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Vertical distribution of vegetation roots and its influence on soil erosion resistance along gully headwalls in the gullied Loess Plateau

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Abstract

Purpose On-wall flow on gully headwalls plays a critical role in gully headcut erosion, and the erosion morphology of gully headwalls caused by on-wall flow scouring varies under different land uses/covers due to variations in soil resistance. However, it is unclear how vegetation roots affect the soil resistance of gully headwalls to on-wall flow scouring.

Materials and methods Taking bare land as the control, this study analysed the vertical distribution of vegetation roots and its influence on the soil properties and antiscourability (*ANS*) of gully headwalls under three land uses (forestland, grassland, and farmland).

Results and discussion The results showed that root mass density (*RMD*), root length density (*RLD*), root surface area density (*RAD*), and root volume density (*RVD*) decreased overall with increasing soil vertical depth at the gully headwall under the three land use types. The soil *ANS* ranked highest to lowest in forestland, grassland, farmland, and bare land. Compared with that of bare land, the *ANS* of each soil layer (0–20, 20–40, 40–60, 60–80, and 80–100 cm) under the three land use types increased by 3.0–9.1, 6.7–8.6, 2.6–10.5, 3.9–5.6, and 0.2–1.9 times, respectively. The *ANS* of the gully headwalls had a logarithmic relationship with *RLD*, *RAD*, and *RVD* ($R^2 = 0.45$–0.56, $P < 0.01$). In particular, the most significant correlation was found between the *ANS* and *RVD* of fine roots (diameters of 0–0.5 mm). The *ANS* decreased with the decrease in root density with vertical depth.

Conclusions Our results reveal that vertically distributed roots determine the vertical variations in soil *ANS* on gully headwalls in the gullied Loess Plateau.

Keywords Gully headwall · Root system · Concentrated flow · Soil antiscourability · Loess Plateau

1 Introduction

Gully headcut retreat, the beginning of gully erosion (Oostwoud Wijdenes and Bryan 2001; Poesen et al. 2011), is usually triggered and accelerated by inappropriate land use and extreme rainfall events (Valentin et al. 2005). Some

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Highlights

- The root parameters decreased on the whole with the deepening of soil layer.
- The soil antiscourability (*ANS*) on gully headwall ranked highest to lowest on forestland, grassland, farmland and bare land.
- The most significant correlation was found between the *ANS* and the root volume density of the fine roots.
- The *ANS* on gully headwall decreased with the root density decreasing from the topsoil to the 80-100 cm layer.

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gullies have been found to have retreated by more than 10 m during a rainstorm event in some regions, such as the Loess Plateau (Jing 1986), resulting in extensive land degradation and ecological damage. Land use/cover change is considered a far more significant force than climatic variation in gully erosion (Poesen et al. 2003). Rational land use changes and vegetation restoration could control gully retreat and sediment yield because vegetation can reduce soil erodibility and improve soil erosion resistance (Chen and Cai 2006). In addition, the gully head retreat rates vary under different root system distributions (Guo et al. 2019; Kang et al. 2021). Therefore, it is of great importance to study the impacts of land use/cover on gully head retreat, which will help to determine a reasonable strategy of vegetation restoration in gully erosion control.

The land use/cover impacts on gully headcut erosion are significant. An increase in the number of plant roots can weaken the degree of gully headcut erosion (Allen et al. 2018; Guo et al. 2020a; Kang et al. 2021). Allen et al. (2018) proposed a daily time step for the time period headcut migration model, and the cover-root factor was one of the principal variables in the model. The root system is also an important factor influencing soil erosion and plays a critical role in improving soil resistance to concentrated flow and can greatly reduce soil loss (Wang et al. 2015). Roots play an important role in reducing soil erosion and can reduce the total erosion by 20% to 48% (Kramer 1936), with the difference in contribution mainly arising from the different root morphology traits of plants (Wang et al. 2021). Previous studies have shown that soil detachment decreases exponentially with the root length density, root surface area density, and root volume ratio (Mamo and Bubenzer 2001; De Baets et al. 2006). Furthermore, the root system plays an important role in gully erosion control through its weakening of soil erodibility, enhancing soil antiscourability (*ANS*) and soil stability at gully heads (Vannoppen et al. 2015; Vanmaercke et al. 2016; Guo et al. 2018, 2020b). Guo et al. (2020b) preliminarily investigated the root effects of different types of vegetation at gully heads on the resistance of soil to concentrated flow, of which roots 0–0.5 mm in diameter showed a greater controlling effect on the soil detachment rate than roots with larger diameters. However, previous studies on the soil erosion resistance of gully heads were mostly conducted on shallow soil profiles (Guo et al. 2019, 2020a). Moreover, most studies have focused on the effects of land use/cover on gully head erosion (Fan et al. 2004; Guo et al. 2020b; Kang et al. 2021).

Gully headcut erosion includes several processes, such as gully headwall erosion by on-wall flow, plunge pool erosion by jet flow and gully head collapse (Guo et al. 2019; Kang et al. 2021). Runoff at gully heads can be divided into on-wall flow and jet flow. On-wall flow plays a critical role in headwall erosion in gully head retreat processes (Chen et al. 2013; DeLong et al. 2014; Guo et al. 2019, 2021; Kang et al. 2021). For example, on-wall flow undercuts the gully headwall, resulting in the occurrence of scour holes and overhanging layers and accelerating gully head collapse (Chen et al. 2013). Guo et al. (2021) found that on-wall flow accounted for 15.7–22.6% of the total flow volume of upstream headcutting on the Loess Plateau, China. Additionally, Chen et al. (2013) demonstrated that the proportion of on-wall flow was 9.3–56.8% in Yuanmou Valley, China. As a result, the proportion of soil loss scoured by on-wall flow relative to total soil loss can reach 26.9–38.6% (Guo et al. 2021). Although the proportion of on-wall flow is relatively small, it plays an important role in the development of gully head scour holes (Chen et al. 2013). Due to on-wall flow scouring and the difference in soil resistance at different parts of gully headwalls, scour holes on the gully headwall form at different speeds with various morphologies. Many studies have concluded that when concentrated flow initiates erosion of a given gully head composed of a soft lower layer and a hard upper layer, the lower layer is eroded at a faster rate than the upper layer, resulting in a scour hole on the headwall and a hanging soil body (Römkens et al. 1997; Stein and LaTray 2002; Chen et al. 2013). When the scour hole reaches a critical size, the hanging soil above becomes thinner and more unstable and eventually collapses (Collison 2001; Chen et al. 2013). This is one of the important modes of gully headcut erosion (Stein and Julien 1993). The gully head morphology mentioned above is determined by the interaction between the soil erodibility of the gully head and flow shear stress during gully head erosion (Stein and Julien 1993; Moore 1997; Temple and Moore 1997; Collison 2001; Kang et al. 2021). Accordingly, the difference in soil erosion resistance at different vertical depths of gully headwalls directly affects gully head retreat processes. A previous study on the vertical distribution of roots along the streambank showed that at forested and herbaceous sites, more than 55 to 75% of the total root length density was concentrated in the upper 30 cm, and the values at herbaceous sites were significantly greater than those at forested sites (Wynn et al. 2004). Because the vegetation root tensile strength and spatial density increase the soil cohesion and strength of streambanks, different species perform differently at different soil depths, and the roots of all species associated with an increase in strength were concentrated in the 0–50 cm layer of soil (Simon and Collison 2002). However, few studies have considered the vertical root system distribution and its influence on the soil erosion resistance of gully headwalls, which is not conducive to the accurate analysis of gully headcut erosion processes and reasonable planning of soil and water conservation measures. Land use/cover plays an important role in the gully headcut erosion process (Kang et al. 2021) and can directly affect gully head retreat rates (Morgan and

Mngomezulu 2003; Li et al. 2015; Torri et al. 2018). Different land uses, such as badland areas, forested areas, pasture, and cropland, have different erosion resistances, which in turn influence gully head retreat (Torri et al. 2018). Different types of land use involve different plants, and the vertical root distributions of different plants in the soil vary (Wynn et al. 2004). Therefore, relevant research studies are of great significance to the selection of suitable species for vegetation restoration for gully head erosion control.

