.057)	0.46[c] (±0.075)	0.36[c] (±0.121)	0.24[a] (±0.083)	0.19[a] (±0.054)	0.17[a] (±0.044)	0.13[a] (±0.030)	0.09[a] (±0.021)	0.07[a] (±0.015)	0.07[a] (±0.012)	0.06[a] (±0.014)	0.06[ab] (±0.008)
Fest_1+2+Conv L	0.03[a] (±0.040)	0.03[a] (±0.022)	0.02[ab] (±0.021)	0.02[a] (±0.016)	0.10[a] (±0.013)	0.02[a] (±0.013)	0.02[a] (±0.009)	0.01[a] (±0.007)	0.01[a] (±0.002)	0.01[a] (±0.002)	0.01[a] (±0.003)	0.01[a] (±0.001)
Fest_1+2+Conv N	0.16[a] (±0.019)	0.11[a] (±0.011)	0.09[ab] (±0.012)	0.06[a] (±0.010)	0.06[a] (±0.018)	0.05[a] (±0.012)	0.05[a] (±0.010)	0.04[a] (±0.008)	0.04[a] (±0.007)	0.03[a] (±0.006)	0.03[a] (±0.004)	0.04[ab] (±0.004)
Fest_1+2 L	0.03[b] (±0.007)	0.03[b] (±0.006)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[b] (±0.003)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[b] (±0.004)	0.02[c] (±0.005)
Fest_1+2 N	0.20[a] (±0.063)	0.20[a] (±0.085)	0.17[ab] (±0.054)	0.15[a] (±0.035)	0.13[a] (±0.029)	0.11[a] (±0.018)	0.11[a] (±0.019)	0.09[a] (±0.017)	0.09[a] (±0.012)	0.07[a] (±0.011)	0.07[a] (±0.009)	0.06[ab] (±0.003)
Fest_1 L	0.25[a] (±0.034)	0.19[a] (±0.015)	0.17[ab] (±0.007)	0.15[a] (±0.010)	0.13[a] (±0.012)	0.13[a] (±0.014)	0.12[a] (±0.013)	0.10[a] (±0.011)	0.10[a] (±0.007)	0.08[a] (±0.009)	0.07[a] (±0.006)	0.07[ab] (±0.005)
Fest_1 N	0.27[a] (±0.026)	0.24[a] (±0.026)	0.21[a] (±0.016)	0.16[a] (±0.009)	0.16[a] (±0.010)	0.14[a] (±0.006)	0.12[a] (±0.005)	0.11[a] (±0.006)	0.10[a] (±0.005)	0.09[a] (±0.005)	0.08[a] (±0.004)	0.08[b] (±0.003)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-8: Differences in mean flow shear stress (Pa) (n=4) for each inflow rate 1.4 – 2.6 (l s^{-1}), at the sample, between the roots only treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Shear Stress (Pa) at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	0.06^{a} (±0.019)	0.05^{a} (±0.016)	0.04^{a} (±0.013)	0.04^{a} (±0.007)	0.04^{a} (±0.007)	0.04^{ab} (±0.005)	0.04^{a} (±0.004)	0.04^{a} (±0.003)	0.03^{ab} (±0.004)	0.03^{ab} (±0.004)	0.03^{b} (±0.001)	0.11^{a} (±0.066)	0.09^{a} (±0.054)
Conv N	0.05^{a} (±0.006)	0.05^{a} (±0.005)	0.05^{a} (±0.005)	0.05^{a} (±0.005)	0.04^{a} (±0.008)	0.04^{b} (±0.004)	0.04^{a} (±0.007)	0.04^{c} (±0.004)	0.04^{b} (±0.006)	0.04^{b} (±0.006)	0.04^{b} (±0.003)	0.03^{a} (±0.005)	0.04^{a} (±0.006)
Fest_1+2+Conv L	0.02^{a} (±0.001)	0.03^{a} (±0.002)	0.02^{a} (±0.002)	0.02^{a} (±0.001)	0.02^{a} (±0.002)	0.02^{a} (±0.002)	0.02^{a} (±0.001)	0.02^{a} (±0.002)	0.02^{ab} (±0.002)	0.02^{a} (±0.001)	0.02^{a} (±0.002)	0.01^{a} (±0.002)	0.02^{a} (±0.002)
Fest_1+2+Conv N	0.04^{a} (±0.002)	0.04^{a} (±0.004)	0.04^{a} (±0.002)	0.04^{a} (±0.003)	0.03^{a} (±0.002)	0.03^{ab} (±0.003)	0.03^{a} (±0.002)	0.03^{a} (±0.001)	0.03^{ab} (±0.001)	0.03^{ab} (±0.002)	0.03^{a} (±0.002)	0.02^{a} (±0.001)	0.02^{a} (±0.001)
Fest_1+2 L	0.02^{b} (±0.006)	0.03^{a} (±0.006)	0.02^{b} (±0.006)	0.02^{b} (±0.003)	0.02^{b} (±0.003)	0.02^{b} (±0.003)	0.02^{b} (±0.002)	0.01^{b} (±0.002)	0.01^{c} (±0.002)	0.01^{c} (±0.002)	0.01^{c} (±0.001)	0.01^{a} (±0.001)	0.01^{a} (±0.001)
Fest_1+2 N	0.05^{a} (±0.002)	0.05^{a} (±0.003)	0.05^{a} (±0.002)	0.04^{a} (±0.001)	0.04^{a} (±0.002)	0.04^{ab} (±0.002)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{ab} (±0.002)	0.03^{a} (±0.001)	0.02^{a} (±0.001)	0.02^{a} (±0.001)
Fest_1 L	0.06^{a} (±0.005)	0.06^{a} (±0.006)	0.05^{a} (±0.002)	0.04^{a} (±0.002)	0.04^{a} (±0.000)	0.04^{ab} (±0.001)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.03^{ab} (±0.001)	0.03^{ab} (±0.001)	0.03^{a} (±0.001)	0.03^{a} (±0.004)	0.02^{a} (±0.001)
Fest_1 N	0.06^{a} (±0.003)	0.06^{a} (±0.003)	0.05^{a} (±0.002)	0.04^{a} (±0.001)	0.04^{a} (±0.001)	0.04^{ab} (±0.001)	0.04^{a} (±0.000)	0.03^{a} (±0.001)	0.03^{ab} (±0.001)	0.03^{ab} (±0.000)	0.03^{a} (±0.001)	0.03^{a} (±0.001)	0.02^{a} (±0.000)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

4.4.5 Flow velocity

For the roots and shoots treatments flow velocity was statistically similar ($p<0.05$) at inflow rates of 1.4 – 2.3 l s^{-1} and statistically different at all other inflow rates (&). At an inflow rate of 2.5 l s^{-1} the Conv N (0.09 m s^{-1}) and Fest_1 N (0.08 m s^{-1}) treatments had a significantly ($p<0.05$) higher flow velocity than that of the Fest_1+2 N (0.04 m s^{-1}) treatment. Further, at an inflow rate of 2.6 l s^{-1} the Fest_1+2 N (0.04 m s^{-1}) treatment had a significantly ($p<0.05$) lower flow velocity than the Conv L (0.06 m s^{-1}), Conv N (0.09 m s^{-1}), Fest_1+2+Conv N (0.07 m s^{-1}) and the Fest_1 N (0.07 m s^{-1}) treatments. This suggests that the Fest_1+2 N treatment would have the lowest soil erosion risk and sediment concentration at these higher inflow rates. At the lowest inflow rate (0.2 l s^{-1}) Fest_1 L (0.80 m s^{-1}) had a significantly greater ($p<0.05$) flow velocity than all other treatments except for Fest_1 N (0.41 m s^{-1}), Conv L (0.39 m s^{-1}) and Conv N (0.48 m s^{-1}). This suggested that these treatments would yield the highest sediment concentration as opposed to the other roots and shoots treatments.

For the roots only treatments flow velocity was significantly different at all inflow rates 0.2 – 2.6 l s^{-1} and statistically similar at all other inflow rates (Table 4-11 Table 4-12). Conv L (0.17 m s^{-1}) was significantly greater ($p<0.05$) than Conv N (0.09 m s^{-1}) at an inflow rate of 2.5 l s^{-1}. This suggested that the risk of soil erosion would be greater for the Conv L treatment as opposed to the Conv N treatment which is as expected. The lowered seeding rate of 60% would result in differences in plant physical traits and should result in a lowered percentage cover, number of stems etc which would adversely affect soil erosion mitigation potential. Further, the roots only treatment which performed the best in terms of reductions in flow velocity was Fest_1+2 L. This was because it had a significantly lower ($p<0.05$) flow velocity than that of all other experimental roots only treatments for all tested inflow rates (0.2 – 2.6 l s^{-1}). At an inflow rate of 0.2 Conv N had a significantly higher ($p<0.05$) flow velocity (0.57 m s^{-1}) than all other treatments except for Conv L (0.42 m s^{-1}). This suggested that the Conv N would have a higher sediment yield at this inflow rate.

Table 4-9: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate 0.2 – 1.3 (l s^{-1}), at the sample, between the roots and shoots grass sward treatment. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Velocity at specific flow rates (l s^{-1})											
Treatment	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Conv L	0.39^{acd} (±0.10)	0.37^{ac} (±0.10)	0.29^{ab} (±0.07)	0.26^{ab} (±0.07)	0.24^{bcd} (±0.06)	0.20^{ab} (±0.05)	0.18^{ac} (±0.04)	0.17^{ac} (±0.04)	0.16^{bcd} (±0.04)	0.15^{bcd} (±0.03)	0.13^{bcd} (±0.03)	0.13^{ac} (±0.03)
Conv N	0.48^{a} (±0.13)	0.42^{a} (±0.12)	0.34^{b} (±0.09)	0.33^{a} (±0.09)	0.28^{b} (±0.07)	0.24^{a} (±0.06)	0.24^{c} (±0.06)	0.23^{c} (±0.06)	0.22^{b} (±0.05)	0.20^{b} (±0.05)	0.19^{b} (±0.04)	0.17^{c} (±0.04)
Fest_1+2 L	0.19^{bd} (±0.04)	0.15^{b} (±0.03)	0.14^{ac} (±0.03)	0.13^{bc} (±0.03)	0.12^{ad} (±0.02)	0.11^{bc} (±0.02)	0.11^{ab} (±0.02)	0.11^{ab} (±0.02)	0.10^{acd} (±0.02)	0.10^{acd} (±0.02)	0.10^{acd} (±0.01)	0.10^{ab} (±0.01)
Fest_1+2 N	0.09^{b} (±0.01)	0.07^{b} (±0.01)	0.07^{c} (±0.01)	0.07^{c} (±0.01)	0.06^{a} (±0.01)	0.05^{c} (±0.01)	0.05^{b} (±0.01)	0.05^{b} (±0.01)	0.05^{a} (±0.004)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{b} (±0.01)
Fest_1+2+C L	0.09^{b} (±0.01)	0.08^{b} (±0.01)	0.07^{c} (±0.01)	0.07^{c} (±0.01)	0.07^{a} (±0.01)	0.06^{c} (±0.004)	0.06^{b} (±0.003)	0.05^{b} (±0.002)	0.05^{a} (±0.002)	0.05^{a} (±0.001)	0.04^{a} (±0.001)	0.05^{b} (±0.002)
Fest_1+2+C N	0.25^{bcd} (±0.04)	0.19^{bc} (±0.05)	0.17^{ac} (±0.04)	0.13^{bc} (±0.02)	0.13^{acd} (±0.02)	0.12^{bc} (±0.02)	0.11^{ab} (±0.02)	0.10^{ab} (±0.01)	0.09^{ad} (±0.01)	0.09^{ad} (±0.01)	0.08^{ad} (±0.01)	0.10^{ab} (±0.01)
Fest_1 L	0.80^{a} (±0.20)	0.52^{a} (±0.05)	0.41^{ab} (±0.06)	0.32^{ab} (±0.04)	0.25^{abcd} (±0.02)	0.24^{ab} (±0.02)	0.20^{abc} (±0.02)	0.19^{abc} (±0.02)	0.17^{abcd} (±0.02)	0.16^{abcd} (±0.02)	0.13^{abcd} (±0.01)	0.13^{abc} (±0.01)
Fest_1 N	0.41^{ac} (±0.01)	0.35^{ac} (±0.01)	0.29^{ab} (±0.01)	0.28^{a} (±0.01)	0.24^{bc} (±0.01)	0.22^{a} (±0.01)	0.19^{ac} (±0.01)	0.18^{ac} (±0.01)	0.18^{bc} (±0.01)	0.17^{bc} (±0.01)	0.15^{bc} (±0.01)	0.15^{ac} (±0.01)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-10: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate 1.4 – 2.6 (l s^{-1}), at the sample, between the roots and shoots grass sward treatment. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Velocity at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	0.12^{a} (±0.03)	0.11^{a} (±0.02)	0.11^{a} (±0.03)	0.10^{a} (±0.02)	0.08^{a} (±0.01)	0.08^{a} (±0.01)	0.08^{a} (±0.01)	0.08^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{abc} (±0.01)	0.07^{abc} (±0.01)	0.06^{ab} (±0.01)
Conv N	0.15^{a} (±0.03)	0.13^{a} (±0.02)	0.12^{a} (±0.03)	0.12^{a} (±0.02)	0.11^{a} (±0.02)	0.10^{a} (±0.02)	0.10^{a} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.01)	0.09^{b} (±0.01)
Fest_1+2 L	0.09^{a} (±.01)	0.09^{a} (±0.01)	0.08^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{bcd} (±0.01)	0.06^{bcd} (±0.01)	0.05^{ac} (±0.01)
Fest_1+2 N	0.06^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.05^{a} (±0.01)	0.04^{d} (±0.002)	0.04^{d} (±0.00)	0.04^{c} (±0.00)
Fest_1+2+C L	0.06^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.07^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{a} (±0.01)	0.06^{cd} (±0.01)	0.05^{cd} (±0.01)	0.06^{ac} (±0.01)
Fest_1+2+C N	0.10^{a} (±0.01)	0.11^{a} (±0.003)	0.10^{a} (±0.002)	0.10^{a} (±0.001)	0.09^{a} (±0.001)	0.09^{a} (±0.001)	0.08^{a} (±0.0001)	0.08^{a} (±0.001)	0.08^{a} (±0.001)	0.08^{a} (±0.01)	0.08^{abc} (±0.001)	0.07^{ab} (±0.002)	0.07^{ab} (±0.002)
Fest_1 L	0.12^{a} (±0.01)	0.11^{a} (±0.01)	0.11^{a} (±0.01)	0.10^{a} (±0.01)	0.09^{a} (±0.004)	0.08^{a} (±0.004)	0.09^{a} (±0.01)	0.09^{a} (±0.01)	0.08^{a} (±0.01)	0.08^{a} (±0.003)	0.08^{abcd} (±0.01)	0.07^{abcd} (±0.004)	0.07^{abc} (±0.01)
Fest_1 N	0.12^{a} (±0.001)	0.11^{a} (±0.003)	0.11^{a} (±0.003)	0.11^{a} (±0.003)	0.10^{a} (±0.002)	0.10^{a} (±0.002)	0.09^{a} (±0.001)	0.09^{a} (±0.002)	0.09^{a} (±0.002)	0.09^{a} (±0.001)	0.08^{ab} (±0.002)	0.08^{a} (±0.001)	0.07^{ab} (±0.001)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-11: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate 0.2 – 1.3 (l s^{-1}), at the sample, between the roots only treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Velocity at specific flow rates (l s^{-1})											
Treatment	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Conv L	0.42[bc] (±0.04)	0.31[a] (±0.06)	0.29[ab] (±0.06)	0.27[a] (±0.07)	0.26[a] (±0.06)	0.24[a] (±0.06)	0.20[a] (±0.05)	0.20[a] (±0.05)	0.18[a] (±0.04)	0.16[a] (±0.04)	0.15[a] (±0.05)	0.14[a] (±0.03)
Conv N	0.57[c] (±0.04)	0.52[b] (±0.06)	0.43[b] (±0.06)	0.32[a] (±0.08)	0.27[a] (±0.06)	0.25[a] (±0.05)	0.22[a] (±0.04)	0.17[a] (±0.03)	0.15[a] (±0.02)	0.15[a] (±0.02)	0.13[a] (±0.02)	0.14[a] (±0.01)
Fest_1+2 L	0.08[d] (±0.01)	0.07[c] (±0.02)	0.07[c] (±0.01)	0.07[b] (±0.01)	0.06[b] (±0.01)	0.06[b] (±0.01)	0.06[b] (±0.01)	0.06[b] (±0.01)	0.06[b] (±0.01)	0.05[b] (±0.01)	0.06[b] (±0.01)	0.06[b] (±0.01)
Fest_1+2 N	0.28[a] (±0.07)	0.28[a] (±0.01)	0.25[a] (±0.08)	0.24[a] (±0.04)	0.22[a] (±0.03)	0.20[a] (±0.02)	0.20[a] (±0.02)	0.17[a] (±0.02)	0.17[a] (±0.02)	0.14[a] (±0.02)	0.14[a] (±0.01)	0.13[a] (±0.004)
Fest_1+2+C L	0.29[ab] (±0.03)	0.27[a] (±0.02)	0.24[a] (±0.02)	0.22[a] (±0.02)	0.20[a] (±0.02)	0.18[a] (±0.02)	0.17[a] (±0.01)	0.16[a] (±0.01)	0.15[a] (±0.003)	0.14[a] (±0.003)	0.14[a] (±0.01)	0.12[a] (±0.002)
Fest_1+2+C N	0.28[ab] (±0.02)	0.27[a] (±0.01)	0.24[a] (±0.01)	0.22[a] (±0.01)	0.20[a] (±0.02)	0.19[a] (±0.02)	0.17[a] (±0.01)	0.16[a] (±0.01)	0.16[a] (±0.01)	0.15[a] (±0.01)	0.14[a] (±0.01)	0.13[a] (±0.01)
Fest_1 L	0.36[ab] (±0.04)	0.29[a] (±0.02)	0.27[ab] (±0.02)	0.25[a] (±0.01)	0.23[a] (±0.01)	0.23[a] (±0.02)	0.22[a] (±0.02)	0.20[a] (±0.01)	0.18[a] (±0.01)	0.16[a] (±0.02)	0.15[a] (±0.01)	0.15[a] (±0.01)
Fest_1 N	0.36[ab] (±0.02)	0.34[ab] (±0.02)	0.31[ab] (±0.02)	0.26[a] (±0.01)	0.25[a] (±0.01)	0.23[a] (±0.01)	0.21[a] (±0.01)	0.20[a] (±0.01)	0.19[a] (±0.01)	0.17[a] (±0.01)	0.17[a] (±0.01)	0.16[a] (±0.01)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-12: Differences in mean flow velocity (m s^{-1}) (n=4) for each inflow rate 1.4 – 2.6 (l s^{-1}), at the sample, between the roots only treatments. Values in parentheses indicate ±1 Standard Error (S.E).

	Flow Velocity at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	0.13^{a} (±0.03)	0.12^{a} (±0.03)	0.11^{a} (±0.02)	0.11^{a} (±0.01)	0.10^{a} (±0.01)	0.10^{a} (±0.01)	0.10^{a} (±0.01)	0.09^{ab} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.001)	0.09^{bc} (±0.003)	0.17^{c} (±0.09)	0.16^{c} (±0.08)
Conv N	0.12^{a} (±0.01)	0.11^{a} (±0.01)	0.11^{a} (±0.01)	0.11^{a} (±0.01)	0.10^{a} (±0.01)	0.11^{a} (±0.01)	0.10^{a} (±0.01)	0.11^{b} (±0.01)	0.09^{a} (±0.01)	0.09^{a} (±0.001)	0.10^{c} (±0.004)	0.09^{a} (±0.01)	0.10^{bc} (±0.01)
Fest_1+2 L	0.07^{b} (±0.01)	0.08^{b} (±0.01)	0.07^{b} (±0.01)	0.06^{b} (±0.01)	0.06^{b} (±0.01)	0.05^{b} (±0.01)	0.05^{b} (±0.01)	0.05^{c} (±0.004)	0.05^{b} (±0.01)	0.05^{b} (±0.004)	0.04^{d} (±0.003)	0.04^{b} (±0.002)	0.04^{d} (±0.002)
Fest_1+2 N	0.12^{a} (±0004)	0.12^{a} (±0.004)	0.11^{a} (±0.003)	0.10^{a} (±0.002)	0.10^{a} (±0.003)	0.10^{a} (±0.004)	0.09^{a} (±0.002)	0.08^{a} (±0.001)	0.08^{a} (±0.002)	0.08^{a} (±0.004)	0.08^{a} (±0.002)	0.07^{a} (±0.002)	0.07^{ab} (±0.003)
Fest_1+2+C L	0.12^{a} (±0.001)	0.11^{a} (±0.003)	0.11^{a} (±0.003)	0.10^{a} (±0.002)	0.09^{a} (±0.003)	0.09^{a} (±0.004)	0.08^{a} (±0.002)	0.09^{a} (±0.003)	0.08^{a} (±0.004)	0.08^{a} (±0.002)	0.08^{a} (±0.004)	0.07^{a} (±0.004)	0.07^{a} (±0.004)
Fest_1+2+C N	0.12^{a} (±0.003)	0.12^{a} (±0.01)	0.11^{a} (±0.004)	0.11^{a} (±0.01)	0.10^{a} (±0.004)	0.10^{a} (±0.01)	0.09^{a} (±0.004)	0.09^{a} (±0.003)	0.08^{a} (±0.003)	0.08^{a} (±0.003)	0.08^{a} (±0.003)	0.08^{a} (±0.002)	0.07^{ab} (±0.001)
Fest_1 L	0.13^{a} (±0.01)	0.12^{a} (±0.01)	0.11^{a} (±0.001)	0.10^{a} (±0.002)	0.10^{a} (±0.001)	0.10^{a} (±0.002)	0.09^{a} (±0.002)	0.09^{a} (±0.001)	0.08^{a} (±0.000)	0.08^{a} (±0.004)	0.08^{a} (±0.003)	0.07^{a} (±0.002)	0.07^{ab} (±0.001)
Fest_1 N	0.14^{a} (±.004)	0.13^{a} (±0.01)	0.12^{a} (±0.003)	0.11^{a} (±0.001)	0.10^{a} (±0.002)	0.10^{a} (±0.002)	0.09^{a} (±0.001)	0.09^{ab} (±0.002)	0.09^{a} (±0.001)	0.09^{a} (±0.001)	0.08^{ab} (±0.002)	0.08^{a} (±0.001)	0.07^{ab} (±0.001)

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different (p <0.05) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

4.4.6 Sediment Concentration

The sediment concentration was determined for the roots and shoots treatment vs the bare soil control (Table 4-13 Table 4-14). Sediment concentration data was calculated for 0.2 l s^{-1}, but this was removed from all analysis as this was any loose soil being removed from the transference of the mesocosm into the flume. This was because the sediment concentration were below the EA limits after 0.2 l s^{-1} which suggested that all loose material had been removed. There were no significant differences ($p<0.05$) in sediment concentration between the roots and shoots 0.03 m grass sward length treatments and the bare soil treatments for an inflow rate of 0.5 l s^{-1}. There were no significant differences ($p<0.05$) between the experimental roots and shoots treatments for the inflow rates 0.9 – 1.6 l s^{-1}, 1.8 – 2 l s^{-1} and 2.2 – 2.6 l s^{-1}. For all inflow rates that the bare soil treatment was run (0.3 – 0.8 l s^{-1}) the EA acceptable limit of 1000 mg l^{-1} was breached meaning that a major event for water body degradation had occurred. Fest_1+2 N was above the limit at inflow rate 0.3 l s^{-1}. Fest_1 L was above the limit at inflow rates 0.3 – 0.4 l s^{-1}. The following treatments never exceeded the 1000 mg l^{-1} limit, Conv N, Fest_1+2 L, Fest_1+2+C L and Fest_1 N and Conv L.

The sediment concentration was also determined for the roots only treatment vs the bare soil control (Table 4-15 Table 4-16). There were no significant differences ($p<0.05$) between the experimental grass treatments and the bare soil control for 0.3 l s^{-1}. There were no significant differences between experimental grass treatments for inflow rates of 0.9 – 1.6 l s^{-1}, 1.8 – 2 l s^{-1} and 2.2 – 2.6 l s^{-1}. The bare soil control sediment concentration was higher than the EA acceptable limit for every flow rate for which it was run for (0.3 – 0.8 l s^{-1}). Conv L and Fest_1 L both exceeded the 1000 mg l^{-1} acceptable limit for the inflow rate of 0.3 l s^{-1}. Conv N was associated with sediment concentrations greater than the acceptable limits for 1.0 l s^{-1}, 1.8 l s^{-1} and 2.6 l s^{-1}. Fest_1 N was greater than the acceptable limits for 0.9 – 1.1 l s^{-1}.

Table 4-13: Mean sediment concentration (n=4) for every experimental treatment and inflow rates 0.3 – 1.3 l s^{-1} for the roots and shoots only treatments.

	Sediment Concentration (mg l^{-1}) at specific flow rates (l s^{-1})										
Treatment	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Bare Soil	3623^{c}	3978^{b}	14079^{a}	2128^{c}	7965^{b}	1463^{d}	NDA	NDA	NDA	NDA	NDA
Conv L	266^{a}	189^{a}	278^{a}	146^{a}	146^{a}	83.3^{a}	168^{a}	174^{a}	152^{a}	407^{a}	191^{a}
Conv N	157^{a}	236^{a}	208^{a}	156^{a}	209^{a}	191^{ab}	206^{a}	213^{a}	254^{a}	150^{a}	115^{a}
Fest_1+2 L	131^{a}	131^{a}	103*	8.1^{a}	140^{a}	92.1^{a}	134^{a}	150^{a}	81.4^{a}	77.4^{a}	28.5^{a}
Fest_1+2 N	578^{ab}	281^{a}	312^{a}	259^{a}	124^{a}	146^{ab}	185^{a}	197^{a}	168^{a}	38^{a}	211^{a}
Fest_1+2+C L	128^{a}	245^{a}	252^{a}	107^{a}	117^{a}	108^{ab}	87.0^{a}	79.3^{a}	80^{a}	112^{a}	138^{a}
Fest_1+2+C N	367^{ab}	461^{a}	390^{a}	334^{a}	170^{a}	238^{abc}	337^{a}	134^{a}	199^{a}	156^{a}	233^{a}
Fest_1 L	1544^{b}	1068^{a}	617^{a}	812^{b}	385^{a}	398^{c}	186^{a}	285^{a}	176^{a}	143^{a}	167^{a}
Fest_1 N	826^{ab}	256^{a}	366^{a}	287^{a}	338^{a}	314^{bc}	230^{a}	144^{a}	226^{a}	140^{a}	227^{a}

NDA (No data available). Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-14: Mean sediment concentration (mg l^{-1}) (n=4) for every experimental treatment and inflow rates 1.4 – 2.6 l s^{-1} for the roots and shoots only treatments.

	Sediment Concentration (mg l^{-1}) at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	437^{a}	237^{a}	114^{a}	180^{a}	205^{a}	174^{a}	175^{a}	325^{a}	157^{a}	129^{a}	65.1^{a}	50.6^{a}	79.5^{a}
Conv N	266^{a}	165^{a}	94.3^{a}	44.3^{a}	208^{a}	88^{a}	111^{a}	64.2^{a}	120^{a}	80.1^{a}	152^{a}	150.8^{a}	110^{a}
Fest_1+2 L	48.0^{a}	85.8^{a}	83.6^{a}	118^{a}	117^{a}	79.2^{a}	63.4^{a}	29.7^{a}	27.4^{a}	91.9^{a}	95.8^{a}	135^{a}	198^{a}
Fest_1+2 N	91.6^{a}	130^{a}	104^{a}	45.4^{a}	106^{a}	145^{a}	172^{a}	168^{ab}	142^{a}	85.1^{a}	108^{a}	232^{a}	136^{a}
Fest_1+2+C L	42.9^{a}	137^{a}	237^{a}	147^{a}	140^{a}	185^{a}	213^{a}	98.2^{a}	110^{a}	99.1^{a}	134^{a}	173^{a}	92.4^{a}
Fest_1+2+C N	101^{a}	136^{a}	112^{a}	132^{a}	190^{a}	142^{a}	139^{a}	81.7^{a}	49.0^{a}	102^{a}	114^{a}	89.7^{a}	3.8^{a}
Fest_1 L	346^{a}	427^{a}	399^{a}	358^{b}	315^{a}	228^{a}	249^{a}	192^{b}	316^{a}	190^{a}	308^{a}	170^{a}	324^{a}
Fest_1 N	127^{a}	123^{a}	194^{a}	167^{a}	165^{a}	299^{a}	251^{a}	50.4^{a}	134^{a}	102^{a}	266^{a}	253^{a}	215^{a}

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p<0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis.

Table 4-15: Mean sediment concentration (mg l^{-1}) (n=4) for every experimental treatment and inflow rates 0.3 – 1.3 (l s^{-1}) for the roots only treatments.

	Sediment Concentration (mg l^{-1}) at specific flow rates (l s^{-1})										
Treatment	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
Bare Soil	3623^{b}	3978^{b}	14079^{a}	2128^{c}	7965^{b}	1463^{d}	NDA	NDA	NDA	NDA	NDA
Conv L	1037^{a}	766^{a}	337^{a}	359^{a}	261^{a}	146^{a}	198^{a}	259^{a}	84.9^{a}	278^{a}	212^{a}
Conv N	200^{a}	384^{a}	275^{a}	355^{a}	717^{a}	158^{ab}	325^{a}	1509^{a}	581^{a}	550^{a}	6637^{a}
Fest_1+2 L	564^{a}	476^{a}	252^{a*}	197^{a}	324^{a}	210^{a}	100^{a}	87.5^{a}	142^{a}	109^{a}	33.2^{a}
Fest_1+2 N	637^{a}	367^{a}	145^{a}	277^{a}	190^{a}	129^{ab}	174^{a}	192^{a}	194^{a}	162^{a}	177^{a}
Fest_1+2+C L	253^{a*}	165^{a}	198^{a}	157^{a}	112^{a}	116^{a}	149^{a*}	183^{a}	175^{a}	71.8^{a}	135^{a}
Fest_1+2+C N	303^{a}	258^{a}	4940^{a}	232^{a}	352^{a}	129^{abc}	169^{a}	157^{a}	185^{a}	93.6^{a}	426^{a}
Fest_1 L	1279^{a}	388^{a}	306^{a}	325^{b}	385^{a*}	415^{c}	285^{a}	312^{a}	250^{a}	341^{a}	220^{a}
Fest_1 N	453^{a}	366^{a}	431^{a}	326^{a}	830^{a}	193^{bc}	2224^{b}	1461^{a}	1155^{a}	210^{a}	259^{a}

NDA (No data available). Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. * (n=3)

Table 4-16: Mean sediment concentration (mg l^{-1}) (n=4) for every experimental treatment and inflow rates 1.4 – 2.6 (l s^{-1}) for the roots only treatments.

	Sediment Concentration (mg l^{-1}) at specific flow rates (l s^{-1})												
Treatment	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6
Conv L	232^{a}	334^{a}	421^{a}	354^{a}	273^{a}	237^{a}	181^{a}	140^{a}	129^{a*}	176^{a}	156^{a}	196^{a}	108^{a}
Conv N	209^{a}	614^{a}	715^{a}	364^{a}	1249^{a}	337^{a}	731^{a}	856^{a}	268^{ab}	164^{a}	909^{a}	572^{a}	2057^{a}
Fest_1+2 L	128^{a}	158^{a}	94.2^{a}	97^{a}	64^{a*}	124^{a}	239^{a}	144^{a}	141^{a}	143^{a}	138^{a}	78.1^{a}	111^{a}
Fest_1+2 N	110^{a}	36.9^{a}	140^{a}	41.3^{a}	49.5^{a}	72.9^{a}	154^{a}	240^{ab}	189^{a}	151^{a}	53.7^{a}	144^{a}	278^{a}
Fest_1+2+C L	136^{a}	156^{a}	123^{a}	153^{a}	49.7^{a}	110^{a}	104^{a}	86.4^{a}	123^{a}	96.1^{a}	141^{a}	35.1^{a}	98.3^{a}
Fest_1+2+C N	250^{a}	224^{a}	143^{a}	273^{a}	170^{a}	179^{a}	275^{a}	77.4^{a}	84.6^{a}	64.6^{a}	140^{a}	147^{a}	133^{a}
Fest_1 L	198^{a}	177^{a}	180^{a}	316^{b}	238^{a}	242^{a}	316^{a}	197^{b}	442^{b}	239^{a}	150^{a}	222^{a}	74.3^{a}
Fest_1 N	714^{a}	568^{a}	583^{a}	311^{a}	389^{a}	386^{a}	401^{a}	490^{a}	459^{b}	262^{a}	482^{a}	600^{a}	413^{a}

Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, Fest_1+2+Conv (Conventional mixture of *Lolium perenne* and *Festuca rubra*, *Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1 (*Festulolium cv Prior*). Treatments followed by N are the normal recommended seeding rate, treatments followed by L are 60% of the recommended seeding rate. For each inflow rate, values followed by the same letter are not significantly different ($p < 0.05$) following One-Way ANOVA and *post-hoc* Fisher LSD Analysis. * (n=3)

4.4.7 Correlation between plant traits and sediment concentration.

Plant traits are often associated with soil erosion mitigation potential and as there were significant differences in both sediment concentration and plant traits this relationship can be explored further. Plant traits were correlated with sediment concentration, flow velocity and shear stress by way of Spearman's rank (Table 4-17). The plant traits can be used to try and explain why there were significant differences in these variables, so they have been correlated for each flow rate. Only sediment concentration and plant trait correlations have been shown here.

