Response of Grassland Slope Erosion to Vegetation Characteristics

Dongdong Wang1,2,3*, Zaijian Yuan1, Dawei Jing2, and Chunyu Zhao2

1 Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Guangdong Institute of Eco-environment Science & Technology, Guangzhou, 510650, P. R. China
2 College of Ecology, Resources and Environment, Dezhou University, Dezhou, Shandong 253023, China
3 State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
E-mail: 1534849533@qq.com (Dr. Dongdong Wang).

Abstract. The grassland erosion research on steep slopes is the basis and difficulty, which was studied by artificial rainfall experiments. Results showed the following: (1) Decreasing the stream power (Ro) is main way to decrease the interrill erosion. (2) The regulation effect of grass on stream power and soil erodibility are mainly achieved by grass cover and root volume, separately. (3) The contribution rates of root volume (RV), and soil bulk density (SD) to RK is 73.61%-97.94, and 0.04%-0.22%.

Keywords: Interrill erosion, Herbaceous vegetation, Soil erodibility, Hydrodynamic parameters, Soil erosion model.

1. Introduction
Rangelands cover nearly half of the Earth’s land surface, especially locating in town development. Interrill erosion are important erosion processes to model, because they can dominate on many undisturbed rangeland hillslopes with an adequate vegetation cover, which has long been recognised [1]. The Water Erosion Prediction Project, and RHEM [2-4] were the term used to estimate interrill erosion. But mechanism of interrill erosion reduction on rangeland was not still given full expain. Therefore, understanding the mechanism interrill erosion on rangelands is vital to develop interrill erosion models and equations that could be used to evaluate and control rangeland health [5,6].

In recent years, our understanding has not improved much. So many researchers proved that vegetation can reduce the impact force of water by reducing runoff [7-10], and raindrop kinetic energy, and increase soil resistance to erosion by increasing soil aggregate stability and cohesion and by stabilising the soil through the binding action of its roots [11-13]. However, no experiments have given systematic research so that our understanding is limited, especially under steep slope conditions. The major objectives of this study are as follows: (1) To recognise the effects of grass characteristics on the Ro, RK; (2) To quantitatively analyse the effects of Ro, RK on the and REM.

2. Materials and Methods

2.1. Experiment soil and experiment location
The experiment was conducted in the artificially simulated rainfall hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, CAS & MWR. The test soil was loessal soil taken from Ansai, Shaanxi located in the hinterland of the Loess Plateau. *Poa pratensis* L. was selected in the experiment, and the planting method was strip planting.

### 2.2. Equipment

The main equipment of the test included runoff cells and simulated rainfall. The runoff cell included a mobile variable slope steel cell in the center cell and the border zone, and the adjustable slope range was 0°–30°. The center cell scale was 80×60×25 cm, which is the observation area of runoff and sediment production. The bottom was opened at a spacing of 10 cm to facilitate the infiltration to the bottom flow out of the small hole. The boundary region was a ring area around the central community with a width of 30 cm and a depth of 25 cm. The boundary area is completely consistent with the soil loading, long grass, bottom openings, and other conditions of the central community. This area facilitates the splashing out and in of the central community and the soil, respectively. Thus, the unit area erosion and the sediment yield of the central plot can accurately represent those of a small plot surrounded by a uniform straight slope in the field. The peripheral dimension of the runoff cell was 140×120 cm. The water content of the soil was adjusted to 14% before packing, which is the typical level during the flood season on the Loess Plateau when maximum erosion occurs. After the soil was packed, *Poa pratensis* L. was transplanted in a banded uniform layout. When a stable growth of vegetation was established, the simulated rainfall experiments began approximately 2 months after planting.

| S(°) | I(mm/min) | C(%) | Replicates | unit |
|------|-----------|------|------------|------|
| 15   | 0.7,1.0,1.5,2,0,2.5 | 0,30,40,50,60,70 | 2 | 60 |
| 7,10,15,20,25 | 1.5 | 0,30,40,50,60,70 | 2 | 60 |

Remark: 12 units were repeated

Total: 108

This experiment designed three external factors (rainfall intensity, slope, cover). Six vegetation cover (0% [equivalent to bare slope], 30%, 40%, 50%, 60% and 70%), five rainfall intensities (0.7, 1, 1.5, 2 and 2.5 mm/min) and five slopes (7°, 10°, 15°, 20° and 25°) were tested with two replicates of each run, totalling to 108 experimental units (table 1).

