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

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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. Belowground 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 utilized in this study can be used to inform rapid screening of candidate grass species for soil erosion control.

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.

KEYWORDS

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

1 | INTRODUCTION

1.1 | 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).

1.2 | Plant traits affecting soil erosion in GWWs

1.2.1 | Selection of plant traits that affect soil erosion processes

Figure 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 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).

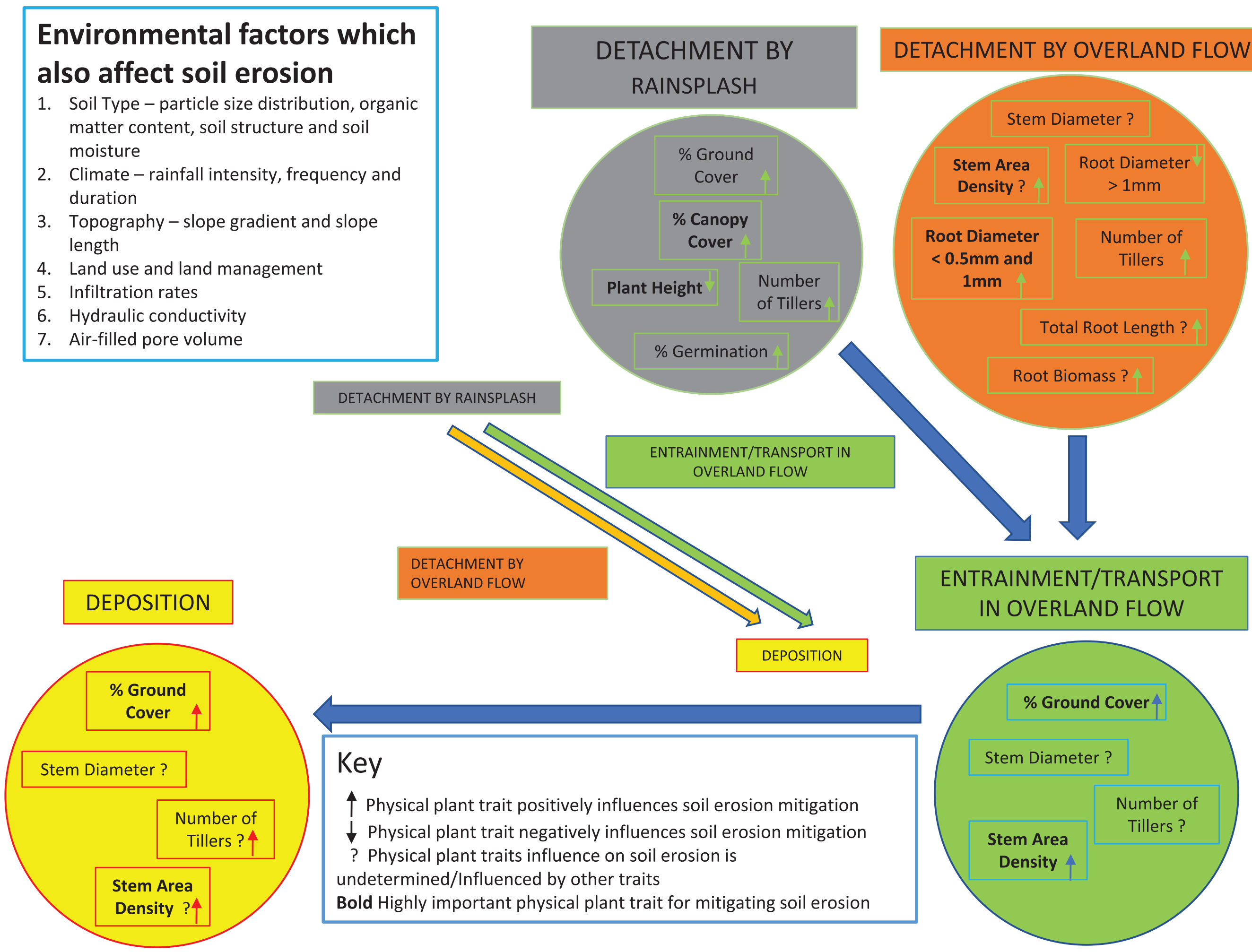

FIGURE 1 Soil erosion processes as affected by plant traits

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 | METHODOLOGY

2.1 | Experimental set-up

2.1.1 | 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 soil association, known to be at high risk of water erosion (Evans, 1990; Hollis & Hodgson, 1974). The microcosms were similar 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 <1.0% and an EC of 4.25 mS/cm. Water holding capacity was estimated at 20% (Cornell University, 2010). No fertiliser was applied to the soil.

Before filling the microcosms, the soil was thoroughly mixed, air dried and sieved by hand through a < 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.

2.1.2 | 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.

