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Effect of Ecologically Restored Vegetation Roots on the Stability of Shallow Aggregates in Ionic Rare Earth Tailings Piles

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Abstract: Aggregate stability is considered an essential indicator of changes in the physical properties of soils, and vegetation roots play a crucial role in the stability of shallow soil aggregates in ionic rare earth tailings piles during ecological remediation. In this paper, the influence of the law of ecologically restored vegetation roots on the stability of shallow aggregates of ionic rare earth tailing piles was investigated by means of field investigation tests, indoor experiments and mathematical statistics. The influence of different types of root systems on the stability of the shallow depth range aggregates of tailings piles was investigated; the correlation between vegetation root systems and the main physical parameters of rare earth tailings was clarified; and a mathematical correlation model characterizing the characteristic parameters of vegetation root systems was constructed. The evaluation index of the stability of rare earth tailings piles was constructed, and the influence of the law of the ecological restoration of vegetation root systems on the strength of shallow aggregates of ionic rare earth tailings piles was revealed. The results of the study showed that compared with the RD (root density), the root characteristic parameter with the largest response weight to the rare earth tailings pile is the RL (root length density), and the root characteristic parameter with the largest response weight to the water content is the RV (root volume). Suitable vegetation roots can effectively enhance the content of shallow large aggregates of rare ionic earth tailing piles. With the increase of the depth of a tailing pile, the content of large aggregates continues to decrease, and the content of micro aggregates continues increasing. This indicates that the vegetation root system changed the shallow soil of the rare earth tailing pile from disorderly to orderly through its own growth pattern, which effectively improved the stability of the shallow aggregates of the tailing pile and improved the physical properties of the tailing.

Keywords: ionic rare earth tailings pile; ecological restoration; aggregates stability; root system characteristics parameters; relevance analysis

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1. Introduction

An ionic rare earth tailings pile is a kind of industrial slag pile which suffers from leaching erosion, disordered soil structure, weak bonding or no gluing [1,2]. The early heap leaching and pool leaching processes will produce about 2000 cubic meters of tailings for every 1 ton of mixed rare earth obtained [3,4]. Relevant reports show that in the Southern Jiangxi Province, there are nearly 200 million tons of rare earth tailings that have been left behind, occupying an area of 97.34 square kilometers of mountains' forests, and the cost of comprehensive treatment is expected to exceed CNY 40 billion [5]. Currently, the treatment of ionic rare earth tailing pile reactors, using traditional mine ecological restoration technology, has shown initial results. However, due to the erosion of the ionized rare earth tailings pile by the leaching liquid during mining, the large number of pollutants accumulated in the soil will affect the quality of the soil for a long time, resulting in changes in the internal physical properties of the soil, which seriously affects the growth of ecological restoration vegetation. As a result, the problems of ecological restoration in local areas, such as low vegetation survival rate and serious shallow soil erosion, have still not been effectively solved [6–8].

Aggregates are the basic unit that constitute soil structure. Its stability is considered to be an important indicator to measure the change of the physical properties of the soil, which directly affects the behavior and mechanical effects of the shallow soil-water interface [9]. A large number of research results show that the root parameters of vegetation will have different degrees of influence on the structure, particle size, content, distribution and other characteristic indicators of the aggregates, thus changing the overall stability of shallow soils [10,11]. Haoxin Hao et al. investigated the effect of root characteristics on the stability of conventional soils. They found that the root length density increased the content of large aggregates in the shallow layer and gradually decreased with the depth. The root length density changes the structure and distribution of soil aggregates, thus playing the ability to control the separation soil [12]. Iván Prieto et al., through the test method, found that the mass density of the root system influenced the content of deep aggregates, and the root system failed to wrap the deep soil, resulting in the stability of deep soil aggregates being much lower than that of the shallow soil [13]. Greenwald, Konrad et al. investigated the effect of vegetation roots on the stability of soil aggregates in the Alps. They found that with the increase of root density, the aggregates content in the soil increase, and vegetation coverage and diversity have a positive impact on the overall stability of root density guidance [14].

In recent years, in order to effectively break through the problems of ecological restoration and the management of ionized rare earth mines, many scholars have carried out a lot of research on the micromechanical properties of ionized rare earth ores (including tailings). Xiaojun Wang et al., through the indoor simulated leaching test, found that compared with pure water leaching, $(NH_4)_2SO_4$ leaching fluid leads to particle movement and reconstruction, reducing the number of pore sizes and pore quantity. In addition, it was found that the seepage effects are caused by a chemical action of ion exchange rather than the physical action caused [15]. Lingbo Zhou et al. explored the evolution of pore structure in the leaching process through indoor experiments. They found that the number of small and medium pores increased significantly, and the number of medium–large pores decreased sharply during the ion exchange process. The porous structure evolution showed the opposite trend with the completion of the ion exchange process [16]. YunZhang Rao et al., through indoor column leaching tests, direct shear tests and the application of fractal theory, found that the ion exchange during the leaching process destroyed the soil skeleton. Moreover, the overall shear strength of the soil is declining. The fractal theory has a good effect on the characterization of particle gradation and shear strength parameters [17]. GuanShi Wang et al. analyzed the shear expansion characteristics of ionic rare earth ore bodies through plastic work increments, put forward the shear expansion equation of ionic rare earth ore bodies and constructed an elastic–plastic constitutive model suitable for ionic rare earth ore bodies. The elastic–plastic stiffness matrix of this model, under a general stress state, proves that it has a good fitting effect on the indoor three-axis CD test results of ionic rare earth ore bodies [18].

The above research generally considers the change law and characteristics of the physical and mechanical properties of ionic rare earth ore bodies (including tailings), and there is no targeted research that has been conducted on the mechanism of the effect of vegetation roots on the stability of shallow aggregates in ecological restoration. This paper takes the ionized rare earth tailings pile after ecological restoration as the research background. Through investigation and testing, the correlation between the vegetation root system and the main physical parameters of the rare earth tailing is clarified, and then a mathematical correlation model that can characterize the characteristic parameters of the vegetation root system and the evaluation index of the stability of the rare earth tailing aggregates is constructed, revealing the influence law of the ecologically restored vegetation root system on the stability of the shallow aggregates of the rare ionic earth tailing pile. Finally, the necessary essential theoretical basis for the comprehensive management of the ionic rare earth mine is provided.

2. Materials and Methods

2.1. Study Area and Grass Selection

The study site is in the planned rare earth mining area in the south of Ganzhou City, Jiangxi Province, China (Figure 1), which has a subtropical monsoon climate with an average annual temperature of 20.4 °C and a total rainfall of 1644.73 mm. The geographical location is between 24°29′~27°09′ N and 113°54′~116°38′ E, with a total area of 39,379.64 square kilometers. This area is formed by the accumulation of rare earth mines left by early heap leaching and pond leaching and is affected by leaching erosion and weathering camp force. The survival rate of ecological restoration vegetation in this area is low, and local soil erosion problem still exists, so this area was selected for experimental study. In this experiment, three types of vegetation commonly found in rare earth tailings piles (Figure 2), Paspalum notatum Flugge, Setaria viridis and Cynodon dactylon (L.), were selected, and they have various types of vegetation characteristics (Table 1).

Figure 1. Study area.

Figure 2. Vegetation sample.