### 2.3. Measurements

The rainfall lasted 40 min. The observation was conducted every 1, 2, and 3 min for the first 6 min after the start of runoff and every 3 min thereafter from the starting time to the end of the rainfall (the last observation interval is less than 3 min). The flow rate and sediment concentration of the community outlet were collected in a small bucket for a period, and the weight of the muddy water sample was accurately weighed with a balance. The flow velocity and muddy water temperature were respectively measured by permanganate staining and thermometer. The water temperature was monitored. The Reynolds number (Re) was calculated for each case where runoff occurred, and the mean flow velocity was obtained by multiplying the surface velocity by 0.6 if the flow was laminar, by 0.70 if the flow was transitional and by 0.80 if the flow was turbulent [11]. Plant root characteristics (including root surface area, root length, root volume, and root diameter) were determined using WinRHIZO Root Analyzer. Root dry weight is to rinse the living roots, put them in an 80 °C oven to dry to a constant quality, and weigh to obtain. The measurement of the coverage of the planting base is to cut off the ground part of the grass and leave the grass base at a height of 1 cm, and then use the same method as the grassland plot coverage.
The runoff rate is the runoff depth per unit area per unit time, whereas the erosion rate is the sediment weight per unit area per unit time. The cumulative EM is the sum of the erosion rate measured during each sampling event, multiplied by time per unit area in the runoff time. The REM under a specific slope and rainfall intensity is calculated as EM of a bare soil minus the EM of soil with the given cover, divided by the erodibility of bare soil. The RK under a specific slope and rainfall intensity is calculated from the erodibility of bare soil minus the erodibility of the soil with the given cover, divided by the erodibility of bare soil. The Rω under a specific slope and rainfall intensity is calculated as the stream power on bare soil at the given slope, minus the stream power of the given cover and slope, divided by the stream power on bare soil at the given slope. All statistical analyses were carried out using Excel or SPSS 18.0.

The three hydraulic parameters (shear stress (τ, Pa) [14], stream power (ω, W m⁻²) [15] and unit stream power (U, m s⁻¹) [16] are calculated as Dongdong Wang, et al (2018). The contribution of independent variables to the dependent variable is calculated as follows:

\[ O_i = \frac{R^2}{\sum \beta_i^2} \times 100\% \]

where \( O_i \) is the contribution of the \( i \)th factor; \( R^2 \) is the multiple correlation coefficient, \( \beta_i = \frac{\sigma_x}{\sigma_y}b_i \) is the regression coefficient of the \( i \)th factor, \( \sigma_i \) is the mean square deviation of the \( i \)th factor and \( \sigma_y \) is the mean square deviation of the dependent variable.

3. Results

3.1. Roω

3.1.1. Stream Power-the Best for Describing Intermill Erosion among the Three Hydraulic Parameters Considered. The relationship between the EM and shear stress or stream power under different cover densities can be defined by power function equations (table 2). The \( R^2 \) of the equations are large (generally greater than 0.95), and the value of the \( R^2 \) for a given shear stress equation is less than that calculated for a stream-power equation under the same conditions. Moreover, the relationship between EM and unit stream power under different cover densities can also be fitted to logarithmic equations (table 2), although the \( R^2 \) of those equations is small. Hence, stream power is the best for describing intermill erosion among the three hydraulic parameters considered.