2.1.3 | Rainfall scenario treatments

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.

2.1.4 | Species treatments and seeding rates

As shown in Table 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 F*estulolium* 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 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

TABLE 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).

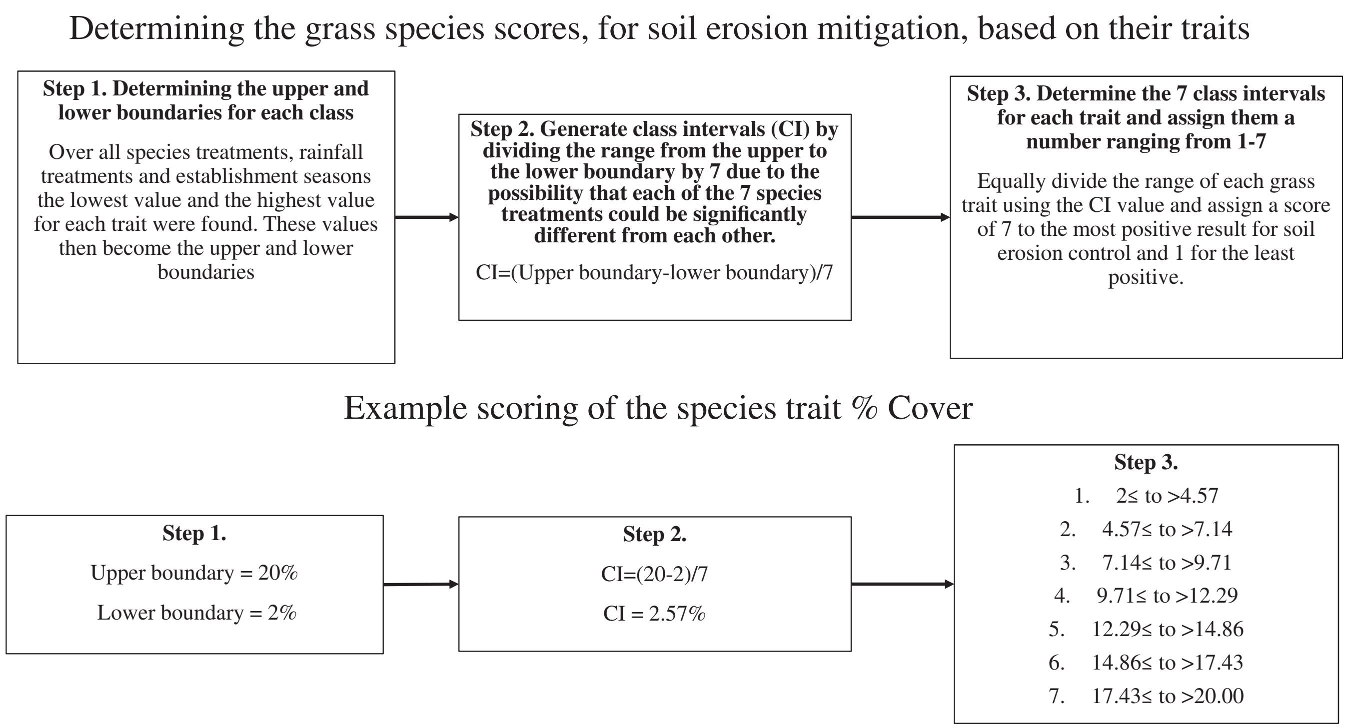

FIGURE 2 Schematic of the determination of boundaries, intervals and scoring values for each plant trait, with a worked example of the % cover grass trait

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:

TABLE 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 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 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.

no rainfall (Drought), normal rainfall (Norm_R) and twice the normal amount of rainfall (Excess_R).

2.2 | Experimental 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.

2.3 | 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). 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). Using the % cover data as a worked example, the class range was 2% to 20%, with a class interval of 2.57% (Figure 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.

TABLE 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**

The drought and rainfall excess values are variances from the normal rainfall value. Scores that are negative show a reduction in theoretical erosion control under the extreme rainfall scenarios (drought and excess rainfall) as compared to normal rainfall scenarios.