Table 1. Vegetation characteristics [19,20].(Reproduced or adapted from [19,20], with permission from Acta Agriculturae Universitatis Jiangxiensis and China University of Mining and Technology, Beijing, China, 2012, 2019.)

Vegetation Sample	Feature Description
Paspalum notatum Flugge	The vegetation has a well-developed root system, suitable for tropical and subtropical growth, drought-resistant and erosion-resistant root system and a high foliage survival rate.
Setaria viridis	This annual herbaceous vegetation has well-developed fibrous roots, wide rhizomes, a warm and temperate climate, strong water absorption and good survival ability.
Cynodon dactylon (L.)	Growing in warm areas and wasteland slopes, its rhizome has a robust spreading ability, strong resistance, high coverage and a good function of fixing and retaining soil.

2.2. Sample Collection and Parameters

The test was conducted in autumn when the rainfall was moderate so that the natural environment could reduce the damage to the adhesion of the sample particles [21]. Three ionic rare earth tailings under a vegetation cover were selected as the study samples, and rootless tailings were used as the control group samples. The lots with uniform plant distribution and good growth on the ionic rare earth tailings piles were selected as the sampling points for the models. The field survey found that the root length of ionic rare earth tailing pile vegetation is generally around 20–30 cm, and the effective zone of root action is concentrated in the shallow layer of the tailing pile [22]. The ring knife and soil cutter were used to take samples in stratified layers (Horizon 0.0~10.0 cm, Horizon 10.0~20.0 cm, Horizon 20.0~30.0 cm) within the vertical depth of the set sample, and another trial samples' collection was conducted after the rainfall (Figure 3). Rare earth tailings and root system samples were obtained separately and marked accordingly. A total of 12 rare earth tailings pile samples were collected at different depths of the soil layer with a ring knife. The parameter information such as the number of vegetation roots collected in different soil layers is shown in Table 2. The collected air-dried samples are used to determine the mechanical aggregates' content according to the appropriate geotechnical test methods. The basic physical parameters of the vegetation root system were determined using high precision vernier calipers. Basic physical parameters of the vegetation root system (Table 2) and physical parameters of rare earth tailings (Table 3) are provided.

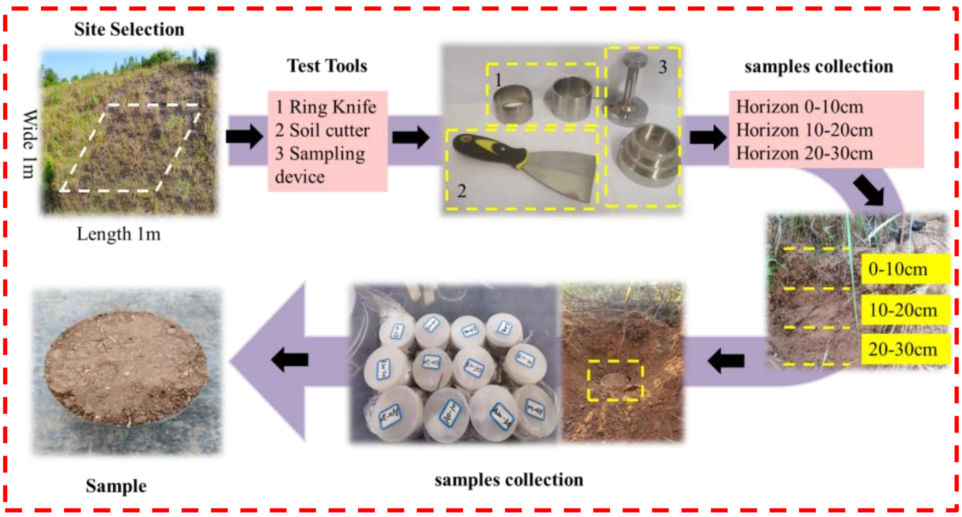


Figure 3. Sampling process.

Table 2. Basic physical properties of vegetation root systems.

Sample Type	Depth /cm	Length of Horizontal Extension /cm	Number of Root Systems /Root	Average Diameter /cm	Root Depth /cm
Root of Setaria viridis	0–10	16.0	103	0.371	29
	10–20	9.3	49	0.283	
	20–30	8.3	28	0.226	
Root of Cynodon dactylon (L.)	0–10	18.0	116	0.419	26
	10–20	11.9	52	0.297	
	20–30	9.6	28	0.187	
Root of Paspalum notatum Flugge	0–10	18.5	122	0.436	33
	10–20	14.6	75	0.302	
	20–30	9.8	42	0.251	

Table 3. Basic physical properties of rare earth tailings.

Sample Type	Depth /cm	Weight Capacity /g·cm^{-3}	Water Content /%	Porosity /%
Tailings with Paspalum notatum Flugge root system	0–10	1.31	11.0	37.4
	10–20	1.46	15.2	35.3
	20–30	1.54	18.1	34.1
Tailings with Setaria viridis root system	0–10	1.34	10.5	36.5
	10–20	1.58	12.5	34.5
	20–30	1.62	17.1	33.4
Tailings with Cynodon dactylon (L.) root system	0–10	1.32	9.7	37.2
	10–20	1.48	10.3	34.9
	20–30	1.58	11.8	33.8
Rootless tailings	0–10	1.62	4.5	33.4
	10–20	1.77	5.4	33.2
	20–30	1.73	7.8	33.3

2.3. Root System Characteristic Parameters

Relying on root physical parameters cannot directly characterize the effect on the stability of rare earth tailings' aggregates. Therefore, the three characteristic parameters of root length density (RL), root density (RD) and root volume (RV) were selected to analyze the root growth morphology of vegetation [23,24]. RL is the sum of root length per unit volume, reflecting the ability of the root system to absorb nutrients and water; RD is the sum of root number per unit volume, reflecting the impact resistance of root-containing tailings; RV is the volume of the vegetation root system per unit volume, reflecting the growth distribution and extension characteristics of the root system in the tailings pile. The specific calculation formula is as follows.

$$\rho_{RL} = \frac{L_A}{V_h} \quad (1)$$

$$\rho_{RD} = \frac{M}{V_h} \quad (2)$$

$$\rho_{RV} = \frac{V_A}{V_h} \quad (3)$$

where ρ_{RL} is the root length density in cm·cm^{-3}; L_A is the sum of root lengths per unit volume, in mm; V_h is the unit volume, which is taken as 1000 cm^3 in this paper, ρ_{RD} is the root density in root·cm^{-3}; M is the sum of the number of roots per unit volume, in roots; ρ_{RV} is the volume of the root system in cm^3·cm^{-3}; V_A is the sum of the root volume per unit volume in cm^3. Vegetation root system characteristics parameters are provided in Table 4.

Table 4. Root system characteristic parameters.