| C(%) | Empirical equation | \( R^2 \) | Empirical equation | \( R^2 \) | Empirical equation | \( R^2 \) |
|------|--------------------|--------|--------------------|--------|--------------------|--------|
| 0    | EM = 9.454τ^1.458  | 0.921  | EM = 50.10ω^1.099  | 0.956  | EM= 0.948ln(U) + 4.545 | 0.486  |
| 30   | EM = 5.457τ^1.274  | 0.899  | EM = 52.81ω^1.127  | 0.967  | EM= 0.958ln(U) + 4.532 | 0.535  |
| 40   | EM = 4.674τ^1.270  | 0.903  | EM = 58.45ω^1.167  | 0.967  | EM= 0.924ln(U) + 4.368 | 0.559  |
| 50   | EM = 4.067τ^1.254  | 0.915  | EM = 59.29ω^1.186  | 0.960  | EM= 0.897ln(U) + 4.226 | 0.608  |
| 60   | EM = 3.624τ^1.283  | 0.906  | EM = 71.26ω^1.256  | 0.958  | EM= 0.838ln(U) +3.967 | 0.612  |
| 70   | EM = 3.394τ^1.318  | 0.931  | EM = 84.72ω^1.332  | 0.934  | EM= 0.757ln(U) + 3.598 | 0.624  |

Note: The significance level of the equation is 0.01.

3.1.2. Grass Contribute to Roω. Grass affects stream power mainly through grasscover and stem basal cover. The relationship between Roω and grasscover, and stem basal covers is analysed using the data from the experiments described with the equation listed in tables 3 and 4. Tables 3 and 4 also showed the contribution rate of the influence of grass cover(GC), and Phytyl cover(PC) on reduction...
of stream power. The response of \( R_\omega \) to GC, and PC can be described with logarithmic function equations, and the correlation coefficients are all around 0.9 (tables 3 and 4), which contribution rates are 82.86%-97.51%, and 1.48%-14.82% (table 3), or 86.36%-97.51%, and 1.48%-20.44% (table 4).

**Table 3.** Relationships of reduction percentage of stream power with grass cover and Phytyl cover under different rainfall intensities.

| I(mm/min) | Empirical equation          | \( R^2 \) | F test                        | Contributions rate (%) |
|-----------|-----------------------------|-----------|-------------------------------|------------------------|
| 0.7       | \( R_\omega=0.343\text{Ln}(GC)-0.042\text{Ln}(PC)+0.499 \) | 0.998     | F= 853>F(2,2)0.01 =99        | GC: 97.16 PC: 2.73     |
| 1.0       | \( R_\omega=0.457\text{Ln}(GC)-0.075\text{Ln}(PC)+0.614 \) | 0.935     | F=14>F(2,2)0.1=9             | GC: 89.12 PC: 4.46     |
| 1.5       | \( R_\omega=0.209\text{Ln}(GC)-0.019\text{Ln}(PC)+0.326 \) | 0.989     | F=98>F(2,2)0.05 =19          | GC: 97.51 PC: 1.48     |
| 2.0       | \( R_\omega=0.278\text{Ln}(GC)-0.0426\text{Ln}(PC)+0.312 \) | 0.999     | F=1947>F(2,2)0.01 =99        | GC: 95.79 PC: 4.16     |
| 2.5       | \( R_\omega=0.272\text{Ln}(GC)-0.143\text{Ln}(PC)+0.459 \) | 0.977     | F=70>F(2,2)0.05 =19          | GC: 82.86 PC: 14.82    |

Note: \( R_\omega \) is reduction percentage of stream power, %; GC is grass cover, %. PC is Phytyl cover, %.