For sediment concentration, there were no significant correlations, either negative or positive found for any of the plant traits for any of the flow rates (Table 4-17).

Table 4-17: Correlations between sediment concentration and plant traits, stem area density, number of tillers, % canopy cover, % ground cover, stem diameter, number of stems, AGBM (dw) (g).

Variable	Correlations (Sediment Concentration and plant traits statistica (1)) Marked correlations are significant at p < .05000 N=51 (Casewise deletion of missing data)						
	Stem Area Density	Number of tillers	% Canopy Cover	% Ground Cover	Stem Diameter	Number of Stems	AGBM (dw) (g)
0.2 l s^{-1}	0.13	-0.07	0.11	-0.29	0.26	-0.16	0.04
0.3 l s^{-1}	0.03	0.05	-0.25	-0.41	0.31	-0.41	-0.18
0.4 l s^{-1}	-0.10	-0.32	-0.14	-0.18	0.05	-0.29	-0.09
0.5 l s^{-1}	-0.29	-0.05	-0.09	-0.06	-0.33	0.04	0.02
0.6 l s^{-1}	-0.03	0.02	0.03	-0.07	0.09	-0.23	-0.06
0.7 l s^{-1}	-0.14	0.18	-0.06	-0.10	0.06	-0.29	-0.25
0.8 l s^{-1}	-0.03	0.21	-0.17	-0.24	0.16	-0.21	-0.16
0.9 l s^{-1}	-0.03	0.29	-0.01	-0.09	0.19	-0.25	-0.14
1 l s^{-1}	-0.16	0.20	0.05	0.09	-0.09	-0.16	-0.17
1.1 l s^{-1}	-0.11	0.34	0.02	-0.01	-0.02	-0.17	-0.23
1.2 l s^{-1}	-0.24	0.03	-0.00	-0.08	-0.19	-0.22	-0.09
1.3 l s^{-1}	-0.08	0.12	0.07	0.01	-0.07	-0.04	-0.07

4.5 Discussion

4.5.1 Plant Traits

For number of tillers the Fest_1 lowered seeding rate treatment (3.5) was significantly higher than Fest_1 recommended seeding rate (2) which suggested that the Fest_1 lowered seeding rate treatment would be better at soil erosion control than the Fest_ 1 Norm treatment as an increased number of tillers is better in terms of soil erosion control as they will influence % ground cover (Morgan 2007). The increased number of stems will impart an increased frictional component on the flow resulting in a decreased flow velocity and more chance of deposition occurring. On the other hand, for number of stems the Conv recommended seeding rate (142) was significantly higher than the Fest_1 lowered seeding rate (62) which suggested that the Fest_1 lowered seeding rate treatment would be worse at soil erosion control than the Conv recommended seeding rate treatment.

However, the number of stems and number of tillers need to be converted into a SAD to ascertain a more accurate picture of what experimental treatments should be used in grassed water ways. For SAD the Fest_1+2 recommended seeding rate and Fest_1+2+C lowered seeding rate treatments both had a statistically similar and high value of .044 mm^{-2} mm^{2} which suggested that those treatments would be the best as an increased SAD is better in terms of soil erosion control. This is due to the increased frictional component imparted to flow which will decrease flow velocity and result in a lowered chance of detachment and entrainment. However, it was not as high as 10,000 per m^2 which is the number which has been shown to be effective at reducing soil erosion (Morgan and Rickson 1995; Morgan 2007). The highest number of stems (142) occurred in the Conv treatment and when converted was only 4,733 stems per m^2. The lowest number of stems (62) occurred in the Fest_1 L treatment and when converted was only 2,300 stems per m^2. Therefore, the grass traits can be improved in terms of providing a frictional component to flow to increase the hydraulic retention time and mitigate against soil erosion more effectively. However, these plant traits have been shown to decrease soil erosion when compared to the bare soil treatment.

Moreover, it is not just about each individual plant trait, it is about all the plant traits combined and how they link to the erosivity of flow and erodibility of the soil. Plant traits need to be looked at as a whole when designing GWWS as they will influence the critical flow velocity and shear stress needed for erosion to occur. The flow shear stress and velocity are further explained below.

4.5.2 Flow shear stress

In this experiment the flow shear stress was (0.01 - 0.71 Pa) for experimental grass roots and shoots treatments as well as roots only treatments, and it was (0.01 - 0.53 Pa) for bare soil treatments. Winterwerp et al., (2012) and Maity and Maiti (2017) both show that increased flow shear stress leads to an increased erosion rate, however the sediment concentration was higher for the bare soil treatments as opposed to the experimental grass treatments. This might be due to the bare soil having a lower critical threshold in terms of flow velocity for erosion to occur as it will not have any of the mechanical reinforcements that the roots provide or the frictional component imparted by the above ground grass sward. Singh & Thompson (2016) found that the critical shear stress in a GWW ranged from 1.6 – 3.2 Pa which was higher than the shear stress values found within this study. Li et al., (2023) found shear stress of erosion plots to be between 0.6 – 1.75 Pa which overlaps the values found for shear stress within this study. Winterwerp et al., (2012) found that flow shear stress to be between 0 – 3 Pa which is of a similar range the flow shear stress which was achieved in this study. However, they also had quite a low erosion rate of 0.01 - 0.02 g m^{-2} s^{-1}. The sediment concentrations for the bare soil in this study went up to about 14,000 mg l^{-1} which would be 14 g l^{-1}.

The flow shear stress was significantly different on more occasions for the roots only treatments as opposed to the roots and shoots treatments. Further, the Conv N roots only treatment had a significantly lower flow shear stress at the higher in flow rates, suggesting that there would be a lowered sediment concentration for this treatment. The flow shear stress was significantly lower or statistically the lowest for Fest_1+2 N as compared to most other treatments suggesting that this treatment would be good at erosion control .

In this experiment erosion started at the lowest inflow rate for all the experimental grass treatments, there was not a time where the erosion rate was zero. Therefore, the critical shear stress threshold for erosion to start to occur was lower than 0.3 l s^{-1} inflow. Winterwerp (2012) also found similar results, that erosion occurred at low shear stress which implied that the critical shear stress threshold for erosion to begin was <0.1 Pa. This was the same as within this study as the shear stress was also <0.1 Pa.

4.5.3 Flow velocity

In this experiment the recorded flow velocities were <1 m s^{-1} and there were more significant differences between the roots and shoots treatments as opposed to the roots only treatments. Even though there were significant differences in plant traits between experimental treatments, the flow velocity was statistically similar for inflow rates of 1.4 – 2.3 l s^{-1} therefore this suggested that although there were significant differences in plant traits there were not different enough to impact on flow velocity. Further, this also suggested that the sediment concentration would be similar for these inflow rates. This is because a decreased flow velocity is associated with an increased risk of sediment deposition (Gavrić et al., 2019). There were no differences in flow velocities within the roots only treatments, therefore it would not matter which roots only treatments was used so it would not matter if the grass sward were removed. It also showed that any significant differences in below ground plant traits did not affect a grass species ability to mitigate soil erosion even if the grass sward was completely removed.

At the highest inflow rate (2.6 l s^{-1}) the Fest_1+2 N treatment had a significantly lower flow velocity as opposed to the four other treatments, Conv L, Conv N, Fest_1+2+C N and Fest_1 N suggesting that it would be better suited to control for soil erosion. However, the sediment concentration needs to be looked at to see if the erosivity indicators of flow shear stress and flow velocity are correct.

Pan et al., (2016) found flow velocities of 3.0 – 6.2 cm s^{-1} for bare soil treatments of plot lengths of 1 m, the flow velocities achieved for bare soil here ranged from 0. 13 – 2 m s^{-1}. Therefore, the velocities found in this study for bare soil were all higher than that which was found within Pan et al., (2016) as 0.062 m s^{-1} was lower. However, all flow velocities corresponded to a slope of 8.7 % to 50 % (Pan et al., 2016) which would imply that the flow velocities should be higher. For the same slope of 8.7 % or more and same plot length they also found that grass species reduced flow velocities to 1.6 – 3.5 cm s^{-1} in one of their grass treatment plots (Pan et al., 2016). When converted to m s^{-1} that is 0.016 – 0.035 m s^{-1}, again the flow velocities found for the species treatments containing grass were higher at 0.04 – 0.48 m s^{-1}. Further, the slopes were once again the same or higher which would imply that the flow velocity should be greater within this study. However, that is not the case which would suggest that the plant species and their plant traits used here are better in terms of reducing flow velocities.

4.5.4 Sediment concentration in relation to the EA guidelines for a Category 1 major event

The EA (2016) guidelines for a discharge event to be classified as a Category 1 major event is 1000 mg l^{-1} of suspended sediment. Within this study this was reached in the bare soil and several of the experimental treatments. For the bare soil treatment 1000 mg l^{-1} was reached for every inflow rate (0.3 – 0.8 l s^{-1}) therefore it performed worse than all the experimental treatments, as expected. This is because it is widely known that vegetation traits provide a frictional component to water flow (Hewlett 1987; Gavrić et al., 2019) preventing detachment of soil.

Conv N, Fest_1+2 L and Fest_1 N treatments did not achieve the 1000 mg l^{-1} (EA 2016) limit for sediment concentration for the roots and shoots treatment. Therefore, it is recommended that these treatments are used instead of other treatments.

Interestingly, Fest_1+2+C L and the Fest_1+2+C L roots only treatments did not reach the EA 1000 mg l^{-1} threshold. This suggested that it did not matter if the treatments were roots only or roots and shoots for this species mixture, which may influence management practices. It will be a safer option to use in case of over grazing or overuse of machinery. Further, these were the only roots only treatments that did not go above the EA 1000 mg l^{-1} limit.

Within this study, when the inflow rate was increased there was a pulse of sediment which was eroded near the beginning of each flow rate and that was when the sediment was collected, therefore the sediment concentrations may be on the higher side. Winterwerp et al., (2012) also increased their flow velocity in small steps and found that each step had a burst of sediment occurring at the start of the new step which was similar to this study.

Furthermore, there was an abundance of loose sediment within the 0.2 l s^{-1} inflow rate due to the method of extracting, transporting and inserting the mesocosm into the hydraulic flume. The values for the 0.2 l s^{-1} inflow rate have been discounted from the experiment because of the values being an overestimation for actual sediment concentrations.

4.6 Conclusions

The following plant traits were statistically different in the experimental grass treatments; number of stems, number of tillers, stem area density, root total length, root total length ≤ 0.25 cm in diameter, root diameter and root surface area. The effectiveness at the different experimental grass treatments in terms of mitigating soil erosion might be explained by differences in plant traits. Fest_1 L had the highest number of tillers, but also had the lowest number of stems, however it was less than 10,000 stems per m^2 which has previously been found to influence soil mitigation. Even the treatment which had the highest number of stems had less than half of the recommended stem area density which has been shown to reduce soil erosion. The Fest_1+2 N and Fest_1+2+C L had the highest SAD (4,733) and should therefore be better in terms of soil erosion mitigation as opposed to other treatments. These significant differences in plant traits manifested significant differences in flow velocity, shear stress and sediment concentration. Further, there were also differences at which inflow rate the EA 1000 mg l^{-1} limit was exceeded or whether it was exceeded at all. The Fest_1+2+C L had the highest stem area density but did not exceed the EA 1000 mg l^{-1} limit. It should therefore be recommended to be used in soil erosion mitigation features. A number of other experimental treatments also did not exceed the 1000 mg l^{-1} limit, Conv N, Fest_1+2 L, Fest_1 N and Conv L. Further, the Fest_1+2 N and the Fest_1 N did exceed the EA 1000 mg l^{-1} limit and should therefore not be recommended for use.

4.7 References

Al-hamdan, O.Z., Pierson Jr, F.B., Nearing, M.A., Stone, J.J., Williams, C.J., Moffet, C.A., Kormos, P.R., Boll, J. & Weltz, M.A. (2012). Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modelling. *Earth surface processes and landforms*, 37, 157-168.

Baruti, J.H.M. (2004). *Study of Soil Moisture in relation to soil erosion in the proposed Tancitaro Geopark, Central Mexico: A case of the Zacandaro sub-watershed*. pp 64. Available from: https://webapps.itc.utwente.nl/librarywww/papers_2004/msc/ereg/baruti.pdf

Bainard, L.D., Kilronomos, J.N. & Hart, M.M. (2010). Differential effect of sample preservation methods on plant and arbuscular mycorrhizal fungal DNA. *Journal of Microbiological Methods*, 82 (2), 124-130.

Baxter, C., Rowan, J.S., McKenzie, B.M. & Neilson, R. (2013). Understanding soil erosion impacts in temperate agroecosystems: bridging the gap between geomorphology and soil ecology. *Biogeosciences Discuss*, 10, 7491-7520. doi: 10.5194/bgd-10-7491-2013

Burylo, M., Rey, F., Mathys, N., & Dutoit, T. (2012). Plant root traitsaffecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms,* 37, 1463-1470.

Chen, B. & Zhang, X. (2022). Effects of slope vegetation patterns on erosion sediment yield and hydraulic parameters in slope-gully system. *Ecological Indicators*, 145, 109723. doi: 10.1016/j.ecolind.2022.109723

De Baets, S., Poesen, J., Reubens, B., Muys, B., DeBaerdemaeker, J., & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34(10),1374-1392.

EA, 2016. *Incidents and their classification: the Common Incident Classification Scheme (CICS).* EA. pp 38-39.

Ekholm, P. & Lehtoranta, J., (2012). Does control of soil erosion inhibit aquatic eutrophication? *Journal of Environmental Management*, 93, 140-146.

Fiener, P. & Auerswald, K., (2006). Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research*, 87 (1), 48-58. doi: 10.1016/j.still.2005.02.035

Gavrić, S., Leonhardt, G., Marsalek, J., & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment*, 669, 431-447.

Genney, D.R., Alexander, I.J. & Hartley, S.E. (2000). Exclusion of grass roots from soil organic layers by Calluna: the role of ericoid mycorrhizas. *Journal of Experimental Botany*, 51 (347), 1117-1125.

Grabowksi, R.C., Droppo, I.G., & Wharton, G., (2011). Erodibility of cohesive sediment: The importance of sediment properties. *Earth-Science reviews*, 105 (3-4), 101-120. doi: https://doi.org/10.1016/j.earscirev.2011.01.008

Inman, A. & Consulting, T. (2006). *Soil erosion in England and Wales: causes, consequences and policy options for dealing with the problem*. Available from: http://assets.wwf.org.uk/downloads/soilerosionengwales.pdf Surrey: WWF UK.

IPCC (2013). *Summary for Policymakers*. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. United Kingdom: Cambridge University Press.

Khodashenas, S.R., Abderrezzak, K.E.K. & Paquier, A. (2008). Boundary shear stress in open channel flow. A comparison among six methods. *Journal of Hydraulic Research*, 46 (5), 598-609. doi: 10.3826/jhr.2008.3203

Knapen, A., Poesen, J., Gyssels, G. & Nachtergaele, J. (2007). Resistance of soils to concentrated flow erosion: A review. *Earth Science Reviews*, 80 (1-2), 75-109. doi: 10.1016/j.earscirev.2006.08.001

Knapen, A. & Poesen, J., (2009). Soil erosion resistance effects on rill and gully initiation points and dimensions. *Earth Surface Processes and Landforms*, 35 (2), 217-228.

Lave, J. & Avouac, J.P. (2001). Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *Journal of Geophysical Research: Solid Earth*, 106, 26,311-26,787. doi: 10.1029/2001JB000359

Lees, C., de Baets, S., Rickson, J. & Simmons, R.W. (2020). Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study. *European journal of soil science*, 1-17. doi: 10.1111/ejss.13045

Li, J., Li, L., Wang, W., Kang, H., Guo, M., Huang, J., Wang, Y., Lou, Y., Tong, X. & Nie, H. (2023). Hydrological and erosion responses of steep spoil heaps to taproot and fibrous root grasses under simulated rainfalls. *Journal of Hydrology*, 618, 129169.

Li, M., Hai, X., Hong, H., Shao, Y., Peng, D., Xu, W., Yang, Y., Zheng, Y. & Xia, Z. (2019). Modelling soil detachment by overland flow for the soil in the Tibet Plateau of China. *Scientific Reports*, 9, 8063. doi: 10.1038/s41598-019-44586-5

Liang, T., Bengough, A.G., Knappett, J.A., Muir Wood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & G. J.Meijer. (2017). Scaling of the reinforcement of soil slopes by liv-ing plants in a geotechnical centrifuge. *Ecological Engineering*,109B, 207-227.

Lick, W. & McNeil, J., (2001). Effects of sediment bulk properties on erosion rates. *Science of the Total Environment*, 266 (1-3), 41-48.

Liu, Z., Baoyin, T., Duan, J., Yang, G., Sun, J. & Li, X. (2018). Nutrient Characteristics in Relation to Plant Size of a Perennial Grass Under Grazing Exclusion in Degraded Grassland. *Frontiers in Plant Science*, 9, 295.

Liu, J.X., Wang, B., Duan, X.W., Yang, Y.F. & Liu G.B. (2022). Seasonal variation in soil erosion resistance to overland flow in gully-filled farmland on the Loess Plateau, China. *Soil and Tillage Research*, 218, 105297. doi: 10.1016/j.still.2021.105297

Lou, Y., Gao, Z., Sun, G., Wu, T., Zhou, F., Ai, J., Cen Y. & Xie, J. (2022). Runoff scouring experimental study of rill erosion of spoil tips. *CATENA*, 214, 106249. doi: 10.1016/j.catena.2022.106249

Lou, Y., Wang, W., Guo, M., Guo, W., Kang, H., Feng, L., Zhu, Y. and Yang, H. (2023). Vegetation affects gully headcut erosion processes by regulating runoff hydrodynamics in the Loess tableland region. *Journal of Hydrology*, 616, 128769. doi: 10.1016/j.jhydrol.2022.128769

Maity, S.K., & Maiti, R. (2017). Sedimentation under variable shear stress at lower reach of the Rupnarayan River, West Bengal, India. *Water science*, 31, 67-92. doi: 10.1016/j.wsj.2017.02.001

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L., & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755-763.

Montieth, H. & Pender, G. (2005). Flume investigations into the influence of shear stress history on a graded sediment bed. *Water Resources Research*, 41 (12). doi: 10.1029/2005WR004297

Morgan, R. P. C. (2007). *Vegetative-based technologies for erosion control*. In A. Stokes, I. Spanos, J. E. Norris, and E. Cammeraat (Eds.), Eco-and ground bio-engineering: The use of vegetation to improve slope stability. Developments in plant and soil sciences, 103. Dordrecht, The Netherlands: Springer.

Morgan, R. P. C., & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach*, London: E & FN Spon.

National Audit Office. (2010). *Tackling diffuse water pollution in England (online),* London: National Audit Office.

Ou, X., Hu, Y., Li, X., Guo., S. & Liu, B., (2021). Advancements and challenges in rill formation, morphology, measurement and modeling. *Catena*, 196, 104932.

Pan, C., Ma, L., Wainwright, J. & Shangguan, Z. (2016). Overland flow resistances on varying slope gradients and partitioning on grassed slopes under simulated rainfall. *Water Resource Research*, 52 (4), 2490-2512.

Pimentel, D. & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, 3(3), 443-463.

Prosser, I. P., Dietrich, W. E., & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. *Geomorphology*, 13 (1-4), 71-86.

Ramos, J.C., Bertol, I., Barbosa, F.T., Bertól, C., Mafra, A.L., Miquelluti, D.J. & Júnior, J.M. (2016). Water erosion in surface soil conditions: runoff velocity, concentration and D50 index of sediments in runoff. *Scientia Agricola*, 73 (3), 286 -293. doi: https://doi.org/10.1590/0103-9016-2015-0110

Regent Instruments (2016). *WinRHIZO 2016 Basic, Reg, Pro & Arabidopsis For Root Measurement*. Canada: Regent instruments Canada Inc.

Routschek, A., Schmidt, J., & Kreienkamp, F. (2014). Impact of climate change on soil erosion - a high-resolution projection on catchment scale until 2100 in Saxony/Germany. *Catena*, 121, 99–109. doi: 10.1016/j.catena.2014.04.019

Schwendel, A.C., Death, R.S. & Fuller, I.C. (2010). The assessment of shear stress and bed stability in stream ecology. *Freshwater Biology*, 55 (2), 261-281. doi: 10.1111/j.1365-2427.2009.02293.x

Shit, P.K., Pourghasemi, H.R., and Bhunia, G.S., 2020. *Effects of Grass on Runoff and Gully Bed Erosion: Concentrated Flow Experiment.* In book: Gully Erosion Studies from India and Surrounding Regions, pp 221-233.Singh, H.V. & Thompson, A.M. (2016). Effects of antecedent soil moisture content on soil critical shear stress in agricultural watersheds. *Geoderma*, 262, 165-173. doi: 10.1016/j.geoderma.2015.08.011

Somsook, K., Azhikoda, G., Duka, M.A. & Yokoyama, K. (2021). Riverbed fluctuation and erosion property of cohesive sediment based on long-term topographic surveys in a macrotidal estuary. *Regional Studies in Marine Science*, 45, 101848. doi: 10.1016/j.rsma.2021.101848

Sun, L., Zhang, B., Yin, Z., Guo, H., Siddique, K.H.M., Wu, S. & Yang, J. (2022). Assessing the performance of conservation measures for controlling slope runoff and erosion using field scouring measurements. *Agricultural Water Management*, 259, 107212. doi: 10.1016/j.agwat.2021.107212

USDA, (2022). *Soil Bulk Density Moisture/Aeration*. USDA. Available from: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053260.pdf [Accessed 1 March 2022].

Vannoppen, W., Vanmaercke, M., De Baets, S. & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666-678.

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G. & Roberts, N.M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics,* 52 (3), 522-555.

White, K., She, Y. & Zhang, W. (2022). A comparison of shear stress estimation methods for a single geobag on a rough bed. *Geotextiles and Geomembranes*, 50 (6), 1230-1243. doi: org/10.1016/j.geotexmem.2022.09.001

Wright, A. J., Ebeling, A., Kroon, H., Roscher, C., Weigelt, A., Buchmann, N. & Eisenhauer, N. (2015). Flooding disturbances increase resource availability and productivity but reduce stability in diverse plant communities. *Nature Communications,* 6, 60-92. doi: 10.1038/ncomms7092

Winterwerp, J.C., van Kesteren, W.G.M., van Prooijen, B. & Jacobs, W. (2012). A conceptual framework for shear flow–induced erosion of soft cohesive sediment beds. *Journal of geophysical research*, 117 (c10). doi: 10.1029/2012JC008072

Xiao, H., Guo, P., Zhang, Q., Hu, H., Hong, H., Zhang, L., Yang, Y., Xia, Z., Li, M., Kang, H. & Zhang, G. (2022). Variation in soil properties and its influence on dynamic change of soil erosion resistance to overland flow in the water-level fluctuation zone of the Three Gorges Reservoir, China. *CATENA*, 213, 106141. doi: 10.1016/j.catena.2022.106141

Ye, Y, Tan, X, Liu, Y., Zhou, C., Shi, F., Lee, Y, & Murphy M.A., 2022. The impact of erosion on fault segmentation in thrust belts: Insights from thermochronology and fluvial shear stress analysis (southern Longmen Shan, eastern Tibet). *Geomorphology*, 397, 108020. doi: 10.1016/j.geomorph.2021.108020

Yi, F, Wang, Z., Baskin, C.C., Baskin, J.M., Ye, R., Sun, H., Zhang, Y., Ye, X., Liu, G., Yang, X. & Huang, Z. (2019). Seed germination responses to seasonal temperature and drought stress are species-specific but not related to seed size in a desert steppe: Implications for effect of climate change on community structure. *Ecology and Evolution*, 9 (4), 2149-2159. doi: 10.1002/ece3.4909

Zhang, Z., Sheng, L., Yang, J., Chen, X., Kong, L. & Wagan, B. (2015). Effects of Land Use and Slope Gradient on Soil Erosion in a Red Soil Hilly Watershed of Southern China. *Sustainability*, 7, 14309-14325.

Zhang, B., Zhang, G., Yang, H. & Zhu, P. (2019). Temporal variation in soil erosion resistance of steep slopes restored with different vegetation communities on the Chinese Loess Plateau. *Catena*, 182. doi: 10.1016/j.catena.2019.104170

5 Development and Evaluation of a Grass Trait Ranking System for Soil Erosion Mitigation.

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5.1 Abstract

A ranking system for potential soil erosion mitigation by vegetation, based on grass traits was devised in a previous study (Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study). The ranking system included the following above ground plant traits; % cover, % emergence, grass sward height (cm), number of stems, stem area density (mm^2 mm^{-2}), above ground biomass (g). It also included the following below ground traits; root length less than / equal to 0.25 mm ⌀ (cm), root surface area (cm^2) and root diameter (mm). The ranking system accounts for the following erosion processes: detachment by rainsplash, detachment via overland flow, and subsequent sediment entrainment, transport, and deposition. The objective of this study is to assess the efficacy of this ranking system to predict soil erosion, flow shear stress and flow velocity in two experiments using a hydraulic flume. For both experiments, all the salient plant traits were measured, as well as flow characteristics and sediment concentrations. The plant trait ranking system was used to compare plant traits with sediment concentrations and flow characteristics to explore the ranking system's ability to predict soil erosion mitigation potential. Grass species selection to control concentrated flow erosion in grassed waterways was based on summer planting whereas Critical flow velocity and shear stress thresholds for grass in grassed water ways was based

on autumn planting. There were differences in plant trait scores for Flume Experiment 1 (Chapter 3), Conv (*Lolium perenne* and *Festuca rubra*), Fest_1+2 (*Festulolium cv Prior* and *Festulolium Bx511*), Fest_1+2+C (*Festulolium cv Prior*, *Festulolium Bx511*, *Lolium perenne* and *Festuca rubra*) and Fest_1 (*Festulolium cv Prior*) had total overall plant trait scores of 33, 42, 54 and 54, respectively. However, these differences were not reflected in soil erosion mitigation: there were no significant differences in sediment concentration observed for Flume Experiment 1 between grass species treatments. Results for the final plant trait ranking scores from Flume Experiment 2 (Chapter 4) ranged from 18 (Conv L & Fest_1 L) to 54 (Fest_1+Fest_2+Conv L R). There were significant differences in sediment concentration, flow velocity and shear stress for Flume Experiment 2. Between the Conv L & Fest_1 L treatments there were no significant differences in shear stress aside from in the roots only treatment at the inflow rate of 2.4 l s^{-1} but there were for flow velocity and sediment concentration. Recommendations for farmers include the summer planting of both Fest_1 and Fest_1+Fest_2+Conv and the autumn planting of Fest_1+Fest_2. Recommendations for future adaptations of this plant trait ranking system include adding a weighting system to emphasise the most important plant traits that determine potential soil erosion mitigation in grass waterways.

5.2 Introduction

5.2.1 Why is a plant trait ranking system needed?

Grass species monocultures and mixtures have different inherent plant traits and as such they will mitigate soil erosion differently, with some being more effective than others. Not one grass species will have all the salient plant traits for reduction of soil erosion. Moreover, not every grass species will be suited to every environmental set of conditions as was shown in Lees et al., (2020). Grass species were grown in both drought and flooded conditions to see how this would affect plant traits (Lees et al., 2020). Plant traits also differed when species were grown as monocultures as opposed to where mixed species were grown.

Currently, there is no universal ranking system for grass species' efficacy in reducing soil erosion, based on their above ground and below ground plant traits.

Grassed waterways (Leroy 2016; Gavrić et al., 2019) and grassed buffer strips (Boger et al., 2018; Li & Pan 2018) are used as soil erosion mitigation features and a ranking system that identifies suitable and effective species will be useful for anyone who wishes to implement these erosion control features successfully. Ideally, the ranking system would allow an easier and quicker comparison of grass species based on their known plant traits. Farmers will be able to see which monoculture or mixture of species will be the most suited to specific site conditions and costs of implementation in the field. Therefore, this ranking system can be used as a tool for influencing farm management practices.

Moreover, if the cost of a certain monoculture or mixture of species is not financially viable yet it is the combination of species which has the best overall score, a government subsidy may need to be offered for that combination to be used. Therefore, this ranking system can be used to influence policy, making the agricultural industry more sustainable and stable for future generations.

5.2.2 Previous attempts at plant trait ranking systems

Ranking systems have been attempted previously by De Baets et al., (2009) and Ghestem et al., (2014). The ranking system in De Baets et al., (2009) relied on the soil erosion process of detachment via overland flow to enable grass species selection to control for rill and gully erosion. The ranking system in Ghestem et al., (2014) relied upon root traits only, as opposed to both above ground and below ground traits, in their criteria for species selection. Ghestem et al., (2014) ranked species as poor, average, or good. Further, De Baets et al., (2009) converted their plant trait values to scores of between 0-4 by way of a statistical analysis to determine how to rank the individual species. In this studies plant trait ranking system the traits are sorted into ranks based on statistical analysis.

5.2.3 Components of this plant trait ranking system

The current ranking system (Lees et al., 2020) builds upon and extends the ranking systems of Ghestem et al., (2014) and De Baets et al., (2009), by including both above ground and below ground plant traits linked to soil erosion mitigation.

The ranking system developed here is based on the work of Unagwu (2017), who developed a ranking system related to the efficacy of different soil amendments. Here the application of the ranking system is to determine the soil erosion mitigation potential of several different grass species to be used in GWWs. The plant trait ranking system was first described and justified in Lees et al., (2020). Within that study, the plant traits were determined for different climatic conditions and the best overall species in terms of soil erosion mitigation potential were found for a number of hypothetical extreme weather conditions. Each grass species mixture or monoculture was subject to the plant trait ranking system for normal conditions, drought conditions or flooded conditions and an overall score was determined, considering all these possible environmental scenarios (Lees et al., 2020).

The grass species traits considered to have an effect on erosion mitigation and were therefore used in this ranking system were: % emergence (Morgan 2007), % cover, plant height (cm), stem area density (mm^2 mm^{-2}) (Morgan & Rickson 1995; Morgan 2007; De Baets et al., 2009; Mekonnen et al., 2016), above ground biomass (g), number of stems, stem diameter (mm), root length cm of (<0.25 mm ⌀) (Laing et al., 2017), root surface area (cm^2) (De Baets et al., 2007; Vanoppen et al., 2015), and root diameter (mm).

The current study also extends the work of De Baets (2009) and Ghestem (2014) as it justifies why each plant trait is given a particular score / value by the way of a One-Way ANOVA. If following statistical analysis, a plant trait is statistically different compared to the value of the same trait for a different species, then it would not be given the same score.

The aim of this study is to assess the validity of this plant trait based ranking system as a tool to identify the most effective grass species for soil erosion mitigation under concentrated flow. This approach can then be used in designing and specifying soil erosion control features. This objective will be met by the following objectives: (a) measuring key plant traits for different monoculture and mixed species configurations; (b) measuring sediment concentrations for the different species configurations; (c) inserting the plant trait values into the devised plant trait ranking system; and d) comparing the plant trait ranking results with the measured rates of sediment concentrations under those different plant species configurations. Recommendations on possible adaptations and refinements to the plant trait ranking system can then be made to improve its quality.

5.3 Methodology

The plant trait based ranking system was developed during the plant growth experiments described in Chapter 2 (Lees et al., 2020), based on the methodology devised by Unagwu (2017). Chapter 2 identified plant species which showed the best promise to be used for soil erosion control. These species were then selected for Flume Experiment 1 (Chapter 3) and Flume Experiment 2 (Chapter 4). They were *Festulolium cv Prior*, *Festulolium Bx511*, a conventional mixture of *Lolium perenne* and Festuca rubra and a mixture containing *Festulolium cv Prior*, *Festulolium Bx511*, *Lolium perenne* and *Festuca rubra*. Moreover, the same grass traits were measured within the 2 flume experiments to allow the ranking system to be compared with the actual measurements of sediment concentration that were also taken in both flume experiments.