Root Samples	Depth /cm	RL /cm·cm^{-3}	RD /Root·cm^{-3}	RV /cm^3·cm^{-3}
Root of Paspalum notatum Flugge	0–10	2.26	0.120	0.334
	10–20	1.10	0.075	0.078
	20–30	0.41	0.042	0.020
Root of Setaria viridis	0–10	1.65	0.103	0.178
	10–20	0.46	0.063	0.029
	20–30	0.23	0.053	0.010
Root of Cynodon dactylon (L.)	0–10	2.09	0.116	0.288
	10–20	0.42	0.052	0.043
	20–30	0.27	0.028	0.007

2.4. Sieve Test for Aggregates Content

The mechanical aggregate content of rare earth tailing pile samples were determined by the Shavinov dry sieving method. Test instruments include a dry sieving machine, sieves with different apertures, electronic scales, test recording papers, etc. Before the test, the collected medium and large pieces of rare earth tailings were broken into small pieces of about 10 mm in diameter along their natural structural fissures, cleaned of impurities such as vegetation roots and whiskers, and dried by natural air. In conducting the test, first, 200 g of mixed air-dried samples were placed in the set of sieve apertures, 10, 7, 5, 3, 2, 1, 0.5, 0.25 mm set of sieves for the top sieve (with a cover and bottom), with a 20 times/min vibration rate for sieving. Secondly, the mass of remaining aggregates on the sieve of each pore size was weighed. The content of mechanically stable aggregates was calculated for each particle size > 10 mm, 10–7 mm, 7–5 mm, 5–3 mm, 3–2 mm, 2–1 mm, 1–0.5 mm, 0.5–0.25 mm, and <0.25 mm, respectively (Figure 4).

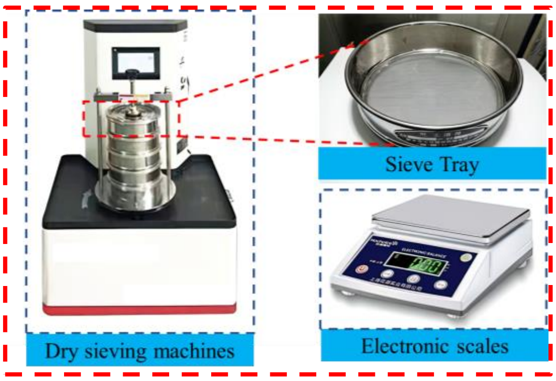


Figure 4. Test of dry sieve.

To show the single grain level change process, in this study, it is proposed that there are large aggregates (>5 mm), medium aggregates (5–2 mm), small aggregates (2–0.25 mm), and micro aggregates (<0.25 mm). This classification is used for a more detailed observation of the effects of different rooting interactions on the shallow stability of ionic rare earth tailings.

2.5. Correlation Analysis Method Selection

Because the vegetation root system samples have multiple characteristic parameters, there may be multiple correlations between the parameters, so the partial correlation analysis method was selected. This characterizes the correlation between the root parameters and the basic physical parameters of the tailings pile sample. When analyzing the correlation between variables Q_1 and Q_2, the influence of the interference variable, Q_3, is controlled, and the partial correlation coefficient between Q_1 and Q_2 is as follows: (Equation (4)). (Q_1, Q_2: Represent the root characteristics parameters (RL, RD and RV) with respect to the bulk density, water content and porosity, respectively. Q_3: Representative root system characteristic parameters (RL, RD and RV) were used as disturbance factors, respectively). Since there are multiple root system characteristic parameters and rare earth tailing pile stability evaluation indexes, PLS regression analysis (partial least squares regression) was selected to analyze the interaction between multiple dependent variables and independent variables, simultaneously, to analyze the influence of root system characteristic parameters on the stability of rare ionic earth tailing pile aggregates [25,26]

$$r_{12(3)} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{1 - {r^2}_{13}}\sqrt{1 - {r^2}_{23}}} \tag{4}$$

where r_{12} is the correlation coefficient of variables Q_1 and Q_2, r_{13} is the correlation coefficient of variables Q_1 and Q_3; and r_{23} is the correlation coefficient of variables Q_2 and Q_3.

The following equation is the significance test statistic for the bias correlation coefficient calculated for the sample.

$$t = \frac{r\sqrt{n - k - 2}}{\sqrt{1 - r^2}} \tag{5}$$

where r is the specific partial correlation coefficient, n is the number of observations, k is the number of control variables and $n - k - 2$ is the degree of freedom.

2.6. Introduction of Stability Evaluation Index

As the most basic unit of tailings structure, the structure, composition and particle size distribution of aggregates have essential effects on nutrient retention and water-holding capacity of the soil, and different vegetation types and land use methods will have a significant impact on the particle size distribution and content of aggregates [27]. The stability of aggregates is an important indicator to evaluate their quality, and standard evaluation methods include MWD (Mean Weight Diameter). MWD (Equation (6)) is one of the common indicators to judge the distribution of agglomerate size and its stability. Its value indicates the strength of soil agglomeration and resistance to erosion. GMD (Geometric Mean Diameter) (Equation (7)) is one of the standard indexes used to judge the grain level distribution and stability of aggregates, and its value indicates the spatial distribution state of soil aggregates and the strength of erosion resistance [28]. Fractal D (Dimension) (Equation (8)) shows the physical properties of the soil; the more significant the D value, the worse the physical properties and structural stability of the aggregates [29].

$$MWD = \frac{\sum_{i=1}^{n} \overline{x_i} w_i}{\sum_{i=1}^{n} w_i} \tag{6}$$

$$GMD = Exp\frac{\sum_{i=1}^{n} w_i In\overline{x_i}}{\sum_{i=1}^{n} w_i} \tag{7}$$

$$D = 3 - lg(M_i/M_0)/lg(d_i/d_{max}) \tag{8}$$

where x_i is the average diameter of the tailing's particle size, in mm. w_i is the proportion of aggregates of different particle sizes to the total aggregates. d_i is the average of two sieve grades. d_{max} is the average value of the largest particle size. m_i is the cumulative particle size mass less than d_i. m_0 is the sum of the masses of the particle classes.

3. Results

3.1. Effect of Root System Parameters on the Physical Properties of Rare Earth Tailings

From the partial correlation analysis results between the root characteristic parameters and the physical parameters of rare earth tailings' samples, it can be found that compared with the RV and RD, the root characteristic parameter with the largest response weight and moisture content of rare earth tailings is RL; the influence of the three root characteristic parameters on the porosity of ionic rare earth tailings is almost the same (Table 5). This result may be due to the interfering influence of the parameters on each other.

Table 5. Linear correlation results (* $p < 0.05$ ** $p < 0.01$).

Parameter Type	Relevance	RL	RD	RV	Bulk Density	Water Content	Porosity
RL	Correlation coefficient	1.000 **	0.998 **	0.979 *	−0.961 *	−0.999 **	0.998 **
	value of p	0.000	0.002	0.021	0.037	0.001	0.002
RD	Correlation coefficient	0.998 **	1.000 **	0.966 *	−0.918	−0.902	0.998 **
	value of p	0.002	0.000	0.034	0.082	0.082	0.002
RV	Correlation coefficient	0.979 *	0.966 *	1.000 **	−0.851	−0.969 *	0.971*
	value of p	0.021	0.034	0.000	0.149	0.031	0.029
Bulk density	Correlation coefficient	−0.961 *	−0.918	−0.851	1.000 **	0.920	−0.935
	value of p	0.037	0.082	0.149	0.000	0.080	0.065
Water content	Correlation coefficient	−0.999 **	−0.902	−0.969 *	0.920	1.000 **	−0.998 **
	value of p	0.001	0.082	0.031	0.080	0.000	0.002
Porosity	Correlation coefficient	0.998 **	0.998 **	0.971 *	−0.935	−0.998 **	1.000 **
	value of p	0.002	0.002	0.029	0.065	0.002	0.000

To effectively reduce the interfering effects between parameters, RL, RD and RV were used as correlation groups with the bulk weight, water content and porosity, respectively. The control interfering terms were used for RL, RD and RV in this process. The correlations between parameters and physical quantities were explored separately, and the mutual effects between the characteristic parameters of the root system could be discharged (Table 6). After excluding the influence of interfering factors, it is found that the most significant response weight for the bulk density of the tailings pile containing the Paspalum notatum Flugge root system is the RL; the most significant response weight to the water content is the RV; the porosity of tailing piles containing the root system show a significant correlation with each parameter. Following this method, the results of the other two vegetation bias correlation analyses are shown in the Supplementary Materials.