Here, the effects of the root vertical distribution on the soil erosion resistance of gully headwalls were studied. The soil *ANS* index is one of the key indicators used to reveal soil erosion resistance (Li et al. 1991; Liu 1997; Zhang et al. 2017). Thus, this paper represents an initial effort to study the variance in soil *ANS* at the soil profile level at gully headwalls under different land use types (bare land, farmland, grassland, and forestland). Field sampling surveys, soil sample collection and soil erosion resistance tests were conducted to analyse the root distribution and to determine the soil properties. The present study aimed to (1) illustrate the vertical distribution characteristics of roots and soil properties in gully headwalls under different land use types, (2) determine the vertical changes in the soil resistance of gully headwalls to concentrated flow, and (3) analyse the effects of vegetation roots and soil properties on the soil erosion resistance of gully headwalls. The results clarify the role of different vegetation root vertical distributions in gully headcut erosion and provide a theoretical basis for establishing optimal vegetation configurations in gully erosion control.

2 Materials and methods

2.1 Study area

This study was carried out in the Nanxiaohegou watershed at the Xifeng Water Conservation Scientific Experiment Station of the Yellow River Conservancy Committee of China (35°41′ ~ 35°44′ N, 107°30′ ~ 107°37′ E). The Nanxiaohegou watershed was selected as a typical small watershed that is representative in terms of terrain and vegetation of the Loess Plateau gully region (Li et al. 2020). The watershed is characterized by elevations of 1050 ~ 1423 m and covers an area of 36.3 km^2, of which the gully slope area and gully area account for 16% and 27%, respectively. The main types of soil are dark loessal and loessal soils, with mainly vertical joints (Guo et al. 2019). This region is characterized by a warm temperate continental climate with a mean annual precipitation of 546.8 mm (from 1954 to 2014), an annual mean temperature of 9.3 °C, and a 155-day frost-free period. This area suffers an annual soil erosion rate of 4350 t km^{-2} a^{-1}. Currently, the vegetation in the watershed is dominated by planted forests (*Platycladus orientalis* (L.) Franco, *Robinia pseudoacacia* L.), shrub communities (*Ziziphus jujuba* var. *spinosa* (Bunge) Hu ex H.F. Chow, *Rosa hugonis* Hemsl.), and native secondary herbaceous plants (*Medicago sativa* L., *Agropyron cristatum* (L.) Gaertn., *Artemisia gmelinii* Web. Ex Stechm).

2.2 Sampling site selection and soil sampling

Based on a previous investigation of the artificial vegetation restoration successional patterns in the study area (Guo et al. 2020a, b), we found that vegetation restoration remained mainly in the herb community stage in the gully head area, with dominant species of *Agropyron cristatum* (Linn.) Gaertn, *Artemisia gmelinii* Web. ex Stechm, *Bothriochloa ischaemum* (Linn.) Keng. Thus, farmland, grassland, and forestland were selected as the typical land uses in this area, and bare land was taken as a control (Table 1). More importantly, it was ensured that the slope aspects and gradients, elevations, and soil types were similar among the four selected sites to minimize the effects of these factors (Guo et al. 2020b). At each selected site, soil was sampled from the slope section 0–1 m below the shoulder line of the gully heads to accurately represent the soil and root properties at the gully headwalls (Fig. 1b) and ensure personnel safety during the sampling process. Soil samples were collected

Table 1 Basic characteristics of the selected sampling sites

Land use type	Dominant vegetation	Slope (°)	Elevation (m)	Soil bulk density (g cm^{-3})	Gully head vegetation coverage (%)
Bare land	-	3	1201	1.22–1.34	0
Farmland	*Zea mays L*	2	1323	1.17–1.33	-
Grassland	*Ziziphus jujuba* Mill. var. *spinosa* (Bunge) Hu ex H. F. Chow, *Artemisia gmelinii* Web. ex Stechm., *Agropyron cristatum* (L.) Gaertn	3	1288	1.28–1.37	90
Forestland	*Platycladus orientalis* (L.) Franco	3	1264	1.19–1.25	In forest: 68 Grass glade: 41

"-" represents farmland that has been harvested without measuring coverage during sampling

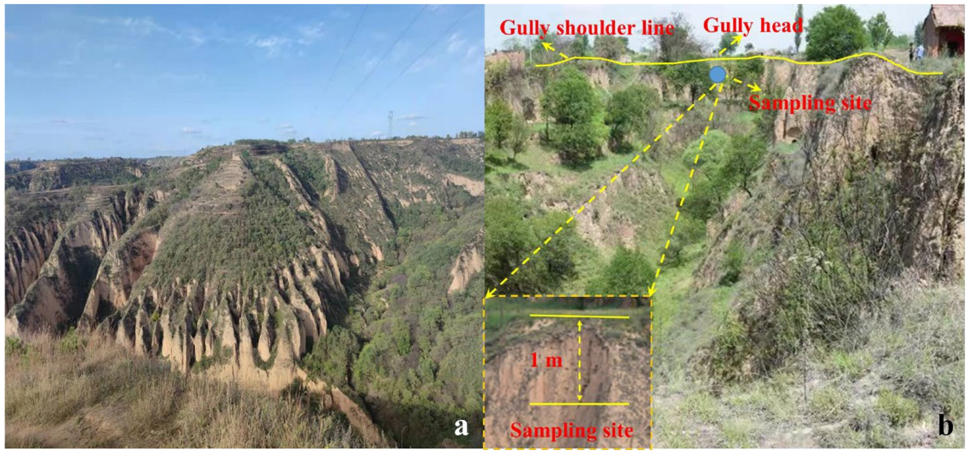

Fig. 1 Geomorphological features of the gully-dominated watershed (**a**); sampling point schematic at a gully headwall (**b**)

from the soil profile at 0–20, 20–40, 40–60, 60–80, and 80–100 cm. At each sampling site, the soil samples were sampled perpendicular to the gully headwalls. Three soil samples were collected from each soil layer using steel cutting rings (500 cm^3: Φ100 mm × 63.7 mm) to measure the soil *ANS*. Six soil samples were collected from each layer using steel cutting rings (100 cm^3: Φ50.46 mm × 50 mm) to determine the soil bulk density (*SBD*) and saturated hydraulic conductivity (*SHC*). Three soil samples were collected in aluminium specimen boxes to determine the natural water content (*NWC*) of the soil. Mixed soil samples weighing between 2 and 3 kg were sampled to determine the soil water-stable aggregates.

2.3 Soil physical parameters and root trait measurements

The *SBD* and *SHC* were determined by the cutting ring method, *NWC* was determined through oven drying at 105 °C, and the soil water-stable aggregate content (*SWA*) was determined by the Yoder method (An et al. 2013; Guo et al. 2018). Dry and wet screening methods were used to screen the content of soil aggregates and determine the *SWA* and the soil structure damage ratio (*SDR*), respectively (Yang et al. 1999).

Figure 2b shows a soil antiscouring sample. Roots were separated by the washing method. First, soil samples in the cutting ring were soaked in clean water for 1 h to disperse the soil from roots and then placed on a sieve with an aperture of 0.05 mm and washed with tap water. Only living roots were selected individually using tweezers. Washed roots were scanned with an Epson Perfection V700 scanner. The WinRHIZO image analysis software was used to analyse root characteristics such as the root length density (*RLD*, cm cm^{-3}), root surface area density (*RAD*, cm^2 cm^{-3}), and root volume density (*RVD*, cm^3 cm^{-3}). Finally, the roots were oven-dried (24 h at 65 °C) and weighed to determine the root mass density (*RMD*, g cm^{-3}) (Guo et al. 2020a; Wang et al. 2021).