Each species monoculture or mixture was ranked, in exactly the same way as Chapter 2, using the same plant traits (Lees at al., 2020). First of all, 7 class boundaries were created for each plant trait, based on the minimum and maximum value for that specific plant trait. This was done to ensure that if there were significant differences between all the 7 different species combinations that they could then be assigned a different number. Then the range (i.e., the maximum value – minimum value) was determined and divided by 7 to create 7 equal class boundaries. For example, in Flume Experiment 1, the number of stems' maximum value was 227 and the minimum value was 97, with a range of 130. By dividing this range by 7 classes gives the class boundaries of 18.57. Thus, values ranging from 97-115.57 having a score of 1 and values ranging from 208.42-227.0 having a score of 7. All class boundaries calculated in this way for data from Flume Experiment 1 can be seen in 8Appendix D.

All original plant trait data underwent statistical analysis via a One-Way ANOVA ($p<0.05$) and a Fisher LSD *post-hoc* test, if the ANOVA indicated that there were significant differences in plant traits between the experimental treatments. The ANOVA was carried out to rank plant traits by their perceived soil erosion mitigation potential. Significantly different values for plant traits had to go within different class boundaries. Whereas significantly similar values for plant traits went into the same class boundary. The higher the number given on the scale of 1-7 the better that experimental treatment would be for erosion control. All the numbers would then be summed to get the final overall erosion mitigation score for each treatment. These treatment scores can then be compared to one another and be used to support decisions in choosing grass mixtures and monocultures for erosion control features such as grassed waterways, grassed buffer and filter strips and grassed swales.

The class boundaries were worked out the same way for Flume Experiment 2 (Chapter 4) using the plant traits measurements that were obtained from that experiment. Data for class boundaries from Flume Experiment 2 (Chapter 4) can be seen in 8Appendix D.

5.3.1 Plant trait ranking system for Flume Experiment 1 (Chapter 3)

A few changes were made to the ranking system developed in Chapter 2 to make it applicable to Flume Experiment 1. For Flume Experiment 1, there was only one seasonal treatment and only one watering (irrigation) regime so the plant trait ranking system was only for one set of environmental conditions and not for the range of environmental conditions as it was in Lees et al., (2020). Furthermore, plant height was kept constant in Flume Experiment 1 at either 1.0 cm or 3.0 cm sward heights (to simulate the mowing regime on grassed waterways in the field). As a result, this data was omitted as it would be the same for all treatments. Also, in Flume Experiment 1, the erosion process of detachment by rainsplash was not simulated, so there are no data to compare these rates from the different treatments with their plant trait ranking scores. The detachment by rainsplash scores have been computed to be used to advise farmers on management practices.

The theoretical ability of the different grass treatments to control detachment via overland flow was estimated from the plant trait ranking scores (Table 5-1). These varied for the different treatments: Fest_1 had a total score of 23, whereas Fest_1+Fest_2+Conv had a score of 24. Conv had a score of 19 and Fest_1+Fest_2 had a score of 23. This implies that the multiple species Fest_1+Fest_2+Conv treatment possesses the plant traits that are theoretically the most effective at providing the best soil erosion control. The monoculture Conv treatment has plant traits that potentially provide the least erosion control. The root diameter was the most similar with only 1 point difference between all the experimental treatments. The biggest differences in scoring came from a) the number of stems, where Fest_1 had a score of 1 and Conv had a score of 6 and b) the stem area density (SAD) where Fest_1 had a score of 6 and Conv had a score of 1.

Table 5-1: Plant trait data and associated scores as related to their theoretical ability to control detachment by overland flow in Flume Experiment 1.

Species Treatments	Number of Stems	SAD (mm^2 mm^{-2})	AGBM (g)	Rl < 0.25 mm ⌀ (cm)	RSA (cm^2)	Rdiam (mm)	Total Score
Fest_1	113.38 (1)	214.32 (6)	9.6 (4**)	182.02 (3)	30.63 (3**)	0.37 (6)	23
Conv	194.75 (6)	87.89 (1)	5.01 (1)	155.06 (2)	30.43 (3**)	0.39 (6)	19
Fest_1+Fest_2	138.25 (3)	149 (3)	5.93 (1**)	196.65 (3)	36.7 (5)	0.41 (6)	21
Fest_1+Fest_2+Conv	146.88 (3)	148.48 (3)	7.86 (4)	220.69 (4)	29.64 (3)	0.31 (7)	24

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). SAD (Stem area density), AGBM (Above ground biomass), Rl < 0.25 mm (cm) (root length <0.25 mm (cm)), RSA (root surface area) and RDiam (root diameter). **Put into a lower category as significantly similar so has to be in the same boundary.

For a grass treatment's ability to control sediment transport and to encourage deposition, the total plant trait scores ranged from 6 (Conv) to 13 (Fest_1) (Table 5-2). The largest variation in scoring was in stem area density (SAD) with Fest_1 having a total score of 6 and Conv having a total score of 1. All other plant traits, % cover, and above ground biomass had a score variation of only 3 points.

Table 5-2: Plant trait data and associated scores as related to their theoretical ability to control sediment transport and encourage deposition in Flume Experiment 1.

Species Treatment	% Cover	SAD (mm^2 mm^{-2})	AGBM (g)	Total Score
Fest_1	24.1 (3)	214.32 (6)	9.6 (4**)	13
Conv	29.8 (4)	87.89 (1)	5.01 (1)	6
Fest_1+Fest_2	28.6 (4)	149 (3)	5.93 (1**)	8
Fest_1+Fest_2+Conv	33 (6)	148.48 (3)	7.86 (4)	13

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv Prior* and Festu*lolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior*, *Festulolium Bx511*, *Lolium perenne* and *Festuca rubra*). SAD (stem area density) and AGBM (above ground biomass). **Put into a lower category as significantly similar so has to be in the same boundary.

The total score in terms of soil erosion mitigation potential varied from 25 for Conv to 37 for Fest_1+2+Conv (Table 5-3). This suggested that Fest_1+Fest_2+Conv would be the best at soil erosion control and Conv would be the worst at soil erosion control based on their species traits alone. Fest_1+2 and Fest_1 had a scores which were in the middle, 29 and 36, respectively. Based on these total scores alone the Fest_1+2+Conv should be recommended for use in soil erosion control features where concentrated flow is present.

Table 5-3: Total overall species scores for each of the experimental grass treatments for detachment via overland flow and control of sediment transport and deposition for Flume Experiment 1.

Species	Detachment via overland flow	Control of sediment transport and deposition	Total Score
Fest_1	23	13	36
Conv	19	6	25
Fest_1+Fest_2	21	8	29
Fest_1+Fest_2+Conv	24	13	37

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*).

5.3.2 Plant trait ranking system Analysis for Flume Experiment 1 (Chapter 3)

Although there were differences in the total scores for erosion control (Table 5-3), Flume Experiment 1 showed that there were no significant differences in sediment concentration between the different grass species mixtures and monocultures. Therefore, it should be the case that there are no differences in total score for the plant trait ranking system for it to be accurate. However, significant differences were found in the plant traits for Flume Experiment 1 and thus significant differences were found within the plant trait based ranking system due to this.

There were differences in score within the sediment transport and deposition (6-13) (Table 5-1) and for the detachment via overland flow (19-24) (Table 5-2) which is reflected in no significant differences in sediment concentration between the grass treatments. Even though there were only small differences in scores for overland flow and sediment transport and deposition, these are still differences so there should have been a difference in sediment concentration.

Flow velocity can be used as an indicator for how efficient grasses are at reducing soil erosion. When taking the flow velocities at the middle of the sample, for an inflow rate of 0.7 l s^{-1}, Conv had the lowest (0.20 m s^{-1}), followed by Fest_1+Fest_2 (0.21 m s^{-1}), followed by Fest_1+Fest_2+C (0.22 m s^{-1}), followed by Fest_1 (0.35 m s^{-1}). This is not in line with Table 5-3, in terms of the overall ranking of the treatments vs the actual recorded values. As Conv has the lowest overall flow velocity it should mean that it has the highest rankings and yet it has the lowest ranking.

Therefore, it can only be assumed that the differences in plant trait scores were not sufficient to result in differences in sediment concentration as the plant traits contained within the ranking system are known to effect soil erosion mitigation. As there were no differences in sediment concentration between the experimental treatments another experiment was devised to try and gain some significant differences to try and validate the plant trait ranking system. Two different seeding rates were used, a lowered and a recommended seeding rate, and the hydraulic flume was used at every increment and ran for longer periods to try and ensure differences between sediment concentration. Further, there was a roots only treatment versus a roots and shoots treatment to try and tease out any differences in sediment concentration.

5.3.3 Plant trait ranking system scores for Flume Experiment 2.

The same species mixtures and monocultures were carried forward from Flume Experiment 1 into Flume Experiment 2. However, there were 2 different seeding rates used in Flume Experiment 2, one which was recommended and carried forward from Flume Experiment 1 and one which was lowered by 40%. Another difference in this study was that there was a roots and shoots treatment (3.0 cm) the same as in Flume Experiment 1 and a roots only treatment (R) where all above ground biomass was removed before hydraulic flume runs. The size of the experimental treatment was the same which would make scores be similar between Flume Experiment 1 and 3, whereas the growth period was longer by 2 weeks which may result in scores being slightly higher for the ranking system from Flume Experiment 2 despite the same species mixtures and monocultures being used.

Again, as the plant height was the same when run in the hydraulic flume, the original plant trait ranking system (Lees et al., 2020) was changed so that the plant height data was omitted. Further, detachment by rainsplash was not simulated and therefore cannot be directly linked to the sediment concentration results for this study.

There were differences in plant trait data and scores for controlling detachment by overland flow for the different experimental treatments (Table 5-4). The total score for detachment by overland flow varied from 8 (Fest_1 N & Fest_1 L) to 27 (Fest_1+Fest_2+Conv L R). There were differences in total score for all treatments which came from the same macrocosm hinting at the inherent variability of plant traits within even the same treatment.

Table 5-4: Plant trait data and scores as related to their theoretical ability to control detachment by overland flow for all species for Flume Experiment 2.

Species	Number of Stems	SAD (mm^2 mm^{-2})	AGB (g)	Rl (cm) less than equal to 0.25 mm ⌀	RSA (cm^2)	Rdiam (mm)	Total Score
Fest_1 L	62.0 (1)	0.019 (1)**	8.91 (1)	608.2 (2)**	116.3 (1)**	0.37 (2)*	8
Fest_1 L R	62.5 (1)	0.023 (1)**	12.54 (3)	512.2 (2)**	107.6 (1)**	0.39 (2)*	10
Fest_1 N	69.0 (1)	0.015 (1)	8.34 (1)	566.2 (3)	99.5 (1)	0.34 (1)	8

Fest_1 N R	68.0 (1)	0.013 (1)	9.79 (1)	759.3 (4)	160.1 (1)**	0.38 (1)	9
Conv L	93.8 (3)	0.014 (1)	10.67 (1)	481.5 (2)	69.0 (1)	0.28 (1)	9
Conv L R	93.8 (3)	0.016 (1)	14.85 (3)	621.3 (2)**	132.7 (1)**	0.38 (1)	11
Conv N	141.5 (5)	0.022 (1)**	9.18 (1)	814.5 (4)	168.4 (2)	0.38 (2)*	15
Conv N R	135.0 (5)	0.017 (1)	11.46 (2)	793.4 (4)	180.6 (2)	0.43 (2)*	16
Fest_1+Fest_2 L	83.0 (3)	0.025 (2)	12.97 (3)	657.6 (3)	193.3 (2)	0.47 (4)*	17
Fest_1+Fest_2 L R	93.0 (3)	0.024 (2)	16.5 (4)	908.4 (5)	226.2 (3)	0.43 (4)*	21
Fest_1+Fest_2 N	113.8 (4)	0.044 (5)	20.96 (6)	625.6 (3)	153.7 (2)	0.42 (1)	21
Fest_1+Fest_2 N R	114.3 (4)	0.039 (4)	14.97 (4)	776.8 (4)	224.8 (3)	0.48 (1)	20
Fest_1+Fest_2+Conv L	117.8 (4)	0.014 (5)	13.68 (3)	959.5 (6)*	280.0 (3)	0.48 (4)*	25
Fest_1+Fest_2+Conv L R	125.8 (4)	0.048 (5)	18.10 (5)	977.2 (6)*	285.2 (3)	0.49 (4)*	27
Fest_1+Fest_2+Conv N	99.3 (3)	0.017 (1)	12.10 (2)	803.4 (4)	225.9 (3)	0.57 (2)	15
Fest_1+Fest_2+Conv N R	104.5 (3)	0.032 (1)**	18.37 (5)	876.2 (5)	253.4 (3)	0.48 (1)	18

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). Experimental treatments followed by letters are as follows L (Lowered seeding rate), N (Normal seeding rate), R (roots only).**Put into a lower category as significantly similar so has to be in the same boundary as others

There were differences in the total scores for the experimental treatments and their potential to control for sediment transport and encourage deposition (Table 5-5). The total score varied from 3 (Fest_1 N, Fest_1 N & Fest_ 1 N R) to 12 (Fest_1+Fest_2 N). There was only one instance where treatments from the same macrocosm (Fest_1 N) displayed the same total score (3).

Table 5-5: Plant trait data and scores as related to their theoretical ability to control sediment transport and encourage deposition for all species for Flume Experiment 1.

Species	% Cover	SAD (mm^2 mm^{-2})	AGB (g)	Total Score
Fest_1 L	12.4 (1)**	0.019 (1)**	8.91 (1)	3
Fest_1 L R	11.5 (1)	0.023 (1)**	12.54 (3)	5
Fest_1 N	13.5 (1)**	0.015 (1)	8.34 (1)	3
Fest_1 N R	13.1 (1)**	0.013 (1)	9.79 (1)	3
Conv L	14.5 (2)	0.014 (1)	10.67 (1)	4

Conv L R	17.1 (3)	0.016 (1)	14.85 (3)	7
Conv N	23.1 (5)	0.022 (1)**	9.18 (1)	7
Conv N R	24.1 (5)**	0.017 (1)	11.46 (2)	8
Fest_1+Fest_2 L	11.0 (1)	0.025 (2)	12.97 (3)	6
Fest_1+Fest_2 L R	11.8 (1)	0.024 (2)	16.5 (4)	7
Fest_1+Fest_2 N	14.3 (1)**	0.044 (5)	20.96 (6)	12
Fest_1+Fest_2 N R	13.4 (1)**	0.039 (4)	14.97 (4)	9
Fest_1+Fest_2+Conv L	14.8 (1)**	0.014 (5)	13.68 (3)	9
Fest_1+Fest_2+Conv L R	14.8 (1)**	0.048 (5)	18.10 (5)	11
Fest_1+Fest_2+Conv N	15.5 (3)	0.017 (1)	12.10 (2)	6
Fest_1+Fest_2+Conv N R	16.5 (3)	0.032 (1)**	18.37 (5)	9

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). Experimental treatments followed by letters are as follows L (Lowered seeding rate), N (Normal seeding rate), R (roots only).**Put into a lower category as significantly similar so has to be in the same boundary as others

The total scores for all the soil erosion processes, detachment via overland flow and control of sediment transport and deposition were different for different experimental treatments (Table 5-6). Total scored ranged from 11 (Fest_1 N & Fest_1 L) to 38 (Fest_1+Fest_2+Conv L R). The scores suggested that the Fest_1 roots and shoots treatments would be the worst at reducing soil erosion within the flume experiment due to that treatment having the joint lowest score. Whereas Fest_1+Fest_2+Conv L R should be the best at mitigating soil erosion within the flume experiment due to it having the highest score.

Table 5-6: Total overall species scores for each of the experimental grass treatments for detachment via overland flow, and control of sediment transport and deposition for Flume Experiment 2.

Species	Detachment via overland flow	Control of sediment transport and deposition	Total Score
Fest_1 L	8	3	11
Fest_1 L R	10	5	15
Fest_1 N	8	3	11
Fest_1 N R	9	3	12
Conv L	9	4	13
Conv L R	11	7	18
Conv N	15	7	22
Conv N R	16	8	24
Fest_1+Fest_2 L	17	6	23
Fest_1+Fest_2 L R	21	7	28
Fest_1+Fest_2 N	21	12	33

Fest_1+Fest_2 N R	20	9	29
Fest_1+Fest_2+Conv L	25	9	34
Fest_1+Fest_2+Conv L R	27	11	38
Fest_1+Fest_2+Conv N	15	6	21
Fest_1+Fest_2+Conv N R	18	9	27

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). Experimental treatments followed by letters are as follows L (Lowered seeding rate), N (Normal seeding rate), R (roots only).

While Flume Experiment 1 had no significant differences in sediment concentration, there were a few significant differences in soil erosion for Flume Experiment 2. However, there were few significant differences in sediment concentration for all the different inflow rates, especially for the roots only treatments which is not in line with the predictions that this plant trait based ranking system has made. The ranking system had predicted that the Fest_1+Fest_2+Conv L R would have the lowest sediment concentration. When looking at detachment by overland flow and control of sediment transport and deposition the Fest_1 L had a score of 11 and the Conv L had a score of 13. This is in line with Fest_1 L having a significantly higher sediment concentration for the aforementioned flow rates as the soil erosion mitigation potential score is lower.

5.3.4 Comparison of plant trait ranking scores between Experiment 1 and Flume Experiment 1.

A direct comparison between the total plant trait ranking scores for each soil erosion process from Experiment 1 and Flume Experiment 1 was compiled (Table 5-7). However, it is important to note that Flume Experiment 1 has omitted the plant trait plant height and detachment via rainsplash values. There are also different experimental conditions between the experiments.

Differences can be seen in overall scores for detachment via overland flow and for the control of sediment transport and deposition (Table 5-7) which suggested that the accuracy of the ranking system could be improved. There was only one instance where the plant trait ranking scores were the same (Fest_1+Fest_2 for detachment via overland flow, 21). However, plants are inherently variable which will have an influence on all trait ranking approaches, yet there were four replicates of each experimental treatment to try and combat this. Another more viable explanation for the differences was that the experimental design was different which can be used to help explain these discrepancies.

Table 5-7: Comparison of overall plant trait scores between Experiment 1 and Flume Experiment 1.

Species	Detachment via overland flow		Control of Sediment transport and deposition	
	Ex 1	Flume Ex 1	Ex 1	Flume Ex 1
Fest_1	18	23	11	13
Conv	14	19	14	6
Fest_1+Fest_2	21	21	16	8
Fest_1+Fest_2+Conv	18	24	14	13

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*).

The experimental treatments were grown for the same amount of time (six weeks) so that could not have affected the species trait ranking. The growth time will surely influence plant traits positively and increase an experimental treatments viability in terms of soil erosion control. Other factors such as the size of the experimental treatment and the environmental conditions may have been responsible for a change in the rankings. The experimental treatments were grown in different size microcosms/mesocosms. During Experiment 1 the microcosms were a 0.07 m wide plastic tube, during Flume Experiment 1 they were grown in 1 x 1.2 m lysimeters before being cut into smaller 0.2 x 0.1 x 0.1 m mesocosms. This would have influenced the following plant traits, aboveground biomass, number of stems, root surface area, root length and caused them to be increased thus increasing their viability to be used in soil erosion control features in terms of this ranking system. However, plant traits such as % cover, and % emergence should not have been influenced too much as they would have stayed the same no matter what size of experimental treatment.

Furthermore, the plant height was cut to the same height in this experiment so the overall scoring system would have to discount that plant trait. Therefore, the plant trait scores from Experiment 1 might be higher because of this.

Due to the increased growth time and increased experimental treatment size this should show an increase in soil erosion mitigation and according to table 5-7 that is mostly the case. All values for detachment via overland flow were higher in Flume Experiment 1. For control of sediment transport and deposition values were also higher in 2 of the treatments. These differences in methodology have helped to explain why there are differences in the scoring system. Therefore, the scoring system can yield different results for the same species monocultures and mixtures and care has to be taken when using it to choose species for soil erosion control features.

5.3.5 Comparison of plant trait ranking scores between Flume Experiment 1 and Flume Experiment 2.

The methodology of Flume Experiment 2 was slightly different from that of Experiment 1-2, the length of the experiment was 10 weeks instead of 6 weeks. However, the mesocosm size was the same as that in Flume Experiment 1. Therefore, it is logical to compare the results for the plant trait scores for Flume Experiment 1 and 3. Further, the same plant traits were used as plant height was omitted for both. Total scores used from Flume Experiment 2 were compared with Flume Experiment 1 for the normal seeding rate in the roots and shoots treatments (Table 5-8).

The scores for the detachment via overland flow soil erosion process varied for each experimental treatment between the two experiments aside from Fest_1+Fest_2 where the score was the same (21) (Table 5-8). The scores differed for all others, an example of a species treatment which was variable was Fest_1. Fest_1 had a higher plant trait score for each soil erosion process in Flume Experiment 1 (23, 13) as opposed to Flume Experiment 2 (8, 3). The same was also true for Fest_1+Fest_2+Conv.

Table 5-8: Comparison of overall plant trait scores between Flume Experiment 1 and Flume Experiment 2.

Species	Detachment via overland flow		Control of Sediment transport and deposition	
	Flume Ex 1	Flume Ex 2	Flume Ex 1	Flume Ex 2
Fest_1	23	8	13	3
Conv	19	15	6	7
Fest_1+Fest_2	21	21	8	12
Fest_1+Fest_2+Conv	24	15	13	6

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*).

5.3.6 Influence on management practices

The data (Table 5-8) can be used to influence management practices as the experiments simulated different planting times. Therefore, it can show when the grass species mixtures or monocultures are best suited for planting based on their plant trait scores. Flume Experiment 1 was simulating a summer planting whereas the Flume Experiment 2 was simulating autumn planting. Therefore, as the scores for Fest_1, Fest_1+2+Conv, Fest_1+2, in terms of plant traits, were always higher for Flume Experiment 1, this showed that they should be planted in summer as opposed to autumn. For Conv the scores are more difficult to interpret as the ones which are highest differ, they are not consistently higher for one experiment as opposed to another.

5.3.7 Improvements and recommendations

One thing to bear in mind is that plant traits are inherently different. This is something to consider when using this ranking system to choose a species mixture or monoculture for soil erosion control features such as grassed waterways. Other factors to take into consideration are the growth time, size of experimental treatment and environmental conditions. A longer growth time will increase the likelihood of a species mixture or monoculture having better plant traits in terms for erosion control and will have different overall scores.

The ranking system is heavily reliant upon a range of plant trait values being known and as evidenced if one is kept the same, such as plant height, then it might not be directly comparable. The range of plant traits can be reduced so that only the same plant traits are used and compared, making the accuracy of the ranking system somewhat diluted. However, it means that the grass species will be directly comparable.

Further, the weighting of plant traits may also be considered to make improvements on this ranking system. As it stands all plant traits are ranked equally therefore no matter the plant trait, it will only give values of 1-7. With the addition of weighting each plant trait this could make the ranking system even more accurate. For example, if SAD or % cover was weighted higher as opposed to the AGB this might affect the end ranking of species in terms of soil erosion control potential. Burylo (2016) found that plant biomass was most positively correlated with sediment trapping efficiency as compared to leaf area and plant roundness for example. Therefore, plant biomass might be considered to be weighted higher in this plant trait ranking system. Furthermore, leaf area and plant roundness could be considered for addition to this plant trait ranking system.

Further, this plant trait ranking system may be expanded upon so that it can be more applicable to the real world by also looking at other characteristics such as evapotranspiration rates, or the hydraulic connectivity of the soil or the bulk density of the soil as these will influence plant traits.

5.3.8 Critical Evaluation of Plant Trait Scoring system

With reference to section 5.3.7 the plant traits are not weighted, and they are all considered to have the same influence on soil erosion control which is most likely not the case. Therefore, a potential problem with this species scoring system is that it assumes all of the plant functional traits affect soil erosion equally. An improvement could be made by introducing the weighting of plant traits. If the plant traits were weighted this would allow for a more accurate result from the species scoring system.

Alternative scoring systems which could be used instead of this one have been developed by De Baets et al., (2009) and Ghestem et al., (2014). However, Ghestem et al., (2014) looked at root traits only and De Baets et al., (2009) only looked at detachment via overland flow. A comparison between all the scoring systems could be researched in the future.

Another potential problem with this plant trait scoring system is that it has only been applied to two experiments which were conducted with the same hydraulic flume. Therefore, this scoring system needs to be applied to further studies to have it further validated. This scoring system has also not been applied to any field scale experiments which is an avenue which can be taken in the future.

A third potential problem with this plant trait scoring system is that it assumes a linear relationship between every plant trait and erosion control, therefore it can be improved upon in the future. For example, the relationship between percentage cover with soil erosion control would drop off as it gets close to 100%. Therefore, it is not a linear relationship. An alternative to this plant trait ranking system using linear relationships would be to change them to the specific relationships between plant traits and soil erosion control. If all of the relationships between specific plant traits and soil erosion control could somehow be incorporated into this plant trait scoring system, it could be made more accurate and precise.

5.4 Conclusions

The plant trait ranking system has been used for the same set of species but under different environmental and experimental conditions. Differences were found within plant trait scores across the 3 experiments, but these may be attributed to differences in growth time and macro/mesocosm size. Based on the plant trait ranking scores recommendations can be made for farm management practices. Fest_1+Fest_2 is recommended for autumn planting, whereas Fest_1 and Fest_1+Fest_2+C are recommended for summer planting. However, the plant trait based ranking system can be improved upon so that it is more reliable. At the moment, it is reliant on a lot of plant traits of different grass species being known. It can be used with a subset of the plant traits however it will become less powerful as a tool in predicting how well a species monoculture or mixture will control for soil erosion.

5.5 References

Boger, A. R., Ahiablame, L., Mosase, E. & Beck, D. (2018). Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. Environmental Science: *Water Research & Technology*, 4, 478-486.

Burylo, M., Rey, F., Mathys, N. & Dutoit, T. (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms*, 37, 1463 - 1470.

De Baets, S., Poesen, J., Knapen, A. & Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms*, 32(9), 1323-1345.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34 (10), 1374-1392.

Gavrić, S., Leonhardt, G., Marsalek, J. & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment,* 669, 431-447.

Ghestem, M., Cao, K., Ma, W., Rowe, N., Leclerc, R., Gadenne, C. & Stokes, A. (2014). A framework for identifying plant species to be used as 'ecological engineers' for fixing soil on unstable slopes. *PLoS One*, 9 (8), e95876.

Leroy, M, Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I. & Marcotte, S. (2016). Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of The Total Environment*, 113-121.

Lees, C., de Baets, S., Rickson, J. & Simmons, R.W. (2020). Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study. *European journal of soil science*, 1-17. DOI: 10.1111/ejss.13045

Li, C. & Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90-103.

Liang, T., Bengough, A.G., Knappett, J.A., MuirWood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & G. J. Meijer. (2017). Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering*, 109B, 207-227. doi: 10.1016/j.ecoleng.2017.06.067

Maity, S.K. & Maiti, R. (2017). Sedimentation under variable shear stress at lower reach of the Rupnarayan River, West Bengal, India. *Water science*, 31, 67-92. doi: 10.1016/j.wsj.2017.02.001

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L. & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755-763.

Morgan, R. P. C. & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach*, London: E & FN Spon.

Morgan, R. P. C. (2007). Vegetative-based technologies for erosion control. In A. Stokes, I. Spanos, J. E. Norris, & E. Cammeraat (Eds.), *Eco-and ground bio-engineering: The use of vegetation to improve slope stability.* Developments in plant and soil sciences (Vol. 103). Dordrecht, The Netherlands: Springer.

Unagwu, B.O, 2017. *Application of organic amendments to restore soil health and productivity of a degraded soil* (PhD thesis). Cranfield University, Cranfield.

Vannoppen, W., Vanmaercke, M., De Baets, S., & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666-678.

6 Wider Implications

6.1 Chapter 2

Plant traits from the plant trait experimental chapter ‘Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study’ were hypothetically linked to soil erosion control in the detachment via rainsplash, detachment via overland flow and for the entrainment and transport of sediment were determined. The following plant traits were determined and are well known in terms of their ability to mitigate soil erosion. Specific above ground traits are, % cover, sward height, number of stems, number of tillers, stem diameter, stem area density and specific below ground traits (root total length, root total surface area, root diameter and root length (cm) of (≤0.25 mm ⌀). This paper will aid farmers and landowners in their management practices as it ranks species treatments in terms of their hypothetical ability to mitigate erosion processes under different climate change scenarios. It will give an indication as to what mixture or monoculture will potential be more effective in erosion control features. This will allow for farmers and landowners to make informed decisions when designing their soil erosion control features.

There were also differing environmental conditions used throughout the experiment, the water conditions simulating drought, normal and flooded conditions as well as the two temperatures, summer, and autumn. This meant that species that did well across all conditions would be able to grow across a range of different environmental conditions. Species which had the highest scores across all scenarios and would therefore be recommended for use are Conv, Fest_1+2+Conv and Fest_2. Fest_1+2 achieved the highest score the autumn establishment and Conv achieved the highest score for summer establishment. Further, for species which only did well in one simulated establishment season this would result in advice being given to the farmer/landowner to plant in that season only.

Further, all the species used within the study were planted at recommended seeding rates and did display the necessary plant traits (mentioned above) that are used for grasses in soil erosion control features such as grassed water ways. This meant that farmers would be able to use these seeding rates to grow grass to have specific plant traits necessary for soil erosion control.

However, there were significant differences in these plant traits and through an extensive literature review these plant traits were known to influence soil erosion. There is information about each plant trait individually but not for plant traits as whole. Therefore, a plant trait ranking system was developed to choose which grass species monoculture or mixture would be the best in terms of soil erosion mitigation potential based on the plant traits that were linked to each stage of soil erosion. The plant trait ranking system can be used to quickly compare grass species effectiveness at erosion control if their plant traits are known. The data gained here is based on experiments which are of short duration (six or ten weeks) so the plant trait scoring system can be used to initially screen monocultures and mixture's ability to mitigate soil erosion. The next step would be trials were soil erosion can be measured to validate this plant trait ranking system.

6.2 Chapter 3

The first hydraulic flume study 'Grass species selection to control concentrated flow erosion in grassed waterways' involved two different grass sward heights, 1.0 cm or 3.0 cm for grass species mixtures and monocultures that were carried forward from the first plant trait experiment as they scored the highest in the plant trait ranking system. Therefore, results from this study can be used to determine which height that soil erosion control features need to prevent soil erosion. As there were no significant differences in sediment concentration this meant that any one of the species used within the study can be used in soil erosion mitigation features. The results used in this study can also be used to inform farmers on their mechanical stressors, grazing or mowing regimes.

As there were no differences in sediment concentration for this study then it showed that farmers can either keep their grass at 1.0 cm or at 3.0 cm and it would yield the same results in terms of soil erosion control. Therefore, they can use whichever management practice that will cost them less to achieve either of these grass sward heights. Further, it also showed that if over grazing or over stressed by machinery then they would still work as erosion mitigation features.

6.3 Chapter 4

The second hydraulic flume study 'Critical flow velocity and shear stress thresholds for grass in grassed water ways' built upon the first hydraulic flume study. It had two different seeding rates, the recommended seeding rate carried forward from previous experiments and a lowered seeding rate at 60% to simulate over grazing, a lowered emergence rate and the overuse of farm machinery. This meant that seeding rate management decisions can be influenced.

Further, the second flume study had two different height treatments 3.0 cm and 0.0 cm, a roots and shoots treatment and a roots only treatment. There were no differences between the roots only treatment, therefore if any of the grass swards became over-grazed or were over mechanically stressed then it would not matter as there was no difference between any of the treatments when there were no shoots.

Finally, the critical shear stress and flow velocity at which soil erosion overcomes the 1000 mg l^{-1} limit as set out by the EA, can be worked out as the hydraulic flume inflow rates were raised in the smallest increments possible (0.1 l s^{-1}). This will influence whether species mixtures of monocultures should be used in soil erosion control features such as grassed waterways. Significant differences were found in sediment concentration, flow velocity and flow shear stress in Flume Experiment 2. Species which breached the 1000 mg l^{-1} limit set out by the EA were Fest_1 L R+S, Fest_1+2 N R+S, Conv L R, Conv N R, Fest_1 N R and Fest_1 L R. However, treatments which were lower than the 1000 mg l^{-1} limit were Conv N R+S, Fest_1+2 L R+S, Fest_1+2+C L R+S, Fest_1 N R+S and Conv L R+S. Therefore, treatments which are recommended are Fest_1+2 L and Fest_1+2+C L.