Table 6. Biased correlation analysis of tailings containing Paspalum notatum Flugge (* $p < 0.05$ ** $p < 0.01$).

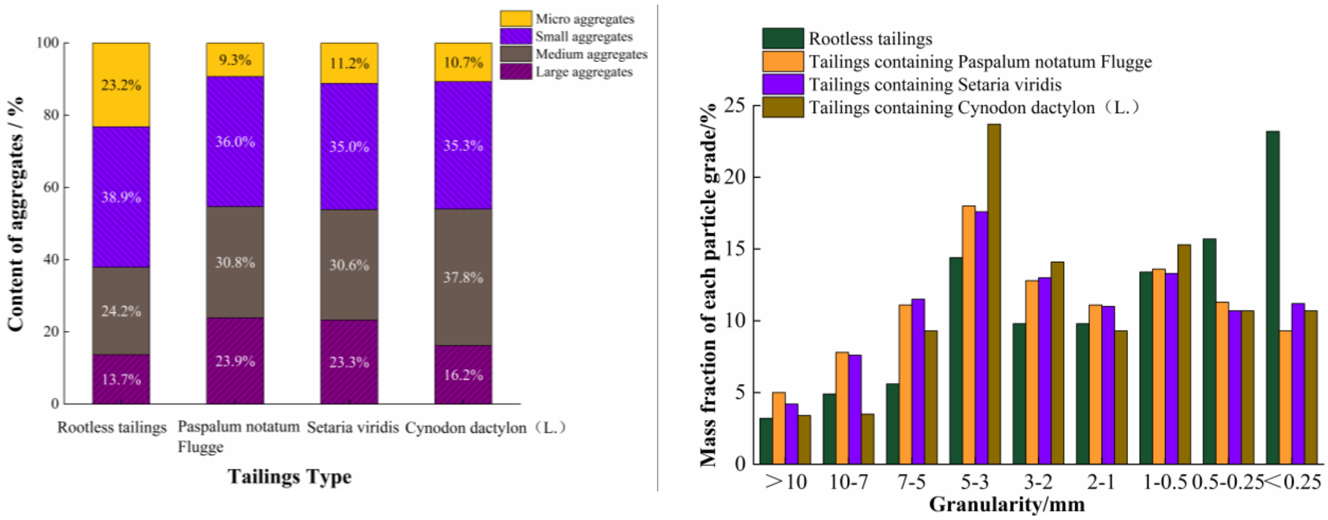
Parameter Type	Relevance	RLRD	RLRV	RDRL	RDRV	RVRL	RVRD
Bulk density	Correlation coefficient	0.898 *	−0.418	0.653	−0.409	0.893	0.865
	value of p	0.038	0.484	0.232	0.495	0.052	0.078
Water content	Correlation coefficient	−0.656	0.332	0.873	0.982 **	−0.870 *	0.830
	value of p	0.229	0.586	0.053	0.003	0.049	0.082
Porosity	Correlation coefficient	0.976 **	−0.654	−0.651	−0.936 *	0.965 *	0.945 *
	value of p	0.003	0.231	0.234	0.042	0.035	0.038

3.2. Effect of Root System on the Stability of Mechanical Aggregates

3.2.1. Distribution Characteristics of Aggregates at the Same Depth

Horizon 0–10 cm:

Changes in the content of rare earth tailing pile sample aggregates under the action of the root system is shown in Figure 5. Compared with the rootless tailings sample, the existence of the root system increases the large and medium aggregates as a whole. Among them, the proportion of large aggregates in the tailing pile samples containing the Paspalum notatum Flugge and Setaria viridis roots increased by 10.2% and 9.6%, respectively. On the contrary, the proportion of small aggregates and micro aggregates slightly decreased, indicating that the root systems of vegetation play the role of wrapping the soil body in the surface layer of the rare earth tailing pile. The developed fibrous roots of the three-vegetation sample promote the soil body to gather each other, which fully increases the stability of the surface aggregates of the rare earth tailing pile, and then plays the role of preventing surface soil erosion. Among them, the Paspalum notatum Flugge and Setaria viridis roots have a more significant effect on >5 mm aggregates, while the Cynodon dactylon (L.) root has a more significant effect on 5–3 mm aggregates.

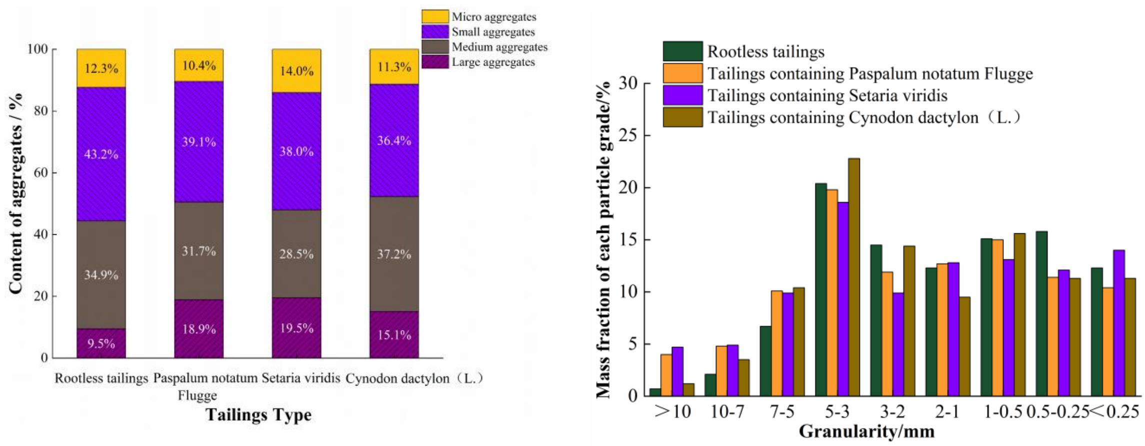


(**a**) (**b**)

Figure 5. Distribution characteristics of aggregates. (**a**) Effect of the root system on aggregates' content; (**b**) particle size distribution of aggregates.

Horizon 10–20 cm:

Changes in the content of rare earth tailing pile sample aggregates under the action of the root system are provided (Figure 6). The existence of vegetation roots makes the proportion of large aggregates higher than that of rootless tailings. The difference between medium aggregates is obvious. The root system of Paspalum notatum Flugge and Setaria viridis makes the aggregates' content of rare earth tailings pile samples smaller than that of rootless tailings, while the Cynodon dactylon (L.) root system makes the content of middle aggregates greater than that of rootless tailings. This is because the root systems of Paspalum notatum Flugge and Setaria viridis grow vertically compared with the root of Cynodon dactylon (L.), and the distribution of aggregates is changed in this deep growth form. The mass fraction of the aggregates of each root-containing tailings sample at 0.5–0.25 mm is less than that of the rootless tailings pile, indicating that the vitality and shape of root growth are enough to change the agglomeration at this depth and turn it into a small aggregate to reduce stability.