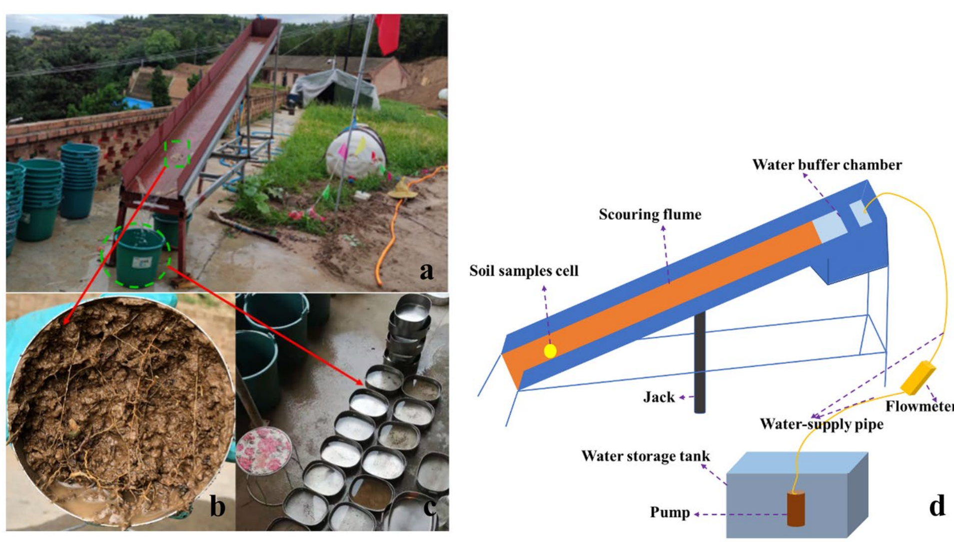

Fig. 2 Sketch map of the experimental plot. **a** Experimental device image. **b** Soil antiscouring sample. **c** Sediment sample poured into aluminium boxes. **d** Diagram of the components of the test device

2.4 Measurement of soil erosion resistance of gully headwalls

The magnitude of the soil *ANS* is related to the soil physical condition (Li et al. 1991; Zhou and Shangguan 2005); therefore, a general method (Fig. 2) was applied to measure the soil *ANS* of gully headwalls. In this method, the flow discharge was designed based on the maximum runoff generation and time–frequency formed by a typical medium storm in the standard plots (20 m × 5 m) in the Nanxiaohegou watershed. Therefore, the flow discharge and scouring time were set to 16 L min^{-1} and 15 min, respectively (Zhang et al. 2017; Guo et al. 2020a). The soil antiscouring samples (Φ100 mm × 63.7 mm) were soaked in water with a water surface height below 1 cm on the cutting ring surface for 12 h to saturation, and then the soil cutting ring samples were removed from the soaking water to remove water by gravity for 12 h (Zhang et al. 2017). Soil moisture contents less than 20% have been shown to have a significant impact on soil erosion rates (Govers et al. 1990). After soaking for 12 h, the soil moisture contents were all greater than 20%, so this study limits the influence of moisture content on the *ANS*. The soil *ANS* was measured in a hydraulic flume 4 m in length, 0.40 m in width, 0.20 m in depth, and 30° in slope (Fig. 2a and d) (Zhang et al. 2017; Guo et al. 2020a). The flume was long and wide enough to achieve steady water flow along the soil surface and to eliminate the flume boundary effects on the flow (Zhang 2017; Guo et al. 2020a). A thin layer of paint and sand particles (with a diameter < 1 mm) were sprayed on the flume surface to simulate hydraulic roughness. The test was started after the flow discharge remained steady at 16 L min^{-1} for 1 min. For each test, the yielding sediment was sampled with barrels at 1 min intervals.

After each test, the supernatant water was removed from the sampling barrels, and the sediment sample was poured into aluminium boxes (Fig. 2c), put in an oven at 105 °C to dry to constant weight, and then weighed.

2.5 Data analysis

The formula used to determine the soil structure damage ratio (*SDR*) is as follows (Yang et al. 1999):

$$SDR = \frac{DSWA_{>0.25} - WSWA_{>0.25}}{DSWA_{>0.25}} \times 100\% \tag{1}$$

where $DSWA_{>0.25}$ and $WSWA_{>0.25}$ are the water-stable aggregate contents of soil with a diameter of > 0.25 mm under dry and wet screening methods, respectively.

Soil resistance to erosion can be expressed by the soil *ANS* (L g^{-1}) index (Li et al. 1991; Liu 1997; Guo et al. 2020a). The *ANS* is calculated as follows:

$$ANS = \frac{q \cdot t}{M} \tag{2}$$

where q is the flow rate (L min^{-1}), t is the scouring time (min), and M is the oven-dried sediment weight for each test (g).

Spearman correlation analysis was performed to analyse the correlations between roots, water-stable aggregates, and *ANS*. Relationships between soil *ANS* and its driving factors were analysed with a simple regression method. All sketches were produced in PowerPoint 2019. All statistical analyses were performed with the SPSS 16.0 software. The figures were produced in the Origin 2021 software and the R 3.6.3 software. One-way analysis of variance was performed with Duncan's test ($P < 0.05$).

3 Results

3.1 Soil physical properties and root morphological traits of gully headwalls

3.1.1 Soil physical properties

Figure 3 shows the *NWC*, *SBD*, and *SHC* for different soil layers under different land use types. The *NWC*s for bare land and farmland were significantly larger than those for grassland and forestland ($P < 0.01$). For bare land and grassland, the *NWC* of the surface layer (0–20 cm) was lower than those of the other soil layers, but it was 138–204% higher than those of the lower layers for forestland. In terms of the *SBD*, there was no significant difference in the *SBD* among the different land use types and soil layers. The *SBD* ranged between 1.19 and 1.37 g cm^{-3}, with an average of 1.26 g cm^{-3} and a small variation (coefficient of variation = 4%). The *SHC* exhibited great differences among different land use types and soil layers, and the *SHC* at the 0–20 cm layer was the highest (1.83 mm min^{-1}) and was significantly higher than those of all other soil layers for farmland.

Figure 4 shows the contents and distribution characteristics of soil aggregates for different land use types. The soil content of water-stable aggregates with a diameter of > 0.25 mm ($SWA_{>0.25}$) at the gully headwall of farmland, grassland and forestland was higher than that of bare land. The $SWA_{>0.25}$ for bare land, grassland and forestland decreased with increasing soil depth and decreased by 38%, 73%, and 38% when the soil layer changed from 0–20 cm to 80–100 cm, respectively. The change trend of $SWA_{>0.25}$ did not clearly vary over the vertical depth for farmland. Moreover, the $SWA_{>0.25}$ for bare land and farmland was mainly composed of aggregates in the 1–0.5 mm and 0.5–0.25 mm diameter classes and contained a few aggregates > 5 mm in diameter. However, the contents of the aggregates > 5 mm in diameter for grassland and forestland were much higher than those for bare land and farmland.