6.4 Chapter 5

The plant trait ranking system that was devised in Experiment 1 (Chapter 2) was applied to Flume Experiment 1 (Chapter 3) and Flume Experiment 2 (Chapter 4). It can be used to show which species should be grown in which seasons as well as highlighting which grass species will be better at soil erosion control overall in terms of mitigating against all erosion processes.

The ranking system was applied to Flume Experiment 1 and there were differences in the soil erosion mitigation potential scores which indicate that there should have been differences in sediment concentration. Fest_1+2+Conv had a score of 37 whereas Conv had a score of 25 which implied that Conv would be worse at mitigating soil erosion. However, the sediment concentration results gained do not validate this. Even though there were significant differences in key plant traits, there was not enough of a difference to drive changes in sediment concentration.

When the ranking system was applied to Flume Experiment 2 there were again differences in plant trait ranking scores indicating that there should be differences in sediment concentration. Fest_1+2+Conv L R had the highest score of 54, whereas Fest_1 L R+S and Conv L R+S had the lowest score of 18. This implied that Fest_1 L R+S and Conv L R+S should yield a significantly similar sediment concentration, however there were significant differences in sediment concentration between these two species treatments. On the other hand, there were no significant differences between shear stress for these two treatments.

From that chapter after the ranking system was applied to both Flume Experiment 1 and Flume Experiment 2, the species mixture of Fest_1+Fest_2 is recommended for autumn planting and establishment, whereas Fest_1 and Fest_1+Fest_2+C are recommended for summer planting and establishment.

6.5 Overall Main Findings

Overall, across all the experiments it can be concluded that the plant traits investigated had no influence on sediment concentration or flow velocity or flow shear stress which contrasts with most of the existing literature (Morgan & Rickson 1995; De Baets et al., 2009; Mekonnen et al., 2016; Kervroedan et al., 2018). An increased stem diameter has been shown to be positively correlated with hydraulic roughness (Kervroedan et al., 2018). Yang et al., (2022) found that an increased stem diameter decreased runoff flow velocity. An increased stem area density would result in there being less detachment by overland flow (Morgan & Rickson 1995; Morgan 2007; De Baets et al., 2009). Furthermore, an increased stem area density has been shown to increase sediment trapping efficiency (Mekonnen et al., 2016) and an increased hydraulic roughness (Kervroedan et al., 2018). Finally, Fu et al., (2022) found that an increased planting density of grass reduced overland flow velocity and shear stress. Above ground traits are known to impart a frictional component to flow, thus lowering flow velocities resulting in a lowered flow erosivity (Al-Hamdan et al., 2012; Kervroedan et al., 2018). The aforementioned above ground plant traits were all measured within the experiments undertaken for this thesis. Even though there were significant differences in plant traits there were no significant differences in sediment concentration which contrasts with previous studies. Any observed significant differences in plant traits were not enough to affect flow characteristics or sediment concentrations.

6.6 References

Al-hamdan, O.Z., Pierson Jr, F.B., Nearing, M.A., Stone, J.J., Williams, C.J., Moffet, C.A., Kormos, P.R., Boll, J. & Weltz, M.A. (2012). Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modelling. *Earth surface processes and landforms*, 37, 157 - 168.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34 (10), 1374 - 1392.

Fu, Y., Wang, D., Sun, W. & Guo, M. (2022). Impacts of grass planting density and components on overland flow hydraulics and soil loss. *Land Degradation & Development*, 34 (1), 234 - 249.

Kevroedan, L., Armand, R., Saunier, M., Ouvry, J.F. & Faucon, M.P. (2018). Plant functional trait effects on runoff to design herbaceous hedges for soil erosion control. Ecological Engineering, 118, 143 – 151. doi: 10.1016/j.ecoleng.2018.04.024

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L. & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755 - 763.

Morgan, R. P. C. & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach,* London: E & FN Spon.

Morgan, R. P. C. (2007). *Vegetative-based technologies for erosion control. In A. Stokes, I. Spanos, J. E. Norris, & E. Cammeraat (Eds.)*, Eco-and ground bio-engineering: The use of vegetation to improve slope stability. Developments in plant and soil sciences (Vol. 103). Dordrecht, The Netherlands: Springer.

Yang, D., Xiong, D. & Zhang, B. (2022). Impacts of grass basal diameter on runoff erosion force and energy consumption in gully bed in dry-hot valley region, Southwest China. *Soil and Landscape Ecology*, 22, 2048 – 2061.

7 Conclusions

7.1 Advances in methodology

As an outcome from this thesis new methodologies have been developed which can be used by other researchers.

- A methodological framework for the ranking of a grasses potential to control for soil erosion by its plant traits has been developed. This has built upon previous attempts by Ghestem et al., (2014) and De Baets et al., (2009). The ranking system within this study differs as it by includes all soil erosion processes, and both above ground and below ground plant traits. This framework to assess the suitability of grass plant traits for soil erosion control features can be used as an initial screening process for mixes and monocultures for their erosion potential at a sub-process level. This is because it is a combination of measuring specific plant traits and the short growth times within this study.
- A methodology for testing grasses and their ability to withstand concentrated flow erosion has been devised. A continuous flow event where the inflow is ramped up simulates the increased duration and intensity of expected rainfall due to climate change. The methodology of steadily increasing flow rates can be used by other researchers to help to assess suitability of grass and other plant species for erosion control in the future. The ASETTE is unique as it provides a continuous flow which can be set to inflow rates precisely, and it is an enclosed system so water is recycled, therefore longer concentrated flow events can be simulated.

7.1.1 Advances in our understanding of grass traits to mitigate soil erosion.

As an outcome of this thesis our understanding of grass and grass resilience to both climate change and erosion has been furthered.

- The grass traits applicable to each soil erosion process have been used to develop a plant trait ranking system. This is helpful to other researchers as the knowledge in plant traits can be applied to other soil erosion mitigation features, not just grassed water ways. Further, the specific grass traits for the following species mixes and monocultures were not known and have now been determined; *Festulolium cv Prior*, *Festulolium Bx511*, *Festulolium cv Prior* and *Festulolium Bx511*, and *Festulolium cv Prior* and *Festulolium Bx511* and the Conv mixture. The species which achieved the highest scores in the plant trait ranking system from Experiment 1 were, Conv, Fest_1+2+Conv and Fest_2. For Flume Experiment 1 the species which achieved the highest soil erosion mitigation potential score was Fest_1+2+Conv (37). For Flume Experiment 2 the species which achieved the highest soil erosion mitigation potential score was Fest_1+2+Conv L R.

- The critical threshold in both flow velocity and flow shear stress for when the 1000 mg l^{-1} major event limit set out by the EA has been determined for the following grass species*;* *Festulolium cv Prior*, *Festulolium Bx511*, *Festulolium cv Prior* and *Festulolium Bx511* and Conv, and the Conv mixture. It has been determined for the recommended seeding rate, a lowered seeding rate of 60% of the recommended, for roots and shoots, as well as roots only. The following treatments did not cross the EA major limit threshold of 1000 mg l^{-1} Conv N R+S, Fest_1+2 L R+S, Fest_1+2+C L R+S, Fest_1 N R+S and Conv L R+S. The following treatments breached the EA major limit threshold of 1000 mg l^{-1} Conv N R, Conv L R, Fest_1 L R and Fest_1 N R at 1.0, 0.3, 0.3 and 0.9 l s^{-1} inflow rates, respectively.

8 Recommendations for Further Research

The literature review and experimental research contained within this PhD has highlighted several areas for which further research can be undertaken in this field of study.

Some areas in which research into the novel festulolium varieties and their suitability to be used in soil erosion control features such as grassed waterways have been addressed. Little was known about them before this study; however, their plant traits have now been researched under different environmental conditions and water regimes. Yet, there is still a lot to learn about the festulolium varieties which have been used throughout this thesis.

One way in which this research could be complimented would be to grow these novel festulolium varieties solely to investigate the below ground plant traits in more detail. Within this study the plant traits were assessed only after a concentrated flow event had taken place and the root profile could not be determined. Although there was data gained for total root length, root diameter and root surface area etc, there was no way to tell where they were situated within the soil. Therefore, an experiment which uses a CT scanner to find out where the roots are situated should be considered. The same samples could then be subjected to concentrated flow events afterwards so that the root traits can be linked to sediment concentration. This type of experiment could be used to see if roots behaved differently when grass species were planted as monocultures or mixtures. This type of experiment could also be used to investigate how root growth and expansion varies over time by using the CT scanner at different points in time as the plants are growing and establishing.

Another way in which this research could be complimented would be to investigate bulk densities and compaction. Within this study there was one bulk density used throughout to simulate a particular location. As bulk density and compaction will affect soil erosion then different bulk densities will need to be investigated to see how they will affect the plant species mixtures and monocultures used in terms of soil erosion mitigation potential. This type of study may be used to find out the optimal bulk density ranges for the species monocultures and mixtures in relation to their plant traits and ability to control for soil erosion.

Furthermore, as compaction is a prominent problem on agricultural land and grassed waterways are going to be situated on this type of land, research can be done in placing compacted layers at different depths within the soil profile to investigate which species mixtures and monocultures can best adapt to it.

The additional research of looking at root traits and bulk density can be combined with the use of a CT scanner. It would be interesting to see how the roots would react to compacted layers. If this were done, the comparison between different grass roots could be determined in the amount of time taken for a compacted layer to be broken through or whether a compacted layer can be broken through at all.

This study used only laboratory and small-scale experiments which creates an issue in scaling them up and comparing them to field scale processes. During the laboratory experiments within this study, the samples had a maximum depth of 10 cm, therefore there was not much chance of infiltration occurring during these hydraulic flume experiments. Moreover, due to the small-scale of the laboratory experiments, the flow depth of simulated flows within this study were higher than overland flow depths that were found in the field. In the field overland flow depths have been found to be between 0 – 20 mm. A field trial is needed as it will allow for more infiltration than within a laboratory scale experiment as the soil depth will be greater.

A way to compliment and further this research would be to conduct a field trial with the novel festulolium varieties. Small scale grassed plots could be installed on natural flow pathways with soil collection tanks at the bottom of them. The volume of soil for each plot could then be measured and compared between the different species monocultures and mixtures. This small scale grassed plot would be larger in size than the laboratory scale experiments, but smaller in size compared to a GWW maybe 2 – 10 m. Having small scale field plots would validate the research within this study and allow for even further whittling down of the species mixture or monoculture which should be used in GWWs. The best performing plot or plots could then be scaled up even further to be used in GWWs. If this were to happen, the species studied would then be used at every scale, thereby validating their use as a soil erosion control measure.

Finally, the plant trait ranking system devised within the growth room study can also be used and adapted by other researchers. As it stands the plant trait ranking system suggests that all plant traits will affect soil erosion equally. Research can be done into different weightings of individual plant traits to improve the ranking system.

REFERENCES

Alewell, C., Ringeval, B., Ballabio, C., Robinson, D.A., Panagos, P. & Borrelli, P. (2020). Global phosphorus shortage will be aggravated by soil erosion. Nature *Communications*, 11, 4546.

Al-hamdan, O.Z., Pierson Jr, F.B., Nearing, M.A., Stone, J.J., Williams, C.J., Moffet, C.A., Kormos, P.R., Boll, J. & Weltz, M.A. (2012). Characteristics of concentrated flow hydraulics for rangeland ecosystems: implications for hydrologic modelling. *Earth surface processes and landforms*, 37, 157 - 168.

Ali, F.H. & Osman, N. 2008. Shear Strength of a Soil Containing Vegetation Roots. *Soils and Foundations*, 48 (4), 587 - 596. doi: 10.3208/sandf.48.587

Almeida, W.S., Seitz., Oliveira, L.F.C. & Carvalho, D.F. (2021). Duration and intensity of rainfall events with the same erosivity change sediment yield and runoff rates. *International Soil and Water Conservation Research*, 9 (1), 69 - 75.

Amundson, R., Berhe, A.A., Hopmans, J.W., Olson, C., Sztein, A.E. & Sparks, D. (2015). Soil and human security in the 21st century. *Science*, 348 (6235). doi: 10.1126/science.1261071

Armfield, 2019. *Sediment Erosion Flume S28*. Issue 3. Armfield.

Bainard, L.D., Kilronomos, J.N. & Hart, M.M. (2010). Differential effect of sample preservation methods on plant and arbuscular mycorrhizal fungal DNA. *Journal of Microbiological Methods,* 82 (2), 124 - 130. doi: 10.1016/j.mimet.2010.05.001

Baruti, J.H.M. (2004). *Study of Soil Moisture in relation to soil erosion in the proposed Tancitaro Geopark, Central Mexico: A case of the Zacandaro sub-watershed*. pp 64. Available from: https://webapps.itc.utwente.nl/librarywww/papers_2004/msc/ereg/baruti.pdf

Baxter, C., Rowan, J. S., McKenzie, B. M. & Neilson, R. (2013). Understanding soil erosion impacts in temperate agroecosystems: Bridging the gap between geomorphology and soil ecology. *Biogeosciences Discussions*, 10, 7491 - 7520.

Berendse, F., Ruijven, J., jongejans, E. & Keesstra, S. (2015). Loss of Plant Species Diversity Reduces Soil Erosion Resistance. *Ecosystems*, 18, 881 - 888.

Bijlard, R., Steendam, G.J., Verhagen, H.J. & Meer, J.V.D. (2016). Determining the critical velocity of grass sods for wave overtopping by a grass pulling device. *Coastal Engineering proceedings,* 1 (35), structures.20. doi: 10.9753/icce.v35.structures.20.

Bingcheng, X., Feng-Min, L. & Lun, S. (2010). Seasonal root biomass and distribution of Switchgrass and Milk vetch intercropping under 2:1 row replacement in a semiarid region in Northwest China. *Communications in Soil Science and Plant Analysis*, 41 (16), 1959 - 1973.

Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H. & Alberts, E.E. (2004). Grass Barriers for Reduced Concentrated Flow Induced Soil and Nutrient Loss. *Soil Science Society of America Journal*, 68 (6), 1963 - 1972.

Boardman, J., Shepheard, M.L., Walker, E. & Foster, I.D.L. (2009). Soil erosion and risk-assessment for on- and off-farm impacts: A test case using the Midhurst area, West Sussex, UK. *Journal of Environmental Management*, 90 (8), 2578 - 2588. doi: 10.1016/j.jenvman.2009.01.018

Boardman, J. (2013). Soil Erosion in Britain: Updating the Record. *Agriculture*, 3, 418 - 442. doi: 10.3390/agriculture3030418

Boardman, J., Vandaele, K., Evans, R. & Foster, I.D.L. (2018). Off- site impacts of soil erosion and runoff: Why connectivity is more important than erosion rates. *Soil Use and Management*, 35 (2), 245 - 256. doi: 10.1111/sum.12496

Boger, A. R., Ahiablame, L., Mosase, E. & Beck, D. (2018). Effectiveness of roadside vegetated filter strips and swales at treating roadway runoff: a tutorial review. *Environmental Science: Water Research & Technology*, 4, 478 - 486.

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L. & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the*

National Academy of Sciences of the United States of America, 117 (36), 21994 - 22001. doi: 10.1073/pnas.2001403117

Bryan, R.B. (2000). Soil erodibility and processes of water erosion on hillslope. *Geomorphology*, 32 (3 - 4), 385 - 415. doi: 10.1016/S0169-555X(99)00105-1

Burylo, M., Rey, F., Mathys, N. & Dutoit, T. (2012). Plant root traits affecting the resistance of soils to concentrated flow erosion. *Earth Surface Processes and Landforms*, 37, 1463 - 1470.

Chase, J. M. & Myers, J. A. (2011). Disentangling the importance of ecological niches from stochastic processes across scales. *Philosophical Transactions of the Royal Society B*, 336 (1576), 2351 - 2363. doi: 10.1098/rstb.2011.0063

Chen, B. & Zhang, X. (2022). Effects of slope vegetation patterns on erosion sediment yield and hydraulic parameters in slope-gully system. *Ecological Indicators*, 145, 109723. doi: 10.1016/j.ecolind.2022.109723

Collins, A.L. & Walling, D.E. (2007). Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrological Processes*, 1448 - 1459. doi: 10.1002/hyp.6269

Collins, A.L. & Anthony, S.G., Hawley, J. & Turner, T. (2009). The potential impact of projected change in farming by 2015 on the importance of the agricultural sector as a sediment source in England and Wales. *Catena*, 79, 243 - 250. doi: 10.1016/j.catena.2009.05.007

Dabney, S.M., Shields, F.D., Temple, D.M. & Langendoen, E.J. (2004). Erosion Processes in Gullies Modified by Establishing Grass Hedges. *American Society of Agricultural Engineers*, 47 (5), 1561 - 1571. doi: 10.13031/2013.17634

De Baets, S., Poesen, J., Knapen, A. & Galindo, P. (2007). Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. *Earth Surface Processes and Landforms,* 32 (9), 1323 - 1345.

De Baets, S., Poesen, J., Reubens, B., Muys, B., De Baerdemaeker, J. & Meersmans, J. (2009). Methodological framework to select plant species for controlling rill and gully erosion. *Earth Surface Processes and Landforms*, 34 (10), 1374 - 1392.

De Baets, S. & Poesen, J. (2010). Empirical models for predicting the erosion-reducing effects of plant roots during concentrated flow erosion. Geomorphology, 118(3 - 4), 425 - 432. https://doi.org/10.1016/j.geomorph.2010.02.011

Deléglise, C., Meisser, M., Mosimann, E., Spiegelberger, T., Signarbieux, C., Jeangros, B. & Buttler, A. (2015). Drought-induced shifts in plants traits, yields and nutritive value under realistic grazing and mowing managements in a mountain grassland. *Agriculture, Ecosystems & Environment*, 213, 94 - 104.

Deletic, A. (2005). Sediment transport in urban runoff over grassed areas. *Journal of Hydrology*, 301, 108-122. doi: 10.1016/j.jhydrol.2004.06.023

Ekholm, P. & Lehtoranta, J., (2012). Does control of soil erosion inhibit aquatic eutrophication? *Journal of Environmental Management*, 93, 140 - 146.

Environment Agency, 2016. *Incidents and their classification: the Common Incident Classification Scheme (CICS)*. Environment Agency. pp 38 - 39.

Evans, R. (1990). Soils at risk of accelerated erosion in England and Wales. *Soil Use and Management*, 6 (3), 125 - 131.

FAO, 1988. *Watershed management field manual - Slope treatment measures and practices".* FAO technical paper 13/3, FAO, Roam.

Fariaszewska, A., Aper, J., Van Huylenbroeck, J., De Swaef, T., Baert, J. & Pecio, L. (2020). Physiological and biochemical responses of forage grass varieties to mild drought stress under field conditions. *International Journal of Plant Production*, 14, 335 - 353.

Fiener, P. (2003). *Concept and effects of a multi-purpose grassed waterway - long-term measuring and mathemati-cal modeling of runoff reduction and sediment trapping*. University thesis.

Fiener, P. & Auerswald, K. (2006). Seasonal variation of grassed waterway effectiveness in reducing runoff and sediment delivery from agricultural watersheds in temperate Europe. *Soil and Tillage Research*, 87 (1), 48 - 58.

Fu, Y., Wang, D., Sun, W. & Guo, M. (2022). Impacts of grass planting density and components on overland flow hydraulics and soil loss. *Land Degradation & Development*, 34 (1), 234 - 249.

Gavrić, S., Leonhardt, G., Marsalek, J. & Viklander, M. (2019). Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of the Total Environment*, 669, 431 - 447.

Genney, D.R., Alexander, I.J. & Hartley, S.E. (2000). Exclusion of grass roots from soil organic layers by Calluna: the role of ericoid mycorrhizas. *Journal of Experimental Botany*, 51 (347), 1117 - 1125. doi: 10.1093/jexbot/51.347.1117

Ghestem, M., Cao, K., Ma, W., Rowe, N., Leclerc, R., Gadenne, C. & Stokes, A. (2014). A framework for identifying plant species to be used as 'ecological engineers' for fixing soil on unstable slopes. *PLoS One*, 9 (8), e95876.

Govers, G. (1990). *Empirical relationships for the transport capacity of overland flow*. Erosion, Transport and Deposition Processes (Proceedings of the Jerusalem Workshop, March-April 1987), 189, 45 - 63.

Grabowski, R.C., Droppo, I.G. & Wharton, G. (2011). Erodibility of cohesive sediment: The importance of sediment properties. *Earth-Science Reviews*, 105 (3-4), 101 - 120. doi: 10.1016/j.earscirev.2011.01.008

Gutteridge, R. J., Zhang, J. P., Jenkyn, J. F. & Bateman, G. L. (2005). Survival and multiplication of Gaeumannomyces graminis var. tritici (the wheat take-all fungus) and related fungi on different wild and cultivated grasses. *Applied Soil Ecology*, 29 (2), 143 - 154. https://doi.org/10.1016/j.apsoil.2004.11.003

Hai, T.L. (2012). *Root characteristics of some grass species on the sea dikes in Viet Nam*. Communications on Hydraulic and Geotechnical Engineering. PhD Thesis. Delft University of Technology. Available from:

https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.875.4710&rep=rep1&type=pdf [Accessed on 20 January 2022]

Hewlett, H. W. M, Boorman, L. A. & Bramley, M. E (1987). *Guide to the design of reinforced grass waterways*. London, the United Kingdom: Construction Industry Research and Information Association (CIRIA).

Hollis, J. M. & Hodgson, J. (1974). *Soils in Worcestershire I (Kidderminster).* Harpenden, England: Soil Survey of England and Wales.

Humphreys, M. W., Yadav, R. S., Cairns, A. J., Turner, L. B., Humphreys, J. & Skøt, L. (2006). A changing climate for grassland research. *New Phytologist*, 169(1), 9 - 26.

Houlbrooke, D.J., Thom, E.R., Chapman, R. & McLay, C.D.A. (1997). A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. *New Zealand Journal of Agricultural Research*, 40, 429 - 435. doi: 10.1080/00288233.1997.9513265

Inman, A. & Consulting, T. (2006). *Soil erosion in England and Wales: causes, consequences and policy options for dealing with the problem*. Available from: http://assets.wwf.org.uk/downloads/soilerosionengwales.pdf Surrey: WWF UK.

IPCC (2013). *Summary for policymakers*. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change, (108 - 112). Cambridge, England: Cambridge University Press.

Kevroedan, L., Armand, R., Saunier, M., Ouvry, J.F. & Faucon, M.P. (2018). Plant functional trait effects on runoff to design herbaceous hedges for soil erosion control. Ecological Engineering, 118, 143 – 151. doi: 10.1016/j.ecoleng.2018.04.024

Khodashenas, S.R., Abderrezzak, K.E.K. & Paquier, A. (2008). Boundary shear stress in open channel flow. A comparison among six methods. *Journal of Hydraulic Research*, 46 (5), 598-609. doi: 10.3826/jhr.2008.3203

Kitchener, B.G.G., Wainwright, J., Parsons, A.J. (2017). A review of the principles of turbidity measurement. *Progress in Physical Geography*, 41 (5), 620-642. doi: 10.1177/0309133317726540

Knapen, A., Poesen, J., Gyssels, G. & Nachtergaele, J. (2007). Resistance of soils to concentrated flow erosion: A review. *Earth Science Reviews*, 80 (1-2), 75-109. doi: 10.1016/j.earscirev.2006.08.001

Knapen, A. & Poesen, J. (2009). Soil erosion resistance effects on rill and gully initiation points and dimensions. *Earth Surface Processes and Landforms*, 35 (2), 217 - 228.

Kroese, J.S., Batista, P.V.G., Jacobs, S.R., Breuer, L., Quinton, J.N. & Rufino, M.C. (2020). Agricultural land is the main source of stream sediments after conversion of an African montane forest. *Scientific Reports*, 10, 14827. doi: 10.1038/s41598-020-71924-9

Lave, J. & Avouac, J.P. (2001). Fluvial incision and tectonic uplift across the Himalayas of central Nepal. *Journal of Geophysical Research: Solid Earth*, 106, 26,311-26,787. doi: 10.1029/2001JB000359

Lees, C., De Baets, S., Rickson, R.J. & Simmons, R.W. (2020). Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study. *European Journal of Soil Science*, 72, 2381 - 2397.

Leonard, J. & Richard, G. (2004). Estimation of runoff critical shear stress for soil erosion from soil shear strength. *Catena*, 3, 233-249.

Leroy, M, Portet-Koltalo, F., Legras, M., Lederf, F., Moncond'huy, V., Polaert, I. & Marcotte, S. (2016). Performance of vegetated swales for improving road runoff quality in a moderate traffic urban area. *Science of The Total Environment*, 566-567, 113 - 121.

Li, C. & Pan, C. (2018). The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. *Journal of Hydrology*, 558, 90 - 103.

Li, J., Li, L., Wang, W., Kang, H., Guo, M., Huang, J., Wang, Y., Lou, Y., Tong, X. & Nie, H. (2023). Hydrological and erosion responses of steep spoil heaps to taproot and fibrous root grasses under simulated rainfalls. *Journal of Hydrology*, 618, 129169.

Li, M., Hai, X., Hong, H., Shao, Y., Peng, D., Xu, W., Yang, Y., Zheng, Y. & Xia, Z. (2019). Modelling soil detachment by overland flow for the soil in the Tibet Plateau of China. *Scientific Reports*, 9, 8063. doi: 10.1038/s41598-019-44586-5

Liang, T., Bengough, A.G., Knappett, J.A., MuirWood, D., Loades, K.W., Hallett, P.D., Boldrin, D., Leung, A.K. & Meijer, G. J. (2017). Scaling of the reinforcement of soil slopes by living plants in a geotechnical centrifuge. *Ecological Engineering*, 109B, 207 - 227.

Lick, W. & McNeil, J. (2001). Effects of sediment bulk properties on erosion rates. *Science of the Total Environment*, 266 (1-3), 41 - 48. doi: 10.1016/s0048-9697(00)00747-6

Liu, B., Xie, Y., Li, Z., Liang, Y., Zhang, W., Fu, S., Yin, S., Wei, X., Zhang, K., Wang, Z., Liu, Y., Zhao, Y. & Guo, Q. (2020). The assessment of soil loss by water erosion in China. *International Soil and Water Conservation Research*, 8 (4), 430 - 439. doi: 10.1016/j.iswcr.2020.07.002

Liu, Z., Baoyin, T., Duan, J., Yang, G., Sun, J. & Li, X. (2018). Nutrient Characteristics in Relation to Plant Size of a Perennial Grass Under Grazing Exclusion in Degraded Grassland. *Frontiers in Plant Science*, 9, 295.

Liu, J.X., Wang, B., Duan, X.W., Yang, Y.F. & Liu G.B. (2022). Seasonal variation in soil erosion resistance to overland flow in gully-filled farmland on the Loess Plateau, China. *Soil and Tillage Research*, 218, 105297. doi: 10.1016/j.still.2021.105297

Lou, Y., Gao, Z., Sun, G., Wu, T., Zhou, F., Ai, J., Cen Y. & Xie, J. (2022). Runoff scouring experimental study of rill erosion of spoil tips. *CATENA*, 214, 106249. doi: 10.1016/j.catena.2022.106249

Lou, Y., Wang, W., Guo, M., Guo, W., Kang, H., Feng, L., Zhu, Y. and Yang, H. (2023). Vegetation affects gully headcut erosion processes by regulating runoff hydrodynamics in the Loess tableland region. *Journal of Hydrology*, 616, 128769. doi: 10.1016/j.jhydrol.2022.128769

Luo, M, Pan, C. & Liu, C. (2020). Experiments on measuring and verifying sediment trapping capacity of grass strips. *CATENA*, 194, 104714. doi: 10.1016/j.catena.2020.104714

MacLeod, C. J. A., Humphreys, M. W., Whalley, R., Turner, L. B., Binley, A., Watts, C. W. & Haygarth, P. M. (2013). A novel grass hybrid to reduce flood generation in temperate regions. *Scientific Reports*, 3, 1 - 7. https://doi.org/10.1038/srep01683

Melville, N. & Morgan, R.P.C. (2006). The influence of grass density on effectiveness of contour grass strips for control of soil erosion on low angle slopes. *Soil Use and Management*, 17 (4), 278 - 281.

Mekonnen, M., Keesstra, S.D., Stroosnijder, L., Baartman, J.E.M. & Maroulis, J. (2014). Soil Conservation Through Sediment Trapping: A Review. *Land Degradation and Development,* 26 (6), 544 - 556. doi: 10.1002/ldr.2308

Mekonnen, M., Keesstra, S. D., Ritsema, C. J., Stroosnijder, L. & Baartman, J. E. M. (2016). Sediment trapping with indigenous grass species showing differences in plant traits in Northwest Ethiopia. *Catena*, 147, 755 - 763.

Met Office (2018a). *Ross-on-Wye climate*. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/public/weather/climate/gcnpm68t8

Met Office (2018b). *Land projection maps: Probabilistic projections*. Met Office. Exeter, Devon. Retrieved from https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/land-projection-maps

Met Office (2022) *Cambridge NIAB climate data*. Met Office. URL https://www.metoffice.gov.uk/pub/data/weather/uk/climate/stationdata/cambridgedata.txt [Accessed on 11 February 2022].

Mganga, K.Z., Kaindi, E., Ndathi, A.J.N., Bosma, L., Kioko T., Kadenyi, N., Musyoki, G.K., Wambua, S., Steenbergen, F. & Musimba, N.K.R. (2021). Plant Morphoecological Traits, Grass-Weed Interactions and Water Use Efficiencies of Grasses Used for Restoration of African Rangelands. *Frontiers in Ecology and Evolution*, doi: 10.3389/fevo.2020.613835

Mishra, P.K., Rai, A., Abdelrahman, K., Rai, S.C. & Tiwari, A. (2022). Land Degradation, Overland Flow, Soil Erosion, and Nutrient Loss in the Eastern Himalayas, India. *Land*, 11 (2), 179. doi: 10.3390/land11020179

Moody, J.A., Smith, J.D. & Ragan, B.W. (2005). Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires. *Journal of Geophysical Research Earth Surface*, 110 (F1), doi:10.1029/2004JF000141.

Montgomery, D. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences*, 104 (33), 13268 - 13272.

Montieth, H. & Pender, G. (2005). Flume investigations into the influence of shear stress history on a graded sediment bed. *Water Resources Research*, 41 (12). doi: 10.1029/2005WR004297

Morgan, R. P. C. & Rickson, R. J. (1995). *Slope stabilisation and erosion control: A bioengineering approach,* London: E & FN Spon.

Morgan, R.P.C. & Rickson, R.J. (2005). *Slope stabilisation and erosion control: a bioengineering approach*. 2nd Edition. London: E & FN Spon.

Morgan, R.P.C. (2005). *Soil Erosion and Conservation*. Third Edition. Blackwell publishing Ltd.

Morgan, R. P. C. (2007). *Vegetative-based technologies for erosion control. In A. Stokes, I. Spanos, J. E. Norris, & E. Cammeraat (Eds.)*, Eco-and ground bio-engineering: The use of vegetation to improve slope stability. Developments in plant and soil sciences (Vol. 103). Dordrecht, The Netherlands: Springer.

National Audit Office. (2010). *Tackling diffuse water pollution in England* (online), London: National Audit Office Retrieved from https://www.nao.org.uk/wp-content/uploads/2010/07/1011188.pdf

National Engineering Handbook. (2007). *United States Department of Agriculture*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail//?cid=nrcs141p2_024573 Part 654, Chapter 8.

New York stormwater management design manual, (2015). Available from: https://www.dec.ny.gov/chemical/29072.html. Appendix L.

Ou, X., Hu, Y., Li, X., Guo., S. & Liu, B. (2021). Advancements and challenges in rill formation, morphology, measurement and modeling. *Catena*, 196, 104932.

Pan, C., Shangguan, Z. & Ma, L. (2015). Assessing the dye-tracer correction factor for documenting the mean velocity of sheet flow over smooth and grassed surfaces. *Hydrological processes*, 29 (26), 5369 - 5382. doi: 10.1002/hyp.10565

Pimentel, D. & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, 3 (3), 443 - 463.

Pirchio, M., Fontanelli, M., Frasconi, C., Martelloni, L., Raffaelli, M., Peruzzi, A. & Grossi, N. (2018). Autonomous mower vs. rotary mower: Effects on turf quality and weed control in tall fescue Lawn. *Agronomy*, 8 (2), 15. doi: 10.3390/agronomy8020015

Plainwater, (2015). Shear Stress & Permissible Velocity. *New York State Stormwater Management Design Manual* (January, 2015). Available from: https://plainwater.com/water/shear-stress-permissible-velocity/

Prosser, I. P., Dietrich, W. E. & Stevenson, J. (1995). Flow resistance and sediment transport by concentrated overland flow in a grassland valley. Geomorphology, 13 (1–4), 71 - 86.