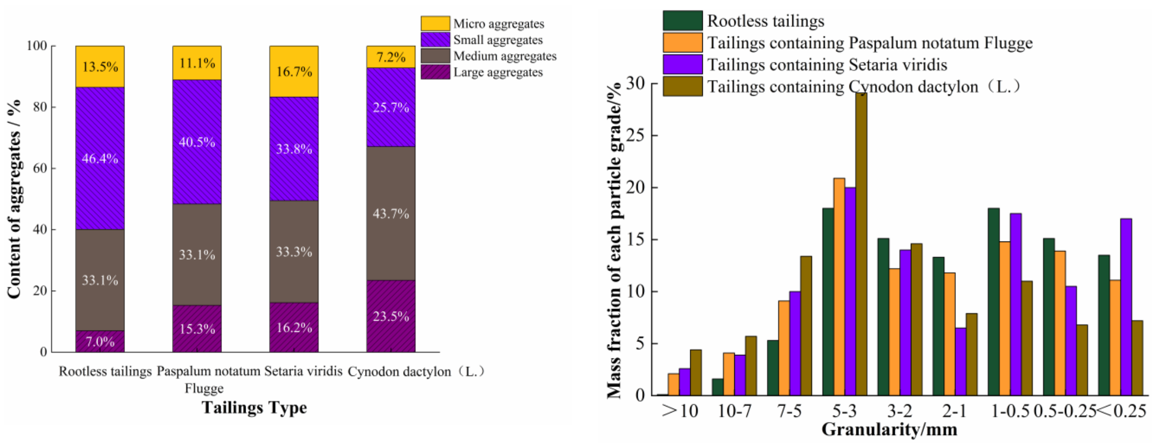


(**a**) (**b**)

Figure 6. Distribution characteristics of aggregates. (**a**) Effect of the root system on aggregates' content; (**b**) particle size distribution of aggregates.

Horizon 20–30 cm:

Changes in the content of rare earth tailings pile sample aggregates under the action of the root system are shown in Figure 7. Compared with the sample of the rootless tailings pile, the overall large aggregates of this depth have increased, including the largest number of root tailings containing Cynodon dactylon (L.), which is 3.4 times more than the rootless tailings. This is because the growth depth of the vegetation root system is limited. Compared with the upper end, the lower root system is sparse and less dynamic, which makes it difficult to wrap the soil, so it has less impact on the change of this depth of the aggregates. It also fully shows that the vegetation root system reduces soil erosion by changing the stability of shallow aggregates. The variability of medium aggregates is obvious. The positive effect of the Cynodon dactylon (L.) root system was obvious, and the mass fraction of medium aggregates reached 43.7%. However, the proportion of medium aggregates containing the Paspalum notatum Flugge and Setaria viridis roots tailings samples is not much different from that of rootless tailings piles, and small agglomerates have been reduced. The micro aggregates also showed some degree of variability, with the Paspalum notatum Flugge root system continuing to show reverse action, the Setaria viridis root system showing positive action and the Cynodon dactylon (L.) root system showing extremely strong reverse action, with a nearly 50% reduction in micro agglomerate content compared to the rootless tailings.



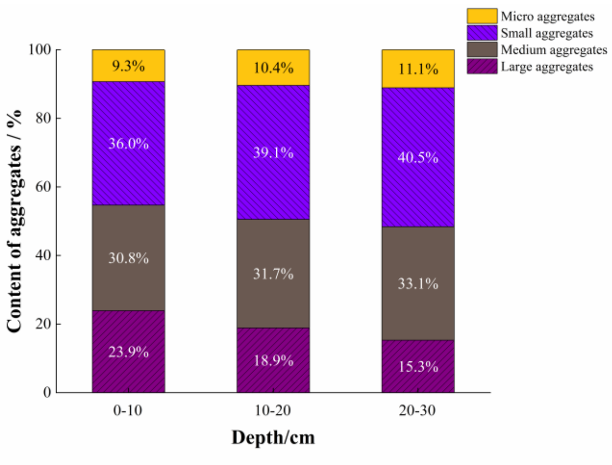
(**a**) (**b**)

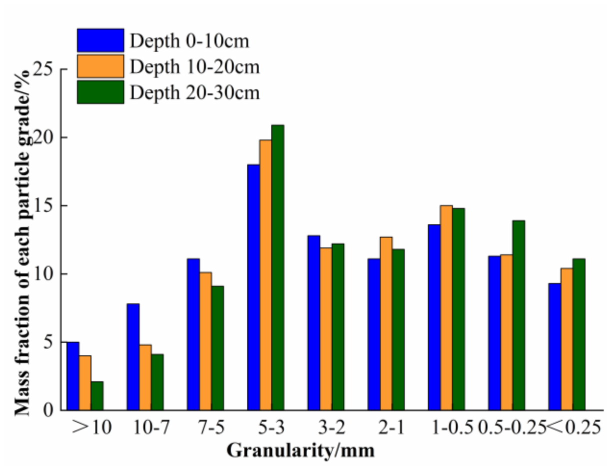
Figure 7. Distribution characteristics of aggregates. (**a**) Effect of root system on aggregates' content; (**b**) particle size distribution of aggregates.

3.2.2. Effect of Root System of Different Species on Aggregate Characteristics and Distribution

Paspalum notatum Flugge:

The variation of aggregates' content with depth for the rare earth tailing pile samples is shown in Figure 8. The overall large aggregates of the root-bearing tailings pile decreased continuously with depth. However, the content of large aggregates in the deep layer is similar to that in the shallow layer. This means that the primary roots of Paspalum notatum Flugge grow vertically and act as a wrapper around the soil in the shallow layer. The content of medium, small and large aggregates showed a slight fluctuation with depth, indicating that the growth of the fibrous roots of Paspalum notatum Flugge is more uniform, and the gathering ability of the surrounding soil is similar, which can play a good role in aggregation. Furthermore, the content of aggregates at different depths varies significantly. The content of >5 mm aggregates decreased continuously with depth, and the most significant number of aggregates was found in 5–3 mm and increased with depth. In terms of <2 mm aggregates, the percentage of aggregates at 0–10 cm depth was smaller than at other depths, indicating that the effect of the Paspalum notatum Flugge root system on small aggregates mainly existed within the surface depth of 0–10 cm.