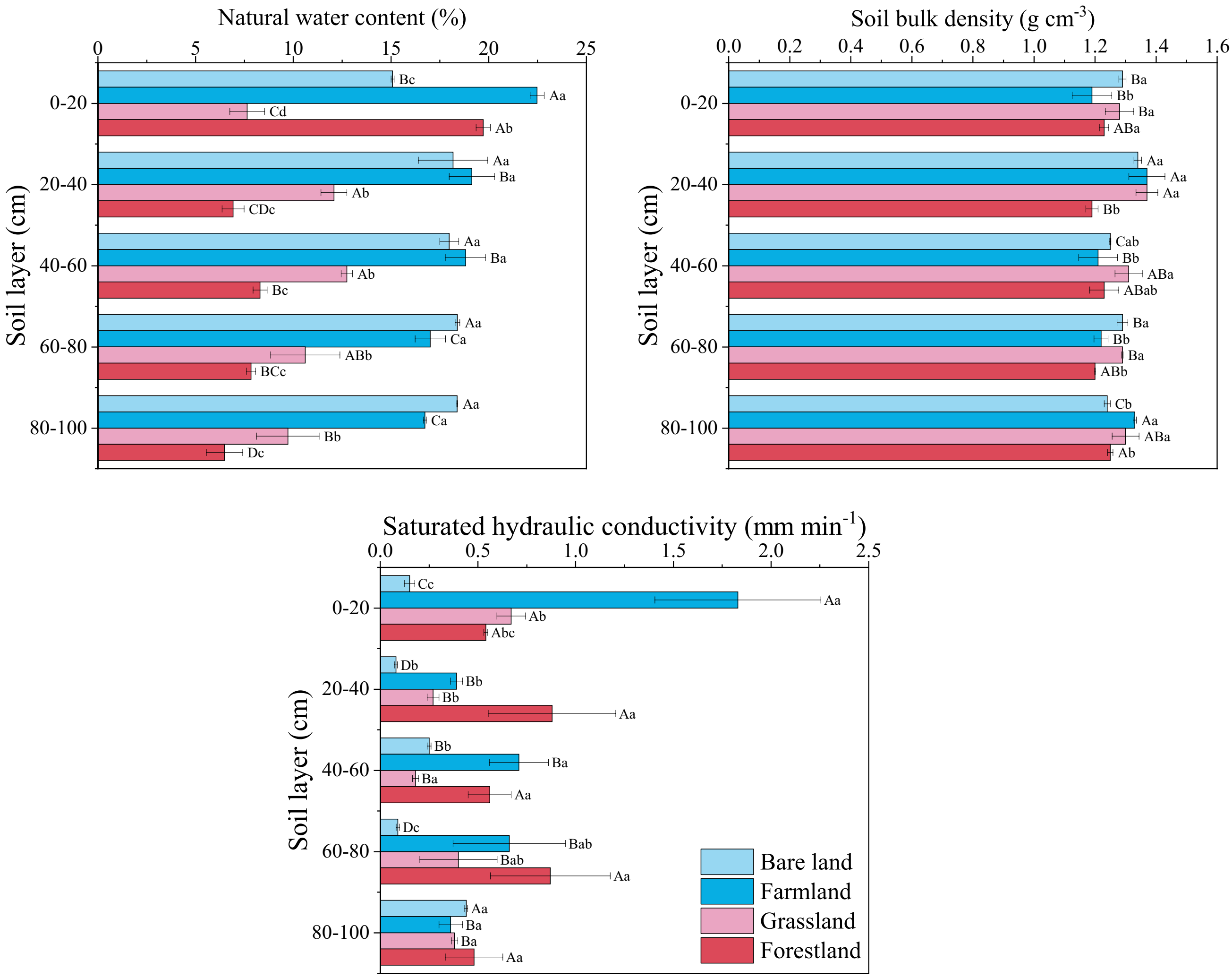

Fig. 3 The *NWC*, *SBD*, and *SHC* at different soil layers for different land use types. *NWA*, natural water content; *SBD*, soil bulk density; *SHC*, saturated hydraulic conductivity. Capital letters and lowercase letters indicate significant differences between different soil layers in the same land and significant differences in the same soil layer, respectively. Note: Duncan's statistical analysis was used

Figure 5 shows the *SDR* characteristics at different gully headwalls. The *SDR* in bare land was the largest (average of 80.75%), followed by those in farmland (average of 61.94%) and grassland (average of 44.93%), and the *SDR* in forestland was the smallest (average of 39.60%). The *SDR* in bare land, grassland, and forestland increased with increasing soil layer depth, but that in farmland was the highest at soil depths of 0–20 and 20–40 cm. As the soil layers increased from 0–20 cm to 80–100 cm, the *SDR* in grassland, forestland and bare land increased by 374%, 146% and 16%, respectively.

3.1.2 Root morphological traits

The root parameters (*RMD*, *RLD*, *RAD*, and *RVD*) decreased with increasing soil depth under farmland and grassland, while they increased first and then decreased under forestland (Fig. 6). With increasing soil depth, the difference in root parameters among the different soil use types decreased. The root characteristic parameters in the soil layers below 40 cm in farmland were very small, indicating that crop roots were mainly concentrated in the 0–40 cm soil layer. The root parameters in the topsoil layer (0–20 cm) of grassland were significantly higher than those of farmland and forestland, with levels 4.8–7.2 times and 2.5 times those of farmland and forestland, respectively.

As shown in Fig. 7, for each land use type, the *RLD* mainly included roots with a diameter of 0–0.5 mm, followed by 0.5–1 mm, both of which accounted for more than 91% of the *RLD*. The *RAD* was also dominated by roots with a diameter of 0–0.5 mm, accounting for 38–80%, followed by roots with a diameter of 0.5–1 and 1–2 mm, accounting for 16–37%. However, the *RVD* showed a different trend, where the volume of roots with diameters of 1–2, 2–3, and > 3 mm increased significantly.

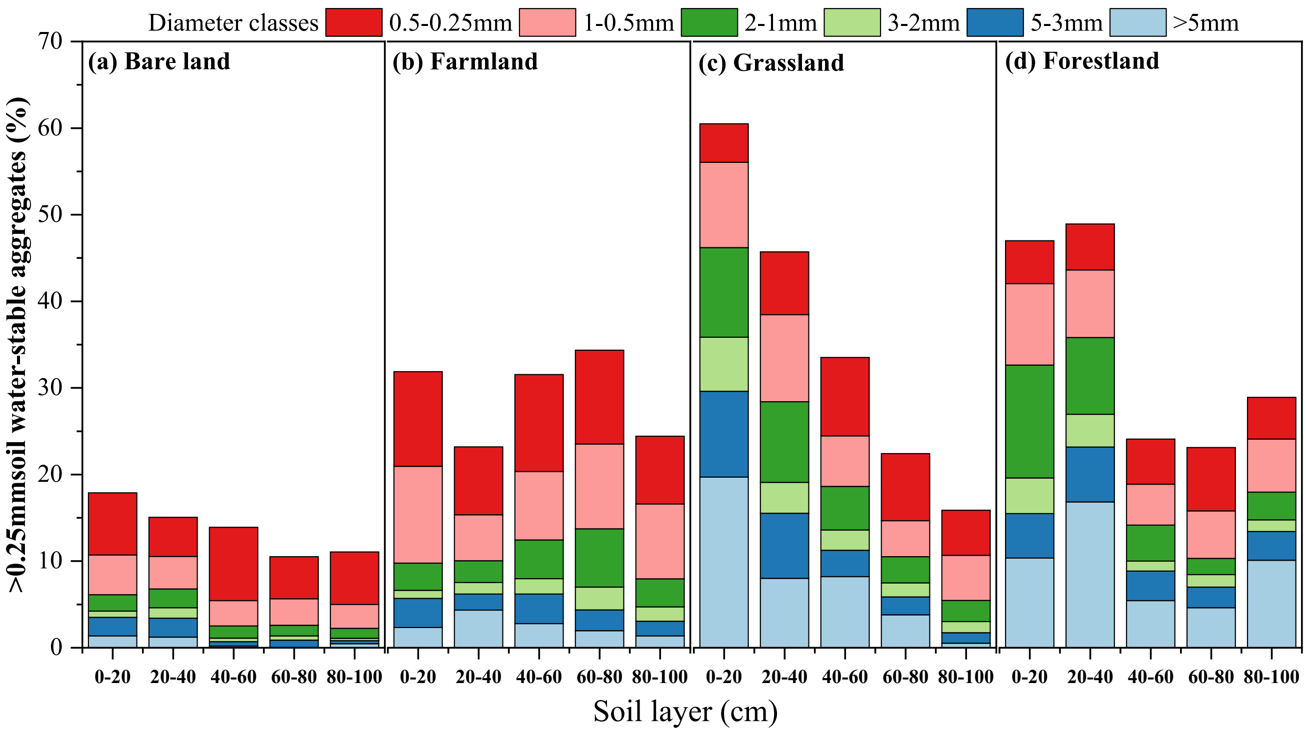

Fig. 4 Content and distribution characteristics of soil aggregates for different land use types

3.2 Soil antiscourability characteristics

There were significant differences in the *ANS* of gully headwalls under different land use types (Fig. 8). The *ANS* of forestland was significantly higher than that of other types of land use, among which bare land had the lowest *ANS*. Overall, the land use types ranked in order of highest to lowest *ANS* values were forestland, grassland, farmland and bare land. The *ANS* varied in the range of 3.22–8.21 L g^{-1}, 3.72–38.48 L g^{-1}, 5.19–69.07 L g^{-1}, and 9.22–83.19 L g^{-1} in bare land, farmland, grassland, and forestland, respectively. The average *ANS* values for forestland, grassland and farmland were 8.7, 5.9, and 4.5 times the average of that for bare land, respectively.