**Table 4.** Relationships of reduction percentage of stream power with grass cover and Phytyl cover under different slopes.

| S(°) | Empirical equation          | \( R^2 \) | F test                        | Contributions rate (%) |
|------|-----------------------------|-----------|-------------------------------|------------------------|
| 7    | \( R_\omega=0.236\text{Ln}(GC)-0.031\text{Ln}(PC)+0.34 \) | 0.999     | F=719>F(2,2)0.01 =99        | GC: 96.70 PC: 3.16     |
| 10   | \( R_\omega=0.263\text{Ln}(GC)-0.062\text{Ln}(PC)+0.28 \) | 0.999     | F=2526>F(2,2)0.01 =99       | GC: 90.66 PC: 9.30     |
| 15   | \( R_\omega=0.209\text{Ln}(GC)-0.019\text{Ln}(PC)+0.32 \) | 0.989     | F=98>F(2,2)0.05 =19         | GC: 97.51 PC: 1.48     |
| 20   | \( R_\omega=0.434\text{Ln}(GC)-0.12\text{Ln}(PC)+0.389 \) | 0.986     | F=68>F(2,2)0.05 =19         | GC: 86.36 PC: 12.20    |
| 25   | \( R_\omega=0.133\text{Ln}(GC)+0.05\text{Ln}(PC)+0.470 \) | 0.986     | F=70>F(2,2)0.05 =19         | GC: 78.17 PC: 20.44    |

Note: \( R_\omega \) is reduction percentage of stream power, %; GC is grass cover, %. PC is Phytyl cover, %.

### 3.2. Effect of Herbaceous Vegetation on RK

In recent years, soil erodibility is most commonly used in the soil-loss equations USLE and RUSLE [17]. Soil erodibility is generally regarded as a measure of the susceptibility of a soil to erode. Stream power is the best hydraulic parameter to describe interrill erosion, among the three hydraulic parameters calculated. As discussed above, soil erodibility is calculated though the erosion rate as a function of stream power. Tables 5 and 6 present the results of the Pearson correlation analysis between RK and grass root characteristics or soil characteristics under the experimental conditions. Table 5 shows the following: RK was positively related to root length(RL), root surface area(SA), and root volume(RV) with good correlation. The correlation coefficient was in the range of 0.916-0.950. Table 6 shows the following: reduction of soil erodibility was positively related to organic matter (OM), <0.002 particle composition (PG), soil bulk density(SD), and soil porpsrsity(SP) with good
correlation. The correlation coefficient was in the range of 0.939-0.961. However, under the test conditions, PG and OM change very little, and it is easy to magnify the measurement error. SD and SP are consistent in expressing soil compactness. Moreover, R^2 of the correlation between RK and SD is 0.944, which is slightly larger than R^2 of SP with 0.939. Therefore, SD under the test conditions is the most suitable soil characteristic index for evaluating RK on the steep slope of the grassland.

### Table 5. Pearson correlation analysis between RK and root characteristics.

|    | RL  | RA   | RV    | RD    | RW    | RK    |
|----|-----|------|-------|-------|-------|-------|
| RL | 1   | 0.998** | 0.991* | 0.497 | 0.973** | 0.916* |
| RA | 0.998** | 1     | 0.998** | 0.545 | 0.962** | 0.933* |
| RV | 0.991** | 0.998** | 1     | 0.599 | 0.943* | 0.950* |
| RD | 0.497 | 0.545 | 0.599 | 1     | 0.301 | 0.790 |
| RW | 0.973** | 0.962** | 0.943* | 0.301 | 1     | 0.800 |
| RK | 0.916* | 0.933* | 0.950* | 0.790 | 0.800 | 1     |

Note: **: Significant correlation at 0.01 level or at 0.05 level. RL: Root length, RA: The average root surface area, RV: The average root volume, RD: The average root diameter, RW: Root dry weight, RK: Reduction of soil erodibility.

### Table 6. Pearson correlation analysis between RK and soil characteristics.

|    | OM   | PG   | SD    | SP    | RK    |
|----|------|------|-------|-------|-------|
| OM | 1    | -0.968** | 0.996** | -0.996** | -0.960** |
| PC | -0.968** | 1    | -0.948* | 0.948*    | 0.961** |
| SD | 0.996** | -0.948* | 1     | -1.000** | -0.944* |
| SP | -0.996** | 0.948* | -1.000** | 1     | 0.939* |
| RK | -0.960** | 0.960** | -0.944* | 0.939* | 1     |

Note: OM: Organic matter, PG: < 0.002 particle composition, SD: Soil bulk density, SP: Soil porpsity, RK: Reduction of soil erodibility.