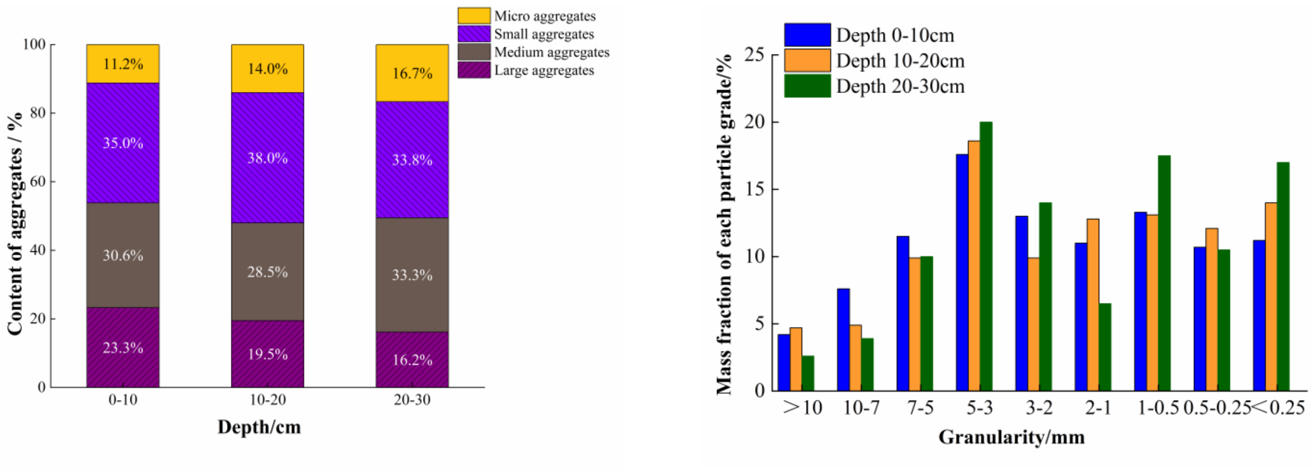
(**a**) (**b**)

Figure 8. Distribution characteristics of aggregates. (**a**) Effect of depth on aggregates' content; (**b**) effect of depth on the particle size of aggregates.

Setaria viridis:

The variation of agglomerate content with depth for the rare earth tailing pile samples is provided (Figure 9). The large aggregates decrease with depth, indicating that the shallow root system of Setaria viridis is well-developed and can play a good role in the aggregation of the shallow soil. The medium and small aggregates showed fluctuating changes, and the large aggregates showed a positive trend with depth changes. The differences in the content of large aggregates at different depths of the same grain size were more significant. The agglomerate mass fraction decreased gradually with depth in the interval of 10–7 mm and then decreased to the lowest in the depth of 20–30 cm, followed by a slight increase. The medium agglomerate content fluctuated continuously with depth, with 5–3 mm aggregates behaving differently from the sizeable agglomerate variation described above, and the 20–30 cm depth agglomerate content was the largest. While the variability of agglomerate content at each depth was significant in the 3–2 mm interval, the lowest agglomerate content was found at the 10–20 cm depth and then increased significantly, indicating that vegetation roots did not perceive the current grain level interval strongly at this depth and its role was not prominent. The differences between small aggregates and large agglomerate contents at different depths of the same grain level were significant. At the

2–1 mm interval, the minimum value appeared at a 20–30 cm depth. At the 1–0.5 mm interval, the maximum value appeared at a 20–30 cm depth. As for large aggregates, the increase of large aggregates under the action of vegetation roots decrease with increasing depth, indicating that vegetation roots have less and less ability to modify and repair micro aggregates with increasing depth.



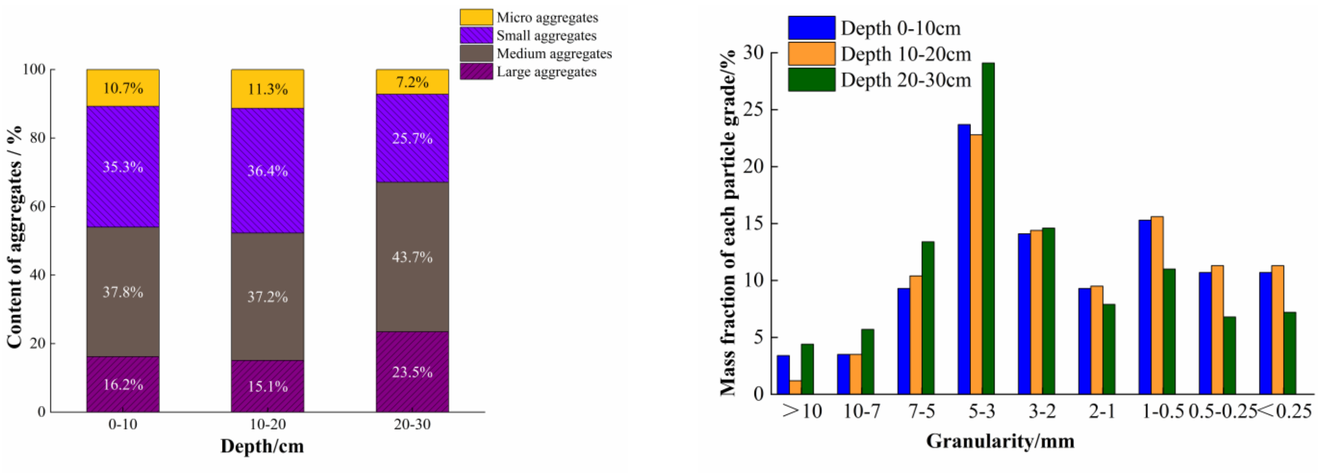
(**a**) (**b**)

Figure 9. Distribution characteristics of aggregates. (**a**) Effect of depth on aggregates' content; (**b**) effect of depth on the particle size of aggregates.

Cynodon dactylon (L.):

The variation of aggregate content with depth for the rare earth tailing pile samples is shown in Figure 10. The large aggregates reached the maximum depth of 20–30 cm and then decreased. This indicates that the effect of the Cynodon dactylon (L.) root system on rare ionic earth tailing pile samples is persistent and shows a strengthening trend with depth instead, which may be related to the vegetation root system's morphology. The content of large aggregates at different depths of the same grain size varied significantly. In the interval > 10 mm, the lowest mass fraction of aggregates was found at a 10–20 cm depth under the action of the Cynodon dactylon (L.) root system, but then rebounded; and the content of aggregates at the 20–30 cm depth was more significant than that at the 0–10 cm depth. The 10–5 mm interval showed a similar pattern. This may be related to this interval's slow decline of the root parameters of the Cynodon dactylon (L.) roots. The 2–1 mm, 1–0.5 mm, 0.5–0.25 mm and <0.25 mm particle sizes show the opposite trend to that of large aggregates. This indicates that it dramatically affects the modification of small micro aggregates at a 20–30 cm depth. The effect of the Cynodon dactylon (L.) root system on ionic rare earth tailings' mechanical stability aggregates do not show an obvious pattern with depth, but its effect in the interval of >2 mm and <2 mm is evident at a 20–30 cm depth, with the increase of large aggregates and the decrease of micro aggregates.

Combined with the above results, it is found that the presence of vegetation roots has different effects on the distribution characteristics of rare ionic earth tailing pile samples' aggregates at different depths. The performance is that the root system gathers the shallow soil of the rare earth tailings pile through its growth form, so that the content of large aggregates has increased significantly, and the content of medium and small aggregates has also changed. the aggregates distribution of different soil layers of rare earth tailings piles has changed from disorder to order, thus alleviating the soil erosion of shallow soils and improving the overall stability of rare earth tailings piles.



(**a**) (**b**)

Figure 10. Distribution characteristics of aggregates. (**a**) Effect of depth on aggregates' content; (**b**) effect of depth on the particle size of aggregates.

4. Discussion

4.1. Analysis of the Effect of Root System Action on the Stability of Rare Earth Tailings

The above test analysis alone does not fully explain the impact of the vegetation root system on the stability of ionic rare earth tailings' aggregates. Therefore, the aggregates evaluation index will be introduced below, taking into account the influence of the root system on the stability of the aggregates of ion-type rare earth tailings piles.