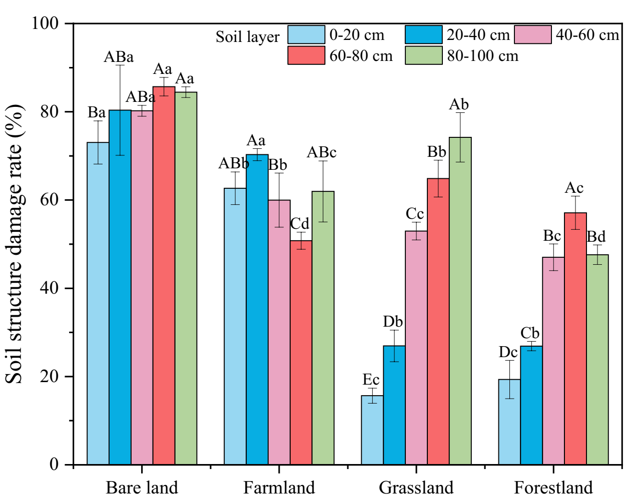

Fig. 5 Soil structure damage rates of different gully headwalls. Capital letters and lowercase letters indicate significant differences between different soil layers in the same land and significant differences in the same soil layer, respectively. Note: Duncan's statistical analysis was used

The *ANS* of the gully headwall for bare land, grassland, and forest decreased with increasing soil depth. The *ANS* in the 80–100 cm soil layer decreased by 61% for bare land, 89% for farmland and forestland, and 92% for grassland compared to the corresponding values in the 0–20 cm layer. Furthermore, the variation in the *ANS* values among the different land use types gradually weakened with increasing soil depth. Specifically, the *ANS* of farmland also decreased with increasing soil layer depth overall, and the *ANS* in the 20–40 cm layer was the highest. In addition, compared with those of bare land, the *ANS* values of the other three land use types in the 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers increased by 3.0–9.1, 6.7–8.6, 2.6–10.5, 3.9–5.6, and 0.2–1.9 times, respectively. The *ANS* values of the different soil layers in forestland were always the maximum.

3.3 Relationship between *ANS* and the root characteristics and soil properties

Figure 9 shows the correlation matrix of the *ANS*, soil properties and root characteristic index values. *ANS* had a

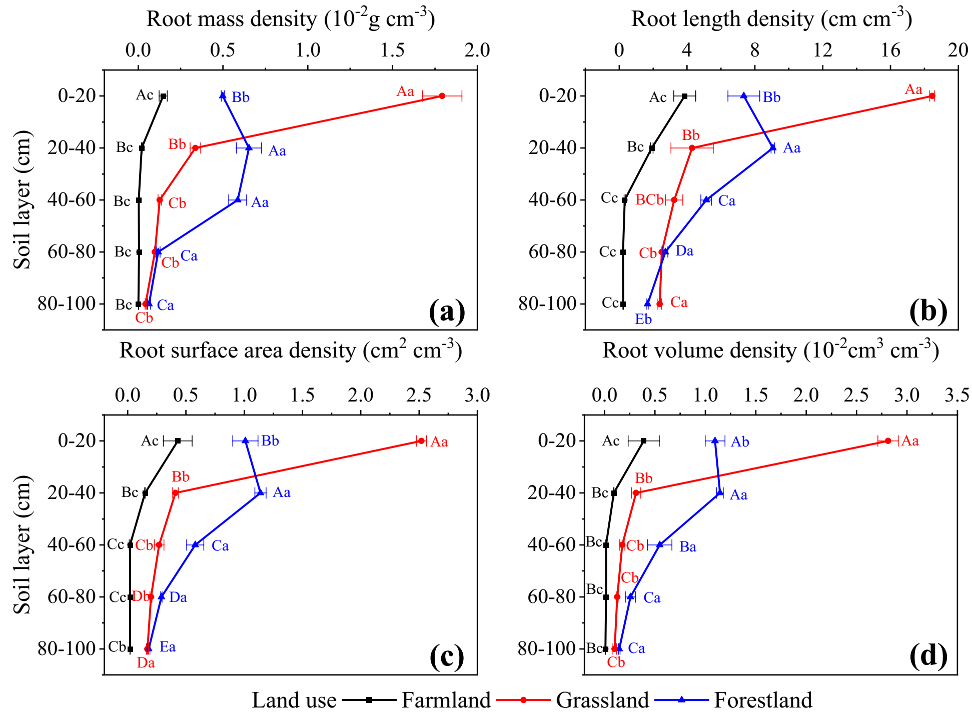

Fig. 6 Vertical variations in *RMD*, *RLD*, *RAD*, and *RVD* at the gully headwalls under different land use types. *RMD*, root length density; *RLD*, root length density; *RAD*, root surface area density; *RVD*, root volume density. Capital letters and lowercase letters indicate significant differences between different soil layers in the same land and significant differences in the same soil layer, respectively. Note: Duncan's statistical analysis was used

nonsignificant correlation with *SBD* and *SHC*, whereas it had a significant positive correlation with $SWA_{>0.25}$, *RLD*, *RAD*, and *RVD* and a significant negative correlation with *SDR*, with the strongest correlation. Regression analysis between the *ANS* and the root and soil characteristics of the gully headwall (Fig. 10) showed that there was a power relationship between *ANS* and $SWA_{>0.25}$ ($P < 0.01$) and a logarithmic relationship between *ANS* and *SDR*, *RLD*, *RAD*, and *RVD* ($P < 0.01$).

Table 2 shows the relationship between the root characteristics of each diameter class and *ANS*. *ANS* was significantly positively correlated with all selected indexes of roots with a diameter less than 3 mm ($P < 0.05$) and not significantly correlated with the indexes of roots with a diameter > 3 mm. The correlation coefficient between the root characteristics and *ANS* presented the order $r_{0.5–1} > r_{0–0.5} > r_{1–2} > r_{2–3}$ for the root length density and $r_{0–0.5} > r_{0.5–1} > r_{1–2} > r_{2–3}$ for the root surface area density and volume density.

4 Discussion

The plant root system plays an important role in improving soil *ANS*. Roots can directly conserve soil by root networks or indirectly improve soil erosion resistance by improving soil properties and promoting soil aggregate formation (Gyssels et al. 2005; De Baets et al. 2007; Guo et al. 2020a, b).

4.1 The direct effects of roots on *ANS* on gully headwalls

Our results showed a positive correlation between the *ANS* on gully headwalls and root characteristics with a logarithmic relationship (Figs. 9 and 10). This result was similar to prior research that has shown soil erosion resistance was closely related to root traits (Zhou and Shangguan 2005; Zhang et al. 2017; Guo et al. 2020a; Wang et al. 2021). Vegetation root systems can influence the soil erosion process by mechanical reinforcement, such as root unwinding and binding effects, and plant anchoring (Burylo et al. 2009, 2010; Ma et al. 2018). Plant roots, interweaving within the soil, bind soil particles or aggregates together and concatenate them (Ma et al. 2018). Enlarging the contact area between soil and plant roots can enhance soil stability and resistance to runoff and thereby improve soil *ANS* (Zhou and Shangguan 2005).

The *ANS* of gully headwalls was significantly positively correlated with the < 3 mm root system characteristics but not significantly correlated with roots > 3 mm (Table 2), indicating that the < 3 mm root system had a significant promoting effect on improving soil resistance. A previous study showed that fine roots (with a diameter < 3 mm) are more effective than coarse roots for soil fixation (Gyssels et al. 2005). Guo et al. (2020b) found that roots with diameters less than 0.5 mm have a greater effect on soil detachment than roots with a larger diameter. Li et al. (1991) also found