Quine, T. A. & Walling, D. E. (1991). Rates of soil erosion on arable fields in Britain: Quantitative data from Caesium 137 measurements. *Soil Use and Management*, 7 (4), 169 - 176.

Ramos, J.C., Bertol, I., Barbosa, F.T., Bertól, C., Mafra, A.L., Miquelluti, D.J. & Júnior, J.M. (2016). Water erosion in surface soil conditions: runoff velocity, concentration and D50 index of sediments in runoff. *Scientia Agricola*, 73 (3), 286 - 293. doi:: 10.1590/0103-9016-2015-0110

Regent Instruments (2016). *WinRHIZO 2016 Basic, Reg, Pro & Arabidopsis For Root Measurement*. Canada: Regent instruments Canada Inc.

Restrepo, J.D. & Syvitski, J.P.M. (2006). Assessing the Effect of Natural Controls and Land Use Change on Sediment Yield in a Major Andean River: The Magdalena Drainage Basin, Colombia. *Ambio*, 35 (2), 65 - 74.

Rickson, R.J. (2014). Can control of soil erosion mitigate water pollution by sediments? *Science of The Total Environment*, 468 - 469, 1187-1197. doi: 10.1016/j.scitotenv.2013.05.057

Routschek, A., Schmidt, J. & Kreienkamp, F. (2014). Impact of climate change on soil erosion - a high-resolution projection on catchment scale until 2100 in Saxony/Germany. *Catena*, 121, 99 - 109. doi: 10.1016/j.catena.2014.04.019

Sardans, J. & Penuelas, J. (2013). Plant-soil interactions in Mediterranean forest and shrublands: impacts of climatic change. *Plant Soil*, 365, 1-33. doi: 10.1007/s11104-013-1591-6

Schwendel, A.C., Death, R.S. & Fuller, I.C. (2010). The assessment of shear stress and bed stability in stream ecology. *Freshwater Biology*, 55 (2), 261-281. doi: 10.1111/j.1365-2427.2009.02293.x

Shit, P.K., Pourghasemi, H.R. & Bhunia, G.S. (2020). Effects of Grass on Runoff and Gully Bed Erosion: Concentrated Flow Experiment. *In book: Gully Erosion Studies from India and Surrounding Regions,* pp 221-233.

Silgram, M., Jackson, D.R., Bailey, A., Quinton, J. & Stevens, C. (2010). Hillslope scale surface runoff, sediment and nutrient losses associated with tramline wheelings. *Earth Surface Processes and Landforms*, 35 (6), 699-706. doi: 10.1002/esp.1894

Singh, B. K., Munro, S., Potts, J. M. & Millard, P. (2007). Influence of grass species and soil type on rhizosphere microbial community structure in grassland soils. *Applied Soil Ecology*, 36 (2 - 3), 147 - 155. doi: 10.1016/j.apsoil.2007.01.004

Singh, H.V. & Thompson, A.M. (2016). Effects of antecedent soil moisture content on soil critical shear stress in agricultural watersheds. *Geoderma*, 262, 165-173. doi: 10.1016/j.geoderma.2015.08.011

Smith, M.W., Cox, N.J. & Bracken, L.J. (2011). Modeling depth distributions of overland flows. *Geomorphology*, 125 (3), 402-413.

Somsook, K., Azhikoda, G., Duka, M.A. & Yokoyama, K. (2021). Riverbed fluctuation and erosion property of cohesive sediment based on long-term topographic surveys in a macrotidal estuary. *Regional Studies in Marine Science*, 45, 101848. doi: 10.1016/j.rsma.2021.101848

Stagge, J.H., Davis, A.P., Jamil, E. & Kim, H. (2012). Performance of grass swales for improving water quality from highway runoff. *Water Research*, 46 (20), 6731-6742. doi: 10.1016/j.watres.2012.02.037

Staton, M. & Bosch, B. (2015). *Grassed waterways can help maintain soil quality and productivity*. Michigan State University. Available from: https://www.canr.msu.edu/news/grassed_waterways_can_help_maintain_soil_quality_and_productivity [Accessed 3rd December 2021]

Sun, L., Zhang, B., Yin, Z., Guo, H., Siddique, K.H.M., Wu, S. & Yang, J. (2022). Assessing the performance of conservation measures for controlling slope runoff and erosion using field scouring measurements. *Agricultural Water Management*, 259, 107212. doi: 10.1016/j.agwat.2021.107212

Unagwu, B.O, 2017. *Application of organic amendments to restore soil health and productivity of a degraded soil (PhD thesis).* Cranfield University, Cranfield.

U.C. Cooperative Extension. (2003). *Estimated Costs & Potential Benefits for Non-engineered Grassed Waterways*. U.C. Cooperative Extension. Available from: http://awqa.org/wp-content/toolkits/Other/Non-EngGrassedWater.pdf [Accessed on 4 December 2021].

USDA. (2022). *Soil Bulk Density Moisture/Aeration*. USDA. Available from: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053260.pdf [Accessed on 1 March 2022].

Vannoppen, W., Vanmaercke, M., De Baets, S. & Poesen, J. (2015). A review of the effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, 150, 666 - 678.

Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J. & Smith, C.J. (2009). Tolerable versus actual soil erosion rates in Europe. *Earth-Science Reviews*, 94 (1 - 4), 23 - 38.

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G. & Roberts, N.M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. Reviews of *Geophysics*, 52 (3), 522 - 555.

White, K., She, Y. & Zhang, W. (2022). A comparison of shear stress estimation methods for a single geobag on a rough bed. *Geotextiles and Geomembranes*, 50 (6), 1230-1243. doi: org/10.1016/j.geotexmem.2022.09.001

Wilkinson, B.H. & McElroy, B.J. (2007). The impact of humans on continental erosion and sedimentation. GSA Bulletin, 119 (1 - 2), 140 - 156. doi: 10.1130/B25899.1

Wilson, H.M, Cruse, R.M. & Burras, C.L. (2011), Perennial grass management impacts on runoff and sediment export from vegetated channels in pulse flow runoff events. Biomass and Bioenergy, 35 (1), 429 – 436. doi: 10.1016/j.biombioe.2010.08.059

Wright, A. J., Ebeling, A., Kroon, H., Roscher, C., Weigelt, A., Buchmann, N. & Eisenhauer, N. (2015). Flooding disturbances increase resource availability and productivity but reduce stability in diverse plant communities. *Nature Communications*, 6, 60 - 92.

Xiao, H., Guo, P., Zhang, Q., Hu, H., Hong, H., Zhang, L., Yang, Y., Xia, Z., Li, M., Kang, H. & Zhang, G. (2022). Variation in soil properties and its influence on dynamic change of soil erosion resistance to overland flow in the water-level fluctuation zone of the Three Gorges Reservoir, China. *CATENA*, 213, 106141. doi: 10.1016/j.catena.2022.106141

Xiao, P., Yang, E. & Jiao, P. (2014). Effect of Grass on Reducing Runoff and Sediment and its Critical Flow Shear Stress. *Advanced Materials Research*, 1010-1012, 1145-1148. doi: 10.4028/www.scientific.net/AMR.1010-1012.1145

Yang, D., Xiong, D. & Zhang, B. (2022). Impacts of grass basal diameter on runoff erosion force and energy consumption in gully bed in dry-hot valley region, Southwest China. *Soil and Landscape Ecology*, 22, 2048 – 2061.

Ye, Y, Tan, X, Liu, Y., Zhou, C., Shi, F., Lee, Y, & Murphy M.A., 2022. The impact of erosion on fault segmentation in thrust belts: Insights from thermochronology and fluvial shear stress analysis (southern Longmen Shan, eastern Tibet). *Geomorphology*, 397, 108020. doi: 10.1016/j.geomorph.2021.108020

Zhang, Z., Sheng, L., Yang, J., Chen, X., Kong, L. & Wagan, B. (2015). Effects of Land Use and Slope Gradient on Soil Erosion in a Red Soil Hilly Watershed of Southern China. *Sustainability*, 7, 14309 - 14325. doi: 10.3390/su71014309

Zhang, B., Zhang, G., Yang, H. & Zhu, P. (2019). Temporal variation in soil erosion resistance of steep slopes restored with different vegetation communities on the Chinese loess plateau. *Catena*, 182, 104170.

Zhou Y., Watts D., Li Y. & Cheng X. (1998). A case study of effect of lateral roots of Pinus yunnanensis on shallow soil reinforcement. *Forest Ecology and Management,* 103, 107 - 120. Catena, 182. doi: 10.1016/j.catena.2019.1041

Zhu, Y., Zhang, Y., Yang, J., Nguyen, B.T. & Wang, Y. (2022). A novel method for calculating disturbed water depth and flow velocity of stormwater runoff during the heavy rainfall events. *Journal of Hydrology*, 612, Part A, 128064.

Zuazo, V. H. D. & Pleguezuelo, C. R. R. (2008). Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, 28 (1), 65 – 86.

APPENDICES

Appendix A Selecting plant traits for soil erosion control in grassed waterways under a changing climate: A growth room study.

A.1 Autumn Plant Traits

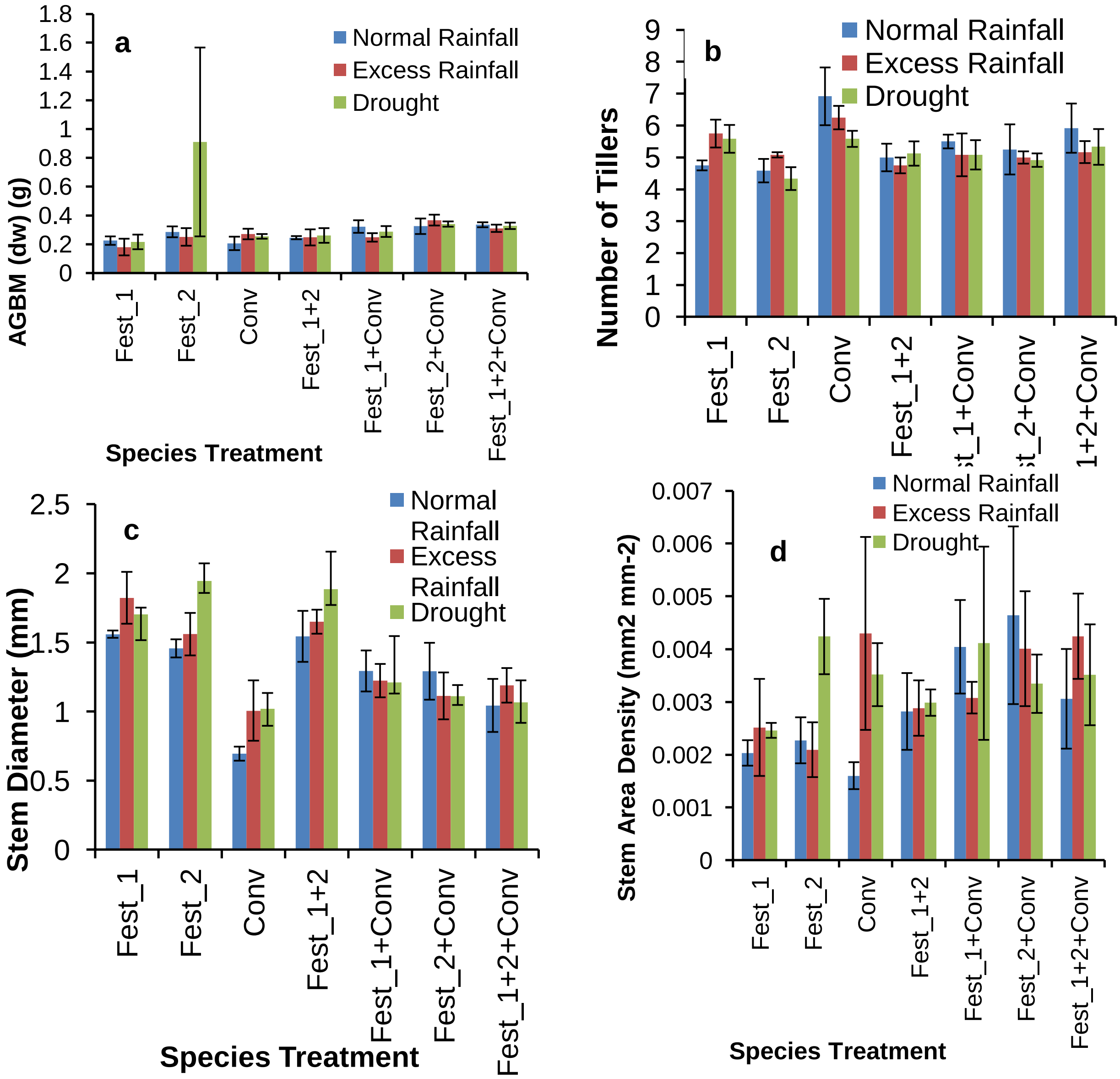
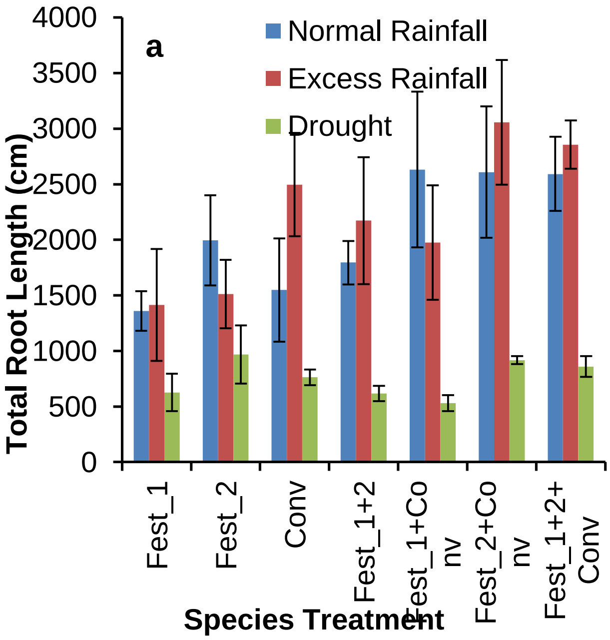
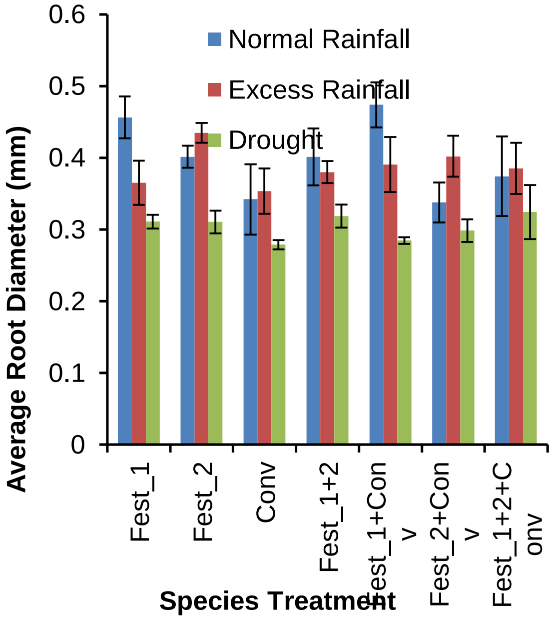


Figure A-0-1: Aboveground plant traits (a) Stem diameter (mm), (b) Number of tillers, (c) AGB (g) and (d) Stem Area Density (mm^2 mm^{-2}) for autumn establishment according to species treatment and rainfall scenario. Error bars represent ±1 standard error.





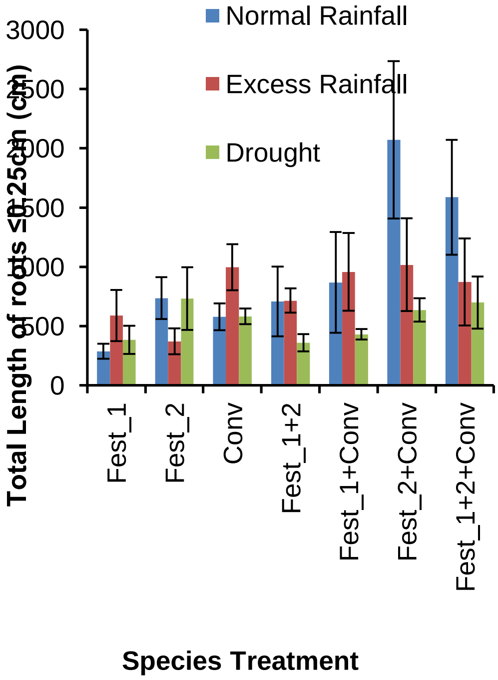


Figure A-0-2: Belowground plant traits (a) total root length (cm), (b) average root diameter (mm) and (c) Total root length ≤0.25mm in diameter (cm) for autumn establishment according to species and rainfall scenario treatments. Error bars represent ± 1 standard erro

A.2 Correlations between plant trait variables

Table A-1: Summer establishment: Pearson's correlations for all plant traits (n=84). Where co-dependency was found (≥ 0.7) selected variables became redundant and were not included in the trait-based scoring system.

Vegetation Trait	BG Biomass (FW)	BG Biomass (DW)	Total Root Length	RSA	RDiam	RL ≥0.25mm	G%	Grass (FW)	PH	%Cover	Number of tillers	Number of Stems	Stem Diameter	SAD	ABG (FW)	ABG (DW)
BG Biomass (FW)		.824**	-.913**	-.899**	.489**	-.782**	-.140	-.120	-.145	.044	-.039	.010	-.100	.481	-.069	-.070
BG Biomass (DW)	.824**		-.764**	-.733**	.595**	-.745**	-.135	.011	-.182	.164	.044	.057	.009	.422	.076	.120
Total Root Length	-.913**	-.764**		-.945**	-.521**	-.836**	.050	.143	.142	-.011	.054	.021	.063	-.089	.046	.040
RSA	-.899**	-.733**	-.945**		-.542	.882**	.065	.084	.196	-.071	.098	-.032	.046	-.090	.045	.008
RDiam	.489**	.595**	-.521**	.542		-.799**	.233*	.023	.011	.066	-.085	-.121	.267*	.191	.122	.122
RL ≥0.25mm	-.782**	-.745**	-.836**	.882**	-.799**		-.129	.051	.082	-.053	.112	.049	-.134	-.098	-.069	-.071
%G	-.140	-.135	.050	.065	.233*	-.129		.114	.242*	.025	-.059	-.030	.226*	.202	.198	.196
Grass (FW)	-.120	.011	.143	.084	.023	.051	.114		-.255*	.333**	-.303**	.443**	-.285**	.043	-.076	.204
PH	-.145	-.182	.142	.196	.011	.082	.242*	-.255*		-.205	.299**	-.569**	.578**	.058	.422**	.315**
%Cover	.044	.164	-.011	-.071	.066	-.053	.025	.333**	-.205		.249*	.628**	-.222*	.264	.523**	.577**
Number of Tillers	-.039	.044	.054	.098	-.085	.112	-.059	-.303**	.299**	.249*		-.108	.228*	.173	.583**	.478**
Number of Stems	.010	.057	.021	-.032	-.121	.049	-.030	.443**	-.569**	.628**	-.108		-.677**	-.075	-.033	.145

Stem Diameter	-.100	.009	.063	.046	.267*	-.134	.226*	-.285**	.578**	-.222*	.228*	-.677**		**.731**	.402**	.261*
SAD	.481	.422	-.089	-.090	.191	-.098	.202	.043	.058	.264	.173	-.075	**.731**		.032	-.033
ABG (FW)	-.069	.076	.046	.045	.122	-.069	.198	-.076	.422**	.523**	.583**	-.033	.402**	.032		**.808****
ABG (DW)	-.070	.120	.040	.008	.122	-.071	.196	.204	.315**	.577**	.478**	.145	.261*	-.033	**.808****	

Percentage germination (G%); percentage ground cover (C%); Plant height (PH (cm)); stem area density (SAD (mm^2 mm^{-2})); above ground DW or FW biomass (ABG (g)); root length of roots >0.25 mm in diameter (RL (m)); root surface area (RSA); mean root diameter (RDiam (mm))

*Significantly different at <0.05 **Significantly different at <0.01

Table A-2: Autumn establishment: Pearson's correlations for all plant traits (n=84). Where co-dependency was found (≥ 0.7) selected variables became redundant and were not included in the trait-based scoring system.

Vegetation Trait	BG Biomass (FW)	BG Biomass (DW)	Total Root Length	RSA	RDiam	RL ≥0.25mm	G%	Grass (FW)	PH	%Cover	Number of tillers	Number of Stems	Stem Diameter	SAD	ABG (FW)	ABG (DW)
BG Biomass (FW)		.704**	.978**	.983**	.445**	.529**	.277*	.664**	.154	.585**	.026	.295**	-.099		.683**	.014
BG Biomass (DW)	.704**		.700**	.703**	.375**	.290**	.280**	.610**	.063	.615**	.085	.349**	-.200	.208	.585**	-.001
Total Root Length	.978**	.700**		.995**	.396**	.583**	.199	.666**	.135	.579**	.043	.319**	-.095	.317	.661**	.016
RSA	.983**	.703**	.995**		.425**	.560**	.209	.661**	.141	.587**	.047	.310**	-.095	.305	.670**	.012
RDiam	.445**	.375**	.396**	.425**		-.286**	.030	.252*	.341**	.103	.053	-.192	.081	-.111	.407**	-.014
RL ≥0.25mm	.529**	.290**	.583**	.560**	-.286**		.052	.373**	.012	.332**	-.118	.311**	-.094	.358	.327**	.010
%G	.277*	.280**	.199	.209	.030	.052		.186	-.162	.286**	.016	.243*	-.131	.081	.259*	.001
Grass (FW)	.664**	.610**	.666**	.661**	.252*	.373**	.186		.161	.535**	.044	.322**	-.210		.635**	.102
PH	.154	.063	.135	.141	.341**	.012	-.162	.161		-.237*	-.348**	-.481**	.381**	-.038	.488**	.251*
%Cover	.585**	.615**	.579**	.587**	.103	.332**	.286**	.535**	-.237		.232*	.778**	-.490**	.306	.468**	.047
Number of Tillers	.026	.085	.043	.047	.053	-.118	.016	.044	-.348**	.232*		.226*	-.156	-.011	-.081	-.105
Number of Stems	.295**	.349**	.319**	.310**	-.192	.311**	.243*	.322**	-.481**	.778**	.226*		-.688**	.270	.163	.020
Stem Diameter	-.099	-.200	-.095	-.095	.081	-.094	-.131	-.210	.381**	-.490**	-.156	-.688**		.426	-.016	.105
SAD	.165	.208	.317	.305	-.111	.358	.081	.224	-.038	.306	-.011	.270	.426		.294	.163

ABG (FW)	.683**	.585**	.661**	.670**	.407**	.327**	.259*	.635**	.488**	.468**	-.081	.163	-.016	.294		.305**
ABG (DW)	.014	-.001	.016	.012	-.014	.010	.001	.102	.251*	.047	-.105	.020	.105	.163	.305**	

Percentage germination (G%); percentage ground cover (C%); Plant height (PH (cm)); stem area density (SAD (mm^2 mm^{-2})); above ground DW or FW biomass (ABG (g)); root length of roots >0.25 mm in diameter (RL (m)); root surface area (RSA); mean root diameter (RDiam (mm))

*Significantly different at <0.05 **Significantly different at <0.01

A.3 ANOVA outputs for summer establishment conditions

Two-way factorial ANOVA output tables (Statistica 13.2 Dell Inc.) for summer establishment condition. Species treatment and rainfall scenario are independent variables and plant traits are dependent variables.

Table A-3: Univariate ANOVA results for % germination

	Degr. of Freedom	SS	MS	F	p
Intercept	1	571328.4	571328.4	2747.172	0.000000
Treatment	6	1758.2	293.0	1.409	0.225249
Rainfall Scenario	2	410.2	205.1	0.986	0.378692
Treatment*Rainfall Scenario	12	3383.4	282.0	1.356	0.211311
Error	63	13102.1	208.0		
Total	83	18653.8			

Table A-4: Univariate ANOVA results for plant height (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	164577.6	164577.6	1260.465	0.000000
Treatment	6	2425.3	404.2	3.096	0.010131
Rainfall Scenario	2	76.4	38.2	0.293	0.747324
Treatment*Rainfall Scenario	12	1050.4	87.5	0.670	0.772858
Error	63	8225.8	130.6		
Total	83	11778.0			

Table A-5: Univariate ANOVA results for % ground cover

	Degr. of Freedom	SS	MS	F	p
Intercept	1	7657.190	7657.190	1218.189	0.000000
Treatment	6	426.476	71.079	11.308	0.000000
Rainfall Scenario	2	237.167	118.583	18.866	0.000000
Treatment*Rainfall Scenario	12	123.667	10.306	1.640	0.103341
Error	63	396.000	6.286		
Total	83	1183.310			

Table A-6: Univariate ANOVA results for number of tillers

	Degr. of Freedom	SS	MS	F	p
Intercept	1	3475.716	3475.716	1170.094	0.000000
Treatment	6	46.442	7.740	2.606	0.025510
Rainfall Scenario	2	89.415	44.708	15.051	0.000005
Treatment*Rainfall Scenario	12	86.066	7.172	2.415	0.012076
Error	63	187.139	2.970		
Total	83	409.062			

Table A-7: Univariate ANOVA results for number of stems

	Degr. of Freedom	SS	MS	F	p
Intercept	1	7907.440	7907.440	3810.086	0.000000
Treatment	6	1659.476	276.579	133.266	0.000000
Rainfall Scenario	2	10.667	5.333	2.570	0.084556
Treatment*Rainfall Scenario	12	18.667	1.556	0.750	0.698154
Error	63	130.750	2.075		
Total	83	1819.560			

Table A-8: Univariate results for stem diameter (mm)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	366.2519	366.2519	2177.123	0.000000
Treatment	6	34.5242	5.7540	34.204	0.000000
Rainfall Scenario	2	6.7164	3.3582	19.962	0.000000
Treatment*Rainfall Scenario	12	9.4291	0.7858	4.671	0.000022
Error	63	10.5983	0.1682		
Total	83	61.2681			

Table A-9: Univariate results for stem area density

	Degr. of Freedom	SS	MS	F	p
Intercept	1	0.005152	0.005152	510.5122	0.000000
Treatment	6	0.000209	0.000035	3.4484	0.005221
Rainfall Scenario	2	0.000379	0.000189	18.7564	0.000000
Treatment*Rainfall Scenario	12	0.000578	0.000048	4.7718	0.000017
Error	63	0.000636	0.000010		
Total	83	0.001801			

Table A-10: Univariate results for AGBM (FW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	1900.383	1900.383	1176.215	0.000000
Treatment	6	32.683	5.447	3.371	0.006033
Rainfall Scenario	2	387.972	193.986	120.065	0.000000
Treatment*Rainfall Scenario	12	197.225	16.435	10.172	0.000000
Error	63	101.788	1.616		
Total	83	719.668			

Table A-11: Univariate ANOVA results for AGBM (DW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	45.37890	45.37890	3205.371	0.000000
Treatment	6	0.34110	0.05685	4.016	0.001815
Rainfall Scenario	2	2.08102	1.04051	73.497	0.000000
Treatment*Rainfall Scenario	12	1.43988	0.11999	8.476	0.000000
Error	63	0.89190	0.01416		
Total	83	4.75390			

Table A-12: Univariate results for BGBM (FW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	8780.617	8780.617	601.1228	0.000000
Treatment	6	136.723	22.787	1.5600	0.173705
Rainfall Scenario	2	1107.436	553.718	37.9076	0.000000
Treatment*Rainfall Scenario	12	1078.002	89.834	6.1500	0.000001
Error	63	920.243	14.607		
Total	83	3242.403			

Table A-13: Univariate results for BGBM (DW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	30.75820	30.75820	147.9333	0.000000
Treatment	6	1.86101	0.31017	1.4918	0.195526
Rainfall Scenario	2	3.64918	1.82459	8.7755	0.000435
Treatment*Rainfall Scenario	12	6.25819	0.52152	2.5083	0.009237
Error	63	13.09892	0.20792		
Total	83	24.86730			

Table A-14: Univariate ANOVA results for total root length (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	12531835	12531835	124.5981	0.000000
Treatment	6	870627	145104	1.4427	0.212693
Rainfall Scenario	2	2645989	1322995	13.1539	0.000017
Treatment*Rainfall Scenario	12	2730751	227563	2.2625	0.018609
Error	63	6336416	100578		

Table A-15: Univariate ANOVA results for total root surface area

	Degr. of Freedom	SS	MS	F	p
Intercept	1	166709.3	166709.3	100.0429	0.000000
Treatment	6	13775.4	2295.9	1.3778	0.237440
Rainfall Scenario	2	35406.2	17703.1	10.6237	0.000106
Treatment*Rainfall Scenario	12	41605.2	3467.1	2.0806	0.031079
Error	63	104981.8	1666.4		
Total	83	195768.6			

Table A-16: Univariate ANOVA results for mean root diameter (mm)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	11.11635	11.11635	157.0972	0.000000
Treatment	6	0.42061	0.07010	0.9907	0.439361
Rainfall Scenario	2	0.00372	0.00186	0.0263	0.974047
Treatment*Rainfall Scenario	12	0.95089	0.07924	1.1198	0.360709
Error	63	4.45794	0.07076		
Total	83	5.83317			

Table A-17: Univariate ANOVA results for length of roots ≤0.25 mm in diameter (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	12663784	12663784	63.39264	0.000000
Treatment	6	713294	118882	0.59510	0.733067
Rainfall Scenario	2	4629241	2314620	11.58658	0.000052
Treatment*Rainfall Scenario	12	5585594	465466	2.33004	0.015362
Error	63	12585348	199767		
Total	83	23513477			

A.4 ANOVA outputs for Autumn establishment conditions

Two-way factorial ANOVA output tables (Statistica 13.2 Dell Inc.) for autumn establishment condition. Species treatment and rainfall scenario are independent variables and plant traits are dependent variables.