The MWD of rare earth tailings pile sample aggregates changes with depth under root action (Figure 11). It can be found that the MWD value gradually decreases with increasing depth, indicating that the aggregates' resistance of the deep layer of the rare earth tailings pile is weak. At a depth of 0–20 cm, the MWD under the action of Paspalum notatum Flugge roots is greater than that of various types of tailings, indicating that the Paspalum notatum Flugge root system of the tailings pile samples at this depth can improve the overall stability and corrosion resistance of the ion-type rare earth tailing pile accumulation. The variability of MWD values of aggregates of each root-bearing tailings pile at a 20–30 cm depth gradually decreases, and the MWD values of root-bearing tailings' aggregates in this area continue to decrease compared with the previous depth, but the decrease is significantly reduced.

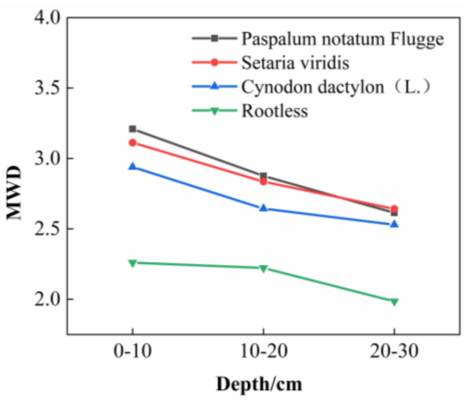


Figure 11. The effect of depth on MWD.

The GMD of rare earth tailings pile sample aggregates changes with depth under root action (Figure 12). It can be found that with the increase of depth, the GMD value of each type shows a downward trend, indicating that the agglomeration distribution at the deep soil of the rare earth tailings pile is relatively scattered, and the corrosion resistance is poor. At a depth of 0–20 cm, the GMD difference of tailings' aggregates is not significant, but they are higher than rootless tailings' samples. This shows that this deep vegetation root system gathers the soil aggregates, so that its distribution changes from disorderly to orderly and improves the spatial state of the distribution of the aggregates. In the 20–30 cm deep soil layer, the GMD value difference of the tailings' aggregates gradually increases, indicating that the vegetation root system cannot convert aggregates.

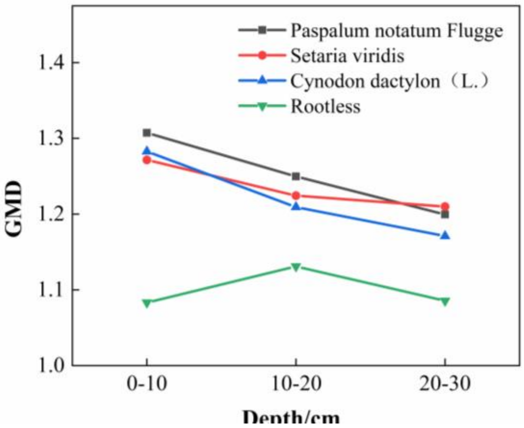


Figure 12. The effect of depth on GMD.

Under the action of the root system, the D value of rare earth tailings' aggregates changes with depth (Figure 13). In the range of 0–30 cm, the D value of the rootless sample gradually decreases, and the D value of the root-containing sample gradually increases. The larger the fractal dimension D value, the worse the physical properties and stability of the soil. In the range of 0–20 cm, the D values of the rootless tailing samples were much larger than those of the root-containing tailings samples, and the positive effect played by Paspalum notatum Flugge and Cynodon dactylon (L.) on the soil body was similar. This shows that the root system played a role in improving the tailings soil's physical properties and the shallow aggregates' stability. Comparing the above discussion and analysis with the research of other scholars, it is found that the stability indicators of the aggregates of rare earth tailings' samples under the action of the root system are similar to the conventional soil under the action of the root system, and the vegetation root system shows an improvement in the physical and chemical properties and structural stability of the tailings pile at a depth. This shows that the vegetation root system can effectively improve the nature of the soil and play a role in ecological restoration [30–32].

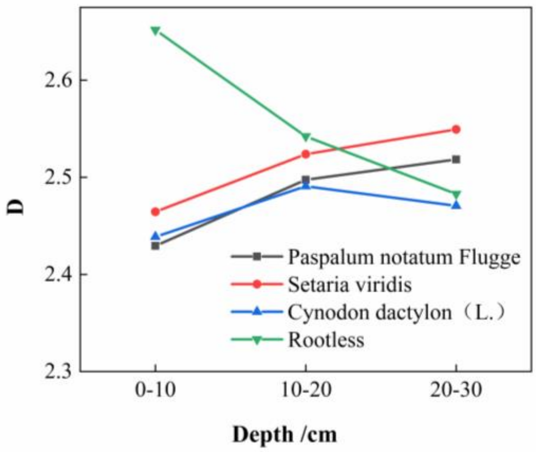


Figure 13. The effect of depth on D.

4.2. Mechanisms of the Influence of Root Characteristic Parameters on the Stability of Tailings' Aggregates

The vegetation root characteristics parameters RL, RD and RV are taken as independent variables, and the aggregates stability evaluation indicators MWD, GMD and D are taken as dependent variables. The PLS regression analysis method was used to calculate the relationship equation between dependent variables and independent variables (Table 7), and the standardized regression coefficient plots were obtained (Figure 14). The magnitude of the absolute value of the standardized regression coefficient indicates the magnitude of the influence of each parameter of the vegetation root system.

The RL is always dominant among the different vegetation root characteristics parameters. Among the indicators of aggregates' stability, the RL and RD degree of Paspalum notatum Flugge had the most significant influence on MWD, GMD and D. RV contributed little to the stability of the aggregates. The RL of Setaria viridis has the highest degree of influence on MWD and D, followed by RV; RL has the highest degree of influence on GMD, followed by RD and little influence on RV. The RL of Cynodon dactylon (L.) has the highest degree of influence on MWD, GMD and D, followed by RV, which has minimal influence.

In summary, the influence on the index of cluster stability is not determined by a single vegetation root characteristic parameter but through the interaction between characteristic root parameters. RL is an important parameter affecting aggregate stability compared to RD and RV on the aggregate stability index. RD and RV play an auxiliary role in improving the stability of aggregates based on the dominance of RL. Through the preliminary investigation, it is found that the effective length of the three vegetation root systems was concentrated in the shallow layer of the rare earth tailing pile specimens, which also indicated that the root system mainly changed the distribution of the shallow soil aggregates to improve the erosion and overall stability of the rare earth tailing pile.

Table 7. Correlation equation for the variable tailings containing the Paspalum notatum Flugge root system.