### Table 7. Relationships of reduction percentage of soil erodibility with root volume and soil bulk density under different slopes.

| S (°) | Empirical equation | R^2  | F test                  | Contributions rate (%) | RV | SD |
|-------|--------------------|------|------------------------|------------------------|----|----|
| 7     | RPK=0.131Ln(RV)+0.035Ln(SD)-0.288 | 0.980 | F=348>F(2,2)0.05 =19   | 97.94                  | 0.06 | 0.22 |
| 10    | RPK=0.061Ln(RV)-0.323Ln(SD)+0.161 | 0.958 | F= 22>F(2,2)0.05 =19   | 95.58                  | 0.22 | 0.04 |
| 15    | RPK=0.098Ln(RV)-0.210Ln(SD)-0.02  | 0.908 | F=226>F(2,2)0.01=99    | 90.74                  | 0.22 | 0.04 |
| 20    | RPK=0.123Ln(RV)+0.044Ln(SD)-0.388 | 0.969 | F=30>F(2,2)0.05 =19    | 96.75                  | 0.22 | 0.10 |
| 25    | RPK=0.0168Ln(RV)-0.079Ln(SD)+0.025 | 0.738 | F=3>F(2,2)0.3 =2       | 73.61                  | 0.14 | 0.04 |

Note: RPK is reduction percentage of soil erodibility, %; RV is root volumer, cm^3; SD is soil bulk density, g/cm^3.
Grass affects soil erodibility is mainly through root volume and soil bulk density. The relationship between RK and RV, and SD is analysed using the data from the experiments described with the equation listed in table 7. Binary logarithmic equation can describe the response of RV, and SD to the RK. The contribution rates are 73.61%-97.94, and 0.04%-0.22% (table 7).

3.3. Contributions of Rω and RK to REM

The control of stream power and soil erodibility by herbaceous vegetation is apparent in changing the rate of interrill erosion. The complete herbaceous vegetation generally reduces the stream power and soil erodibility. This result is similar to that of the previous studies [18-20]. The results described in the present study indicate that the relationship between REM and stream power or soil erodibility could explain the mechanism, by which the herbaceous vegetation cover affects interrill erosion, as indicated in the following equation:

\[ REM = 0.95R_\omega + 0.79RK + 0.11 \]

\( R^2 = 0.95, \ Sig < 0.01; F(2,42) = 365.53 > F(2,42)_{0.01} = 5.15 \)  

Equation 5 indicates that the relationship between the REM and the R\( _\omega \) or RK could be linear. In addition, Eq. 5 shows a positive correlation between the REM and the R\( _\omega \) or RK, thus supporting the hypothesis that herbaceous vegetation reducing effect of stream power much more than reducing effect of soil erodibility. The contribution rates of the RK and R\( _\omega \) are 33.55% and 61.02%, respectively, totalling to 94.57%.

4. Discussion

4.1. Sheet Erosion Mechanism of Grassland Slope Under Steep Slope Conditions

In the previous research and the results of this experiment, the influence of rain intensity and slope on the grassland erosion force showed a stable positive correlation, and only grass was able to resist the erosion force. The grassland erosion mechanism is deeply explained in terms of the influence of grass characteristics on erosion forces. The results of this experiment show that the contribution of grass to R\( _\omega \) mainly comes from grass cover and planting cover. In the late rains, the grass is flat on the ground, and the role of grass is maximized. In addition, the blade of grass has a positive effect on the flow rate of the water flow [13, 21], but the grass base cannot display the double effect of the grass cover. Therefore, the contribution of grass cover to the impact of R\( _\omega \) is significantly greater than that of planting.

Grass affects RK through roots and root improvement soil properties. Further analysis of the correlation between vegetation characteristics and RK shows that the contribution of grass to RK mainly comes from grass root volume and soil bulk density, which is different from previous research [22]. Because the effect of root consolidation soil can achieve the best effect in a short time [23], and the roots need to improve soil properties for a long time and change little, so the contribution of grass root volume to RK is much greater than the contribution of soil bulk density to RK.