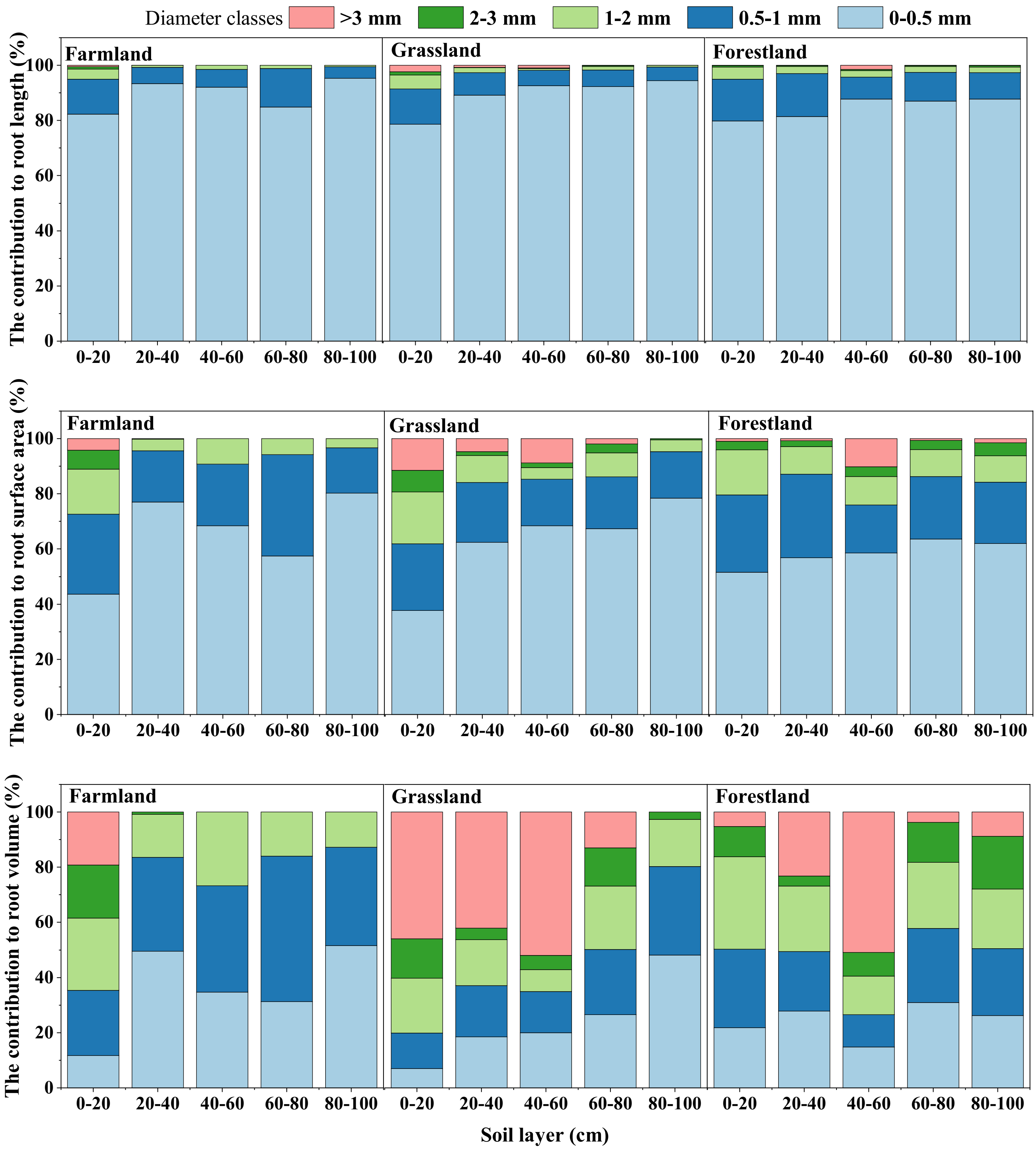

Fig. 7 The proportions of roots with different diameter classes contributing to root mass, root length, surface area, and volume for different soil layers at the gully headwalls under different land use types

that soil *ANS* depends mainly on the effective root density distribution and root entanglement, and it was noted that the most effective root density is that of roots with a diameter < 1 mm. A shallow and dense root network composed of fine roots, especially roots with diameters < 1 mm, is the most effective control measure to prevent soil loss in the processes of water erosion, playing an important role in improving soil erosion resistance (Gyssels et al. 2005). However, De Battisti et al. (2019) found that coarser roots are more important than smaller roots in binding the sediment, which may be related

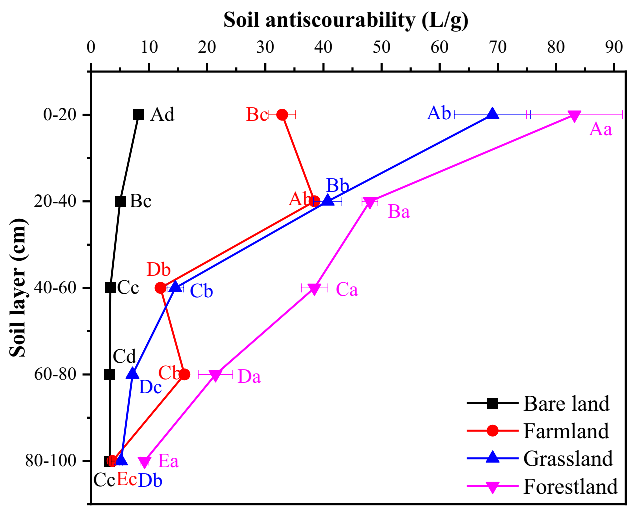

Fig. 8 Variations in soil antiscourability at different land use gully headwalls. Note: capital letters and lowercase letters indicate significant differences between different soil layers in the same land and significant differences in the same soil layer, respectively. Note: Duncan's statistical analysis was used

to the soil texture. The soil in the study of De Battisti et al. (2019) had a high sand content (more than 25%), while in this study, the soil was loessal soils and mainly composed of silt and clay (note: based on observations, we assume that the soil in this study had higher clay contents than the soils of De Battisti et al. (2019)). Therefore, the role of root systems with different diameters in different soil textures needs to be further studied.

In our experiment, in the 0–20 cm soil layer, the root system of the grassland was significantly greater than that of the forestland, and the *ANS* of the forestland was significantly higher than that of the grassland. Similar to the results by Fu et al. (2009), the land use involving mixtures of forest and grass was more effective than a land use combination of grass and shrubs in terms of soil erosion control. In our study, according to the comparison of vegetation composition between grassland and forestland, the dominant species in grassland was *Artemisia gmelinii*, among which *Artemisia gmelinii* accounted for the largest proportion and tap root vegetation. The understorey of forestland includes weeds, and the root system of weeds is mainly fibrous (Zhou et al. 2011). The degree of soil reinforcement by vegetation roots is highly plant specific and depends on the root system characteristics, such as the root architecture (Reubens et al. 2011). Studies show that fibrous-root vegetation has stronger effects on improving soil erosion resistance than tap-root vegetation (Guo et al. 2020b; Wang et al. 2021). In this study, although the root density of grassland was higher than that of forestland, the root contents of 0–0.5 mm and 0.5–1 mm in forestland were higher than those in grassland (e.g., the contributions to the surface area of 0–1 mm roots for grassland and forestland were 61.85 ± 3.64% and 79.54 ± 3.15% in the 0–20 cm soil layer, respectively (Fig. 7)), and some research work has shown that fine roots, especially roots with diameters < 1 mm, are the most effective control measure to prevent soil loss (Li et al. 1991; Gyssels et al. 2005).

Furthermore, this study found that the vertical distribution of *ANS* on gully headwalls in soil showed a similar trend to that of roots in soil. The roots gradually decreased with vertical depth, and the *ANS* on the gully headwalls also decreased with vertical depth (Figs. 3 and 8). This indicates that root density directly affects the vertical distribution of *ANS* on gully headwalls. Because of the distribution of roots, the *ANS* in grassland and forestland was much larger than that in bare land with no roots, and the *ANS* values of grassland and forestland were 8.7 times and 5.9 times that of bare land, respectively. Furthermore, this explains why the vertical wall at the gully head developed from the base during gully headcut erosion with a root system in Guo et al. (2019) and Kang et al. (2021) in the Loess Plateau.