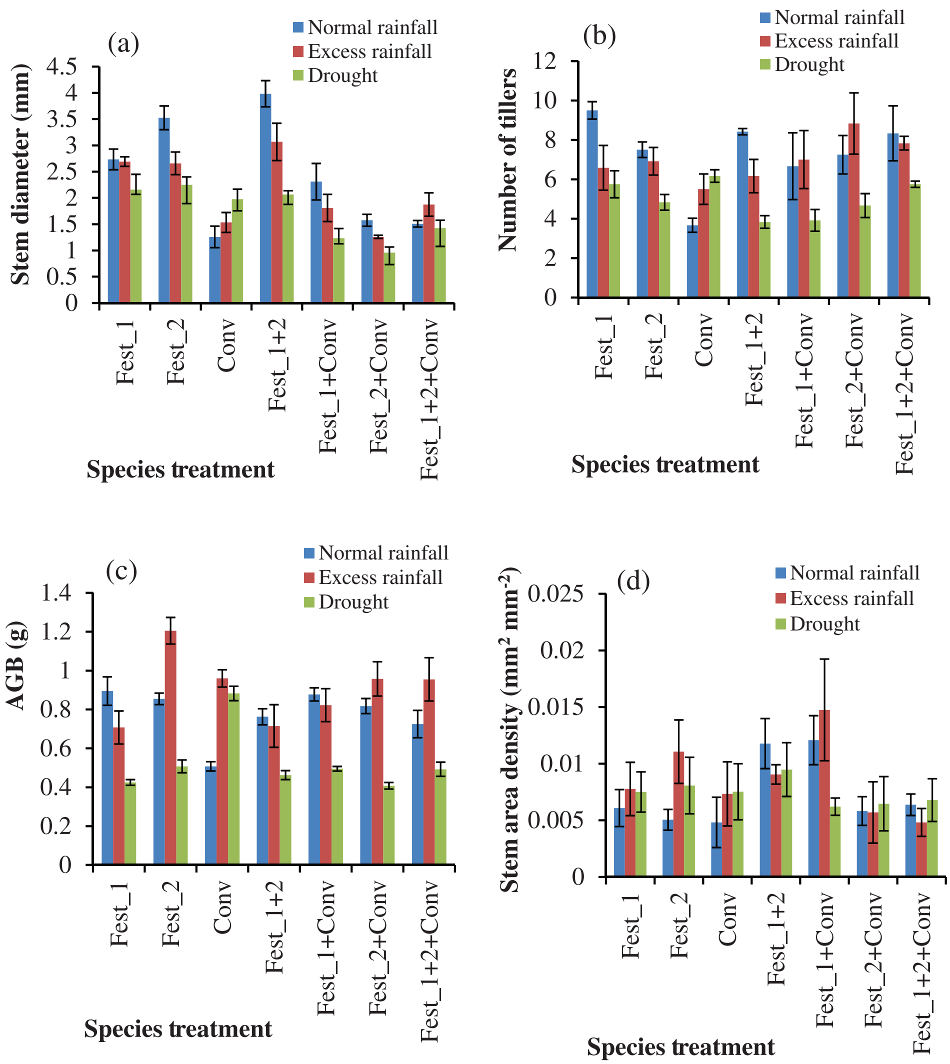

FIGURE 3 Aboveground plant traits, (a) stem diameter (mm), (b) number of tillers, (c) AGB (g) and (d) stem area density (mm^2 mm^{-2}), for summer establishment, according to species treatment and rainfall scenario. Error bars represent ±1 standard error

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).

2.4 | Plant trait measurements

2.4.1 | Aboveground 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, root total surface area, 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 (SAD) was calculated using the following equation:

$$\text{Stem area Density} = \frac{\text{Surface area of the stems}*\text{number of stems}}{\text{Surface area of the microcosm}} \quad (1)$$

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).

2.4.2 | 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.

3 | RESULTS

3.1 | 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 Supplementary Information Figures 1 and 2 and Tables 3a-3o and 4a-4o. 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 3a).

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 3b) 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 (Figure 2b) 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 (Tables 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 3c). Fest_2 had significant differences between Drought (0.51 g), Norm_R (0.86 g) and Excess_R (1.21 g) conditions (Figure 2c).

The stem diameter and number of tillers were significantly different, yet no statistically significant differences were observed in stem area density for autumn establishment (Table 2-4). 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.