Table A-18: Univariate ANVOA results for % germination

	Degr. of Freedom	SS	MS	F	p
Intercept	1	392940.6	392940.6	872.7252	0.000000
Treatment	6	11673.5	1945.6	4.3211	0.001034
Rainfall Scenario	2	172.0	86.0	0.1910	0.826581
Treatment*Rainfall Scenario	12	2877.1	239.8	0.5325	0.885429
Error	63	28365.5	450.2		
Total	83	43088.1			

Table A-19: Univariate ANOVA results for plant height (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	48236.51	48236.51	8508.342	0.000000
Treatment	6	525.58	87.60	15.451	0.000000
Rainfall Scenario	2	5.26	2.63	0.464	0.630951
Treatment*Rainfall Scenario	12	106.37	8.86	1.564	0.125876
Error	63	357.17	5.67		
Total	83	994.38			

Table A-20: Univariate ANOVA results for % ground cover

	Degr. of Freedom	SS	MS	F	p
Intercept	1	6545.503	6545.503	1220.697	0.000000
Treatment	6	526.060	87.677	16.351	0.000000
Rainfall Scenario	2	71.113	35.557	6.631	0.002435
Treatment*Rainfall Scenario	12	61.762	5.147	0.960	0.495686
Error	63	337.813	5.362		
Total	83	996.747			

Table A-21: Univariate ANOVA results for number of tillers

	Degr. of Freedom	SS	MS	F	p
Intercept	1	2345.096	2345.096	2712.573	0.000000
Treatment	6	18.212	3.035	3.511	0.004643
Rainfall Scenario	2	1.104	0.552	0.638	0.531517
Treatment*Rainfall Scenario	12	8.151	0.679	0.786	0.662949
Error	63	54.465	0.865		
Total	83	81.932			

Table A-22: Univariate ANOVA results for number of stems

	Degr. of Freedom	SS	MS	F	p
Intercept	1	7695.429	7695.429	2376.529	0.000000
Treatment	6	1844.905	307.484	94.958	0.000000
Rainfall Scenario	2	2.571	1.286	0.397	0.673965
Treatment*Rainfall Scenario	12	39.095	3.258	1.006	0.454165
Error	63	204.000	3.238		
Total	83	2090.571			

Table A-23: Univariate results for stem diameter (mm)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	153.4637	153.4637	1419.689	0.000000
Treatment	6	7.5743	1.2624	11.678	0.000000
Rainfall Scenario	2	0.3300	0.1650	1.527	0.225222
Treatment*Rainfall Scenario	12	1.0040	0.0837	0.774	0.674336
Error	63	6.8101	0.1081		
Total	83	15.7184			

Table A-24: Univariate ANOVA results for stem area density

	Degr. of Freedom	SS	MS	F	p
Intercept	1	0.000874	0.000874	261.0974	0.000000
Treatment	6	0.000025	0.000004	1.2242	0.305950
Rainfall Scenario	2	0.000004	0.000002	0.6225	0.539851
Treatment*Rainfall Scenario	12	0.000032	0.000003	0.8000	0.648957
Error	63	0.000211	0.000003		
Total	83	0.000272			

Table A-25: Univariate ANOVA results for AGBM (FW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	426.6011	426.6011	1032.496	0.000000
Treatment	6	8.8974	1.4829	3.589	0.004013
Rainfall Scenario	2	3.5396	1.7698	4.283	0.018022
Treatment*Rainfall Scenario	12	3.3707	0.2809	0.680	0.764208
Error	63	26.0300	0.4132		
Total	83	41.8377			

Table A-26: Univariate ANOVA results for AGBM (DW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	7.826305	7.826305	88.67537	0.000000
Treatment	6	0.598629	0.099771	1.13045	0.355175
Rainfall Scenario	2	0.181460	0.090730	1.02801	0.363641
Treatment*Rainfall Scenario	12	0.952357	0.079363	0.89922	0.552484
Error	63	5.560250	0.088258		
Total	83	7.292695			

Table A-27: Univariate results for BGBM (FW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	1900.383	1900.383	208.5784	0.000000
Treatment	6	20.743	3.457	0.3795	0.889452
Rainfall Scenario	2	26.521	13.261	1.4554	0.241038
Treatment*Rainfall Scenario	12	98.403	8.200	0.9000	0.551714
Error	63	574.001	9.111		
Total	83	719.668			

Table A-28: Univariate ANOVA results for BGBM (DW)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	0.763811	0.763811	631.2899	0.000000
Treatment	6	0.037531	0.006255	5.1699	0.000224
Rainfall Scenario	2	0.042064	0.021032	17.3831	0.000001
Treatment*Rainfall Scenario	12	0.019469	0.001622	1.3409	0.218930
Error	63	0.076225	0.001210		
Total	83	0.175289			

Table A-29: Univariate ANOVA results for total root length (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	237109917	237109917	409.5423	0.000000
Treatment	6	9693928	1615655	2.7906	0.018011
Rainfall Scenario	2	36268847	18134423	31.3222	0.000000
Treatment*Rainfall Scenario	12	7517729	626477	1.0821	0.390288
Error	63	36474683	578963		
Total	83	89955186			

Table A-30: Univariate ANOVA results for total root surface area

	Degr. of Freedom	SS	MS	F	p
Intercept	1	166709.3	166709.3	100.0429	0.000000
Treatment	6	13775.4	2295.9	1.3778	0.237440
Rainfall Scenario	2	35406.2	17703.1	10.6237	0.000106
Treatment*Rainfall Scenario	12	41605.2	3467.1	2.0806	0.031079
Error	63	104981.8	1666.4		
Total	83	195768.6			

Table A-31: Univariate ANOVA results for mean root diameter (mm)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	11.11635	11.11635	157.0972	0.000000
Treatment	6	0.42061	0.07010	0.9907	0.439361
Rainfall Scenario	2	0.00372	0.00186	0.0263	0.974047
Treatment*Rainfall Scenario	12	0.95089	0.07924	1.1198	0.360709
Error	63	4.45794	0.07076		
Total	83	5.83317			

Table A-32: Univariate ANOVA results for length of roots ≤0.25 mm in diameter (m)

	Degr. of Freedom	SS	MS	F	p
Intercept	1	12663784	12663784	63.39264	0.000000
Treatment	6	713294	118882	0.59510	0.733067
Rainfall Scenario	2	4629241	2314620	11.58658	0.000052
Treatment*Rainfall Scenario	12	5585594	465466	2.33004	0.015362
Error	63	12585348	199767		
Total	83	23513477			

Appendix B Grass species selection to control concentrated flow erosion in grassed waterways

B.1 Plant Trait Analysis

All data was transformed using log (10) to ensure it was normally distributed. All data was subject to a one-way ANOVA and if found to be statistically different P<0.05 a follow up Fisher-LSD *post-hoc* test was used.

Table B-33: AGBM (FW), AGBM (DW), and % Germination ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition												
Effect	Degr. of Freedom	AGBM Log10 SS	AGBM Log10 MS	AGBM Log10 F	AGBM Log10 p	AGBM (DW) (g) log10 SS	AGBM (DW) (g) log10 MS	AGBM (DW) (g) log10 F	AGBM (DW) (g) log10 p	% Germination log 10 SS	% Germination log 10 MS	% Germination log 10 F	% Germination log 10 p
Intercept	1	76.01768	76.01768	5371.302	0.000000	22.56169	22.56169	1527.208	0.000000	102.5378	102.5378	3.445301E+20	0.00
Code	3	0.01493	0.00498	0.352	0.788221	0.31933	0.10644	7.205	0.000990	0.1001	0.0334	1.120896E+17	0.00
Error	28	0.39627	0.01415			0.41365	0.01477			0.0000	0.0000		
Total	31	0.41120				0.73298				0.1001			

Table B-34: AGBM DW *Post-hoc*

Cell No.	LSD test; variable AGBM (DW) (g) log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .01477, df = 28.000				
	Code	AGBM (DW) (g) log10 Mean	1	2	3
4	Conv	0.692285	****		
1	Fest_1+2	0.815372	****	****	
2	Fest_1	0.887680		****	****
3	Fest_1+2+Conv	0.963359			****

Table B-35: Number of Tillers, Number of Stems and Av Stem Diameter ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition												
	Degr. of Fredom	Number of tillers per plant log10 SS	Number of tillers per plant log10 MS	Number of tillers per plant log10 F	Number of tillers per plant log10 p	Number of stems log 10 SS	Number of stems log 10 MS	Number of stems log 10 F	Number of stems log 10 p	Av Stem Diameterlog10 SS	Av Stem Diameterlog10 MS	Av Stem Diameterlog10 F	Av Stem Diameterlog10 p
Intercept	1	7.830698	7.830698	1959.244	0.000000	149.2788	149.2788	48709.82	0.000000	0.506936	0.506936	134.1304	0.000000
Code	3	0.179370	0.059790	14.959	0.000005	0.2268	0.0756	24.67	0.000000	0.089176	0.029725	7.8650	0.000585
Error	28	0.111910	0.003997			0.0858	0.0031			0.105824	0.003779		
Total	31	0.291280				0.3126				0.195000			

Table B-36: Number of Tillers per plant *post-hoc*

Cell No.	LSD test; variable Number of tillers per plant log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00400, df = 28.000			
	Code	Number of tillers per plant log10 Mean	1	2
1	Fest_1+2	0.445761	****	
3	Fest_1+2+Conv	0.452155	****	
2	Fest_1	0.456623	****	
4	Conv	0.624185		****

Table B-37: Number of Stems *post-hoc*

Cell No.	LSD test; variable Number of stems log 10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00306, df = 28.000				
	Code	Number of stems log 10 Mean	1	2	3
3	Fest_1+2+Conv	2.051553		****	
1	Fest_1+2	2.137508	****		
2	Fest_1	2.163579	****		
4	Conv	2.286768			****

Table B-38: Average Stem Diameter *post-hoc*

Cell No.	LSD test; variable Av Stem Diameterlog10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00378, df = 28.000				
	Code	Av Stem Diameterlog10 Mean	1	2	3
4	Conv	0.046927		****	
1	Fest_1+2	0.128735	****		
3	Fest_1+2+Conv	0.132159	****		
2	Fest_1	0.195635			****

Table B-39: Stem Area Density, Total Root length, Total Root Length <= 0.25 cm diameter ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition												
	Degr. of Freedom	Stem Area Density log10 SS	Stem Area Density log10 MS	Stem Area Density log10 F	Stem Area Density log10 p	Total Root Length (cm) log10 SS	Total Root Length (cm) log10 MS	Total Root Length (cm) log10 F	Total Root Length (cm) log10 p	Total Root Length less than or equal to 0.25cm in diameter (cm) log10 SS	Total Root Length less than or equal to 0.25cm in diameter (cm) log10 MS	Total Root Length less than or equal to 0.25cm in diameter (cm) log10 F	Total Root Length less than or equal to 0.25cm in diameter (cm) log10 p
Intercept	1	147.4104	147.4104	16904.27	0.000000	200.9358	200.9358	33885.78	0.000000	163.0976	163.0976	15773.51	0.000000
Code	3	0.6027	0.2009	23.04	0.000000	0.0235	0.0078	1.32	0.286565	0.0712	0.0237	2.30	0.099424
Error	28	0.2442	0.0087			0.1660	0.0059			0.2895	0.0103		
Total	31	0.8468				0.1896				0.3607			

Table B-40: Stem Area Density *post-hoc*

Cell No.	LSD test; variable Stem Area Density log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00872, df = 28.000				
	Code	Stem Area Density log10 Mean	1	2	3
4	Conv	1.936250		****	
3	Fest_1+2+Conv	2.160461	****		
1	Fest_1+2	2.167318	****		
2	Fest_1	2.321146			****

Table B-41: Total Surface Area, Root Fresh Weight, and Root Dry Weight ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition												
	Degr. of Freedom	Total Surface Area log10 SS	Total Surface Area log10 MS	Total Surface Area log10 F	Total Surface Area log10 p	Average total root fresh weight log10 SS	Average total root fresh weight log10 MS	Average total root fresh weight log10 F	Average total root fresh weight log10 p	Average Root dry weight log10 SS	Average Root dry weight log10 MS	Average Root dry weight log10 F	Average Root dry weight log10 p
Intercept	1	71.56267	71.56267	9832.644	0.000000	2.262868	2.262868	70.81393	0.000000	33.25975	33.25975	370.1287	0.000000
Code	3	0.04289	0.01430	1.964	0.142205	0.475152	0.158384	4.95645	0.006954	0.74350	0.24783	2.7580	0.060890
Error	28	0.20379	0.00728			0.894744	0.031955			2.51608	0.08986		
Total	31	0.24668				1.369896				3.25958			

Table B-42: Root Fresh Weight *post-hoc*

Cell No.	LSD test; variable Average total root fresh weight log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .03196, df = 28.000			
	Code	Average total root fresh weight log10 Mean	1	2
3	Fest_1+2+Conv	0.109878	****	
2	Fest_1	0.184270	****	
1	Fest_1+2	0.376792		****
4	Conv	0.392749		****

Table B-43: Plant Height and Root Diameter ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition								
	Degr. of Freedom	Av Plant Height log10 SS	Av Plant Height log10 MS	Av Plant Height log10 F	Av Plant Height log10 p	Average Root Diameter log10 SS	Average Root Diameter log10 MS	Average Root Diameter log10 F	Average Root Diameter log10 p
Intercept	1	68.51868	68.51868	24142.19	0.000000	5.618794	5.618794	1250.844	0.000000
Code	3	0.34436	0.11479	40.44	0.000000	0.027723	0.009241	2.057	0.130466
Error	26	0.07379	0.00284			0.116792	0.004492		
Total	29	0.41815				0.144515			

Table B-44: Plant Height *post-hoc*

Cell No.	LSD test; variable Av Plant Height log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00284, df = 26.000				
	Code	Av Plant Height log10 Mean	1	2	3
4	Conv	1.328816			****
1	Fest_1+2	1.538772	****		
2	Fest_1	1.593915	****	****	
3	Fest_1+2+Conv	1.597080		****	

B.2 Shear Stress Analysis

Table B-45: Shear Stress at 1.0 cm ANOVA at 0.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.2 SS	log 10 m 0.2 MS	log 10 m 0.2 F	log 10 m 0.2 p
Intercept	1	12.89412	12.89412	41.51792	0.000032
A	3	0.36628	0.12209	0.39313	0.760230
Error	12	3.72681	0.31057		
Total	15	4.09309			

Table B-46: Shear Stress at 3.0 cm ANOVA at 0.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.2 SS	log 10 m 0.2 MS	log 10 m 0.2 F	log 10 m 0.2 p
Intercept	1	18.60312	18.60312	80.64998	0.000001
A	3	1.53132	0.51044	2.21291	0.139309
Error	12	2.76798	0.23066		
Total	15	4.29930			

Table B-47: Shear Stress for 3.0 cm at 0.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.3 SS	log 10 m 0.3 MS	log 10 m 0.3 F	log 10 m 0.3 p

Intercept	1	17.20473	17.20473	156.9933	0.000000
A	3	0.57533	0.19178	1.7500	0.210096
Error	12	1.31507	0.10959		
Total	15	1.89040			

Table B-48: Shear Stress for 1.0 cm at 0.4 l s^{-1}

	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition

Effect	Degr. of Freedom	log 10 m 0.4 SS	log 10 m 0.4 MS	log 10 m 0.4 F	log 10 m 0.4 p
Intercept	1	5.595733	5.595733	26.87576	0.000228
A	3	0.531588	0.177196	0.85106	0.492423
Error	12	2.498490	0.208207		
Total	15	3.030078			

Table B-49: Shear Stress for 3.0 cm at 0.4 $l\ s^{-1}$

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.4 SS	log 10 m 0.4 MS	log 10 m 0.4 F	log 10 m 0.4 p
Intercept	1	15.00875	15.00875	226.4436	0.000000
A	3	0.40934	0.13645	2.0587	0.159364
Error	12	0.79536	0.06628		
Total	15	1.20471			

Table B-50: Shear Stress for 0.5 l s^{-1} inflow rate for 3.0 cm

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.5 SS	log 10 m 0.5 MS	log 10 m 0.5 F	log 10 m 0.5 p
Intercept	1	14.90197	14.90197	1032.015	0.000000
A	3	0.13532	0.04511	3.124	0.066054
Error	12	0.17328	0.01444		
Total	15	0.30860			

Table B-51: Shear Stress for 1.0 cm at 0.6 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.6 SS	log 10 m 0.6 MS	log 10 m 0.6 F	log 10 m 0.6 p
Intercept	1	3.273026	3.273026	15.90235	0.001801
A	3	0.717068	0.239023	1.16132	0.364801
Error	12	2.469844	0.205820		
Total	15	3.186912			

Table B-52: Shear Stress for 3.0 cm at 0.6 l s^{-1}

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.6 SS	log 10 m 0.6 MS	log 10 m 0.6 F	log 10 m 0.6 p
Intercept	1	12.85720	12.85720	823.5991	0.000000
A	3	0.18897	0.06299	4.0349	0.033753
Error	12	0.18733	0.01561		
Total	15	0.37630			

Table B-54: Shear Stress for 3.0 cm at 0.6 l s^{-1} post hoc

Cell No.	LSD test; variable log 10 m 0.6 (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Homogenous Groups, alpha = .05000 Error: Between MS = .01561, df = 12.000			
	A	log 10 m 0.6 Mean	1	2
1	Conv-3cm	-0.979779	****	
3	Fest_1+2-3cm	-0.964043	****	
2	Fest_1+2+Conv-3cm	-0.931220	****	
4	Fest_1-3cm	-0.710653		****

Table B-53: Shear Stress for 3.0 cm at 0.7 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.7 SS	log 10 m 0.7 MS	log 10 m 0.7 F	log 10 m 0.7 p
Intercept	1	11.57584	11.57584	518.6432	0.000000
A	3	0.26187	0.08729	3.9110	0.036834
Error	12	0.26783	0.02232		
Total	15	0.52971			

Table B-54: Shear Stress for 3.0 at 0.7 l s^{-1} post hoc

Cell No.	LSD test; variable log 10 m 0.7 (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Homogenous Groups, alpha = .05000 Error: Between MS = .02232, df = 12.000			
	A	log 10 m 0.7 Mean	1	2
1	Conv-3cm	-0.949347	****	
3	Fest_1+2-3cm	-0.927360	****	
2	Fest_1+2+Conv-3cm	-0.893981	****	
4	Fest_1-3cm	-0.631640		****

Table B-54: Shear Stress for 1.0 cm at 0.8 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.8 SS	log 10 m 0.8 MS	log 10 m 0.8 F	log 10 m 0.8 p
Intercept	1	2.146931	2.146931	19.65392	0.000816
A	3	0.395010	0.131670	1.20536	0.349711
Error	12	1.310841	0.109237		
Total	15	1.705851			

Table B-55: Shear Stress for 3.0 cm at 0.8 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 0.8 SS	log 10 m 0.8 MS	log 10 m 0.8 F	log 10 m 0.8 p
Intercept	1	5.398373	5.398373	730.8433	0.000000
A	3	0.007944	0.002648	0.3585	0.785465
Error	6	0.044319	0.007386		
Total	9	0.052263			

Table B-56: Shear Stress for 1.0 cm at 1 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 1 SS	log 10 m 1 MS	log 10 m 1 F	log 10 m 1 p
Intercept	1	0.960988	0.960988	7.004795	0.021310
A	3	0.536874	0.178958	1.304454	0.318158
Error	12	1.646280	0.137190		
Total	15	2.183154			

Table B-57: Shear Stress for 1.0 cm at 1.2 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 1.2 SS	log 10 m 1.2 MS	log 10 m 1.2 F	log 10 m 1.2 p
Intercept	1	0.729635	0.729635	17.19049	0.001992
A	3	0.092778	0.030926	0.72863	0.557955

Error	10	0.424441	0.042444		
Total	13	0.517219			

Table B-58: Shear Stress for 1.0 cm at 1.4 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Water Depth Data (Different Shear Stress Equations) (version 1)) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	log 10 m 1.4 SS	log 10 m 1.4 MS	log 10 m 1.4 F	log 10 m 1.4 p
Intercept	1	0.181768	0.181768	4.543990	0.077032
A	1	0.008645	0.008645	0.216106	0.658415
Error	6	0.240012	0.040002		
Total	7	0.248656			

B.3 Sediment Concentration Analysis

Table B-59: Sediment Concentration for 1.0 cm at a 0.2 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.2 log10 SS	Sediment Concentration 0.2 log10 MS	Sediment Concentration 0.2 log10 F	Sediment Concentration 0.2 log10 p
Intercept	1	0.999421	0.999421	285.3433	0.000000
Treatment	3	0.009529	0.003176	0.9068	0.466489
Error	12	0.042030	0.003503		
Total	15	0.051559			

Table B-60: Sediment Concentration for 3.0 cm at a 0.2 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.2 log10 SS	Sediment Concentration 0.2 log10 MS	Sediment Concentration 0.2 log10 F	Sediment Concentration 0.2 log10 p
Intercept	1	0.824617	0.824617	2479.285	0.000000
Treatment	3	0.000541	0.000180	0.542	0.663259
Error	11	0.003659	0.000333		
Total	14	0.004200			

Table B-61: Sediment Concentration for 3.0 cm at a 0.3 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	Sediment Concentration 0.3 log 10 SS	Sediment Concentration 0.3 log 10 MS	Sediment Concentration 0.3 log 10 F	Sediment Concentration 0.3 log 10 p
Intercept	1	0.811196	0.811196	5375.013	0.000000
Treatment	3	0.000186	0.000062	0.411	0.748112
Error	12	0.001811	0.000151		
Total	15	0.001997			

Table B-62: Sediment Concentration for 1.0 cm at a 0.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	Sediment Concentration 0.4 log10 SS	Sediment Concentration 0.4 log10 MS	Sediment Concentration 0.4 log10 F	Sediment Concentration 0.4 log10 p
Intercept	1	0.930043	0.930043	2652.999	0.000000
Treatment	3	0.002000	0.000667	1.902	0.183154
Error	12	0.004207	0.000351		
Total	15	0.006207			

Table B-63: Sediment Concentration for 3.0 cm at a 0.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	Sediment Concentration 0.4 log10 SS	Sediment Concentration 0.4 log10 MS	Sediment Concentration 0.4 log10 F	Sediment Concentration 0.4 log10 p
Intercept	1	0.740647	0.740647	11067.28	0.000000
Treatment	3	0.000157	0.000052	0.78	0.527961
Error	11	0.000736	0.000067		
Total	14	0.000893			

Table B-64: Sediment Concentration for 1.0 cm at a 0.5 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	Sediment Concentration 0.5 log10 SS	Sediment Concentration 0.5 log10 MS	Sediment Concentration 0.5 log10 F	Sediment Concentration 0.5 log10 p
Intercept	1	0.800737	0.800737	5265.089	0.000000
Treatment	3	0.000166	0.000055	0.364	0.780060
Error	12	0.001825	0.000152		
Total	15	0.001991			

Table B-65: Sediment Concentration for 1.0 cm at a 0.6 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.6 log10 SS	Sediment Concentration 0.6 log10 MS	Sediment Concentration 0.6 log10 F	Sediment Concentration 0.6 log10 p
Intercept	1	0.877214	0.877214	4365.548	0.000000
Treatment	3	0.000730	0.000243	1.212	0.347568
Error	12	0.002411	0.000201		
Total	15	0.003142			

Table B-66: Sediment Concentration for 3.0 cm at a 0.6 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.6 log10 SS	Sediment Concentration 0.6 log10 MS	Sediment Concentration 0.6 log10 F	Sediment Concentration 0.6 log10 p
Intercept	1	0.677586	0.677586	11406.09	0.000000
Treatment	3	0.000168	0.000056	0.94	0.455410
Error	10	0.000594	0.000059		
Total	13	0.000762			

Table B-67: Sediment Concentration for 3.0 cm at a 0.7 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.7 log10 SS	Sediment Concentration 0.7 log10 MS	Sediment Concentration 0.7 log10 F	Sediment Concentration 0.7 log10 p
Intercept	1	0.767030	0.767030	15509.04	0.000000
Treatment	3	0.000022	0.000007	0.15	0.927740
Error	12	0.000593	0.000049		
Total	15	0.000616			

Table B-68: Sediment Concentration for 1.0 cm at a 0.8 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.8 log10 SS	Sediment Concentration 0.8 log10 MS	Sediment Concentration 0.8 log10 F	Sediment Concentration 0.8 log10 p
Intercept	1	0.825555	0.825555	6036.429	0.000000
Treatment	3	0.000995	0.000332	2.425	0.116289
Error	12	0.001641	0.000137		
Total	15	0.002636			:

Table B-69: Sediment Concentration for 3.0 cm at a 0.8 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 0.8 log10 SS	Sediment Concentration 0.8 log10 MS	Sediment Concentration 0.8 log10 F	Sediment Concentration 0.8 log10 p
Intercept	1	0.639640	0.639640	6229.948	0.000000
Treatment	3	0.000218	0.000073	0.709	0.568407
Error	10	0.001027	0.000103		
Total	13	0.001245			

Table B-70: Sediment Concentration for 3.0 cm at a 1.0 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 1 log10 SS	Sediment Concentration 1 log10 MS	Sediment Concentration 1 log10 F	Sediment Concentration 1 log10 p
Intercept	1	0.845891	0.845891	5899.527	0.000000
Treatment	3	0.000383	0.000128	0.890	0.474265
Error	12	0.001721	0.000143		
Total	15	0.002103			

Table B-71: Sediment Concentration for 3.0 cm at a 1.2 l s^{-1} inflow rate ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition

Effect	Degr. of Freedom	Sediment Concentration 1.2 log10 SS	Sediment Concentration 1.2 log10 MS	Sediment Concentration 1.2 log10 F	Sediment Concentration 1.2 log10 p
Intercept	1	0.821930	0.821930	3457.126	0.000000
Treatment	3	0.000474	0.000158	0.664	0.589958
Error	12	0.002853	0.000238		
Total	15	0.003327			

Table B-72: Sediment Concentration for 3.0 cm at a 1.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Sediment Concentration 1.4 log10 SS	Sediment Concentration 1.4 log10 MS	Sediment Concentration 1.4 log10 F	Sediment Concentration 1.4 log10 p
Intercept	1	0.495079	0.495079	10579.73	0.000000
Treatment	2	0.000385	0.000192	4.11	0.065944
Error	7	0.000328	0.000047		
Total	9	0.000712			

B.4 Flow Velocity Analysis

Table B-73: Flow Velocity for 1.0 cm at 0.2 l s^{-1} ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 SS	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 MS	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 F	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 p
Intercept	1	8.484867	8.484867	803.3074	0.000000
Treatment	3	0.038008	0.012669	1.1995	0.359316
Error	10	0.105624	0.010562		

Total	13	0.143632			

Table B-74: Flow Velocity for 3.0 cm at 0.2 l s^{-1} ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	Degr. of Freedom	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 SS	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 MS	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 F	Flow Velocity 0.2 l s^{-1} MS (m s-1) log10 p
Intercept	1	10.25247	10.25247	554.4856	0.000000
Treatment	3	0.00637	0.00212	0.1149	0.949360
Error	10	0.18490	0.01849		
Total	13	0.19127			

Table B-75: Flow Velocity for 3.0 cm at a 0.3 l s^{-1} inflow rate ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	Degr. of Freedom	Flow Velocity 0.3 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.3 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.3 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.3 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	9.400907	9.400907	539.1785	0.000000
Treatment	3	0.031116	0.010372	0.5949	0.631311
Error	11	0.191792	0.017436		
Total	14	0.222908			

Table B-76: Flow Velocity for 1.0 cm at a 0.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	4.095402	4.095402	318.6087	0.000000
Treatment	3	0.012215	0.004072	0.3168	0.813089
Error	11	0.141394	0.012854		
Total	14	0.153609			

Table B-77: Flow Velocity for 3.0 cm at a 0.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.4 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.4 l s-1 MS (m $s^{-1)}$ log10 p
Intercept	1	7.337023	7.337023	1813.248	0.000000
Treatment	3	0.006235	0.002078	0.514	0.682992
Error	9	0.036417	0.004046		
Total	12	0.042652			

Table B-78: Flow Velocity for 3.0 cm at a 0.5 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.5 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.5 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.5 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.5 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	7.945011	7.945011	1237.996	0.000000
Treatment	3	0.060142	0.020047	3.124	0.066054
Error	12	0.077012	0.006418		
Total	15	0.137154			

Table B-79: Flow Velocity for 1.0 cm at a 0.6 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.6 l s^{-1} MS log10 SS	Flow Velocity 0.6 l s^{-1} MS log10 MS	Flow Velocity 0.6 l s^{-1} MS log10 F	Flow Velocity 0.6 l s^{-1} MS log10 p
Intercept	1	2.877289	2.877289	2302.331	0.000000
Treatment	3	0.022902	0.007634	6.109	0.012465
Error	10	0.012497	0.001250		
Total	13	0.035399			

Table B-80: Flow Velocity for 1.0 cm at a 0.6 l s^{-1} inflow rate LSD *post-hoc*

	LSD test; variable Flow Velocity 0.6 l s^{-1} MS log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00125, df = 10.000

Cell No.	Treatment	Flow Velocity 0.6 l s^{-1} MS log10 Mean	1	2
3	Fest_1+2-1cm	-0.511503	****	
2	Fest_1+2+Conv-1cm	-0.485435	****	
1	Conv-1cm	-0.427521		****
4	Fest_1-1cm	-0.407707		****

Table B-81: Flow Velocity for 3.0 cm at a 0.6 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.6 l s^{-1} MS log10 SS	Flow Velocity 0.6 l s^{-1} MS log10 MS	Flow Velocity 0.6 l s^{-1} MS log10 F	Flow Velocity 0.6 l s^{-1} MS log10 p
Intercept	1	5.995504	5.995504	1558.648	0.000000
Treatment	3	0.009021	0.003007	0.782	0.530754
Error	10	0.038466	0.003847		
Total	13	0.047487			

Table B-82: Flow Velocity for 3.0 cm at a 0.7 l s^{-1} inflow rate ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition

Effect	Degr. of Freedom	Flow Velocity 0.7 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.7 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.7 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.7 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	5.599871	5.599871	1684.434	0.000000
Treatment	3	0.009409	0.003136	0.943	0.455848
Error	10	0.033245	0.003324		
Total	13	0.042654			

Table B-83: Flow Velocity for 1.0 cm at a 0.8 l s^{-1} inflow rate ANOVA

	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	Degr. of Freedom	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	1.932508	1.932508	1098.533	0.000000
Treatment	3	0.019628	0.006543	3.719	0.049641
Error	10	0.017592	0.001759		
Total	13	0.037220			

Table B-84: Flow Velocity for 1.0 cm at a 0.8 l s^{-1} inflow rate Fisher LSD *post-hoc*

Cell No.	LSD test; variable Flow Velocity 0.8 l s^{-1} MS (m s-1) log10 (Ex 2 Middle of sample log10 analysis) Homogenous Groups, alpha = .05000 Error: Between MS = .00176, df = 10.000			
	Treatment	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 Mean	1	2
2	Fest_1+2+Conv-1cm	-0.413440	****	
3	Fest_1+2-1cm	-0.412428	****	
1	Conv-1cm	-0.340552		****
4	Fest_1-1cm	-0.335110		****

Table B-85: Flow Velocity for 3.0 cm at a 0.8 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 0.8 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	2.954295	2.954295	899.9071	0.000000
Treatment	3	0.003531	0.001177	0.3585	0.785465
Error	6	0.019697	0.003283		
Total	9	0.023228			

Table B-86: Flow Velocity for 1.0 cm at a 1.0 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 1 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 1 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 1 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 1 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	1.240143	1.240143	411.6032	0.000000
Treatment	3	0.020058	0.006686	2.2191	0.148725
Error	10	0.030130	0.003013		
Total	13	0.050188			

Table B-87: Flow Velocity for 1.0 cm at a 1.2 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	Flow Velocity 1.2 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 1.2 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 1.2 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 1.2 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	0.783700	0.783700	207.7863	0.000001
Treatment	3	0.009551	0.003184	0.8441	0.507253
Error	8	0.030173	0.003772		
Total	11	0.039724			

Table B-88: Flow velocity for 1.0 cm at a 1.4 l s^{-1} inflow rate ANOVA

Effect	Univariate Results for Each DV (Ex 2 Middle of sample log10 analysis) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	Flow Velocity 1.4 l s^{-1} MS (m s^{-1}) log10 SS	Flow Velocity 1.4 l s^{-1} MS (m s^{-1}) log10 MS	Flow Velocity 1.4 l s^{-1} MS (m s^{-1}) log10 F	Flow Velocity 1.4 l s^{-1} MS (m s^{-1}) log10 p
Intercept	1	0.331514	0.331514	21.72723	0.002311
Treatment	2	0.016929	0.008464	0.55475	0.597535
Error	7	0.106806	0.015258		
Total	9	0.123735			

Table B-91: Spearmans rank correlations for plant traits and shear stress

Variable	Spearman Rank Order Correlations (Statistica input plant traits) MD pairwise deleted Marked correlations are significant at p <.05000 M 0.2	M 0.3	M 0.4	M 0.5	M 0.6	M 0.7	M 0.8	M 1	M 1.2	M 1.4
AGBM (FW) (g)	0.222548	-0.462068	0.305380	-0.477742	0.394831	-0.459717	0.538620	0.547488	0.554738	0.589831
AGBM (DW) (g)	0.103218	-0.195640	0.202200	-0.170169	0.215765	-0.154298	0.296737	0.246975	0.333237	0.489061
% Germination	-0.246743	-0.038827	-0.175580	0.000000	-0.178608	-0.029120	-0.019741	-0.080890	0.020029	0.268899
% Ground cover	0.334541	0.103539	0.296670	0.103539	0.366297	0.126188	0.095666	0.139130	0.133526	0.121557
Number of tillers per plant	0.098495	0.067948	-0.015496	0.062959	-0.030619	0.076129	-0.092435	-0.035620	-0.046529	-0.402450
Number of stems	0.226785	-0.132647	0.123190	-0.162429	0.199633	-0.145579	0.138575	0.232182	0.230648	0.093463
Total Root Length (cm)	-0.113484	0.220426	-0.151787	0.227480	-0.172319	0.202008	-0.240001	-0.227284	-0.302814	-0.049966
Total Root Length less than or equal to 0.25cm in diameter (cm)	-0.022184	0.152633	-0.025665	0.161254	-0.027864	0.129513	-0.153012	-0.120695	-0.181931	0.073164
Total Surface Area	-0.371986	0.161254	-0.459762	0.134215	-0.437030	0.111878	-0.308231	-0.309184	-0.358202	-0.133390
Average Root Diameter	-0.289302	-0.070536	-0.347204	-0.096400	-0.283776	-0.088562	-0.132966	-0.118148	-0.112797	-0.186033

B.5 Soil Moisture Data

Table B-89: Soil moisture content (Volumetric %) of macrocosms for each depth (200, 300 or 400 mm) and date the readings were taken (T2-T8).