4.2. Future Research of Erosion Mechanism of Grassland Slope

The influence of changes in space-time scale on erosion is very different [24], and the factors that affect erosion are also very different [25]. This experiment analyzes the erosion mechanism from a small space-time scale at multiple levels, providing a basis for a more applicable erosion model. But the effectiveness of the erosion model must be explained from the large-scale erosion factor level. Under large-scale conditions, vegetation characters such as vegetation density, vegetation types, soil properties, and vegetation layout determine the law of erosion changes [26-29], and there are few related studies. The erosion model did not fully considers these factors less [12], and the model is less effective in current applications [30-33].
5. Conclusion
Vegetation decreases the interrill erosion mainly by Ro. Grass cover and root volume deeply affect stream power and soil erodibility separately. The impact of vegetation characteristics on soil erosion and vegetation itself and its derivative effect on soil properties should be soil erosion research focus, especially under large-scale conditions.

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References
[1] Wang D D, Wang Zh L, Zhang Q W, Zhang Q L, Tian N L, Liu E 2018 Sheet erosion rates and erosion control on steep rangelands in loess regions [J] Earth Surf. Process. Landforms 43: 2926–2934.
[2] Wei H, Nearing M A and Stone J J 2007 A comprehensive sensitivity analysis framework for model evaluation and improvement using a case study of the rangeland hydrology and erosion model [J] Trans. ASABE 50(3): 945-953.
[3] Wei H, Nearing M A and Stone J J and Breshears D D 2008 A dual Monte Carlo approach to estimate model uncertainty and its application to the rangeland hydrology and erosion model [J] Trans. ASABE 51(2): 515-520.
[4] Wei H, Nearing M A, Stone J J, Guertin D P, Spaeth K E, Pierson F B, Nichols M H and Moffett C A 2009 A new splash and interrill erosion equation for rangelands [J] SSSA J. 73(4): 1386-1392.
[5] Pellant M, Shaver P, Pyke D A and Herrick J E 2005 Interpreting indicators of rangeland health, version 4. Tech. Ref. 1734–6. BLM/ST-00/001+1734/REV05 Bur. of Land Manage. Denver CO.
[6] Pyke D A, Herrick J E, Pellant M 2002 Rangeland health attributes and indicators for qualitative assessment [J] Journal of Range Management 55(6): 584-597.
[7] Wainwright J, Parsons A J, Schlesinger W H, Abrahams A D 2002 Hydrology vegetation interactions in areas of discontinuous flow on a semi-arid Bajada, southern New Mexico [J] J. Arid Environ. 51(3): 319–338.
[8] Rey F 2003 Influence of vegetation distribution on sediment yield in forested marly gullies [J] Catena 50(2): 549-562.
[9] Puigdefabregas J 2005 The role of vegetation patterns in structuring runoff and sediment fluxes in drylands Earth Surf. Processes Landforms 30(2): 133–147.
[10] Kimiti D W, Riginos C, Belnap J 2017 Low-cost grass restoration using erosion barriers in a degraded African rangeland [J] Restoration Ecology 25(3): 376-384.
[11] Gyssels G, Poesen J, Bochet E, Li Y 2005 Impact of plant roots on the resistance of soils to erosion by water: a review [J] Progress in Physical Geography 29(2): 189-217.
[12] Ren Geng, Guanghui Zhang, Qianhong Ma, Hao Wang 2017 Effects of landscape positions on soil resistance to rill erosion in a small catchment on the Loess Plateau [J] Biosystems Engineering: 95-108.
[13] Haoxin Hao, Yujie Wei, Danni Cao, Zhonglu Guo, Zhihua Shi 2020 Vegetation restoration and fine roots promote soil infiltrability in heavy-textured soils [J] Soil & Tillage Research.