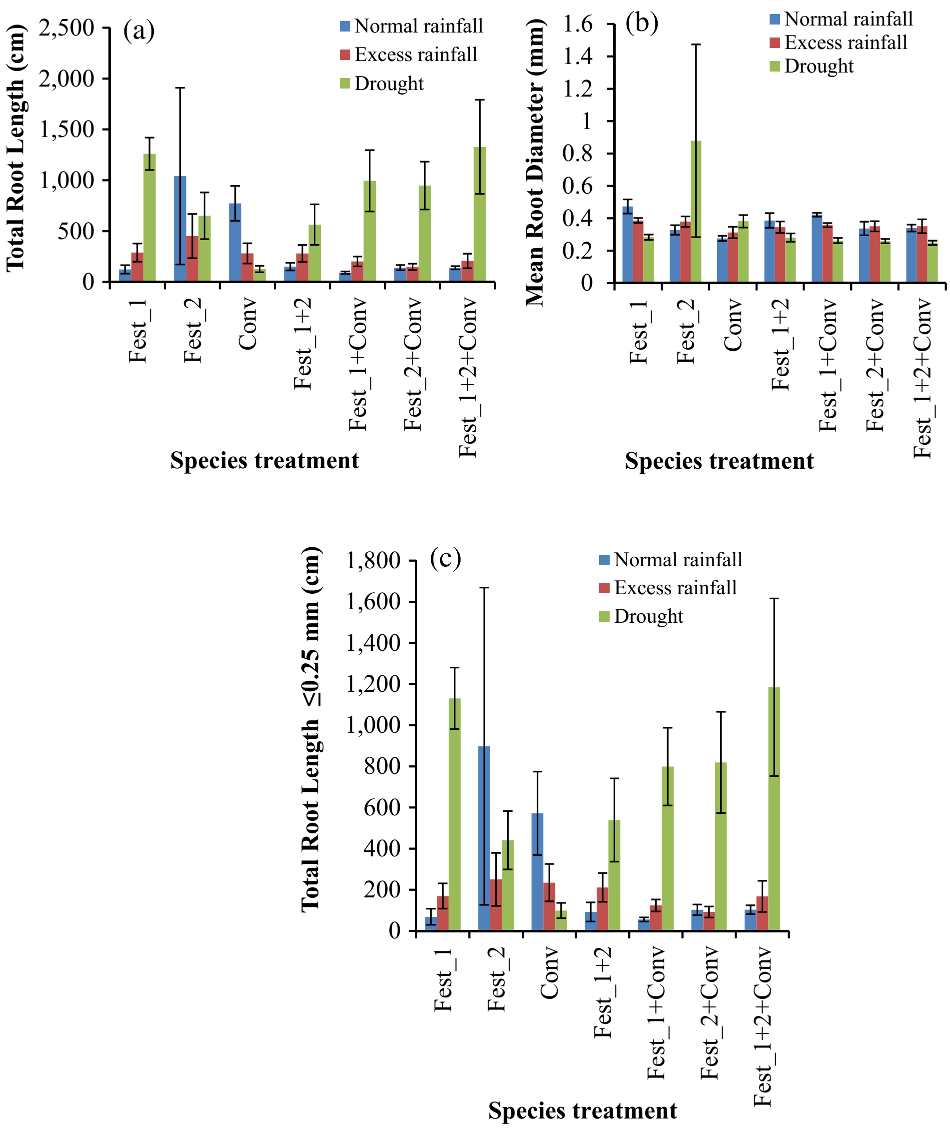

FIGURE 4 Belowground plant traits, (a) total root length (cm), (b) mean root diameter (mm) and (c) total root length ≤ 0.25 mm in diameter (cm), for summer establishment, according to species and rainfall scenario treatments. Error bars represent ±1 standard error

3.2 | Differences in belowground 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 3a). Fest_2 showed no significant differences in root length between the three rainfall scenarios under summer establishment (Figure 4a).

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 (Figure 4b).

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 (Table 3). 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 (Figure 4c).

The belowground biomass (BGB), total root surface area and root to shoot ratio all followed a similar trend (see Section 3.4) to the total root length and for brevity are not shown in Figure 4.

3.3 | 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.

3.4 | 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 1) were scored following the approach explained in 2.4 (Tables 2-4). The final treatment-specific plant trait scores are presented in Table 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). 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).

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 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 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 (Table 4).

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 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.

4 | DISCUSSION

4.1 | Grass physical traits

4.1.1 | 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.

4.2 | 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).

4.3 | 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 5). Furthermore, under autumn establishment, Fest_1 + 2 showed the highest soil erosion mitigation potential (mix of two species) (Table 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 1), had a higher soil erosion mitigation potential than the monoculture of *Festulolium* (Table 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.

4.4 | 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).

4.5 | 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.

5 | 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.

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AUTHOR CONTRIBUTIONS

Corina Lees: Data curation; formal analysis; investigation; methodology; validation; visualization; writing-original draft. **Robert Simmons:** Conceptualization; funding acquisition; project administration; supervision; writing-review and editing. **Jane Rickson:** Supervision; writing-review and editing. **Sarah De-Baets:** Conceptualization; funding acquisition; project administration; supervision; writing-review and editing.

DATA SHARING AND ACCESSIBILITY STATEMENT

The data will be available on the Cranfield University research data repository, Cranfield Online Research Data (CORD).

CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest or relationships, financial or otherwise, that might be perceived as influencing the objectivity of this research.

AUTHOR CONTRIBUTIONS

Corina Lees developed the original idea and the protocol, generated and analysed data, and wrote the manuscript. Sarah De Baets and Robert Simmons contributed to the development of the original idea and the experimental protocol, and prepared/revised the manuscript. Jane Rickson contributed to revising the manuscript.

DATA AVAILABILITY

All data supporting this study are openly available from the Cranfield University research data repository (CORD) at https://figshare.com/s/a48c215886e16d1fecd2

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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