	Soil Moisture Content (Volumetric %)																				
Species Treatme nt	**200 mm (T2)**	**300 mm (T2)**	**400 mm (T2)**	**200 mm (T3)**	**300 mm (T3)**	**400 mm (T3)**	**200 mm (T4)**	**300 mm (T4)**	**400 mm (T4)**	**200 mm (T5)**	**300 mm (T5)**	**400 mm (T5)**	**200 mm (T6)**	**300 mm (T6)**	**400 mm (T6)**	**200 mm (T7)**	**300 mm (T7)**	**400 mm (T7)**	**200 mm (T8)**	**300 mm (T8)**	**400 mm (T8)**
Conv	7.1	6.3	15.3	7.1	6.0	14.1	7.9	5.1	13.1	7.4	3.9	11.9	7.0	4.0	11.4	6.8	3.6	10.9	6.4	3.2	10.1
Conv	7.0	5.2	14.9	6.4	4.9	13.7	7.9	5.6	13.3	8.3	4.9	11.4	7.3	4.3	11.3	7.1	4.2	10.3	6.9	4.0	9.5
Conv	7.3	6.8	14.9	7.0	5.5	13.6	7.4	4.2	13.5	8.3	5.2	11.4	7.9	4.8	10.8	6.9	4.4	10.8	6.8	4.2	9.5

Fest_1	9.4	12.3	20.1	11.8	10.0	17.2	11.5	18.6	22.0	12.3	18.0	20.8	10.6	17.8	22.4	10.2	17.0	21.8	9.9	16.8	20.9
Fest_1	10.9	12.1	17.8	11.1	11.5	17.2	12.8	18.2	20.7	11.1	18.2	22.7	10.6	18.2	21.4	10.2	17.5	20.5	9.2	17.1	21.1
Fest_1	10.1	12.1	18.7	10.4	10.9	19.7	12.0	18.2	22.2	11.9	18.1	20.5	11.5	17.5	20.3	11.0	17.0	20.2	10.3	16.7	19.7
Fest_1+2	13.3	13.6	19.5	11.8	12.5	17.6	13.7	11.0	14.1	12.9	12.1	13.8	11.9	12.1	15.7	10.6	10.8	15.0	9.2	9.7	13.7
Fest_1+2	15.0	12.8	17.7	13.5	11.9	16.3	12.6	12.7	16.4	14.4	10.4	14.3	12.1	10.9	15.3	12.0	9.6	13.0	10.4	8.7	12.2
Fest_1+2	15.0	14.1	17.4	13.8	11.5	14.4	12.8	11.3	16.0	14.1	11.1	13.7	12.6	11.2	13.7	11.3	11.2	13.8	9.9	9.8	12.4
Fest_1+2 +Conv	12.5	19.6	23.0	11.6	18.1	21.1	13.1	10.4	16.4	13.9	11.8	17.0	11.7	11.9	19.5	13.1	10.6	16.4	12.9	1.1	18.5
Fest_1+2 +Conv	11.7	20.0	23.7	10.7	18.4	23.1	11.3	11.6	18.9	12.9	11.2	19.4	13.4	10.4	17.2	11.5	11.9	17.9	13.6	11.2	16.7
Fest_1+2 +Conv	12.3	20.2	22	11.3	18.4	20.9	11.3	11.7	18.9	14.8	10.6	16.4	13.0	11.6	16.8	11.8	10.7	18.8	12.0	12.6	18.5
Bare Soil	12.0	22.0	21.4	12.8	20.1	21.6	12.4	20.1	21.2	12.0	18.9	21.7	12.7	19.5	21.1	12.6	19.5	21.0	13.9	20.8	21.5
Bare Soil	12.3	21.8	20.9	12.0	19.2	21.9	12.9	19.5	21	12.1	20	20.0	11.8	19.5	21.5	11.8	18.6	21.6	14.1	19.9	21.3
Bare Soil	13.0	20.5	21.5	12.6	20.5	21.5	12.1	18.9	21.6	13	19.9	19.9	12.8	19.7	21.1	12.0	19.8	20.8	13.1	20.1	21.8
Bare Soil		2.6			3.4		10.2	4.6	5.9	9.1	5.3	7.0	7.1	4.3	7.9	8.5	4.4	2.3	9.4	4.9	9.1
Bare Soil		3.2			3.5		9.1	3.9	6.1	9.6	4.3	6.9	5.9	4.3	8.2	7.0	4.0	8.5	9.0	5.0	8.9

Bare Soil		3.1			2.9		8.1	3.7	6.8	7.7	4.3	7.9	7.3	4.3	7.8	6.5	4.1	8.3	9.4	4.5	8.7

T2 - 03/07/2019, T3 - 08/07/2019, T4 – 11/07/2019, T5 – 15/07/2019, T6 – 17/07/2019, T7 – 19/07/2019, T8 – 22/07/2019.

Table B-90: Soil moisture content (Volumetric %) of macrocosms for each depth (200, 300 or 400 mm) and date the readings were taken (T9-T16).

	Soil Moisture Content (Volumetric %)																				
Treatment	200 mm (T9)	300 mm (T9)	400 mm (T9)	200 mm (T10)	300 mm (T10)	400 mm (T10)	200 mm (T12)	300 mm (T12)	400 mm (T12)	200 mm (T13)	300 mm (T13)	400 mm (T13)	200 mm (T14)	300 mm (T14)	400 mm (T14)	200 mm (T15)	300 mm (T15)	400 mm (T15)	200 mm (T16)	300 mm (T16)	400 mm (T16)
Conv	12.1	11.8	10.3	8.9	8.3	9.3	10.5	4.0	9.2	8.8	3.9	8.2	5.7	2.1	7.8	7.4	2.5	7.9	6.5	5.5	8.1
Conv	12.9	11.6	9.8	9.4	7.8	8.6	10.1	4.4	8.1	8.1	4.0	8.4	6.2	2.2	8.1	6.8	2.3	8.0	6.8	5.5	7.8
Conv	13.1	12.1	10.6	9.2	7.6	8.4	9.1	3.2	8.4	8.0	3.0	8.7	6.5	2.8	7.8	6.7	1.6	8.2	6.4	5.6	7.9
Fest_1	10.6	17.8	20.8	8.3	15.2	18.9	11.6	18.1	20.6	11.3	17.4	19.6	7.5	11.9	15.0	7.8	11.2	13.4	7.5	10.2	11.0
Fest_1	10.3	17.2	20.6	8.9	15.6	18.1	12.7	18.1	18.8	12.6	17.2	18.2	6.9	11.9	15.6	7.9	11.3	13.5	6.9	10.0	12.5
Fest_1	9.9	17.6	19.9	8.4	16.3	17.8	12.2	17.9	19.3	12.0	17.0	18.7	7.3	17.2	14.9	7.2	11.0	14.3	7.3	10.4	11.9

Fest_1+2	10.8	9.3	13.8	9.8	7.8	12.1	13.2	7.3	9.2	10.7	7.3	8.8	7.6	8.1	8.3	8.7	6.5	7.6	7.4	6.2	7.0
Fest_1+2	11.3	9.3	12.3	8.9	7.4	10.9	12.1	8.5	9.5	10.0	8.1	9.1	8.1	5.8	6.1	8.5	6.8	8.2	8.1	5.7	7.2
Fest_1+2	9.9	9.8	12.3	9.1	8.3	11.8	12	7.9	9.6	9.5	7.9	9.9	8.3	7.9	7.5	8.9	6.2	8.0	7.7	6.5	7.5
Fest_1+2 +Conv	12.3	10.3	16.8	10.8	9.8	14.9	16.0	12.6	19.3	16.9	17.6	14.2	12.3	12.1	17.1	14.3	10.4	15.8	10.5	10.5	16.4
Fest_1+2 +Conv	13.1	10.8	16.3	10.3	9.4	15.1	17.0	13.4	18.0	14.2	14.5	13.7	11.1	12.1	20.2	13.0	11.8	16.8	11.4	9.2	15.3
Fest_1+2 +Conv	13.2	11.7	18.2	10.1	10.3	13.8	14.5	14.7	19.9	14.2	19.7	21.5	12.2	10.8	18.0	12.4	11.4	18.9	11.9	9.6	13.9
Bare Soil	14.2	18.7	21.1	12.3	18.2	18.9	13.7	22.6	24.8	14.7	23.2	24.2	13.4	22.3	14.0	14.6	23.2	24.0	14.8	21.7	24.5
Bare Soil	14.5	18.3	20.8	12.2	16.9	19.2	14.8	23.3	24.4	15.5	22.3	24.1	14.7	21.9	21.0	15.8	22.7	24.0	15.0	22.9	23.8
Bare Soil	14.1	19.6	21.8	12.8	16.8	18.6	15.2	22.4	24.3	13.9	21.9	24.9	14.0	23.6	24.4	15.2	21.9	24.8	16.3	22.1	23.9
Bare Soil	8.8	5.6	10.8	6.2	6.8	10.9	11.9	7.3	22	7.2	8.0	23.4	5.9	6.4	20.1	7.6	7.4	19.5	9.5	6.7	19.0
Bare Soil	9.5	6.8	10.9	6.4	5.3	10.8	10.4	6.5	22.2	7.3	8.3	23.0	5.9	6.6	19.8	8.4	6.8	19.2	10.6	6.5	18.5
Bare Soil	9.5	6.9	9.4	7.2	5.9	10.3	9.0	6.6	22.2	8.5	7.1	21.9	6.7	6.4	19.3	8.1	6.7	19.2	10.7	6.5	18.9

T9 – 24/07/2019, T10 – 25/07/2019, T11 – 29/07/2019, T12 – 31/07/2019, T13 – 02/08/2019, T14 – 07/08/2019, T15 – 14/08/2019, T16 – 16/08/2019.

Appendix C Grass species selection to control concentrated flow erosion in grassed waterways

C.1 Sediment Concentration Analysis

Table C-91: Univariate ANOVA test for sediment concentration for 0.2 l s^{-1}

Effect	Univariate Tests of Significance for 0.2 l s^{-1} (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	SS	Degr. of Freedom	MS	F	p
Intercept	151104214	1	151104214	35.47227	0.000004
Sample	90146901	7	12878129	3.02319	0.019975
Error	102234821	24	4259784		

Table C-92: *Post-hoc* test for sediment concentration for 0.2 l s^{-1}

Cell No.	LSD test; variable 0.2 l s^{-1} (Soil failure data) Homogenous Groups, alpha = .05000 Error: Between MS = 4260E3, df = 24.000			
	Sample	0.2 l s^{-1} Mean	1	2
6	F12L	466.827	****	
8	F12CL	554.629	****	
1	CL	1007.065	****	
2	F1N	1491.799	****	
7	F12LR	2455.980	****	
5	F12N	2648.448	****	
3	F1L	2776.892	****	
4	F1LR	5982.504		****

Table C-93: Univariate ANOVA test for sediment concentration for 0.3 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	0.3 l s^{-1} SS	0.3 l s^{-1} MS	0.3 l s^{-1} F	0.3 l s-1 p
Intercept	1	13832913	13832913	46.38222	0.000001
Sample	7	7538435	1076919	3.61095	0.009047
Error	23	6859460	298237		
Total	30	14397895			

Table C-94: *Post-hoc* test for sediment concentration for 0.3 l s^{-1}

Cell No.	LSD test; variable 0.3 l s^{-1} (Soil failure data) Homogenous Groups, alpha = .05000 Error: Between MS = 2982E2, df = 23.000				
	Sample	0.3 l s^{-1} Mean	1	2	3
8	F12CL	127.920	****		
6	F12L	131.379	****		
1	CL	265.768	****		
7	F12LR	564.132	****	****	
5	F12N	577.812	****	****	
2	F1N	925.524	****	****	****
4	F1LR	1278.808		****	****
3	F1L	1496.951			****

Table C-95: Univariate ANOVA test for sediment concentration for 0.4 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	0.4 l s^{-1} SS	0.4 l s^{-1} MS	0.4 l s^{-1} F	0.4 l s^{-1} p
Intercept	1	3688895	3688895	27.74288	0.000028
Sample	7	1688774	241253	1.81438	0.134871
Error	22	2925279	132967		
Total	29	4614054			

Table C-96: *Post-hoc* test for sediment concentration for 0.4 l s^{-1}

Cell No.	LSD test; variable 0.4 l s-1 (Soil failure data) Homogenous Groups, alpha = .05000 Error: Between MS = 1330E2, df = 22.000			
	Sample	0.4 l s^{-1} Mean	1	2
6	F12L	130.7534	****	
1	CL	188.9664	****	
2	F1N	217.3112	****	
8	F12CL	244.8408	****	
5	F12N	280.8823	****	
4	F1LR	388.0068	****	****
7	F12LR	476.3067	****	****
3	F1L	900.0522		****

Table C-97: Univariate ANOVA test for sediment concentration for 0.5 – 0.7 l s^{-1}

Effect	Degr. of Freedom	0.5 l s^{-1} SS	0.5 l s^{-1} MS	0.5 l s^{-1} F	0.5 l s^{-1} p	0.6 l s^{-1} SS	0.6 l s^{-1} MS	0.6 l s^{-1} F	0.6 l s^{-1} p	0.7 l s^{-1} SS	0.7 l s^{-1} MS	0.7 l s^{-1} F	0.7 l s^{-1} p
	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition												
Intercept	1	6618632	6618632	0.560461	0.462378	1927689	1927689	16.76615	0.000518	2175325	2175325	13.22943	0.001541
Sample	7	110799373	15828482	1.340344	0.280977	994873	142125	1.23614	0.327678	1072952	153279	0.93218	0.502720
Error	21	247994575	11809265			2414475	114975			3453045	164431		
Total	28	358793949				3409349				4525997			

Table C-98: Univariate ANOVA test for sediment concentration for 0.8 – 1.0 l s^{-1}

Effect	Degr. of Freedom	0.8 l s^{-1} SS	0.8 l s^{-1} MS	0.8 l s^{-1} F	0.8 l s^{-1} p	0.9 l s^{-1} SS	0.9 l s^{-1} MS	0.9 l s^{-1} F	0.9 l s^{-1} p	1 l s^{-1} SS	1 l s^{-1} MS	1 l s^{-1} F	1 l s^{-1} p
	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition												
Intercept	1	1510102	1510102	47.19368	0.000001	1039969	1039969	58.27543	0.000000	930119.5	930119.5	109.2476	0.000000
Sample	7	534659	76380	2.38702	0.054418	262178	37454	2.09876	0.085034	147033.0	21004.7	2.4671	0.048132
Error	23	735953	31998			410453	17846			195819.0	8513.9		
Total	30	1270613				672630				342852.0			

Table C-99: *Post-hoc* test for sediment concentration for 1.0 l s^{-1}

Cell No.	LSD test; variable 1 l s-1 (Soil failure data) Homogenous Groups, alpha = .05000 Error: Between MS = 8513.9, df = 23.000				
	Sample	1 l s^{-1} Mean	1	2	3
8	F12CL	79.2622	****		
7	F12LR	107.1464	****		
2	F1N	133.6169	****	****	
6	F12L	150.2838	****	****	****
1	CL	173.5530	****	****	****
5	F12N	197.2382	****	****	****
4	F1LR	267.4292		****	****
3	F1L	283.5008			****

Table C-100: Univariate ANOVA test for sediment concentration for 1.1 – 1.3 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition												
	Degr. of Freedom	1.1 l s^{-1} SS	1.1 l s^{-1} MS	1.1 l s^{-1} F	1.1 l s^{-1} p	1.2 l s^{-1} SS	1.2 l s^{-1} MS	1.2 l s^{-1} F	1.2 l s^{-1} p	1.3 l s^{-1} SS	1.3 l s^{-1} MS	1.3 l s^{-1} F	1.3 l s^{-1} p
Intercept	1	636961.4	636961.4	57.03043	0.000000	657836	657836.1	21.83521	0.000146	430864.4	430864.4	28.31671	0.000033
Sample	7	82954.2	11850.6	1.06104	0.422815	406709	58101.3	1.92853	0.117973	149639.2	21377.0	1.40491	0.257595
Error	20	223376.0	11168.8			602546	30127.3			304318.1	15215.9		
Total	27	306330.1				1009255				453957.3			

Table C-101: Univariate ANOVA test for sediment concentration for 1.4 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	1.4 l s^{-1} SS	1.4 l s^{-1} MS	1.4 l s^{-1} F	1.4 l s^{-1} p
Intercept	1	666813.2	666813.2	62.40812	0.000024
Sample	9	877848.6	97538.7	9.12881	0.001474
Error	9	96162.5	10684.7		
Total	18	974011.1			

Table C-102: *Post-hoc* test for sediment concentration for 1.4 l s^{-1}

Cell No.	LSD test; variable 1.4 l s^{-1} (Soil failure data) Homogenous Groups, alpha = .05000 Error: Between MS = 10685., df = 9.0000			
	Sample	1.4 l s^{-1} Mean	1	2
3	F1N	0.000	****	
9	F12CL	30.769	****	
7	F12L	50.152	****	
8	F12LR	127.576	****	
4	F1L	141.176	****	
5	F1LR	144.005	****	
10	F12CLR	157.915	****	
2	CLR	196.500	****	
6	F12N	243.655	****	
1	CL	1055.838		****

Table C-103: Univariate ANOVA test for sediment concentration for 1.5 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	1.5 l s^{-1} SS	1.5 l s^{-1} MS	1.5 l s^{-1} F	1.5 l s^{-1} p
Intercept	1	792687.5	792687.5	40.50170	0.000380
Sample	9	360246.0	40027.3	2.04516	0.178893
Error	7	137002.0	19571.7		
Total	16	497248.0			

Table C-104: Univariate ANOVA test for sediment concentration for 1.6 l s^{-1}

Effect	Univariate Results for Each DV (Soil failure data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	1.6 l s^{-1} SS	1.6 l s^{-1} MS	1.6 l s^{-1} F	1.6 l s^{-1} p
Intercept	1	762719.0	762719.0	33.97328	0.000644
Sample	9	333691.5	37076.8	1.65149	0.260489
Error	7	157153.9	22450.6		
Total	16	490845.4			

Appendix D Shear Stress Statistical Analysis for Flume Experiment 2

For Roots and Shoots treatments

Table D-1: Univariate ANOVA test for shear stress for 0.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.2 SS	AS 0.2 MS	AS 0.2 F	AS 0.2 p
Intercept	1	2.314136	2.314136	30.88894	0.000010
Sample code	7	1.546574	0.220939	2.94908	0.022319
Error	24	1.798031	0.074918		
Total	31	3.344605			

Table D-2: Post-hoc test for shear stress for 0.2 l s^{-1}.

Cell No.	LSD test; variable AS 0.2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .07492, df = 24.000				
	Sample code	AS 0.2 Mean	1	2	3
5	FCLRS	0.032453	****		
4	F2NRS	0.036214	****		
3	F2LRS	0.107510	****	****	
6	FCNRS	0.159244	****	****	
1	CLRS	0.323300	****	****	****
8	FNRS	0.326005	****	****	****
2	CNRS	0.451784		****	****
7	FLRS	0.714832			****

Table D-3: Univariate ANOVA test for shear stress for 0.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.3 SS	AS 0.3 MS	AS 0.3 F	AS 0.3 p
Intercept	1	1.171992	1.171992	49.47586	0.000000
Sample code	7	0.612408	0.087487	3.69327	0.007555

Error	24	0.568516	0.023688		
Total	31	1.180923			

Table D-4: Post-hoc test for shear stress for 0.3 l s^{-1}

Cell No.	LSD test; variable AS 0.3 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .02369, df = 24.000				
	Sample code	AS 0.3 Mean	1	2	3
5	FCLRS	0.025978	****		
4	F2NRS	0.026324	****		
3	F2LRS	0.078501	****	****	
6	FCNRS	0.109679	****	****	
8	FNRS	0.251890		****	****
1	CLRS	0.299443		****	****
7	FLRS	0.359034			****
2	CNRS	0.380157			****

Table D-5: Univariate ANOVA test for shear stress for 0.4 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.4 SS	AS 0.4 MS	AS 0.4 F	AS 0.4 p
Intercept	1	0.646891	0.646891	51.51962	0.000000
Sample code	7	0.289112	0.041302	3.28934	0.013483
Error	24	0.301349	0.012556		
Total	31	0.590461			

Table D-6: Post-hoc test for shear stress for 0.4 l s^{-1}

Cell No.	LSD test; variable AS 0.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .01256, df = 24.000					
	Sample code	AS 0.4 Mean	1	2	3	4
4	F2NRS	0.022197	****			

5	FCLRS	0.022418	****			
3	F2LRS	0.071815	****	****		
6	FCNRS	0.094856	****	****	****	
8	FNRS	0.192435		****	****	****
1	CLRS	0.205515		****	****	****
7	FLRS	0.257767			****	****
2	CNRS	0.270442				****

Table D-7: Univariate ANOVA test for shear stress for 0.5 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.5 SS	AS 0.5 MS	AS 0.5 F	AS 0.5 p
Intercept	1	0.469539	0.469539	57.97513	0.000000
Sample code	7	0.222981	0.031854	3.93315	0.005410
Error	24	0.194375	0.008099		
Total	31	0.417357			

Table D-8: Post-hoc test for shear stress for 0.5 l s^{-1}

Cell No.	LSD test; variable AS 0.5 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00810, df = 24.000				
	Sample code	AS 0.5 Mean	1	2	3
4	F2NRS	0.021183		****	
5	FCLRS	0.024278		****	
6	FCNRS	0.062860	****	****	
3	F2LRS	0.064285	****	****	
1	CLRS	0.173706	****		****
7	FLRS	0.179852	****		****
8	FNRS	0.180161	****		****
2	CNRS	0.262734			****

Table D-9: Univariate ANOVA test for shear stress for 0.6 l s^{-1}

	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition

Effect	Degr. of Freedom	AS 0.6 SS	AS 0.6 MS	AS 0.6 F	AS 0.6 p
Intercept	1	0.307029	0.307029	64.12566	0.000000
Sample code	7	0.132649	0.018950	3.95785	0.005229
Error	24	0.114910	0.004788		
Total	31	0.247559			

Table D-10: Post-hoc test for shear stress for 0.6 l s^{-1}

Cell No.	LSD test; variable AS 0.6 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00479, df = 24.000				
	Sample code	AS 0.6 Mean	1	2	3
4	F2NRS	0.018436	****		
5	FCLRS	0.021166	****		
3	F2LRS	0.055804	****	****	
6	FCNRS	0.057190	****	****	
7	FLRS	0.122790		****	****
8	FNRS	0.148215		****	****
1	CLRS	0.158848			****
2	CNRS	0.201169			****

Table D-11: Univariate ANOVA test for shear stress for 0.7 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.7 SS	AS 0.7 MS	AS 0.7 F	AS 0.7 p
Intercept	1	0.218329	0.218329	69.68997	0.000000
Sample code	7	0.083757	0.011965	3.81930	0.006333
Error	24	0.075189	0.003133		
Total	31	0.158946			

Table D-12: Post-hoc test for shear stress for 0.8 l s^{-1}

Cell No.	LSD test; variable AS 0.7 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00313, df = 24.000				
	Sample code	AS 0.7 Mean	1	2	3

4	F2NRS	0.016168		****	
5	FCLRS	0.017082		****	
3	F2LRS	0.050615	****	****	
6	FCNRS	0.053581	****	****	
7	FLRS	0.115471	****		****
1	CLRS	0.119347	****		****
8	FNRS	0.131389	****		****
2	CNRS	0.157146			****

Table D-13: Univariate ANOVA test for shear stress for 0.8 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.8 SS	AS 0.8 MS	AS 0.8 F	AS 0.8 p
Intercept	1	0.167247	0.167247	66.80348	0.000000
Sample code	7	0.068313	0.009759	3.89806	0.005678
Error	24	0.060086	0.002504		
Total	31	0.128399			

Table D-14: Post-hoc test for shear stress for 0.8 l s^{-1}

Cell No.	LSD test; variable AS 0.8 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00250, df = 24.000				
	Sample code	AS 0.8 Mean	1	2	3
4	F2NRS	0.015528		****	
5	FCLRS	0.016126		****	
3	F2LRS	0.045883	****	****	
6	FCNRS	0.047098	****	****	
7	FLRS	0.091978	****		****
1	CLRS	0.101345	****		****
8	FNRS	0.103442	****		****
2	CNRS	0.156953			****

Table D-15: Univariate ANOVA test for shear stress for 0.9 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	AS 0.9 SS	AS 0.9 MS	AS 0.9 F	AS 0.9 p
Intercept	1	0.145957	0.145957	62.33073	0.000000
Sample code	7	0.062819	0.008974	3.83237	0.006219
Error	24	0.056200	0.002342		
Total	31	0.119019			

Table D-16: Post-hoc test for shear stress for 0.9 l s^{-1}

Cell No.	LSD test; variable AS 0.9 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00234, df = 24.000 Sample code	AS 0.9 Mean	1	2	3
5	FCLRS	0.013730	****		
4	F2NRS	0.014732	****		
6	FCNRS	0.040791	****	****	
3	F2LRS	0.045947	****	****	
7	FLRS	0.080152	****	****	
1	CLRS	0.096613		****	****
8	FNRS	0.097499		****	****
2	CNRS	0.150828			****

Table D-17: Univariate ANOVA test for shear stress for 1.0 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition Degr. of Freedom	AS 1 SS	AS 1 MS	AS 1 F	AS 1 p
Intercept	1	0.116579	0.116579	67.28779	0.000000
Sample code	7	0.050933	0.007276	4.19970	0.003765
Error	24	0.041581	0.001733		
Total	31	0.092514			

Table D-18: Post-hoc test for shear stress for 1.0 l s^{-1}

	LSD test; variable AS 1 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00173, df = 24.000

Cell No.	Sample code	AS 1 Mean	1	2	3
5	FCLRS	0.012684	****		
4	F2NRS	0.013297	****		
6	FCNRS	0.035632	****	****	
3	F2LRS	0.041554	****	****	
7	FLRS	0.069376	****	****	
1	CLRS	0.082070		****	****
8	FNRS	0.092378		****	****
2	CNRS	0.135875			****

Table D-19: Univariate ANOVA test for shear stress for 1.1 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.1 SS	AS 1.1 MS	AS 1.1 F	AS 1.1 p
Intercept	1	0.098472	0.098472	67.06953	0.000000
Sample code	7	0.040261	0.005752	3.91746	0.005528
Error	24	0.035237	0.001468		
Total	31	0.075498			

Table D-20: Post-hoc test for shear stress for 1.1 l s^{-1}

Cell No.	LSD test; variable AS 1.1 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00147, df = 24.000				
	Sample code	AS 1.1 Mean	1	2	3
5	FCLRS	0.011969	****		
4	F2NRS	0.013427	****		
6	FCNRS	0.032096	****	****	
3	F2LRS	0.040238	****	****	
7	FLRS	0.065444	****	****	****
1	CLRS	0.074951		****	****
8	FNRS	0.084635		****	****
2	CNRS	0.121025			****

Table D-21: Univariate ANOVA test for shear stress for 1.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.2 SS	AS 1.2 MS	AS 1.2 F	AS 1.2 p
Intercept	1	0.076495	0.076495	72.26404	0.000000
Sample code	7	0.030645	0.004378	4.13565	0.004104
Error	24	0.025405	0.001059		
Total	31	0.056050			

Table D-22: Post-hoc test for shear stress for 1.2 l s^{-1}

Cell No.	LSD test; variable AS 1.2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00106, df = 24.000				
	Sample code	AS 1.2 Mean	1	2	3
5	FCLRS	0.011606	****		
4	F2NRS	0.014082	****		
6	FCNRS	0.028926	****	****	
3	F2LRS	0.038185	****	****	
7	FLRS	0.050347	****	****	
1	CLRS	0.063575		****	****
8	FNRS	0.075247		****	****
2	CNRS	0.109171			****

Table D-23: Univariate ANOVA test for shear stress for 1.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.3 SS	AS 1.3 MS	AS 1.3 F	AS 1.3 p
Intercept	1	0.071875	0.071875	87.54452	0.000000
Sample code	7	0.022260	0.003180	3.87332	0.005876
Error	24	0.019704	0.000821		
Total	31	0.041964			

Table D-24: Post-hoc test for shear stress for 1.3 l s^{-1}

Cell No.	LSD test; variable AS 1.3 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00082, df = 24.000				
	Sample code	AS 1.3 Mean	1	2	3
5	FCLRS	0.012094	****		
4	F2NRS	0.014517	****		
6	FCNRS	0.037575	****	****	
3	F2LRS	0.038255	****	****	
7	FLRS	0.048557	****	****	
1	CLRS	0.061712		****	****
8	FNRS	0.071273		****	****
2	CNRS	0.095160			****

Table D-25: Univariate ANOVA test for shear stress for 1.4 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.4 SS	AS 1.4 MS	AS 1.4 F	AS 1.4 p
Intercept	1	0.057771	0.057771	98.17827	0.000000
Sample code	7	0.010337	0.001477	2.50953	0.043679
Error	24	0.014122	0.000588		
Total	31	0.024459			

Table D-26: Post-hoc test for shear stress for 1.4 l s^{-1}

Cell No.	LSD test; variable AS 1.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00059, df = 24.000				
	Sample code	AS 1.4 Mean	1	2	3
4	F2NRS	0.017434		****	
5	FCLRS	0.019232	****	****	
3	F2LRS	0.036267	****	****	
6	FCNRS	0.039903	****	****	
7	FLRS	0.042752	****	****	****
8	FNRS	0.054447	****		****
1	CLRS	0.054473	****		****

2	CNRS	0.075405			****

Table D-27: Univariate ANOVA test for shear stress for 1.5 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.5 SS	AS 1.5 MS	AS 1.5 F	AS 1.5 p
Intercept	1	0.055096	0.055096	124.3740	0.000000
Sample code	7	0.004459	0.000637	1.4381	0.236454
Error	24	0.010632	0.000443		
Total	31	0.015091			

Table D-28: Univariate ANOVA test for shear stress for 1.6 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.6 SS	AS 1.6 MS	AS 1.6 F	AS 1.6 p
Intercept	1	0.048224	0.048224	141.6323	0.000000
Sample code	7	0.003564	0.000509	1.4955	0.216196
Error	24	0.008172	0.000340		

Table D-29: Univariate ANOVA test for shear stress for 1.7 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.7 SS	AS 1.7 MS	AS 1.7 F	AS 1.7 p
Intercept	1	0.040048	0.040048	145.5465	0.000000
Sample code	7	0.003114	0.000445	1.6168	0.178638
Error	24	0.006604	0.000275		
Total	31	0.009718			

Table D-30: Univariate ANOVA test for shear stress for 1.8 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.8 SS	AS 1.8 MS	AS 1.8 F	AS 1.8 p
Intercept	1	0.031072	0.031072	181.5411	0.000000

Sample code	7	0.002597	0.000371	2.1677	0.074603
Error	24	0.004108	0.000171		
Total	31	0.006705			

Table D-31: Univariate ANOVA test for shear stress for 1.9 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.9 SS	AS 1.9 MS	AS 1.9 F	AS 1.9 p
Intercept	1	0.026701	0.026701	195.1950	0.000000
Sample code	7	0.002192	0.000313	2.2889	0.061637
Error	24	0.003283	0.000137		
Total	31	0.005475			

Table D-32: Univariate ANOVA test for shear stress for 2.0 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2 SS	AS 2 MS	AS 2 F	AS 2 p
Intercept	1	0.024279	0.024279	205.6739	0.000000
Sample code	7	0.002143	0.000306	2.5934	0.038363
Error	24	0.002833	0.000118		
Total	31	0.004976			

Table D-33: Post-hoc test for shear stress for 2.0 l s^{-1}

Cell No.	LSD test; variable AS 2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00012, df = 24.000					
	Sample code	AS 2 Mean	1	2	3	4
4	F2NRS	0.013760				****
5	FCLRS	0.019124	****			****
3	F2LRS	0.021962	****	****		****
1	CLRS	0.028443	****	****	****	****
6	FCNRS	0.029891	****	****	****	
7	FLRS	0.031674	****	****	****	
8	FNRS	0.035317		****	****	

2	CNRS	0.040189			****	

Table D-34: Univariate ANOVA test for shear stress for 2.1 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.1 SS	AS 2.1 MS	AS 2.1 F	AS 2.1 p
Intercept	1	0.022863	0.022863	218.7243	0.000000
Sample code	7	0.001681	0.000240	2.2980	0.060765
Error	24	0.002509	0.000105		
Total	31	0.004190			

Table D-35: Univariate ANOVA test for shear stress for 2.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.2 SS	AS 2.2 MS	AS 2.2 F	AS 2.2 p
Intercept	1	0.021273	0.021273	217.8267	0.000000
Sample code	7	0.001332	0.000190	1.9477	0.105697
Error	24	0.002344	0.000098		
Total	31	0.003675			