[14] Morgan R P 2005 Soil Erosion and Conservation Blackwell Science Ltd., Oxford.
[15] Nearing M A, Bradford J M, Parker S C 1991 Soil detachment by shallow flow at low slopes [J] Soil Science Society of America Journal 55(2): 351-357.
[16] Yang C T 1976 Minimum unit stream power and fluvial hydraulics J. Hydr. Div-ASCE. 102: 919–34.
[17] Renard K G, Foster G R, Weesies G A, Mccool D K, Yoder D C 1997 Predicting soil erosion by water: a guide to conservation planning with the revised universal soil loss equation (RUSLE) [J] Agriculture Handbook (Washington): 703.
[18] Mamo M, Bubenzer G D 2001a Detachment rate, soil erodibility, and soil strength as influenced by living plant roots part i: laboratory study [J] Transactions of the ASAE American Society of Agricultural Engineers 44(5): 1167-1174.
[19] Mamo M, Bubenzer G D 2001b Detachment rate, soil erodibility, and soil strength as influenced by living plant roots, part ii: field study [J] Transactions of the ASAE 44(5): 1175-1181.
[20] Gyssels G, Poesen J, Liu G, Van D W, Knapen A, Sd B 2006 Effects of cereal roots on detachment rates of single- and double-drilled topsoils during concentrated flow [J] European Journal of Soil Science 57(3): 381–391.
[21] Perkins Kim S, Stock Jonathan D, Nimmo John R 2018 Vegetation influences on infiltration in Hawaiian soils [J] Ecohydrology 11(5): 1.
[22] Zhang B J, Zhang G H, Yang H Y, Wang H 2019 Soil resistance to flowing water erosion of seven typical plant communities on steep gully slopes on the Loess Plateau of China [J] Catena: 173
[23] Alam S, Banjara A, Wang J, William B, Patterson, Baral S 2018 Novel approach in sampling and tensile strength evaluation of roots to enhance soil for preventing erosion [J] Open Journal of Soil Science: 330-349.
[24] Marcella B, Stefano F, Francesca O, Eugenio C 2016 Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy) [J] Soil and Tillage Research: 176-189.
[25] Usman S, Noma S S, Kudiri A M 2016 Dynamic surface soil components of land and vegetation types in Kebbi State Nigeria [J] Eurasian Journal of Soil Science 5(2): 113-120.
[26] Xiao L, Liu G B, Xue S 2016 Effects of vegetational type and soil depth on soil microbial communities on the Loess Plateau of China [J] Archives of Agronomy and Soil Science 62(12): 1665-1677.
[27] Guo M, Wang W, Shi Q, Chen T, Kang H, Li J 2019 An experimental study on the effects of grass root density on gully headcut erosion in the gully region of China's Loess Plateau [J] Land Degradation and Development 30(17): 2107-2125.
[28] Guo M M, Wang W L, Wang T C, Wang W X, Kang H L 2020 Impacts of different vegetation restoration options on gully head soil resistance and soil erosion in loess tablelands [J] Earth Surface Processes and Landforms 45(4): 1038-1050.
[29] Panos P, Pasquale B, Jean P, Cristiano B, Emanuele L, Katrin M, Luca M, Christine A 2015 The new assessment of soil loss by water erosion in Europe [J] Environmental Science & Policy: 438-447.
[30] Nouwakpo S K, Weltz M, Hernandez M, Champa T, Fisher J 2016 Performance of the rangeland hydrology and erosion model for runoff and erosion assessment on a semiarid reclaimed construction site [J] Journal of Soil & Water Conservation 71(3): 220-236.
[31] Chau N L, Chu L M 2017 Fern cover and the importance of plant traits in reducing erosion on steep soil slopes [J] Catena: 98-106.
[32] Misra R K, Rose C W 2010 Application and sensitivity analysis of process-based erosion model Guest [J] European Journal of Soil Science 47(4): 593-604.
[33] Melville N, Morgan R P C 2001 The influence of grass density on effectiveness of contour grass strips for control of soil erosion on low angle slopes [J] Soil Use and Management 17(4): 278-281.