Root	Dependent Variable	Relational Equation of the Independent Variable
Paspalum notatum Flugge	MWD	MWD = −45 × RL + 37 × RD + 8 × RV (R2 = 0.973 SEE = 21)
	GMD	GMD = −66 × RL + 54 × RD + 12 × RV (R2 = 0.965 SEE = 26)
	D	D = −20 × RL + 16 × RD + 3 × RV (R2 = 0.975 SEE = 20)
Setaria viridis	MWD	MWD = 6.161 × RL − 0.267 × RD − 4.980 × RV (R2 = 0.962 SEE = 30)
	GMD	GMD = −6.439 × RL + 4.606 × RD + 2.802 × RV (R2 = 0.981 SEE = 15)
	D	D = −4.556 × RL + 0.343 × RD + 3.250 × RV (R2 = 0.959 SEE = 35)
Cynodon dactylon (L.)	MWD	MWD = 14.802 × RL − 5.698 × RD − 8.186 × RV (R2 = 0.963 SEE = 28)
	GMD	GMD = 29.903 × RL − 12.271 × RD − 16.839 × RV (R2 = 0.978 SEE = 19)
	D	D = −87.427 × RL + 41.237 × RD + 45.778 × RV (R2 = 0.983 SEE = 13)

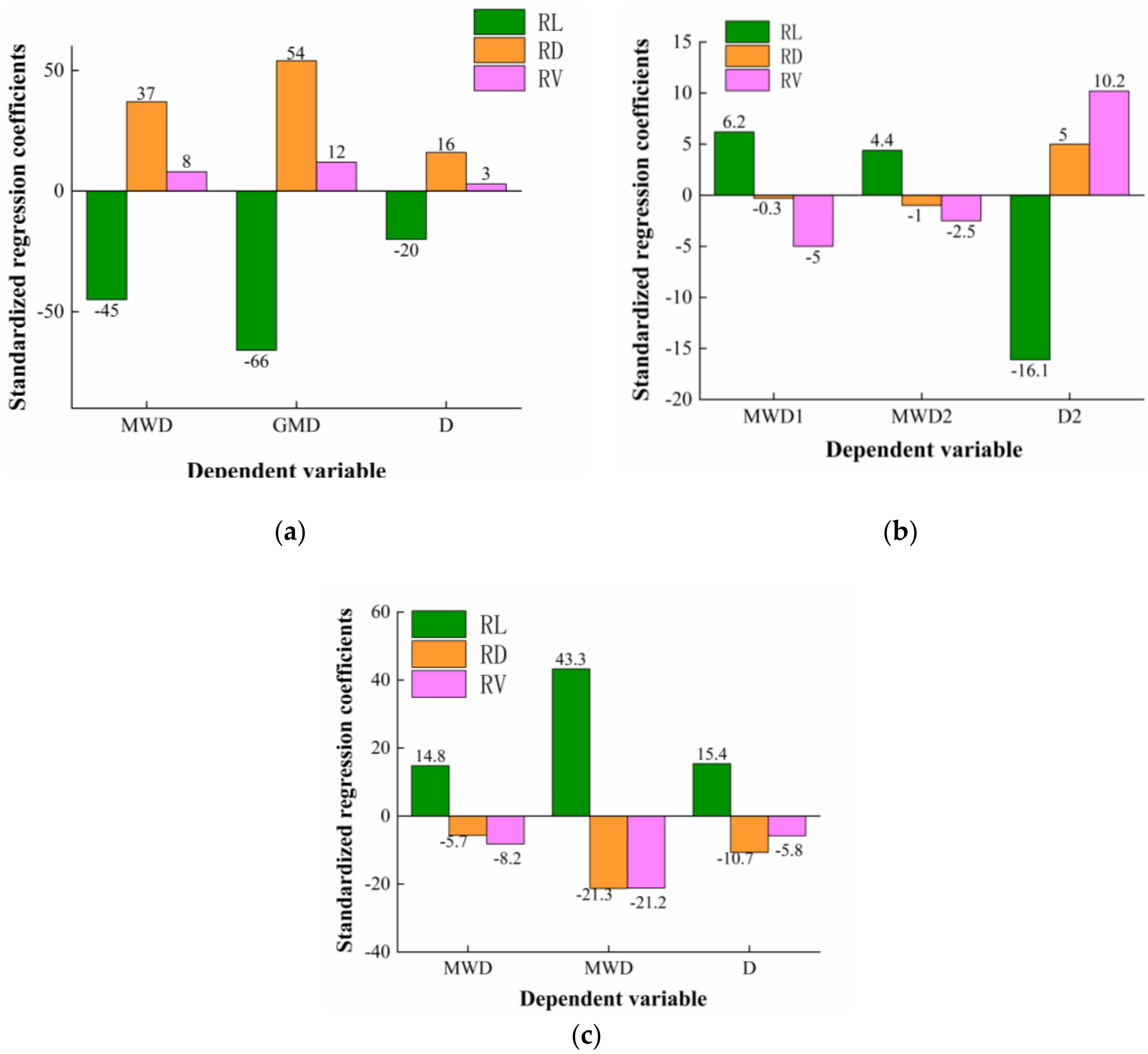


Figure 14. Standardized regression coefficient graph. (**a**) Paspalum notatum Flugge; (**b**) Setaria viridis; (**c**) Cynodon dactylon (L.).

5. Conclusions

In this paper, through on-site investigation and testing, indoor testing and mathematical statistical analysis, the distribution characteristics of different soil formation aggregates of ionic rare earth tailings' specimens were obtained under the action of root systems, and aggregates' evaluation indicators were introduced to compare and analyze the distribution of rootless rare earth tailings samples' aggregates. The correlation between the vegetation root characteristic parameters and the physical parameters of the rare earth tailings pile was clarified, and the influence of the existence of the root system on the distribution characteristics of different depth aggregates of rare earth tailings' specimens was explored. Finally, the method of mathematical statistical analysis was used to analyze the root characteristic parameters and the stability evaluation index of rare earth tailings, as well as the mutual influence between them.

1. The vegetation roots effectively improved shallow aggregates' content and spatial distribution in the rare earth-tailing pile. The vegetation root system is not limited to transforming small aggregates and sticking to large aggregates but changes the distribution of soil aggregates according to its own growth needs. By changing

the content and distribution of aggregates, the root system changes the soil of rare earth tailings from disorderly to orderly, thus relieving soil erosion and improving the overall stability of shallow soil. This shows that the rare earth tailings pile can improve the overall stability of the soil through afforestation during ecological restoration.

2. An analysis of stability indicators of rare earth tailings' aggregates under the influence of root systems found that the vegetation root system effectively improved the stability of rare earth tailing pile aggregates, enhanced their ability to resist external forces, hydraulic dispersion or changes in external hydrological conditions while maintaining their original form, increased the corrosion resistance of their aggregates, optimized spatial distribution, improved physical properties and enhanced structural stability. The stability index of rootless tailings' aggregates varies haphazardly. The stability of root-containing tailings' aggregates shows a continuous weakening with increasing depth until it tends to be similar to rootless tailings, indicating that the vegetation root system has a specific improvement effect on the aggregates at their depths and gradually weakens with depth downward, and does not significantly modify the aggregates below their root distribution areas.
3. Statistical analysis of root system characteristic parameters and aggregates stability was performed. It was found that the root system of Paspalum notatum Flugge is superior to other root systems in maintaining the stability of rare earth tailings, because all of its root parameters are greater than those of other root systems. Different root parameters played different roles in the stability index of the aggregates, and the root length density, RL, is the critical factor affecting the stability of the aggregates. Therefore, when we carry out ecological restoration of rare earth tailings piles, we can prioritize Paspalum notatum Flugge with long roots for ecological restoration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13040993/s1, Table S1: Biased correlation analysis of tailings containing Setaria viridis (* $p < 0.05$ ** $p < 0.01$); Table S2: Biased correlation analysis of tailings containing Cynodon dactylon (L.) (* $p < 0.05$ ** $p < 0.01$).

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Data Availability Statement: All data generated or analyzed during this study are included in this published article.

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Conflicts of Interest: The authors declare that there are no competing interest in the submission of this manuscript.

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