4.2 The indirect effects of roots on *ANS* on gully headwalls

Our study showed that the *ANS* of gully headwalls was significantly correlated with aggregate-related indicators ($SWA_{>0.25}$ and *SDR*) ($P < 0.001$) (Fig. 9). The aggregate content had a significant relationship with the root system, especially with roots 0–0.5 mm in diameter (Table 3). Therefore, it can be concluded that the root system can indirectly affect the *ANS* by affecting the soil properties. This result is similar to those of De Baets et al. (2006) and Vannoppen et al. (2015). Fattet et al. (2011) also concluded that aggregate stability was closely related to root density. In addition, soil aggregate stability can directly affect soil erosion (An et al. 2009; Li et al. 2010). In our study, the *SWA* in the 0–40 cm soil layer displayed the order grassland > forestland > farmland > bare land (Fig. 7). This result was similar to that reported by An et al. (2013), who found that the *SWA* in farmland was less than that in grassland and forestland. Additionally, An et al. (2013) and Fattet et al. (2011) reported similar results that herbaceous vegetation was more efficient than trees in improving aggregate stability. In our study, it was also found that in the soil layers below 40 cm, although the root contents of grassland and forestland were significantly higher than that of farmland, the *SWA* did not significantly vary among the three types of land use (Fig. 4). The root density near the surface was high, and the larger production of root exudation and soil structure would be promoted (Merbach et al. 1999); thus, a high aggregate content in the upper layer of soil was formed. Plant roots and decomposition of organic material are known as some of the primary drivers of soil aggregate stabilization (Lucas et al. 2014; Six et al. 2004; Smith

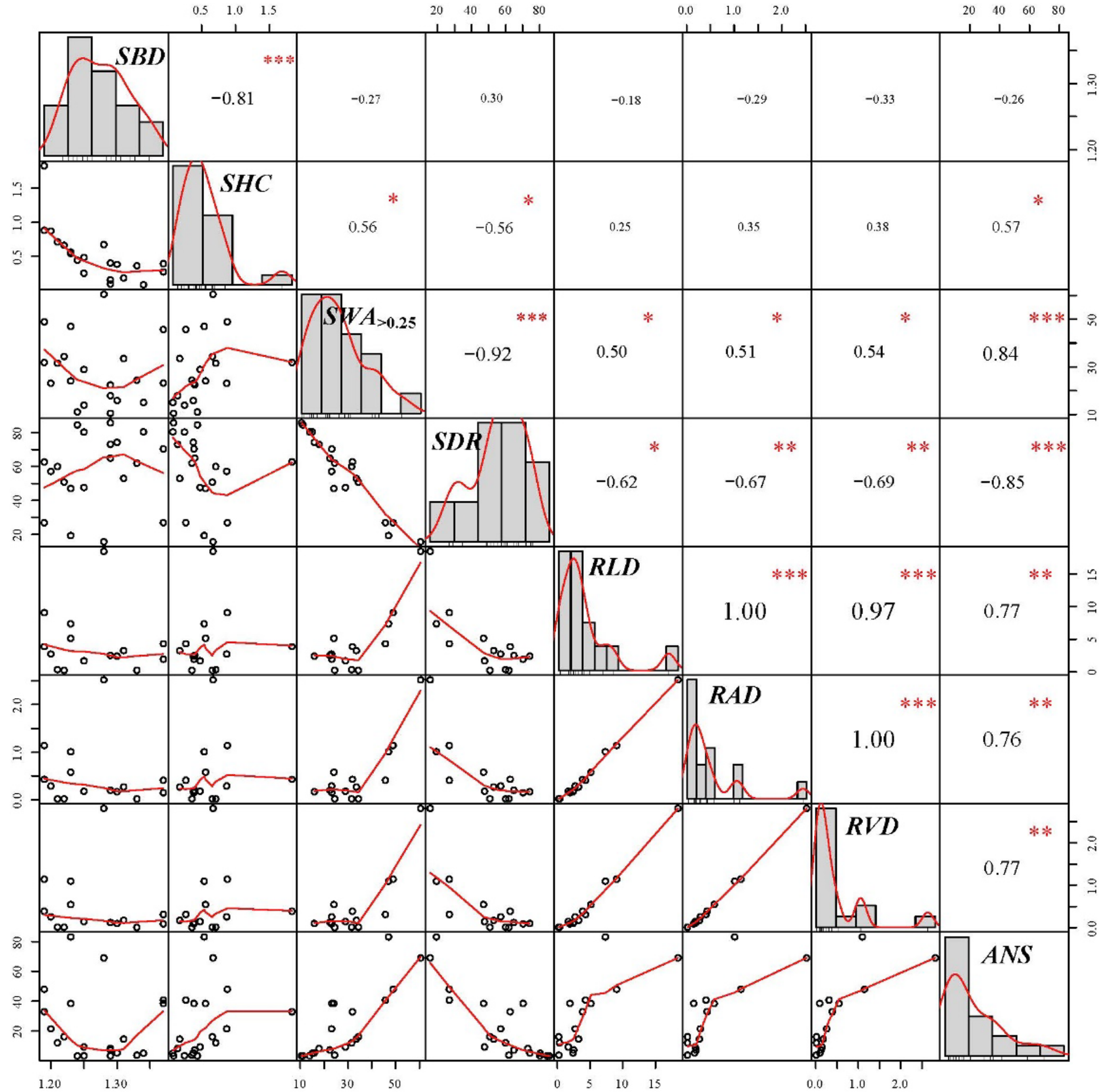

Fig. 9 Correlation between *ANS* at the gully headwall and soil and root characteristics. *, **, and *** indicate significance at the 0.05, 0.01, and 0.001 levels, respectively. Note: Spearman's correlation analysis was used

et al. 2022; Tang et al. 2011). The soil aggregate stability decreased with depth and was correlated with a decrease in the measured root parameters (e.g., *RLD*, *RAD*, etc.). However, exactly why this relationship exists is likely beyond the scope of this paper without further research.

In this study, the content of water-stable aggregates in soil containing roots was higher than that in bare land without roots (Fig. 7). This was mainly because root systems distributed in soils could provide a structural framework for the formation and initial stability of water-stable aggregates (Jastrow et al. 1998), promote the aggregation of small aggregates to large aggregates and improving the water stability of aggregates (Tang et al. 2016). Roots improve soil erosion resistance by promoting the formation of soil aggregates (An et al. 2013). Jastrow et al. (1998) showed that roots of different diameters have different effects on the formation of aggregates. Very fine roots (< 0.2 mm) are directly involved in the formation

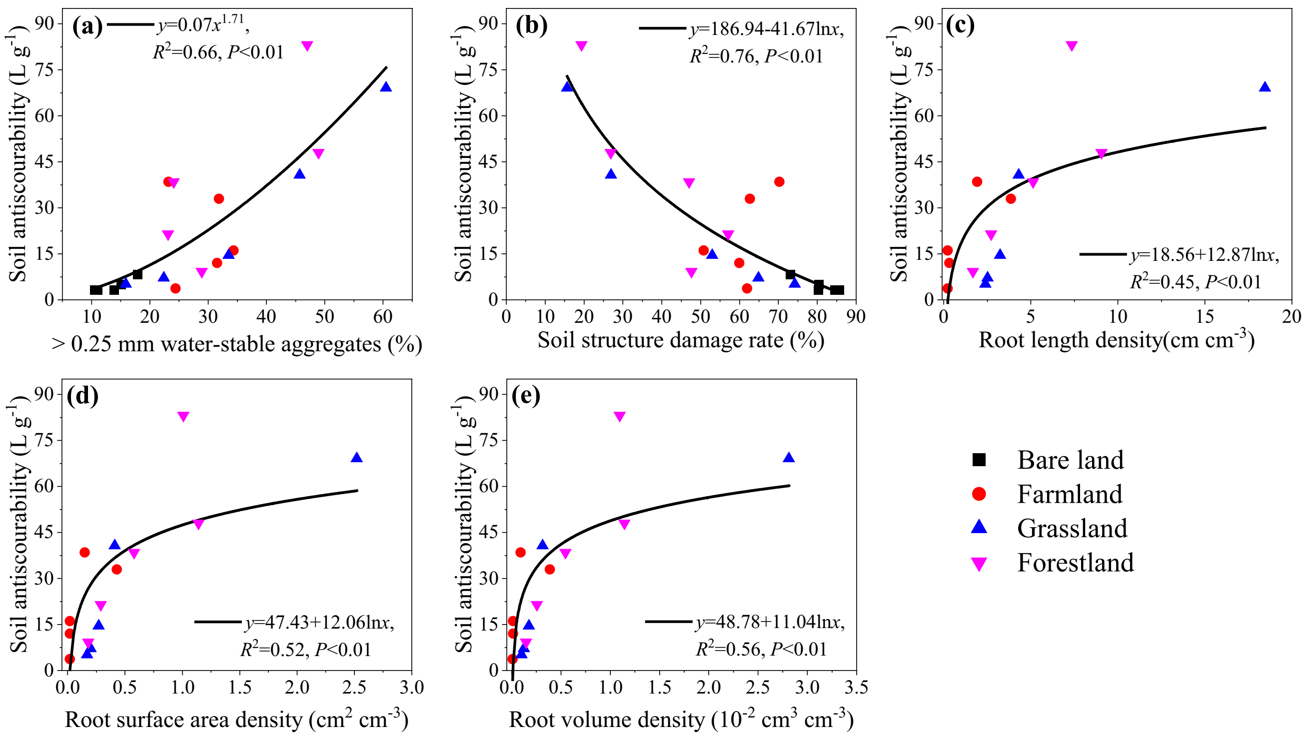

Fig. 10 The relationship between the *ANS* of gully headwalls and root and soil characteristics