Table D-36: Univariate ANOVA test for shear stress for 2.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.3 SS	AS 2.3 MS	AS 2.3 F	AS 2.3 p
Intercept	1	0.018900	0.018900	243.5931	0.000000
Sample code	7	0.001218	0.000174	2.2419	0.066365
Error	24	0.001862	0.000078		
Total	31	0.003080			

Table D-37: Univariate ANOVA test for shear stress for 2.4 l s^{-1}

	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition

Effect	Degr. of Freedom	AS 2.4 SS	AS 2.4 MS	AS 2.4 F	AS 2.4 p
Intercept	1	0.016628	0.016628	255.1923	0.000000
Sample code	7	0.001480	0.000211	3.2448	0.015174
Error	23	0.001499	0.000065		
Total	30	0.002979			

Table D-38: Post-hoc test for shear stress for 2.4 l s^{-1}

Cell No.	LSD test; variable AS 2.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00007, df = 23.000					
	Sample code	AS 2.4 Mean	1	2	3	4
4	F2NRS	0.010703				****
5	FCLRS	0.017755	****			****
3	F2LRS	0.018811	****	****		****
1	CLRS	0.023194	****	****	****	
6	FCNRS	0.025456	****	****	****	
7	FLRS	0.026666	****	****	****	
8	FNRS	0.030366		****	****	
2	CNRS	0.033173			****	

Table D-39: Univariate ANOVA test for shear stress for 2.5 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.5 SS	AS 2.5 MS	AS 2.5 F	AS 2.5 p
Intercept	1	0.014246	0.014246	267.6149	0.000000
Sample code	7	0.001645	0.000235	4.4134	0.003095
Error	23	0.001224	0.000053		
Total	30	0.002869			

Table D-40: Post-hoc test for shear stress for 2.5 l s^{-1}

Cell No.	LSD test; variable AS 2.5 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00005, df = 23.000				
	Sample code	AS 2.5 Mean	1	2	3

4	F2NRS	0.009886			****
5	FCLRS	0.013810	****		****
3	F2LRS	0.016487	****		****
1	CLRS	0.022353	****	****	
7	FLRS	0.024061	****	****	
6	FCNRS	0.024169	****	****	
8	FNRS	0.028766		****	
2	CNRS	0.032745		****	

Table D-41: Univariate ANOVA test for shear stress for 2.6 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.6 SS	AS 2.6 MS	AS 2.6 F	AS 2.6 p
Intercept	1	0.013344	0.013344	232.8813	0.000000
Sample code	7	0.001207	0.000172	3.0096	0.021347
Error	23	0.001318	0.000057		
Total	30	0.002525			

Table D-42: Post-hoc test for shear stress for 2.6 l s^{-1}

Cell No.	LSD test; variable AS 2.6 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00006, df = 23.000				
	Sample code	AS 2.6 Mean	1	2	3
4	F2NRS	0.009886		****	
3	F2LRS	0.015363	****	****	
5	FCLRS	0.018763	****	****	
1	CLRS	0.020722	****	****	
6	FCNRS	0.021331	****		****
7	FLRS	0.023818	****		****
8	FNRS	0.024850	****		****
2	CNRS	0.032001			****

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Table D-43: Univariate ANOVA test for shear stress for 0.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.2 SS	AS 0.2 MS	AS 0.2 F	AS 0.2 p
Intercept	1	1.919163	1.919163	276.1339	0.000000
Sample code	7	0.556493	0.079499	11.4385	0.000003
Error	24	0.166803	0.006950		
Total	31	0.723296			

Table D-44: Post-hoc test for shear stress for 0.2 l s^{-1}

Cell No.	LSD test; variable AS 0.2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00695, df = 24.000				
	Sample code	AS 0.2 Mean	1	2	3
3	F2LR	0.030744		****	
6	FCNR	0.186417	****		
5	FCLR	0.194260	****		
4	F2NR	0.198213	****		
7	FLR	0.248138	****		
8	FNR	0.271853	****		
1	CLR	0.299341	****		
2	CNR	0.530199			****

Table D-45: Univariate ANOVA test for shear stress for 0.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.3 SS	AS 0.3 MS	AS 0.3 F	AS 0.3 p
Intercept	1	1.402510	1.402510	166.7528	0.000000
Sample code	7	0.413676	0.059097	7.0264	0.000132
Error	24	0.201857	0.008411		
Total	31	0.615534			

Table D-46: Post-hoc test for shear stress for 0.3 l s^{-1}

Cell No.	LSD test; variable AS 0.3 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00841, df = 24.000				
	Sample code	AS 0.3 Mean	1	2	3
3	F2LR	0.025609		****	
6	FCNR	0.169303	****		
5	FCLR	0.174274	****		
7	FLR	0.194639	****		
4	F2NR	0.198852	****		
1	CLR	0.203121	****		
8	FNR	0.244248	****		
2	CNR	0.464773			****

Table D-47: Univariate ANOVA test for shear stress for 0.4 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.4 SS	AS 0.4 MS	AS 0.4 F	AS 0.4 p
Intercept	1	1.004810	1.004810	94.15735	0.000000
Sample code	7	0.246713	0.035245	3.30267	0.013223
Error	24	0.256119	0.010672		

Table D-48: Post-hoc test for shear stress for 0.4 l s^{-1}

Cell No.	LSD test; variable AS 0.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .01067, df = 24.000				
	Sample code	AS 0.4 Mean	1	2	3
3	F2LR	0.022420		****	
6	FCNR	0.148016	****	****	
5	FCLR	0.148050	****	****	
4	F2NR	0.167499	****	****	
7	FLR	0.168125	****	****	
1	CLR	0.190218	****		
8	FNR	0.210093	****		

2	CNR	0.363190			****

Table D-49: Univariate ANOVA test for shear stress for 0.5 l s^{-1}

	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	Degr. of Freedom	AS 0.5 SS	AS 0.5 MS	AS 0.5 F	AS 0.5 p
Intercept	1	0.660710	0.660710	120.7689	0.000000
Sample code	7	0.101439	0.014491	2.6488	0.035227
Error	24	0.131301	0.005471		
Total	31	0.232740			

Table D-50: Post-hoc test for shear stress for 0.5 l s^{-1}

	LSD test; variable AS 0.5 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00547, df = 24.000			
Cell No.	Sample code	AS 0.5 Mean	1	2
3	F2LR	0.021510		****
5	FCLR	0.130303	****	
6	FCNR	0.130584	****	
4	F2NR	0.145247	****	
7	FLR	0.149012	****	
8	FNR	0.163033	****	
1	CLR	0.171926	****	
2	CNR	0.237917	****	

Table D-51: Univariate ANOVA test for shear stress for 0.6 l s^{-1}

	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	Degr. of Freedom	AS 0.6 SS	AS 0.6 MS	AS 0.6 F	AS 0.6 p
Intercept	1	0.502240	0.502240	154.8209	0.000000
Sample code	7	0.067957	0.009708	2.9926	0.020908
Error	24	0.077856	0.003244		
Total	31	0.145813			

Table D-52: Post-hoc test for shear stress for 0.6 l s^{-1}

Cell No.	LSD test; variable AS 0.6 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00324, df = 24.000			
	Sample code	AS 0.6 Mean	1	2
3	F2LR	0.020708		****
5	FCLR	0.108928	****	
6	FCNR	0.115459	****	
4	F2NR	0.127999	****	
7	FLR	0.129180	****	
1	CLR	0.155881	****	
8	FNR	0.158664	****	
2	CNR	0.185418	****	

Table D-53: Univariate ANOVA test for shear stress for 0.7 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.7 SS	AS 0.7 MS	AS 0.7 F	AS 0.7 p
Intercept	1	0.397290	0.397290	171.6365	0.000000
Sample code	7	0.052470	0.007496	3.2383	0.014528
Error	24	0.055553	0.002315		
Total	31	0.108024			

Table D-54: Post-hoc test for shear stress for 0.7 l s^{-1}

Cell No.	LSD test; variable AS 0.7 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00231, df = 24.000			
	Sample code	AS 0.7 Mean	1	2
3	F2LR	0.018870		****
5	FCLR	0.097554	****	
6	FCNR	0.101540	****	
4	F2NR	0.111292	****	
7	FLR	0.126551	****	
1	CLR	0.134512	****	

8	FNR	0.135707	****	
2	CNR	0.165365	****	

Table D-55: Univariate ANOVA test for shear stress for 0.8 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.8 SS	AS 0.8 MS	AS 0.8 F	AS 0.8 p
Intercept	1	0.298233	0.298233	205.7659	0.000000
Sample code	7	0.033604	0.004801	3.3121	0.013042
Error	24	0.034785	0.001449		
Total	31	0.068389			

Table D-56: Post-hoc test for shear stress for 0.8 l s^{-1}

Cell No.	LSD test; variable AS 0.8 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00145, df = 24.000			
	Sample code	AS 0.8 Mean	1	2
3	F2LR	0.018137		****
5	FCLR	0.088911	****	
6	FCNR	0.090794	****	
1	CLR	0.100932	****	
4	F2NR	0.108531	****	
8	FNR	0.115376	****	
7	FLR	0.120027	****	
2	CNR	0.129604	****	

Table D-57: Univariate ANOVA test for shear stress for 0.9 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 0.9 SS	AS 0.9 MS	AS 0.9 F	AS 0.9 p
Intercept	1	0.223390	0.223390	243.2497	0.000000
Sample code	7	0.024569	0.003510	3.8218	0.006770
Error	23	0.021122	0.000918		
Total	30	0.045691			

Table D-58: Post-hoc test for shear stress for 0.9 l s^{-1}

Cell No.	LSD test; variable AS 0.9 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00092, df = 23.000			
	Sample code	AS 0.9 Mean	1	2
3	F2LR	0.017292		****
6	FCNR	0.082614	****	
5	FCLR	0.082974	****	
4	F2NR	0.085326	****	
2	CNR	0.089484	****	
7	FLR	0.100120	****	
1	CLR	0.111678	****	
8	FNR	0.112711	****	

Table D-59: Univariate ANOVA test for shear stress for 1.0 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1 SS	AS 1 MS	AS 1 F	AS 1 p
Intercept	1	0.187372	0.187372	324.2274	0.000000
Sample code	7	0.019577	0.002797	4.8394	0.001809
Error	23	0.013292	0.000578		
Total	30	0.032869			

Table D-60: Post-hoc test for shear stress for 1.0 l s^{-1}

Cell No.	LSD test; variable AS 1 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00058, df = 23.000			
	Sample code	AS 1 Mean	1	2
3	F2LR	0.017717		****
5	FCLR	0.073349	****	
2	CNR	0.074635	****	
6	FCNR	0.077488	****	
4	F2NR	0.088150	****	
7	FLR	0.095417	****	

1	CLR	0.095914	****	
8	FNR	0.102118	****	

Table D-61: Univariate ANOVA test for shear stress for 1.1 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.1 SS	AS 1.1 MS	AS 1.1 F	AS 1.1 p
Intercept	1	0.139711	0.139711	259.8008	0.000000
Sample code	7	0.013734	0.001962	3.6484	0.008589
Error	23	0.012369	0.000538		
Total	30	0.026102			

Table D-62: Post-hoc test for shear stress for 1.1 l s^{-1}

Cell No.	LSD test; variable AS 1.1 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00054, df = 23.000			
	Sample code	AS 1.1 Mean	1	2
3	F2LR	0.016208		****
5	FCLR	0.065120	****	
4	F2NR	0.065492	****	
2	CNR	0.070032	****	
6	FCNR	0.070367	****	
7	FLR	0.079987	****	
1	CLR	0.084734	****	
8	FNR	0.087565	****	

Table D-63: Univariate ANOVA test for shear stress for 1.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.2 SS	AS 1.2 MS	AS 1.2 F	AS 1.2 p
Intercept	1	0.123627	0.123627	243.7549	0.000000
Sample code	7	0.011425	0.001632	3.2182	0.015765
Error	23	0.011665	0.000507		
Total	30	0.023090			

Table D-64: Post-hoc test for shear stress for 1.2 l s^{-1}

Cell No.	LSD test; variable AS 1.2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00051, df = 23.000			
	Sample code	AS 1.2 Mean	1	2
3	F2LR	0.016813		****
2	CNR	0.060379	****	
5	FCLR	0.062095	****	
6	FCNR	0.066020	****	
4	F2NR	0.068640	****	
7	FLR	0.073559	****	
1	CLR	0.076205	****	
8	FNR	0.083788	****	

Table D-65: Univariate ANOVA test for shear stress for 1.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.3 SS	AS 1.3 MS	AS 1.3 F	AS 1.3 p
Intercept	1	0.104140	0.104140	436.4778	0.000000
Sample code	7	0.008648	0.001235	5.1777	0.001199
Error	23	0.005488	0.000239		
Total	30	0.014135			

Table D-66: Post-hoc test for shear stress for 1.3 l s^{-1}

Cell No.	LSD test; variable AS 1.3 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00024, df = 23.000				
	Sample code	AS 1.3 Mean	1	2	3
3	F2LR	0.018619			****
5	FCLR	0.053891	****		
4	F2NR	0.056274	****	****	
6	FCNR	0.061195	****	****	
2	CNR	0.062181	****	****	
1	CLR	0.066901	****	****	

7	FLR	0.069361	****	****	
8	FNR	0.077365		****	

Table D-67: Univariate ANOVA test for shear stress for 1.4 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.4 SS	AS 1.4 MS	AS 1.4 F	AS 1.4 p
Intercept	1	0.081627	0.081627	427.6282	0.000000
Sample code	7	0.003766	0.000538	2.8183	0.028321
Error	23	0.004390	0.000191		
Total	30	0.008156			

Table D-68: Post-hoc test for shear stress for 1.4 l s^{-1}

Cell No.	LSD test; variable AS 1.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00019, df = 23.000			
	Sample code	AS 1.4 Mean	1	2
3	F2LR	0.024926		****
4	F2NR	0.049439	****	
5	FCLR	0.050279	****	
2	CNR	0.052570	****	
6	FCNR	0.054003	****	
7	FLR	0.058298	****	
1	CLR	0.060808	****	
8	FNR	0.062057	****	

Table D-69: Univariate ANOVA test for shear stress for 1.5 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.5 SS	AS 1.5 MS	AS 1.5 F	AS 1.5 p
Intercept	1	0.072162	0.072162	449.3528	0.000000
Sample code	7	0.002345	0.000335	2.0862	0.086720
Error	23	0.003694	0.000161		
Total	30	0.006039			

Table D-70: Post-hoc test for shear stress for 1.5 l s^{-1}

Cell No.	LSD test; variable AS 1.5 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00016, df = 23.000			
	Sample code	AS 1.5 Mean	1	2
3	F2LR	0.027752		****
5	FCLR	0.046006	****	****
2	CNR	0.047418	****	
6	FCNR	0.049468	****	
4	F2NR	0.050206	****	
1	CLR	0.054750	****	
7	FLR	0.055306	****	
8	FNR	0.056830	****	

Table D-71: Univariate ANOVA test for shear stress for 1.6 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.6 SS	AS 1.6 MS	AS 1.6 F	AS 1.6 p
Intercept	1	0.059168	0.059168	591.6895	0.000000
Sample code	7	0.001941	0.000277	2.7727	0.030319
Error	23	0.002300	0.000100		
Total	30	0.004241			

Table D-72: Post-hoc test for shear stress for 1.6 l s^{-1}

Cell No.	LSD test; variable AS 1.6 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00010, df = 23.000			
	Sample code	AS 1.6 Mean	1	2
3	F2LR	0.023792		****
5	FCLR	0.044131	****	
1	CLR	0.044929	****	
4	F2NR	0.045967	****	
6	FCNR	0.046673	****	
7	FLR	0.047689	****	

2	CNR	0.047818	****	
8	FNR	0.050094	****	

Table D-73: Univariate ANOVA test for shear stress for 1.7 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.7 SS	AS 1.7 MS	AS 1.7 F	AS 1.7 p
Intercept	1	0.049209	0.049209	1118.169	0.000000
Sample code	7	0.002460	0.000351	7.985	0.000061
Error	23	0.001012	0.000044		
Total	30	0.003472			

Table D-74: Post-hoc test for shear stress for 1.7 l s^{-1}

Cell No.	LSD test; variable AS 1.7 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00004, df = 23.000			
	Sample code	AS 1.7 Mean	1	2
3	F2LR	0.017438		****
5	FCLR	0.039680	****	
4	F2NR	0.041458	****	
6	FCNR	0.042540	****	
7	FLR	0.043599	****	
1	CLR	0.043746	****	
8	FNR	0.044270	****	
2	CNR	0.047456	****	

Table D-75: Univariate ANOVA test for shear stress for 1.8 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.8 SS	AS 1.8 MS	AS 1.8 F	AS 1.8 p
Intercept	1	0.040021	0.040021	687.9232	0.000000
Sample code	7	0.001914	0.000273	4.7007	0.002150
Error	23	0.001338	0.000058		
Total	30	0.003252			

Table D-76: Post-hoc test for shear stress for 1.8 l s^{-1}

Cell No.	LSD test; variable AS 1.8 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00006, df = 23.000			
	Sample code	AS 1.8 Mean	1	2
3	F2LR	0.016289		****
5	FCLR	0.036106	****	
4	F2NR	0.037385	****	
1	CLR	0.037678	****	
7	FLR	0.037901	****	
6	FCNR	0.039623	****	
2	CNR	0.041738	****	
8	FNR	0.042031	****	

Table D-77: Univariate ANOVA test for shear stress for 1.9 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 1.9 SS	AS 1.9 MS	AS 1.9 F	AS 1.9 p
Intercept	1	0.039104	0.039104	1254.971	0.000000
Sample code	7	0.002035	0.000291	9.329	0.000018
Error	23	0.000717	0.000031		
Total	30	0.002752			

Table D-78: Post-hoc test for shear stress for 1.9 l s^{-1}

Cell No.	LSD test; variable AS 1.9 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00003, df = 23.000				
	Sample code	AS 1.9 Mean	1	2	3
3	F2LR	0.015770			****
5	FCLR	0.033628	****		
4	F2NR	0.036828	****	****	
7	FLR	0.038065	****	****	
6	FCNR	0.038102	****	****	
8	FNR	0.039390	****	****	

1	CLR	0.039585	****	****	
2	CNR	0.044056		****	

Table D-79: Univariate ANOVA test for shear stress for 2.0 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2 SS	AS 2 MS	AS 2 F	AS 2 p
Intercept	1	0.032741	0.032741	834.1689	0.000000
Sample code	7	0.001586	0.000227	5.7742	0.000599
Error	23	0.000903	0.000039		
Total	30	0.002489			

Table D-80: Post-hoc test for shear stress for 2.0 l s^{-1}

Cell No.	LSD test; variable AS 2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00004, df = 23.000			
	Sample code	AS 2 Mean	1	2
3	F2LR	0.015041		****
5	FCLR	0.030449	****	
6	FCNR	0.033755	****	
7	FLR	0.034295	****	
4	F2NR	0.034734	****	
8	FNR	0.035692	****	
1	CLR	0.038000	****	
2	CNR	0.039204	****	

Table D-81: Univariate ANOVA test for shear stress for 2.1 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.1 SS	AS 2.1 MS	AS 2.1 F	AS 2.1 p
Intercept	1	0.030671	0.030671	1559.234	0.000000
Sample code	7	0.001810	0.000259	13.146	0.000001
Error	23	0.000452	0.000020		
Total	30	0.002263			

Table D-82: Post-hoc test for shear stress for 2.1 l s^{-1}

Cell No.	LSD test; variable AS 2.1 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00002, df = 23.000				
	Sample code	AS 2.1 Mean	1	2	3
3	F2LR	0.014131		****	
4	F2NR	0.029597	****		
6	FCNR	0.031287	****		
5	FCLR	0.032134	****		
7	FLR	0.032894	****		
8	FNR	0.034725	****		
1	CLR	0.035427	****		
2	CNR	0.042585			****

Table D-83: Univariate ANOVA test for shear stress for 2.2 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.2 SS	AS 2.2 MS	AS 2.2 F	AS 2.2 p
Intercept	1	0.026635	0.026635	841.0360	0.000000
Sample code	7	0.001232	0.000176	5.5589	0.000766
Error	23	0.000728	0.000032		
Total	30	0.001961			

Table D-84: Post-hoc test for shear stress for 2.2 l s^{-1}

Cell No.	LSD test; variable AS 2.2 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00003, df = 23.000				
	Sample code	AS 2.2 Mean	1	2	3
3	F2LR	0.014354			****
4	F2NR	0.027687	****		
5	FCLR	0.029721	****	****	
6	FCNR	0.029752	****	****	
7	FLR	0.031534	****	****	
8	FNR	0.032786	****	****	

1	CLR	0.033095	****	****	
2	CNR	0.036634		****	

Table D-85: Univariate ANOVA test for shear stress for 2.3 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.3 SS	AS 2.3 MS	AS 2.3 F	AS 2.3 p
Intercept	1	0.024196	0.024196	743.0478	0.000000
Sample code	7	0.001146	0.000164	5.0296	0.001434
Error	23	0.000749	0.000033		
Total	30	0.001895			

Table D-86: Post-hoc test for shear stress for 2.3 l s^{-1}

Cell No.	LSD test; variable AS 2.3 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00003, df = 23.000				
	Sample code	AS 2.3 Mean	1	2	3
3	F2LR	0.013821			****
5	FCLR	0.026965	****		
4	F2NR	0.027162	****	****	
6	FCNR	0.028049	****	****	
7	FLR	0.029128	****	****	
8	FNR	0.030865	****	****	
1	CLR	0.033145	****	****	
2	CNR	0.035384		****	

Table D-87: Univariate ANOVA test for shear stress for 2.4 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.4 SS	AS 2.4 MS	AS 2.4 F	AS 2.4 p
Intercept	1	0.023329	0.023329	2465.357	0.000000
Sample code	7	0.001678	0.000240	25.326	0.000000
Error	23	0.000218	0.000009		
Total	30	0.001895			

Table D-88: Post-hoc test for shear stress for 2.4 l s^{-1}

Cell No.	LSD test; variable AS 2.4 (Ex 3 flow velocity and shear stress data) Homogenous Groups, alpha = .05000 Error: Between MS = .00001, df = 23.000				
	Sample code	AS 2.4 Mean	1	2	3
3	F2LR	0.011569			****
4	F2NR	0.025738	****		
6	FCNR	0.026562	****		
5	FCLR	0.026997	****		
7	FLR	0.027238	****		
8	FNR	0.029339	****		
1	CLR	0.034493		****	
2	CNR	0.038520		****	

Table D-89: Univariate ANOVA test for shear stress for 2.5 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.5 SS	AS 2.5 MS	AS 2.5 F	AS 2.5 p
Intercept	1	0.038472	0.038472	24.99337	0.000047
Sample code	7	0.019186	0.002741	1.78057	0.139879
Error	23	0.035403	0.001539		
Total	30	0.054589			

Table D-91: Univariate ANOVA test for shear stress for 2.6 l s^{-1}

Effect	Univariate Results for Each DV (Ex 3 flow velocity and shear stress data) Sigma-restricted parameterization Effective hypothesis decomposition				
	Degr. of Freedom	AS 2.6 SS	AS 2.6 MS	AS 2.6 F	AS 2.6 p
Intercept	1	0.031892	0.031892	29.11528	0.000020
Sample code	7	0.014845	0.002121	1.93606	0.111784
Error	22	0.024098	0.001095		
Total	29	0.038943			

Appendix E

E.1 Plant Trait ranking system class boundaries

Table D-105: Plant Trait Ranking System Class Boundaries for Experiment 1.

Scores	No. seeds Germtd 2 weeks	% Germination	Grass FW (g)	Plant Height	% Cover	No. Tillers	No. Stems	Stem Diameter	Stem Area Density
1.00	3.71	28.60	0.11	29.49	4.57	3.76	3.86	1.05	0.004
2.00	6.43	40.50	0.21	45.88	7.14	5.19	6.71	1.66	0.007

3.00	9.14	52.40	0.30	62.27	9.71	6.62	9.57	2.26	0.010
4.00	11.86	64.30	0.39	78.66	12.29	8.04	12.43	2.86	0.014
5.00	14.57	76.20	0.48	95.05	14.86	9.47	15.29	3.46	0.017
6.00	17.29	88.10	0.58	111.44	17.43	10.90	18.14	4.07	0.020
7.00	20.00	100.00	0.67	127.83	20.00	12.33	21.00	4.67	0.024

Table D-106: Plant trait ranking system class boundaries for Experiment 1 cont.

Scores	AGBM (FW)	AGBM (DW)	BGBM (FW)	BGBM (DW)	Total Root Length	Root to Shoot Ratio	Total Surface Area	Avg Root Diam (mm)	Length of roots <=0.25 mm
1.00	1.91	0.25	1.68	0.20	723.91	2.97	82.53	0.27	429.75
2.00	3.27	0.44	3.08	0.40	1376.28	5.72	155.48	0.32	843.45
3.00	4.64	0.62	4.49	0.59	2028.66	8.47	228.43	0.36	1257.16
4.00	6.01	0.81	5.89	0.78	2681.03	11.22	301.39	0.41	1670.86
5.00	7.38	0.99	7.30	0.97	3333.41	13.97	374.34	0.46	2084.57
6.00	8.74	1.18	8.70	1.17	3985.78	16.72	447.29	0.51	2498.27
7.00	10.11	1.36	10.11	1.36	4638.16	19.47	520.24	0.55	2911.98

Table D-107: Plant trait ranking system class boundaries for Experiment 2.

Score	% Germination	Plant Height (cm)	% Cover	AGB (g)	Number of stems	SAD (cm^2 cm^{-2})	Total Root length <0.25	RSA (cm^2)	Rdiam (mm)
1	40.625-46.53	16.8-22.45	20-22.71	3.76-5.02	97-115.57	60.27-90.3	58.81-109.19	8.68-15.81	0.24-0.33
2	46.53-52.41	22.45-28.1	22.71-25.42	5.02-6.28	115.57-134.14	90.3-120.33	109.19-159.57	15.81-22.94	0.33-0.42
3	52.41-58.29	28.1-33.75	25.42-28.13	6.28-7.54	134.14-152.71	120.33-150.36	159.57-209.95	22.94-30.07	0.42-0.51
4	58.29-64.17	33.75-39.4	28.13-30.84	7.54-8.80	152.71-171.28	150.36-180.39	209.95-260.33	30.07-37.20	0.51-0.60

5	64.17-70.05	39.4-45.05	30.84-33.55	8.80-10.06	171.28-189.85	180.39-210.42	260.33-310.71	37.20-44.33	0.60-0.69
6	70.05-75.93	45.05-50.7	33.55-36.26	10.06-11.32	189.85-208.42	210.42-240.45	310.71-361.09	44.33-51.46	0.69-0.78
7	75.93-81.81	50.7-56.4	36.26-39.00	11.32-12.61	208.42-227	240.45-270.48	361.09-411.47	51.46-58.61	0.78-0.88

Table D-108: Plant trait ranking system class boundaries for Experiment 3.

Score	Stem Area Density (cm^2 cm^{-2})	AGBM (dw) (g)	Number of Tillers	Number of Stems	Stem Diameter (mm)
1.00	0.0689-0.0180	7.1500-9.8271	1.4000-1.7714	50-69.86	1.13-1.34
2.00	0.0180-0.0265	9.8271-12.5043	1.7714-2.1429	69.86-89.71	1.34-1.55
3.00	0.0265-0.0350	12.5043-15.1814	2.1429-2.5143	89.71-109.57	1.55-1.76
4.00	0.0350-0.0435	15.1854-17.8586	2.5143-2.8857	109.57-129.43	1.76-1.96
5.00	0.0435-0.0519	17.8586-20.5357	2.8857-3.2571	129.43-149.29	1.96-2.17
6.00	0.0519-0.0604	20.5357-23.2129	3.2571-3.6286	149.29-169.14	2.17-2.38
7.00	0.0604-0.0689	23.2129-25.8900	3.6286-4.0000	169.14-189	2.38-2.58

Table D-109: Plant trait ranking system for class boundaries for Experiment 3 continued.

Score	Height (cm)	% Canopy Cover	% Ground Cover	% Germination	Rl <0.25 mm	RSA (cm^2)	Rdiam (mm)
1.00	31.88-34.12	60-65.57	9.0-12.0	58.41-61.95	127.13-311.43	13-105.80	0.24-0.55
2.00	34.12-36.37	65.57-71.14	12.0-15.0	61.95-65.50	311.43-495.74	105.80-198.60	0.55-0.87
3.00	36.37-38.61	71.14-76.71	15.0-18.0	65.50-69.04	495.74-680.04	198.60-291.40	0.867-1.18
4.00	38.61-40.85	76.71-82.29	18.0-21.0	69.04-72.58	680.04-864.34	291.40-384.20	1.18-1.49
5.00	40.85-43.09	82.29-87.86	21.0-24.0	72.58-76.12	864.34-1048.65	384.20-477.00	1.49-1.81
6.00	43.09-45.34	87.86-93.43	24.0-27.0	76.12-79.66	1048.65-1232.95	477.00-569.80	1.81-2.12
7.00	45.34-47.58	93.43-99.00	27.0-30.0	79.66-83.21	1232.95-1417.25	569.80-662.60	2.12-2.43

E.2 Detachment via rainsplash scores

Table D-110: Plant trait data and scores as related to their theoretical ability to control detachment by rainsplash for all species for Flume Experiment 1.

Species	% Emergence	% Cover	SAD (mm^2 mm^{-2})	AGB (g)	Total Score
Fest_1	67.93 (5)	24.1 (3)	214.32 (6)	9.6 (4**)	18
Conv	50.32 (2)	29.8 (4)	87.89 (1)	5.01 (1)	8
Fest_1+Fest_2	69.8 (5)	28.6 (4)	149 (3)	5.93 (1**)	13
Fest_1+Fest_2+Conv	60.61 (4)	33 (6)	148.48 {3)	7.86 (4)	17

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). **Put into a lower category as significantly similar so has to be in the same boundary.

Table D-111: Plant trait data and scores as related to their theoretical ability to control detachment by rainsplash for all species for Flume Experiment 2.

Species	% Emergence	% Ground Cover	SAD (mm^2 mm^{-2})	AGB (g)	Total Score
Fest_1 L	70.3 (4)	12.4 (1)**	0.019 (1)**	8.91 (1)	7
Fest_1 L R	70.3 (4)	11.5 (1)	0.023 (1)**	12.54 (3)	9
Fest_1 N	75.9 (5)	13.5 (1)**	0.015 (1)	8.34 (1)	8
Fest_1 N R	75.9 (5)	13.1 (1)**	0.013 (1)	9.79 (1)	8
Conv L	58.4 (1)	14.5 (2)	0.014 (1)	10.67 (1)	5
Conv L R	58.4 (1)	17.1 (3)	0.016 (1)	14.85 (3)	8
Conv N	59.4 (1)	23.1 (5)	0.022 (1)**	9.18 (1)	8
Conv N R	59.4 (1)	24.1 (5)**	0.017 (1)	11.46 (2)	9
Fest_1+Fest_2 L	83.2 (7)	11.0 (1)	0.025 (2)	12.97 (3)	13
Fest_1+Fest_2 L R	83.2 (7)	11.8 (1)	0.024 (2)	16.50 (4)	14
Fest_1+Fest_2 N	86.0 (1)	14.3 (1)**	0.044 (5)	20.96 (6)	13
Fest_1+Fest_2 N R	86.0 (1)	13.4 (1)**	0.039 (4)	14.97 (4)	10
Fest_1+Fest_2+Conv L	78.06 (5)	14.8 (1)**	0.014 (5)	13.68 (3)	14
Fest_1+Fest_2+Conv L R	78.06 (5)	14.8 (1)**	0.048 (5)	18.10 (5)	16
Fest_1+Fest_2+Conv N	83.09 (7)	15.5 (3)	0.017 (1)	12.10 (2)	13
Fest_1+Fest_2+Conv N R	83.09 (7)	16.5 (3)	0.032 (1)**	18.37 (5)	16

Fest_1 (*Festulolium cv prior*), Conv (a mixture of *Lolium perenne* and *Festuca rubra*), Fest_1+Fest_2 (*Festulolium cv prior* and *Festulolium Bx511*) and Fest_1+Fest_2+Conv (*Festulolium cv prior, Festulolium Bx511, Lolium perenne* and *Festuca rubra*). Experimental treatments followed by letters are as follows L (Lowered seeding rate), N (Normal seeding rate), R (roots only). **Put into a lower category as significantly similar so has to be in the same boundary as others.