of aggregates, while fine roots (0.2–1 mm) are largely indirectly involved (Jastrow et al. 1998). When the roots are finer, the correlations between water-stable aggregates with a diameter greater than 2 mm and *RLD*, *RAD*, and *RVD* are higher (Table 3). Table 3 indicates that the *SWA* with diameters of 2–1 mm has a significant positive correlation with roots with a diameter < 2 mm ($P < 0.05$), and the *SWA* with diameters of 0.5–0.25 mm has a significant negative correlation with roots with a diameter of 0–0.5 mm for each index parameter (*RLD*, *RAD*, *RVD*) ($P < 0.05$). Roots can promote the formation of water-stable aggregates with diameters > 2 mm, and roots with diameters of 0–0.5 mm are more likely to promote the aggregation of small aggregates into larger soil aggregates. Moreover, some studies have indicated that the presence of roots with a diameter < 0.5 mm is the best index to explain the variations in the stability of aggregates (Fattet et al. 2011).

4.3 Implications of this study

In our study, the gully headwalls containing roots had significantly higher *ANS* values than the gully headwalls without roots, and the *ANS* of gully headwall soil increased logarithmically with *RLD*, *RAD*, and *RVD* (Fig. 10). At a given vertical depth, the *ANS* under each land use type changed significantly with the root system. The *ANS* of the lower layer with fewer roots (or no roots) was significantly less than that of the upper layer with a higher root content. Moreover, the difference in *ANS* between the surface layer (0–20 cm) and bottom layer (80–100 cm) of bare land was only 4.99 L g^{-1}, while those of grassland and forestland were 63.88 L g^{-1} and 73.97 L g^{-1}. Grassland and forestland with abundant roots have a much higher *ANS* in the surface layer than in the lower layer. When runoff passes through the gully head, the erosion resistance of the lower layer is weak, and the erosion speed is fast, thus forming scour holes in the lower soil layer on the gully headwall (Chen et al. 2013; Zhang et al. 2016). At various vertical depths, the scour holes on gully headwalls are affected by the difference in soil erosion resistance, for example, as shown in Fig. 11. This is the reason why compared with the lack of roots in bare land, the presence of roots is conducive to the formation of scour holes at the gully head and changes the headcut retreat associated with gully erosion (Guo et al. 2019; Kang et al. 2021).

Vegetation restoration is one of the important measures to control gully headcut erosion (Vanmaercke et al. 2016). Reasonable configuration of the vegetation root network should be considered in the selection of vegetation. Many studies have found that the mixed vegetation planting mode was better than the single vegetation planting mode in controlling soil erosion (Fu et al. 2009). The combination of herbaceous plants, shrubs, and trees is the most effective measure

Table 2 Correlation analysis between *ANS* and root characteristics

	RLD (mm cm^{-3})					*RAD* (cm^{2} cm^{-3})					*RVD* (cm^{3} cm^{-3})				
Diameter classes/mm	0–0.5	0.5–1	1–2	2–3	> 3	0–0.5	0.5–1	1–2	2–3	> 3	0–0.5	0.5–1	1–2	2–3	> 3
ANS	0.758**	0.793**	0.730**	0.595*	0.496	0.805**	0.757**	0.698**	0.567*	0.511	0.841**	0.750**	0.694**	0.564*	0.507

* and ** indicate significance at the 0.05 and 0.01 levels, respectively

Table 3 Correlation between $SWA_{>0.25}$ and root characteristics

	RLD (0–0.5 mm)	*RLD* (0.5–1 mm)	*RLD* (1–2 mm)	*RLD* (2–3 mm)	*RLD* (> 3 mm)	*RAD* (0–0.5 mm)	*RAD* (0.5–1 mm)	*RAD* (1–2 mm)	*RAD* (2–3 mm)	*RAD* (> 3 mm)	*RVD* (0–0.5 mm)	*RVD* (0.5–1 mm)	*RVD* (1–2 mm)	*RVD* (2–3 mm)	*RVD* (> 3 mm)
SWA (> 5)	0.86***	0.87***	0.78**	0.71**	0.65**	0.78**	0.73**	0.71**	0.65**	0.66**	0.79***	0.72**	0.71**	0.65**	0.66**
SWA (5–3 mm)	0.85***	0.85***	0.82***	0.76**	0.72**	0.81***	0.79***	0.78**	0.72**	0.73**	0.80***	0.79***	0.78**	0.72**	0.74**
SWA (3–2 mm)	0.82***	0.85***	0.83***	0.75**	0.71**	0.80***	0.81***	0.80***	0.72**	0.71**	0.80***	0.80***	0.80***	0.72**	0.71**
SWA (2–1 mm)	0.64*	0.70**	0.63*	0.49	0.41	0.66**	0.63*	0.59*	0.45	0.42	0.69**	0.63*	0.58*	0.45	0.42
SWA (1–0.5 mm)	0.28	0.38	0.39	0.35	0.27	0.28	0.40	0.39	0.34	0.26	0.28	0.40	0.38	0.34	0.27
SWA (0.5–0.25 mm)	−0.57*	−0.53*	−0.47	−0.39	−0.36	−0.58*	−0.46	−0.44	−0.37	−0.38	−0.60*	−0.46	−0.44	−0.37	−0.38

*, **, and *** indicate significance at the 0.05, 0.01, and 0.001 levels, respectively

Fig. 11 Morphological characteristics of scour holes in gully headwalls

for soil and water conservation (Fu and Gulinck 1994). Although the soil resistance of forestland was the best in our study, planting trees near gully banks and/or heads may have aggravated the occurrence of gully erosion in some studies in recent years. Nyssen et al. (2006) also found that planting trees in some unreasonable locations could increase gully erosion. Oostwoud Wijdenes et al. (2000) concluded that gully head activity significantly increased as a result of increased apricot acreage in southeastern Spain. Therefore, the arrangement of mature forests and grasslands in the middle and upper slopes can significantly reduce soil erosion (Fu et al. 2009) in the process of controlling gully headcut erosion. In the selection of vegetation for gully heads, attention should be given to the combination of herbaceous plants and shrubs (Guo et al. 2020b). In other words, we recommend selecting a recovery model that combines shallow-rooted plants with deep-rooted plants.

5 Conclusion

The characteristics of the soil properties and soil *ANS* at gully headwalls in bare land and three vegetation types were studied. We found that overall, *RMD*, *RLD*, *RAD*, and *RVD* showed similar variations with vertical depth in the gully headwall soil under different vegetation types, all of which decreased with increasing soil depth. The $SWA_{>0.25}$ in bare land, grassland, and forestland decreased gradually with increasing soil depth. The average *ANS* for forestland, grassland, and farmland was 8.7 times, 5.9 times, and 4.5 times greater than that for bare land, respectively. The *ANS* at each layer of the gully headwalls in bare land, grassland, and forest decreased with increasing soil depth. The *ANS* had a significant positive correlation with $SWA_{>0.25}$, *RLD*, *RAD*, and *RVD* and had a significant negative correlation with the rate of soil structure damage. *ANS* showed a logarithmic relationship with *RLD*, *RAD*, and *RVD* (R^2 values were 0.45, 0.52, and 0.56, respectively; $P < 0.01$). Overall, because of the decrease in root density, the *ANS* decreased. In the process of gully head management, attention should be given to the combined use of herbaceous plants and shrubs.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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